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RESERVOIR QUALITY PREDICTION OF THE ABU MADI FORMATION IN THE WEST EL MANZALA FIELD, ONSHORE NILE DELTA BASIN

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التنبؤ بجودة الخزان لتكوين أبو ماضي – حقل غرب المنزلة – حوض دلتا النيل البرية

الخلاصة: يمثل خزان أبو ماضي أهمية إقتصادية هامة بدلتا النيل البرية لما يحتويه من كميات واعدة للغازات. يهدف البحث إلي دراسة الخزان الجوفي لمتكون أبو ماضي بحقل غرب المنزلة بغرض التنمية من خلال دراسة المعاملات البتروفيزيقية بإستخدام بيانات القياسات المعملية للعينات اللبية وسجلات الرصد البئري وإيجاد علاقات رياضية يمكن منها التنبؤ بالنطاقات عالية الجودة من الخصائص البتروفيزيقية. وبالتالي فإنه من الأهمية بمكان تقدير نفاذية الخزان بدقة مناسبة وقد تم تقييم خزان أبو ماضي في منطقة الدراسة إلى ثلاث وحدات للتدفق الهيدروليكي. تتميز وحدة التدفق الأولى بالحجر الرملي عالي الجودة ، مع نفاذية عالية تتراوح ما بين 300 و 1957 ملي دارسي وتتراوح المسامية ما بين 22 و 29 ٪ كما تتراوح قيم مؤشر التدفق ما بين 3 و 10. وتتميز وحدة التدفق الثاني بالحجر الرملي عالي الجودة ، مع نفاذية تتراوح ما بين 10 و 235 ملي دارسي ، و المسامية ما بين 15 و 27 ٪ ، و قيم مؤشر التدفق ما بين 1.5 و 3. وتتكون وحدة التدفق الثالثة من الحجر الرملي ذو النوعية الرديئة ، مع قيم نفاذية منخفضة تتراوح ما بين 1 و 10 ملي دارسي ، قيم المسامية ما بين 10 و 18 ٪ ، و قيم مؤشر التدفق ما بين 0.6 و 1.5. وتأتى أهمية البحث أنه يمكن من خلال ربط القياسات المعملية والسجلات البئرية بعلاقات رياضية يمكن التعرف علي خصائص الخزان في النطاقات الخالية من العينات الصخرية اللبية. وتساهم هذه النتائج في عملية تطوير حقل غرب المنزلة ، بدلتا النيل البرية.

ABSTRACT: *The Abu Madi Formation is a major gas reservoir in Egypt's onshore Nile Delta. Characterizing reservoir distribution and quality in the West El Manzala Field is critical for exploration, development, and production. Predicting reservoir permeability is especially challenging yet essential for simulation, forecasting, and field development. This study focuses on accurately estimating Abu Madi Formation permeability in the West El Manzala Field. The Abu Madi reservoir was classified into three hydraulic flow units (HFUs) based on core analysis data. HFU-1 contains very high-quality sandstone with permeability ranging between 300 and 1957 mD, porosity of 22 to 29%, and flow zone indicator (FZI) values of 3 to 10. HFU-2 comprises good quality sandstone with 10 to 235 mD permeability, 15 to 27% porosity, and FZI of 1.5 to 3. HFU-3 consists of poor-quality sandstone with 1 to 10 mD permeability, 10 to 18% porosity, and 0.6 to 1.5 FZI. Neural network models predicted permeability in uncored wells by integrating core measurements of FZI with wireline logs for selected cored wells. This enabled reservoir quality estimation across the field, delivering key insights for development planning in West El Manzala.*

1. INTRODUCTION

Exploration activities by oil companies in the 1960s revealed the hydrocarbon potential of Egypt's Nile Delta. Advances in geological and geophysical techniques have since allowed ongoing discovery and appraisal of the region's stratigraphic traps. The Upper Messinian Abu Madi Formation is a major gas reservoir onshore, containing high-quality fluvial sandstone reservoirs (EGPC, 1994).

West El Manzala Field is located in the eastern part of the Nile Delta Onshore, at the western edge of El Manzala Lake, and east of the Domeitta Nile branch. It lies between Latitudes 31º 11' N, 31º 21' N. and Longitudes 31º 42’ E, 31º 48’ E. West El Manzala Field is covering about 82.2 km² (Fig. 1).

West El Manzala Field was discovered by Sharabas-1 well in June 2009, as an exploratory well. It was followed by Faraskour-1 exploratory well in August 2009, based on the results from El Wastani East-2 offset well, which is the closest successful well to drill to the Upper Abu Madi reservoir (UAM) located 7.7km North West from Faraskour-1 well location, tested 12 MSCF/d of gas 243 bbl/d of condensate on choke size 28"/64" with 2853 WHFP, from a 23.5 m pay zone in Upper Abu Madi reservoir. Faraskour-1 well was targeting the Upper Messinian reservoir (Abu Madi reservoir) resulting in 23.5m net pay with 19% porosity and 45% water saturation within Upper Abu Madi, and 2m net pay with 19% porosity and 60% water saturation within Lower Abu Madi (LAM). The total well depth (TD) was 2913 m MD/ 2905.44m TVDSS. This well was followed by Faraskour-3 well as an appraisal well, which is located approximately 1994m south east of Faraskur-1well. Faraskour-3 was targeting the same reservoir level, which was drilled on November 16, 2010. This appraisal well resulted in 1.5 m net pay in UAM with an average porosity of 20.4% and Water saturation of 66%. Two pay intervals have been encountered in the Lower Abu Madi reservoir: LAM I with 10.4 m net pay of 21.4 % porosity and 49.3 % water saturation, LAM II with 10.4m of 22.5 % average porosity and 38.6 % water saturation, with total well

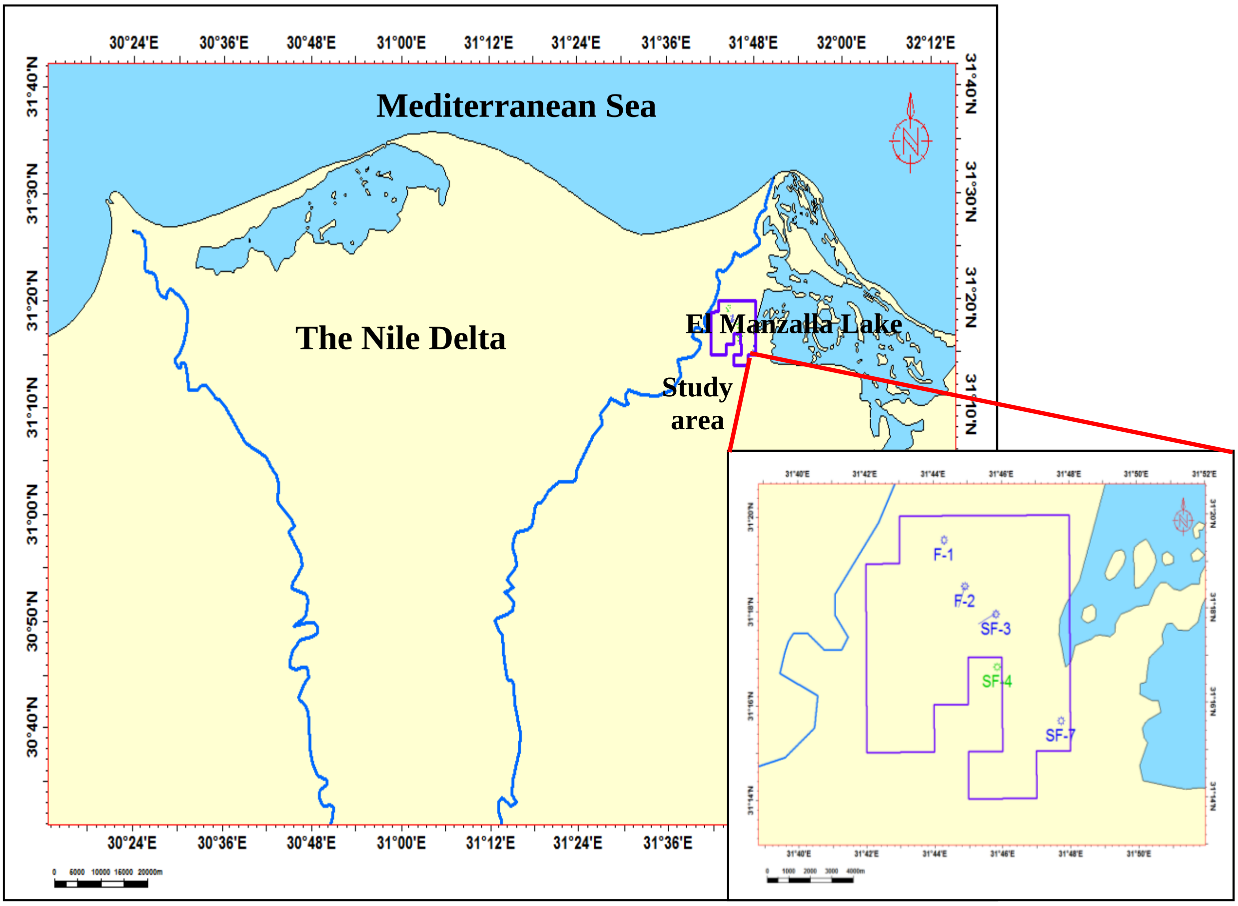

Fig. 1: Location map of the study area showing the location of the studied wells in the onshore Nile Delta region.

