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Petrophysical evaluation for the Upper Messinian Abu Madi Formation in Abu Qir Field, West Nile Delta, Egypt.

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Abstract: The sediments of Upper Messinian Abu Madi Formation host the main gas-bearing payzones in the onshore region of the Nile Delta. Abu Madi Formation has been extensively-studeid in the central and eastern parts of the Nile Delta. In these regions, the Messinian incised valleys were infilled by the fluvio-marine sediments of Abu Madi Formation. On the other hand, the incisions and their infill facies in the western Nile Delta are poorly studied. Therefore, the the present study investigates the petrophysical characteristics derived from the interpretation of well logs in four wells (AQ-24, AQ-16, AQ-7 and AQ-4) of the Abu Madi deposits in the Abu Qir field in the Western Nile Delta. The study concluded that the Abu Madi Formation consists of a transgressive, fining-upward succession where the shale content increases upward. Abu Madi level III has the best reservoir properties with effective porosity values up to 27%, and net pay thicknesses greater than 10 m. Petrophysical analyses reveal a paramount impact of depositional setting and shaliness on the distribution of Abu Madi pay zones in the Western Nile Delta.

keywords: keywords: : Abu Madi Formation; well logs; petrophysical evaluation; Abu Qir Field; Nile Delta; Messinian

1.Introduction

The Nile Delta lies on the northern margin of the NE-African plate and the southern part of the Eastern Mediterranean Basin (Fig. 1). The Nile delta covers an onshore area of about 25,000km2 and about 35,000km2 in the offshore (19). The Nile Delta and its offshore extension in the Mediterranean form the biggest gas producing province in Egypt (12). It hosts huge onshore and offshore gas discoveries (e.g. Abu Madi, Abu Qir, and S. Batra) (Fig. 1). Abu Madi gas field was the first discovery in the Nile Delta which produces mainly gas from the Late Messinian sandstones of Abu Madi Formation (10). These sandstones present the infill-facies of the Abu Madi canyon which was incised during the Messinian salinity crisis (MSC) (28). In Abu Madi main canyon, significant gas and condensate accumulations have been discovered onshore (El-Qar’a, Abu Madi, W.Al-Khilala and S.Batra fields) and offshore (Baltim North, South and East fields) within the Upper Messinian Abu Madi fluvial sandstone. The main canyon system in the central Nile Delta has been studied extensively (4., 10, 28; 15); the Abu Madi system eastern tributaries were also investigated (16), whereas the western Abu Madi system has never been investigated. The present study focuses on the western part of Abu Madi canyon through a detailed analysis of the Messinian sedimentary succession in Abu Qir gas field wells (Fig. 1). The main objectives of this study include:

- Detailed petrophysical evaluation of Abu Madi Formation in Abu Qir Field.
- Define the controls on lithofacies and matrix characteristics on the petrophysical properties of the Abu Madi Formation.
- Identify the spatial distribution of the different petrophysical parameters in the study region.

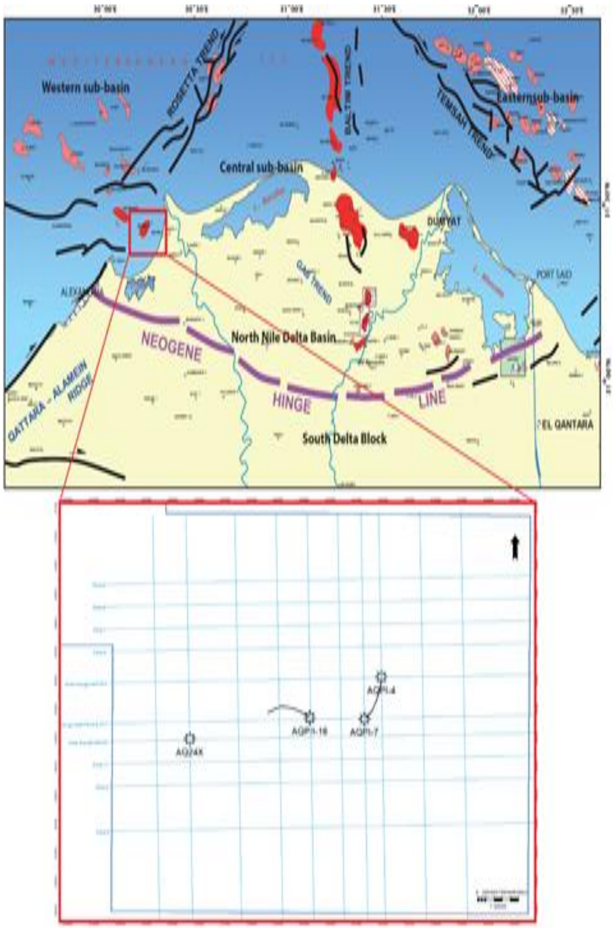

Fig. 1. Location map of the study area in the northwestern part of the Nile Delta

