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Lithological And Petrophysical Characteristics Of The Late Miocene Abu Madi Reservoir, West Al Khilala Field, On-Shore Nile Delta, Egypt

Eysa, E. A.[1], El Khadragy, A. A.[1], Hashim, A.[2] and Abd El Kader, A.[3]
[1] *Department of geology, Faculty of Science, Zagazig University, Egypt.*
[2] *Petroceltic Company, Egypt*
[3] *Mansoura Petroleum Company, Egypt*

Abstract: *The on-shore Nile Delta is one of the most promising areas for gas exploration and production in Egypt. The present study deals with the petrophysical evaluation by the integration of well logs with the core data to illustrate the reservoir characterization of the Late Miocene Abu Madi Formation at West Al Khilala Field, Nile delta, Egypt. The study area is about 47.6 km^{2}and considered to be a commercial gas area producing about 24.72 MMSCF/D. This study is based on seven drilled wells scattered across the reservoir to establish the different properties of the reservoir such as the lithology, shale volume, porosity, fluid saturation, net pay thickness, and hydrocarbon saturation. This study reveals that the presence of gas-bearing sandstone interval ranged from 23 ft. to 114.5 ft. of net pay zone. The detailed petrophysical analysis of the reservoir attains good hydrocarbon potentiality in terms of good porosity (19.4 to 23.4%), low shale volume (6.8 to 20.2%) and water saturation (9 to 57%). The constructed cross-plots of the Neutron-Bulk Density and M-N display that, the main lithology of the reservoir is quartz mineral with intergranular porosity types based on the dia-porosity cross plot ($Ø_S$-Q_{ND}), which is interpenetrated with mainly dispersed shale type and little of laminated types within the pore spaces. The analysis of pressure data is concerned mainly with locating the different fluid contacts anddetermining the pressure gradients of the gas-bearing zone. Very close pressure regimes are detected for the investigated gas anomaly throughout the study area. Pressure gradient ranges from 0.078 to 0.12 psi/ft with an average of 0.0995 psi/ft, while the water gradient ranged from 0.40 psi/ft to 0.43 psi/ft with an average of 0.4225 psi/ft.. The study of Abu Madi Formation indicates a clastic sandstone reservoir with good petrophysical parameters for production, dispersed shale type distribution and intergranular porosity type*
Keywords: *Abu Madi Reservoir, Late Miocene, Nile Delta, West Al Khilala Field*

I. Introduction

The Nile Delta Basin had become the most important energy source in Egypt in the last few decades in the early 1960s with the recent gas discoveries of the West Al Khilala Field. The Nile Delta produce mainly gas with few wells had produced gas with oil [1]. The Nile Delta is made up of prograding siliclastics sediments deposited since the Paleogene whose thickness may exceed 4 to 5 Km [2 & 3]. Miocene and Pliocene reservoirs have produced major volume of gas (3.8 Billion barrel reported in 2000) and there is proven reserve of 62 TCF [4].

The geology and the entrapment mechanism of the Nile Delta are still under discussion because the Nile Delta does not have any outcrops of older rocks, where it covered by the Holocene soils. Well logs analysis is usually the main tool of investigation and evaluation of the subsurface formations parameters such as porosity, permeability, and water saturation. The dominant function of those parameters is to assess the hydrocarbon content and behavior of the subsurface reservoirs.

The West Al Khilala area is about 47.6 km2lies to the central onshore part of the Nile Delta between latitudes 31°17` 0.6" to 31° 21` 39.5" N, and longitudes 31° 13` 54.8" to 31° 18` 0.5" E., about 10 Km southwest of Abu Madi gas Field. It covers an area of about 47.6 km2 (Fig. 1). The West Al Khilala Field is considered as the southwest extension of Abu Madi main channel or paleovalley. The main reservoir bodies of Abu Madi Formation are represented by sandstones, mainly fluvial, developed in the active channel belts as a response to the relative fall/rise of the sea level [5 & 6].

The main target of this study is to achieve comprehensive evaluation of the hydrocarbon reservoir of the Abu Madi Sandstones for the selected studied wells in West Al Khilala Field using the well logging and core data as well as the pressure data.

II. Geological Setting And Stratigraphic Framework

Geologically, the Nile Delta lies on the slightly deformed outer margin of the African plate. It includes the continental shelf stretching from about 80 Km West of Alexandria to North Sinai, the continental slope and the Nile submarine fan that is, Nile Cone [7]. The on-shore Nile Delta basin is structurally and stratigraphically divided into eastern, central and western sub-basins. These basins are characterized by the presence of thick Plio-Pleistocene sediments associated with extensive NW trending shallow listric faults. While the Miocene sediments characteristics by the presence of Abu Madi channel which considered to be the main gas-producing horizon in the Nile Delta.

[8] stated that the Nile Delta was structurally controlled by different fault patterns, which were tectonically extended from Late Paleozoic to recent (Fig. 2). These fault patterns had different trends as E-W trend called the hinge zone, NW-SE trend called El Temsah Trend, NE-SW trend called Rosetta trend and N-S trend called Baltim trend. These previous faults effect on the Nile Delta area controlling the reservoir trapping with minor other faults.

Many authors had dealt with studying the structural setting of the Nile Delta area as [9, 10, 11, 12, 13, 14, 15, 16, 17, 18& 19] and others. The sedimentary rocks penetrated in the Nile Delta basin consist of thick clastics sediments (Fig. 3) representing Miocene-Holocene time interval [7]. These rocks were described by [6, 14& 20].

The Late Miocene rocks include the Qawasim and Abu Madi formations [21]. At the base of sequence, the Qawasim Formation includes sandstone and conglomerate with variegated color of shale intercalation [22]. The Abu Madi Formation is the main gas-producing horizon in the Nile Delta [7]. It comprises a series of thick, cross-bedded sand bodies, interbedded with thin calcareous shales [22] that reset unconformably on the Qawasim Formation [7]. The Kafr El Sheikh Formation is the thickest rock unit deposited in the area of study and in the Nile Delta generally [7]. It deposited in the form of prograding clastics sheets that composed of thick shale unit intercalations with some minor occurrence of sands, siltstones and argillaceous limestones [7& 23]. The El-Wastani formation consists of commutation of thick quartzose sandstone and clay beds that trend to thinning towards the top [22]. While the MitGhamr Formation composed mainly of thick layers of coarse to medium loose sand grains and pebbles at its base with clay interbeds [22].

III. Material And Methodology

The open hole log data (gamma ray, resistivity, neutron porosity and formation density) of seven wells (W. Al Khilala-1, 2, 3, 4, 5, 6 &6ST) were used in this study. The data was corrected to the different environmental effects. This study has been carried out through qualitative and quantitative analyses by means of the Interactive Petrophysics (IP V. 4.2) program. Cross-plots were used to show the lithologic and mineralogical components of the Abu Madi reservoir. The shale content was calculated from gamma ray, neutron, density and resistivity logs. The corrected porosity was estimated using a combination of the density and neutron logs, after applying various corrections. The water saturation was computed with Indonesian equation. Corrected well logs and derived reservoir parameters are plotted versus depth, including the vertical cross-plots and lithology identification cross-plots using charts of [24]. These cross-plots give a quick view about the rock and mineral contents in a qualitative way. Some of these cross-plots give the amount of lithologic contents in a quantitative way. Such cross-plots are neutron-bulk density, and M–N cross-plots. Furthermore, the available formation pressure data of the sandstone anomalyis also interpreted and plotted against depth, in order to locate the different fluid contacts and illustrate the prevailing pressure regimes.

IV. Results And Discussions

4.1 Neutron-Bulk Density Cross-Plot

The PhiNeu - RHOZ cross plot (Fig. 4) shows that, the main lithology of the reservoir is the sandstone with some scattered points fallen at the northwestern part of the sandstone line reflecting the presence of gas effect within the formation. Few points plotted around the limestone line in most wells and very few points around the dolomite line in West Al Khilala-2, 3 and 5 wells reflecting a weak presence of carbonate and dolomite.

4.2 M–N Cross-Plot

The M–N cross-plots (Fig. 5) reveal that the most points concentrated around the quartz sandstone line which reveals the predominance of quartz mineral and the main lithology is sandstone, while few points are scattered downward due to effect of sulfur. There are some points aligned at the northern part of the cross plot due to the gas effect of the reservoir.

4.3 Shale types Cross-Plot

The dia-porosity cross-plots (ØN- ØD) (Fig. 6) of [25] display that the shale type within the reservoir was mainly dispersed type. The Scanning Electron Microscopy (SEM) for W. Al Khilala-2 and 5 wells (Fig. 7) reveals that the kaolinite is the most predominant clay mineral type with some dolomite crystal. The other points shifted outside the triangle areas as a result of the enormous effect of the gas saturation within the studied interval.

4.4 Porosity types Cross-Plot

The Sonic/Neutron Density (ØS-ØND) dia-porosity cross plots (Fig. 8) display that the type of porosity in the reservoir is an intergranular porosity that could be noticed throughout the SEM in W. Al Khilala-2 & 5 wells (Fig. 9) as an example. However, the shifted points presented on the northwest side of the chart cross plot due to the gas effect within the reservoir.

