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Petrophysical characteristics of Wakar Formation, Port Fouad marine field, north Nile Delta, Egypt

Adel Mohamed · Elkhedr Ibrahim · Ahmed Sabry

Abstract Petrophysical characteristics of the late Miocene Wakar Formation of Port Fouad Marine Field have been evaluated through the analysis of well-logging records of nine exploratory and development wells, distributed in the northeastern offshore area of the Nile Delta. These records have been analyzed through utilizing the ELAN Plus petrophysics software in order to identify the lithological constituents and fluid saturation parameters. The gas potentialities of the studied formation have been evaluated through number of isoparameteric maps. The litho-saturation analysis indicates that the Wakar Formation in the studied wells is mainly gas-bearing with some water-bearing sand levels. The analytical formation evaluation reveals that the lithological facies consists mainly of sandstone, shale, and siltstone. The disseminated shale is mainly of dispersed type and some of laminated habitat. It also points to the dominance of the intergranular porosity. The isoparametric maps of the petrophysical parameters show that the level S1 of Wakar Formation is the main reservoir.

Keywords Wakar formation · Port Fouad Marine Field · Petrophysical parameters

Introduction

Exploration of offshore Mediterranean in Egypt is getting more and more important due to gas reserve discovered in

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Port Fouad, Baltim and Temsah concessions. Today, the Egyptian natural gas sector is expanding rapidly, with production having more than doubled between 1999 and 2003. Egypt's government released a revised estimate of proven natural gas reserves in December 2005, which put the figure at 67 trillion cubic feet, based on several new findings. Historically, petroleum exploration in the Nile Delta started in the 1940s with gravity, magnetic, and seismic data acquisition. However, it was not until 1963, when International Egyptian Oil Company (IEOC) acquired the first concession, that intensive exploration efforts began. The first detailed seismic survey, performed at Abu Madi in the 1960s, revealed many promising structural features. Two structures were drilled but unfortunately resulted in dry holes (Mit Ghamr-1 and Kafr El Sheikh-1). The first offshore gas discovery, Abu Qir-1× well, was announced by Phillips in 1969. This discovery well led to WEPCO's gas and condensate production from the sandstone reservoirs of the Abu Madi and Sidi-Salim Formations. Until 2007, the IEOC had drilled more than 17 wells in the Port Fouad Marine Field.

The present study deals with the evaluation of subsurface geology and hydrocarbon potentialities of the Tortonian Miocene Wakar Formation that were encountered in nine exploratory and development wells. These wells were distributed in the Port Fouad Marin Field in the eastern part of the offshore Nile Delta area (Figs. 1 and 2). The investigated area covers offshore concession to the north of Port Fouad city with 13.85 in width and 10.40 km in length and a total area of 144 km^2. The study area lies between the latitudes 31° 29″ 14′.92 and 31° 34″ 46′.11 N and longitudes 32° 26″ 29′.04 and 32° 35″ 19′.48E. Comprehensive analytical formation evaluation has been applied on the available well logs to identify the lithological constituents and petrophysical and fluid saturation parameters using Schlumberger software (ELAN plus) and Loganal software. The hydrocarbon potentialities of the studied

Fig. 1 Geographical location of the Port Fouad Marine Gas Field
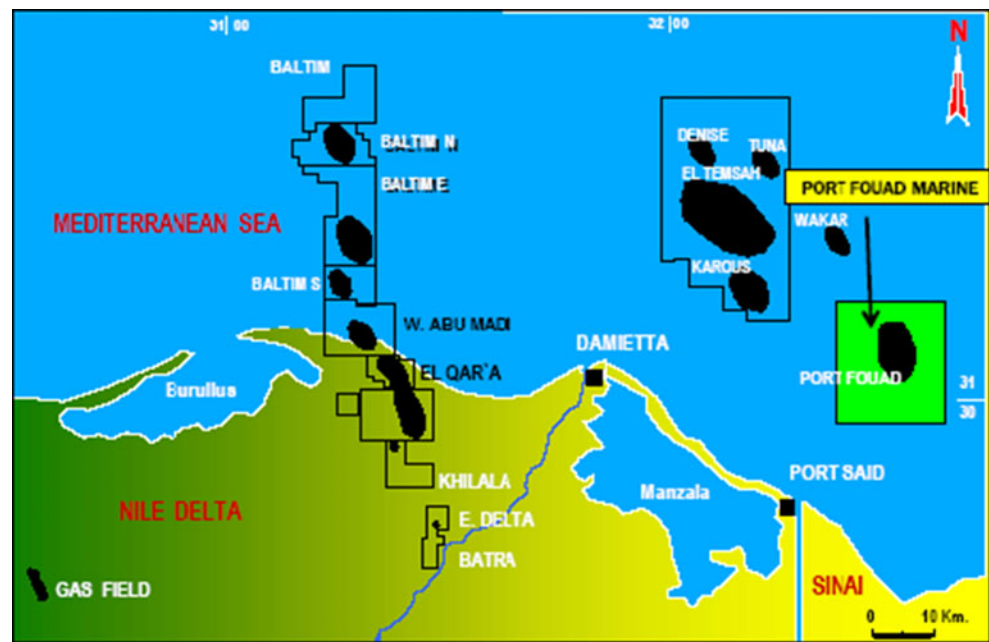
formation have been evaluated through integration of the stratigraphic, well-logging data to infer petrophysical parameters. The well-logging data comprise resistivity, sonic, neutron, density, nuclear magnetic resonance, spontaneous potential, caliper, and gamma ray and natural gamma ray spectrometry logs, where the geological data are represented by composite logs.

General geologic and structural settings

The southern apex of the Delta is located at Latitude N 30°, some 30 km north of Cairo, where the Nile River splits into two branches, the western Rosetta branch of

Fig. 2 Location map of the studied wells in Port Fouad Marine Field

239 km and the eastern Damietta branch of 245 km. Both distributaries meander separately through the Delta to the sea (El-Ashry 1979). The Nile Delta appears to be more strongly developed on its eastern flank, due to long-shore currents sweeping large amounts of fluvial deposits eastward. The ancient distributaries disappeared due to intensive irrigation construction in the onshore Delta plain and were eventually reduced to the two mentioned branches. The generalized lithostratigraphic sequence of the Nile Delta, compiled (after Schlumberger 1984; EGPC 1994; Kamel et al. 1998; Raslan 2002), is shown in Fig. 3. The present study will focus only on Wakar Formation which is the main interest of this paper.