depth (TD) of 2900m MD/ 2806.35m TVDSS. Therefore, the field became a mature field and the development strategy was started by adding new wells such as Faraskour-2, South Faraskour-1, and South Faraskour-6 wells.

Abu Madi Formation is one of the main hydrocarbon reservoirs in the Nile Delta province, due to its high petrophysical parameters, such as in the Baltim field Sarhan, M.A. (2023). The big challenge in the exploration and development phases is the reservoirs compartmentalization and connectivity. Salem et al., (2005) reported that the main proven reservoirs of the North Nile Delta basin were the Late Miocene sequences (Abu Madi and Qawasim reservoirs).

Because the reservoirs of the Nile Delta are of stratigraphic trap type, they contain high amounts of clay minerals, which affect the accuracy of the petrophysical parameters and reservoir characterization leading to inaccuracy in the hydrocarbon reserve estimation. so that, the reservoir characterization has to be implemented in such shaly sand reservoirs, with a high degree of facies heterogenities.

This paper aimed to classify the cored reservoir intervals into different reservoir rock types and flow units based on porosity, and permeability relationship. Additionally, evaluated the petrophysical properties of the reservoir intervals. Finally, predict the permeability and reservoir quality of uncored wells by integrating ANN techniques with core analysis data and evaluate the effectiveness of this approach as an exploration tool in the WEM area and onshore Nile Delta basin.

2. GEOLOGICAL SETTING

The Abu Madi Formation consists of a sequence of thick layers of rarely conglomeratic sandstone interbedded with shale layers, which repeated and became thicker in the upper part. The sand is composed of quartz, which varies in grain size and is almost loose. The conglomeratic levels in the sandy matrix represent the lower part of the Abu Madi Formation, indicating the lower unconformity. The Abu Madi reservoir proved to be the best reservoir in the Nile Delta, having good porosity. The overwhelming gas fields in the Nile Delta had been produced from the Abu Madi Formation (Schlumberger, 1984). These sandstones were considered the main gas-producing zone in the Nile Delta fields. The main reservoir in the study area is the Abu Madi Formation, that composed of well-defined fluvial sandstone channels with interbeds of shale and silt, favoring a very good quality reservoir.

During the Messinian age (from 7.24 to 5.33 My), the Mediterranean was isolated gradually from the Atlantic Ocean, leading to the wide extension precipitation of gypsum (from 5.96 to 5.6 My), massive salt deposition (from 5.6 to 5.5 My) and a sudden falling in sea level, followed by the creation of brackish water environments from "Lago-Mare" (Lake Sea) facies (Roveri et al., 2014). This sea-level severe drop caused a huge fall in the Mediterranean Sea water level, which was followed by wide erosion and the formation of large canyons incisions expanded around the Mediterranean, in addition to the spreading of salt deposits in the depocenter of the basin (Dolson et al., 2005). The Mediterranean's Messinian salinity crisis triggered the development of 5 major Paleo-drainage systems along the northern coastline of Egypt. The major canyons were filled with deposits of the Qawasim and Abu Madi Formation (Pigott and Abdel-Fattah., 2014).

At the start of the Pliocene, a great sea transgression flooded all the Nile Delta basins, producing the Kafr El Sheikh Formation, which is characterized by the deposition of thick marine shales with thin layers of interbedded sandstones. A sudden sea-level drop at the Early Pleistocene age led to the deposition of the El Wastani Formation, which is a low-stand deltaic system of shelf-margin deposits. The Oligocene - Neogene stratigraphic succession within the Nile Delta area by (El Heiny and Enani, 1996 and Vandre et al., 2007) as shown in (Fig. 2).

During the Late Cretaceous-Miocene, the Jurassic-Early Cretaceous rift basins were inverted with the development of the Syrian arc series of large northeast-southwest oriented folds south of the Nile Delta and Eastern Mediterranean regions (Darwish, M.,1996, and Kusky. T.M., 2003). The tectono-stratigraphic evolution of the eastern Nile Delta is shown in Fig. (3). The "hinge line" is an Upper Cretaceous carbonate shelf edge, that forms the southern boundary of the thick Neogene sediments in the Nile Delta. It is an essential element, that affected the overall stratigraphic and tectonic evolution of the Nile Delta basins. A subsequent rifting phase (Gulf of Suez rift) occurred during the Oligo-Miocene with a dominant extension orientated in northwest faults due to the divergence of the African plate away from the Arabian plate. The Oligo-Miocene or older E-W and NW trending faults in the Nile Delta were suggested to be related to the initial rifting phases of the Gulf of Suez. The gross seismic stratigraphic framework of the study area is described, concerning the main representative seismic section, perpendicular to the depositional direction of the Messinian depositional system. as shown in (Fig. 3).

3. DATASET AND METHODOLOGY

The available data of the studied area are well-logging data, including composite log, Gamma-Ray, Density, Neutron, Resistivity, and Sonic logs provided by El Wastani Petroleum Company in LAS and ASCII formats. In addition to the core analysis results for Faraskur-3 well for the Abu Madi reservoir.

3.1. Core and well logs Analysis

To achieve the work, correlation, and integration of core and log data, were carried out using linear and non-linear regressions, to build relevant relationships between the log and core data, and to determine the individual reservoir parameters, such as shale volume, porosity, fluid saturation, permeability, and hydraulic flow units (HFUs) of the reservoir litho-facies.

Finding a relationship between the core and log data is the best solution to predict the reservoir parameters in the un-cored wells, as indirect methods for plotting data of several wells and generating a correlation between the variables, to estimate the rock types and permeability in un-cored wells.

a- Core gamma depth correction

The natural gamma radiation of the cores was measured and the maximized smoothed gamma emission intensity of cores and the spectral gamma are plotted against the core depth, to detect the core depth shift.

b- Core Data to Reservoir Condition Correction:

To estimate the valid reservoir parameters from the well logs, they first have to be calibrated to the available core data. The most important parameter that affects the porosity and permeability of any reservoir, is the net of overburden pressure. It is the difference between the overburden and internal pore pressure.

3.2. Reservoir Rcok typing

The rock-typing techniques, such as (Leverett's, 1941) reservoir quality index RQI and (Winland, 1972) and flow zone indicator FZI (Amaefule, 1993) were used to define the reservoir into different hydraulic flow units (HFUs) and predict the reservoir permeability.

a- Hydraulic flow characterization

Rock typing is a process for reservoir rock classification into units, it is characterized by a unique set of petrophysical properties e.g. porosity-permeability relationship and electric properties. The Porosity and permeability data are available from the core analysis. Several semi-empirical equations have subsequently been proposed to improve the estimation of rock permeability, as subjected to various loading conditions (Panda and Lake, 1994; Bernabé et al., 2003; Costa, 2006; and some modified KC models are listed here.