4.5 Hydrocarbon litho-saturation correlation panel

Evaluation of the gas potential of the reservoir rocks is based on the results of well logging analysis carried out for the wells in the study area using the Interactive Petrophysics (IP. Ver. 4.0). Figure 10 exhibit the correlation panel of hydrocarbon lithosaturation of the Late Miocene Abu Madi Formation for W. Al Khilala-1, 2, 3, 4, 5, 6, &6ST wells.

The correlation panel for each individual well composed of eleven tracks. The first two tracks is the depth track in MD and TVDSS. The 3rd track displays the GR log. The 4th track shows the resistivity curves (RXOZ, AIT 60&AIT 90). The 5th track shows the measured porosity logs (RHOZ&TNPH). The 6th track shows the interpreted lithology. The 7th track shows the interpreted fluid type. The 8th track shows the interpreted pay flag for the reservoir. The 9th track shows the interpreted (Vsh). The 10th track shows the interpreted effective porosity (PHIE). The 11th track shows the interpreted water saturation (Sw).

From QFL triangle, the Abu Madi reservoir displays a quartz arenite sandstone lithology based on the core data analysis (Fig. 11), which characterized by low values for the GR, RHOZ&TNPH logs and increasing values for the resistivity logs reflecting a presence for the hydrocarbon in the Abu Madi Formation. The reservoir composed mainly of sandstone interval bearing hydrocarbon. The lithology characterized by loose, off white color, transparent to translucent, fine to very fine grains grading to siltstone, well sorted, rounded grains with calcareous cement matter and no oil shows and minor streaks of shale interbeds [22].

4.6 Lateral distribution of reservoir parameters

The log data analysis reveals that, the Abu Madi reservoir is recorded with different thicknesses in all wells in the study area ranging from 25 ft. to 170 ft. Table-1 illustrates the main petro-physical characteristics of the interest zones (gross thickness, net thickness, water saturation, effective porosity, shale volume and hydrocarbon saturation) in all evaluated wells in the study area. The estimated petrophysical parameters of Abu Madi reservoir, which illustrated in lateral distribution panel (Fig.10). This distribution showed that average reservoir parameters in the West Al Khilala Field about Øe = 21.1%, Vsh = 13.3%, Sw =38.6% and Sh = 61.4%. Figure (12) illustrates the lateral distribution map of shale volume that ranges from 6.8% (W. Al Khilala-4 Well) to 20.2% (W. Al Khilala-6 Well) with general increasing towards the central part of the reservoir. The water saturation ranges from 9% (W. Al Khilala-1 Well) to 57.7% (W. Al Khilala-5 Well) with northwest and southeast increasing towards the reservoir edges (Fig. 13). Effective porosity ranges from 19.4% (W. Al Khilala-5 Well) to 23.4% (W. Al Khilala-4 Well) with increasing in the south east direction trend as shown in (Fig. 14). The net pay thickness of the Abu Madi reservoir ranges from 8.75' (W. Al Khilala-6 Well) to 114.5% (W. Al Khilala-2 Well) with northeastern directional trend (Fig. 15). The hydrocarbon saturation ranged from 42.3% (W. Al Khilala-5) to 91% (W. Al Khilala-1) with increasing towards the northeast direction (Fig. 16).
From the previous evaluation and maps, we can conclude that, the central part of the reservoir is the best area for the reservoir characteristics around the W. Al Khilala-1 and 2 wells.

4.7 Pressure data analysis

The analysis of pressure data is an important tool to detect the reservoir characteristics. It can be used to differentiate between the different hydrocarbons (oil and/or gases), in terms of their pressure gradients and slopes, when they have different pressure regimes. By systematically measuring the pressure points opposite each reservoir and then plotting them as a function of depth, we can identify the nature of fluids (gas, oil, or water) and specify the different fluid contacts by studying the abrupt changes in the pressure gradients [26]. In the present study, four wells were analyzed and interpreted (Tables-2) in which the gas pressure gradient ranges from 0.078 to 0.12 psi/ft with average of 0.0995 psi/ft, while the water pressure gradient ranges from 0.40 psi/ft to 0.43 psi/ft with average of 0.4225 psi/ft. Figure (17) shows the results of selected examples of W. Al Khilala-2, 5, 6 and 6ST wells. The tops and the bottoms of the encountered gas zones are clearly located and differentiated considerable depth sections, which display a close range of pressure gradient indicating a connected reservoir and homogenous prevailing pressure reservoir.

V. Figures and Tables

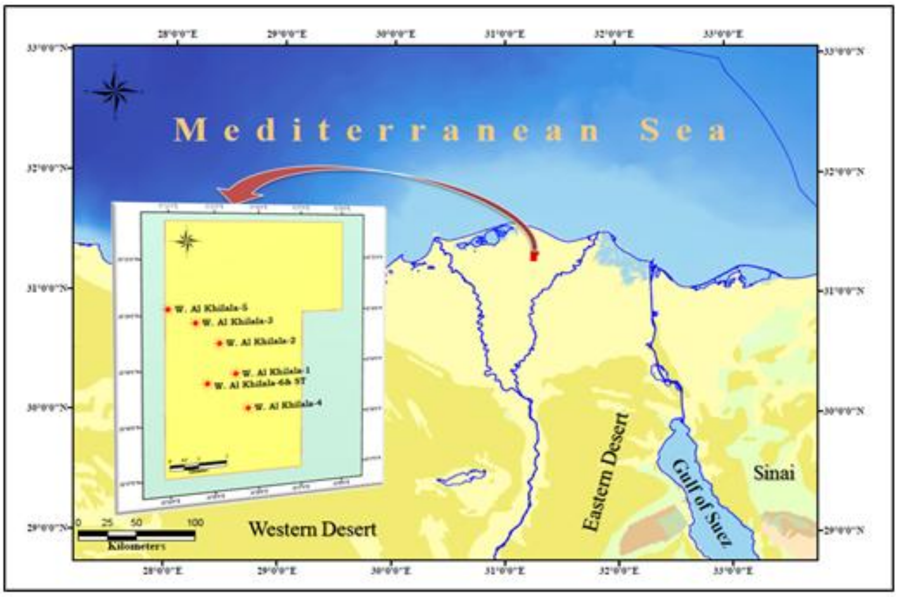

Fig. 1: Location map of W. Al Khilala Field (Study Area).

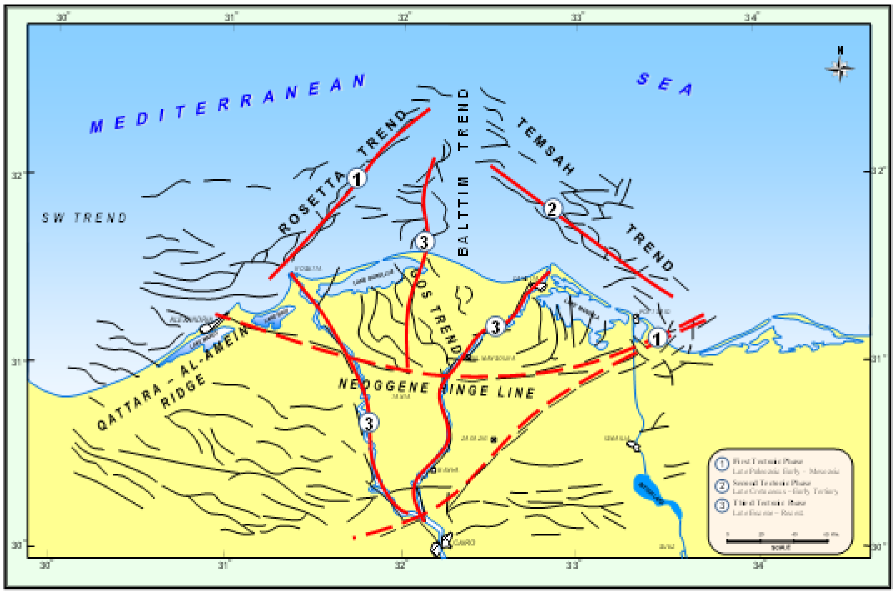

Fig. 2: Nile Delta tectonic setting map, [8].