2.Geological Setting

The geological knowledge of the Nile Delta is still somewhat limited, as the area does not have any exposures of ancient rocks since it is covered by Holocene soils. The Tertiary and Mesozoic stratigraphic sequences, which are exposed along the borders of the Delta and in the Western Desert, are better known (Said, 1962). The major structural features of the Nile Delta and Mediterranean Sea is the hinge zone, which affects the pre-Miocene formations and extending E-W across the mid-Delta area (13) (Fig. 1). The hinge zone drops the southern Delta Cretaceous-Middle Eocene carbonate platform down by 4573 m to 5488 m from the thick Tertiary basinal deposits which have variations to the north (12). The onshore Nile Delta region is divided by the flexure zone which is known as a hinge line, into two structural sedimentary sub-provinces: The South Nile Delta block and the North Nile Delta basin (Fig.1) (6). The lithofacies stratigraphy of the Nile Delta is much different from that adapted for the outcrops around it. On the basis of an extensive survey of borehole (24), it has been proposed that the clastic sediments of the Nile Delta can be grouped into three sedimentary cycles: a Miocene cycle, a Plio-Pleistocene cycle and a Holocene cycle. The section is relatively uniform over the whole Nile Delta. The thickness of the Nile Delta may exceed 20,000 ft. overlays Paleogene carbonate and clastics. The main control on sedimentation in the Nile Delta area during the Neogene and Quaternary were the Nile River current that is northward-flowing position and the Messenian Salinity Crises (MSC). The Messinian period (belonging to the Late Miocene stage, from 7.24 to 5.33 Ma) in this period sea level became more Regressive due to isolation of Mediterranean sea from Atlantic Ocean this event is called the Messinian Salinity Crisis. Due to this event thick evaporates accumulated in basins accompanied by continental deposition on the margins (23). Late Miocene contains mixed of siliciclastic-carbonate successions that have been mentioned in multiple locations along the Mediterranean basin (7; 8; 9). The Messinian carbonates did not cover all Delta, but carbonates have been concentrated in the western and central Mediterranean (5; 8; 3; 6). In the eastern part carbonates belong to Early and Middle Miocene only but there is slightly carbonates belong to Late Miocene ages along the coasts of Israel, Northern Sinai, Crete, Cyprus, and have never been recorded to the west of Sinai Peninsula (5). The Messinian Abu Madi Formation represents the only preserved syn-MSC sedimentary facies in the onshore Nile Delta region that deposited during MSC and constitutes the infill succession of the Eonile canyon. The Abu Madi Formation was subdivided into three levels (III, II, and I, Fig. 2) are represented with vertical transition from fluvial to estuarine and marine facies (12., 10; 11; 15). The stratigraphic framework of Abu Qir offshore area was achieved by the accurate identification of the rock units. The litho-stratigraphy of the Abu Qir area shows that the Abu Madi Formation is bounded by two main unconformities related to the beginning and end of the MSC in the Nile Delta (Fig. 2).

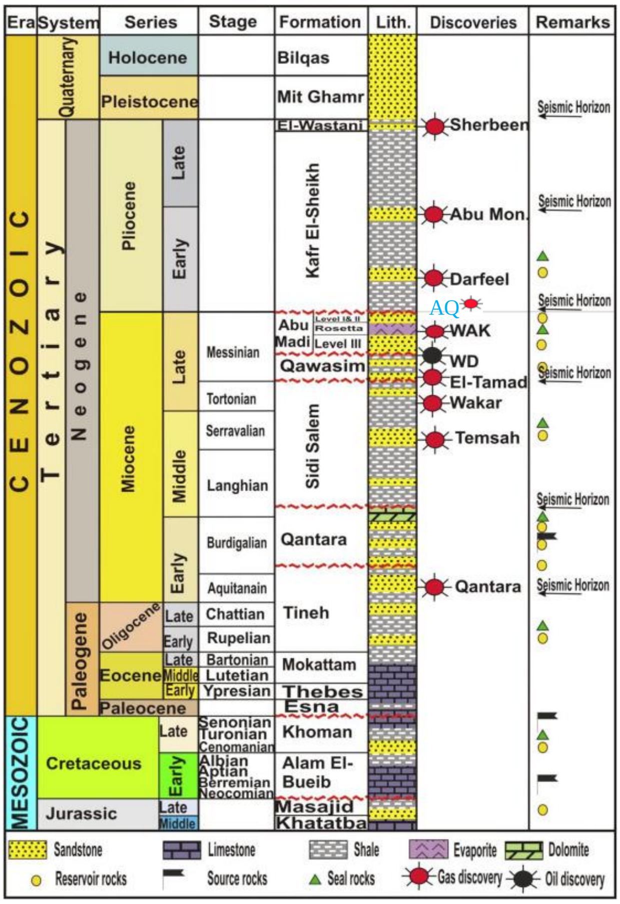

Fig. 2. A generalized lithostratigraphic column of the Nile Delta (Leila et al., 2019).

