Use of Well Logs for Petrophysical Evaluation of Abu Madi Reservoir in Abu Madi-ElQara-Nidoco Area, Northern Nile Delta, Egypt

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Abstract

The open-hole wire line log data of seven wells are used to study the petrophysical characteristics of the Late Miocene Abu Madi Formation (levels II and III) in Abu Madi-El-Qara-Nidoco area, northern Nile Delta, Egypt. The vertical variation of the petrophysical characteristics is presented as lithosaturation cross-plots. The parameters distribution maps (shale volume, effective porosity, fluid saturation, net pay thickness and hydrocarbon saturation) are used to represent the lateral variation of petrophysical characteristics. Cross plots show that the main reservoir lithology is shaly sandstone with laminated to dispersed shale in level II and dispersed shale and minor laminated shale in level III. The shale volume ranges from 0.19 to 0.71 for level II and from 0.19 to 0.47 for level III. The effective porosity ranges from 0.03 to 0.22 for level II and from 0.06 to 0.19 for level III. The hydrocarbon saturation reaches up to 0.88 for level II and up to 0.81 for level III. The net-pay thickness ranges from 50 to 101 m for level II and from 30 to 153 m for level III. The net-pay thickness ranges from 75 to 90 m for level II and from 22 to 110 m for level III. Maps show that the most favorable places for hydrocarbon reservoirs occupy southwestern part for Abu Madi level II reservoir and in the middle, the middle-west, the middle-east and the southeastern parts for Abu Madi level III reservoir.

Keywords: Petrophysical parameters; Shale content; Effective porosity; Shale type; Net reservoir; Reservoir flag; Net pay; Pay flag.

Introduction

The thick sequence of Neogene-Quaternary clastics in the Nile Delta basin is considered to be prospective for oil and gas. The offshore parts and the northern parts of the onshore area of the Nile Delta are favorable sites for hydrocarbon generation and accumulation [1]. Abu Madi sandstone is the main proven reservoir within the Miocene (Messinian) deltaic sequences of the northern Delta basin [2].

The discoveries in the Nile Delta make it one of the most world known deltas. Abu Madi-El-Qara-Nidoco area is a giant field located in the northeastern part of the Nile Delta. Abu Madi field is the first commercial discovery in the Nile Delta, where IEOC (Italian Egyptian Oil Company) achieved the first gas discovery from the early Pliocene Abu Madi formation in the northeastern part of the onshore delta by drilling the Abu Madi-1 well [3].

The study area is located in the northern part of the Nile Delta, between longitude 31°13'48" and 31°24'36" E and latitude 31°21'36" and 31°37'12" N (Figure 1). Seven wells (AM-16, AM-18, AM-20, AM-21, El-Qara-3, Nidoco-7 and Nidoco-10) are available to evaluate Abu Madi Formation.

Abu Madi Formation includes thick bodies of cross-beded sandstones that are occasionally pebbly with thin shale interbeds in Abu Madi well-1 type section. The lower part of the formation is the most sand rich (level I) [4].

The main objective of the present study is to quantitatively evaluate the petrophysical parameters of the hydrocarbon reservoir; including the shale content, effective porosity and water and hydrocarbon saturations. Construction of the lithosaturation crossplots in addition to distribution parameters maps have been accomplished to represent the vertical and lateral distribution of petrophysical parameters of the two reservoirs rock units (Abu Madi levels II and III).

Geological Settings

The Nile Delta is an old feature started to build by the advent of the Upper Pliocene and took its form by the beginning of the Pleistocene [5-7]. Mesozoic beds were penetrated only in a few wells across the

Figure 1: Location map of the study area showing well locations.

Citation: Ghoneimi A, Ibrahim Sh A, El-Kenawy A, Farrag Kh (2018) Use of Well Logs for Petrophysical Evaluation of Abu Madi Reservoir in Abu Madi-ElQara-Nidoco Area, Northern Nile Delta, Egypt. J Geol Geophys 7: 323. doi: 10.4172/2381-8719.1000323

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middle and southern parts of the Nile Delta because of the northward thickening of the Tertiary section [8]. Near the hinge line, the wells penetrating the Pre-Miocene formations include the series from Upper Jurassic to Oligocene. They consist of shore shelf and lagoonal deposits [3,9,10].

