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WELL LOG ANALYSIS AND PRESSURE MEASUREMENTS TO EVALUATE THE MIOCENE RESERVOIRS, PORT FOUAD MARINE FIELD, EASTERN MEDITERRANEAN, EGYPT

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تحليل تسجيلات الآبار وقياسات الضغوط لتقييم خزانات الميوسين بحقل بورفؤاد البحرى شرق البحر المتوسط، مصر

الخلاصة: يعد الجزء البحرى من دلتا النيل واحداً من أكثر المناطق الواعدة لإستكشاف وإنتاج الغاز في مصر والشرق الأوسط. تتعامل الدراسة الحالية مع تقييم الطبقات الرملية الحاملة للغاز في الجزء البحرى لدلتا النيل بإستخدام التسجيلات الجيوفيزيائية وقياسات الضغط المتاحة.الرواسب التي تمثل منتصف وأواخر عصر الميوسين (تكوينى وقار و سيدى سالم) الممثلة بأربع آبار موزعة في أماكن متفرقة من منطقة إمتياز بورفؤاد حيث تمت دراستهم وتحليلهم لمعرفة العوامل البتروفيزيائية المختلفة المهمة لتقييم صخر الخزان. هذه الدراسة توضح وجود عدة طبقات رملية حاملة للغاز في تكويني وقار و سيدى سالم والتي تصاحبهما مؤشرات هيدروكربونية جيدة علي أعماق مختلفة، التحاليل البتروفيزيائية المفصلة لهذه الطبقات تظهر أن المستوى S1 يحتوى علي خصائص جيدة مما يجعله خزاناً واعداً يحتوى علي غاز في جميع الآبار ماعدا البئر (PFM S-1) الذى ثبت جفافها، بينما المستويان (S2 , S3) في منطقة الدراسة إما عبارة عن طبقات طينية أو طبقات رملية تحمل مياه فقط. وبالرغم من ذلك فإن المستوى (Wakar S1) يحوى خصائص فريدة والتي تتمثل في مسامية جيدة (١٨ إلي ٣٠%)، محتوى طيني قليل (أقل من ١٠%) و كميات غاز عالية (٤١ إلي ٩٢%). وقد أجري تحليل قياسات الضغط بهدف تحديد الفواصل بين الموائع المختلفة و حساب معدلات تغير الضغط للطبقات الحاملة للغاز وكذا التعرف علي الكثافات المختلفة للمحتوى الهيدروكربونى. وقد تراوحت معدلات الضغط ما بين ٠,٠٦٥ إلى٠,٣٢٥ (رطل علي البوصة المربعة/قدم) للمستوى (Wakar S1).

ABSTRACT: *The off-shore Nile Delta is one of the most promising areas for gas exploration and production in Egypt and the Middle East. The present study deals with the evaluation of the gas-bearing sand intervals at the off-shore Nile Delta of Egypt using the available geophysical logs and pressure datasets. The Middle to Late Miocene sediments (Wakar and Sidi Salim Formations) of four wells distributed in Port Fouad concession are analyzed and studied for determining the different petrophysical parameters that are necessary for reservoir evaluation. This study reveals the presence of multi gas-bearing sand zones in Wakar S1 level and Sidi Salim Formation, with good hydrocarbon potential, encountered at different depth levels. The detailed petrophysical analysis of these zones show that S1 level has good reservoir parameters and gas potentiality in all wells except in PFM S-1 well which is dry, while S2 and S3 levels are either shaled out or water bearing in the study area. However, the Wakar S1 level exhibits unique characteristics in terms of the good porosity (18 to 30%), low shale volume (Vsh<10%) and high gas potentiality (41 to 92%). The analysis of pressure data is concerned mainly with locating the different fluid contacts, determining the pressure gradients of the gas-bearing zones, and defining the different hydrocarbon densities. Pressure gradient ranges of 0.065 to 0.325 psi/ft are indicated for Wakar S1 level.*

1. INTRODUCTION

The off-shore Nile Delta is a world-class hydrocarbon basin, with target reservoirs ranging in age from the Early Pliocene to Early Oligocene, with charge coming from both Jurassic and Tertiary aged source rocks. An extensive period of exploration took place in the off-shore Nile Delta and many sand anomalies of good hydrocarbon potentiality are defined at different levels in the Miocene, Pliocene and Pleistocene sediments (Lashin; 2012).

Port Fouad field is a big gas field discovered in 1992 by the International Egyptian Oil Company (IEOC). It lies in Petrobel's offshore North Port Said block, with reserves proven so far at 3 Trillion Cubic Feet (TCF) from reservoirs lying at a depth of 4,000 meters. Port Fouad field came on stream in April 1996 to initial production 70 MCF/d of gas and 3,500 b/d of condensate.

The main objective of this study is to define the possible gas-bearing sand levels of the Late Miocene sediments (Wakar and Sidi Salim Formations) in the off-shore Northeastern part of the Nile Delta, and evaluate their petrophysical parameters and locating the fluid contacts using the available logs and pressure datasets.

2. GEOLOGIC SETTING

The area of study (Port Fouad Marine Field) is located in the eastern sub-basin at the northeastern off-shore part of the Nile Delta of Egypt between latitudes 31° 25' and 31° 40' N and longitudes 32° 20' and 32° 45' E (Figure 1), about 60 km North of Port Said city. It lies at water depths ranging between 22.5-28 m.