Stratigraphically, Wakar Formation is assigned in the eastern sub-basin to Late Miocene age (Tortonian–Early Messinian). It is equivalent to the Qawasim Formation in the central sub-basin (Kamel et al. 1998). The NW–SE trending Temsah faults separates the eastern sub-basin from the central sub-basin. In the eastern sub-basin, Wakar Formation unconformably overlies the Sidi Salim Formation and underlies the Rosetta evaporates (Kamel et al. 1998). The Wakar Formation is present in the eastern sub-basin in the study area of Port Fouad Marine Field. The structural contour map on the top of the Wakar and the equivalent Qawasim Formation shows an irregular paleo-relief pattern dipping generally north and NW-wards. This pattern is dissected by a number of faults running mainly NE-SW and NW-SE directions. It is noticeable that these faults affected the underlying Sidi Salim Formation. The depth to the Wakar Formation in Port Fouad Marine Field varies from 2,540 m in the SW of the study area to 2,725 m
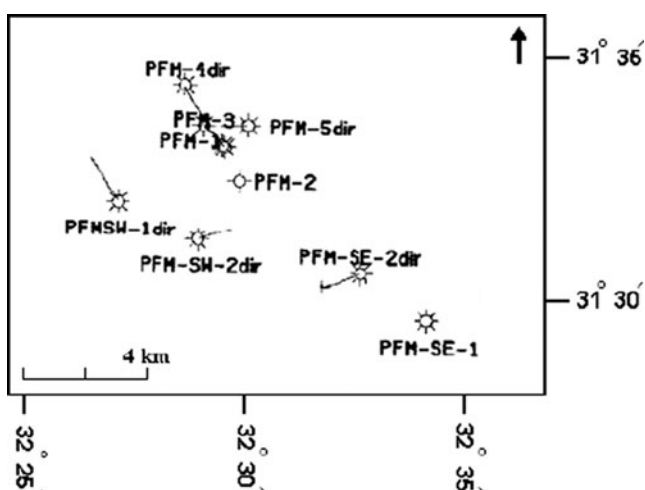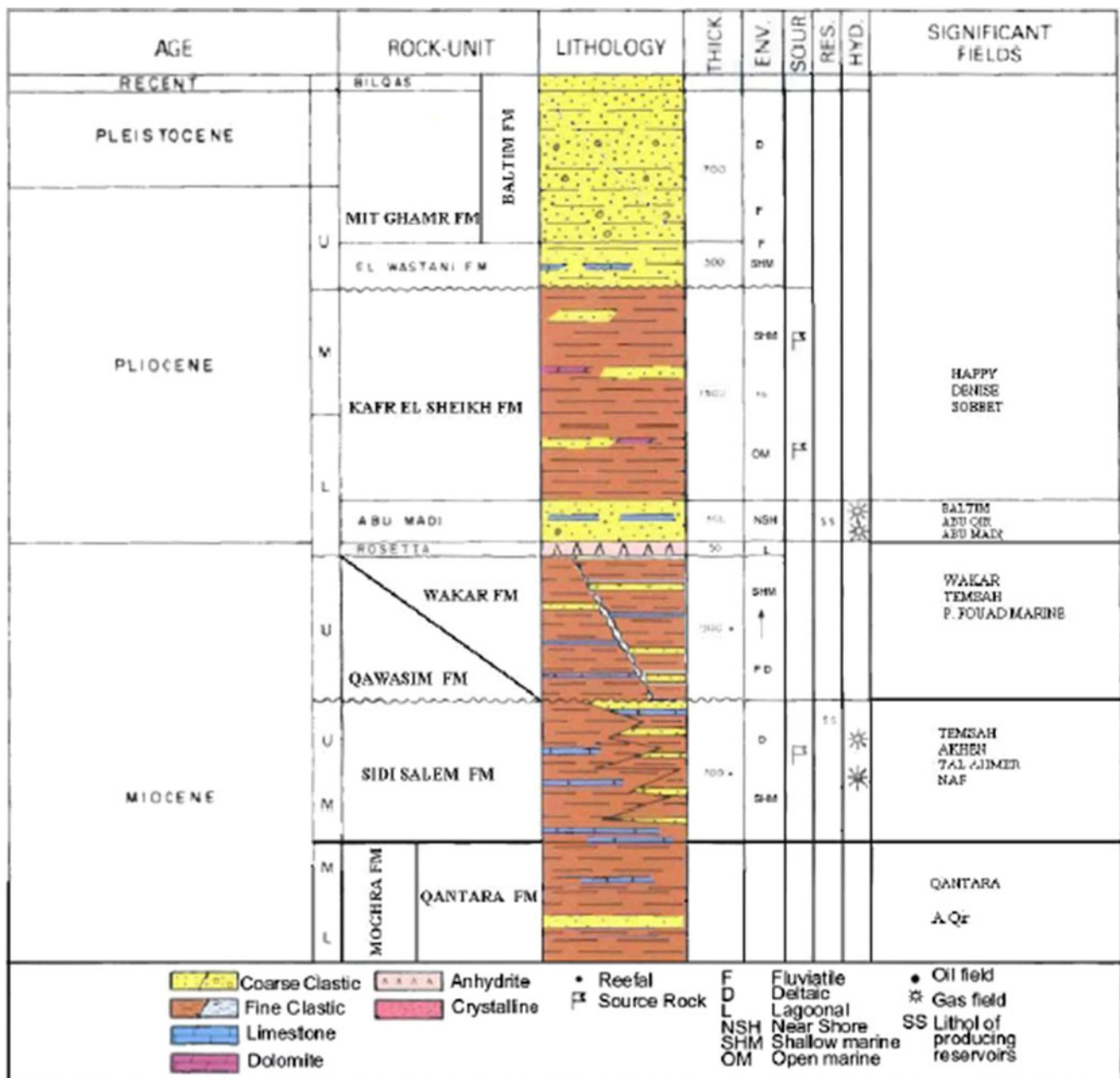
Fig. 3 A generalized stratigraphic column of the Nile Delta area (compiled from Schlumberger 1984; EGPC 1994; Kamel et al. 1998; Raslan 2002)

at the north (Fig. 4). The maximum thickness of Wakar Formation in the study area is 763 m at the PFM SE-1 well (Fig. 5).

The delta is structurally divided into two sub-provinces by a faulted hinge line running WNW to ESW across the area at the latitude of the Kafr El Sheikh city. This hinge line is the most significant structural feature of the Nile Delta region and is known as the faulted flexure that separates the south delta province from the north delta basin. In the southern delta province, the subsurface structure is complicated by the interaction between tectonic elements of different

ages. These are the E-NE and NE trending folds of Late Cretaceous to Eocene age (the Syrian arc folds). The Oligocene to Early Miocene NW-SE trending faults are associated with a major uplift in the south coupled with basaltic extrusion. The Late Miocene and Pliocene delta subsidence are mainly concentrated along the axis of the Nile valley. Generally and from the structural point of view, we can say that the northern deltas were controlled by four reactivated fault systems known as the Bardawil Line, Qattara-Eratosthenes Line, Pelusium Line, and Hinge zone. The Bardawil Line controlled facies distribution in the NE delta area (study area).
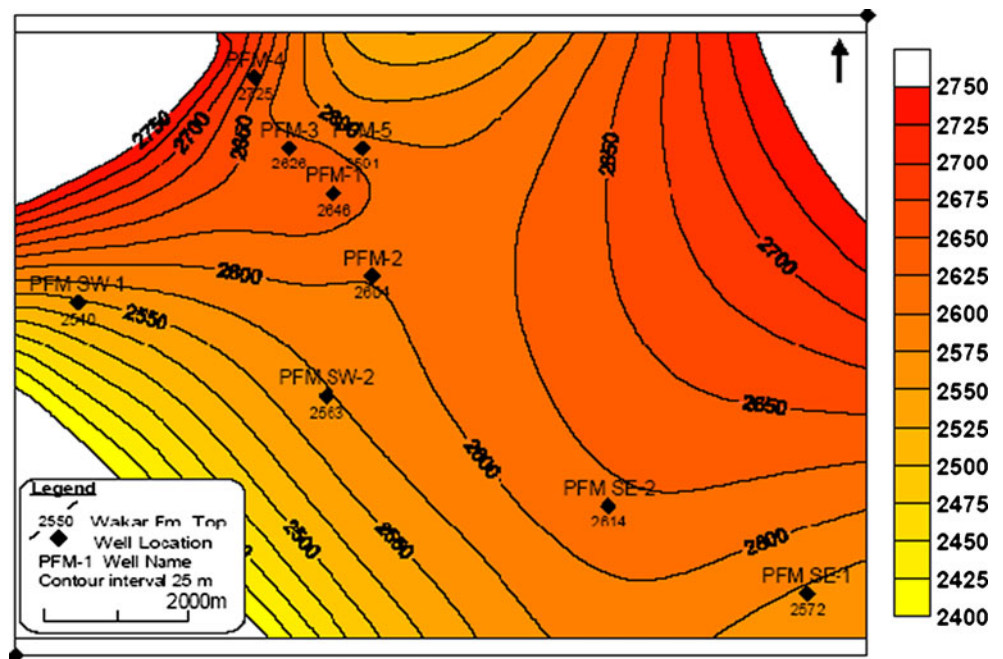
Data analysis and processing

Several specific analysis steps are employed in the well-
logging data in the study area for interpretation process:

1. Filtering the raw log response data to remove and
   correct anomalous data points.
2. Correct neutron, sonic, density, and resistivity logs for
   mud filtrate invasion.

