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Full Length Research Paper

Analysis of well log and pressure data of the gas-bearing sand reservoirs of Kafr El-Sheikh formation: Case study from the off-shore Nile Delta-Egypt

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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 evaluation of the gas-bearing sand anomalies at the off-shore Nile Delta of Egypt using the available well logging and the pressure datasets. The early to middle Pliocene sediments (Kafr El Sheikh Formation) of eleven wells scattered in the Darfeel and Port Fouad Concessions are analyzed and studied for determining the different petrophysical parameters necessary for reservoir evaluation. This study reveals the presence of three gas-bearing sand zones (anomalies-1, -2 and -3), with good hydrocarbon potential, encountered at different depth levels at the Early Pliocene sediments of Kafr El Sheikh Formation. The detailed petrophysical analysis of these zones shows that anomalies-1 and 2 attain good reservoir parameters, while anomaly-3 is not penetrated in majority of wells in the study area. However, anomaly-2 exhibits unique characteristics; in terms of the good porosity (27 to 33%), low shale volume (Vsh<10%) and high gas potentiality (42 to 93%), which it attains. The constructed petrophysical property maps of gas anomalies-1 and -2, reveal an observed diminish of gas saturation towards the eastern flank of the study area. The potential accumulations with the best reservoir cut-off parameters, are recognized in the central and western parts of Darfeel Concession. The analysis of pressure data is concerned mainly with locating the different fluid contacts and determining the pressure gradients of the gas-bearing zones. Very close pressure regimes are detected for most of the investigated gas anomalies through out the study area. Pressure gradient ranges of 0.331 to 0.345 psi/ft and 0.314 to 0.444 psi/ft are indicated for anomalies-1 and 2, respectively.

Key words: Well logs, pressure data, gas-bearing sand anomalies, off-shore Nile Delta, Egypt.

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. Exploration activity in Northern Egypt and the coastal parts of the Nile Delta goes back to the mid of the 1950's. Standard Oil Company of Egypt (SOE) was the first in this respect, followed by many oil companies which began to execute contracts for exploring the potentiality of the Egyptian Nile Delta. The first commercial discovery was that of Abu Madi-1 well in 1966 which was drilled by the International Egyptian Oil Company (IEOC) and produced natural gas from Abu Madi Formation. After that, an extensive period of exploration took place in the off-shore Nile Delta and many sand anomalies of good hydrocarbon potentiality are indicated at different levels in the Miocene, Pliocene and Pleistocene sediments.

Nowadays, the Lower to Middle Pliocene sediments (Kafr El Sheikh Formation) are considered among the most promising targets for hydrocarbon exploration in the off-shore Nile Delta. These sediments have attracted the

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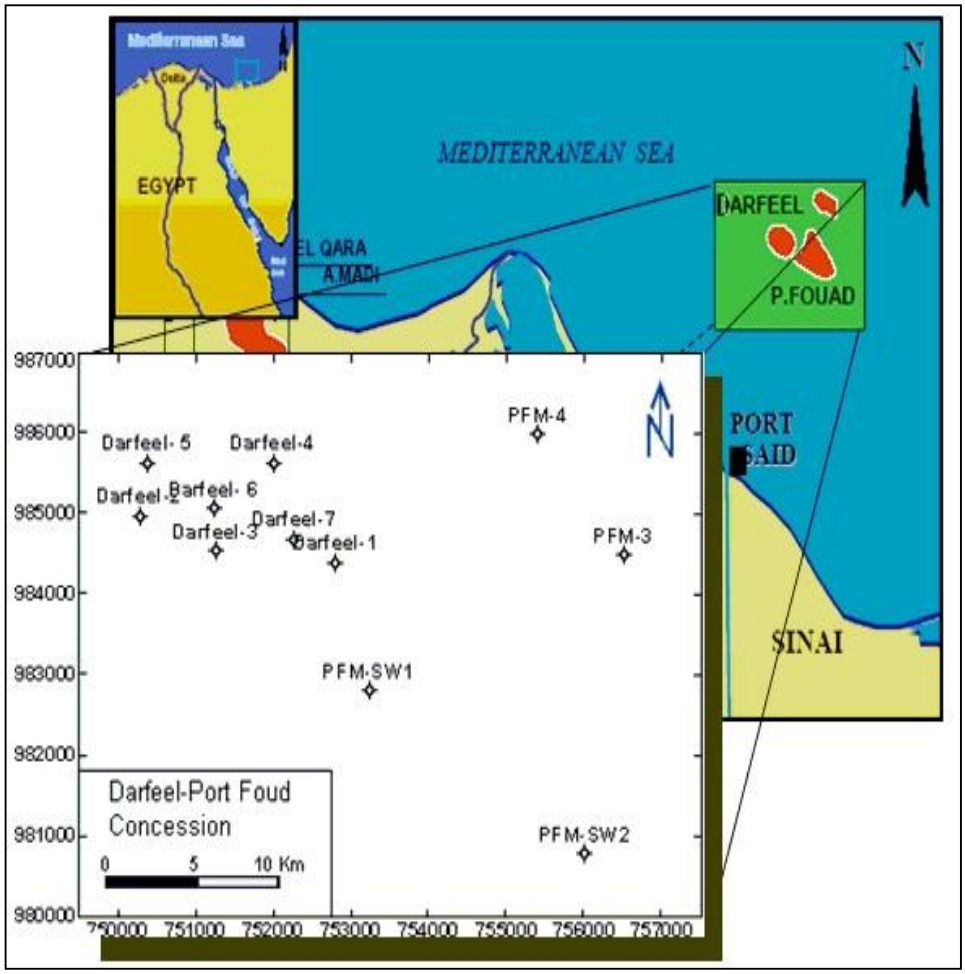

Figure 1. Base map of the investigated area showing location of the study wells.

attention of hydrocarbon explorationists in the Nile Delta since Buseili-1 well encountered gas reservoir in its basal sands. Using well log data, this formation can be subdivided into three units. The top part is shale with streaks of sand; the middle part comprises the main sand unit, while the lower part contains mixed section of shale and sand beds. In general, these sediments in addition to the Late Pliocene ones (El Wastani Formation), are considered the most important reservoirs in the off-shore Nile Delta, as they encounter many gas anomalies at different depth levels.

The main objective of this study is to detect the possible gas-bearing sand anomalies of the Pliocene sediments (Kafr El-Sheikh Formation) in the off-shore Northeastern part of the Nile Delta, evaluating their petrophysical parameters and locating their fluid contacts using the available log and pressure datasets.

Geologic setting

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 strati-graphically 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.