3. Materials and methods

The current study is based on a diverse subsurface dataset comprising borehole wireline logs, and side-wall cores (SWC) and oil samples from Abu Qir oil field in the northwestern part of Nile Delta Basin. The wireline logs comprise a complete suite of electric, radioactive and acoustic logs from four wells (AQ-24 , AQ-16 , AQ-7 and AQ-4). Ninty six (96) SWC samples were retrieved from the Abu Madi Formation during Upper Miocene – Lower Pliocene period within the Abu Qir offshore well in AQ-24 well.

3.1. Petrophysical formation evaluation

The available well logs will be interpreted using Schlumberger Techlog software in order to identify the petrophysical properties (formation shaliness, porosities, and fluid saturations) of the reservoir and pay zone intervals. Values of shale volume will be computed applying the single-log method (GR and LLD), whereas the combination of NPHI-RHOB logs will be used in the calculation of porosity values (effective porosity ∅e and total porosity ∅T). Water saturation (Sw) estimation will also be computed in order to define the pay zone intervals.

3.2. Wireline logging analysis

The studied wireline logs involve gamma ray (GR), caliper (Cali), density (RHOB), neutron (NPHI), shallow (LLS) and deep resistivity (LLD), and acoustic compressional and shear sonic logs (DTCO, DTSH, respectively). These logs were interpreted using Schlumberger 2010 Techlog software (1; 19). Wireline logging interpretation allows a qualitative assessment of different petrophysical properties as well as the lithologic characteristics of the studied sedimentary successions. Clay volume distribution in the studied reservoirs was determined using a single log (GR), whereas a combined neutron-density logging estimation was utilized to deduce total (PHIT) and effective (PHIE) porosity values. Additionally, water saturation (Sw) was calculated using Modified Simandoux equation which is more appropriate for Sw calculations in shale-rich reservoirs (20). Formation water resistivity (Rw) and cementation factor (m) values for the studied reservoirs were deduced from Pickett plot (21).

4. Results

4.1. Litho-saturation characteristics

Abu Madi Formation is subdivided into three intervals from bottom to top as the following lower Abu Madi , middle Abu Madi and upper Abu Madi (Fig.3.). The values of GR logrange from 18 API to 36 API in lower Abu Madi. This interval displays fining-upward succession suggesting an upward increase in the shale/sand ratio. Middle Abu Madi has GR values between 15 API and 48 API, where multiple gamma ray patterns are observed signifying variable depositional cycles where sand and shales are alternating. Upper Abu Madi has GR values in the range of 18 API and 40 API. By comparing GR patterns in the Abu Madi intervals, the coarsest sandstone facies occur in Abu Madi level III, whereas shale content with common shale streaks in the middle (level II) and Upper Abu Madi (level I). Abu Madi Formation in AQ-24 well there are many depositional cycles during deposition of

Abu Madi Formation. The succession of sediments is fining-upward succession of clastic-rich facies means depositional environment is fluvial to fluvio-marine deposited during a transgressive episode. Such depositional conditions caused an upward increase in the sand/mud ratio. The shallow and deep resistivity curves show different values at different depths, and are separated in several zones indicating the presence of movable hydrocarbons. The deep resistivity is high in the Upper Abu Madi zone suggesting a high content of hydrocarbon saturation. The value of deep resistivity in the middle Abu Madi is (1- 6 ohm.m) high amount of hydrocarbons. In the lower Abu Madi,shallow and deep resistivity valuesare almost similar (1.5ohm.m), so hydrocarbons are not movable and water saturation is relatively high (Fig.3).

