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Hydrocarbon Potentialities and Reservoir Characterization of Lower Cretaceous Successions of Masila Oil Field, Yemen

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Abstract. Reservoir characterization, in general, is the process of integrating various qualities and quantities of data in a consistent manner to describe reservoir properties of interest at inter well locations. For reservoirs, reservoir characterization is the process of integrating seismic data of various qualities and well data of limited quantities in a consistent manner to assign reservoir properties to a large extent of the reservoir using the seismic data. Geostatistics is especially useful in the characterization of reservoirs because it is a technique that enables the propagation of reservoir properties in a manner that is statistically coherent and consistent. It allows the application of concepts such as trends and variability of properties as well as subjective interpretation in the description of reservoir. The basic inputs in the reservoir characterization process are the geological framework, well log data, seismic amplitude data, well test data and any other data which can be correlated to rock properties, such as porosity, permeability, saturation, thickness, and lithofacies.

Evaluation of the hydrocarbons potentiality in the porous zones encountered in the Lower Cretaceous formations of Masila Oil Field, Yemen, is based on the data of eight wells. Some points of interest will be considered in these formation evaluation processes such as the geological aspects, technique utilized and the presentation forms of the obtained petrophysical parameter values. The basic logging data are in the form of spontaneous potential (SP), Caliper (CL), Deep (LLS, LLD), and Shallow (MSFL) resistivity logs, porosity tools (Density, Neutron and Sonic), litho-density (PEF) and Gamma-Ray (GR). Different cross-plots such as Rho-PHIN, Rho-DTN and M-N were tested for lithology identification for the two formations in the studied wells. Such formation evaluation and the presentation forms of the obtained petrophysical parameters have frequently proven that the formations have high hydrocarbon saturation in this area and containing many pay zones.

Keywords: Hydrocarbon Potentiality; Reservoir Characterization; Qishn and Saar Formations; Masila.

I. Introduction

In general, the stratigraphy as well as structural geology of Yemen, including the Masila area, were studied and published by many geologists (*e.g.* Beydoun *et al.,* 1964 and 1966; Beydoun and Greenwood, 1968; Beydoun *et al.,* 1996; Bosence *et al.,* 1995; and Watchorn *et. al.,* 1998). Discussions on the petroleum geology of Yemen including the study area have been reported by Haitham and Nani (1990); Mills (1992). Redfern and Jones (1995) studied in detail the evaluation of the stratigraphy and basin structure of the interior rift basins of Yemen. They concluded that the Masila basin is formed during the Lower Cretaceous period after breakup of the Gondwana land. Wetzal and Mortan (1948) studied the Lower Cretaceous sequence including the Saar and Qishn units. A summary of these main stratigraphic results was published by Beydoun (1964 and 1966); and Beydoun and Greenwood (1968). Figure 1 shows a simplified geological map of Yemen, showing the location of study area.

A generalized stratigraphic column of the study area including the Lower Cretaceous sequence is shown in Fig. 2. The Lower Cretaceous sequence is divided, from base to top, into Saar and Qishn Formations. The Saar Formation is identified in the subsurface by Mills (1992) and in outcrop by Beydoun (1964). The overlying Qishn Formation is divided into seven lithological units in outcrop (Canadian Oxy Company, 1992, 1999, 2003, 2004). However, in the subsurface of the study area, the formation is divided into two members: Lower Clastic Member and Upper Carbonate Member. The Lower Clastic Member is further subdivided into two units: Lower and Upper. About 90% of the reserves are found in the Upper Unit of Qishn Formation. The remaining 10% of the reserves are found in at least seven other distinct reservoir units (clastic and carbonate rocks) ranging from Late Jurassic to Early Cretaceous in addition to the fractured Cambrian granitic rocks (Fig. 2).

Beydoun *et. al.,* (1993) studied the lithofacies and hydrocarbon habitat of the Qishn Formation. They concluded that the largest hydrocarbon accumulation occur in the reservoir sands of the Qishn Formation. This reservoir has produced at rates of up to 12.67 MSTB/D of 29-33 ^{o}API gravity oil. Putnam *et al.* (1997) divided the upper unit of the Lower Qishn Clastic Member into three subunits.

The main goal of this investigation represents part of an integrated study of a state-of-the-art-computer packages to evaluate and build a 3D geological model of the Lower Cretaceous reservoirs in the Masila area. The Masila area is located in the Hadhramaut region in east central Yemen (Fig. 1). Oil was first discovered in the area in late 1990 with commerciality being declared in late 1991. Oil production began in July 1993. By the end of December 1999, the daily production rate was 210,000 STB/D of very low GOR (Gas/Oil Ratio) oil under partial to full water drive, and the cumulative production is a little-bit over 400 million STB (Canadian Oxy Company, 2004). The total known oil-in-place exceeds 1.6 billion STB, with proved ultimate recoverable oil reserves approaching 900 million STB. In addition, the reserve estimates (proved, probable, and possible) are in excess of one billion barrels of recoverable oil (Canadian Oxy Company, 2004). Naji *et al.*, (2010) discussed the sedimentology and quantitative well logs petrophysical parameters of Lower Qishn Clastic Reservoir of the Masila Oilfield.