Many authors had dealt with studying the Nile Delta cone as a whole with special emphasis on its off-shore marine parts (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; Amori et al., 2000; William and Paul, 2000; Zaghloul et al., 2001; Marten et al., 2004; Lashin and Abd El-Aal, 2005).

The study area 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 town.

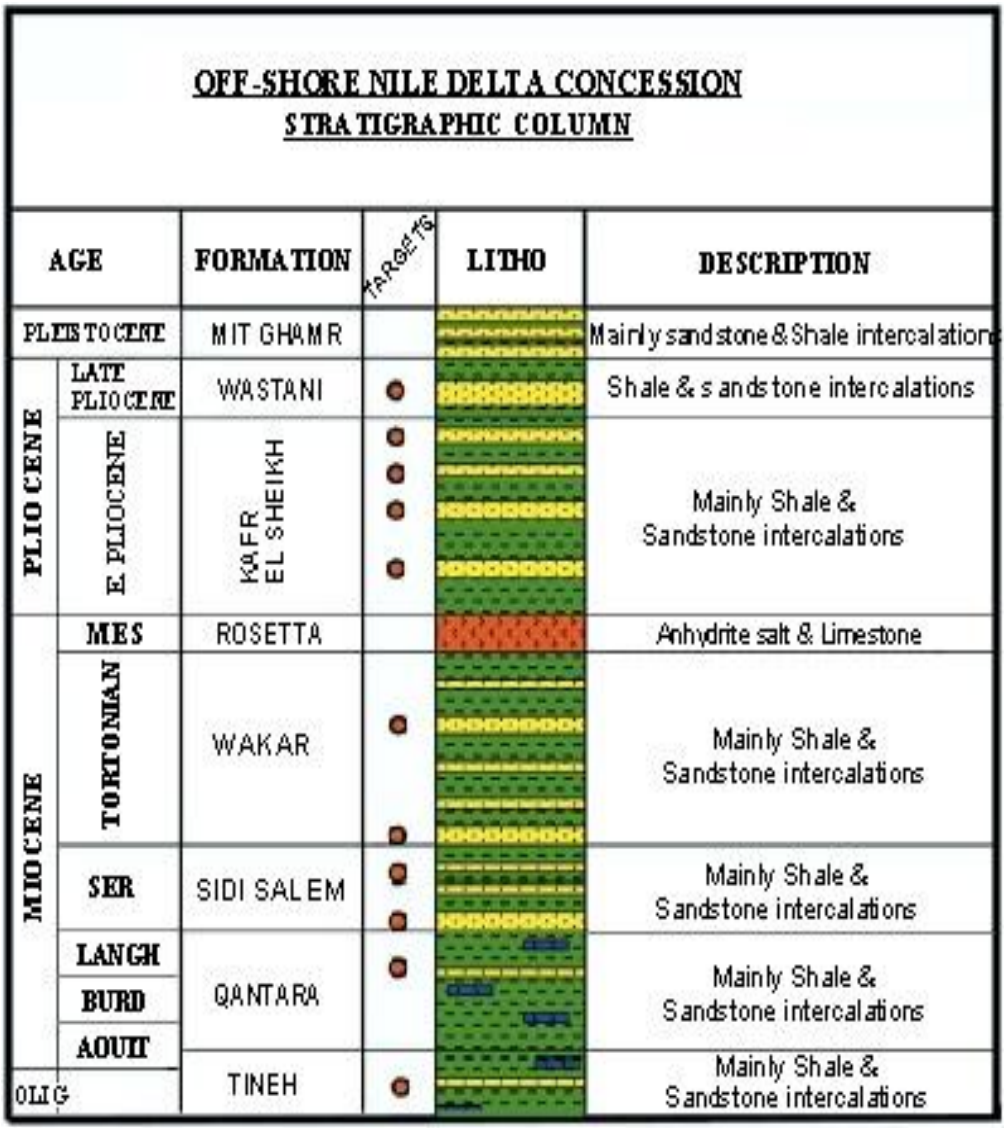

Figure 2. Generalized stratigraphic column of the offshore North-eastern part of the Nile Delta (Badri et al., 2000).

It is represented by some wells in the Darfeel-Port Fouad gas fields and covered mainly by thick clastic sequence of the Neogene - Quaternary sediments. The hydrocarbon potential of the study area is concentrated mainly in the sand embedded clastic zones of the Plio-Pleistocene aged sediments. These clastics encounter the major gas-bearing anomalies and in so doing, represent the main target for the exploration and production processes.

Figure 2 exhibits the generalized startigraphic column of the off-shore Nile Delta. It appears clear that, the Plio-Pleistocene sediments unconformably overly the evaporitic section of Rosetta Formation. They are represented by two formations (Kafr El Sheikh and El Wastani) and consist mainly of thick shale sections embedded and alternating with many sand beds at different depth levels and with variable thicknesses. These sand beds represent the main gas anomalies and together with the overlying and underlying shale beds, constitute the ideal stratigraphic traps to be explored in the off-shore Nile Delta.

METHODOLOGY

The different wireline logging suites (Gamma ray, neutron, density, sonic, resisitivity, caliper, etc) are used in the analysis and performing the necessary calculations. The most important petrophysical parameters necessary for characterizing the potential reservoirs are deduced like, porosity (total and effective), shale volume, permeability, fluid saturation (water and hydrocarbon). Furthermore, the available pressure data (formation pressure and hydrostatic pressure) of some sand anomalies are also interpreted and plotted against depth, in order to locate the different fluid

Table 1. Showing the different deduced petrophysical parameters of a number of wells in the study wells.

	Well	Darfeel-2	Darfeel-3	Darfeel-5	Darfeel-6	Darfeel-7	PFM SW-1	PFM SW-2	PFM-4
	Gross sand (m)	22	25	30	32	12	4	10	26
	Net pay (m)	18	22	20	21	12	4	8	0
	Porosity (%)	22	24	24	28	30	31	33	24
Anomaly-1	Shale volume (%)	16	11	9	10	3	5	2	8
	Water saturation (%)	83	76	82	55	53	66	59	100
	Gas saturation (%)	17	24	18	45	47	34	41	0
	Depth (m)	1353-1404	1227-1254	1435-1476	1172-1204	1498-1510	1641-1645	1273-1288	1975-2008
	Gross sand (m)	39	35	46	32	70	6	20	22
	Net pay (m)	39	30	44	20	70	4	12	0
	Porosity (%)	29	30	27	28	29	30	29	26
Anomaly-2	Shale volume (%)	11	6	4	8	5	6	3	7
	Water saturation (%)	19	32	58	44	15	56	64	100
	Gas saturation (%)	81	68	42	56	85	44	36	0
	Depth (m)	1662-1697	1450-1488	1735-1791	1378-1398	1732-1832	2012-2018	1437-1457	2188-2210
	Gross sand (m)	--	--	--	--	--	23	6	--
	Net pay (m)	--	--	--	--	--	13	6	--
	Porosity (%)	--	--	--	--	--	26	30	--
Anomaly-3	Shale volume (%)	--	--	--	--	--	7	4	--
	Water saturation (%)	--	--	--	--	--	78	60	--
	Gas saturation (%)	--	--	--	--	--	22	40	--
	Depth (m)	--	--	--	--	--	2774-2797	2631-2637	

contacts and illustrate the prevailing pressure regimes. The different deduced petro-physical parameters are interpreted and represented in a number of petrophysical data logs (PDL) and lateral distribution maps (gross sand, net pay sand, shale volume, porosity and water and hydrocarbon saturation maps).