Paleocene and Eocene sediments in the Western Desert and the western side of the Delta were mainly deposited in narrow and elongated basins trending northeast-southwest. This situation most probably extends to the area of the Nile Delta [11]. The Early to Middle Eocene were deposited in a narrow elongated E-W trending basin with a distinct flexure zone in the mid-Delta area [12]. Oligocene sediments are represented by the Tineh Formation of Late Oligocene-Early Miocene age, which is composed of a series of marine to fluvio-marine shales and sandstone interbeds [13].

Neogene-Quaternary rock units in the Nile Delta area were grouped into three sedimentary cycles with different environmental parameters [14]. The Neogene-Quaternary subsurface succession in the northern part of the Nile Delta basin has been subdivided into eight formations arranged from base to top: Sidi Salem, Qawasim, Rosetta, Abu Madi, Kafir El-Sheikh, El-Wastani, Mit Ghamr and Bilqas formations [3,13,15]. The generalized litho-stratigraphic column of Abu Madi area [13] is shown in Figure 2.

The Nile Delta is divided into two geological provinces; the deep offshore Nile Delta province, north of the continental shelf and the onshore Nile Delta province. The onshore Nile Delta is subdivided by the Hinge Zone into the South Nile Delta block and the North Nile Delta basins [3,10,16].

### Well Log Data

The available open-hole wire line log data of seven wells (AM-16, AM-18, AM-20, AM-21, El Qara-3, Nidoco-7 and Nidoco-10) are used in this study (Table 1). These logs include the caliper (CL), gamma ray (GR), spontaneous potential (SP), formation density (RHOB), neutron porosity (NPHI), sonic (DT) and resistivity logs (LLD, LLS, MSFL, ILD, ILM, AT10, AT90). The well logs are digitized by converting field analog prints into digital data (0.5 m interval) which stored as a data base for easy access and calculation.

### Petrophysical Analysis

The well logs data are analyzed using the Interactive Petrophysics software (version 3.5). These conventional logs are used as a supplementary method for getting some results about lithology, porosity, and fluid type. For logs interpretation, the data are needed to be in good conditions. The borehole conditions and mud types can affect the quality of the logs and make some troubles in log readings or cause stationary readings of the logs, which are not correct and lead to miss-interpretation of the logs. In this study, the logs have varying qualities without any evidence of stationary readings.

The gamma ray, density, neutron and sonic logs are used as lithology and porosity indicators. The neutron-density, neutron-sonic and M-N cross-plots are used to determine lithology [17-20].

The formation water resistivity (Rw) calculated from SP log is used to create a continuous Rw curve (Rwsp). This is useful for estimating Rw values over a number of zones. The result Rwsp curve is corrected to the well temperature curve. Table 2 contains the petrophysical constants used in the log data analysis.

The calculated Rw of Abu Madi Formation in wells AM-18, AM-20, AM-21 and Nidoco-7 are ranging from 0.04 to 0.05 ohm-meter. The value in well AM-16 is ranging from 0.04 to 0.07 ohm-meter. The graphical technique, where the mono porosity crossplot (Pickett crossplot), is constructed between the resistivity of uninvaded zone and the porosity deduced from porosity tools [17-20], this method had been used to calculate Rw of Abu Madi Formation in well Nidoco-10, where SP log is not available in this well. The Rw value in this well (Nidoco-10) is ranging from 0.02 to 0.05 ohm-meter.

Shale content (Vsh) is calculated from the combination of density and neutron logs using the double clay indicator and the GR clay indicator using the linear method. The determination of effective porosity (Φeff) is executed in both clean and shaly rock units by the combination of the density and neutron logs measurement by using a mathematical equation of Poupan and Gaymard [17-20].

