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Integration between well logging and seismic reflection techniques for structural analysis and reservoir characterizations, Abu El Gharadig basin, Egypt

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KEYWORDS
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Well logging;
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Abstract Abu El Gharadig basin is located in the northern part of the Western Desert, Egypt. Geophysical investigation in the form of thirty (3D) seismic lines and well logging data of five wells have been analyzed in the oil field BED-1 that is located in the northwestern part of Abu El Gharadig basin in the Western Desert of Egypt. The reflection sections have been used to shed more light on the tectonic setting of Late Jurassic–Early Cretaceous rocks. While the well logging data have been analyzed for delineating the petrophysical characteristics of the two main reservoirs, Bahariya and Kharita Formations. The constructed subsurface geologic cross sections, seismic sections, and the isochronous reflection maps indicate that the area is structurally controlled by tectonic trends affecting the current shape of Abu El Gharadig basin. Different types of faults are well represented in the area, particularly normal one. The analysis of the average and interval velocities versus depth has shown their effect by facies changes and/or fluid content. On the other hand, the derived petrophysical parameters of Bahariya and Kharita Formations vary from well to another and they have been affected by the gas effect and/or the presence of organic matter, complex lithology, clay content of dispersed habitat, and the pore volume.

1. Introduction

The northern sector of the Western Desert, Egypt, is an attractive and promising basin from viewpoint of hydrocarbon exploration and is structurally one of the highly complex areas in the Western Desert. Its importance is related to the active depositional history, which resulted in the development of several depositional basins: Matruh, Shushan, Alam El-Bueib,

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Natrun, Siwa, Abu El Gharadig and Gindi basins (Fig. 1a). The present study is concentrated on Abu El Gharadig basin because it is considered one of the most important basins that developed during the late Cretaceous-Tertiary. Many studies have been carried out in that basin (e.g. Nessim et al., 1992; Bayoumi and Lotfy, 1989; Nabawy and ElHariri, 2008, and Rizk et al., 2013). It is located 128 km south of the Mediterranean coast and about 260 km west of Cairo (Fig. 1b). It is an east–west oriented intracratonic graben of 300 km long and 60 km wide. Abu EL Gharadig basin is controlled by a NE-SW oriented, nearly symmetrical, doubly plunging anticline that is about 17 km long and 5 km wide. This basin shares the same deformation history with other Syrian Arc folds in northern Egypt (Moustafa, 2008). There are three main types

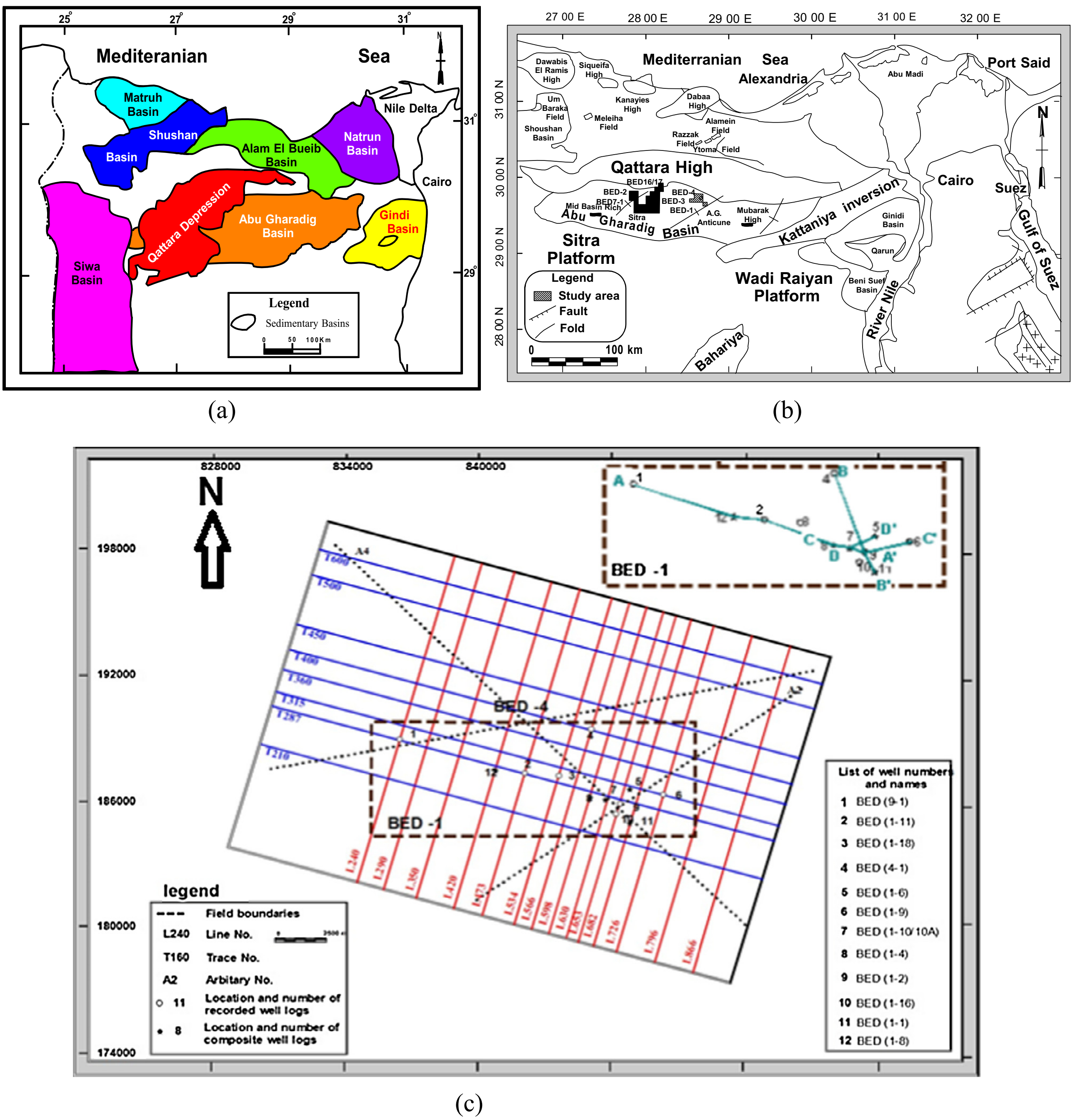

Figure 1 (a) Location map showing the distribution of the sedimentary basins in Western Desert (EGPC, 1992). (b) Map showing the study area within Abu EL Gharadig Basin (Helba and Bakry, 1996). (c) Base map showing the distribution of the seismic lines and wells used in BED-1 area. Inset shows the distribution of the four cross section profiles.

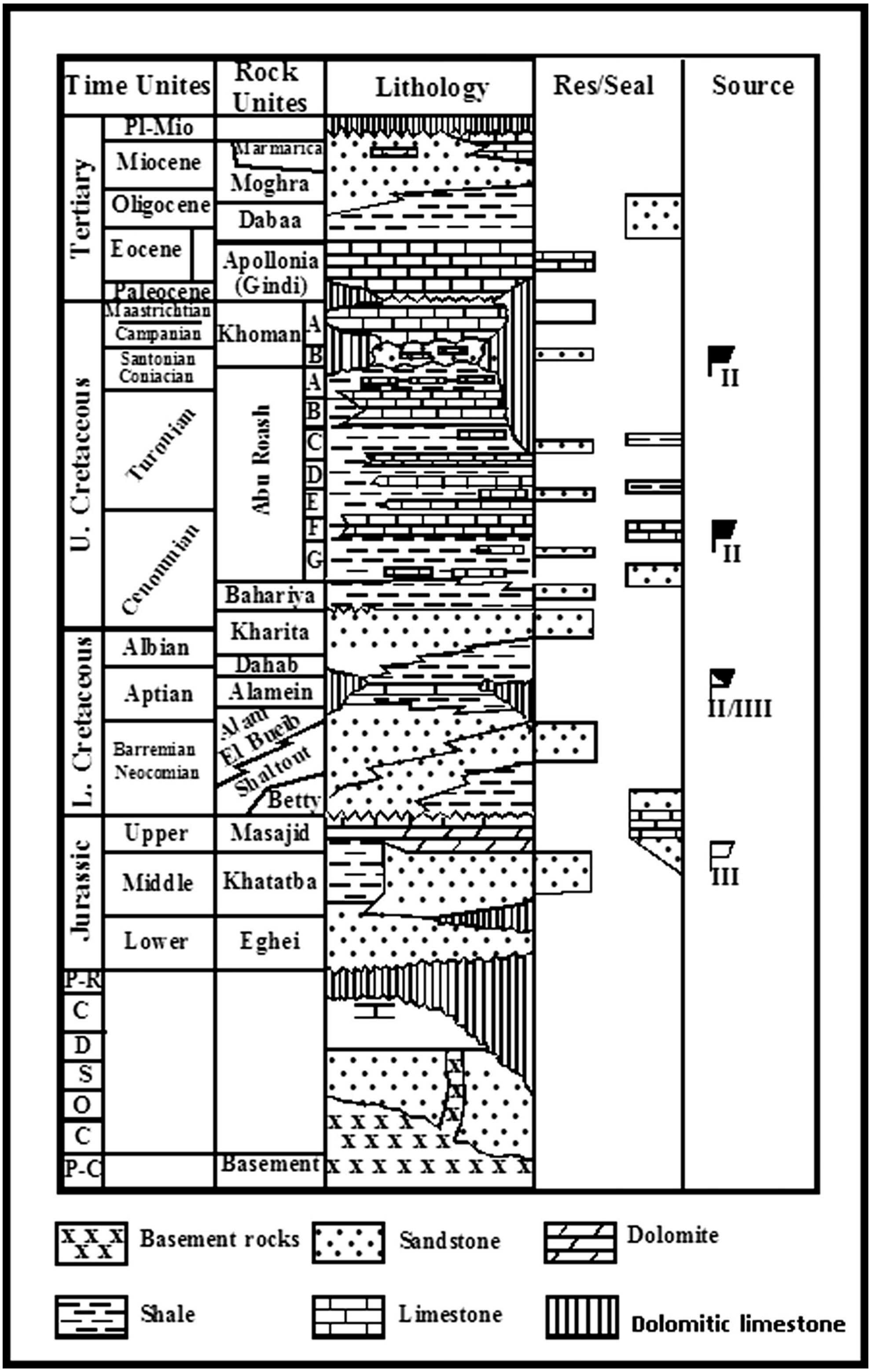

Figure 2 Regional lithostratigraphic section of the study area (after Bayoumi, 1996).