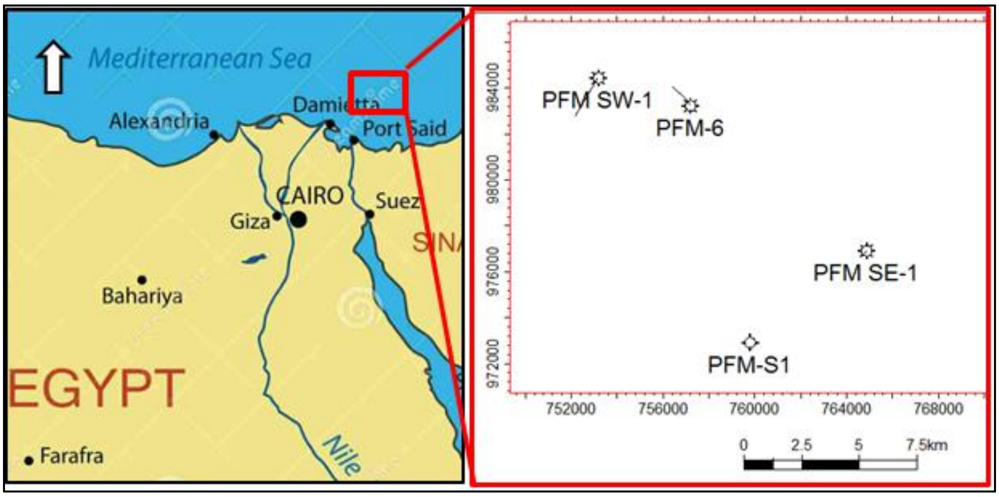

Figure 1: Location map showing the distribution of the studied wells.

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 (EGPC, 1994). The off-shore Nile Delta basin is structurally and stratigraphically divided into eastern, central and western sub-basins. These sub-basins are characterized by the presence of thick Plio-Pleistocene sediments associated with extensive NW trending shallow listric faults (Lashin; 2012).

Many authors had dealt with studying the Nile Delta cone as a whole (Kenyon et al., 1975; Maldonado and Stanley, 1976; Ryan, 1978; Ross et al., 1978; Deibis et al., 1986; Sarhan and Hemdan, 1994; Bertello et al., 1996; Kempler et al., 1996; Barsoum et al., 1998; Kamel et al., 1998; Reeder et al., 1998& 2000; William and Paul, 2000; Zaghloul et al., 2001; Marten et al., 2004; Lashin and Abd El-Aal, 2005).

Figure 2 represents the generalized stratigraphic column of the off-shore Nile Delta showing the Middle to Late Miocene sediments un-conformably underlying the evaporitic section of Rosetta Formation. They are represented by two formations (Wakar and Sidi Salim Formations) and consist mainly of thick shale sections embedded and alternated with many sand beds at different depth levels and with variable thicknesses. These sand beds represent the main gas bearing zones and together with the overlying and underlying shales constitute the ideal stratigraphic traps in the off-shore Nile Delta.

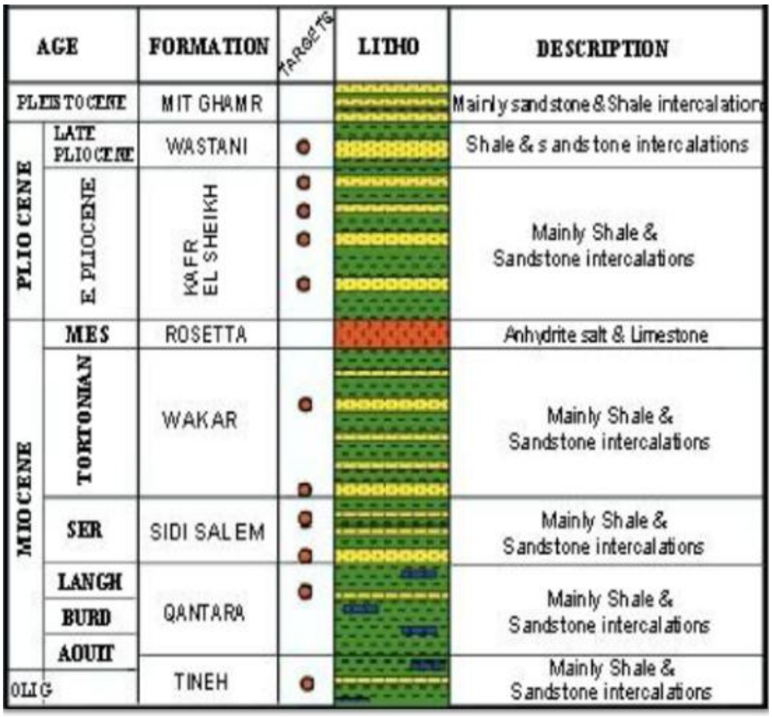

Figure 2: Generalized stratigraphic column of the offshore north-eastern part of the Nile Delta (Badri et al., 2000).

3. MATERIALS AND METHODS

In the present study the evaluation of reservoir properties was done through four wells (Figure 1) on data that include various geophysical logs and formation tops. The available geophysical logs of the four wells are in a digitized form including Gamma Ray (GR), Density (RHOB), Deep Resistivity (ILD), Medium Resistivity (ILM), Shallow Resistivity (ILS), Compressional Sonic (DTCO), Shear Sonic (DTSM) and Neutron Porosity (NPHI) logs are used to characterize the different pay zones.