3D geomodeling, 3D stratigraphic, 3D structural modeling, well logs evaluation and hydrocarbon potentialities in addition to reservoir characterization for the lower Cretaceous successions in the Masila area have been done by Hakimi (2008), Naji (2010), Naji *et al.*, (2010), Naji & Khalil and Khalil and Naji (2010, 2011).

II. Objectives and Available Data

The objective of this work is to study the reservoir characterization of Masila Oil Field and to evaluate the hydrocarbon potentialities of the Lower Cretaceous petroleum reservoirs of the Masila region by integrating a variety of the state-of-the-art computer packages. The packages include:

1. Interactive Petrophysics ^{TM} Software, which is used for well logs interpretation to calculate measurable quantities such as shale volumes, porosity, permeability, and fluid saturations.

2. Reservoir evaluation and characterization, which are based on:
   a. Well log geophysical analysis of the reservoirs.
   b. Subsurface geological evaluation.
   c. Hydrocarbon potentialities.

This work is based on the study of well logs and seismic sections for eight wells, which cover the study area (Fig. 3). These wells are Camaal-4, North Camaal-1, Hemiar-1, South Hemiar-1, Haru-1, Heijah-3, Heijah-5, and Tawila-1. Data used from these wells include: Wells location map, well logs of all wells, digital data of the 3D- seismic sections taken in the area and production history of all wells. The reservoir data is obtained from the Production and Exploration Authority (PEA) of Yemen. The logs in the studied wells include: Formation Resistivities (LLD and LLS), Formation Density Compensated (FDC), Borehole Compensated Sonic (BHC), Compensated Neutron Log (CNL), Litho-Density Log (LDT), and Photoelectric Absorption Index (PEF). These logs are checked and matched for depth before processing and interpretation. Seismic data, which are 3-D seismic lines, were selected in this present work. The 3-D seismic lines are either a specific Seisworks horizon picks format in petrel software or notepad format.

III. Methods of Study

III.1 *Well Log Analysis*

In this work, the well log evaluation has been achieved by using the Interactive Petrophysics ^{TM} Program (IP), which is a PC-based software application for reservoir property analysis and summation. Interactive Petrophysics^{TM} (IP) is developed by the Production Geosciences Ltd. IP's technical support is provided by the Schlumberger Information Solutions (SIS). This program determines and calculates the deterministic and probabilistic models including porosity, water saturation, shale volumes and other properties within user-defined zones. Also, cross-plot endpoints of petrophysics can be determined directly from the plots, which significantly minimize keyboard entries. As parameters are selected from log plots and interactive cross-plots, the analysis results will be updated instantly. Well log analyses provide data on: Shale volume, lithology and facies identification, porosity, permeability, and fluid saturations.

III .1.1 *Calculation and Correction*

The Calculation and Correction Modules provide the user with the functionality to perform log environmental corrections and to compute and convert various basic petrophysical parameters such as temperature gradient, and water resistivity (Rw) from the SP log.

III.1. 1.1 *Temperature Gradient*

The Temperature Gradient module is used to create a continuous temperature curve, and is used in the interpretation modules for converting water resistivities to formation temperatures. The temperature curve can either be calculated by entering a temperature gradient, or by entering temperatures at fixed points and the program will extrapolate between them. The temperature gradient is entered in degrees per 100 feet or meters, depending on the units of the well.

III.1.1.2 *Water Resistivity (RW) from SP Logs*

Water resistivity (Rw), which is determined from SP log module, is used to create a continuous Rw curve. This is useful for estimating Rw values over a number of zones. Water resistivity (RW) was varied with depth to account for the temperature gradient over the computed intervals.

III.1.1.3 *Basic Log Analysis Functions*

The Basic Log Analysis Functions module performs a number of simple log analysis calculations and unit conversions. The module is arranged on three tabs. These are: Porosity, Matrix, and water resistivity (Rw Apparent)/Water saturation (Sw).

III.1.1.4 *Environmental Corrections*

Calculation of the environment corrections such as borehole size, mud weight, mud cake thickness, mud salinity, formation water salinity, temperature and pressure are derived from Logging Service companies (*e.g.* Schlumberger, Baker Atlas, Halliburton, Baker Hughes INTEQ and Sperry Sun). In this work the Schlumberger Corrections are used (Schlumberger, 1986). The Corrections calculations are arranged on tabs, each tab representing a different tool type. The number of tabs is determined by the tool-type corrections available from the Logging Service Company.

III.1.2 *Interpretation*

The following standard modules are available under the Interpretation Menu: Clay Volume, Porosity and Water Saturation.

III.1.2.1 *Clay Volume*

The Clay volume interpretation module is used to interactively calculate clay volume from multiple clay indicators. Clay volume was calculated from single curve (*e.g.* gamma ray (GR), spontaneous potential (SP), and deep resistivity responses (RESD), and double curve (*e.g.* Sonic/Neutron, Neutron/density, and Sonic/density curves).

III.1.2.2 *Porosity and Water Saturation*

The Porosity and Water Saturation interpretation module is used to interactively calculate porosity (PHI), water saturation (Sw), flushed zone water saturation (Sxo), matrix density (RHOMA), hydrocarbon density (RHOHY) and wet and dry clay volumes (VWCL & VDCL).