of faults that dissect Abu Gharadig basin; hinge-transverse, hinge-oblique, and hinge-parallel (Moustafa, 2013). This research focuses on BED-1 and BED-4 oil fields (Fig. 1c) which are located in the western part of Abu El Gharadig basin between Lat. 29°42′ and 30°00′ north and Long. 28°26′ and 28°34′ east. The objective of this study was to shed more light on the subsurface structural setting in this area and to evaluate the petrophysical characterization of Bahariya and Kharita Formations. The seismic data are based on the following materials: 3-D seismic reflection sections (14 lines and 8

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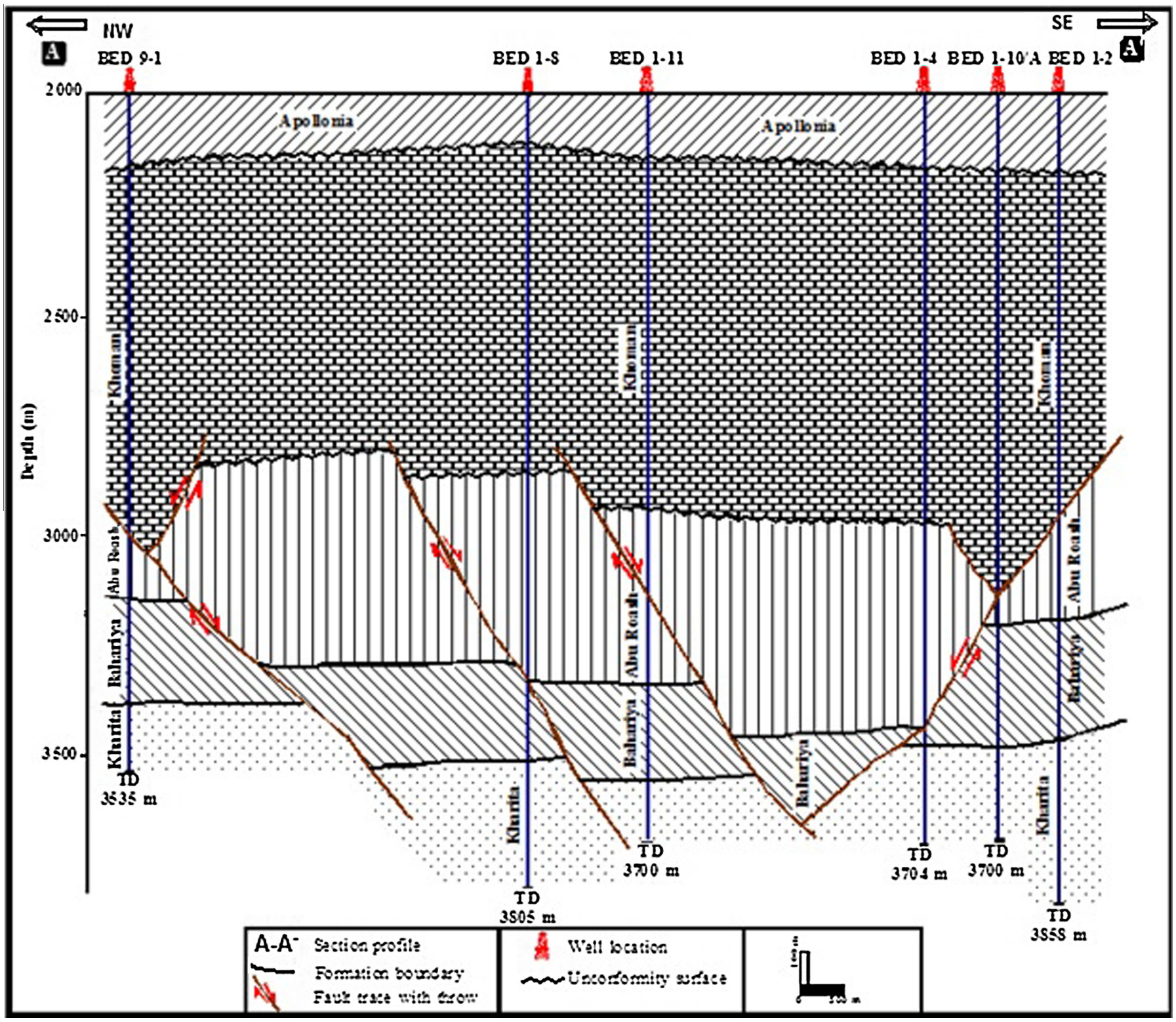


Figure 3 Geologic cross section along profile A-A.

traces and 3 Arbitraries) and a base map of the study area (Fig. 1c). Check shots for wells BED: 9-1, 1-11 and 4-2 are available. On the other hand, various well logging records of 5 wells are used in this study; they are resistivity, sonic, neutron, density, spontaneous potential, caliper, and gamma ray log. These data are for wells BED: 9-1, 1-11, 1-9, 4-1, and 1-16 (Fig. 1c). This is in addition to the presence of a lithologic sequence of some other wells.

2. Geologic setting

The lithostratigraphic column of Abu El Gharadig basin includes six broad cycles commonly separated by unconformities, and these cycles are the following: (1) the Jurassic from the Eghei group at the base to the Masajid Formation at the top; (2) the lower part of the Lower Cretaceous with the Betty Formation at the base to the Alamein Formation at the top; (3) the upper part of the Lower Cretaceous to the Coniacian with the Kharita member at the base to the Abu Roash Formation at the top; (4) the Santonian through Maastrichtian Khoman Formation; (5) the Paleocene through middle Eocene Apollonia Formation; and (6) the Upper Eocene through Miocene which includes the Dabaa Formation at the base and Moghra Formation at the top. Fig. 2 illustrates the general lithostratigraphic column of Abu El Gharadig basin. The sedimentary basins in the north Western Desert occupy two provinces separated by the Ras Qattara-north Sinai uplift. The northern province includes some basins such as Shushan and Matruh basins whereas the southern one includes mainly the Abu Gharadig basin. There are two main tectonic forces affecting the oil and gas production from lower to upper Cretaceous reservoirs: (1) a sinistral shear which resulted in a regional NW tectonics, affected both provinces in Jurassic-Early Cretaceous times, and (2) a dextral shear which resulted in a regional ENE tectonics, affected the southern province (Meshref, 1996). The Abu Gharadig province contains a number of major graben or half-graben structures (Wood, 1984).

Subsurface geological cross sections have been constructed along four profiles (Fig. 1c) based on the available subsurface data gathered from the deep wells in the study area. Two cross sections are selected for illustration trending NW-SE and W-E (Figs. 3 and 4). These cross sections show normal faults that