The Archie’s water saturation equations assume that the formation water is the only electrically conductive material in the formation. The

**Well name** | Available well logs
---|---
AM-16 | CL, GR, SP, RHOB, NPHI, DTL, ILM, and MSFL
AM-18 | CL, GR, SP, RHOB, NPHI, DTL, ILD and MSFL
AM-20 | CL, GR, SP, RHOB, NPHI, DTL, ILD and MSFL
AM-21 | CL, GR, SP, RHOB, NPHI, DTL, ILD, ILM and MSFL
El-Qara-3 | GR, RHOB, NPHI and DTL
Nidoco-7 | CL, GR, SP, RHOB, NPHI, DTL, AT90 and AT 10
Nidoco-10 | CL, GR, RHOB, NPHI, DTL, AT90 and AT 10

*Table 1: The available open hole wire line logs of the studied wells.*
presence of shale requires the existence of another conductive material other than water. The dual water model is an elaborated model to explain the effects of clay on resistivity. In the dual water model the water saturation formation behaves as if it contains two types of water. The first one is the water near the clay (clay water or bound water), the second type is the water far from this water is salt free and its conductivity is independent of the ion concentrations and type of clay. The second type of water is the far water [21].

The porosity and water saturation interpretation module is used to interactively calculate porosity ($\phi$), water saturation ($S_w$), flushed zone water saturation ($S_{xo}$), matrix density ($\rho_{ma}$), hydrocarbon concentrations and type of clay. The second type is the water far from the clay surface (far water) [21].

The well logs analysis is accomplished on Abu Madi reservoir levels II and III. The shale type is determined by choosing the shale model, density ($\rho_{hy}$) and wet and dry clay volumes ($V_{wcl}$ and $V_{dcl}$).

The porosity and water saturation interpretation module is used to interactively calculate porosity ($\phi$), water saturation ($S_w$), flushed zone water saturation ($S_{xo}$), matrix density ($\rho_{ma}$), hydrocarbon concentrations and type of clay. The second type is the water far from the clay surface (far water) [21].

Evaluation of Lithological Components

The gamma-ray, density, neutron, and sonic logs are used as indicators of lithology using lithology identification charts (Diaporosity and Tri-porosity cross-plots). Density-neutron, neutron-sonic and MN cross-plots are used for lithology identification. Figures 5 and 6 illustrate examples to represent the neutron-density crossplots of Abu Madi levels II and III in the available wells. These cross-plots reflect that the main lithology type in Abu Madi level II is shaly sandstone in wells AM-21 and Nidoco-7, but it is sandy-shale in wells

### Table 2: Petrophysical constants used in log data analysis.

| Well name | $V_r$ (Min.) | $\phi$ (Max.) | $S_r$ (Min.) | $S_w$ (Av.) | $\rho_{ma}$ (Min.) | $\rho_{ma}$ (Av.) | $\rho_{hy}$ (Min.) | $\rho_{hy}$ (Av.) | $c_{clay}$ (Min.) | $c_{clay}$ (Av.) | $f$ (Min.) | $f$ (Av.) |
|-----------|--------------|---------------|--------------|-------------|-------------------|-------------------|-------------------|-------------------|-----------------|-----------------|-------------|-------------|
| AM-16     | 0.28         | 0.76          | 0.58         | 0.05        | 0.41              | 0.16              | 0.33              | 1.00              | 0.54            | 0.00            | 0.67        | 0.46        |
| AM-18     | 0.12         | 0.65          | 0.42         | 0.02        | 0.25              | 0.12              | 0.04              | 1.00              | 0.47            | 0.00            | 0.96        | 0.53        |
| AM-20     | 0.49         | 0.89          | 0.71         | 0.03        | 0.21              | 0.07              | 0.39              | 1.00              | 0.97            | 0.00            | 0.61        | 0.03        |
| AM-21     | 0.1          | 0.55          | 0.28         | 0.12        | 0.30              | 0.22              | 0.01              | 0.70              | 0.12            | 0.30            | 0.99        | 0.88        |
| El-Qara-3 | 0.13         | 0.71          | 0.47         | 0.01        | 0.22              | 0.08              | -                 | -                 | -               | -               | -           | -           |
| Nidoco-7  | 0.09         | 0.36          | 0.19         | 0.09        | 0.37              | 0.19              | 0.45              | 1.00              | 0.68            | 0.00            | 0.55        | 0.32        |
| Nidoco-10 | 0.08         | 0.80          | 0.64         | 0.01        | 0.08              | 0.03              | 0.58              | 1.00              | 0.99            | 0.00            | 0.42        | 0.01        |