III.1.3 *Subsurface Maps*

Subsurface analysis is principally based on the lithological study, and depth data of eight wells distributed in the study area. In addition to these drill-hole data, sets of basic maps will be constructed: Isopach maps, facies maps. Isopach maps show the lateral and vertical thickness variations of the investigated rock units. The lithofacies maps illustrate the predominant facies distribution as a direct indication to the environmental conditions of deposition of the considered rock units. After studying the isopach and facies maps of the Lower Cretaceous sequence, study of such variations in three dimensions in the form of 3D modeling will be more helpful to the evaluation of the studied reservoirs potentialities.

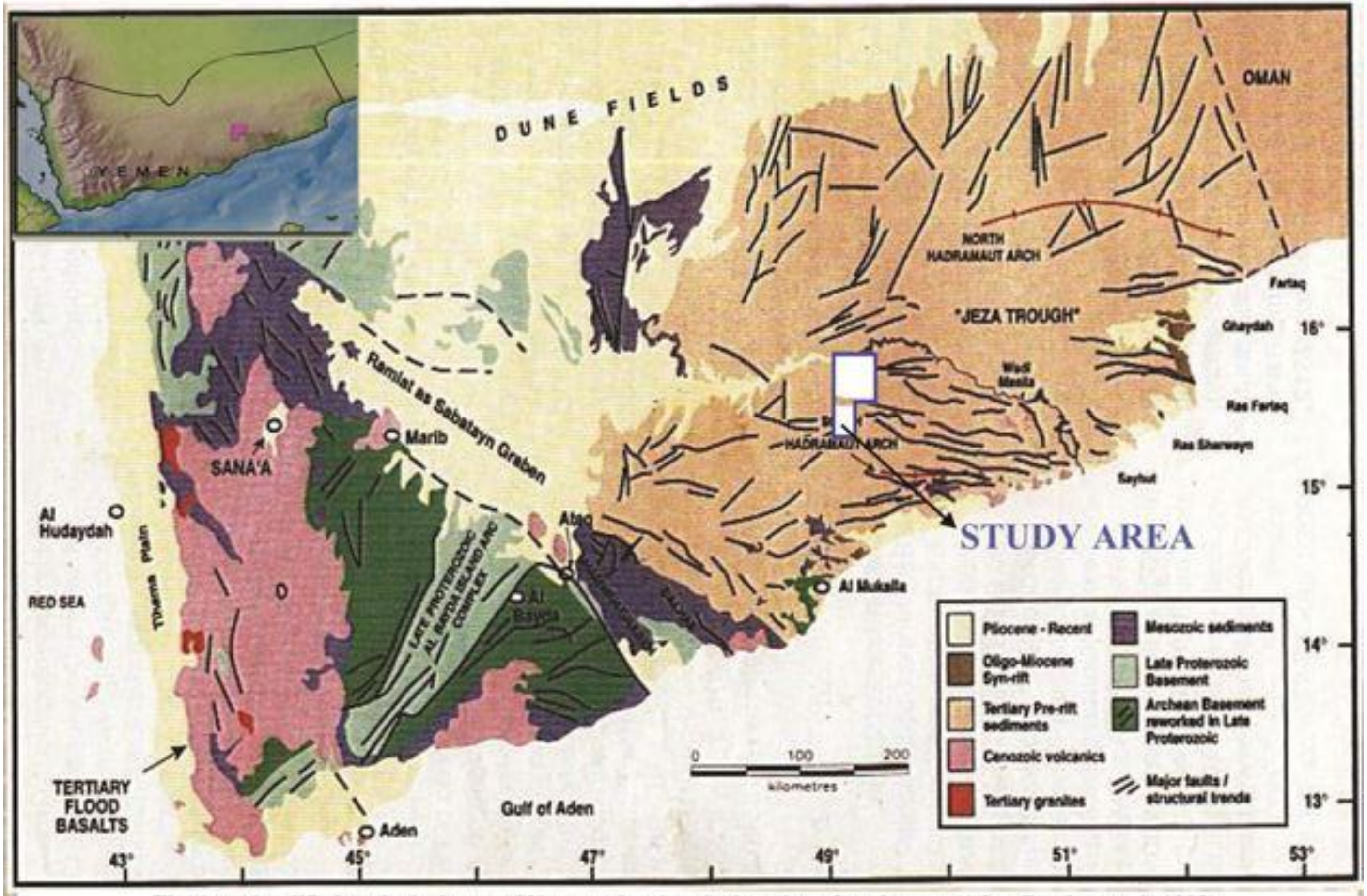

Fig. 1. A simplified geological map of Yemen, showing the location of study area (After Baydon *et al.*, 1993).