3. Normalize logs from all selected wells to determine the
   appropriate ranges of porosity, clay content, water
   resistivity, etc. These data are integrated to verify the
   following petrophysical characterization and hydrocarbon
   potentialities of Wakar sands within the Port Fouad
   Marine Field. Reservoir characterization study is based
   on the following components: log evaluation, lithology
   and fluid analysis, forward modeling and rock property
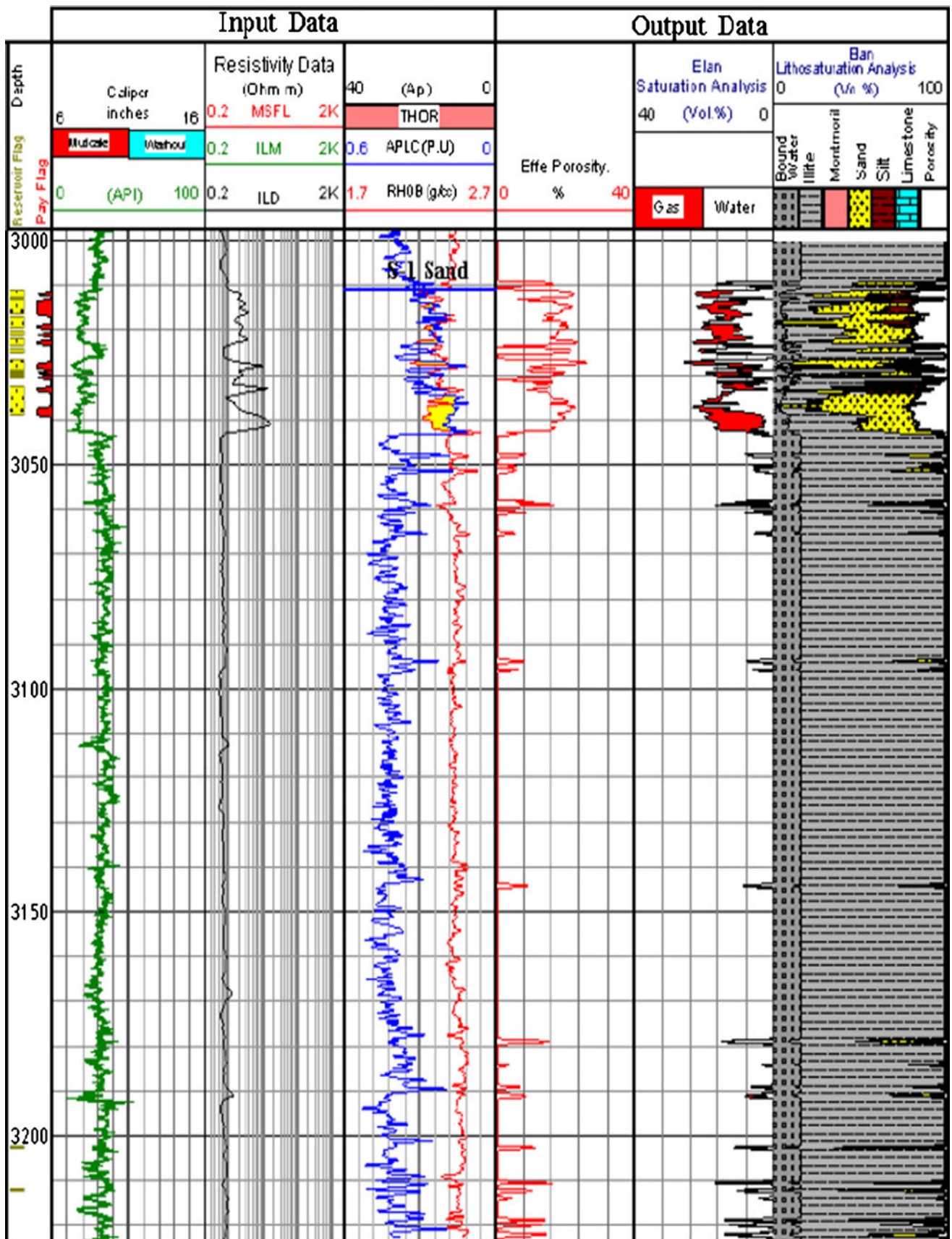   relationships, and cross-plotting.
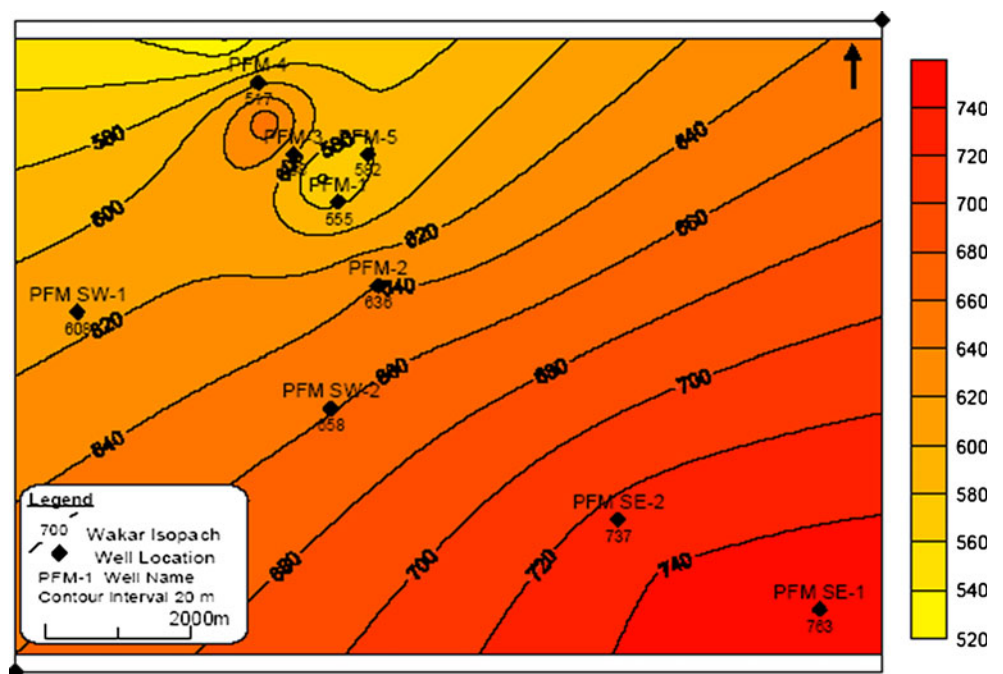
Fig. 6 Lithosaturation cross-plot of Wakar sandstone level (S-1) of the PFM-1 well, Port Fouad Marine Field, Mediterranean Sea
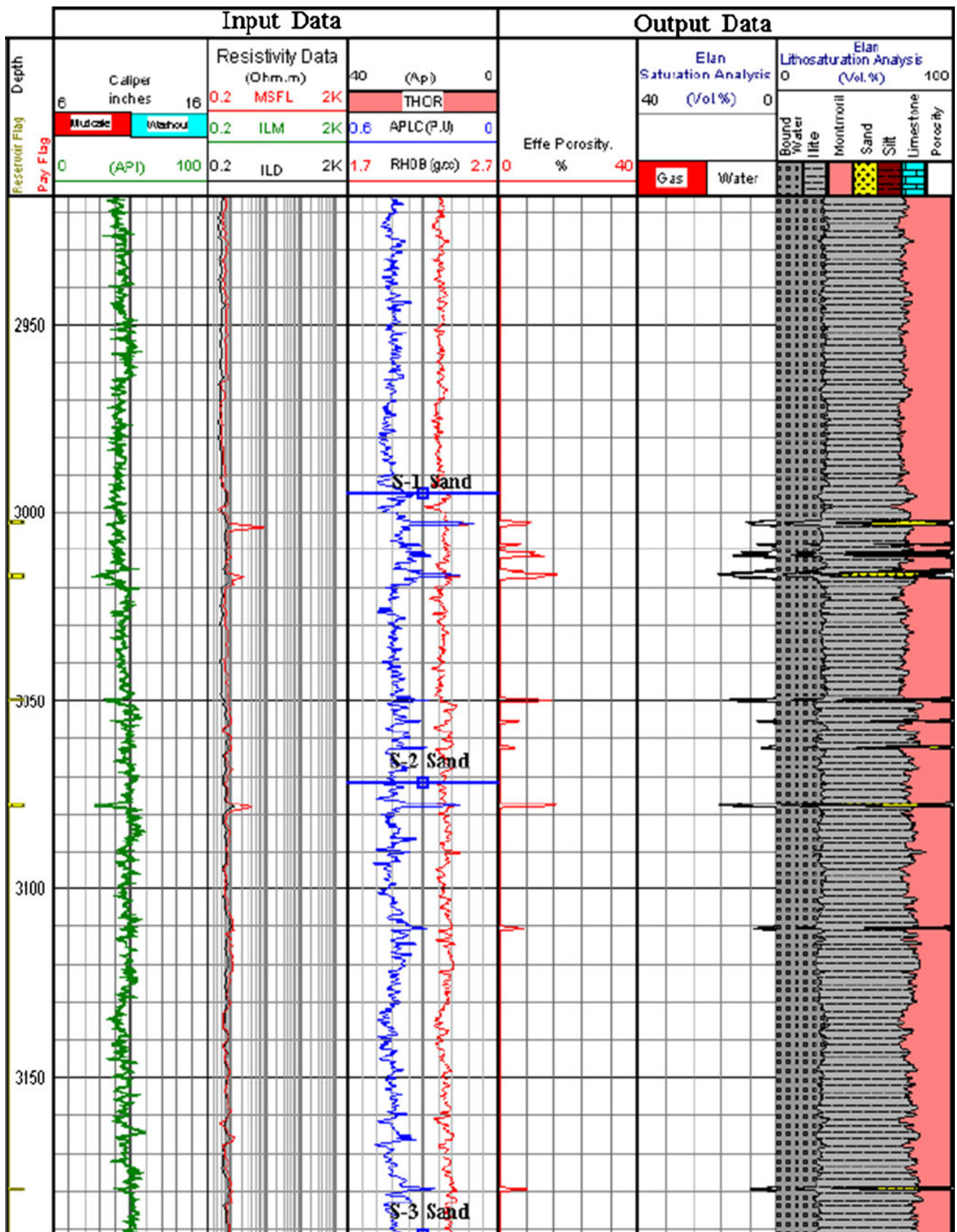
Fig. 7 Lithosaturation cross-plot of Wakar sandstone levels (S-1, S-2) of the PFM-2 well, Port Fouad Marine Field, Mediterranean Sea