The most important petrophysical parameters necessary for characterizing the potential reservoirs are porosity (total and effective), shale volume, fluid saturation (water and hydrocarbon). Furthermore, the available pressure data (formation pressure and hydrostatic pressure) of some sand intervals are also interpreted and plotted against depth, in order to define the different fluid contacts and illustrate the prevailing pressure regimes. The different petrophysical parameters are interpreted and represented in a number of petrophysical models (static models) and iso-parametric maps.

4. RESULTS AND DISCUSSION

4.1. Petrophysical Analysis

The petrophysical analysis of Wakar Formation in the study area reveals the presence of three sand levels (S1, S2 and S3) encountered at varying depths. Level S1 encountered in all wells of study area with different thicknesses showing good to very good petrophysical parameters. Levels S2 and S3 are encountered only in PFM SW-1 well with good petrophysical characters, however both of them are water bearing zones, and shaled out in the other wells of the study area. Sidi Salim Formation is encountered in both PFM SE-1 and PFM S-1 well sat varying depth levels. The petrophysical analysis of Sidi Salim Formation in the study area reveals its productivity from PFM SE-1 well, however its good petrophysical parameters in PFM S-1 well, no pay zone was detected in this well.

Table 1 illustrates the main petrophysical characteristics of both Wakar levels and Sidi Salim Formation in the study area. Table 1 shows that, S1 level is the best in terms of its petrophysical characteristics through all study wells. The estimated petrophysical parameters of S1 level are found to be

Table 1: The calculated petrophysical parameters throughoutthe area of study.

Formation		Wells	PFM SE-1	PFM SW-1	PFM-6	PFM S-1
		Gross sand (m)	5	8.7	33.2	9.5
		Net pay (m)	5	6.7	33.2	0
		Vsh (%)	0	9	3	0
	S1	PHIE (%)	29	24	23 to 29	20 to 27
		Sw (%)	8 to 24	26 to 80	20 to 59	77 to 100
		Sg (%)	92 to 76	20 to 74	41 to 80	0 to 23
		Depth (m)	3102 to 3125	3037 to3069	2974 to 3019	3128 to 3148
		Gross sand (m)		2		
		Net pay (m)		0		
		Vsh (%)		7		
Wakar Fm	S2	PHIE (%)	Shaled out	24	Shaled out	Shaled out
		Sw (%)		67		
		Sg (%)		33		
		Depth (m)		3102 to 3104		
		Gross sand (m)		4	….	
		Net pay (m)		0	….	
		Vsh (%)		9	….	
	S3	PHIE (%)	Shaled out	25	….	Shaled out
		Sw (%)		79	….	
		Sg (%)		21	….	
		Depth (m)		3130 to 3134	….	
		Gross sand (m)	14.1	….	….	10.7
		Net pay (m)	1.3	….	….	0
		Vsh (%)	0	….	….	0
Sidi Salim Fm		PHIE (%)	20 to 25	….	….	20
		Sw (%)	60 to 73	….	….	80
		Sg (%)	27 to 40	….	….	20
		Depth (m)	3298 to 3335	….	….	3403 to 3414

very good in Port Fouad Marine concession (PHIE= 29%, Vsh<10%, Sw= 8-59% and Sg= 41-92%). While Figure 3 represents multi neutron-density cross plot of PFM-6, PFM SW-1, PFM SE-1, and PFM S-1 wells through Wakar Formation. Most of plotted points are either shale or gas affected, reflecting the potentiality of the area of study. The other plotted points lie in the sand line and confirm that Wakar Formation consists of sandstone laminated with shale beds.

4.2. Petrophysical Models

Figures 4 and 5 exhibit the vertical petrophysical output of data logs forPFM-6 and PFM SE-1 wells. These wells are selected to demonstrate the reservoir characteristics of gas-bearing sand intervals in both Wakar S1 level and Sidi Salim Formations. It is shown that, S1 level is well represented in the study area. The reservoir parameters are found in the range of 23% to