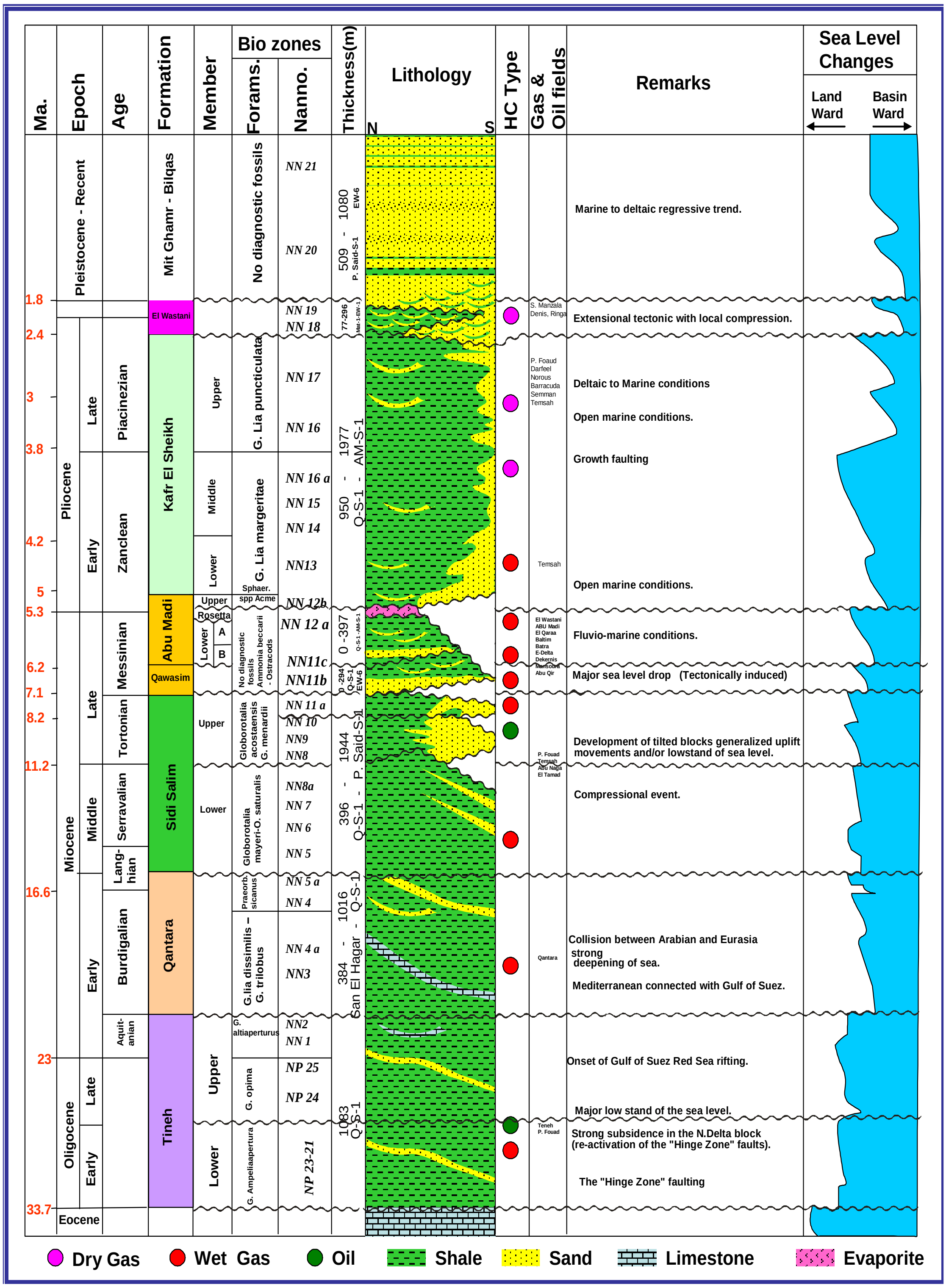

Fig. 2: Generalized stratigraphic column of the West El Manzala Field (WASCO, 2016).

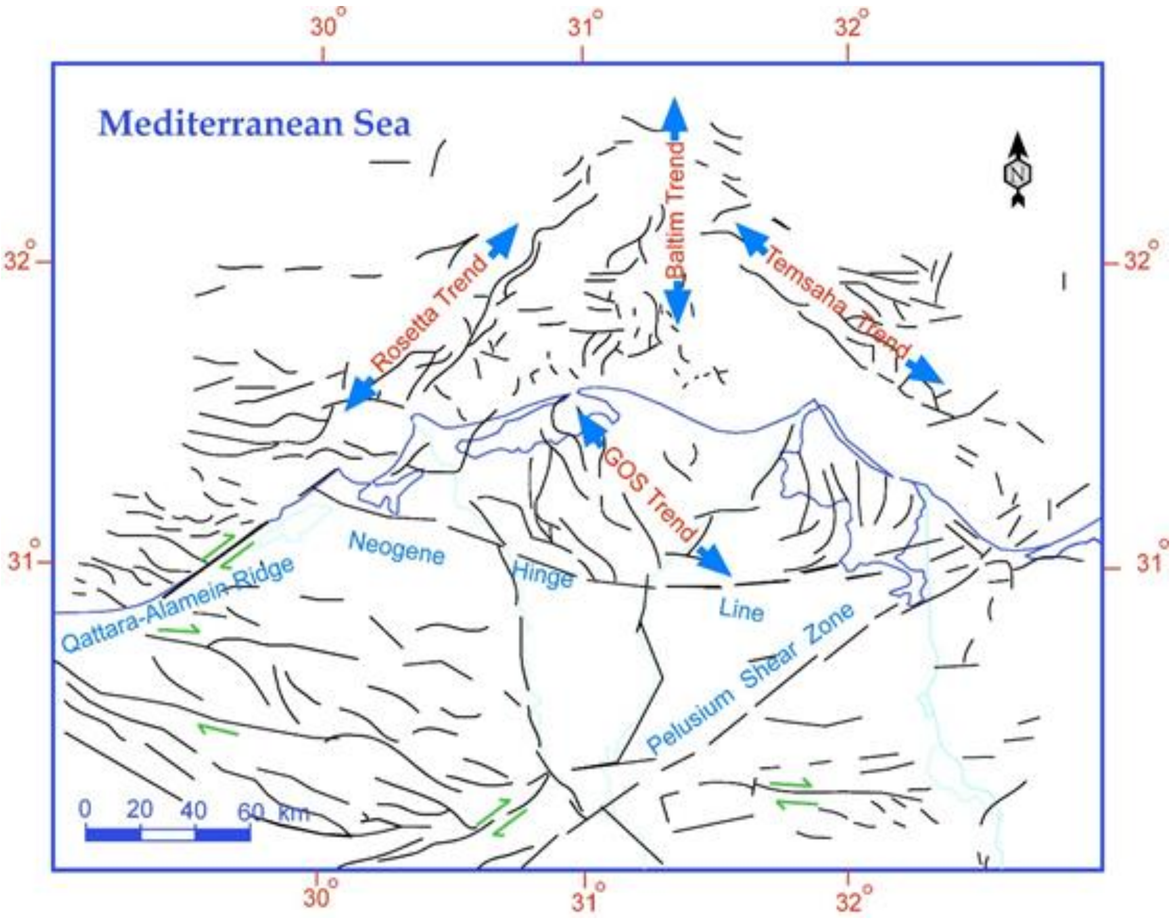

Fig. 3: Nile Delta tectonic setting map (Abdel Aal, et al., 1994).

Bayles et al., (1989) proposed a porosity-permeability relationship based on the fractal pore cross-sectional area, which can be formulated as follows:

$$K = C\frac{\emptyset^{z+2}}{(1-\emptyset)^2} \qquad \text{eq. (1)}$$

Where: c is a constant to determine permeability and z is an exponent parameter for porosity.

A similar permeability formulation based on fractal pore space observations developed by (Costa, 2006) is written as:

$$K = C\frac{\emptyset^{z}}{(1-\emptyset)} \qquad \text{eq.(2)}$$

b- Winland (R35)

Winland of Amoco established an empirical relationship among porosity, permeability, and pore throat radius from mercury intrusion tests, The available data were obtained from the net pay cut-off values in some clastic reservoirs. Winland defined the flow unit, as a reservoir unit with uniform pore throat size distribution and similar flow performance, and determined by R35 (Winland, 1972). The Winland equation was used and published by (Kolodzie Jr., S., 1980) as:

$$\log R35 = 0.732 + 0.588 \log Ka - 0.864 \log \phi \text{ core} \qquad \text{eq.(3)}$$

where: R35 is the pore aperture radius, corresponding to the 35th percentile of mercury saturation, Ka is the air permeability (mD), and ϕ is the porosity (%).