The processing of the well-logging data in this study has been carried out using the ELAN Plus software to evaluate the Wakar reservoir. The shale volume was determined using the gamma ray log data. The porosity was calculated using weighted average neutron density with shale correction. The sonic logs are available, but, nevertheless, data are not used for determining reliable porosity values. This is due to the gas saturation effects and the high accuracy of density neutron calculation. The water saturation was then derived using connate water resistivity being found from apparent connate water, Rwa, method. The pay zone petrophysical sums and averages were computed using V_{shale} cut-off 40%, Porosity cut-off 7%, and Sw cut-off 70%. These cut-off percents were determined from the inspection of the logs and cross-plots of the porosity versus V_{shale}. The output results deduced from the well-logging parameters resulting from the application of the ELAN Plus program, in addition to its input data set are presented in zone-wise litho-saturation cross-plots and map-wise. This is to evaluate the hydrocarbon potentialities of the studied formation in the light of the petrophysical and lithological parameters achieved from the analytical formation evalua-tion for each well individually. This cross-plot displays, in a number of tracks from left to right, the depth (in meters MD) associated with the pay of reservoir flags. After that, there are three tracks in the right-hand side representing the input data that constitute the caliper, gamma ray, resistivity, neutron, and density log data. The last three right-hand-side tracks contain, from the left to the right, the effective porosity, and gas and water saturations. This cross-plot ended with the ELAN Plus lithosaturation analysis. Before discussing the lithosaturation cross-plots, we have to take into consideration that the studied Wakar Formation is gas-bearing and/or condensate, since the negative separation between density and neutron logs appears in the log recordings and is related to the gas saturation (Asquith and Krygowski 2004).