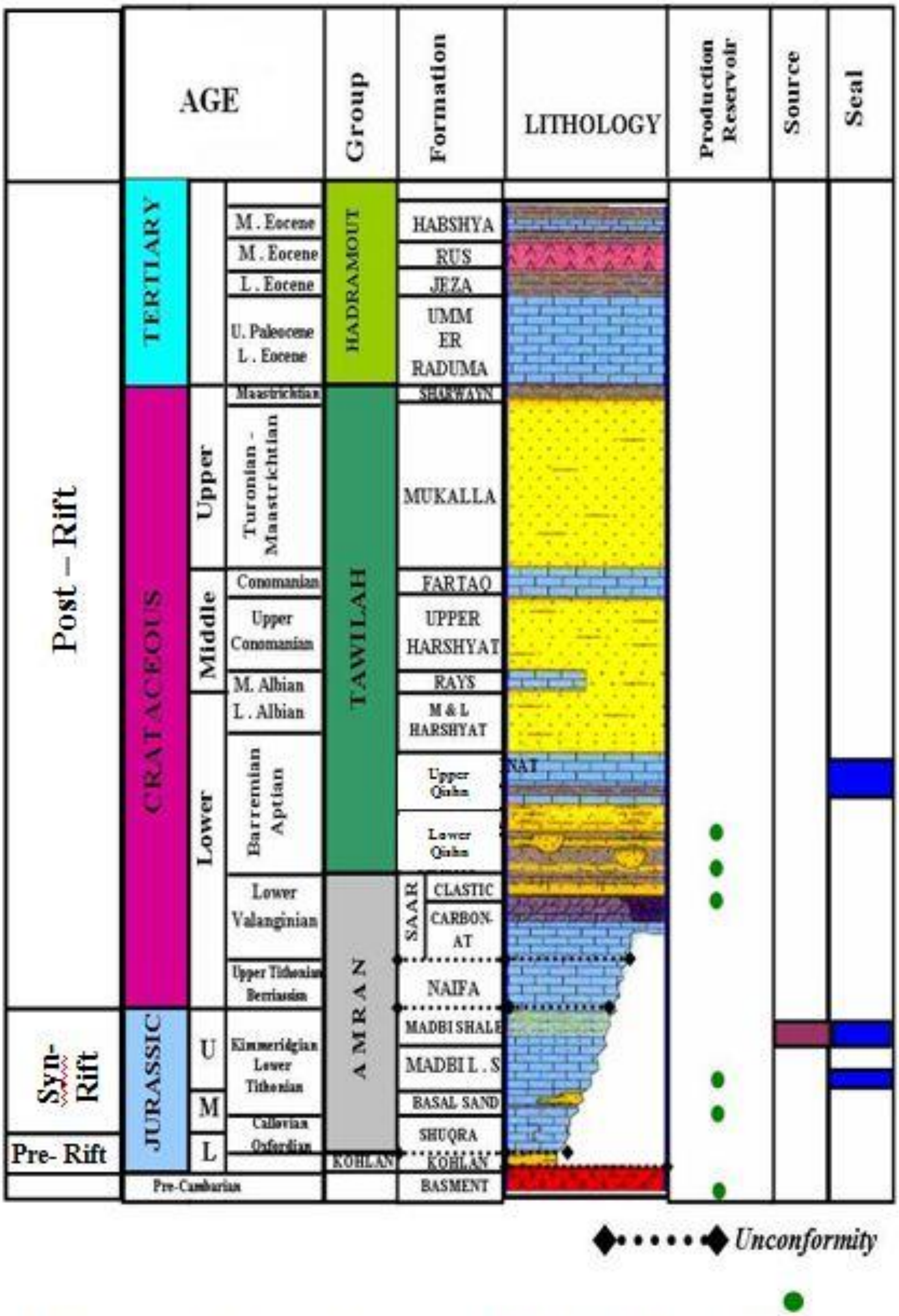

Fig. 2. Litho-Stratigraphic column of study area (Masila Oil Field), Yemen (After Canadian Oxy Company, 2004).