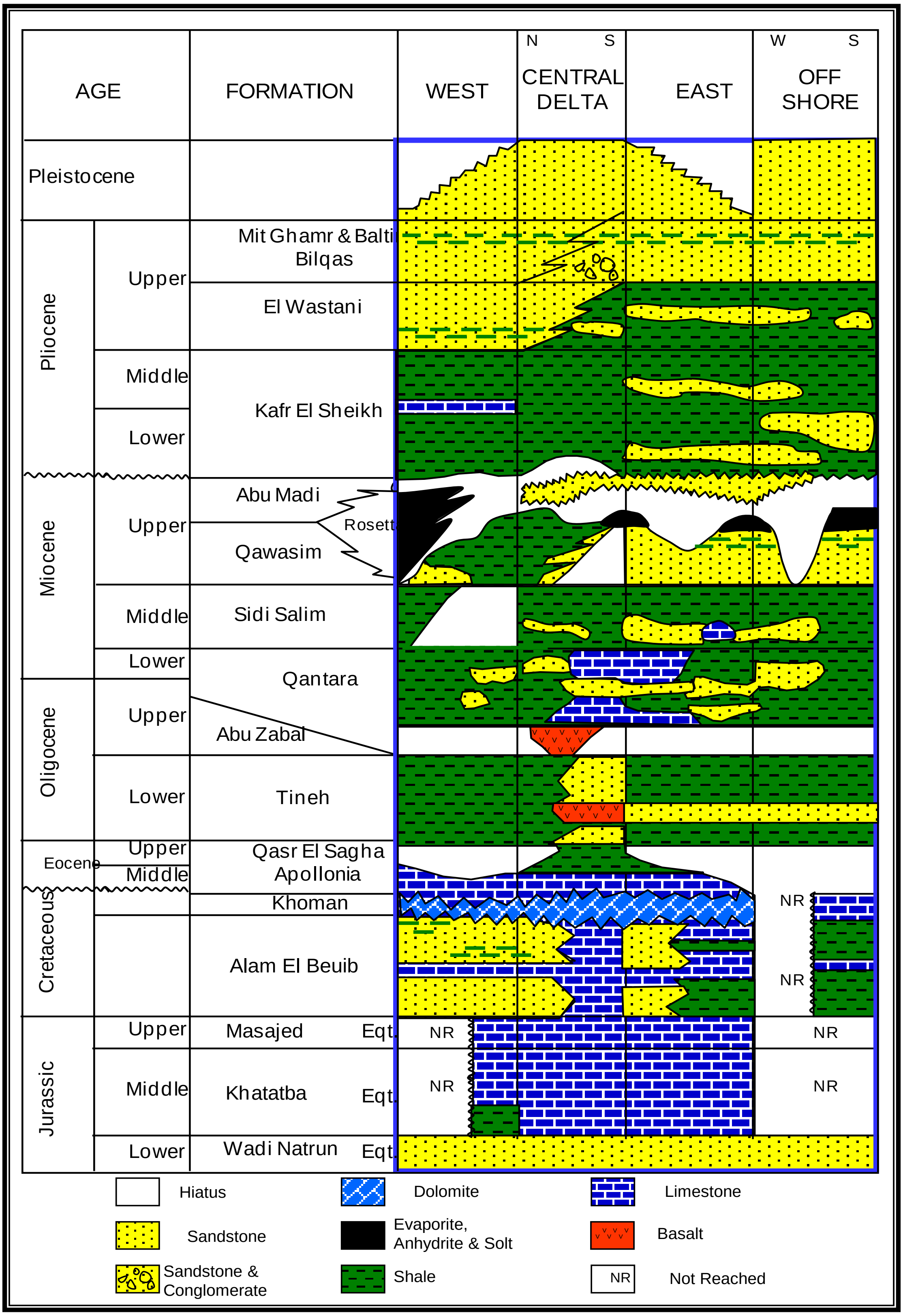

Fig. 3: Generalized lithostratigraphic sections of the Nile Delta [7].

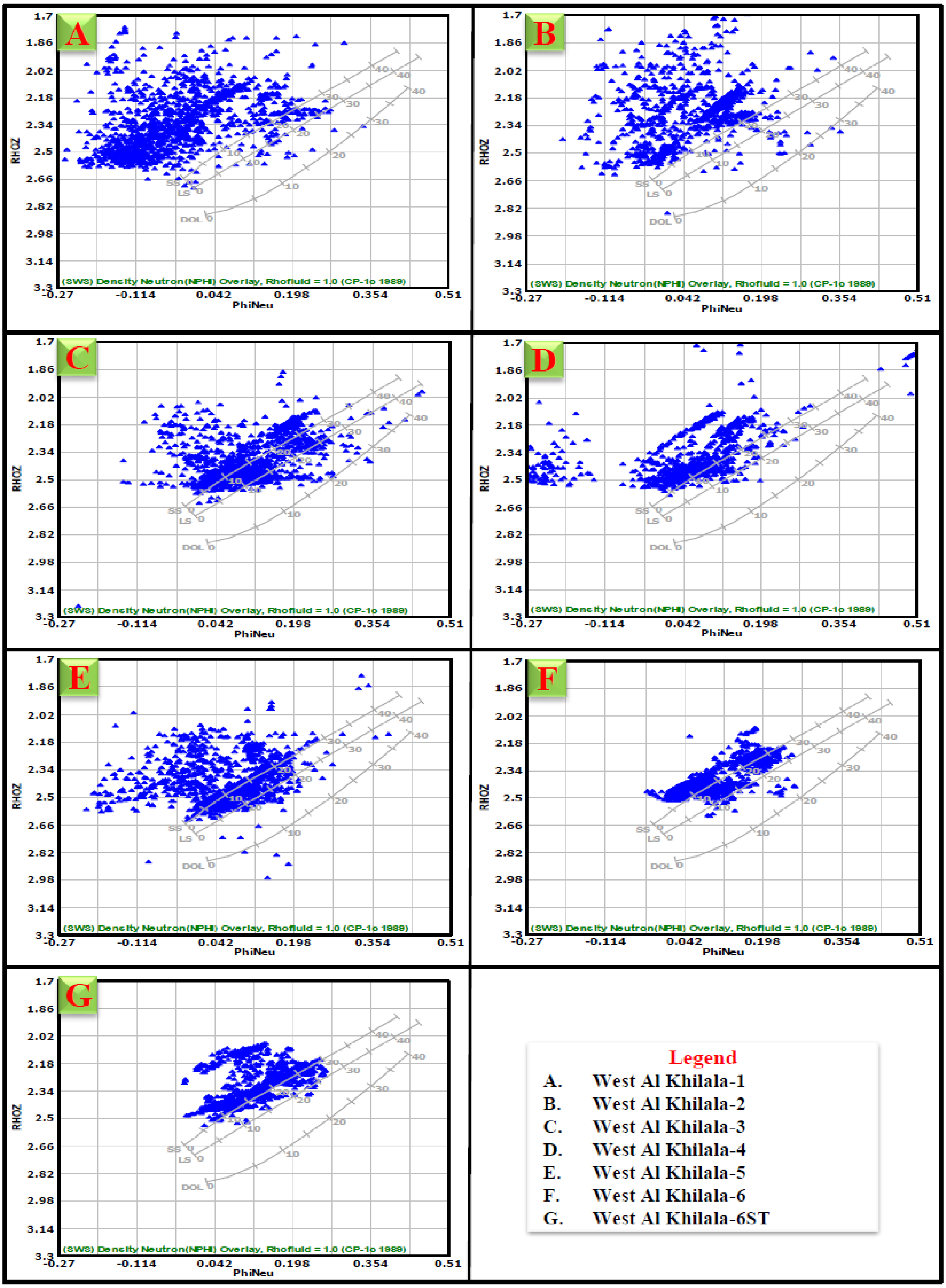

Fig. 4: The PhiNeu - RHOZ Cross plot for the Late Miocene Abu Madi Reservoir in the study area.