The lithosaturation analysis of wakar formation

The petrophysical parameters of the sand intervals within Wakar Formation which is divided into levels have been calculated. These parameters, represented by
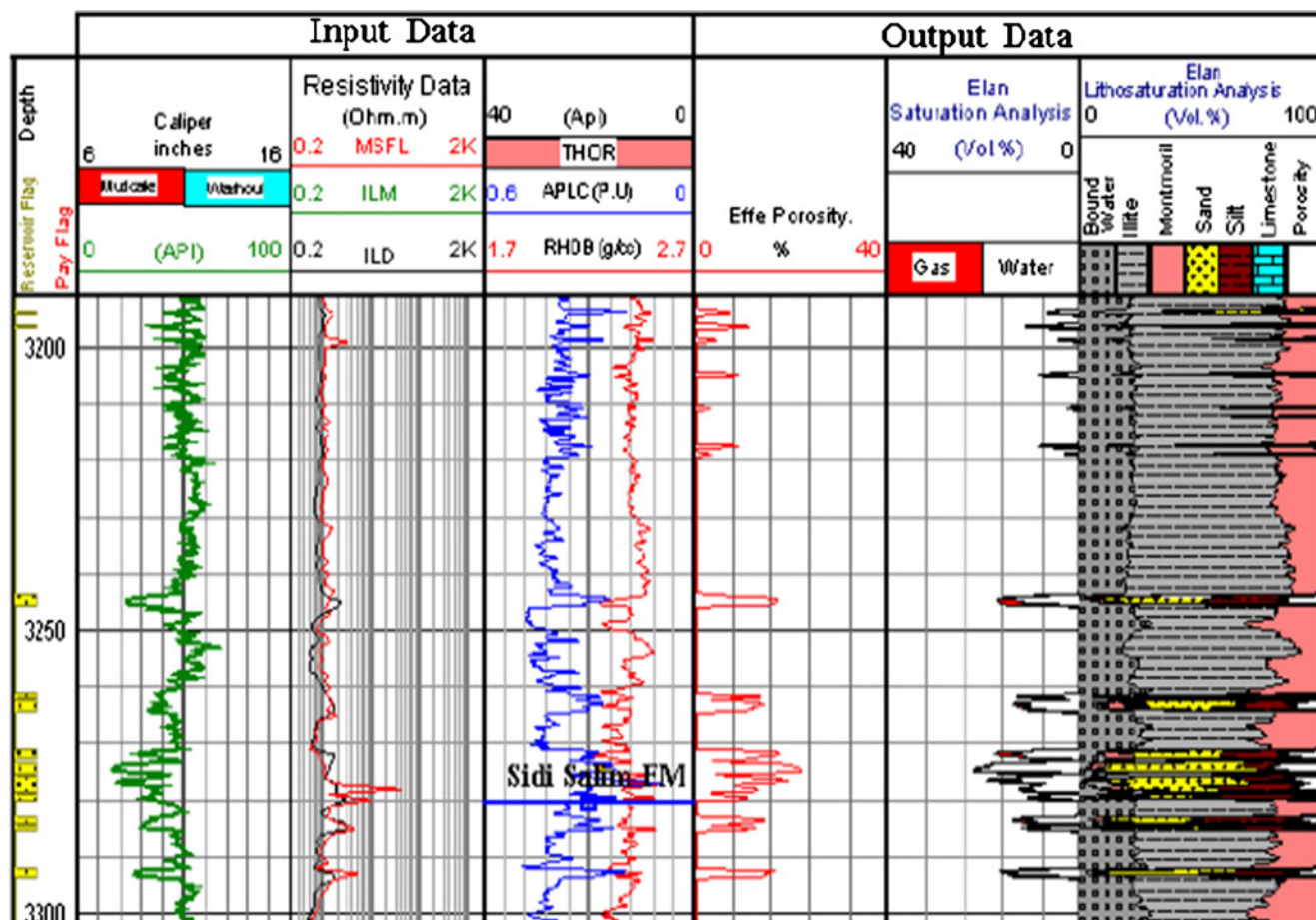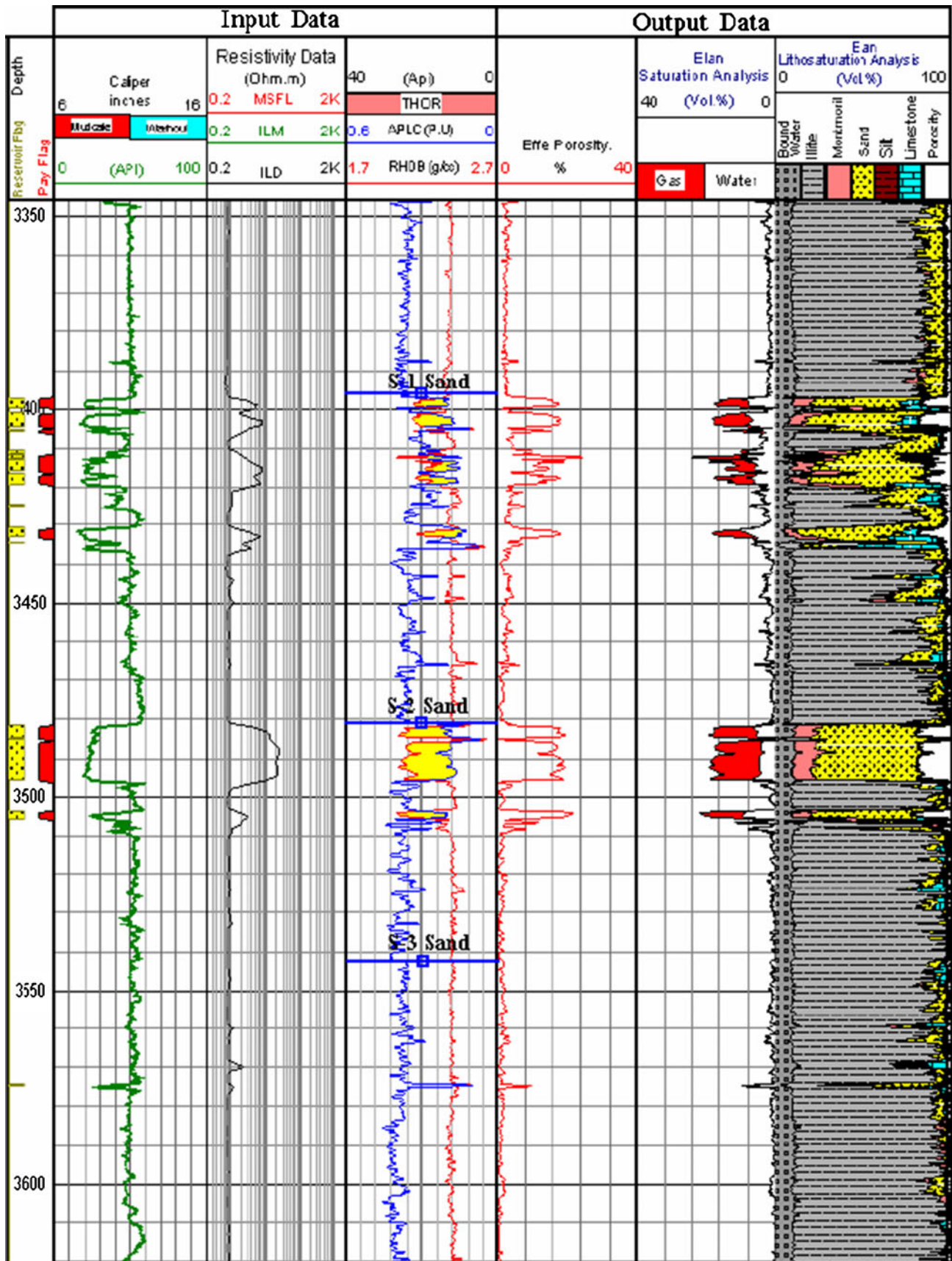

Fig. 8 Litho-saturation cross-plot of Wakar sandstone levels (S-3) of the PFM-2 well, Port Fouad Marine Field, Mediterranean Sea

◀ **Fig. 9** Litho-saturation cross-plot of Wakar sandstone levels (S-1, S-2, S-3) of the PFM SW-2 well, Port Fouad Marine Field, Mediterranean Sea

shale volume, porosity, and the water saturation, vary from well to well. We will discuss these percentages for some selected wells and present only three wells for abbreviation as follows:

The calculated shale volume of PFM-1 well (Fig. 6) for the "Level S-1" sand ranges from 32.6% to 100% with average 24.3%; the effective porosity ranges from 7.2% to 26.2% with average 18.4%; the water saturation ranges from 32.6% to 100% with average 69.9%, and the gas saturation ranges from 95% to 60%. The top of level S-1 interval is 3,011 m with a gross thickness of 17 m. No wire line data are available for levels S-2 and S-3.

The lithosaturation analysis of Wakar Formation in the PFM-2 well (Figs. 7 and 8) shows that the calculated shale volume for the "Level S-1" sand ranges from 22.8% to 38.4% with average 31.7%; the effective porosity ranges from 8% to 17% with average of 12.4%; the water saturation is 100%, and the gas

saturation is 0%. The top of level S-1 interval is 2,987.93 m with a gross thickness of 1.52 m. The levels S-1, 2, and 3 were water-bearing zones, so the well was plugged and abandoned.