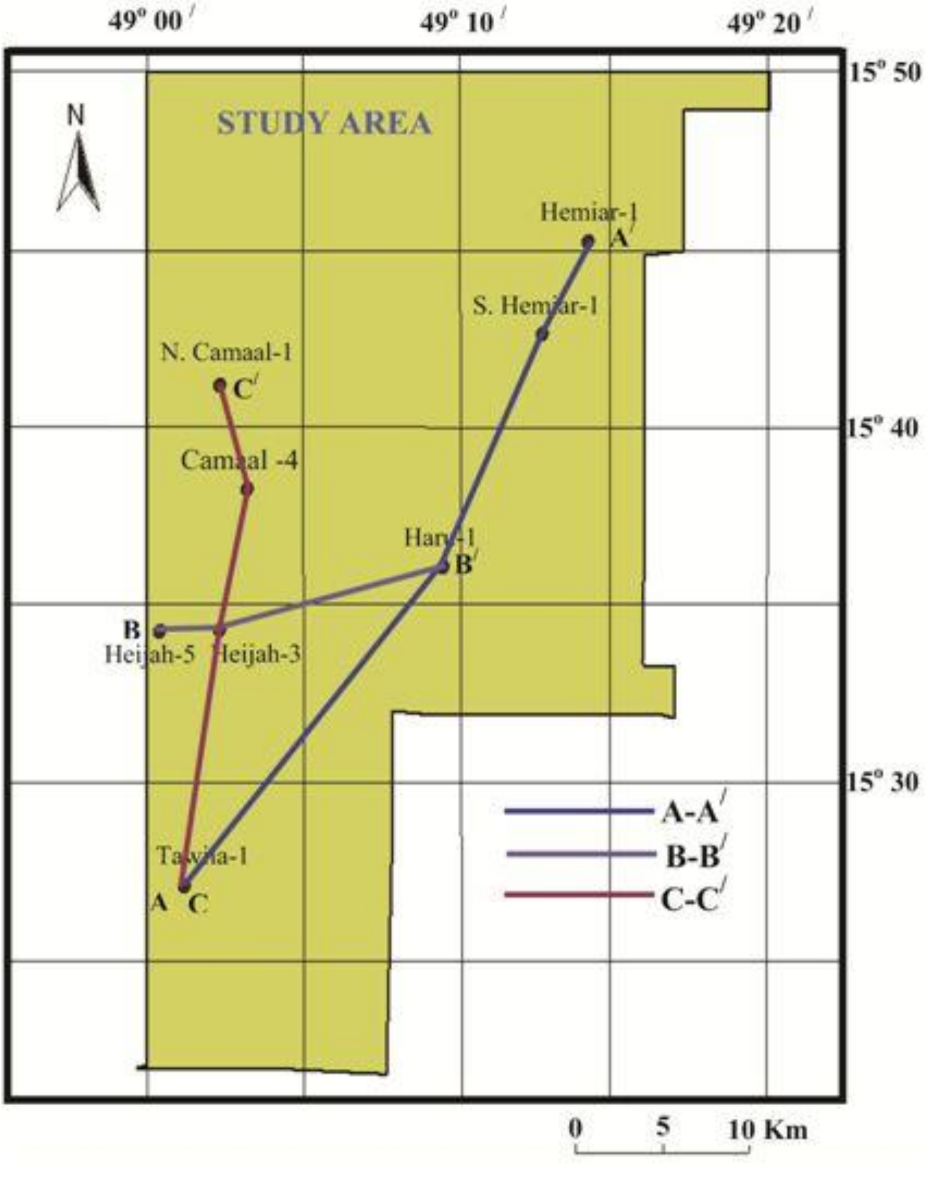

Fig. 3. Map showing cross section lines for the study area.

IV. Hydrocarbon Potentialities of Masila Basin

Petroleum occurs in two rift basins in Yemen: Marib–Al Jawf/Shabwa basin of western Yemen, and Masila-Jeza basin of eastern Yemen. These eastern and western basins are largely separated by a large structural high known as the Mukalla or Jahi-Mukalla High. These basins are part of a system of major rift basins, and various authors have used a variety of names for the main basins and the sub-basins. The western basin is known by a variety of names such as Sabatayn, Marib-Shabwa-Hajar (Beydoun *et al.*, 1996), and Marib-Shabwa basin. Similarly, the eastern basin is also, known as the Say'un al Masila and Jeza-Qamar basin (Beydoun *et al.*, 1996), Say'un basin, and Sir-Say'un basin.

The Madbi shale is a source rock for the Masila block fields which are located over horsts that comprise the Masila Terrace (Mills, 1992). Down faulting of the Madbi source rocks allows upward migration into older Kohlan Formation sandstone reservoirs that are sealed by limestones of the Shuqra Formation. The largest hydrocarbon volumes are accumulated in the Lower Clastic Member that has produced at rates of up to 12.67 MSTB/D of 29-33 ^{o}API gravity oil (Mills, 1992; and Beydoun *et al.*, 1993). This main reservoir is sealed by the tight Qishn Formation limestones (Upper Qishn Carbonate Member). The absence of the Sabatayn salt from this basin provides a direct migration pathway from the Late Jurassic Madbi source rocks to the Early Cretaceous sands (Bosence, 1995). The production facilities for these fields are designed for 120 MSTB/D and the estimated recoverable reserves are 235 million bbls (Mills, 1992). About 90% of the reserves in the Masila Basin are found in the Lower Cretaceous lower Qishn Clastics Member of the Qishn Formation. Also, oil is found in, at least, seven other distinct reservoir units (clastic and carbonate rocks) from Early Cretaceous to late Jurassic age as well as from fractured Cambrian granitic basement rocks (Fig. 2). Based on the unpublished reports by Canadian Oxy Company (2001) and PEPA (2004) and on all available data the following sections summarize the previous study of the hydrocarbon habitat in the Masila Basin.

V. Subsurface Evaluation

Subsurface evaluation is a coordination of the available subsurface geologic information and its interpretation with respect to the predominant geologic conditions during deposition, nature of rock materials and the contained fluids. Results are shown in a number of distribution maps which explain the configuration of the petrophysical analysis in the study area. Subsurface evaluation is based principally on the lithologic and depth data of eight wells distributed in the study area.

In addition to these well data, a set of basic maps such as isopach and lithofacies maps is used.

V.1 *Isopach Maps*

Isopach maps were constructed by using the different thicknesses of the different formations of the Lower Cretaceous age in the study area. An isopach map shows the direction of thinning and thickening of rock units in relation to the thicknesses of their lithologic components that may reveal significant information relevant to the geologic history of the area. These maps provide also useful information for defining the depth of the sedimentary basins. In the following paragraphs, the thickness variation of each rock unit will be discussed in detail by maps as follows:

V.1.1 *Lower Cretaceous Sequence*

The Lower Cretaceous sequence for the studied Masila area reaches the maximum thickness at Camaal-4 well (about 587 m) and the minimum thickness at Heijah-5 well (about 300 m). This thickness increases from western (320m) and eastern (360m) parts toward north central (560m) and southwestern (500m) parts of the study area.