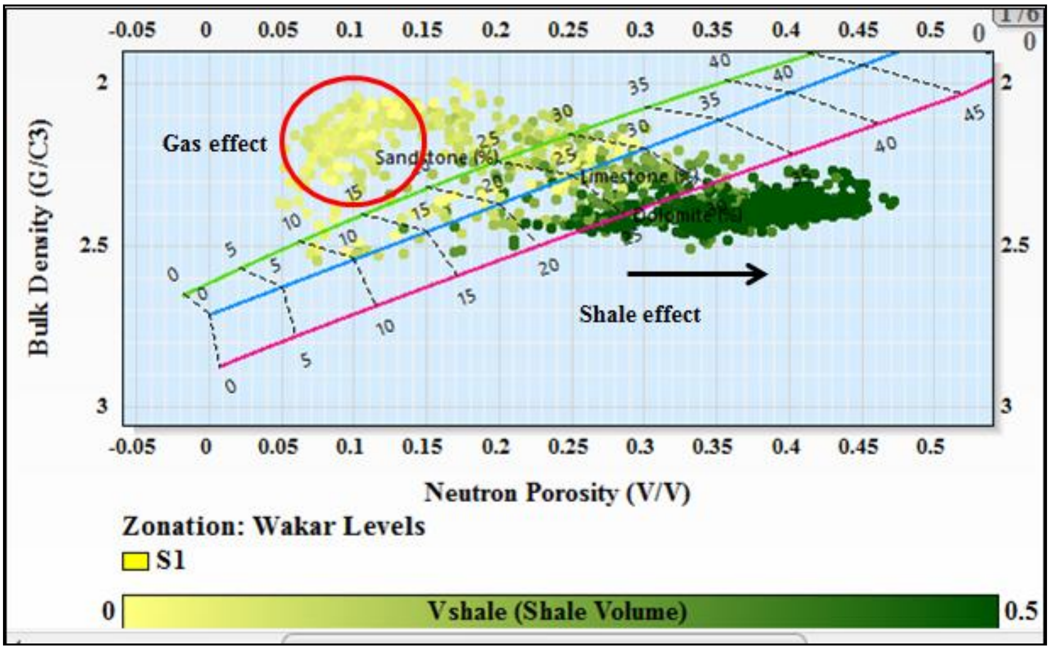

Figure 3: Neutron-Density cross plot through the study area of Wakar Formation.

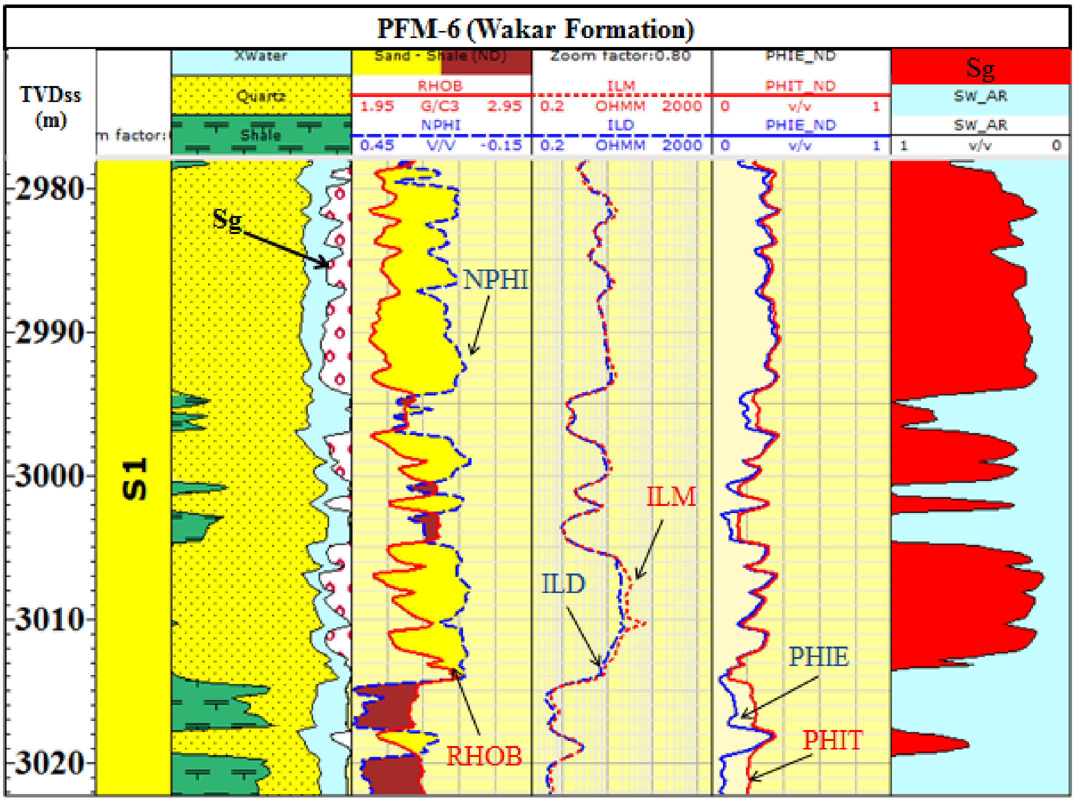

Figure 4: Petrophysical data log of PFM-6 well (Wakar Formation).