The lithosaturation analysis of Wakar Formation in the PFM-3 well illustrates that this well penetrated two gas-bearing sand levels (S-1) and (S-2) and one water-bearing zone (S-3). The calculated shale volume for the "Level S-1" sand ranges from 2.2% to 38.55% with average 20.6%; the effective porosity ranges from 8.1% to 21% with average 14.36%, and the water saturation ranges from 30.7% to 100% with average 64.1%. The top level of S-1 interval is 3,048 m MD with a gross thickness of 9 m. The calculated shale volume for the "Level S-2" sand ranges from 1% to 33% with average 15.8%; the effective porosity ranges from 8.2% to 21.6% with average 15%; and the water saturation ranges from 41.8% to 100% with average 63%. The top of level S-2 interval is 3,104.2 m MD with a gross thickness of 1.83 m. The level S-3 was a water-bearing zone. The calculated shale volume ranges from 15.4% to 39.6% with average 21.14%; the effective porosity ranges from 9% to 12.4% with average 10.29%,
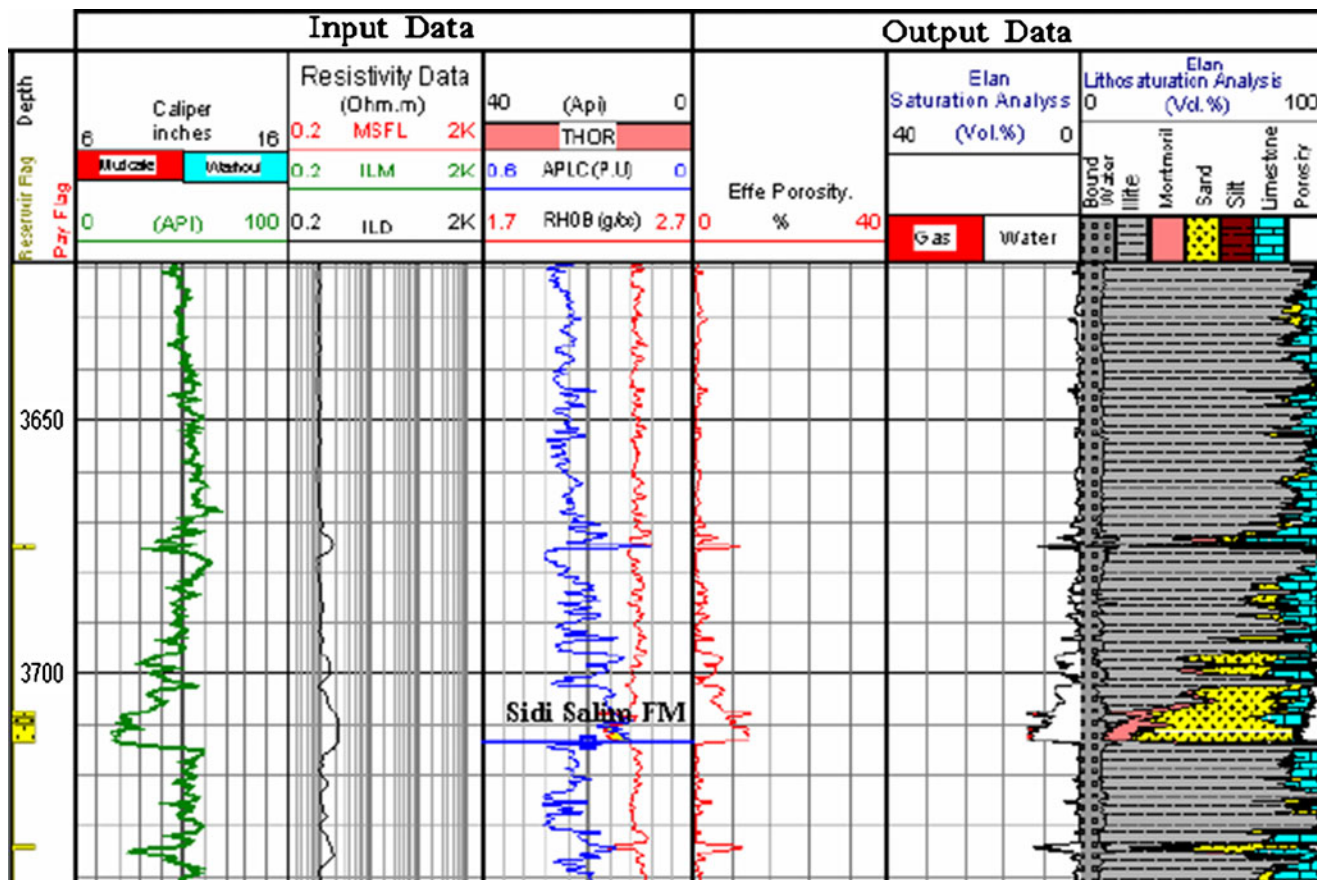

Fig. 10 Lithosaturation cross-plot of Wakar sandstone levels (S-3) of the PFM SW-2 well, Port Fouad Marine Field, Mediterranean Sea
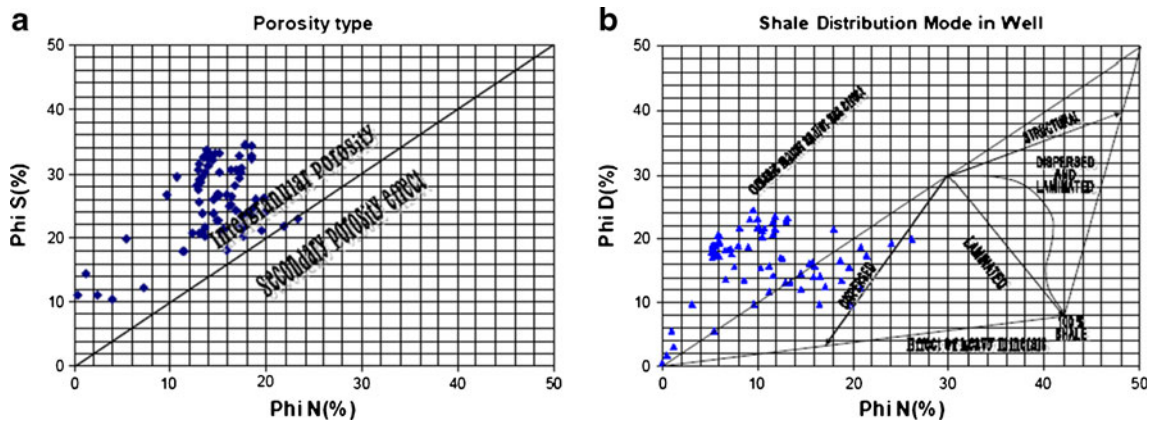
Fig. 11 DIA porosity cross-plots: neutron density/sonic (**a**) and neutron/density (**b**) cross-plots of the studied level S-1 of PFM-3

and the water saturation ranges from 92.4% to 100% with average 97%. The top of level S-3 interval is 3,141 m MD with a gross thickness of 0.46 m.

The lithosaturation analysis of Wakar Formation in the PFM-4 well indicates that this well penetrated two gas-bearing sand levels (S-0B) and (S-1). Two zones are water-bearing levels, (S-2) and (S-3). The calculated shale volume for the "Level S-0B" sand ranges from 9.5% to 39.4% with average 29.2%. The effective porosity ranges from 12% to 23.3% with average 19.4%; the water saturation ranges from 45.8% to 100% with average 66.6%. The top of level S-0B interval is 3,386 m MD with a gross thickness of 1.83 m. The calculated shale volume for the "Level S-1" sand ranges from 22.8% to 39.6% with average 32.2%. The effective porosity ranges from 8.5% to 20.7% with average 16.2%; the water saturation ranges from 58.1% to 100% with average 74.8%. The top of level S-1 interval is 3,477 m MD with a gross thickness of 2.29 m. The calculated shale volume for the "Level S-2" sand ranges from 22.4% to 37.7% with average 30.6%. The effective porosity ranges from 8.42% to 13.7% with average

11.1%; the water saturation ranges from 76.7% to 100% with average 95.15%. The top of level S-2 interval is 3,576 m MD with a gross thickness of 2.13 m. The calculated shale volume for the "Level S-3" sand ranges from 40% to 1% with average 23.7%. The effective porosity ranges from 7% to 19.6% with average 13.6%; the water saturation ranges from 75.7% to 100% with average 93.9%. The top of level S-3 interval is 3,634 m MD with a gross thickness of 17.7 m. The lithosaturation analysis of Wakar Formation in the PFM SW-2 well revealed that this well penetrated two gas-bearing sand levels (S-1) and (S-2), and one water-bearing level (S-2) as shown in Figs. 9 and 10. The calculated shale volume for the "Level S-1" sand ranges from 8.1% to 39.1% with average 21.7%. The effective porosity ranges from 7% to 24.5% with average 14.8%. The water saturation ranges from 38.7% to 100% with average 54.5%. The top of level S-1 interval is 3,397.1 m MD with a gross thickness 15.5 m.