V.1.2 *Saar Formation*

The isopach map of the Saar Formation for study area (Fig. 4) shows that the maximum thickness at Tawila-1 well (229m) and the minimum thickness at Heijah-5 well (31m). This map shows that the thickness is increasing from western and eastern parts toward north central and southwestern parts of the study area. Meanwhile, the thickness of the Saar Formation decrease at western (30m), and eastern (50m) parts of the study area.

V.1.3 *Qishn Formation*

a. *Lower Qishn Clastic Member*

The Lower Qishn Clastic member for study area shows that the maximum thickness is at North Camaal-1 well (227m) and the minimum thickness is at Heijah-5 well (162m). This thickness increases toward north, and northeastern parts of the study area. Meanwhile, the thickness of the Lower Qishn Clastic Member decreases toward western (162m) and southwestern (175m) parts of the study area.

b. *Upper Qishn Carbonate Member*

The isopach Upper Qishn Carbonate member for the study area shows that the maximum thickness is at Haru-1 well (124m) and the minimum thickness is at Heijah-3 well (113m). This map thickness increases from northwestern and western parts toward northeastern (122m) and eastern (123m) parts of the study area.

V.2 ***Lithofacies Maps***

A differentiation of the main lithologies of the rock materials can be achieved through the determination of the shale content. The remaining part of the rock volume can be looked at as the matrix content after excluding the volume occupied by the rock pores and major fractures (porosity). This matrix content can be discriminated as sandstone, limestone, and dolomite (other components such as anhydrite, salt, coal,... *etc*.) can be neglected for encountered reservoir rocks in the Lower Cretaceous. The present analysis is based on the results of all logging data processed from the eight investigated wells.

V.2.1 *Sand/Shale Ratio Map of Upper Qishn Carbonate Member*

Figure 5 shows the areal distribution of the sand/shale ratio of the Upper Qishn Carbonate Member. It has nearly the same configuration and trends as in the sand/shale ratio map for Lower Qishn Clastic. The maximum value of the sand/shale ratio is located in the area at Camaal-1 well (1.48) and the minimum value is located in the area at Heijah-5 (0.35). The sand/shale ratio has shown a general increase toward the north- northwestern and southern parts of the study area.

V.2.2 *Sand/Shale Ratio Map of Lower Qishn Clastic Member*

The areal distribution of the sand/shale ratio of the Lower Qishn Clastic Member shows that the maximum value of sand/shale ratio is located in the area at Camaal-4 well (7.39) while the minimum value is recorded in the area at Heijah-5 (2.9), and Haru-1 (2.3) wells. The sand/shale ratio has shown a general increase toward the north-northwestern and southern parts of the study area similar to the upper Qishn carbonate Member. Meanwhile, the sand/shale ratio decrease in central/western-eastern parts of the study area. It can be concluded that the shale sedimentation was more conspicuous in these parts of the study area.

V.2.3 *Sand/ Shale Ratio Map of Saar Formation*

The interpretation of the aerial distribution of the sand/shale ratio of the Saar Formation shows that the maximum value is recorded in the area at Camaal-4 well (10.2) while the minimum value of the sand/shale ratio is located in the area at Heijah-5 (2.9) and Haru-1 (2.3). The sand/shale ratio has shown a general increase toward the north- northwestern and southern parts of the study area. From the sand/shale ratio maps of the upper and lower Qishn carbonate members and Saar Formation, it can be concluded that the source of the coarse clastic (sands) was originated from western and southern directions (toward shoreline). Meanwhile, the shale sedimentation was more conspicuous in the central/western – eastern parts of the study area.