In Winland's empirical relationship, the highest statistical correlation was at the pore throat size, corresponding to the 35th percentile of the cumulative mercury saturation curve, (Gunter et al., 1997). The concept behind the use of R35 is that, once the different flow unit types have been identified and quantitatively characterized, then the wells are subdivided into smaller units having predictable flow characteristics, solving for R35, we get the relation:

$$R35 = 10 \wedge (0.732 + 0.588 \log Ka - 0.864 \log \varphi) \qquad \text{eq.(4)}$$

3.3. Reservoir Quality Index

Reservoir Quality Index (RQI) for rock typing classification and the flow properties prediction method are based on the Kozeny-Carmen Equation and the concept of the mean hydraulic radius (Carmen, 1937). The derivative of the RQI Equation is based on the assumption that a porous medium can be represented by a bundle of capillary tubes. Kozeny model (Kozeny, 1927) is one of the earliest models proposed to estimate the permeability from the effective porosity and other relevant parameters by the following equation. (Kozeny, 1927).

$$K = \frac{Ø\, r^2}{8\, t} \qquad \text{eq. (5)}$$

where K is the permeability in mD, t is the tortuosity and r is the radius of capillary tubes in µm.

t In equation (5) r was used by Kozeny and Carmen for realistic porous media and the equation was modified in the generalized by (Carmen, 1937) as:

$$K = \frac{1}{\text{fs}.t^2.\ S^2 gv} * \frac{Ø^3}{(1-Ø)^2} \qquad \text{eq. (6)}$$

where: K in µm^2, fs is the shape factor, Ø in fraction, t is the tortuosity, S^2 gv specific surface area of unit grain volume in µm

RQI addresses variable Kozeny constant and S^2 gv term by the flow zone indicator (FZI), which includes all main geological and geometrical characteristics of the porous media as:

$$FZI = \frac{1}{\sqrt{\text{fs}.t^2.\ S^2 gv}} \qquad \text{eq. (7)}$$

$$K = \frac{Ø^3}{(1-Ø)^2} * FZI^2 \qquad \text{eq. (8)}$$

$$\frac{\sqrt{K}}{Ø} = \left[\frac{Ø}{1-Ø}\right] * FZI \qquad \text{eq.(9)}$$

If permeability is expressed in mille Darcie, then, the RQI is defined as follows: (Leverett, 1941).

$$RQI = 0.0314 * \left(\frac{K}{Ø}\right)^{0.5} \qquad \text{eq. (10)}$$

3.4. Hydraulic flow units

Hydraulic flow unit (HFU) is defined as a representative reservoir volume that practically possesses consistent petrophysical and fluid properties (Amaefule et al., 1993). The hydraulic flow unit concept is used to divide a reservoir into distinct petrophysical types, each of which has a unique flow zone indicator (FZI) value (Al-Ajmi, F.A. and S.A. Holditch., 2000). The hydraulic flow unit (HFU) concept provides a probabilistic approach for combining the geological environment units, with available petrophysical data, to delineate the reservoir into "units", with similar fluid flow characteristics. Hydraulic flow units are used to rank the dynamic rock-fluid properties, including the saturation-dependent capillary pressure and the relative permeability. Hydraulic units are characterized by the following:

a) Geological attributes of texture (which include mineralogy, sedimentary structure, bedding contacts, and permeability barriers).

b) Petrophysical properties of porosity, permeability, and capillary pressure.

Amaefule et al., (1993) presented the method for the use of hydraulic flow units (HFUs) to divide rock facies as a result of the considerable variation of permeability even in well-defined rock type, and used the concept of a bundle of capillary tubes and gave an equation which was re-arranged to isolate the variable that is constant within a hydraulic flow unit (HFU). According to (Amaefule et al.,1993 and Guo et al., 2005) the flow units in the reservoir are determined using flow zone indicators (FZI) and reservoir quality index (RQI) as follows. (Leverett, 1941).

$$FZI = \frac{RQI}{Øz} \qquad \text{eq. (11)}$$

$$Øz = \frac{Ø}{(1-Ø)} \qquad \text{eq. (12)}$$

where K is the permeability mD, Ø is the porosity fraction and Øz is the normalized porosity.

The computation of the FZI value involved analyzing the porosity and permeability data samples, where different FZI values correspond to distinct flow units. Each flow unit was characterized by an average FZI value associated with the specific porosity and permeability parameters (Mondal, I. and Singh, K.H.,2022).

The relationship between RQI and Øz is used to show that, the samples with similar FZI values lie close together on a log plot of normalized porosity versus permeability (Amaefule et al., 1993).

Log RQI =Log Øz+Log FZI eq. (13)

3.5. Permeability Prediction

The next step is to predict the permeability for each HFU, depending on the curve of FZI or the average value FZI, using the following equations:

$$K = 1014\, FZI^2 * \frac{Ø^3}{(1-Ø)^2} \qquad \text{eq. (14).}$$

Using the average FZI related to HFU zones as follows:

For average FZI= 4

$$K\_HFU\#1 = 1014 * 16 * \frac{Ø^3}{(1-Ø)^2} \qquad \text{eq. (15)}$$

For average FZI= 2

$$K\_HFU\#2 = 1014 * 4 * \frac{Ø^3}{(1-Ø)^2} \quad \text{eq. (16)}$$

For average FZI= 1

$$K\ HFU\#3 = 1014 * 1 * \frac{Ø^3}{(1-Ø)^2} \quad \text{eq. (17)}$$

4. RESULTS AND DISCUSSION

4.1. Reservoir Characterization

The evaluation of well logs has been performed to determine the petrophysical properties of the Abu Madi reservoir using graphical and computational methods. Log evaluation using 'TechlogTM' (Version, 2020) has been applied to determine shale volume, effective porosity, lithology, and hydrocarbon saturation. The petrophysical analysis in Faraskur-1 well showed the presence of 19m pay in the Upper Abu Madi reservoir with 21.9% average porosity and 43% average water saturation with a gas water contact @ 2618.4 m MD /-2610.66m TVDSS, and 1.8m pay in Lower Abu Madi reservoir with 21% average porosity and 56.5% average water saturation with a gas water contact @ 2668.3 m MD /-2660.74m TVDSS. And the petrophysical analysis in South Faraskur-4 proved 6.6 m thick of net pay in the Upper Abu Madi reservoir with 17.9% average Porosity and 41.9% water saturation, an additional 13.3 m thick of net pay in the Lower Abu Madi reservoir with 20.2% average Porosity and 41.8% water saturation as shown in (figs. 4 & 5).

4.2. Pore Size Distribution (Winland, R35)

The ranges of R35 have distinguished five petrophysical flow units, these are:

1. Mega port: Flow unit with R35, ranging above a threshold of 10 microns.
2. Macro port: Flow unit with R35, ranging between 2 to 10 microns.
3. Mesoport: Flow unites with R35, ranging between 0.5 and 2 microns.
4. Micro port: Flow units with R35, values in the range of 0.2 - 0.5 microns.
5. Nano port: Flow units with R35, values less than 0.2 microns.

A strong positive relationship between pore throat radius (r35) and both permeability and FZI can be observed, which can be used to derive the r35 parameter for the rock sample in the absence of pressure data, (Shalaby, M.R., 2021).

From the porosity-permeability plot, we determined three flow units in the cored interval of Abu Madi Fm (Fig.6) with Mesoport (0.5-2 mic.), Macroport, (2-10 mic.) and Megaport (10-50 mic.). Based on the Winland flow unit classification, three rock units can be characterized.

4.3. Stratigraphic modified Lorenz Plot (SMLP)

The best way, to assess the minimum number of flow units in a reservoir is used a graphical technique based on the stratigraphic modified Lorenz plot (SMLP) (Gunter et al., 1997; and Tiab and Donaldson, 1996). Constructing the SMLP method is a plot of the percent of flow capacity (% Kh) versus percent of storage capacity (%ϕh), in which the partial sums are computed and the totals are normalized to 100%, and arranged in stratigraphic order. The slope of the segments on this plot is indicative of the flow performance. As shown in (Fig.7), the shape of the SMLP curve reflects the flow performance of the reservoir units.

From SMLP results, areas with abrupt slopes are areas with a higher percentage of reservoir flow capacity compared to storage capacity. Steeper slopes indicate faster rates of flow (Bassem SN, 2021). These areas are delineated as having high reservoir process speed and are known as the speed zones, (Chopra AK et al., 1998). Areas on the SMLP with very low or flat slope are regarded as impermeable areas. These areas are the barrier zone of the reservoir. Barrier zone are impermeable zone with very low flow and storage capacities. (Omeje, E.T et al., 2022).