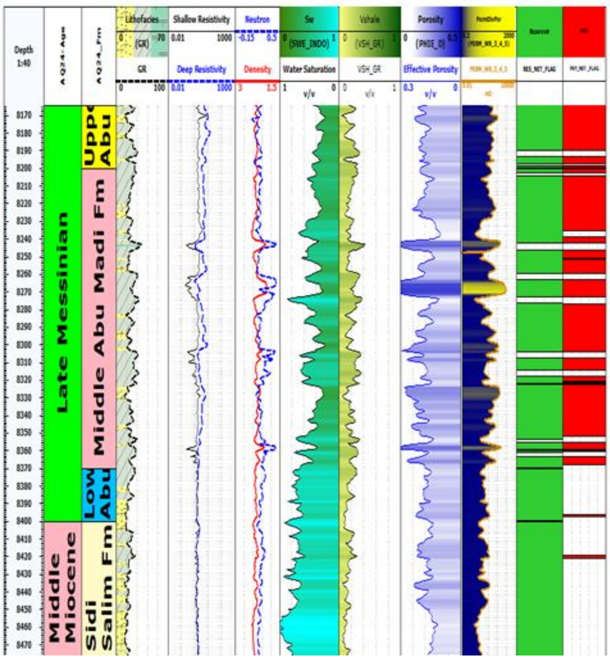

Fig.3. Vertical litho-saturation cross plot showing the lithologic and petrophysical properties of the studied rock units in AQ-24 well.

The neutron porosity values in upper Abu Madi are in the range of 0.1 - 0.4 decimal, whereas the density values are between 2.2 – 2.4 g/cm^3. The neutron porosity values are similar in the middle Abu Madi and upper Abu Madi levels suggesting similar pore system characteristics. Relatively elevated neutron porosity values in the upper Abu Madi occurs at depths between 2487m and 2488 m and also in middle Abu Madi at depths between 2512 m to 2515 m with value (0.4 Decimel). A neutron-density cross-over zones are only reported in the Middle and Upper Abu Madi zones of AQ24- well, suggesting that gas-bearing pay zones only exist in these levels. Water Saturation in AQ-24 well within Abu Madi Formation the value of water saturation is (20% - 90%) this means Abu Madi formation good porosity and permeability .The value of water saturation in the upper Abu Madi (20% - 60%), in middle Abu Madi (20% - 87) and in lower Abu Madi (60% -90%).The higher value of water saturation presented in Lower Abu Madi at depth 1341 m. The value of Shv is 42% in the Middle Abu Madi with thin thickness from (2512 m – 2515m), and the Shv in Abu Madi Formation as a total in AQ-24 well is 22% - 42% (Fig.3). This value refers to Abu Madi Formation is good reservoir and good pay zone. As we mentioned before the lower Abu Madi zone has very low resistivity, this zone may be rich with water formation not hydrocarbons because it has high value of water saturation but in the same time it has low resistivity and low volume of shale.

The value of effective porosity in Abu Madi Formation as whole is (10% - 34%). The value of effective porosity in upper Abu Madi zone is (14% - 20%), in middle Abu Madi (10% - 34%) and in lower Abu Madi (14% - 22%).(Fig.3.).The high value of porosity presented in Middle Abu Madi at depth (2512 m – 2515 m), with value (34%) and the porosity is high in three zones but it is higher in middle Abu Madi than lower Abu Madi and lower Abu Madi has higher value than upper Abu Madi. The value of Permeability in upper Abu Madi is (1- 93 Md), in middle Abu Madi is (0.1 – 757 Md) and in lower Abu is (1 – 13 Md). These values mean Abu Madi Formation is very good reservoir ,but high value is presented in Middle Abu Madi in AQ-24 well at 2521 m with value 757 Md. After studying this petrophysical parameter (Table.1.). We can say Middle Abu Madi is the best zone for oil production and also it has many reservoirs and pays with large thickness and large numbers after that upper Abu Madi zone and lower Abu Madi has not pays and reservoir because of high water saturation.

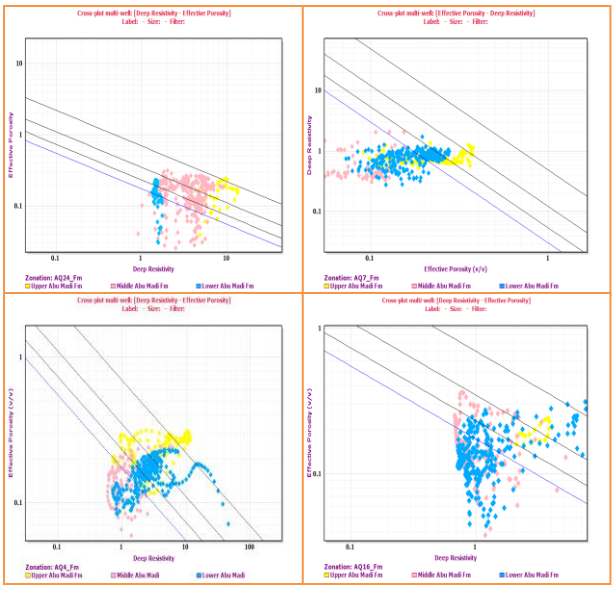

Fig.4. Petrophysical parameters distribution on Pickett plot of porosity function of resistivity of AQ-16, AQ-4, AQ-24 and AQ-7 Wells for Abu Madi Formation in Abu Qir Field.