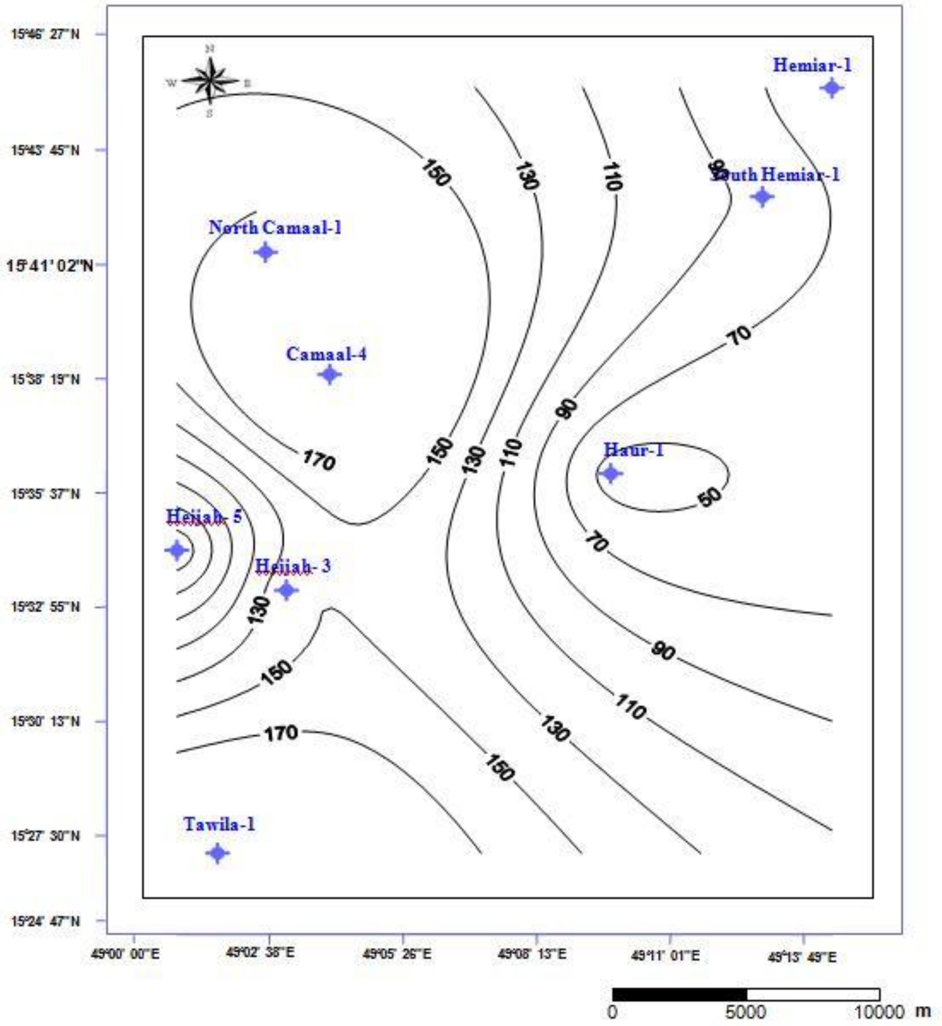

Fig. 4. Isopach map of Saar Formation for the study wells.

V.3 Subsurface Sections

After studying the isopach and lithofacies maps in two dimensions for Lower Cretaceous sequence, it is useful to study such variations in the form of correlation lines for the subsurface section for reservoirs in the study area The first section is in southwest-northeast trend, the second section is located in west-southeast trend and the third is located southwest-northwest trend, taking into consideration top Upper Qishn member as a datum plane. Figure 3 shows the directions of correlation lines through studied wells.

V.3.1 *First Section Line A-A*$^{\backslash}$

The first correlation line A-A$^{\backslash}$ (Fig. 6) is passing through the four wells, which are Tawila-1, Haru-1, South Hemiar-1, and Hemiar-1 wells in SW-NE direction. The Saar Formation is represented in Tawila-1 well (1877m), Haru-1 well (1739m), Hemiar-1 well (1752m), and South Hemiar-1 well (1793m).

The Saar Formation is increasing in thickness from South Hemiar-1 well (87m) toward Tawila-1 well (229m). The clastic facies of Saar Formation is increasing from South Hemiar-1 well toward Tawila-1 well. The Lower Qishn is represented in Tawila-1 well (1704m), Haru-1 well (1541m), Hemiar-1 well (1528m), and South Hemiar-1 well (1571m). The Lower Qishn is increasing in thickness from Tawila-1 (173m) toward South Hemiar-1 well (222m).

The Upper Qishn is represented in Tawila-1 well (1591m), Haru-1 well (1471m), Hemiar-1 well (1405m), and South Hemiar-1 well (1453m). The Upper Qishn is increasing in thickness from Tawila-1 well (113m) toward South Hemiar-1 well (118m) and the clastic facies of the Upper Qishn is increasing from South Hemiar-1 well toward Tawila-1 well.

V.3.2 *Second Section Line B-B*$^{\backslash}$

The second correlation line B-B$^{\backslash}$ (Fig.7) is passing through the three wells Heijah-5, Heijah-3, and Haru-1 wells in W-SE direction. The Saar Formation is represented in Heijah-5 well (1797m), Heijah-3 well (1831m), and Haru-1 well (1739m). The Saar Formation increases in thickness at Heijah-3 well (147m) while decreases at Haru-1 well (40m) and Heijah-5 well (31m). The clastic facies of Saar Formation is increasing from Heijah-5 well toward Haru-1 well. The Lower Qishn is represented in Heijah-5 well (1635m), Heijah-3 well (1635m), and Haru-1 well (1541m). The Lower Qishn is increasing in thickness from Heijah-5 well (162m) toward Haru-1 well (198m). The Upper Qishn is represented in Heijah-5 well (1528m), Heijah-3 well (1522m), and Haru-1 well (1417m). The Upper Qishn is increasing in thickness from Heijah-3 well (113m) toward Haru-1 well (124m), and the clastic facies of Upper Qishn increases at Haru-1 well while decreases at Heijah-5 and Heijah-3 wells.

V.3.3 *Third Correlation Line C-C*$^{\backslash}$

The third correlation line C-C$^{\backslash}$ (Fig. 8) is passing through the three wells, which are North Camaal-1, Heijah-3, and Tawila-1 wells in SW-NW direction. The Saar Formation is represented in North Camaal-1 well (1932m), Heijah-3 well (1831m), and Tawila-1 well (1877m). The Saar Formation increases in thickness at Tawila-1 well (229m) while decreases at Heijah-3 well (147m), and the clastic facies of Saar Formation increasing from North Camaal-1 toward Tawila-1 well. The Lower Qishn is represented in Tawila-1 well (1704m), Heijah-3 well (1635m), and North Camaal-1 well (1704m), the Lower Qishn increases in thickness from Tawila-1 well (173m) toward North Camaal-1 well (228m). The Upper Qishn is represented in North Camaal-1 well (1594m), Heijah-3 well (1522m), and Tawila-1 well (1591m). The thickness of Upper Qishn increases from North Camaal-1 well (110m) toward Tawila-1 well (113m). The clastic facies of Upper Qishn increases at Tawila-1 and North Camaal-1 wells while decreases at Heijah-3 well.