On the other hand, segments with flat behavior have storage capacity, but little flow capacity and are typically reservoir baffles. Segments with neither flow nor storage capacity are considered seals (Gunter et al., 1997), (Salazar Luna, J.M., 2004). Preliminary flow units are interpreted by selecting changes in slope or inflection points in the SMLP curve.

Table 1: Flow unit classification of the Abu Madi reservoir.

	R35 (mic)	PHI (%)	KH (MD)
Megaport	10 - 30	22 -29	300 - 1957
Macroport	2- 10	15 - 27	10 - 235
Mesoport	0.5 – 2	10 -18	1 - 10

A plot of RQI versus Øz for data from the cored interval is shown in: (Fig 8), Equation 13 yields a straight line on a log-log plot of RQI versus Øz with a unit slope, The intercept of this straight line at 1 is the flow zone indicator.

Reservoir quality index (RQI) is a method for classifying rock types and predicting flow properties, which is affected by the changeable value of petrophysical properties and the porosity-permeability relationship as discussed previously, as well as different pore throat size distribution, which is influential in flow performance.

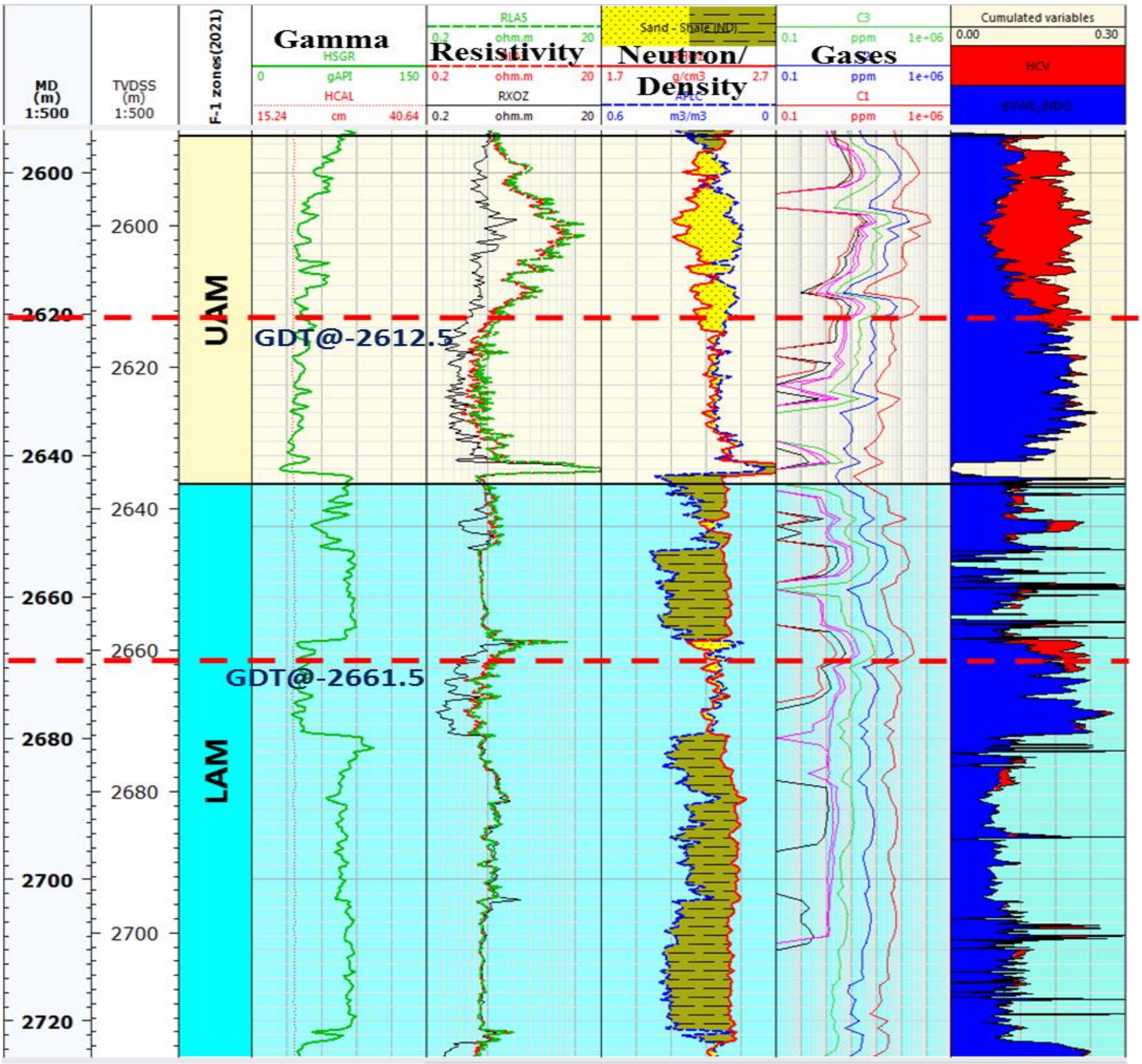

Fig. 4: Litho-saturation cross plot of Abu Madi Formation, Faraskur-1 well.

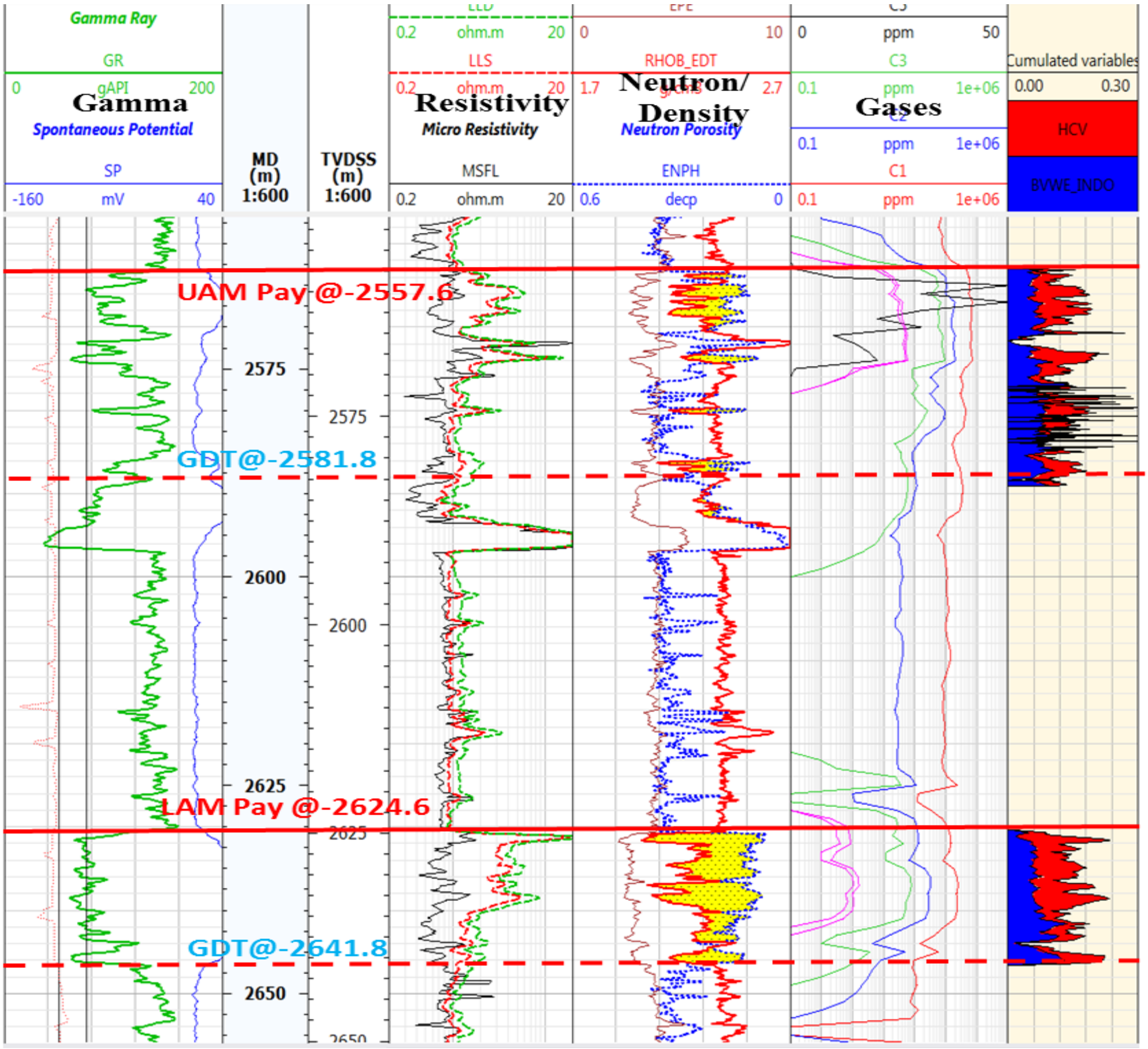

Fig. 5: Litho-saturation cross plot of Abu Madi Formation, South Faraskur-4 well.