The analytical formation evaluation of the different levels of these wells reveals lithological facies consists mainly of sandstone, shale, and siltstone. The DIA porosity sonic/ neutron density (S/ND) cross-plots (e.g., Fig. 11a) indicate
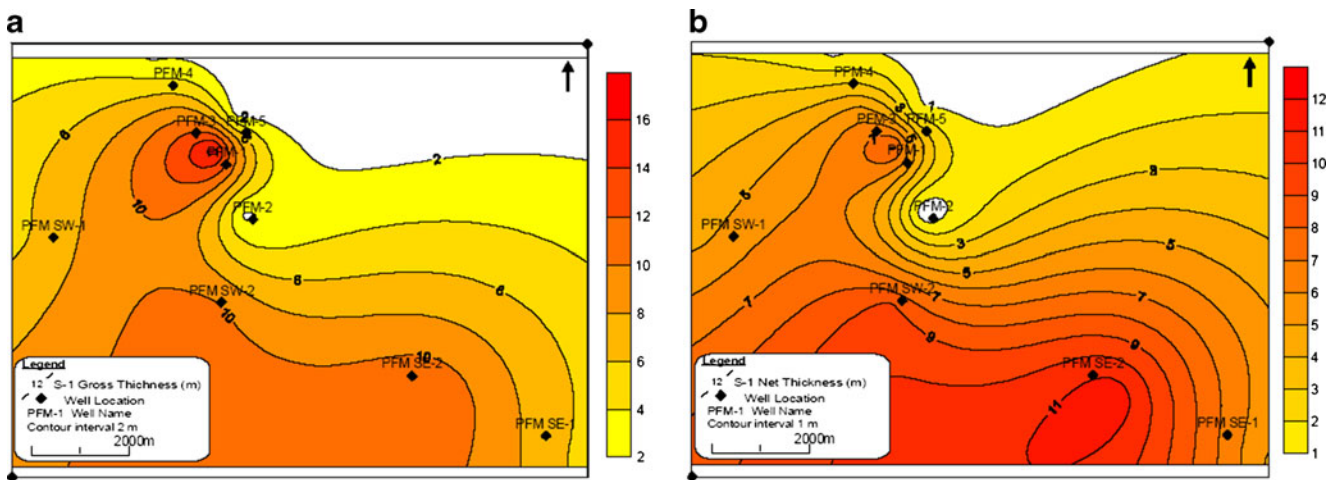

Fig. 12 Gross reservoir thickness (**a**) and net thickness (**b**) contour map for the S1 level of Wakar Formation
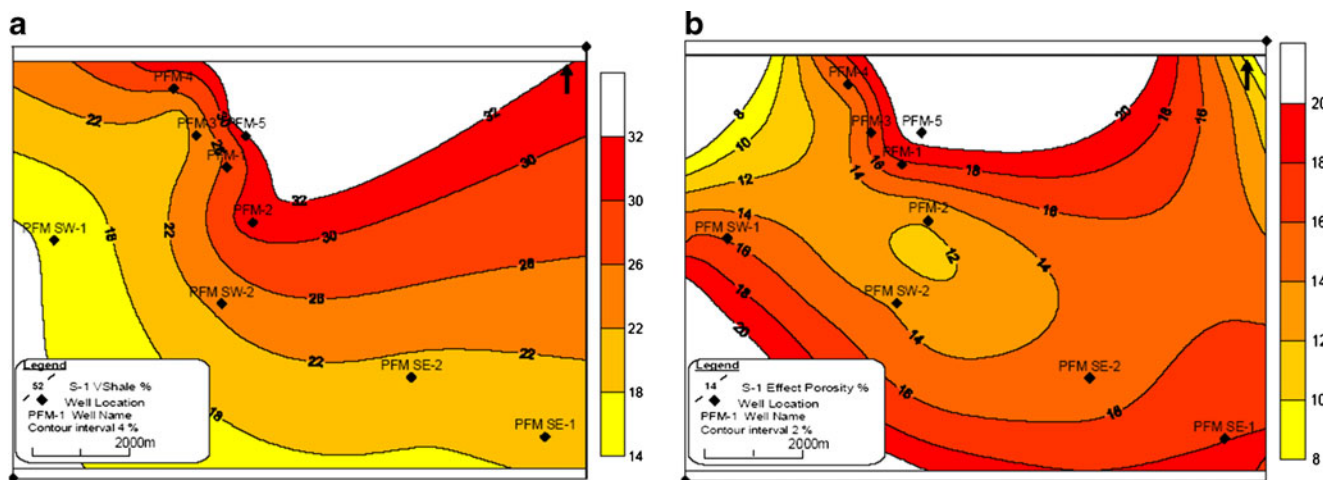
Fig. 13 Shale volume (a) and effective porosity (b) distribution map for the S1 reservoir of Wakar Formation

the dominance of the intergranular porosity. The DIA porosity N/D cross-plots (e.g., Fig. 11b) reveal that the intercalated shale is mainly of dispersed type and some laminated habitat. The laminated shale has less effect on the porosity compared with dispersed shale. The plotted zones outside the triangle in the upper left part are due to the gas effect.

The isoparametric maps of Wakar reservoir

The target potential reservoir in the Port Fouad Marine gas field is Wakar sand, which ranges from "Level S0" to "Level S3". The well-logging-deduced petrophysical parameters are represented by a number of isoparameteric maps showing the aerial distribution of the reservoir as well as the pay zone

characteristics of Wakar Formation. The main reservoir is "Level S1" which is productive in all wells except PFM-2 which drilled outside the sand channel of Level S1 sand, covering an area more than 25 km^2. The "Level S-2" shows pay characteristics only in four wells; three of them are in the south area, which are PFM SE-2, PFM SW-1, and PFM SW-2, and one in the north area, which is PFM-3. On the other hand, Level S-2 is not productive in the rest of the wells due to high water saturation and or high shale content. The "Level S-3" shows zero productivity in all wells due to high water saturation and low effective porosity except the PFM SE-1 well which shows small gas saturation with low effective porosity. The "Level S-0" shows a considerable productivity only in south east of the study area with high gas saturation and high effective porosity. Therefore, Level

Fig. 14 Clay mineral identification from natural gamma ray spectrometry log in Wakar sandstone of the PFM-3 well
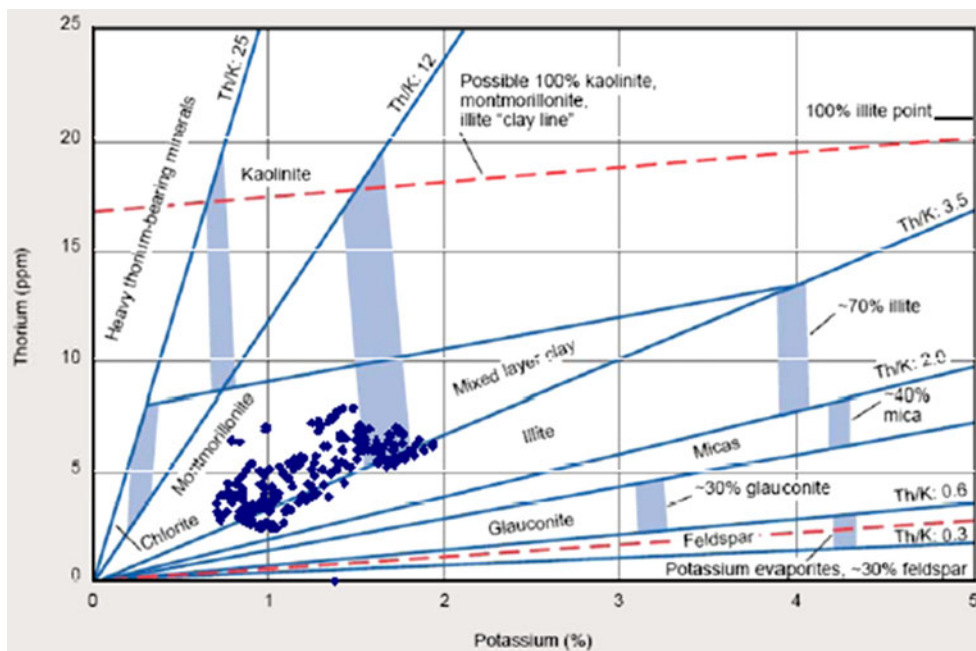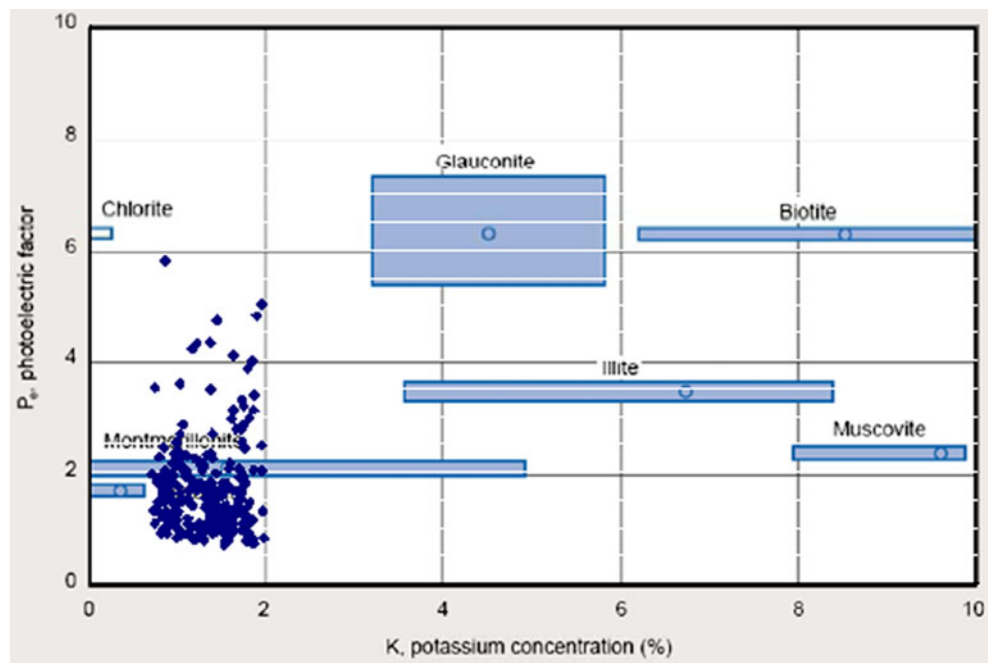
Fig. 15 Clay mineral identification using natural gamma ray spectrometry and litho-density measurements of Wakar sandstone of the PFM-3 well