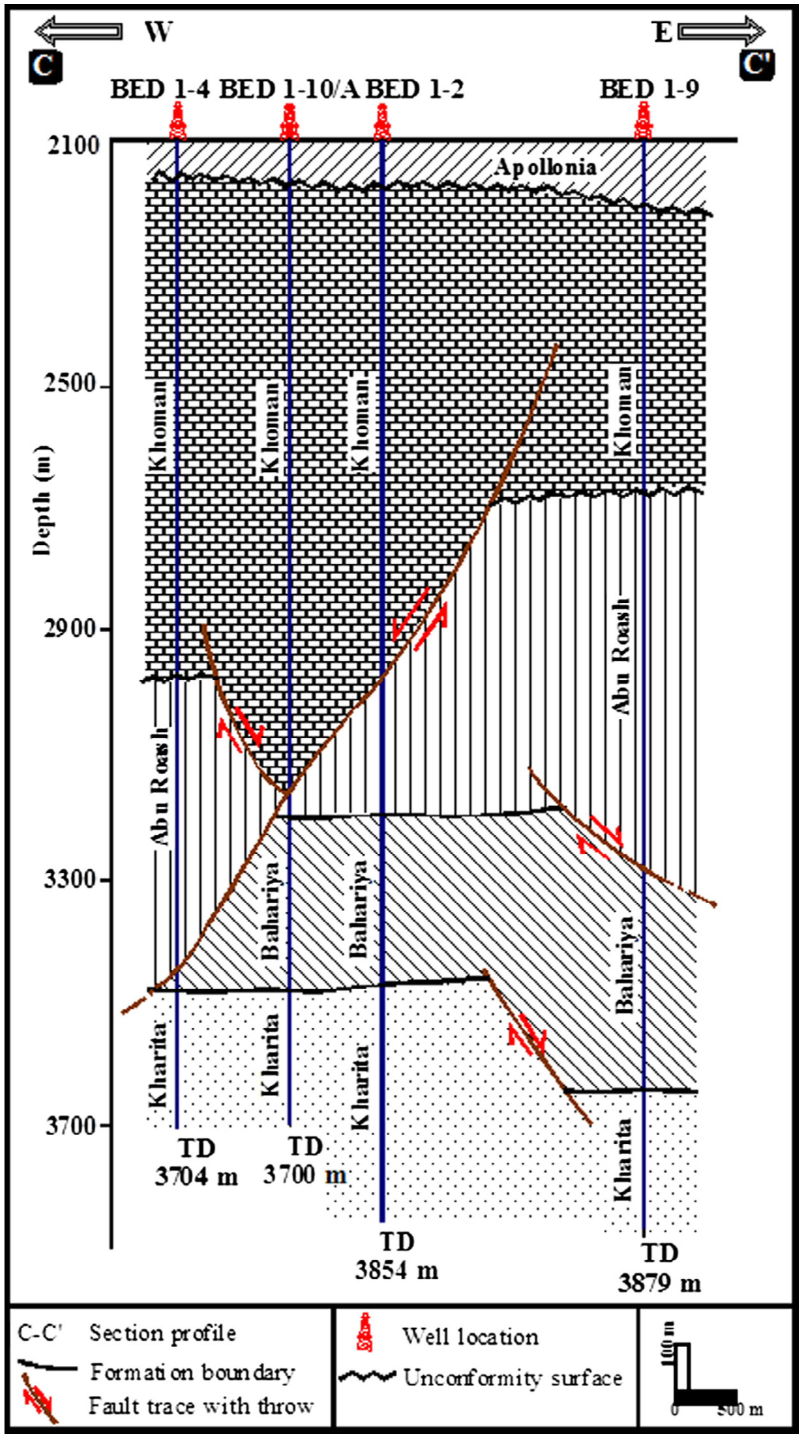
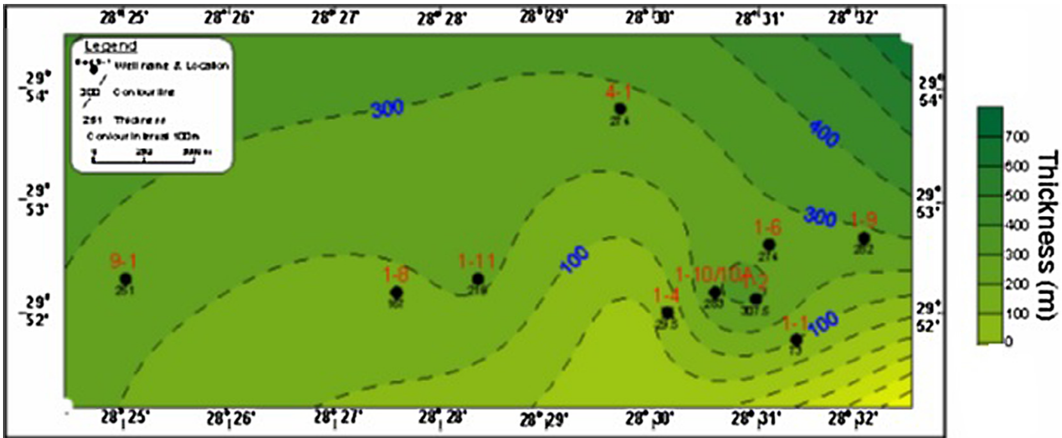
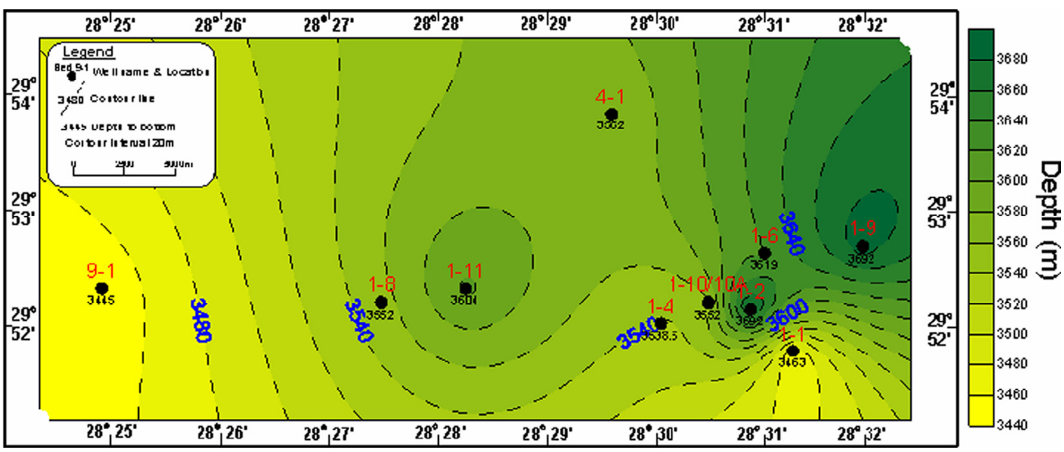


Figure 4 Geologic cross section along profile C-C′.

affected the study area. Most of these faults die out in the Khoman Formation. This indicates that the major tectonic movements have been taken place at the end of the late Cretaceous. These sections elucidate the general structural pattern of the Abu El Gharadig basin which is affected by the structural setting of horst and graben faults and also reverse faults in the form of a positive flower structure to give structural highs and low areas (Harding, 1985). Isopach and depth contour maps are constructed for Bahariya and Kharita Formations since they are petrophysically the main concern in this research. The isopach and structure contour maps established for the Bahariya Formation (Fig. 5a and b) show variable values. This is attributed to the effect of the some faults passing through wells. It also increases in the west of the study area at BED 9-1. The isopach and depth contour maps of Kharita Formation also show variable values of the thickness (Fig. 6a and b)



(a)



(b)

Figure 5 (a) Isopach contour map for Bahariya Formation. (b) Depth contour map for Bahariya Formation.

representing a maximum thickness (536 m) at BED 1-1. This large thickness is strongly affected by the fault which passes between wells BED 1-1 and BED 1-2.

3. Methods and techniques

Approaches have been conducted for a joint combination between well logging data and seismic reflection for studying reservoirs petrophysical characteristics and subsurface structural settings in the area of study. The rationale for this study comes from the great importance of one of the most hydrocarbon potential basins of the Western Desert, Abu El Gharadig basin. It has huge subsurface sedimentary sequences and consequently includes considerable reservoir and source rocks. This basin is primarily extensional in nature and is affected mainly by faulting while folding is relatively subordinate and is often related to the movement of nearby faults.

Seismic data have been processed by Badr Eldin Company. The velocity analysis has been carried out depending on the available check shot data with sonic logs for identifying lithology, nature of sediments and to convert seismic time to depth. The reflection one-way time, average velocity and interval velocity have been constructed versus depth for the studied Formations (Apollonia, Khoman, Abu Roash, Bahariya, and Kharita). Tracing the seismic reflectors has been delineated to establish the stratigraphic sequence and boundaries utilizing the well data, which allow the calibration of seismic times to a common datum.

On the other hand, five wells are petrophysically analyzed in order to evaluate the hydrocarbon potentiality in the area of study. The data set has been digitized in the form of zonation for the two Formations: Bahariya and Kharita. The data were corrected first for different environmental factors and then processed by calculating first the volume of shale from gamma ray and differentiating the zones into clean, shaly and shale depending on the cutoff characteristics. Then, the different petrophysical parameters are calculated such different porosities and saturations. All these parameters are represented in the vertical and lateral distribution form.

4. Velocity analysis

Velocity is a parameter that plays a very important role in the seismic method since it can be used for lithological identifica-

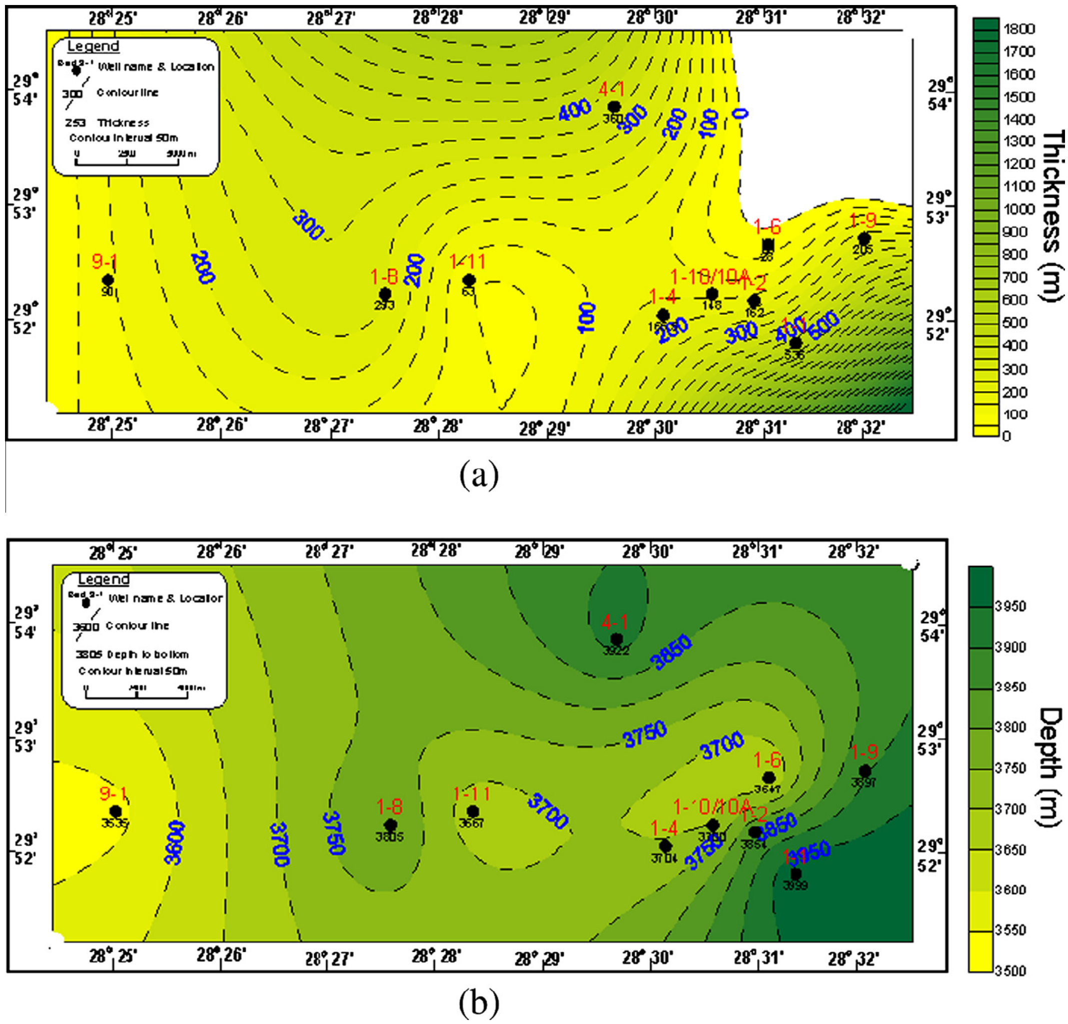


Figure 6 (a) Isopach contour map for Kharita Formation. (b) Depth contour map for Kharita Formation.

tion and converting recorded seismic time to depth. Various factors affect the velocity value such as porosity, density, pressure, temperature, hydrocarbon saturation and lithology variation. The obtained check shot data in addition to sonic logs for six wells are used for applying velocity analysis in the area of study. These wells are BED 4-1, BED 1-2, BED 1-11, BED 1-10/10A, BED 1-1 and BED 1-4. The reflection one-way time, average velocity and interval velocity are plotted versus depth for the Formations (Apollonia, Khoman, Abu Roash, Bahariya, and Kharita). The velocity curves show similarities of results but with few remarkable differences which could be related to the effect of facies changes and/or fluid content (water and hydrocarbons), and this is in addition to the effect of overburden pressure. Fig. 7 is a selective example of these plots of well BED 4-1. The reflection one time-depth curve (T-D curve) shows an increase of time with depth along the entire section. The noticeable increase in time of Abu Roash and Bahariya Formations might be attributed to the effect of shale content of these Formations (Halisch et al., 2009). In contrast, the travel time decreases in Apollonia and Khoman Formations. This is due to the dominance of limestone and chalky limestone facies. Similar to the T-D cross plots, the average velocity tends to increase gradually with depth but with minor decrease for Abu Roash and Bahariya Formations and sharp increase for Khoman and Abu Roash in all wells.