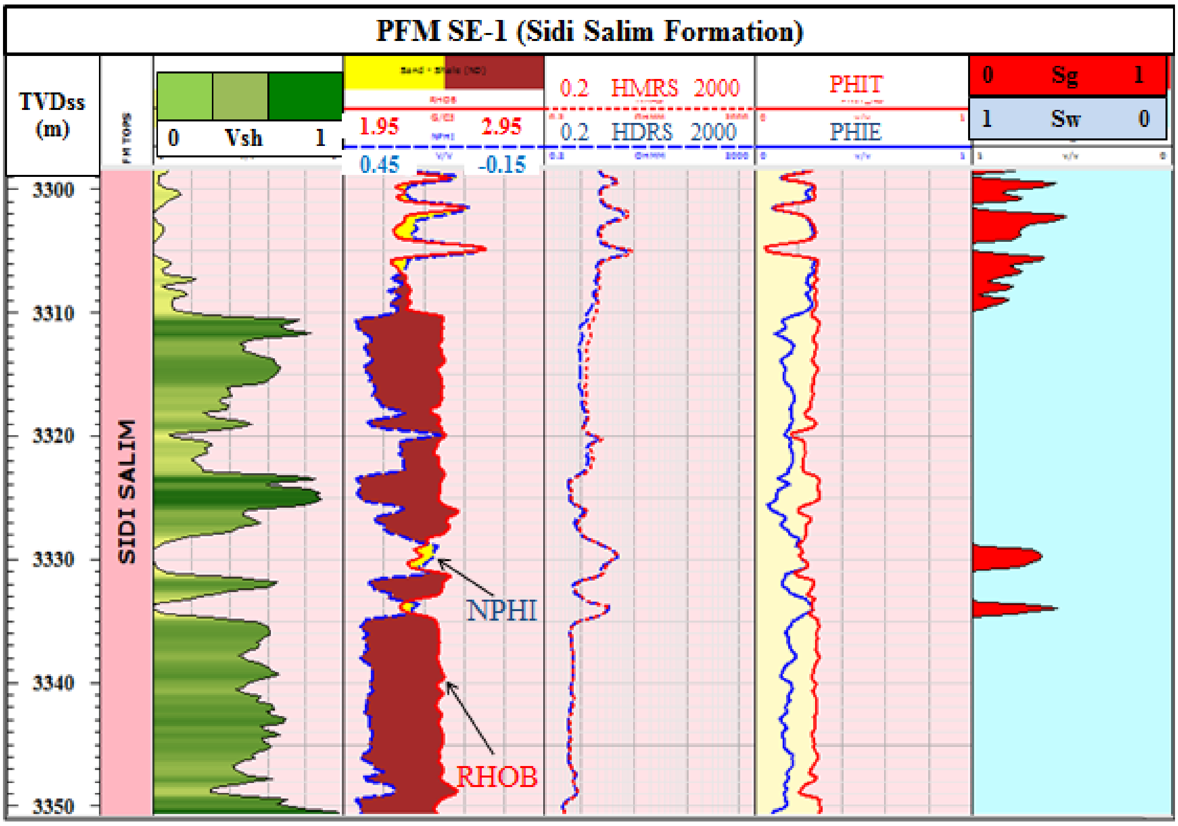

Figure 5: Petrophysical data log of PFM SE-1 well (Sidi Salim Formation).

29% (PFM-6) for porosity, 3% (PFM-6) to 0% (PFM SE-1) for shale volume, 8% (PFM SE-1) to 20% (PFM-6) for water saturation, and 80% (PFM-6) to 92% (PFM SE-1) for gas saturation (Table 1). Sidi Salim Formation, on the other hand, exhibits good reservoir parameters in terms of good porosity (20 to 25%), and fair gas potentiality (40%). The gross and net pay sand sections of S1 level are well recorded in all wells in the study area. However, the type section of S1 is recorded in PFM-6 well with 33.2 m net pay productive sand (Figure 4). The gas crossover effect in both density and neutron logs is very clear in Figure 4 (Track 4) in front of S1 level.

4.3. Iso-Parameteric Maps

Due to the obtained good reservoir parameters a number of lateral distribution maps (iso-parameteric maps) are constructed for Wakar S1 level in the study area (Figures 6 to 8). The net pay sand thickness of S1 level (Figure 6) is well represented in the northern part of the study area, especially in the location occupied by PFM-6 well, where the gas sand reservoir attains its maximum thickness (32 m). The effective porosity distribution maps of S1 level (Figure 7) as well as the water saturation map (Figure 8), show that the north-eastern part attains the best cut off reservoir parameters in the study area. The water saturation increases toward the south western part of the area of study, where Sw equals 100% near to PFM S-1 well. Due to the lack of wells that penetrated Sidi Salim Formation in the area of study (only two wells), the accuracy of the lateral distribution of its petrophysical parameters will be very low, and therefore we did not construct such maps for Sidi Salim Formation.

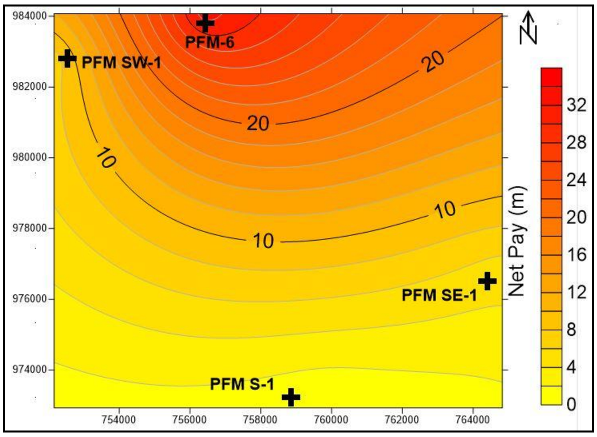

Figure 6: Net pay sand lateral distribution map of S1 level in the study area.

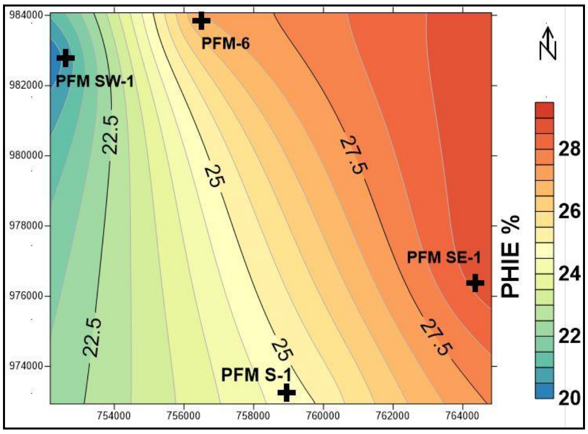

Figure 7: Effective porosity lateral distribution map of S1 level.