4.2. Matrix characteristics

The relationship between effective porosity and deep resistivity in AQ-24 well refers to the Middle Abu Madi zone is better than upper and lower Abu Madi zones in water saturation ,its most producible zone in AQ-24 Well. In AQ-16, AQ-4 and AQ-7 the Lower Abu Madi is the best zone and the most producible zone also. The value of water saturation (Sw) in lower Abu Madi is concentrated between 75% - 50%, So it has good reservoirs and pays according to Fig.4. Upper Abu Madi zone has not pays and reservoirs to ensure from the results of bulk density and neutron porosity from Thomas-Stieber plot (Fig.5.).

Table .1. The values of petrophysical parameters for Abu Qir field and the three units of Abu Madi Formation for the studied wells Abu Qir Concession, Nile Delta, Egypt.

The table shows the results of some petrophysical properties of Abu Madi Formation in four wells (AQ-24,AQ-16,AQ-7 and AQ-4). The table shows the resevoirs of Abu Madi zones also. We used Pickett plot to show the relationship between effective porosity and resistivity as in(Fig.4.).

water saturation (Sw) is concentrated between 75% - 50%, this means that Middle Abu Madi has good porosity and good resistivity , so it has good pay and good reservoir. It may be the

Zones	Well	Top (ft)	Bottm (ft)	Gross (ft)	Net (ft)	Net to Gross	Porosity Thickness (ft%)	Hydrocarbon Porosity Thickness (ft%)	Av_Effective Porosity (%)	Av_Shale Volume (%)	Av_Effective Water Saturation (%)
Upper Abu MadiFm	**AQ-24**	8084	8163	79.000	43.500	0.551	11.622	8.293	27	27	29
Middle Abu Madi	**AQ-24**	8163	8242	79.000	12.000	0.152	2.217	1.036	18	25	53
Lower Abu Madi	**AQ-24**	8242	8398	156.000	37.000	0.237	7.115	4.208	19	25	40
Upper Abu MadiFm	**AQ-16**	9342	9350	8.000	5.000	0.625	1.012	0.604	20	22	40.3
Middle Abu MadiFm	**AQ-16**	9350	9465	115.000	4.000	0.035	0.916	0.493	22	24	46
Lower Abu MadiFm	**AQ-16**	9465	9634	169.000	55.500	0.328	16.040	13.383	29	13	17
Upper Abu MadiFm	**AQ-7**	9207	9267	60.000	50.000	0.833	11.870	3.554	24	20	70
Middle Abu MadiFm	**AQ-7**	9267	9312	45.000	4.000	0.089	0.530	0.052	13	18	90
Lower Abu MadiFm	**AQ-7**	9312	9438	126.000	74.000	0.587	14.427	2.670	20	19	82
Upper Abu MadiFm	**AQ-4**	8084	8163	79.000	43.500	0.551	11.622	8.293	27	22	29
Middle Abu Madi	**AQ-4**	8163	8242	79.000	12.000	0.152	2.217	1.036	18	25	53
Lower Abu Madi	**AQ-4**	8242	8398	156.000	37.000	0.237	7.115	4.208	19	25	41

4.3. Shale distribution

The Thomas-Strieber plot shows the bulk density and neutron porosity in different wells such as AQ -24, AQ -16 and AQ – 4. According to figure.5, the best zone is Lower Abu Madi in AQ -16 and AQ -4 wells, but in AQ -24 the best zone is Middle Abu Madi as in (Fig.5.).

The amount of shale is high in middle Abu Madi ,rarely in lower Abu Madi and upper Abu Madi is shaleness as in AQ-4,but in AQ-16 lower Abu Madi contains smaller amount of shale than middle Abu Madi ,but upper Abu Madi is clean in AQ-24 lower ,middle and upper Abu Madi are mainly clean and shaleness (Fig.5.).