RESULTS AND DISCUSSION

Petrophysical analysis

The petrophysical analysis of Kafr El-Sheikh Formation in the study area reveals the presence of three gas sand anomalies (anomaly-1, anomaly-2 and anomaly-3) encountered at varying depth levels. The petrophysical data logs revealed that anomaly-1 and 2 are recorded with different thicknesses in all wells in the study area, while anomaly-3 is not penetrated in the majority of the wells. Table 1 illustrates the main petro-physical characteristics of these zones in some selected wells in the study area.

Table 1 shows that, anomlay-2 is the best in terms of its petrophysical characteristics and shows that the majority of wells did not reach the gas-bearing anomaly-3, which is recorded only in three wells (Darfeel-1, PFM SW-1 and PFM SW-2 wells) in the study area. However, the estimated petrophysical parameters of anomaly-3 are found to be very good in the Darfeel concession (ϕ=29%, *Vsh*=8%, *Sw*=22% and *SH*=78%) and fair to good in PFM SW concession (Port Fouad Marine Southwest).

Petrophysical data logs

Figures 3 and 4 exhibit the vertical petrophysical data logs of Darfeel-1 and-7 wells. These wells

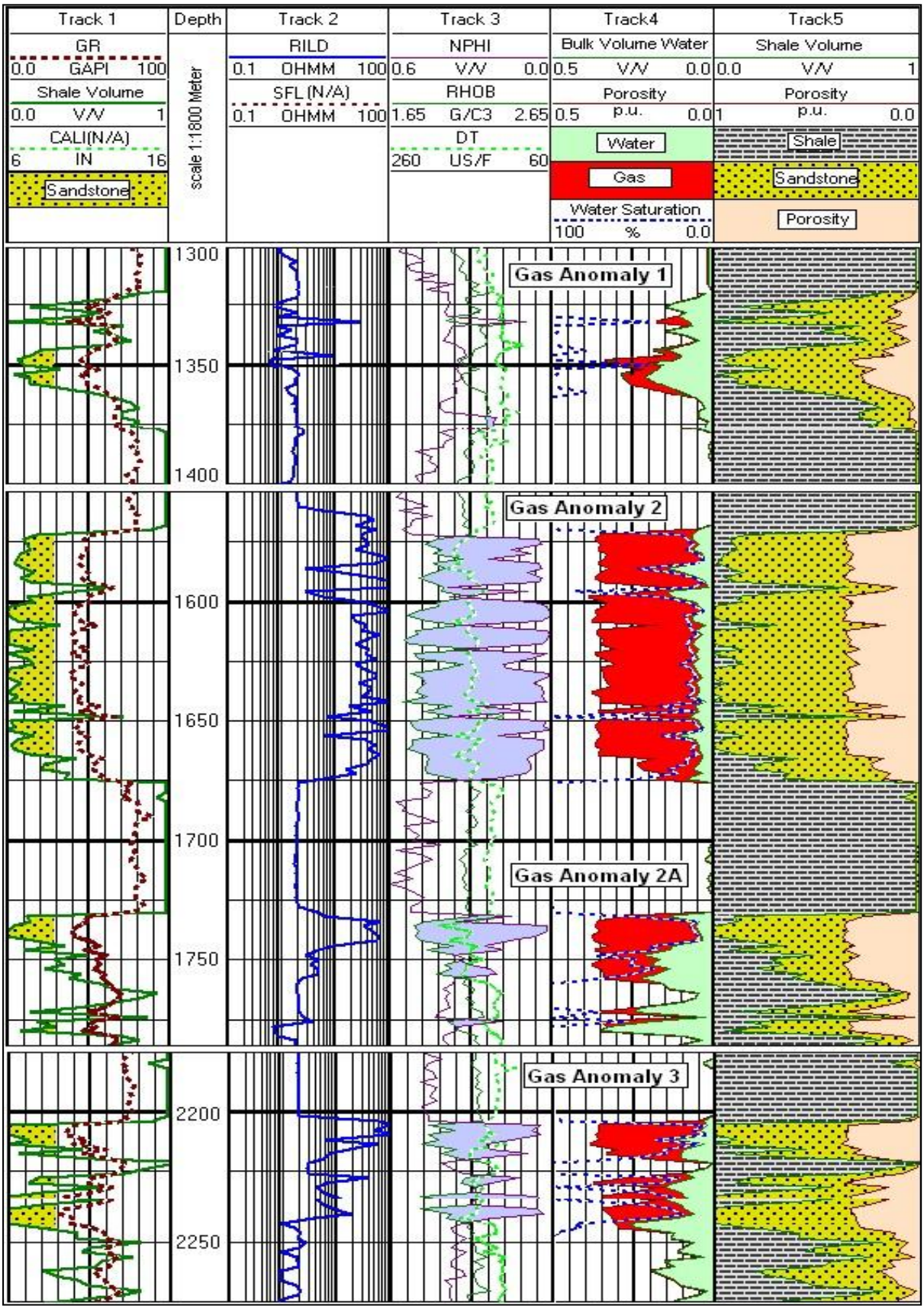

Figure 3. Petrophysical data log of Darfeel-1 well.