### Table 3: Petrophysical evaluation results, Abu Madi formation and Level II reservoir unit.

| Well name | $V_r$ (Min.) | $\phi$ (Max.) | $S_r$ (Min.) | $S_w$ (Av.) | $\rho_{ma}$ (Min.) | $\rho_{ma}$ (Av.) | $\rho_{hy}$ (Min.) | $\rho_{hy}$ (Av.) | $c_{clay}$ (Min.) | $c_{clay}$ (Av.) | $f$ (Min.) | $f$ (Av.) |
|-----------|--------------|---------------|--------------|-------------|-------------------|-------------------|-------------------|-------------------|-----------------|-----------------|-------------|-------------|
| AM-16     | 0.07         | 0.65          | 0.24         | 0.04        | 0.23              | 0.16              | 0.18              | 1.00              | 0.44            | 0.00            | 0.82        | 0.56        |
| AM-18     | -            | -             | -            | -           | -                 | -                 | -                 | -                 | -               | -               | -           | -           |
| AM-20     | 0.03         | 0.63          | 0.21         | 0.06        | 0.25              | 0.17              | 0.01              | 1.00              | 0.19            | 0.00            | 0.99        | 0.81        |
| AM-21     | -            | -             | -            | -           | -                 | -                 | -                 | -                 | -               | -               | -           | -           |
| El-Qara-3 | 0.14         | 0.58          | 0.28         | 0.01        | 0.17              | 0.11              | -                 | -                 | -               | -               | -           | -           |
| Nidoco-7  | 0.12         | 0.60          | 0.19         | 0.12        | 0.24              | 0.19              | 0.31              | 1.00              | 0.55            | 0.00            | 0.69        | 0.45        |
| Nidoco-10 | 0.16         | 0.69          | 0.47         | 0.01        | 0.24              | 0.06              | 0.09              | 1.00              | 0.33            | 0.00            | 0.91        | 0.67        |

### Table 4: Petrophysical evaluation results, Abu Madi formation, Level III reservoir unit (Level III is missing in wells AM-18 and AM-21).

| Well name | $V_r$ (Min.) | $\phi$ (Max.) | $S_r$ (Min.) | $S_w$ (Av.) | $\rho_{ma}$ (Min.) | $\rho_{ma}$ (Av.) | $\rho_{hy}$ (Min.) | $\rho_{hy}$ (Av.) | $c_{clay}$ (Min.) | $c_{clay}$ (Av.) | $f$ (Min.) | $f$ (Av.) |
|-----------|--------------|---------------|--------------|-------------|-------------------|-------------------|-------------------|-------------------|-----------------|-----------------|-------------|-------------|
| AM-16     | -            | -             | -            | -           | -                 | -                 | -                 | -                 | -               | -               | -           | -           |
| AM-18     | -            | -             | -            | -           | -                 | -                 | -                 | -                 | -               | -               | -           | -           |
| AM-20     | 0.03         | 0.63          | 0.21         | 0.06        | 0.25              | 0.17              | 0.01              | 1.00              | 0.19            | 0.00            | 0.99        | 0.81        |
| AM-21     | -            | -             | -            | -           | -                 | -                 | -                 | -                 | -               | -               | -           | -           |
| El-Qara-3 | 0.14         | 0.58          | 0.28         | 0.01        | 0.17              | 0.11              | -                 | -                 | -               | -               | -           | -           |
| Nidoco-7  | 0.12         | 0.60          | 0.19         | 0.12        | 0.24              | 0.19              | 0.31              | 1.00              | 0.55            | 0.00            | 0.69        | 0.45        |
| Nidoco-10 | 0.16         | 0.69          | 0.47         | 0.01        | 0.24              | 0.06              | 0.09              | 1.00              | 0.33            | 0.00            | 0.91        | 0.67        |
AM-18 and El-Qara-3 and shale or silty shale in wells AM-16, AM-20 and Nidoco-10, while the lithology type in level313