S1 is evaluated, and the contour maps have been prepared as follows:

The gross reservoir thickness contour map of the "Level S1" sand (Fig. 12a) shows that the maximum recorded reservoir thickness is 17 m at the PFM-1 well, while it decreases gradually NE and east ward recording the minimum value of 1 m at the PFM-5 well. The net reservoir isopach map of the "Level S1" sand (Fig. 12b) shows a maximum recorded thickness of 11.8 m at the PFM SE-2 well, while it decreases gradually NE and east ward. The ratio of gross reservoir thickness to the net pay thickness of "Level S-1" ranges between 1 and 0. The maximum ratio is 1 recorded SE-ward at the PFM SE-2 well. The volume of shale contour map of the "Level S-1" (Fig. 13a) shows a regular pattern of distribution with a general increasing direction north and NE-wards of the area, recording a maximum value of 33.8% at the PFM-5 well and the minimum value of 13% at the PFM SW-1 well, SW-ward of the study area. The effective porosity contour map of the "Level S-1" (Fig. 13b) shows a regular pattern of distribution with a general increase towards the SE and SW of the area, recording a maximum value of 18.4% at the PFM-1 well. It is noticeable that high effective porosity in SE area corresponds to low value of shale. Natural gamma ray spectrometry log was used in the PFM-3 well to determine the type of clay minerals within the reservoir sand levels S1, S2, and S3 in the Wakar Formation; the clay mineral within the sand levels consists of Montmorillonite and illite (Figs. 14 and 15). This clay has considerable effect on the distribution of the reservoir effective porosity.
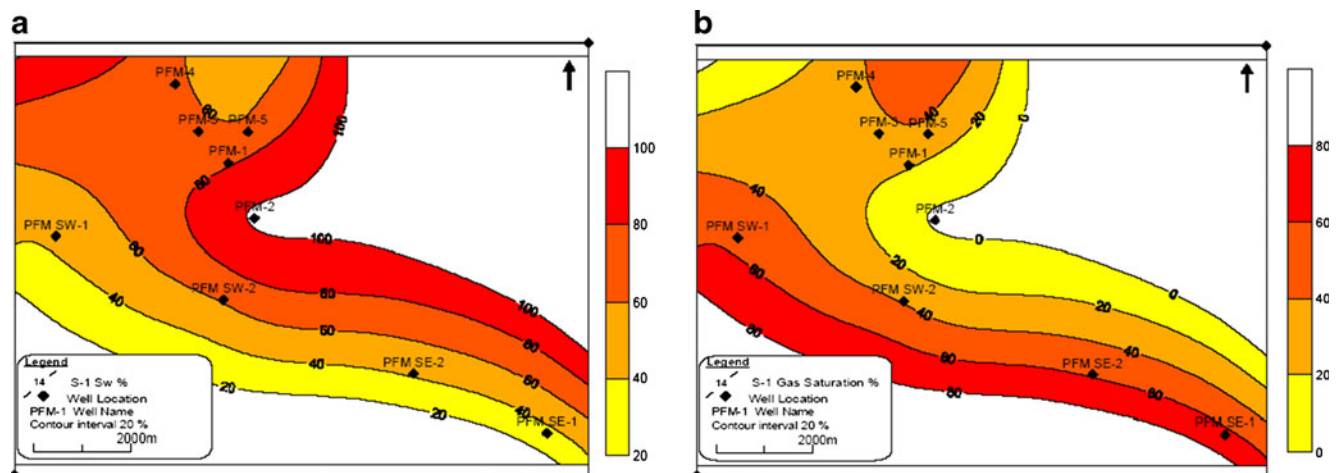

Fig. 16 Water (**a**) and gas (**b**) saturation contour maps for the S1 reservoir of Wakar Formation

The water saturation contour map of the "Level S-1" shows a considerable distribution pattern (Fig. 16) with a general increase NE- and NW-ward, recording a maximum value of 100% at the PFM-2 well. This value decreases gradually south eastward recording a minimum value of 32% at the PFM SE-2 well. On the other hand, gas saturation distribution map of the "Level S-1" sand (Fig. 16b) shows considerable values increasing towards SE and SW recording a maximum value of 68% at the PFM SE-2 well and a minimum value of 0% at the PFM-2 well that was drilled outside the sand channel.

Summary and conclusion

The well-logging-deduced petrophysical parameters, resulting from application of the ELAN Plus software, in addition to its corrected input data, are represented zonewise in vertical cross-plots for each well. In the mean time, the spatial distribution of the weighted petrophysical parameters is also represented by a number of isoparametric maps. These maps illustrate the reservoir characterizations (net pay thickness, net gross thickness, volume of shale, effective porosity, and water and hydrocarbon saturation). The lithosaturation analysis of the studied wells indicates that Wakar Formation is mainly gas with some water-bearing sand levels. The petrophysical characteristics of sand levels vary along the different zones for each well. On the other hand, the analytical formation evaluation of the different levels of these wells reveals lithological facies consisting mainly of sandstone, shale, and siltstone. The DIA porosity neutron/density (N/D) cross-plots indicated that most of the intercalated shale is mainly of dispersed type and some of laminated habitat, which usually has less effect on the effective porosity compared with dispersed shale. The DIA porosity S/ND cross-plots reveal the dominance of the intergranular porosity. The response of natural gamma ray spectrometry log in the PFM-3 well indicates that the clay minerals consist of Montmorillonite and illite within the reservoir sand levels of Wakar Formation. The well-logging-deduced petrophysical parameters are represented by a number of isoparameteric maps. These maps indicate that the main reservoir is level S1 which is productive in all wells except PFM-2, drilled outside the sand channel. The volume of shale and effective porosity maps indicate that there is strong relation between them especially in the south east of the study area, where the low V_{shale} corresponds to high effective porosity in the same area. This indicates that shale is almost of dispersed type.

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