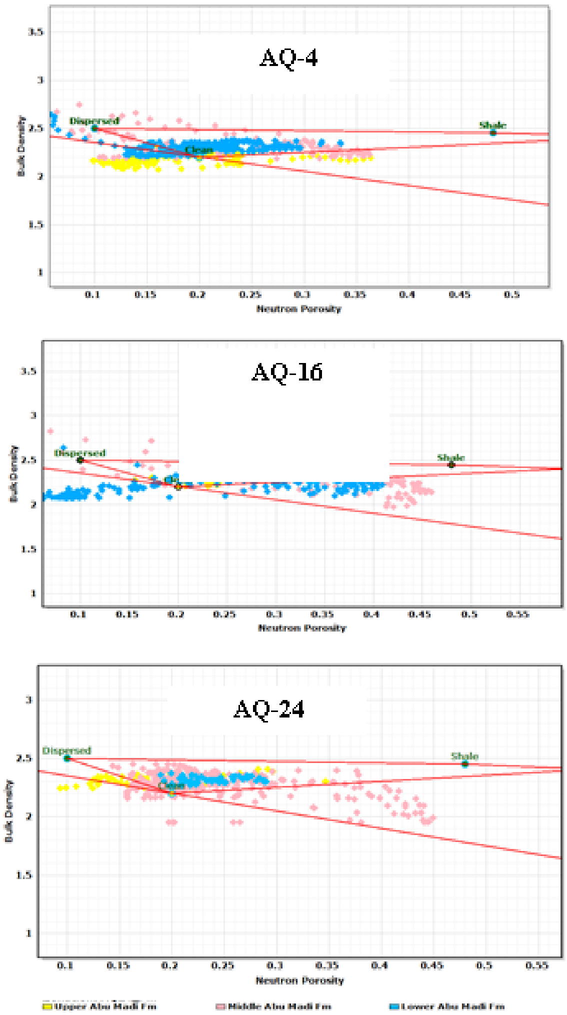

Fig.5. petrophysical parameters distribution on Thomas-Stieber plot of neutron vs density of AQ-16, AQ-4 and AQ-24 Wells for Abu Madi Formation in Abu Qir Field , Nile Delta, Egypt.

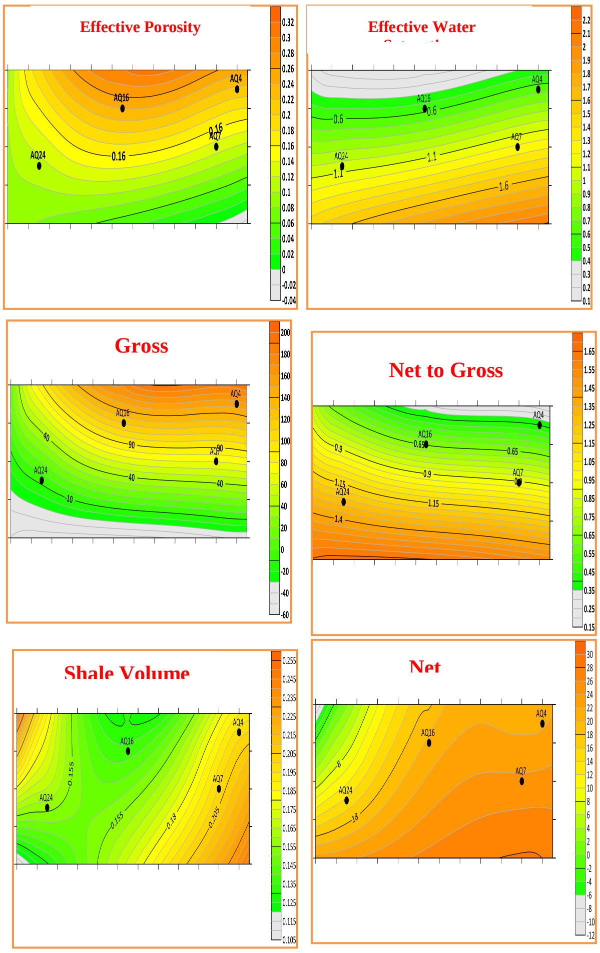

Fig.6. Neutron-density cross plot of Abu Qir field and the three units of Abu Madi

Formation for the AQ-24,AQ-7 and AQ-4 wells , Western Nile Delta , Egypt

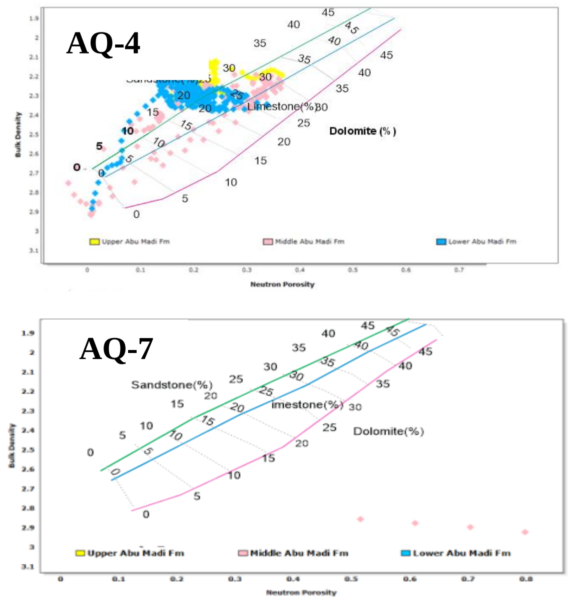

Fig.7. Isoperimetric maps of petrophysical parameters of Lower Abu Madi Reservoir in AQ-4, AQ-24, AQ-16 and AQ-7 wells