Litho-saturation Crossplots

The vertical variation of shale content, lithology, porosity, saturation and net pay zones are presented as lithosaturation crossplots. The net reservoir and net pay intervals in the wells have been presented in Table 5 and as histogram in Figure 7. The litho-saturation crossplots of the studied wells are summarized as petrophysical and lithological characteristics (Figure 8), petrophysical and fluids saturation parameters (Figure 9) and net reservoir and net pay intervals (Figure 10).

Figure 8 displays the proportion of wet clay, silt, sandstone porosity and shale type. It is shown that the lithology of Abu Madi level II is shaly sandstone in wells AM-18, AM-21 and Nidoco-7, while it is sandy shale in wells AM-16 and El-Qara-3 and shale or silty shale in wells AM-20 and Nidico-10; while in level III it is shaly sandstone in well Nidico-7, shaly sandstone to sandy shale in wells AM-16, AM-20 and El-Qara-3, and mainly shale in well Nidico-10. This lithology matches mainly the lithology shown in density-neutron cross plots of Figures 5 and 6 with some differences due to the difference of estimation methods. The shale type of level II is mainly laminated, partly dispersed and rarely structural; while in level III it is mainly dispersed, partly laminated in the top of the level, and rarely structural.

Figure 9 illustrates the porosity (total and effective) and fluid saturation (\(S_w\) and \(S_o\)), in addition to the movable hydrocarbon. These plots show the predominance of gas in level II in wells Am-18, AM-21 and Nidoco-7; and in level III in wells AM-20, AM-16, Nidoco7 and Nidico-10.

Figure 10 shows the input porosity tools including the neutron, density and sonic curves and the cut-offs that define net-reservoir and net-pay. Figures 7 and 10 show the prevalence of net-reservoirs and
Distribution Maps of Petrophysical Parameters

The isoparametric maps (horizontal distribution maps) represent the lateral configuration of the petrophysical analysis in the study area. These maps include thickness maps (isopach) and the petrophysical parameters maps, including shale content (Vsh), effective porosity (PHIE), water saturation (Sw) and hydrocarbon saturation (Sh) distribution maps of Abu Madi Formation, levels II and III.

The shale content (Vsh) of Abu Madi level II reservoir varies from 10% to 70% (Figure 11). It decreases toward the southwestern and northeastern parts and increase at the middle, southeastern and...
northwestern parts. In Abu Madi level III reservoir (Figure 11) the shale content varies from 10% to 50%. It is decreasing at the eastern direction and increasing slowly toward the west (the southwestern part is blanked, because level III is missing in wells AM-18 and AM-21). This distribution shows that the increase or decrease of shale content of the studied fluvio-marine Abu Madi Formation (Figure 2) may be attributed to that it was deposited in a channel of a NW-SE trend. In such depositional environment, the shale is deposited in the channel central course, while the sand or shaly sand was deposited towards the channel flanks to the southwest and northeast directions.

The effective porosity ($\phi_{eff}$) of Abu Madi level II reservoir changes from 2% to 23%. It increases toward northeast and southwest directions and is decreasing toward the middle part (Figure 12a). In Abu Madi level III reservoir the effective porosity changes from 3% to 21%. It increases toward the east and northeastern parts, but decreases at the west as shown in Figure 12b. This distribution indicates that the variation of the effective porosity is mostly due to the variation of shale content which decreases the effectiveness of the porosity. Therefore, the porosity is decreasing in the central course of the proposed channel, where the shale is predominant. Towards the channel flanks the porosity is increasing due to shale decrease.