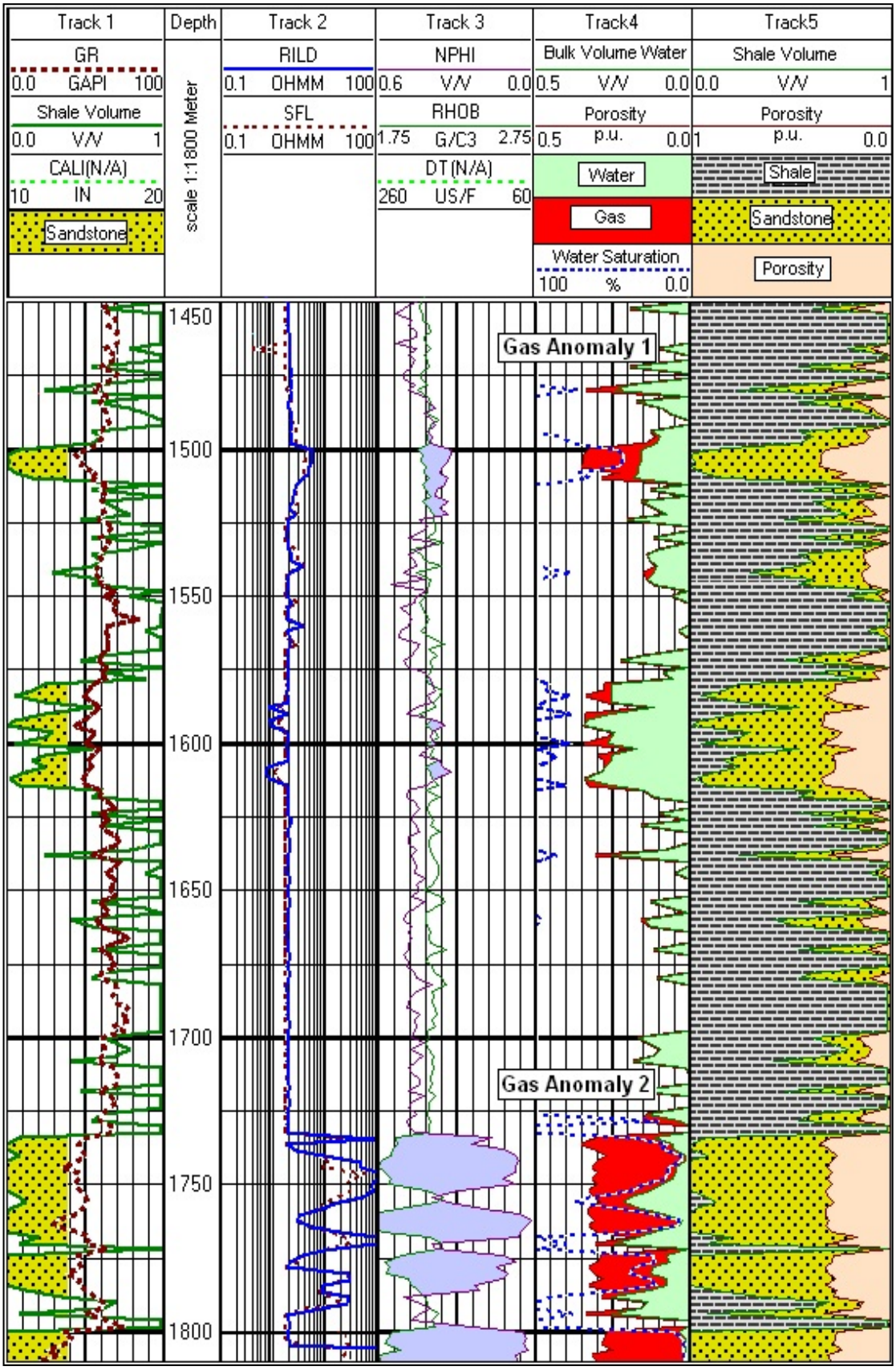

Figure 4. Petrophysical data log of Darfeel-7 well.

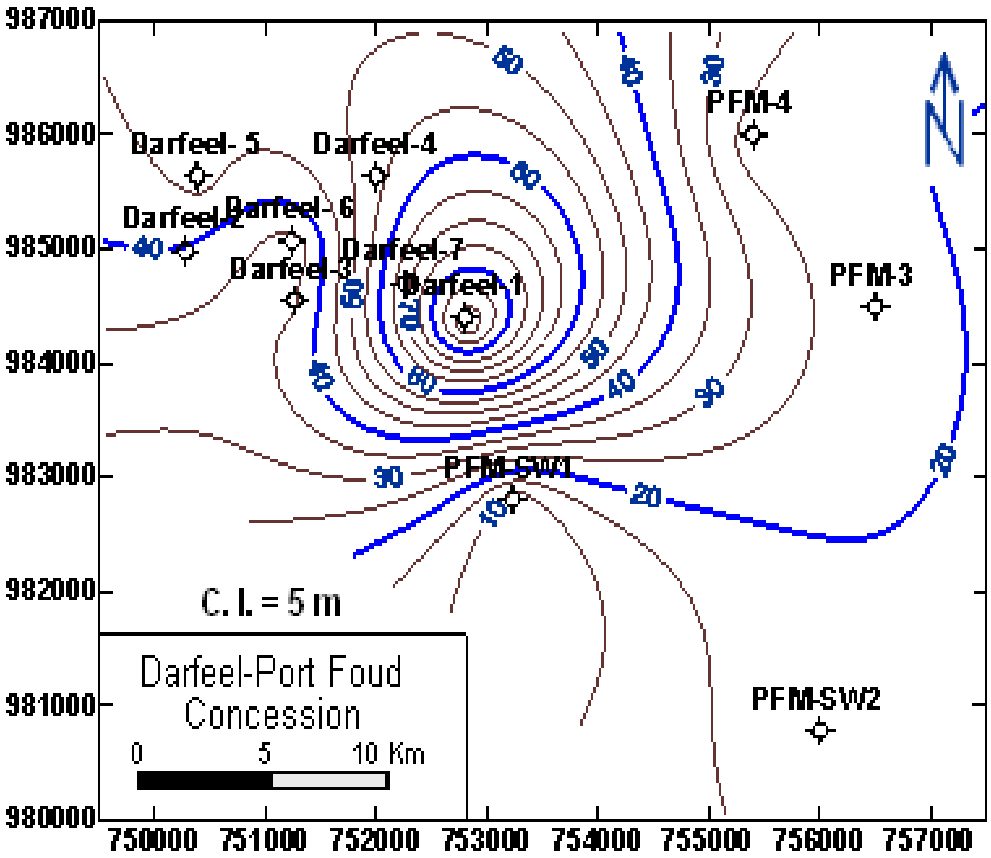

Figure 5. The gross sand lateral distribution map of anomaly-2 in the study area.

are selected to demonstrate the reservoir characteristics of gas-bearing sand anomalies. It appears clear that, anomalies-1 and 2 are well represented in the study area. Regarding anomaly-1, the reservoir parameters are found in the range of 22% (Darfeel-2) to 33% (PFM SW-2) for porosity, 2% (PFM SW-2) to 16% (Darfeel-2) for shale volume, 53% (Darfeel-7) to 83% (Darfeel-2) for water saturation, and 47% (Darfeel-7) to 17% (Darfeel-2) for gas saturation (Table 1).