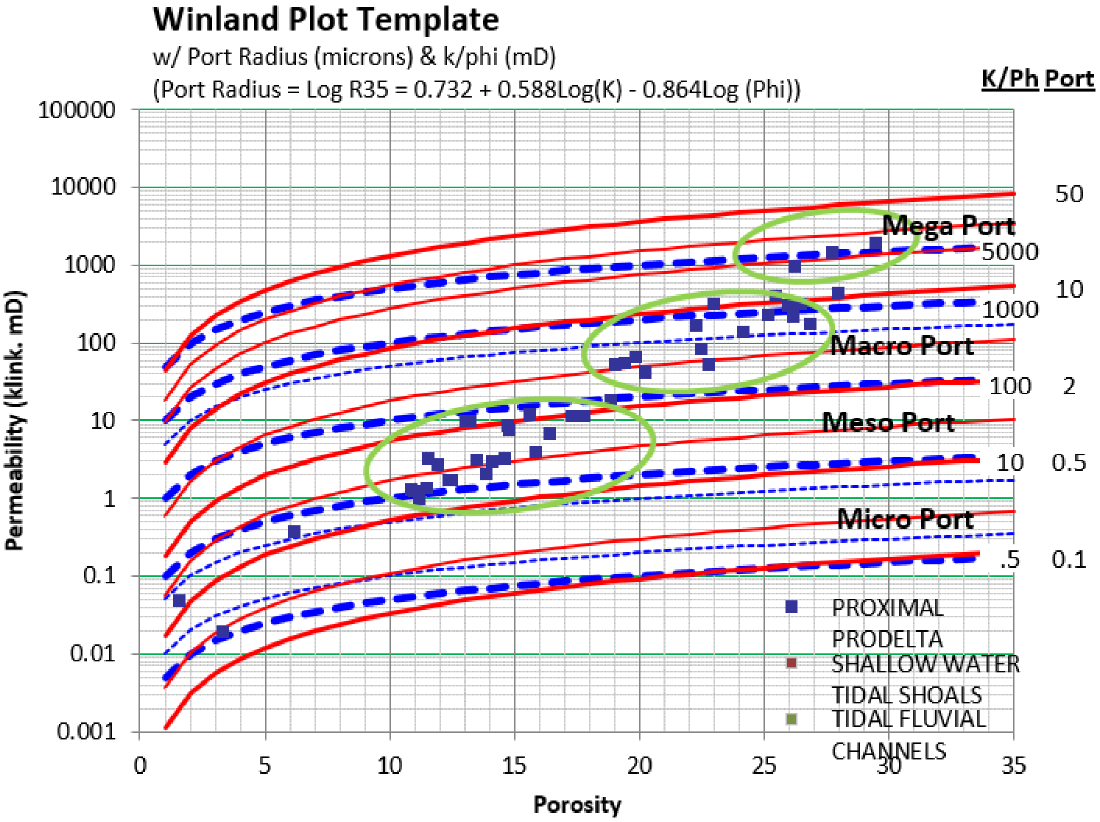

Fig. 6: Abu Madi core data porosity –permeability, overlaid by R35 lines.

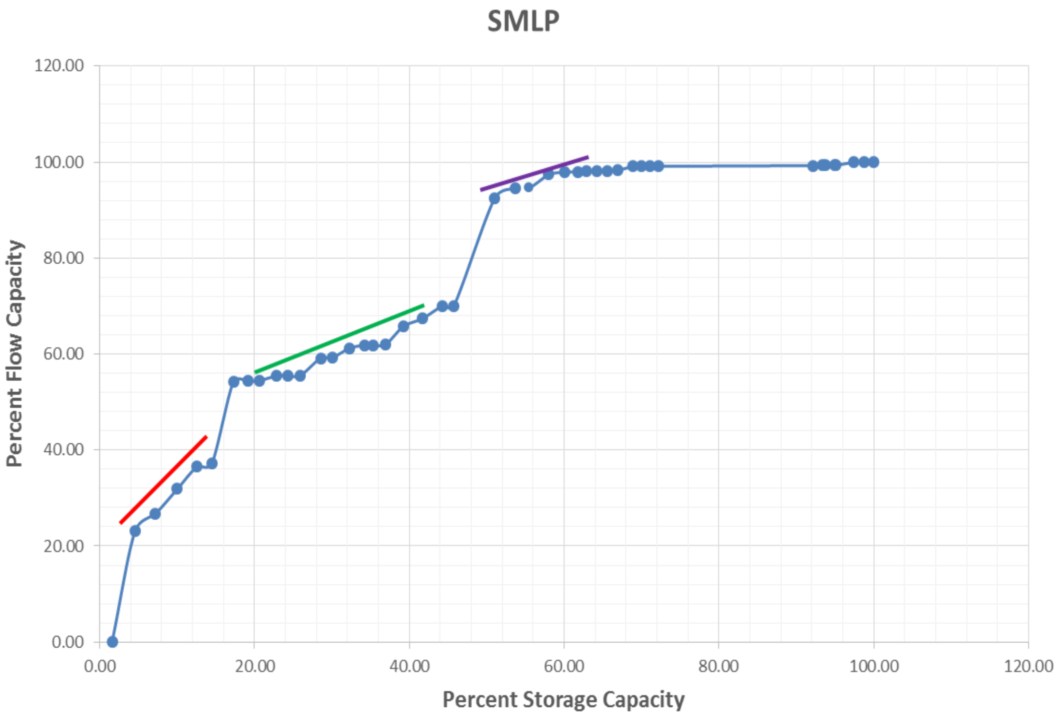

Fig. 7: Faraskur-3 well Stratigraphic Modified Lorenz Plot, sorting by porosity slope changes to define the flow units.

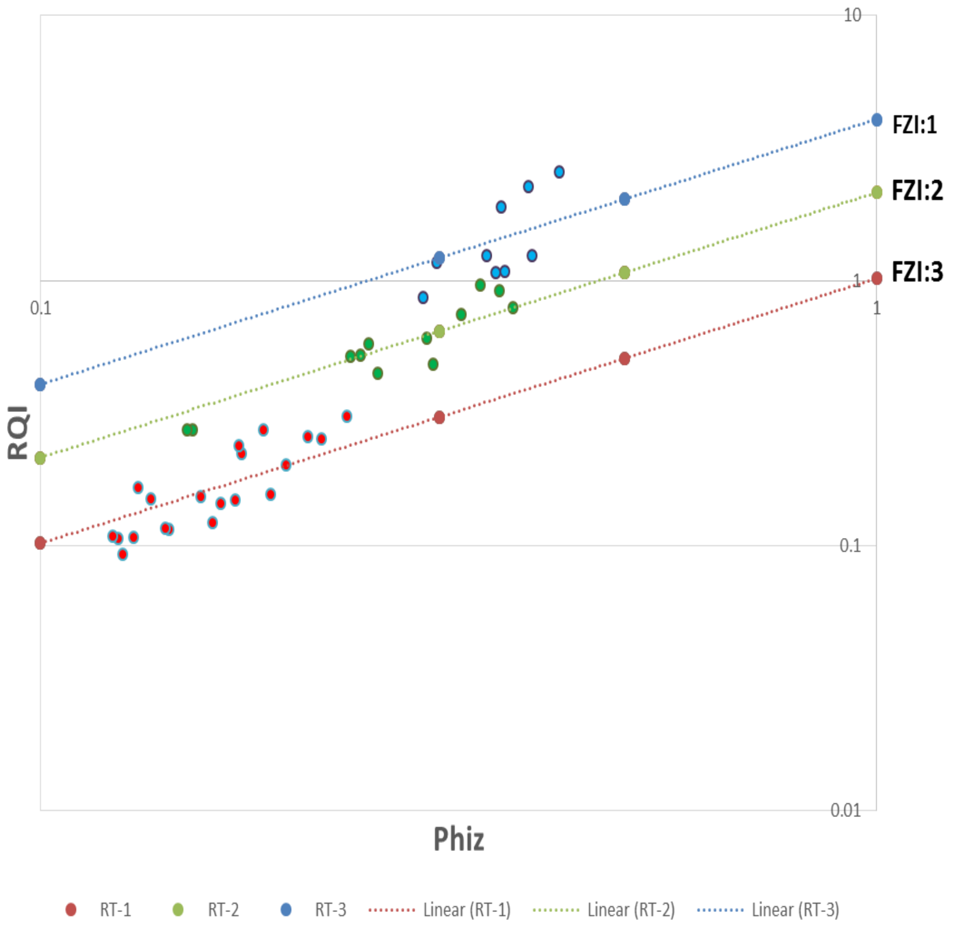

Fig. 8: Determination of FZI from PHIZ and RQI.