The amount of sandstone is very high in middle Abu Madi, upper Abu Madi and low in lower Abu Madi. The amount high density materials (e.g. calcareous or argillaceous components)are very high in lower and middle Abu Madi but low in upper Abu Madi .Dolomite is mainly concentrated in middle Abu Madi but low in upper and lower Abu Madi in AQ-24 well.(Fig.6.).

4.4. Isoperimetric maps

Isoperimetric maps of different petrophysical properties of Lower Abu Madi Reservoir in four wells. Effective Porosity in Lower Abu Madi Reservoir increases northward displaying a pattern of AQ -16 >AQ-4 >AQ -24>AQ -7 wells. The Effective Water Saturation increases toward the direction of south east part, and high in AQ-7 well. Gross increases toward the direction of north east part.it is higher in AQ -4 well.Net to Gross increases toward the direction of south western part,and AQ-24 Well has the higher value similar to the shale volume (Fig.7.).

the shale volume increases toward the direction of south east part, it is high in AQ -7 well.

The figure shows the contour map of different petrophysical properties of Middle Abu Madi Reservoir in four wells .We will start with Effective Porosity in Middle Abu Madi Reservoir increases toward the north direction and it is higher in AQ -16 well. The Effective Water Saturation increases toward the direction of south eastern part similar to Lower Abu Madi. Gross increases toward the direction of north-western part , Net to Gross increases toward the direction of south west part and both are higher in AQ-24well in addition to the shale volume that increases toward the direction of south eastern part. The Net increases toward the north direction and it is higher in AQ -4 (Fig.8.).

The figure shows the contour map of different petrophysical properties of Middle Abu Madi Reservoir in four wells .We will start with Effective Porosity in Upper Abu Madi Reservoir increases toward the north east direction . Effective Porosity , Shale volume and Gross increase toward the direction of the northern part and it is higher in AQ -4 well. The Effective Water Saturation increases toward the direction of south eastern part similar to Lower and Middle Abu Madi.Net to Gross and Net increase toward the south eastern direction and it is higher in AQ -7 well (Fig.9.). The same zones (Lower, Middle and Upper Abu Madi) have different petrophysical properties in different wells.