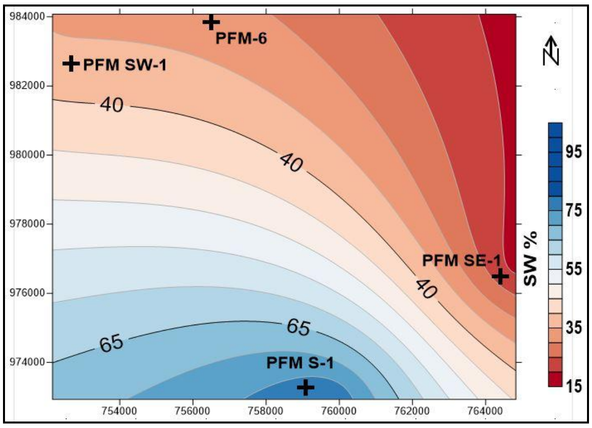

Figure 8: Water saturation lateral distribution map of S1 level.

Table 2: Pressure data for PFM-6 well.

PFM-6 (RFT)						
NO.	Fm.	Level	TVDss (ft)	Hydrostatic Pressure (psi)	Formation Pressure (psi)	Mobility
1	WAKAR	S0	9586.61	7775.26	tight	
2		S1	9858.92	7978.3	7130.2	excl
3			9875.33	7978.5	7131.7	excl
4			9891.73	7988.32	7134.77	excl
5			9914.70	8008.13	S.F.	
6			9916.34	7996.92	7137.8	excl
7			9927.82	8013.31	7138.55	v. good
8			9947.51	8030.4	S.F.	
9			9983.60	8053.6	7146.36	excl
10		S2	10026.25	8085	tight	
11			10075.46	8122.6		

Table 3: Thepressure data for PFM SE-1 well.

PFM SE-1 (RFT)						
NO.	Fm.	Level	TVDss (ft)	Hydrostatic Pressure (psi)	Formation Pressure (psi)	Mobility
1	WAKAR	S1	10265.75	7867.5	NA	
2			10273.95	7871.5	7177.3	excl
3			10280.51	7874.9	7165.1	excl
4			10285.43	7877.9	7166.7	excl
5			10346.46	7923.3	7174.2	excl
6			10349.74	7925.1	7175	excl
7		S2	10596.46	8116.3	7231	fair
8		S3	10669.29	8170.2	7231	excl
9			10672.57	8170.8	7231.9	excl
10			10675.85	8171	NA	
11			10829.40	8285.1	7319.1	excl
12	SIDI SALIM		10918.64	8353	7352.1	good
13			10924.54	8355.6	7353.6	excl
14			10935.04	8363.6	7357.8	excl
15			10944.88	8370.8	7363.6	good
16			11021.98	8432.6	7399.6	good
17			11036.75	8442.6	7402.1	good
18			11127.95	8511.2	7458	excl

4.4. Pressure Data Analysis

Analysis of pressure data is of prime interest in characterizing the multi-anomaly reservoirs. 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 reservoir pressure at several depths for each interesting 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 changes in slope and the continuity of the pressure gradients respectively (Schlumberger, 1986).

In the present study, the available pressure data (formation pressure, hydrostatic pressure and mobility) of two wells were analyzed and interpreted (Tables 2 and 3). In the present study the mobility is given and not calculated due to absence of pressure test procedures. Figures 9 and 10 illustrate the results of two selected examples of the different constructed depth-pressure plots in the study area. In both plots, the tops and the bottoms of the different encountered gas zones are clearly located and differentiated with considerable depth sections, but with different influencing pressure regimes. The gas mobility of the two studied wells ranges from good to excellent indicating good and suitable conditions for migration and accumulation of hydrocarbon (Tables 2 and 3) is dominated. In the pressure test S.F. means seal failure (occurs when the packer fails during the test).

Table 2 represents the pressure points taken at definite reservoir depth points through (Tortonian) Wakar Formation in PFM-6 well. Formation pressure points are in (psi) and the depth is the true vertical depth subsea (TVDss) in (ft). The data plotted in Figure 9 and the different pressure gradients determined and the fluid density of every zone is calculated according to equation (1) and represented in Table 4.

$$\rho_f = \frac{P - P_0}{Z - Z_0} * 0.052 \quad (1)$$

Where, P the fluid pressure at depth Z,P_0 the fluid pressure at depth Z_0,ρ_f the density of the fluid in (ppg), where 1 g/cc equals 8.345 ppg. The pressure unit is (psi), depth is the true vertical depth subsea (feet).

From the mud log and the conventional logs the sand and shale layers are detected and plotted in Figure 9. The calculated pressure gradients in Table 4 represent the different values of fluid densities (A, B and C). The calculated gradients represented by dashed lines as only two points are used in calculations that may affect the accuracy of results.

Table 4: PFM-6 pressure gradients and fluid densities.