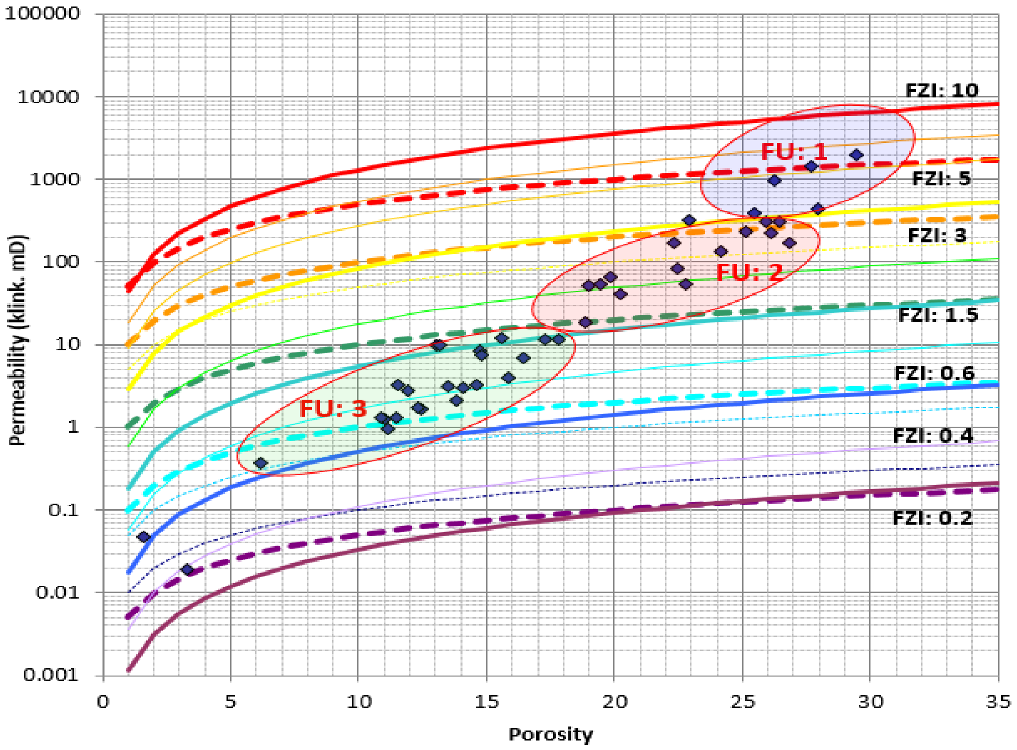

Fig. 9: Porosity vs. horizontal permeability X-plot superimposed on flow zone indicator lines and defined hydraulic flow unit.

When plotting normalized porosity versus permeability on a log plot, the relationship between RQI and phi normalized is used to show that samples with similar FZI values are grouped together. The term "qualitative identification of flow units" refers to the recognition of the number of flow units inside a well, regardless of their depth or distribution, (Abu-Hashish, M.F.,et al., 2022).

The FZI is calculated using equation (11) and equation (12) after the calculation of RQI, where the corrected conventional core analysis data for porosity and permeability were used in the calculation of RQI, then the FZI flow units were defined. Four main hydraulic flow units (HFUs) control the reservoir performance are defined for the cored interval in the Faraskur-3 well. (Fig. 9).

The reservoir quality and heterogeneities of the studied Messinian reservoirs are controlled by depositional sedimentary facies and diagenesis, (Selim, S.S.,et al., 2021).

The reservoir quality and the hydraulic flow unit’s data are given in Table (2).

Table 2: Summary of reservoir quality and Hydraulic Flow Unit (HFUs) for Abu Madi reservoir.

Reservoir Quality	HFUs	(FZI)	PHI (%)	KH (MD)
Very good quality sandstone	HFU-1	3 – 10	22-29	300 - 1957
Good quality sandstone	HFU-2	1.5 – 3	15 - 27	10 - 235
Poor sandstone	HFU-3	0.6 – 1.5	10 -18	1 - 10

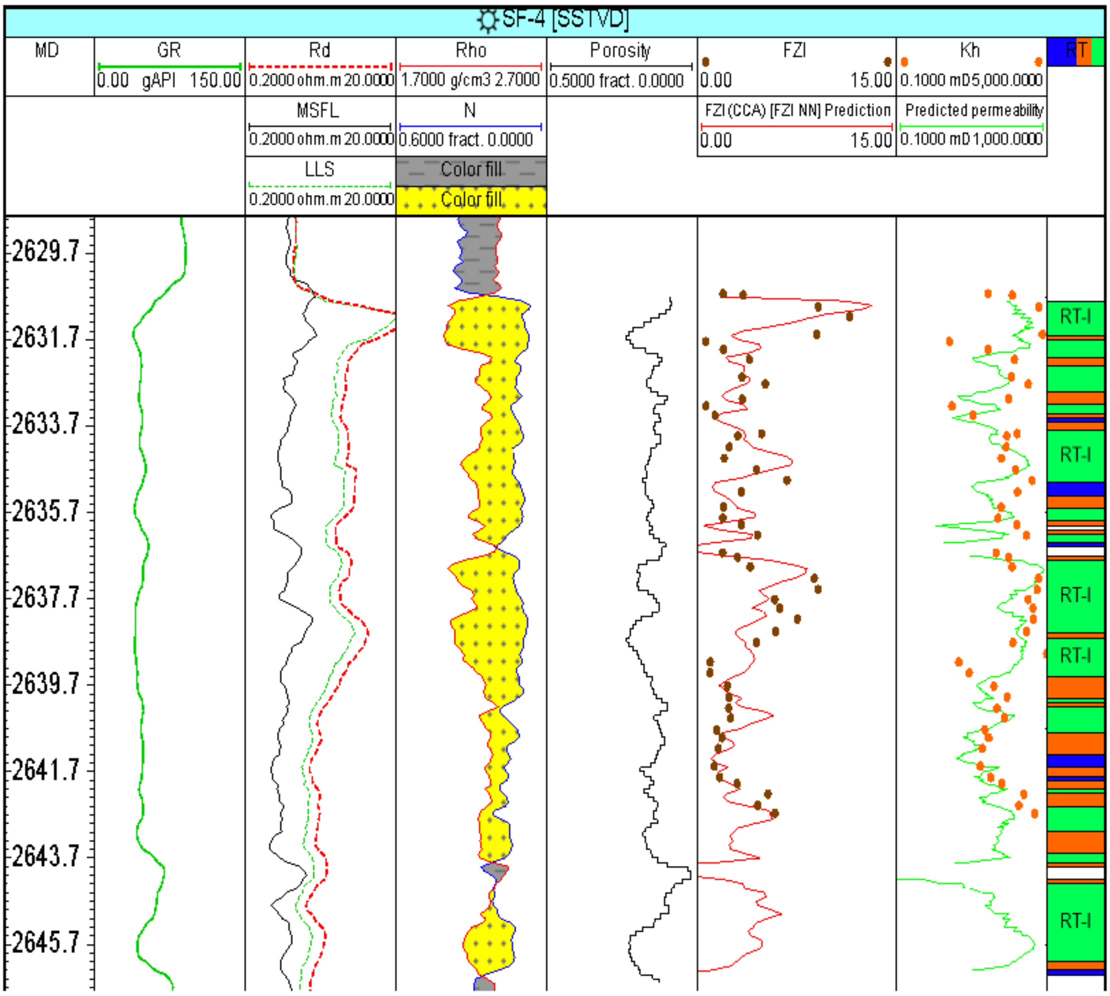

Fig. 10: Correlation of the predicted Permeability and calculated one against the cored interval in SF-4 well.