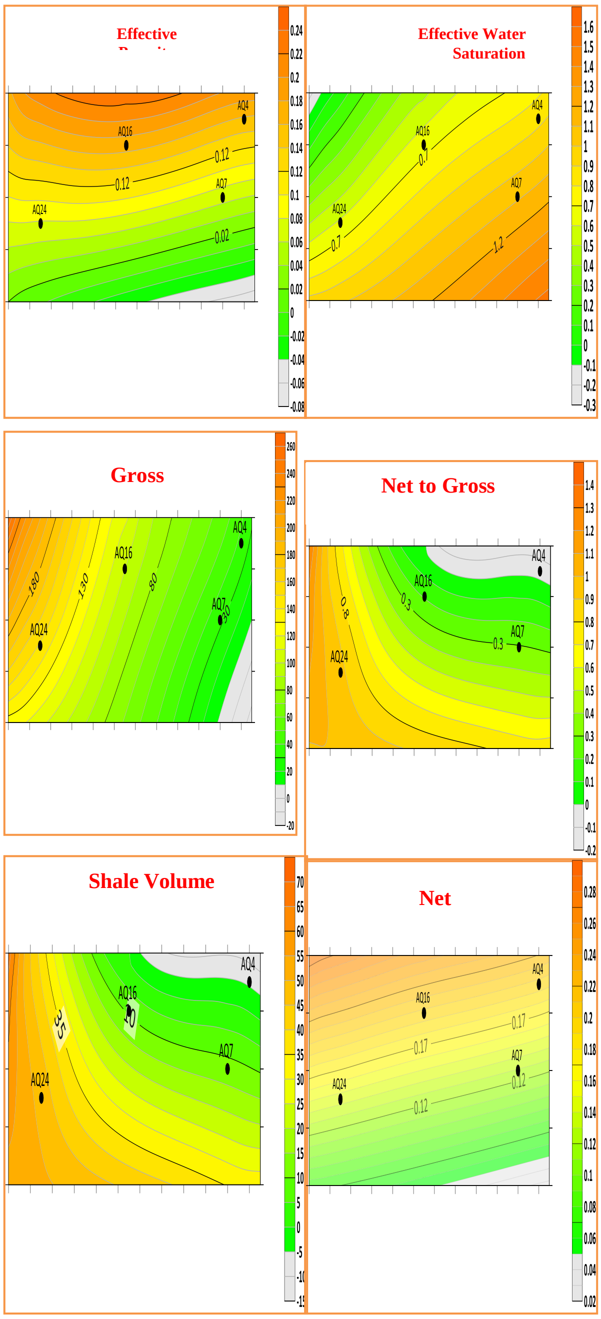

Fig.8. Isoperimetric maps of petrophysical parameters of Middle Abu Madi Reservoir in AQ-4,AQ-24,AQ-16 and AQ-7 Wells.

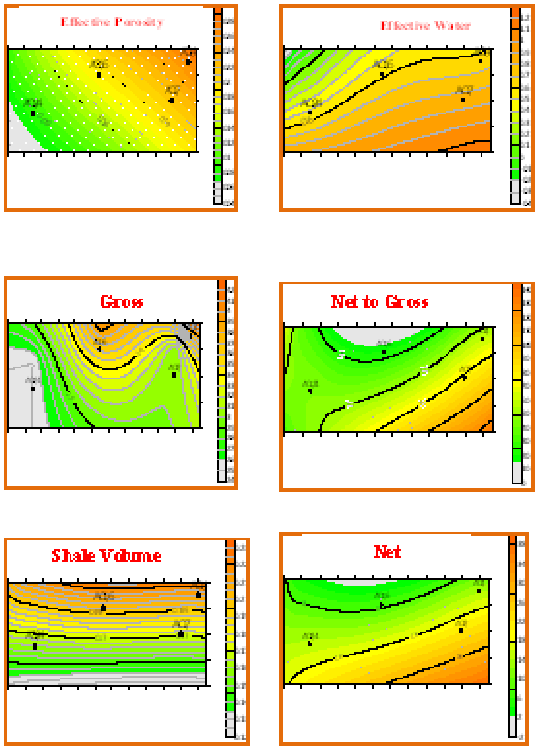

Fig.9. Isoperimetric maps of petrophysical parameters of Upper Abu Madi Reservoir in AQ-4,AQ-24,AQ-16 and AQ-7 Wells.

5. Discussion

Linking the pore system characteristics of sedimentary reservoirs with their lithologic composition and sedimentary evolution is crucial for hydrocarbon exploration and development strategies (e.g. Dolson et al., 2001; El Adl et al., 2021; Yasser et al., 2021). Amaefule et al (1993) proposed that the distribution of fluid flow units and mostly linked to the original matrix of the reservoir facies which controls the occurrence of fluid flow conduits with open pore channel network. Indeed, the deduced matrix and petrophysical characteristics of Abu Madi Formation in the studied Abu Qir Field reveal a link between the Abu Madi pore system and its framework composition. The sand/shale ratio which decreases upward from Abu Madi lower level to Abu Madi Upper level confirms the transgressive infill of the Abu Madi system in Abu Qir region similar to that reported in the central Nile Delta (Leila and Moscariello, 2018; El Adl et al., 2021; Leila et al., 2022). Accordingly, similar depositional system for Abu Madi is interpreted in the north Western Nile Delta region. The fining-upward depositional pattern has impacted the petrophysical characteristics of Abu Madi Formation where greater contents of clays, and argillaceous to calcareous matrix characteristics are reported in Abu Madi Upper interval. The latter also has high contents of water saturation and therefore would act as a baffle or barrier zone for hydrocarbon flow in the region. On the other hand, fluid flow conduits are restricted to the Abu Madi lower and middle units. The isoperimetric maps confirm these observations where hydrocarbon accumulation, in terms of thick pay zones, occurs in the regions where Abu Madi Middle and Lower intervals are thickening.

6. Conclusions

- The lithologic and petrophysical characteristics of Abu Madi Formation in Abu Qir Field, Western Nile Delta have been investigated.
- In Abu Qir Field, Abu Madi sedimentary succession display a transgressive pattern similar to that reported in the central and eastern Nile Delta.
- Quartzose sandstone matrix is more prominent in lower and middle Abu Madi intervals, whereas Abu Madi upper interval is more calcareous and/or argillaceous.
- The lower and middle Abu Madi units are the best zones for future exploration and development in the study region.

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