Anomaly-2, on the other hand, exhibits good reservoir parameters in terms of good porosity (27 to 33%), low shale volume ($Vsh \leq 11\%$) and high gas potentiality (36 to 93%). The gross and net pay sand sections of this anomaly are well recorded in all wells in the study area. However, the type section of anomaly-2 is recorded in Darfeel-1 well with 95 m net pay productive sand (Figure 3). The density log records very low value (ρb<1.8 g/cc) in front of this zone, giving rise to the visual and well known gas anomaly separation in the density-neutron overly (Track 3).

Iso-parameteric maps

Due to the good reservoir parameters which it attains, a number of lateral distribution maps (iso-parameteric maps) are constructed for gas anomaly-2 in the study area (Figures 5 to 10). The gross and net pay sand sections of this anomaly (Figures 5 and 6) are well represented in the central parts of the study area, especially in the locations occupied by Darfeel-1 and Darfeel-2 wells, where the gas sand reservoir attains its maximum section (95 m). To the east, NE and SE directions, the thickness of the net pay sand diminishes gradually.

The shale volume and effective porosity distribution maps of anomaly-2 (Figures 7 and 8) as well as the fluid saturation maps (Figures 9 and 10), show that the central part attains the best cut off reservoir parameters in the study area. A lower shale volume ($Vsh \leq 11\%$) and much higher porosity (ϕ=33 %) and gas saturation (Sg up to 93%) values were obtained for this part of the area.

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

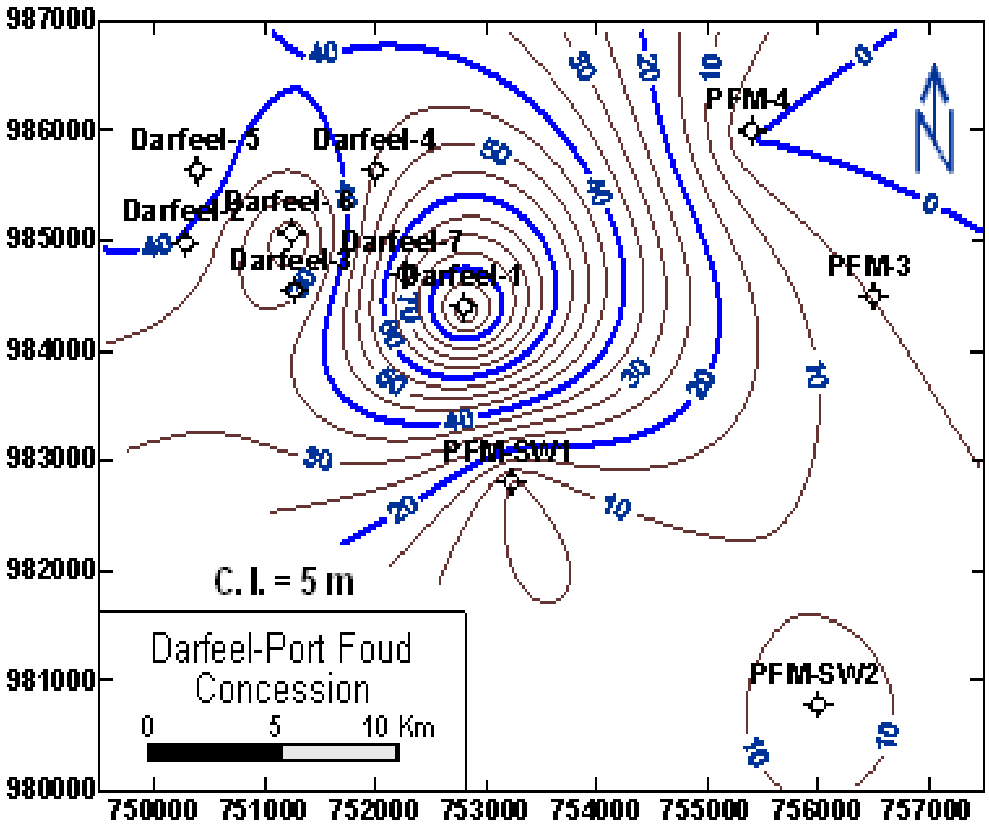

Figure 6. The net pay sand lateral distribution map of anomaly-2 in the study area.

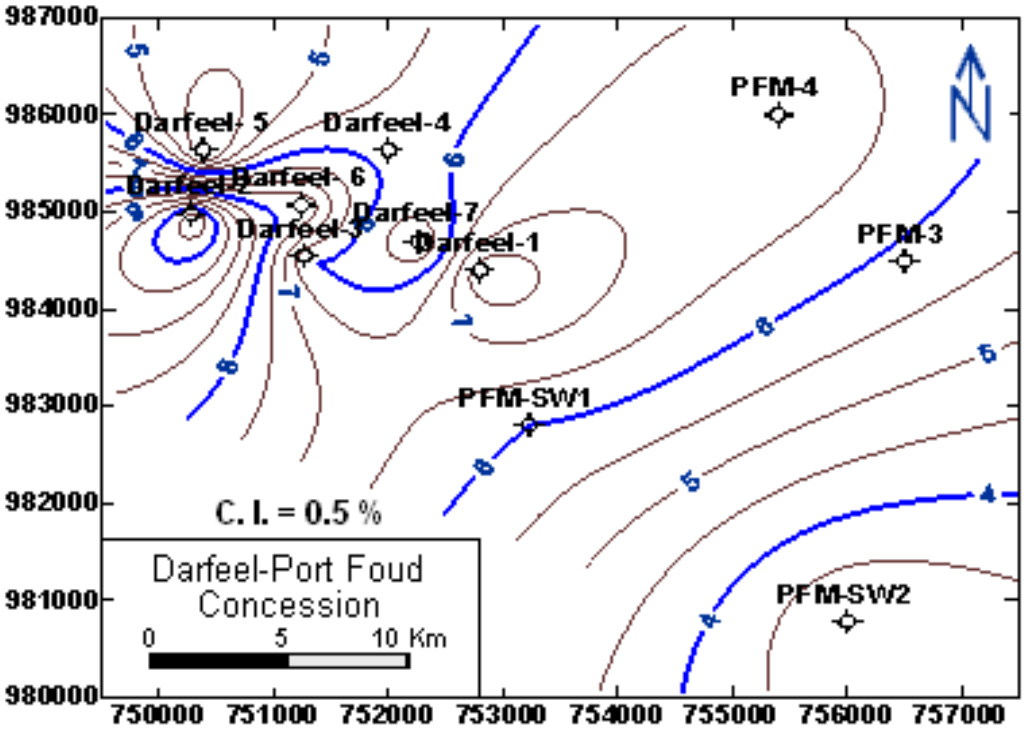

Figure 7. The shale volume lateral distribution map of anomaly-2 in the study area.