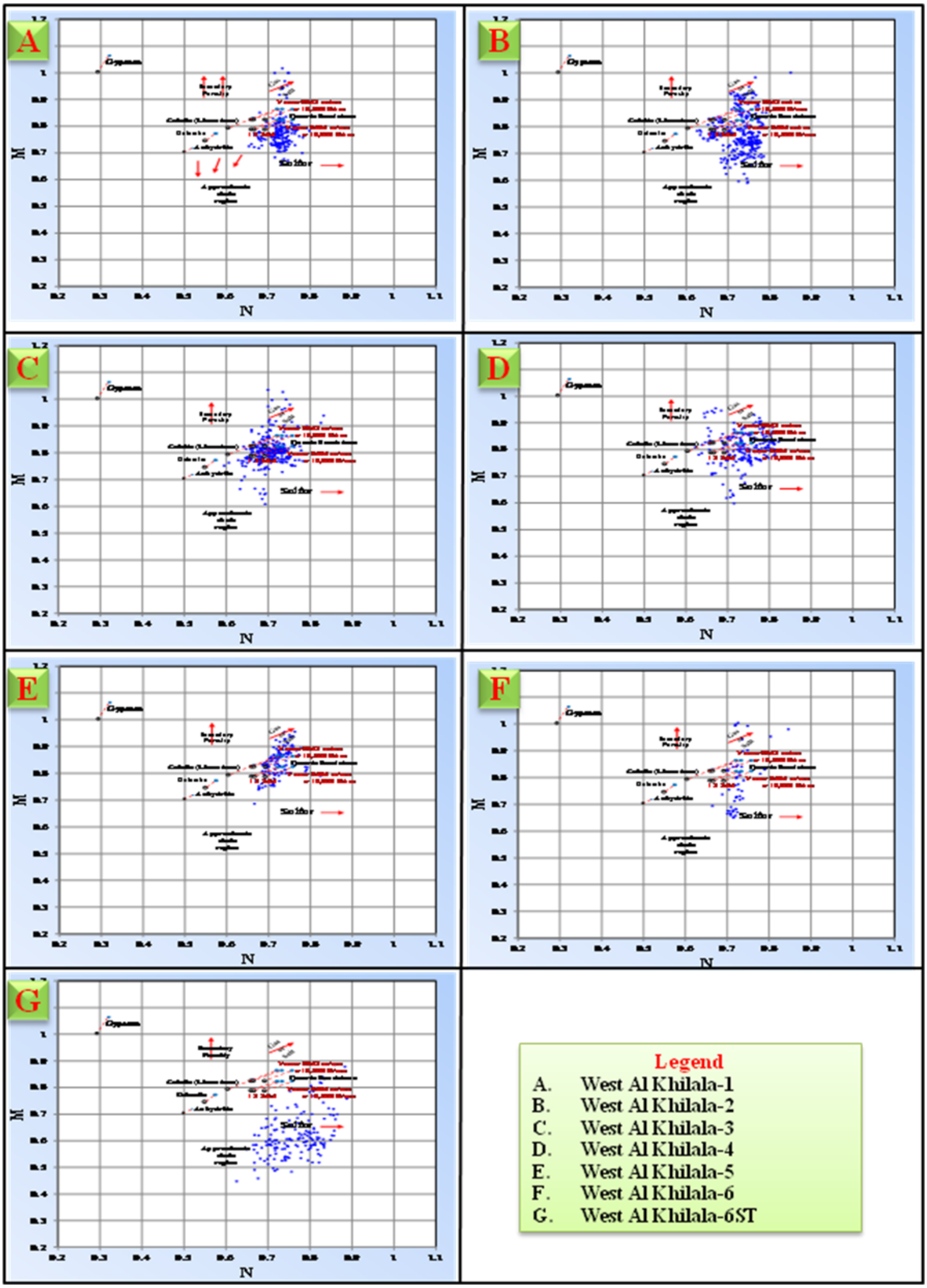

Fig. 5: The M-N cross plot for the Abu Madi Reservoir in the study area.

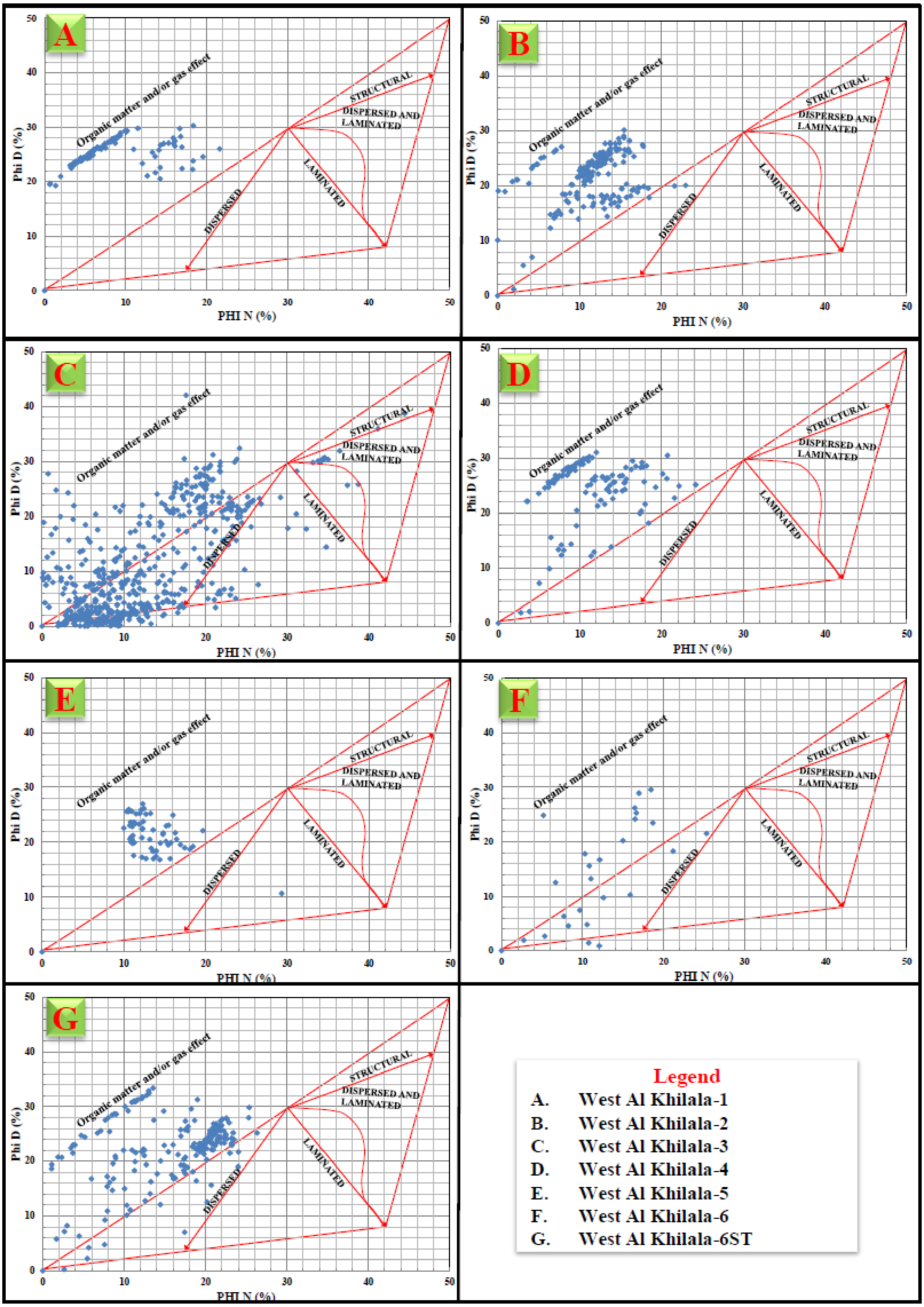

Fig. 6: The Neutron/Density porosity cross plot for the Abu Madi Reservoir.

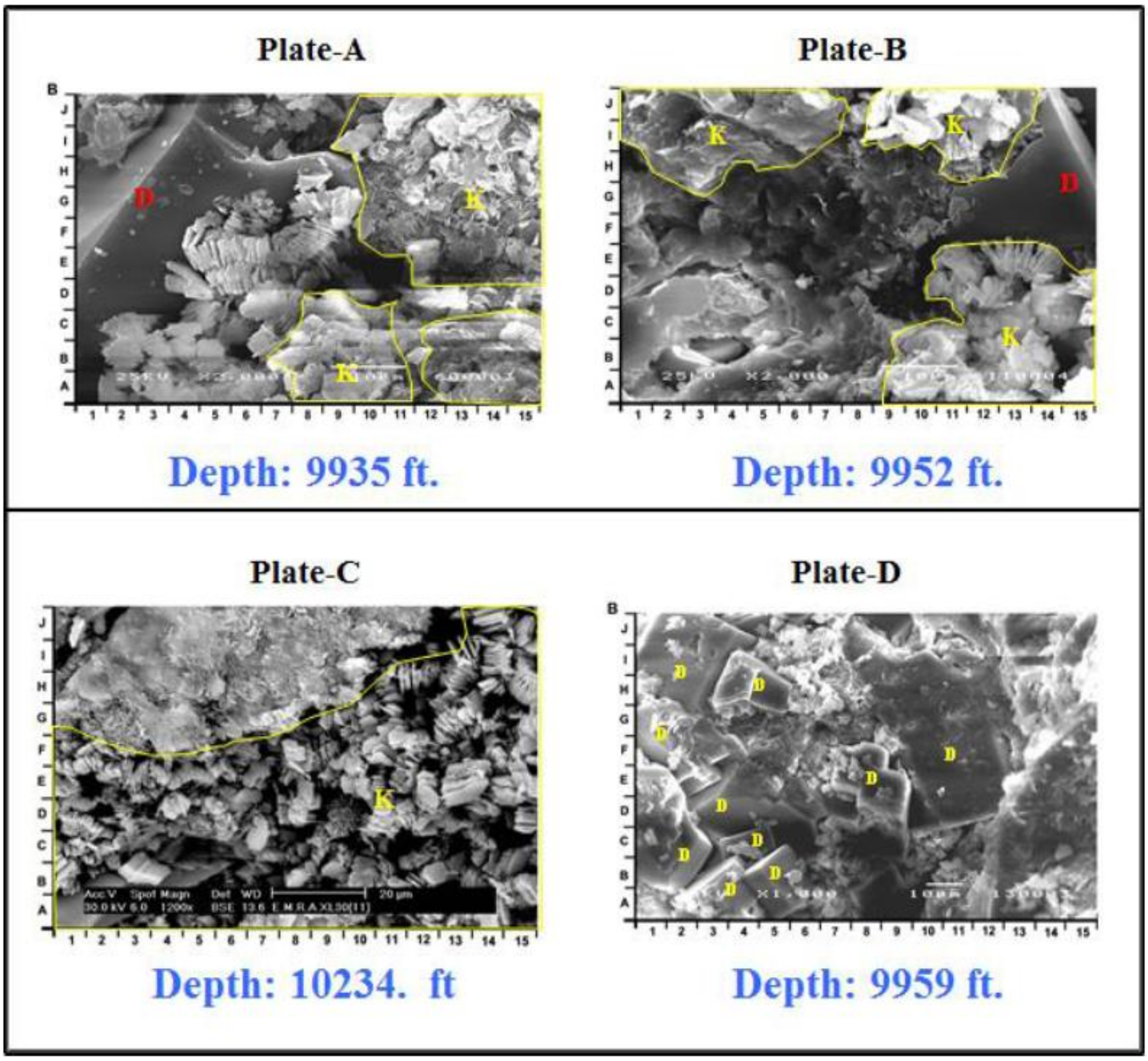

Fig. 7: The SEM Plates for the Abu Madi Reservoir in W. Al Khilala-2 Well (Plate-A & B) and W. Al Khilala-5 Well (Plate-C & D) displaying the kaolinite clay mineral type