5. Seismic interpretation

The seismic data have been processed by Badr Eldin Company. The success of conducting a seismic interpretation depends, largely, on the inter-relationship between the subsurface geological conditions and the acquisition and processing parameters, as well as any peculiar geo-seismic conditions prevailing in the area. The most important of these geo-seismic conditions in the study area is the rapid change of seismic velocity of one or more of the studied Formations. Other conditions are the thickening and facies changes in the studied Formations such as Abu Roash and Bahariya Formations. Based on the seismic lines given, the study area can be differentiated into two main groups: lines that run in S-N lines and traces that run in W-E. They form a closed grid. The first group comprises 13 seismic lines, which cover BED-1 and BED-4. The second group contains 8 traces. A brief interpretation of two selected seismic sections is described. Seismic line

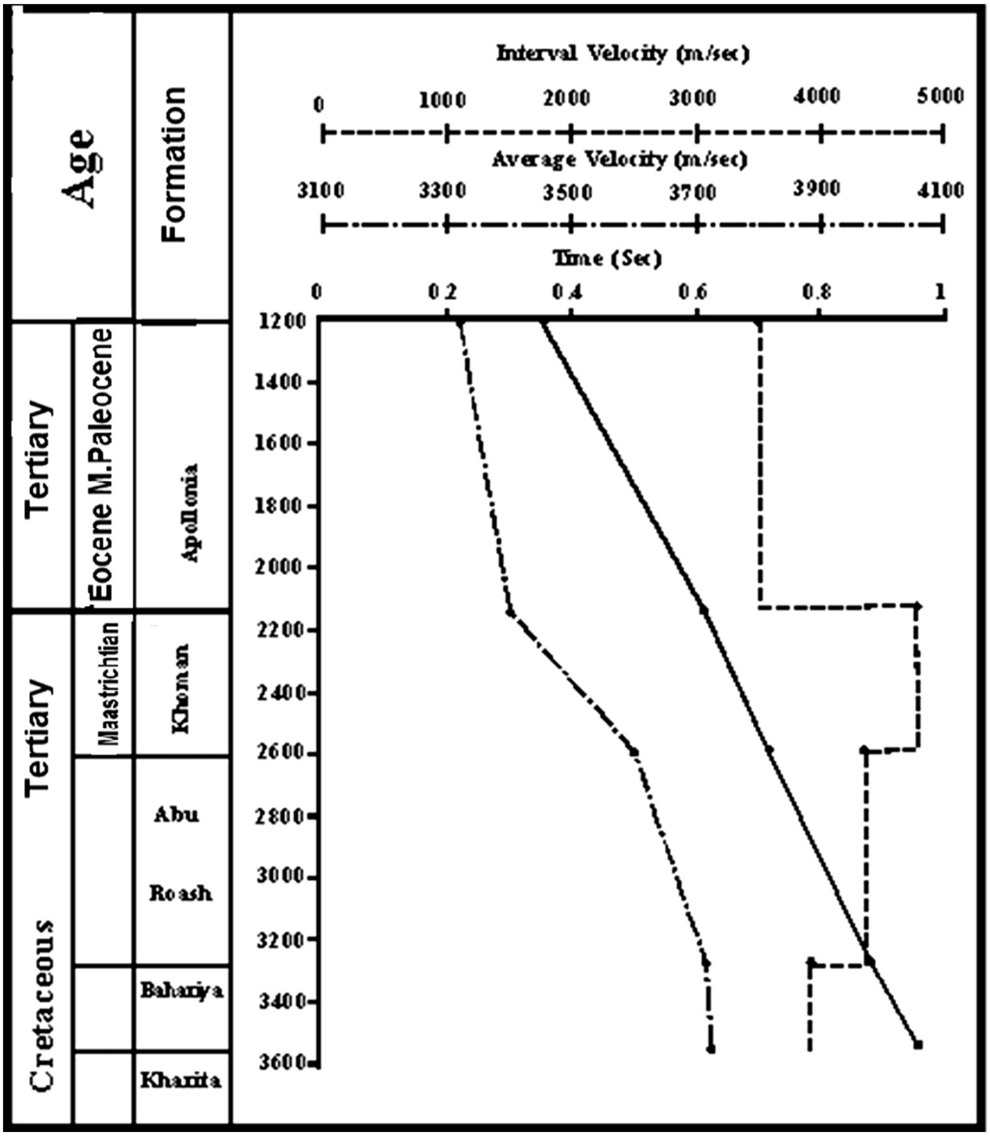


Figure 7 Time and velocities analysis of the studied subsurface lithostratigraphic units in BED 1-2.

L 473 is carried out in S-N direction (Fig. 8). This line passes through BED 1-11 well which is located at the S.P.300. The main normal faults and the structural closures of the Cretaceous reflectors are observed. Apollonia and Khoman reflectors are controlled by some small faults. There are two sets of faults that affect the Cretaceous sequences: one has north west-south east direction and the other has north east-south west direction. The seismic line T 287 runs in W-E direction (Fig. 9). This line shows the main faults which affect the Cretaceous sequences. There are four wells passing along this line: BED 9-1, BED 1-11, BED 1-17 and BED 1-2 wells which are located at the S.P. 250, 480, 550 and 600 respectively. Apollonia and Khoman reflectors appear as strong and continuous reflectors, dissected with a number of the normal faults forming small grabens. On the other hand, parallel faults in the form of step faults are present in the Cretaceous sequences. The lower reflectors of this line are weak and gradually dipping toward the east direction. There are two sets of faults that affect the Cretaceous sequences: one has a trend NW-SE direction and the other has NE-SW direction. These faults have been confirmed using potential field methods (Elkhodary and Youssef, 2013).

6. The litho-saturation cross-plots

BED 9-1 well has been selected as one of the five wells to display the vertical distribution or what is called litho-saturation cross-plot of the well logging analysis. The studied interval of Bahariya and Kharita Formations extends between depths 3194 m and 3535 m below the mean sea level. The corrected data of this well are represented in Fig. 10. The quick look interpretation of the well logging response shows relatively high values of gamma ray, caliper, sonic, and neutron log readings accompanied with relatively low density and resistivity readings to indicate the intercalation of clayey lithological nature within the sand interval that prevails nearly the entire section of Bahariya Formation. Moreover, the hydrocarbon bearing zone of Bahariya Formation is clearly seen at depths

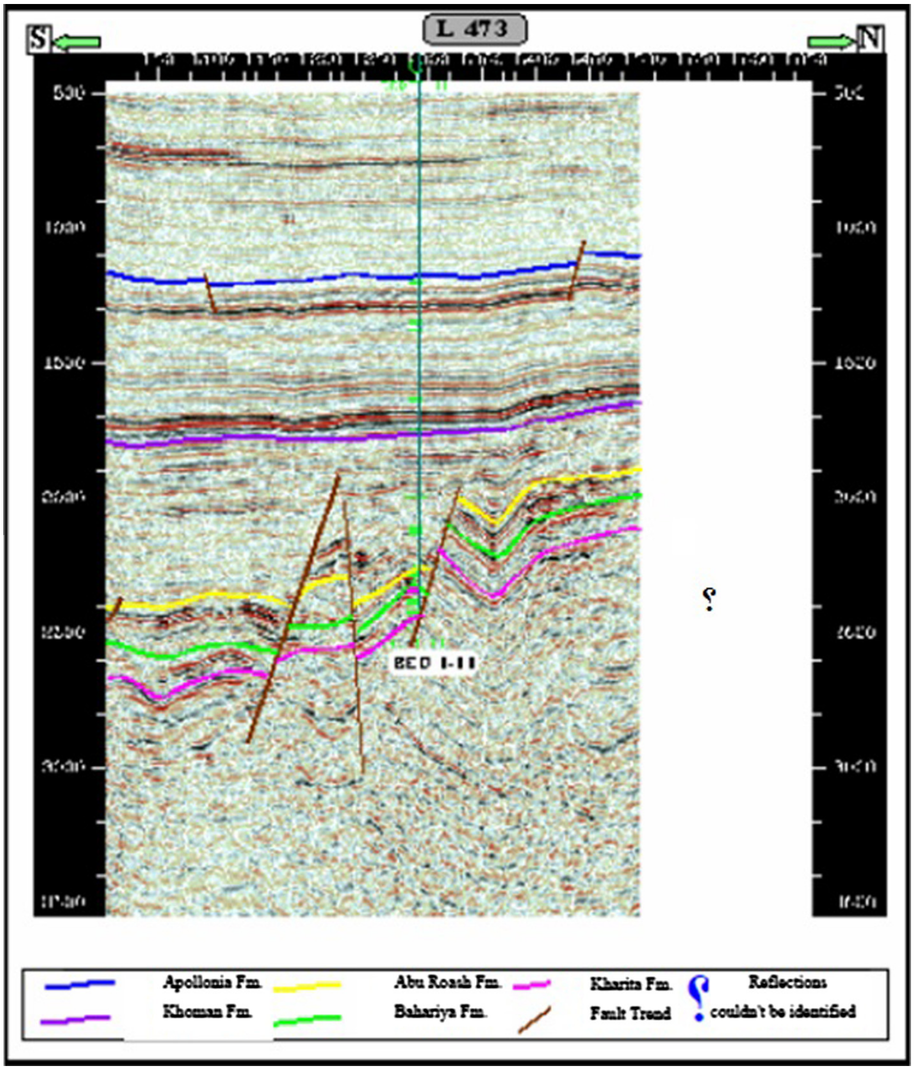


Figure 8 N-S seismic line (L473) passing through BED 1-11 located at the S.P.300, showing the distribution of the different seismic reflectors with different colors and the faults cutting through them.