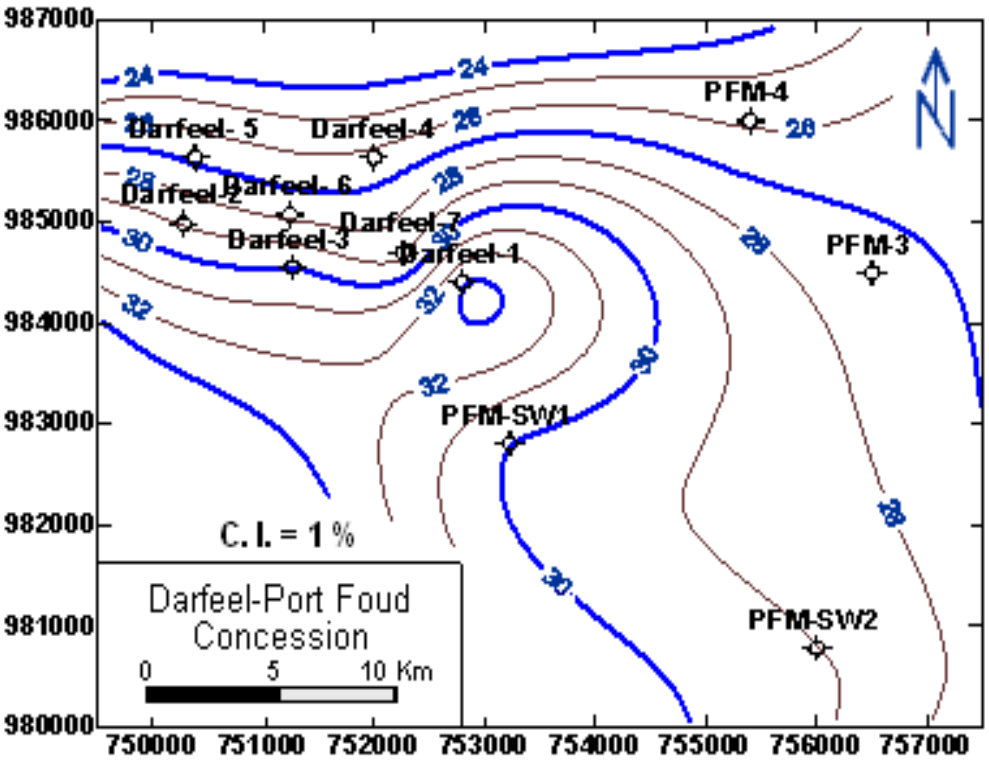

Figure 8. The effective porosity lateral distribution map of anomaly-2 in the study area.

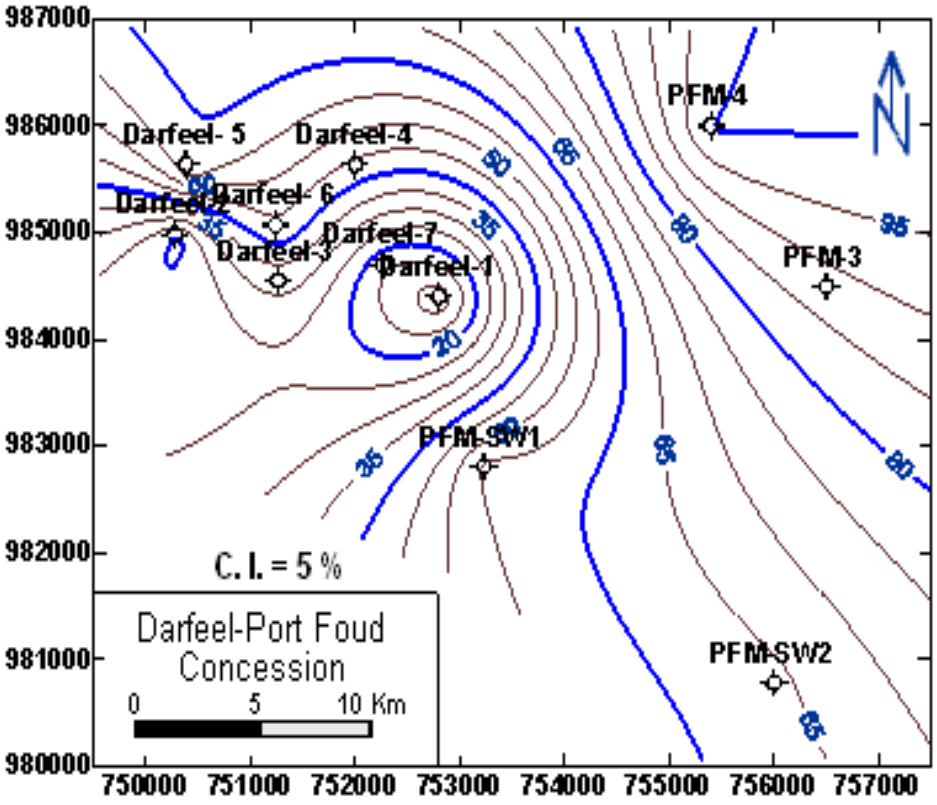

Figure 9. The water saturation lateral distribution map of anomaly-2 in the study area.