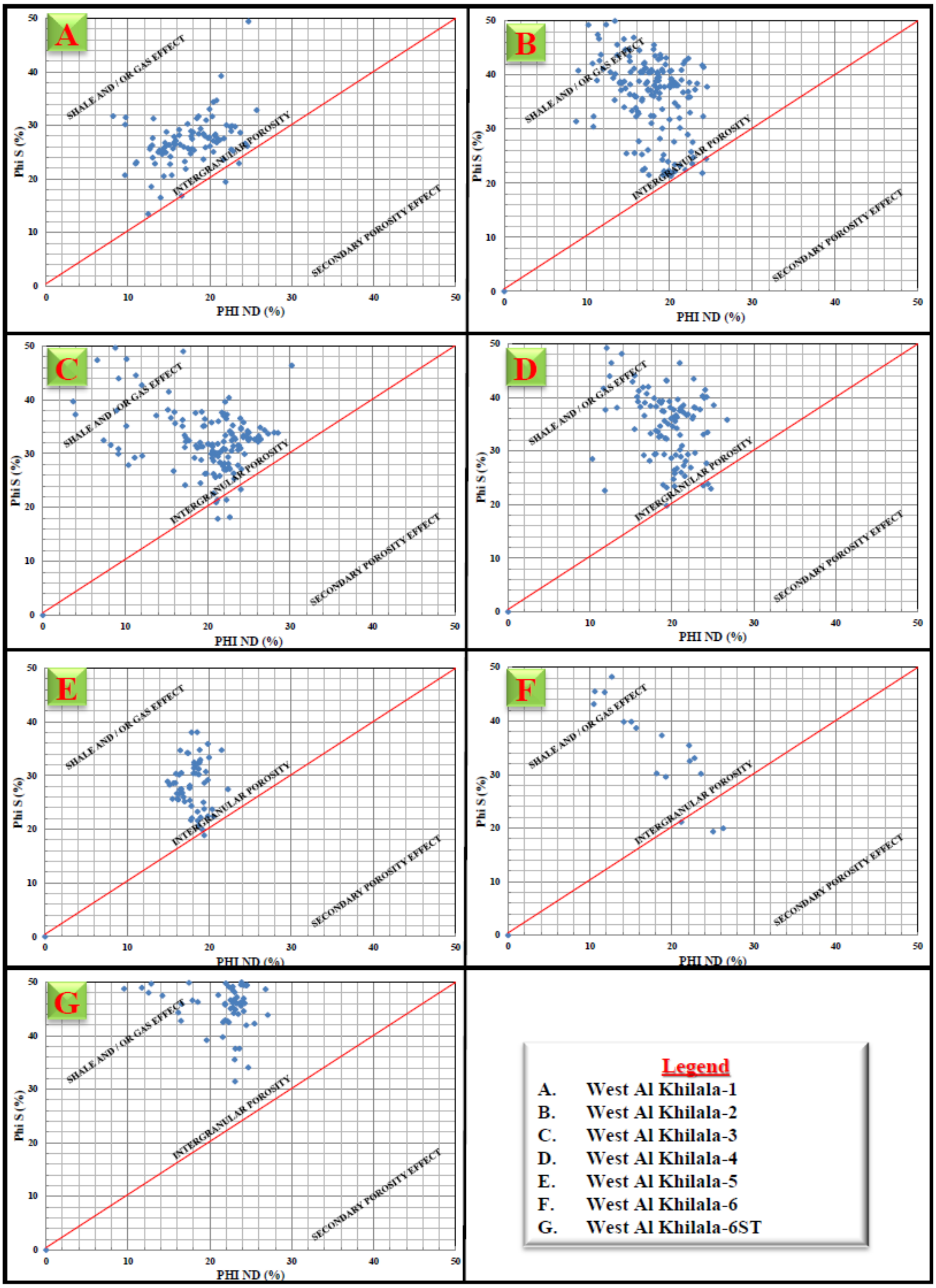

Fig. 8: The Neutron Density /Sonic porosity cross plot for the Abu Madi Reservoir.

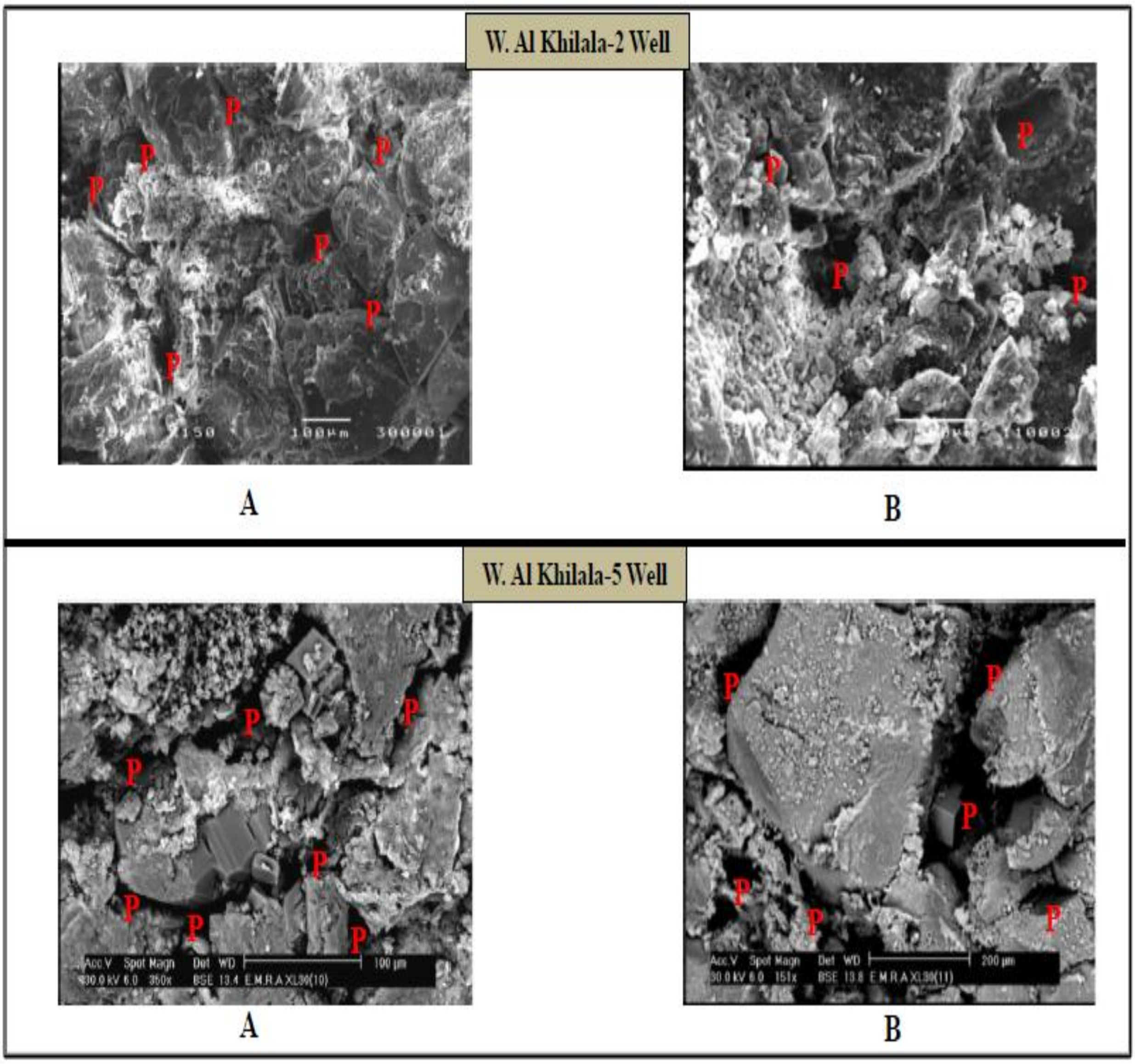

Fig. 9: SEM Image for W. Al Khilala-2 & 5 wells showing the intergranular porosity (P).