The water saturation ($S_w$) of Abu Madi level II reservoir fluctuates between 10% and 100%. It is increasing at the northwestern and eastern parts, but decreasing toward the northeastern and southwestern parts, as shown in Figure 13. While in Abu Madi level III reservoir the water saturation fluctuates between 10% and 60%. It decreases at the middle, northwestern and southeastern parts and increasing toward the northeastern direction, as shown on Figure 13. As shown from this distribution, the water saturation is mainly distributed according to the distribution of shale content. Therefore, water saturation increases...
at locations where the shale content increases at the channel central course.

The hydrocarbon saturation ($S_h$) of Abu Madi level II reservoir varies from 1% to 90%. It is decreasing at eastern and northwestern parts and is increasing toward northeastern and southwestern parts, as shown in Figure 14a. In Abu Madi level III reservoir varies from 4% to 90%. It increases at southeastern, middle and northwestern parts, but it is decreasing in the northeastern direction, as shown in Figure 14b. The predominance of hydrocarbon largely distributed at the flanks of the proposed channel where both the shale content and water saturation decrease and the effective porosity increases.

The total thickness of Abu Madi level II (Figure 15a) varies from about 105 m to 270 m. It increases toward the southwestern and northeastern directions (reaches 270 m in well AM-21 and 155 m in well Nidoco-7), then it is decreasing toward the middle, northwestern and southeastern directions (reaches 90 m in well Nidoco-10 and 110 m in well AM-16). The total thickness of Abu Madi level III varies from 0 to 160 m. It decreases to zero m in the middle, northwestern and southeastern parts, where the lithology of level II is sandy shale in the available drilled wells in these parts. Then, it increases in the northeastern and southwestern directions. The net pay (net flag) thickness of Abu Madi level III (Figure 17b) varies from 0 to 120 m. It decreases to zero in the southwestern direction, where level III is missing in wells AM-18 and AM-21. Then, it increases gradually toward the middle, southeastern, northwestern and northeastern directions.

The net reservoir (reservoir flag) thickness of level II (Figure 16a) varies from 0 to 150 m. It decreases to zero in the middle, northwestern and southeastern parts, where the lithology of level II is sandy shale in the available drilled wells in these parts. Then, it increases in the northeastern and southwestern directions. The net pay (net flag) thickness of Abu Madi level III (Figure 17b) varies from 0 to 120 m. It decreases to zero in the southwestern direction, where level III is missing in wells AM-18 and AM-21. Then, the thickness increases gradually toward the middle, southeastern, northwestern and northeastern directions.
The effective thickness of level II, net reservoir and net pay, increase to 160 m toward the northeastern and southwestern parts, while level III the net reservoir and net pay thickness increase to 160 and 120, respectively, in the northeastern and eastern parts.

The lateral distribution of the petrophysical parameters indicate that the most favorable places for hydrocarbon reservoirs occupy the northeastern and southwestern parts for Abu Madi level II reservoir and in the middle, the middle-west, the middle-east and the southeastern parts for Abu Madi level III reservoir.

Acknowledgement

Authors wish to express sincere gratitude and appreciation to the Egyptian General Petroleum Corporation (EGPC) and the authority of PETROBEL Company (Cairo, Egypt) for permitting and providing the required well log data used in this study.

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Conclusions

The petrophysical analysis carried out in this study is achieved on the most favorable two levels II and III of Abu Madi reservoir. Different cross-plots are constructed (neutron-density, neutron-sonic and M-N crossplots) to display the reservoir lithology. These cross-plots reflect that the lithology in level II and level III varies in the available wells crossplots) to display the reservoir lithology. These cross-plots reflect that the lithology in level II and level III varies in the available wells.
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