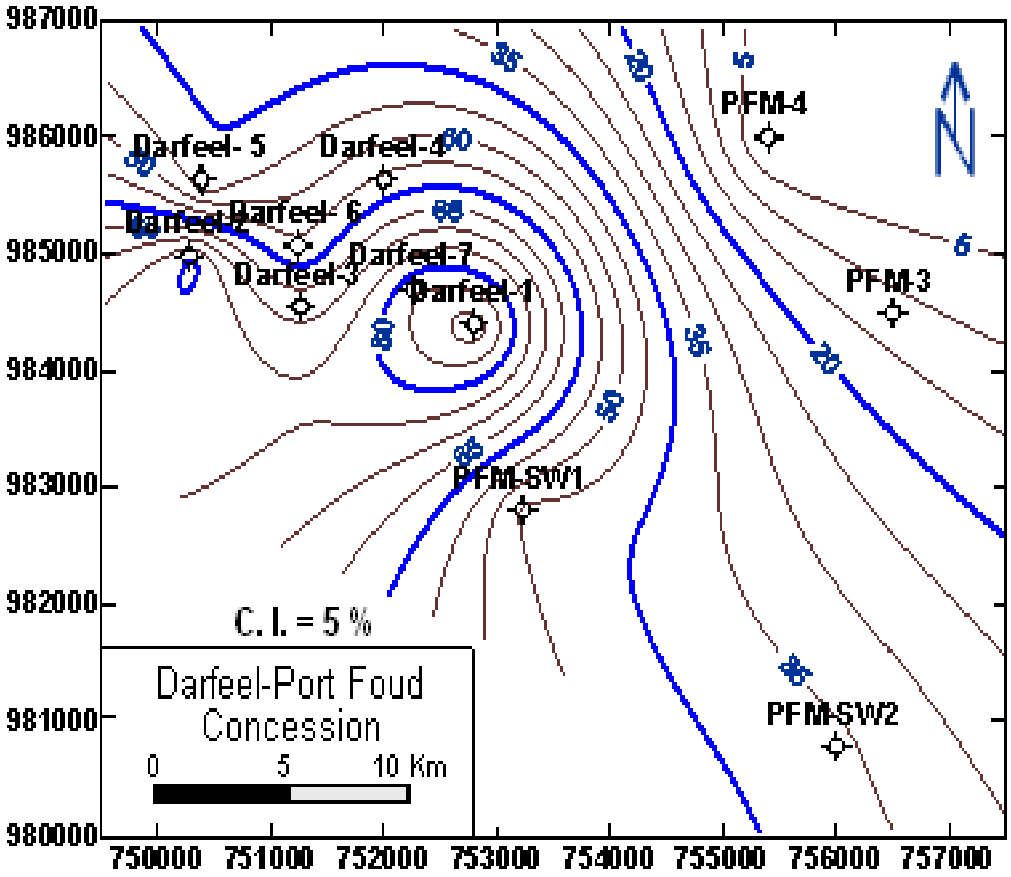

Figure 10. The gas saturation lateral distribution map of anomaly-2 in the study area.

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 (Schlumberger, 1986).

In the present study, the available pressure data (formation pressure and hydrostatic pressure) of four wells were analyzed and interpreted (Tables 2 and 3). Figure 11 (a and b) shows 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 nearly similar influencing pressure regimes. A less extent pressure reversal, which is a characteristic phenomenon in many gas fields in the off-shore Nile Delta, is recognized in the zone occupied by gas anomaly-2 in Darfeel-1 well (Figure 11a). The mobility of gas this zone ranges from very good to excellent indicating that a good and suitable condition for migration and accumulation of hydrocarbon (Table 2) is dominated.

Figures 12 and 13, on the other hand, show composite pressure plots illustrating the different pressure gradients of gas anomalies-1 and -2. Very close pressure gradients in the range of 0.331 psi/ft to 0.345 and 0.314 psi/ft to 0.444 psi/ft are indicated for most of wells throughout the study area for these two anomalies, respectively. An exception is exhibited by anomaly-1 in Darfeel-5 well which shows higher pressure gradient of 0.505 psi/ft. This may be due to the prevailing water-bearing characteristics of the sand anomaly in this well. In general, the close range of pressure gradients indicates a multi-zones reservoir with homogenous prevailing pressure regimes.

SUMMARY AND CONCLUSIONS

The present study aimed to analyse the well log and pressure data of the gas-bearing sand anomalies of the Pliocene sediments of Kafr El Sheikh Formation in the off-shore Nile Delta area (Darfeel-Port Fouad Concession). Complete petrophysical analysis is performed over eleven wells scattered in the study area. Such analysis reveals the presence of two gas-bearing sand anomalies (anomaly-1 and -2).

Table 2. The pressure data of gas anomaly-1.

Well	Depth (m)	Hydrostatic pressure	Formation pressure	Mobility (Permeability)
Darfeel-5	1431	2388.2	1712.5	Good-Fair
	1463	2435.5	1775.12	Good
	1472	2446.8	1776	Good
Darfeel-6	1172.5	2393.7	Tight	-
	1189.5	2393.7	1771.9	Excellent
	1193	2400.6	Tight	-
	1195.5	2405.7	Tight	-
	1200.5	2415.9	Tight	-
	1244.5	2504.8	1834	Excellent
	1261	2536.8	Super Charge	-
	1267.5	2550.6	Super Charge	-
Darfeel-2	1088	1825.9	1436.9	Excellent
	1092	1830.8	1441	Excellent
	1135.8	1888.3	Tight	-
	1136	1888.7	1487	Poor
	1355	2170.9	1766.5	Very Good
	1357.5	2173.9	1766	Very Good
	1360.3	2177.4	1767.1	Very Good
	1360.5	2177.8	Tight	-
	1384.5	2211	1767.5	Very Good
	1386	2213	1767.5	Very Good
	1394.6	2224.7	1768.3	Fair
	1402	2235	1768.8	Very Good
	1404	2237.5	1769.3	Very Good
Darfeel-1	1336	2285.2	1765.2	Poor
	1357.6	2316.3	1765.7	Excellent
	1360.5	2320.5	1766.2	Very Good
	1367	2329.7	Tight	-
	1377	2344.4	1766.1	Poor
	1336	2285.2	1765.2	Poor

Table 3. The pressure data of gas anomaly-2.

Well	Depth (m)	Hydrostatic pressure	Formation pressure	Mobility (Permeability)
Darfeel-5	1741	2854.8	2130.6	Excellent
	1743	2860.2	Seal Failure	-
	1751	2869.4	2132.6	-
	1753	2872.6	2133.8	Poor
	1775	2903.6	Super Charge	-
Darfeel-6	1381	2778.8	2109	Excellent
	1384.5	2786.8	2126.9	Very Good
	1388	2793.4	2127.9	Excellent
	1408	2827	2129	Excellent
Darfeel-2	1664	2613.9	Tight	-
	1644.2	2614.	2124.4	Very Good
	1666	2616.5	2124.9	Very Good
	1670.5	26233	2129.4	Very Good
	1675	2629.6	2125.8	Excellent
	1678	2634.3	2126.4	Excellent

Table 3. Contd.

	1683	2641.8	2126.8	Excellent
	1686.5	2646.9	2127.6	Excellent
	1688	2649.1	2127.2	Excellent
	1689.8	2651.4	Tight	-
	1690	2652	Super Charge	-
	1690.2	2652.2	Super Charge	-
	1692.8	2656	Tight	-
	1693	2656.2	Tight	-
	1693.2	2656.5	Tight	Fair
	1694.4	2658.3	2132.3	-
	1695	2659.3	Tight	-
	1696.9	2663.8	Seal Failure	-
	1697	2662.3	Super Charge	-
	1697.2	2662.9	Tight	-
Darfeel-1	1574	2660.3	2115.9	Very Good
	1595	2665.9	2137	Excellent
	1632	2672.3	2117	Excellent
	1622.5	2685.4	2117.8	Excellent
	1632	2697.5	2118.6	Excellent
	1638	2704.9	2119.1	Excellent
	1645.5	2714.2	2119.8	Excellent
	1653	2723.7	2120.5	Excellent
	1662	2734.6	2121.3	Excellent
	1670	2744.7	2122.3	Excellent