between 3200 and 3325 m since there is a positive separation between Rxo and Rt values. Kharita Formation shows also a positive separation between the shallow and deep resistivities. In the same time, the phenomenon of crossover between ρb and ΦN appears at depths between 3475 and 3485 m (Fig. 10). The volume of shale, determined from gamma ray log, ranges from 20% to 50% (Fig. 11). The mineral composition of Bahariya sandstone is very complex due to the presence of heavy minerals and the presence of siderite, hematite, and pyrite (Ibrahim and Aly, 1994) that might be the main reason of low resistivity readings. Glauconite is also found in this Formation (Halisch et al., 2009) and gives high gamma ray readings. There is an abnormal zone lies within Kharita Formation represented by relatively distinct low values of gamma ray, neutron, and sonic log readings with high resistivity readings to suggest a minimum level of clay content in that horizon (sandstone zone). The clay content of this interval might be of dispersed habitat as shown in the dia-porosity cross plot ΦN – ΦD (Fig. 12a). This figure also indicates the effect of gas saturations and/or organic matter. The cross plot of ΦS – ΦND elucidates the presence of secondary porosity in the clastic reservoir deposits of the of Bahariya Formation (Fig. 12b) to be formed through de-carbonization and framework grain dissolution; carbonate cement plays an important role in the diagenesis of upper Bahariya sandstone and the dissolution of glauconite is an essential factor of enhancing secondary porosity in the studied sandstone (Metwalli et al., 1999). Therefore, the calculated petrophysical analysis illustrates increase in the effective-porosity value, calculated from density and neutron logs, to reach 27% in Bahariya sandstone (Fig. 11). The water saturation (Sw), inferred from Archie equation, ranges from 13% to 87% while movable hydrocarbon saturation (Shm) ranges between 5% and 53% for Bahariya and Kharita Formation. Therefore and based on the lithological, petrophysical and fluid analysis, the studied intervals have been differentiated into zones of reservoir characteristics only (Kh-B1), zones of non-reservoirs or pay characteristics (Bh-C1 & Bh-C2 & Kh-C3) and zones of the reservoir and pay characteristics (Bh-A2 & Kh-A1). The later zones are producing in the investigated intervals.

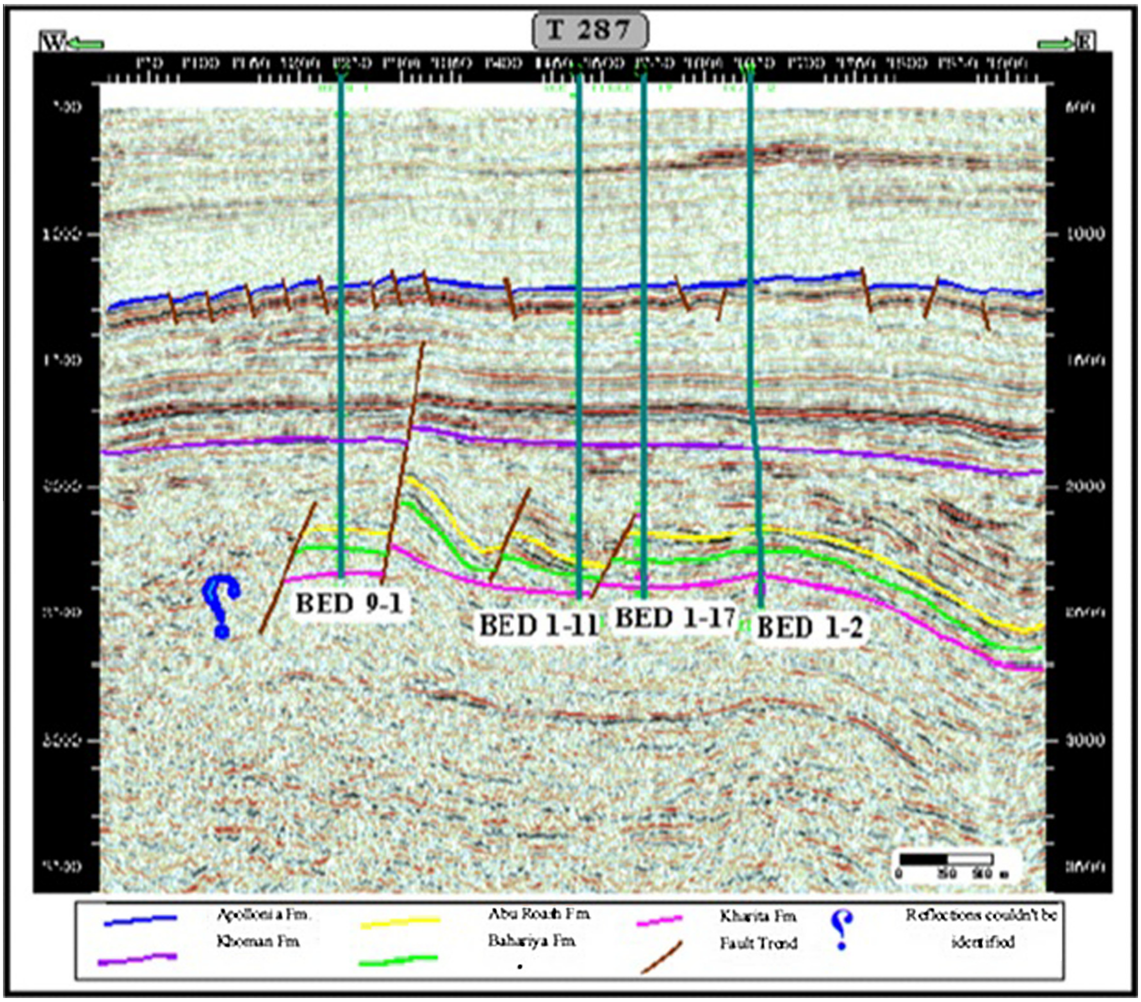


Figure 9 E-W seismic line (T287) passing through BED 9-1, 1-11, 1-17 and 1-2 located at the S.P. 250, 480, 550 and 600 respectively, showing the distribution of the different seismic reflectors with different colors and the faults cutting through them. The unclear reflectors are marked by the red question mark.

7. Iso-parameter distribution maps

The well logging-derived petrophysical parameters are represented in a number of contour maps for the Bahariya and Kharita Formations. Some of these parameters are represented here. Starting with the Bahariya Formation, the volume of shale contour map (Fig. 13a) shows an increase in the northwest direction of the study area, recording a maximum value of 25% at BED 4-1 and a minimum value of 16% at BED 1-11. The effective porosity values (Fig. 13b) increase east and South east directions, recording a maximum value of 18% at BED 1-9, while it decreases generally north and westwards, recording a minimum value of 3% at the BED 4-1. Inspection of both shale and effective porosity maps of this Formation reveals the effect of shale volume minimizing the effective porosity values particularly at the western and northern parts of the area while it plays a minor role at the eastern parts. This indicates the presence of different shale habits from dispersed to structural and/or laminated nature. Regarding the lithology represented in Fig. 14, the sand percentage values of the Bahariya Formation show a maximum thickness of 69% at BED 4-1 and BED 1-11 at the central part while it decreases gradually east and westward, recording a minimum value of 58% at BED 1-9 well. These values indicate the dominance of sand facies within the Bahariya Formation. On the other hand, the carbonate percentage contour map reveals a distribution pattern with low value recording a maximum carbonate value of 6% at BED 1-11 well, while decreases rapidly to 3% northward at BED 4-1 well. The water saturation contour map of Bahariya Formation shows an increasing toward the east and north directions from 57% at BED 1-9 to 63% at BED 4-1 (Fig. 15a). While, the hydrocarbon saturation map illustrates nearly the same distribution pattern but with opposite trends to that of the water saturation (Fig. 15b) displaying maximum recorded value of 48% at BED 9-1, while the minimum value is 23% at BED 4-1. The net reservoir thickness contour map shows a considerable reservoir thickness recording a maximum thickness of 89.04 m at BED 1-16 and a minimum value of 13.13 m at BED 4-1 (Fig. 15c). On the other hand, the volume of shale of the Kharita Formation (Fig. 16a) decreases westward, recording the minimum value of 8% at