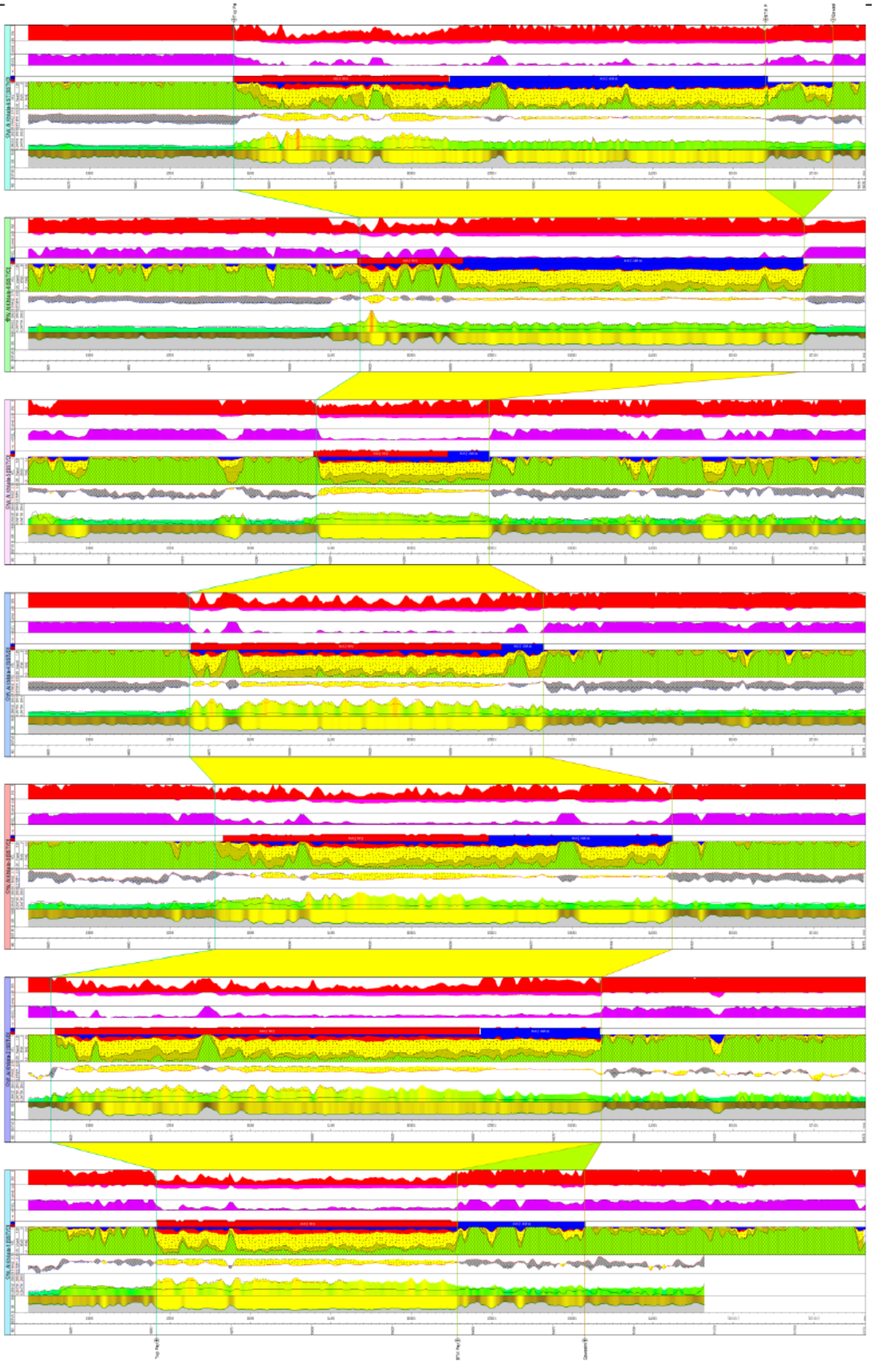

Fig. 10: Litho-saturation correlation panel for the Late Miocene Abu Madi Reservoir in the West Al Khilala Field.

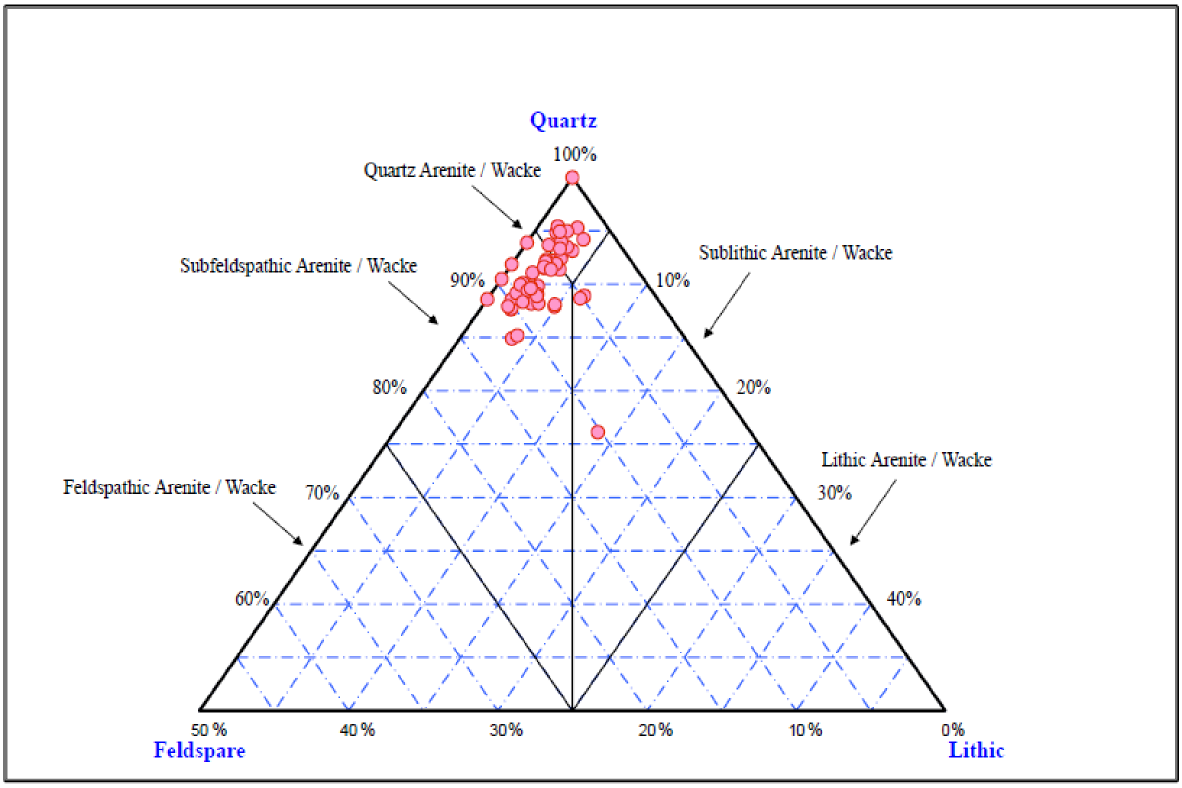

Fig. 11: Quartz-Feldspar-Lithics (QFL) plot of the sandstones in the Abu Madi Formation.

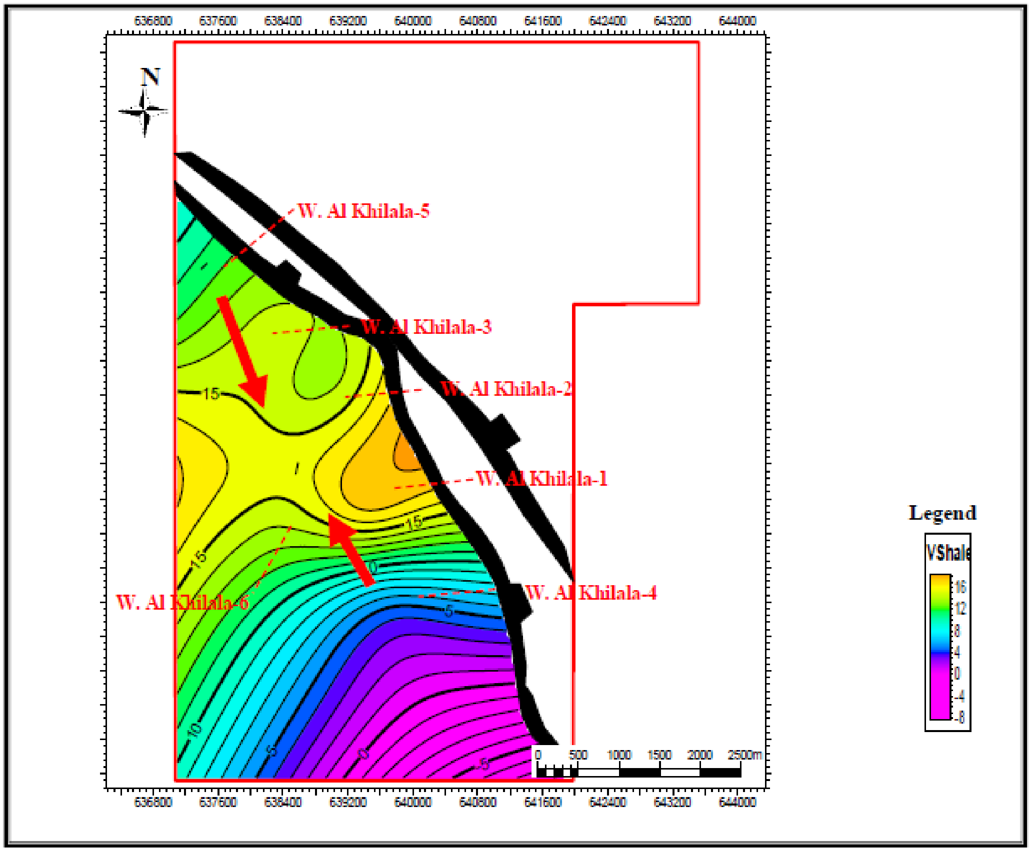

Fig. 12: Shale volume distribution map for the Late Miocene Abu Madi Reservoir.