PFM-6		
	psi/ft	g/cc
A	0.091	0.211
B	***	***
C	0.065	0.151

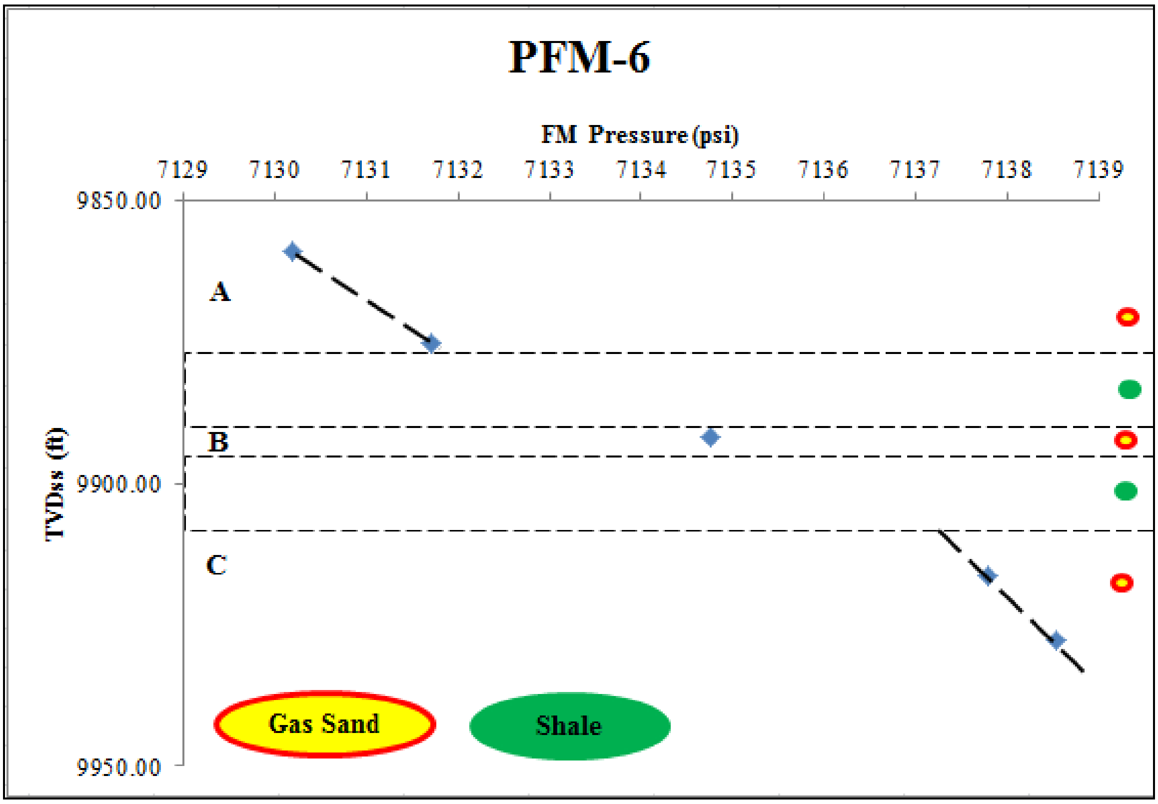

Figure 9: PFM-6 pressure data versus depth.

Table 4 shows that the sand layers A and C are gas bearing which is obvious from their density values. In Figure 9 we have only one pressure point in zone B which is difficult to suppose the trend of this point, but the petrophysical analysis of this zone (B) confirmed its gas potentiality. The productivity of PFM-6 well is 40.44 MMSCF/D (million standard cubic feet/day), as obtained from well testing.

Figure 9 shows also the impossible continuity between these sand layers as the fluid density in A is denser than in C which confirms the vertical discontinuity of these gas sand layers. Therefore the shale layers between these sand intervals act as a barrier that avoids the vertical flow of fluid between the sand layers.

PFM SE-1 well is the deepest well in the study area. The well penetrated both Wakar and Sidi Salim Formations. The measured pressure points through these formations are given in Table 3. Figure 10a represents an illustration of the pressure points of Wakar Formation in psi versus true vertical depth subsea (TVDss) in feet. Figure 10b shows the pressure-depth plot through Sidi Salim Formation.

Figure 10a shows three different pressure gradients A, B and C (Table 5). The lithology of these layers is sand which confirmed from the mud log and the geophysical logs such as gamma ray, neutron and density logs. The sand layer A contains condensate (the drill stem test confirmed the presence of condensate)

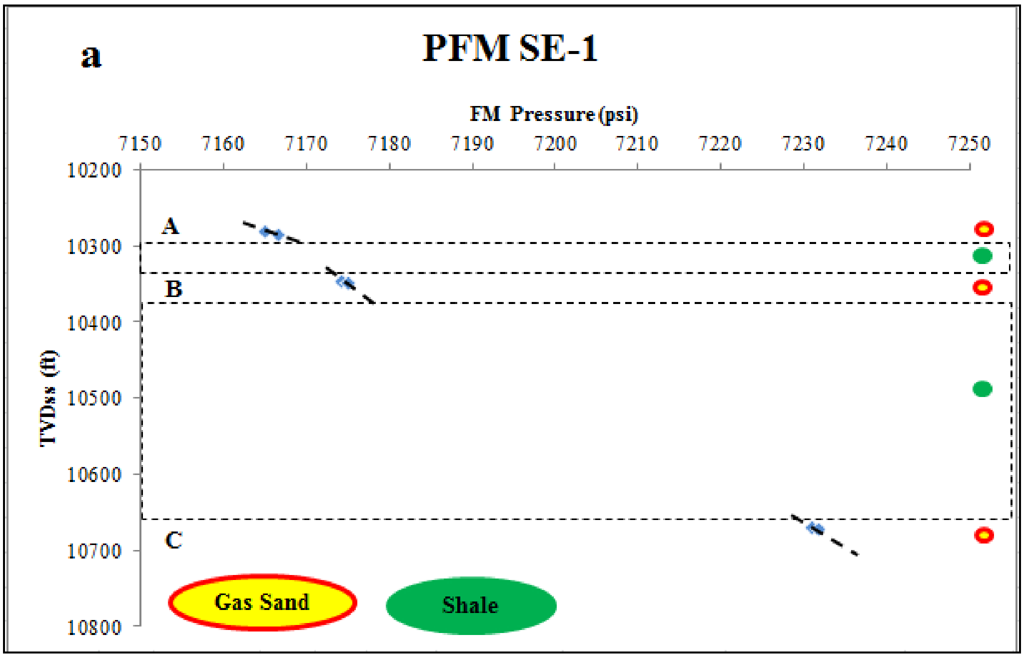

Figure 10a: PFM SE-1 pressure data versus depth (Wakar Formation).