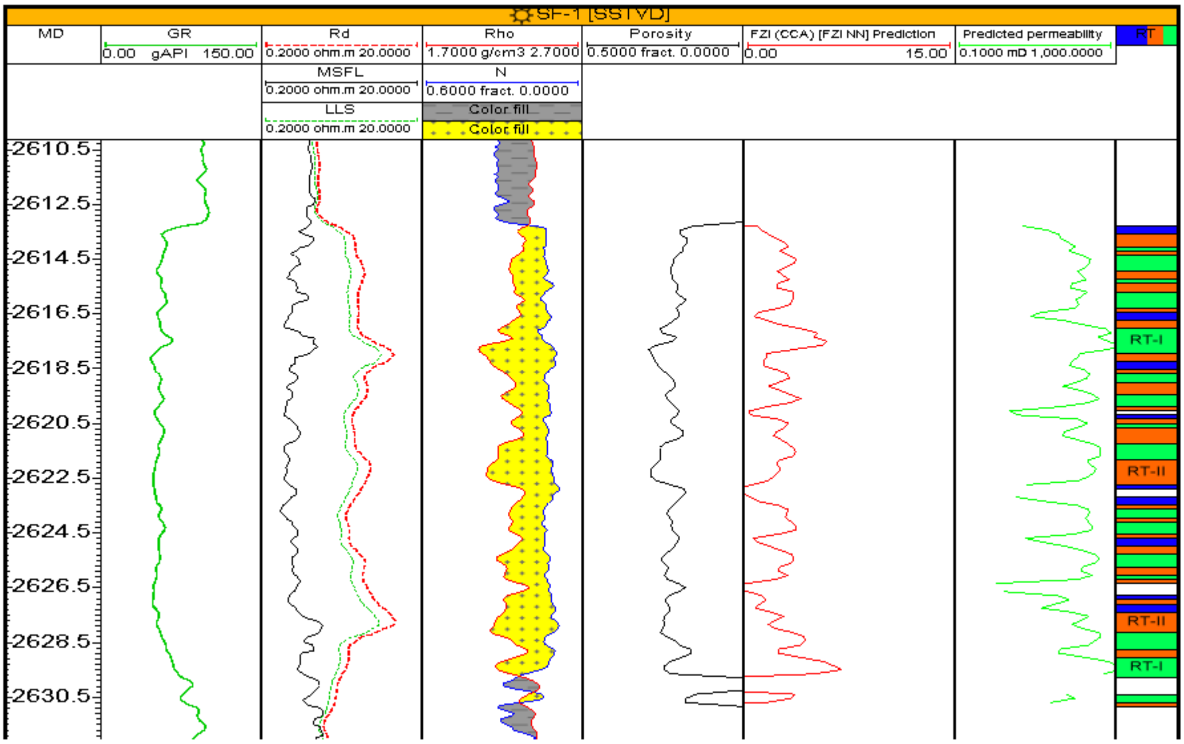

Fig. 11: Permeability prediction in the uncored intervals in F-1 well.

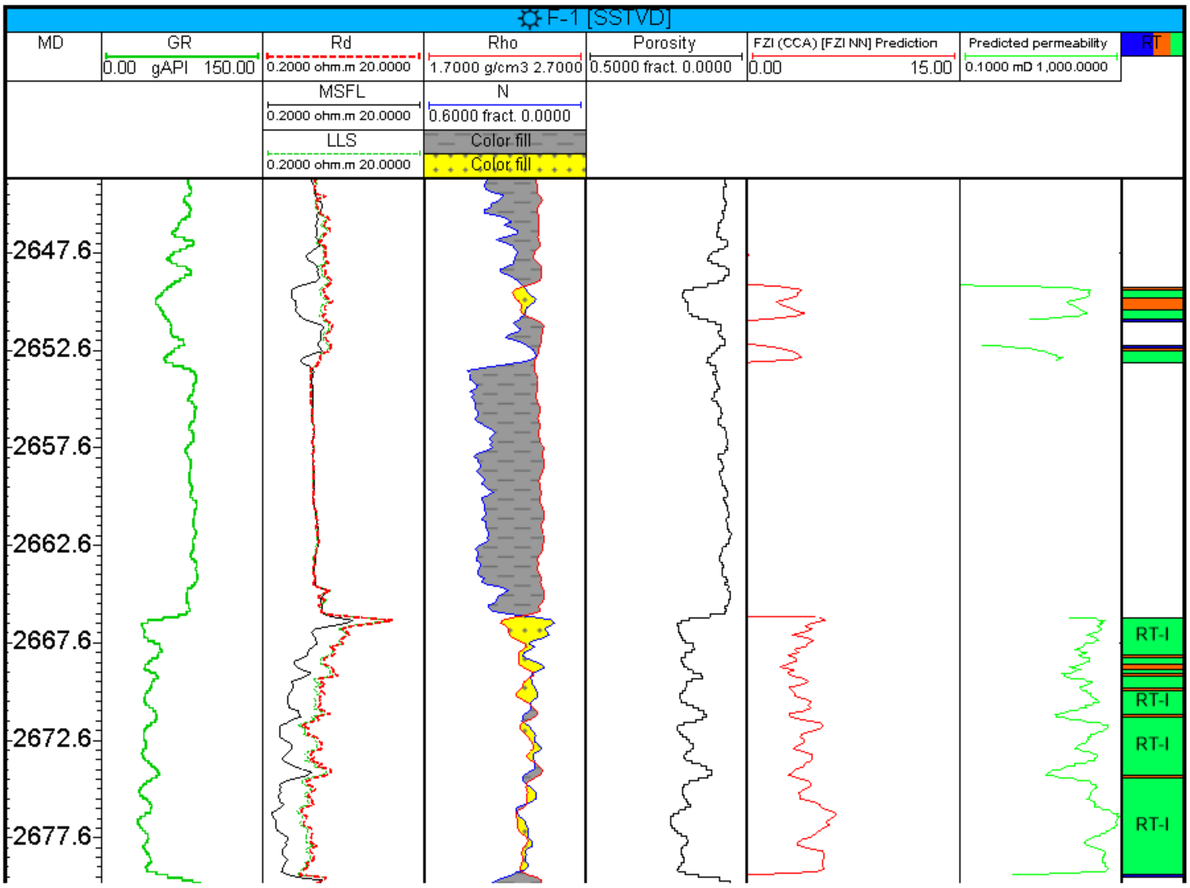

Fig. 12: Permeability prediction in the uncored intervals in SF-1 well.

4.4. Neural network analysis

The neural network technique was used to reduce the multidimensional data sets to lower dimensions for analysis. This technique can be useful in petrophysics and geology, as a preliminary method of combining the multiple logs into a single or two logs, without losing information.

This method is statistical, but its results are seen to be geologically consistent statistical modeling, using the effective porosity (PHIE), shale volume, and photo-electric curves (PEFZ) to predict the FZI curve using the FZI calculated within cored intervals. The correlation of the predicted FZI and calculated one against the cored intervals reflects a similar response and high correlation between the curves as shown in (Fig. 10), then apply it to other logged wells and predict the FZI in the uncored intervals and other wells as shown in (Figs. 11 &12).

CONCLUSION

This study utilized the flow zone indicator (FZI) approach to classify the reservoir rock of the Abu Madi Formation in the West El Manzala field into separate zones with similar rock characteristics of hydraulic flow units (HFU). The prediction of permeability was achieved through integrating core and wireline log data. Log data including gamma ray, density, neutron, resistivity, and sonic logs along with porosity and permeability data from core samples.

The analysis defined three HFUs in the Abu Madi reservoir: HFU-1 contained very good quality sandstone with permeability of 300 to 1957 mD, porosity of 22 to 29%, and FZI of 3 to 10. HFU-2 contained good quality sandstone with permeability of 10 to 235 mD, porosity of 15 to 27%, and FZI of 1.5 to 3. HFU-3 contained poor quality sandstone with permeability of 1 to 10 mD, porosity of 10 to 18%, and FZI of 0.6 to 1.5. By using FZI values, permeability could be predicted from cored to uncored wells and intervals. Neural log analysis integrating core and log data was an effective method for predicting permeability in uncored sections and wells.

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