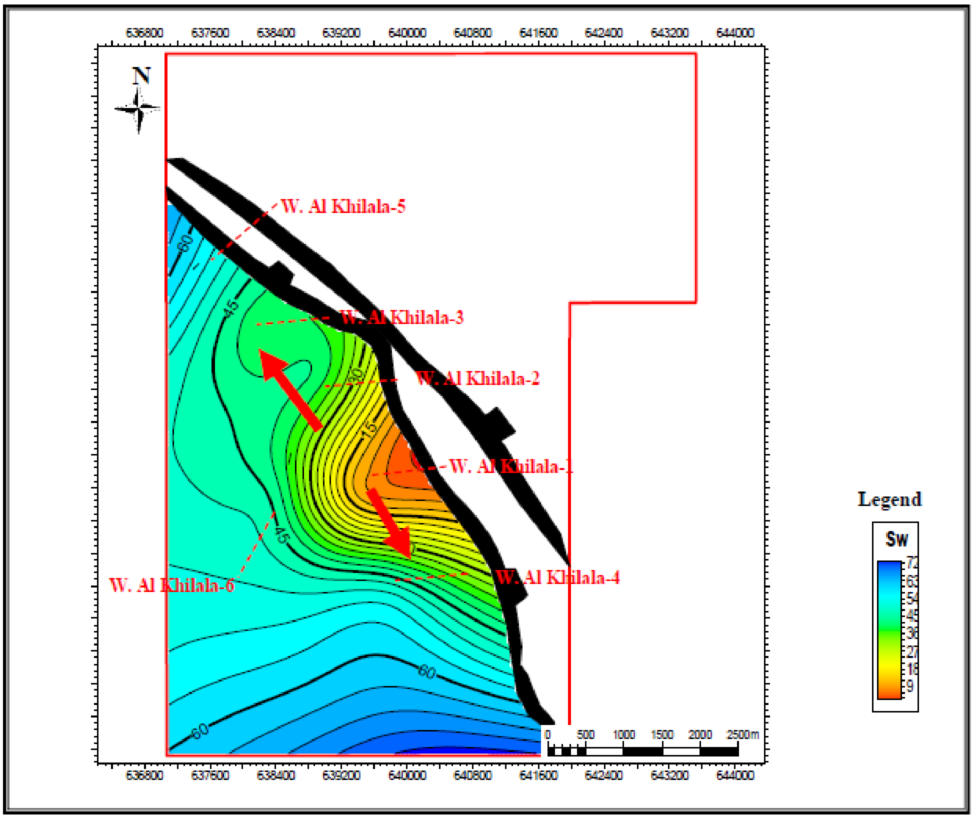

Fig. 13: Water saturation distribution map for the Late Miocene Abu Madi Reservoir.

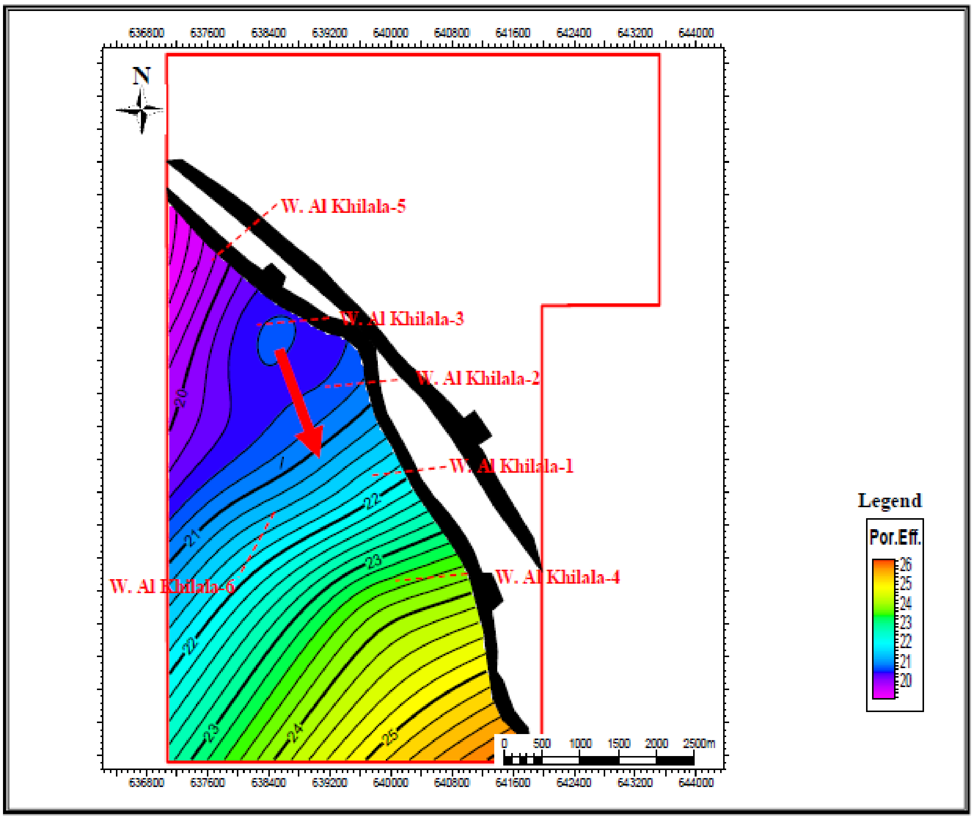

Fig. 14: Effective porosity distribution map for the Late Miocene Abu Madi Reservoir.

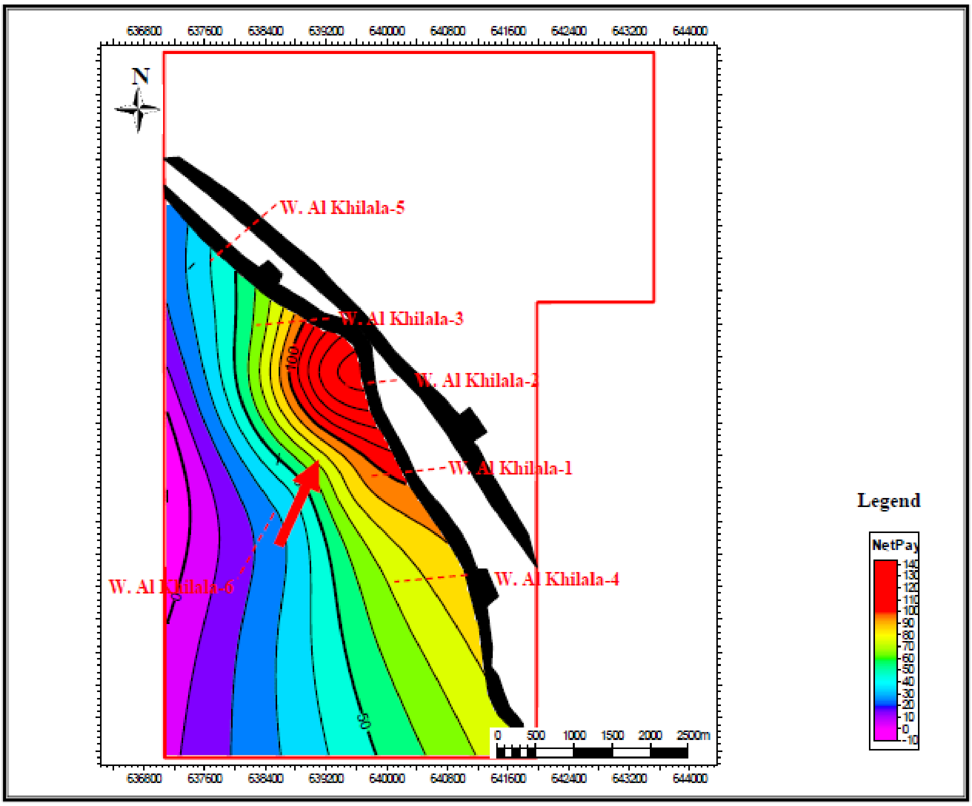

Fig. 15: Net pay Thickness distribution map for the Late Miocene Abu Madi Reservoir.