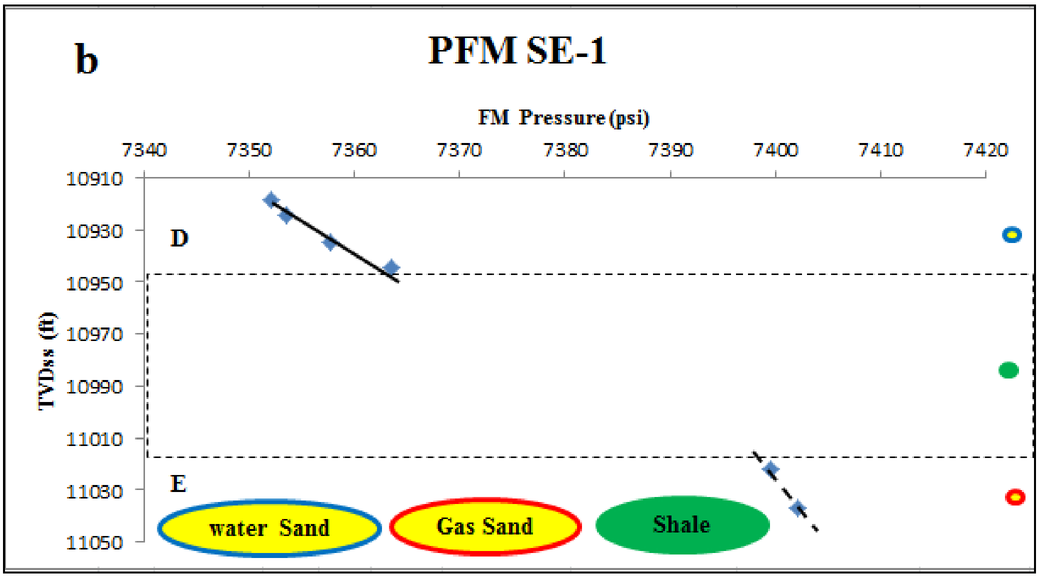

Figure 10b: PFM SE-1 pressure data versus depth (Sidi Salim Formation).

while the other sand layers B and C are gas bearing sand clearly defined as shown in Table 5. The shale layer that separates A and B acts as an effective barrier for the vertical fluid flow as the fluid in A is denser than in B. The shale layer between B and C zones may act as an effective barrier; however the interpolation of the two slopes did not show any meeting point. The productivity of PFM SE-1 well is 37.14 MMSCF/D of gas and 1521 BBL/D (barrel/day) of condensate, which obtained from well testing.

Figure 10b represents the pressure points through Sidi Salim Formation. It shows that there are two different pressure gradients in the sand layers D and E. The sand layer D is a saline water bearing zone (Table 5). However the sand layer E is a gas bearing zone as given in Table 5. The shale layer that separates between D and E is an effective barrier. In PFM SE-1 well we have three productive zones A, B and C in Wakar Formation. In Sidi Salim Formation we have only one potential zone E and zone D is water bearing zone.

Table 5: PFM SE-1 pressure gradients and fluid densities.

PFM SE-1		
	psi/ft	**g/cc**
A	0.325	0.751
B	0.244	0.563
C	0.274	0.634
D	0.438	1.012
E	0.169	0.391

5. SUMMARY AND CONCLUSION

The present study aimed to analyze the well log and pressure data of the gas bearing sand anomalies of the Miocene sediments of Wakar and Sidi Salim Formations in the off-shore Nile Delta area (Port Fouad Marine Concession). A comprehensive petrophysical analysis is performed over four wells scattered in the study area. Such analysis reveals the potentiality of Wakar S1 level in PFM SE-1, PFM SW-1, and PFM-6, where S1 level in the mentioned wells is gas bearing zone. Sidi Salim Formation only potential in PFM SE-1 well, as it contains a gas bearing sand interval. In PFM S-1 both Wakar and Sidi Salim Formations are water bearing zones. The other levels of Wakar Formation (S2 and S3) are either shaled out or water bearing zones in the area of study.

The different deduced petrophysical parameters are interpreted and represented in the form of a number of vertical data logs (static models) and iso-parametric maps. The petrophysical parameters of the gas bearing zone (S1 level) are found to be in the range of (PHIE= 29%, Vsh<10%, Sw= 8-59% and Sg= 41-92%).

The analysis of pressure data helped in delineating the different fluid contacts and determining the pressure gradients of the encountered gas zones. The pressure gradients for the detected gas zones are found in range of 0.065 to 0.325 psi/ft and 0.169 psi/ft for Wakar S1 level and Sidi Salim Formation, respectively.

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