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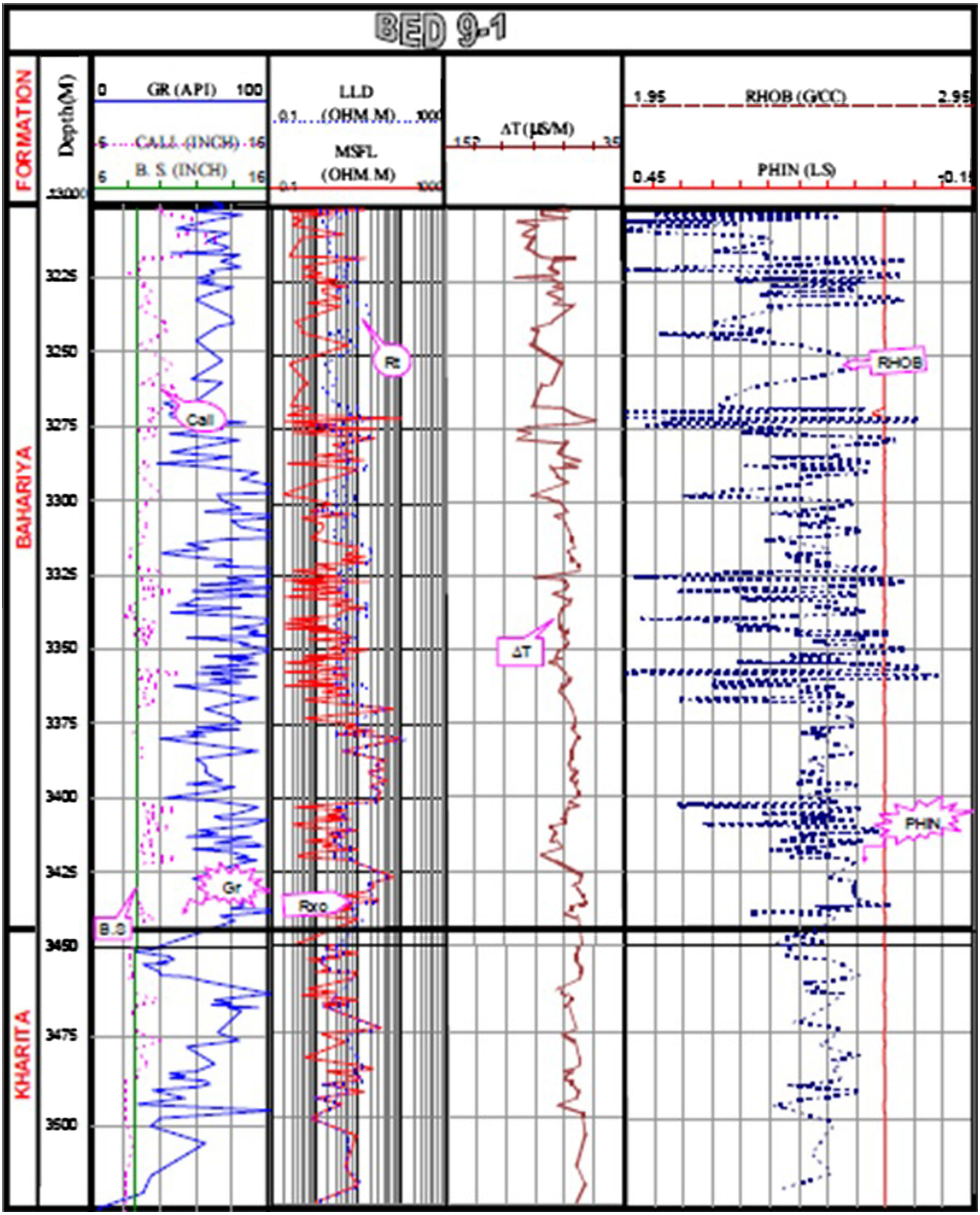

Figure 10 The corrected log data sets for Bahariya and Kharita reservoirs in BED 9-1.

BED 9-1 and the maximum value of 26% at BED 1-11. The effective porosity map shows an irregular pattern recording a maximum value of 15% at BED 1-16 (Fig. 16b). It is noticed that the effective porosity value is mainly affected by shale content only in the central part of the study area, but this manner is not found in the northeastern parts. This might indicate the presence of shale with different habits. The sand percentage distribution map is represented by increasing the values

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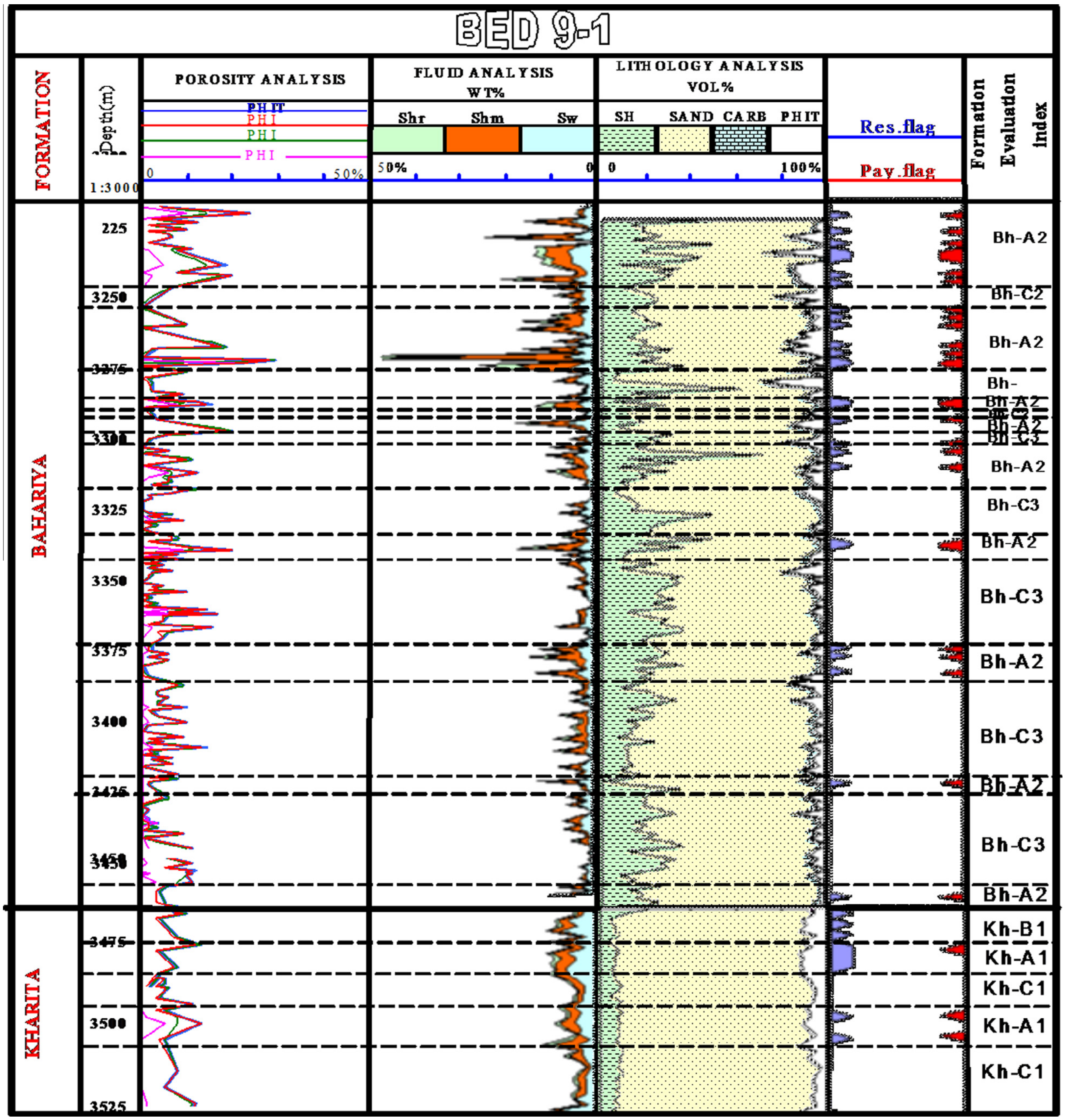


Figure 11 The litho-saturation crossplot for Bahariya and Kharita reservoirs in BED 9-1.

in the east and westward recording maximum value of 85% at BED 9-1 and minimum value toward the northeast direction and at the central part recording a value of 59% at BED 1-16 (Fig. 16c). The carbonate percentage is very less and not represented here. The water saturation distribution map reveals a variation of the water saturation to decrease in the northeastern ward recording a minimum value of 19% at BED 1-16 well and increase toward the east and western parts recording a maximum value of 65% at BED 1-9 (Fig. 17a). On the other hand, the hydrocarbon saturation contour map portrays an expected reverse pattern to that of the water saturation recording the maximum value of 57% at BED 1-16 and a minimum value of 22% at BED 1-9 (Fig. 17b). The net reservoir thickness distribution map (Fig. 17c) shows the reservoir thickness restricted mainly to the northeastward with the maximum value of 89.11 m at BED 1-16. It decreases to the northwards recording a minimum value of 16.14 m at BED 4-1.

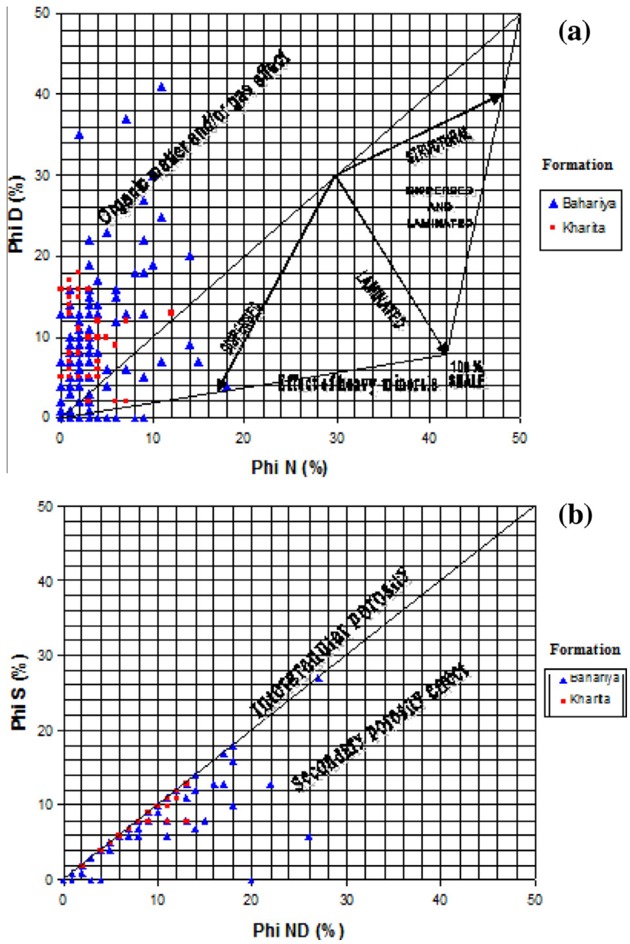


Figure 12 Dia porosity cross plots: (a) neutron/density cross plot of the clean and shaly zones within the studied intervals (Bahariya and Kharita reservoirs) in BED 9-1. (b) Neutron-density/sonic cross plot in BED 9-1.

8. Discussion and conclusion

Four constructed subsurface geological cross sections along four profiles show that the study area is affected by sets of normal faults resulting in great variation of depths and thicknesses of Khoman, Abu Roash, Bahariya and Kharita Formations. The obtained check shot data in addition to sonic logs were used for the velocity analysis. The reflection one-way time, average velocity and interval velocity versus depth are constructed for the studied Formations (Apollonia, Khoman, Abu Roash, Bahariya, and Kharita). These plots show similarities of the constructed velocity curves but with sometimes remarkable differences. These differences could be related to the effect of facies changes and/or fluid content (water and hydrocarbons), and in addition to overburden pressure. The reflection one time-depth (T-D curve) and average velocity curves show the effect of shale content within Abu Roash and Bahariya Formations and the abundance of limestone and chalky limestone within Apollonia and Khoman Formations. The variations of values reflect the different depositional environment of these Formations.