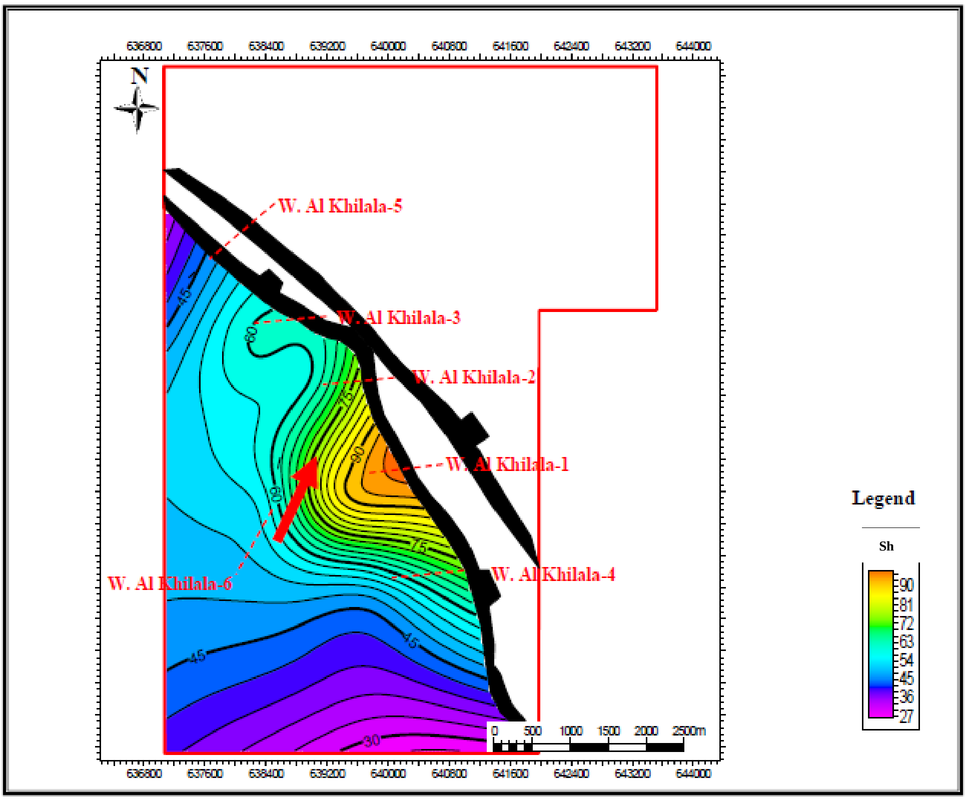

Fig. 16: Hydrocarbon saturation distribution map for the Late Miocene Abu Madi Reservoir.

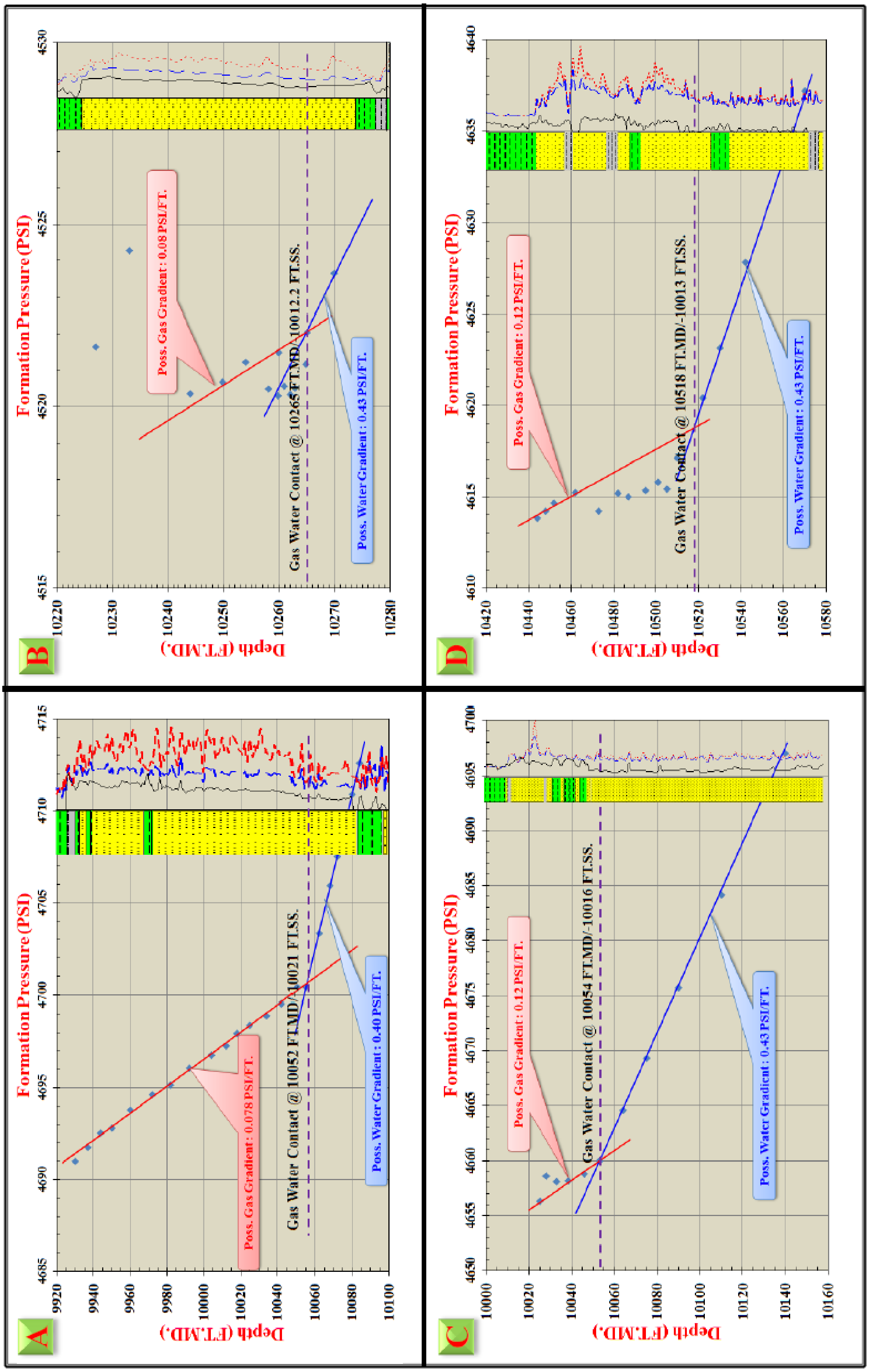

Fig. 17: MDT plots for Late Miocene Abu Madi Reservoir in W. Al Khilala-2 (A), W. Al Khilala-5 (B), W. Al Khilala-6 (C), W. Al Khilala-6ST (D)

Table-1: The petrophysical evaluation parameters for the evaluated wells.

Well Name	Interval (ft)	Gross Pay thickness(ft)) (ft)	Net Pay thickness (ft)	Sw (%)	Φ (%)	Vsh (%)	Sh (%)
W. Al Khilala-1	9951 – 10,045.5	94.	85.5	9	21.6	17.7	91
W. Al Khilala-2	9920 – 10,090	170	114.5	38.8	20.6	14	61.2
W. Al Khilala-3	9977 – 10,118	141	54	40.6	20.5	14.3	59.4
W. Al Khilala-4	9969 – 10,079	110	70.5	42.1	23.4	6.8	57.9
W. Al Khilala-5	10,221.5 –10,280	58.5	23	57.7	19.4	11.3	42.3
W. Al Khilala-6	10,022 – 10,047	25	8.75	40.1	20.4	20.2	59.9
W. Al Khilala-6ST	10,437 – 10,518	97	55.75	41.9	22.2	9.3	58.1

Table-2: The interpreted gas and water gradients from pressure data (MDT)

Well Name	Gas Gradient (PSI/FT)	Water Gradient (PSI/FT)	Contact Depth
W. Al Khilala-2	0.078	0.40	10052 FT.MD/-10021 FT.SS.
W. Al Khilala-5	0.08	0.43	10065 FT.MD/-10012.2 FT.SS.
W. Al Khilala-6	0.12	0.43	10054 FT.MD/-10016 FT.SS.
W. Al Khilala-6ST	0.12	0.43	10518 FT.MD/-10013 FT.SS.
Average	**0.0995**	**0.4225**	

VI. Conclusions And Recommendations

The different cross-plots which are constructed to display the reservoir mineralogy as the Neutron-Bulk density cross plot and M-N cross plot indicated that, the lithology of the Late Miocene Abu Madi reservoir is quartzose sandstone which is intercalated mainly with dispersed clay type and minor laminated shale based on the Thomas-Steiber cross plot. The dia-porosity cross-plots ($Ø_S$-$Q_{ND)}$ indicate an intergranular porosity type. The petrophysical evaluation for the reservoir displays clastic sandstones are the dominant lithology with small intercalations of shale interbeds. The lateral distribution of the petrophysical parameters indicate an increasing in the shale volume in the direction of central part of the reservoir and effective porosity towards the southeast direction, the water saturation towards the northwest and southeast directions and the hydrocarbon saturation in the direction of northeast. So, the central part of the reservoir is the most promising area in the Field.

The petrophysical evaluation for the studied interval reflected a hydrocarbon-bearing sandstone reservoir with average of Phie = 21.1%, Vsh = 13.3%, Sw = 38.6% and SH=61.4%.

The analysis of pressure data (MDT) helped in delineating the fluid contact and determined the reservoir pressure gradient that ranges from 0.078 to 0.12 psi/ft. which reflected a connected and homogenous reservoir.

It also recommended to drilling more wells into / for the central part of the reservoir, in the vicinity of W. Al Khilala-1 Well that considered being the best area for the reservoir for more hydrocarbon production from Abu Madi sandstone for more favorable economic conditions. It also recommended to avoiding drilling into/for the areas of high concentrations of water saturation.

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