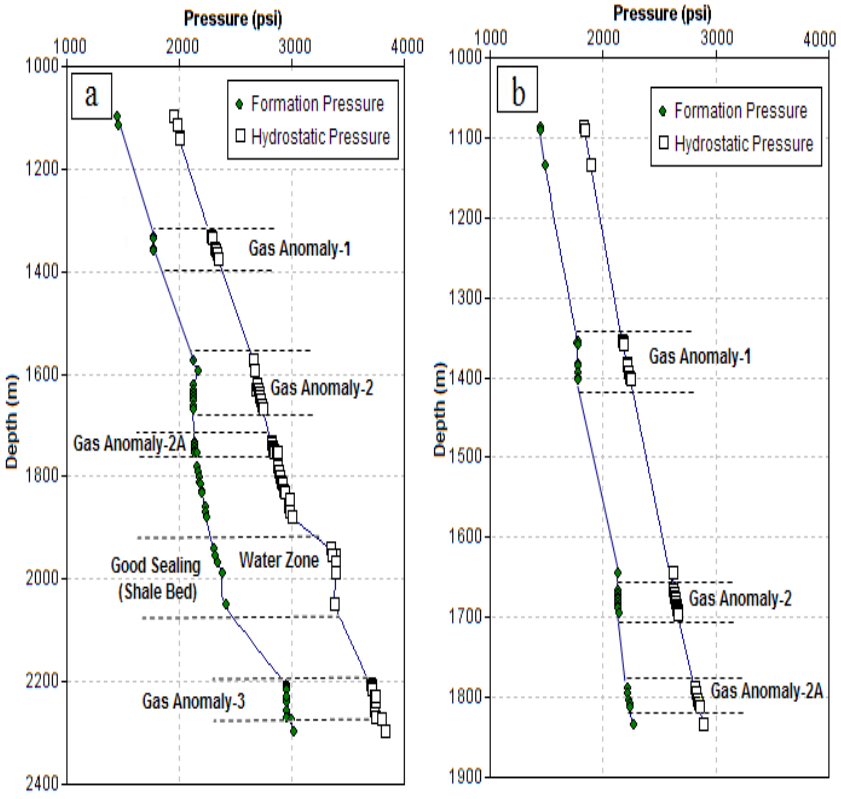

Figure 11. Depth-pressure plots. (a) Darfeel-1 well and (b) Darfeel-2 well.

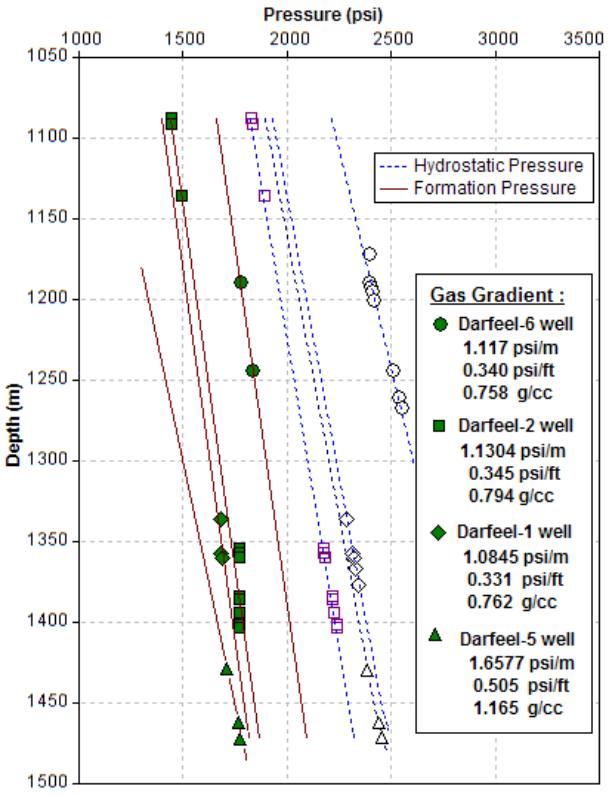

Figure 12. The different pressure gradients of the gas-bearing anomaly-1 in the study area.

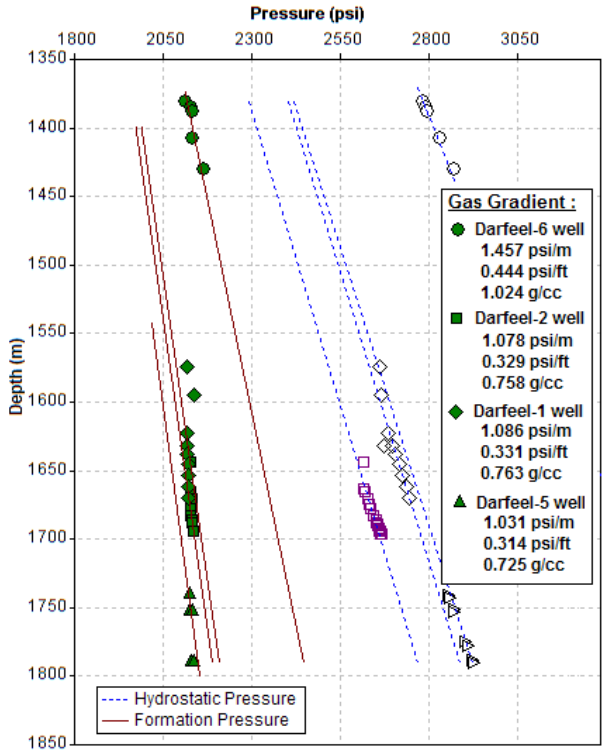

Figure 13. The different pressure gradients of the gas-bearing anomaly-2 in the study area.

The petrophysical parameters of the gas anomaly-1 are found to be in the ranges of 22 to 33%, 2 to 16% and 17 reservoir parameters in the study area in terms of good porosity (27 to 33%), low shale volume (*Vsh* ≤ 11%) and high gas potentiality (36 to 93%).

The different deduced petrophysical parameters are interpreted and represented in the form of a number of vertical data logs and lateral distribution maps. The lateral distribution maps of anomalies-2 show that no hydrocarbons are recognized in the eastern flanks of the study area, while potential accumulations are located in the central and western parts. Good reservoir cut-off parameters of low shale volume (*Vsh* ≤ 11%), much high porosity (ϕ=33%) and gas saturation (*Sg* > 90%) (Values are estimated for this area).

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 anomalies are found so close and similar. Ranges of 0.331 to 0.505 psi/ft and 0.314 to 0.444 psi/ft are found for gas anomalies-1 and -2, respectively. These pressure conditions assume a superimposed multi-layer with homogenous pressure regimes for the gas reservoirs of the Kafr El-Sheikh Formation.

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