Seismic interpretation shows that Apollonia and Khoman reflectors are dissected by a number of normal and reverse faults forming small size grabens and horsts. On the other hand, the main faults affecting the Cretaceous sequence from the Kharita Formation at the bottom to Abu Roash Formation at the top are trending NW-SE, NE-SW, and E-W. Also, these sequences are slightly folded forming minor synclines and anticlines. The northeast trending folds resulted from a combination of compressional stresses initiated from wrenching in addition to arching of the basement. These folds have been developed during the Late Cretaceous-Early Eocene *time* (Abdel Khalek et al., 1989). There was a problem to continue tracing of the Cretaceous sequence due to the faulting effects and the bad quality of data.

Based on the petrophysical analysis of Bahariya and Kharita Formations through utilizing well logging records of five wells and calculating the volume of shale, different types of porosities (total, primary, secondary and effective) and the fluid saturations (water, movable and residual hydrocarbons). Bahariya Formation generally consists of sandstone with interbedded glauconitic shales and siltstones. This shale content increases to the NW and SE direction. The reservoir quality represented by sands is best developed in the lower zone of Bahariya and upper part of Kharita Formation. The mineral composition of the Bahariya sandstone is very complex due to the effect of heavy minerals. The presence of siderite, hematite, clay content, glauconite, and pyrite is indicated by low resistivity and high gamma ray log readings. A remarkable positive separation has been observed between deep resistivity (Rt) and shallow resistivity (Rxo) logs in Bahariya Formation that might point to a possible hydrocarbon saturation. The gas zone may be indicated in the interval between 3200 and 3325 m since separation between the resistivity logs is present. The analysis of the petrophysical parameters shows also that the secondary porosity is common and significant in the Cenomanian clastic reservoir deposits of the upper part of Bahariya Formation. It is formed through de-carbonization and framework grain dissolution (feldspars and glauconite). The clay content of the studied Formations is mainly of dispersed habitat. These petrophysical findings need to be further validated using graphical well log techniques and core samples that could provide information such as the permeability values within the studied reservoir Formations and study whether these reservoirs are at irreducible state or not. This recommendation will be taken into consideration in a supplementary study.

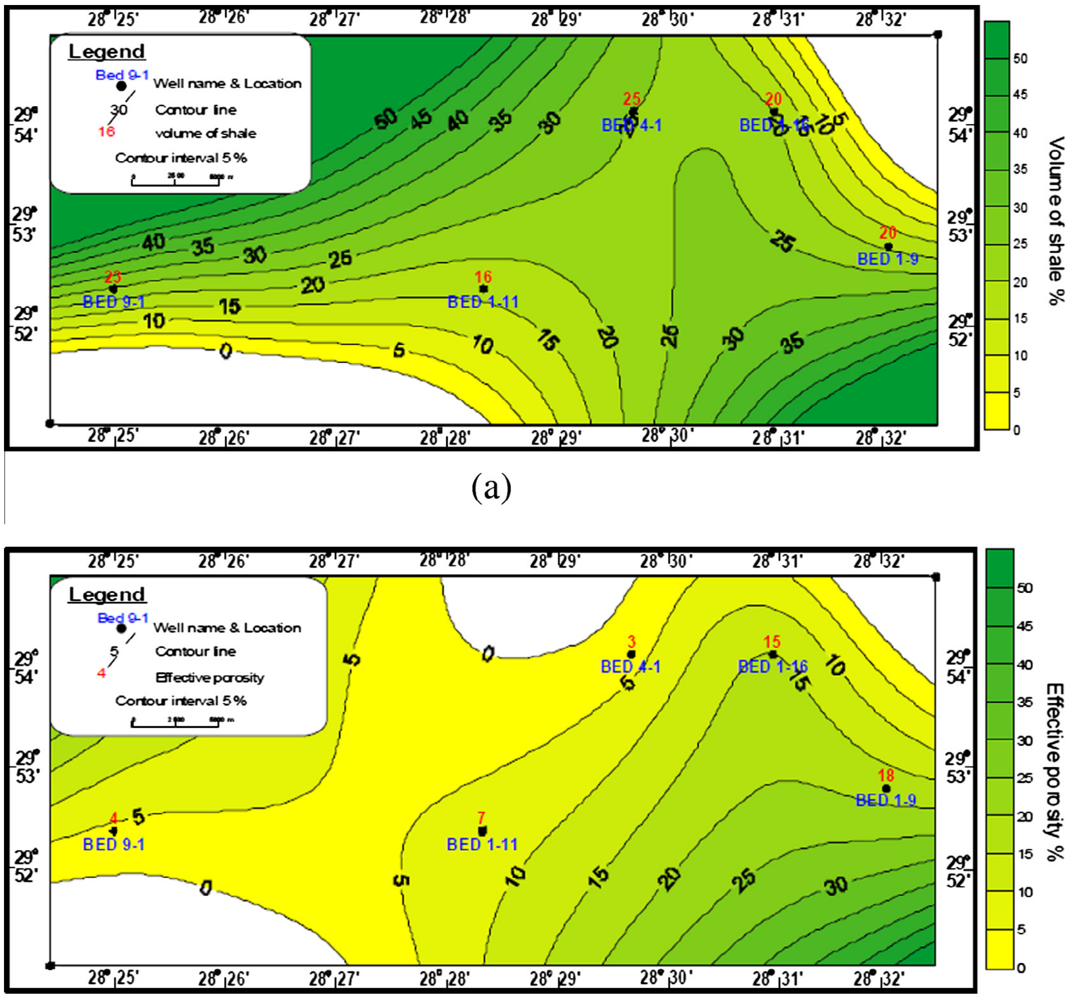


Figure 13 (a) Volume of shale contour map for Bahariya Formation. (b) Effective porosity contour map for Bahariya Formation.

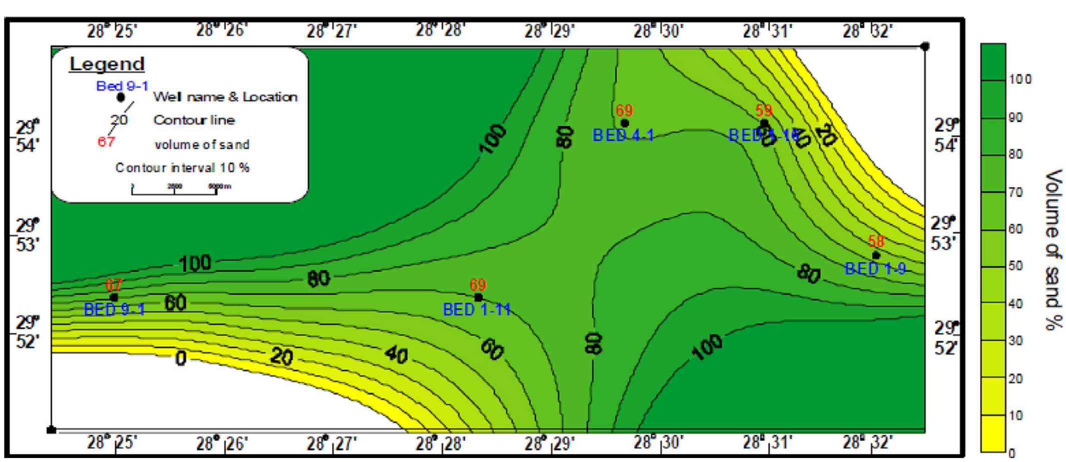
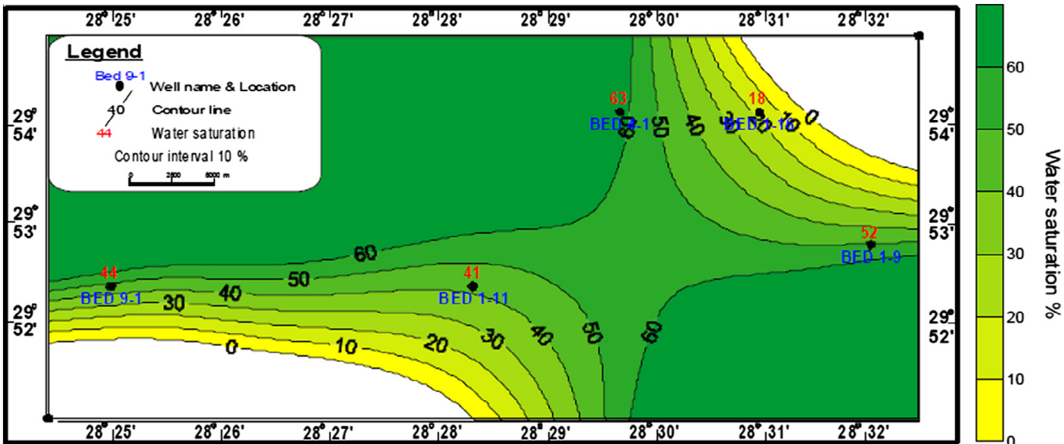
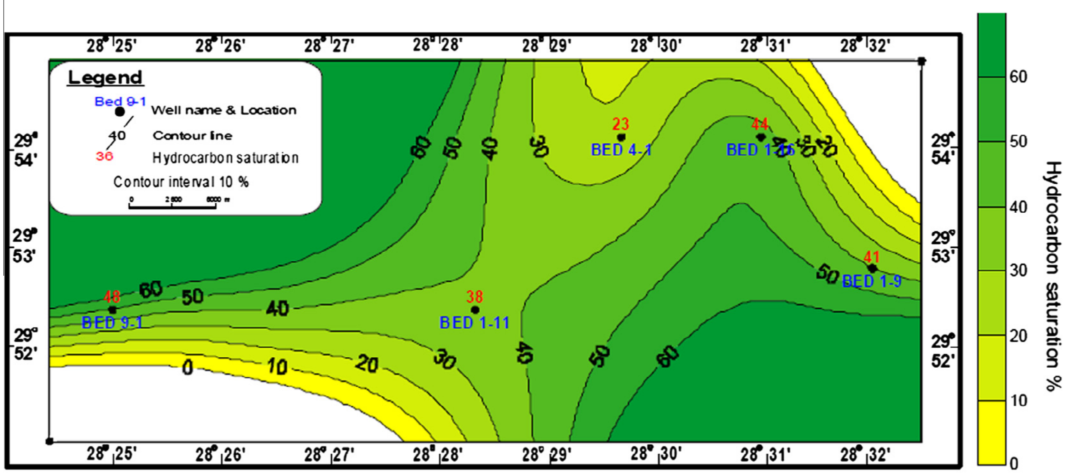


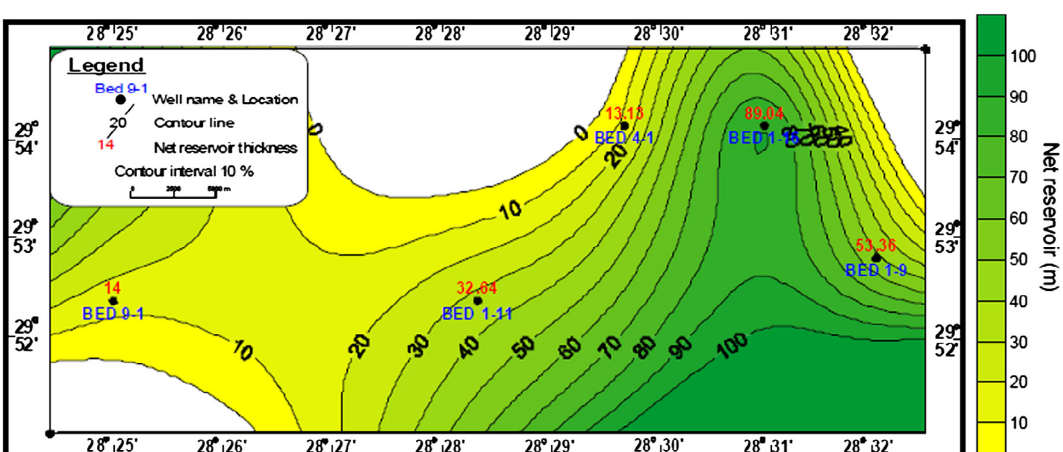
Figure 14 Volume of sand contour map for Bahariya Formation.



(a)



(b)



(c)

Figure 15 (a) Water saturation contour map for Bahariya Formation. (b) Hydrocarbon saturation contour map Bahariya Formation. (c) Net reservoir thickness contour maps for Bahariya Formation.

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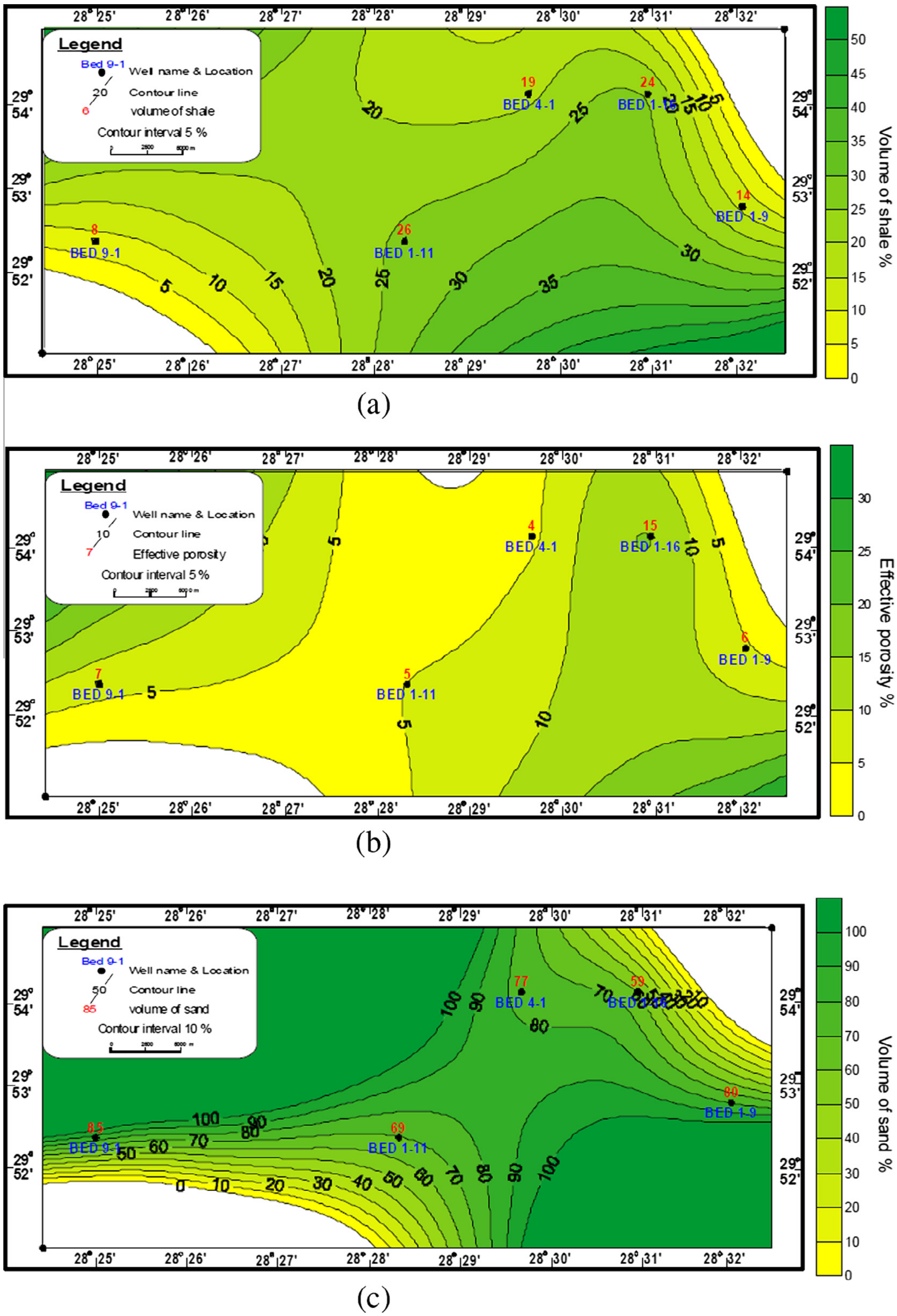

Figure 16 (a) Volume of shale contour map Kharita Formation. (b) Effective porosity contour map Kharita Formation. (c) Volume of sand contour maps for Kharita Formation.

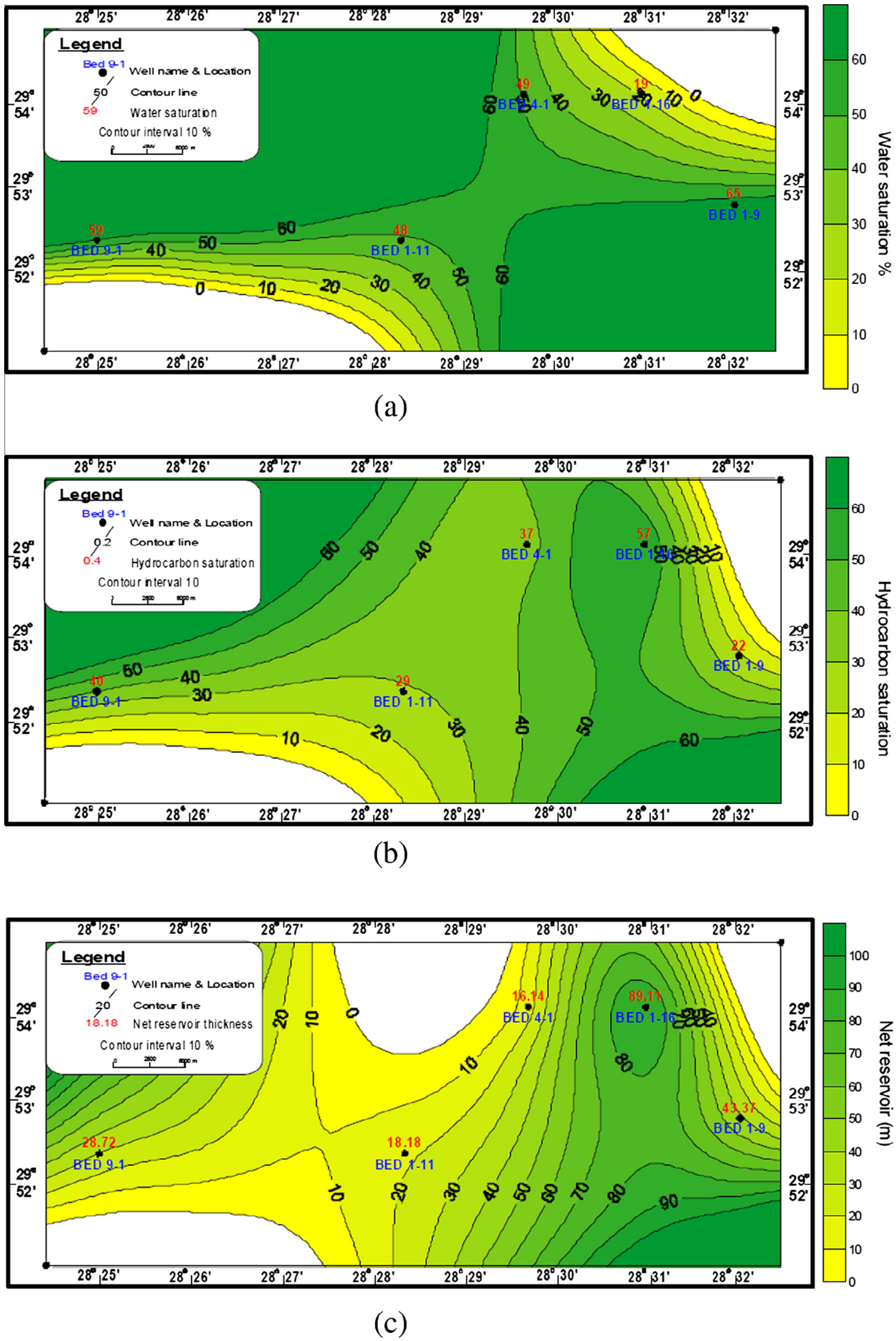

Figure 17 (a) Water saturation contour map Kharita Formation. (b) Hydrocarbon saturation contour map Kharita Formation. (c) Net reservoir thickness contour map for Kharita Formation.

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