VI. Hydrocarbon Potentialities

The main target of this work is to evaluate the hydrocarbon potentiality of reservoir rocks in the study area based on the results of well log analysis carried out for the wells in the study area through vertical petrophysical distribution cross plots of the analyzed data in each well and the horizontal Iso-parametric configuration maps. The vertical distribution, in a form of litho-saturation cross plots (volumetric analysis), shows the changes in lithology content, water and hydrocarbon contents for Lower Cretaceous sequence. The lateral Iso-parametric maps show the petrophysical parameter configuration of the area under study in the form of water and hydrocarbon saturations, total porosity and effective porosity distribution maps for Lower Cretaceous sequence.

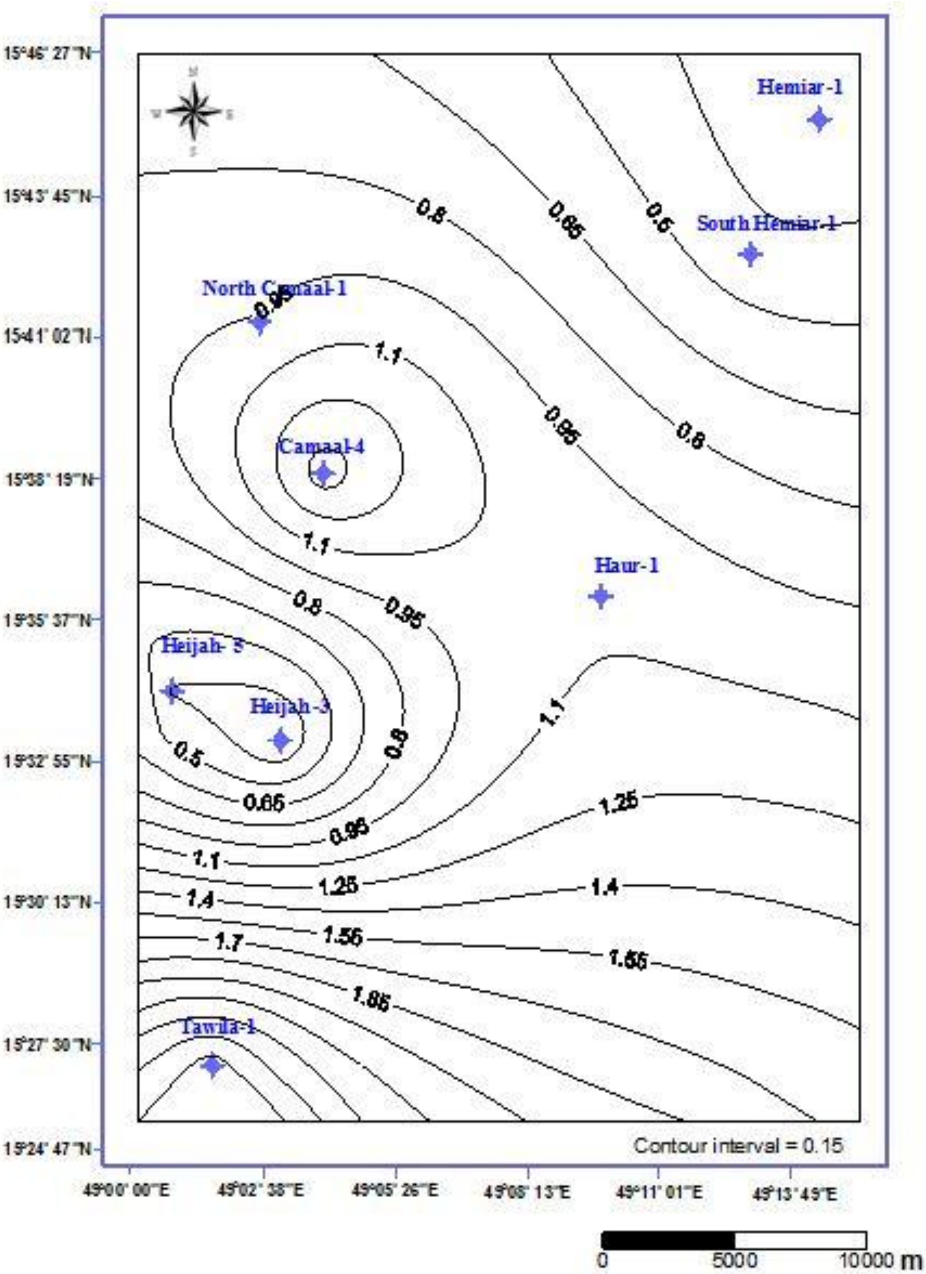

Fig. 5. Sand/shale ratio map of the Upper Qishn Carbonate Member for the study area.

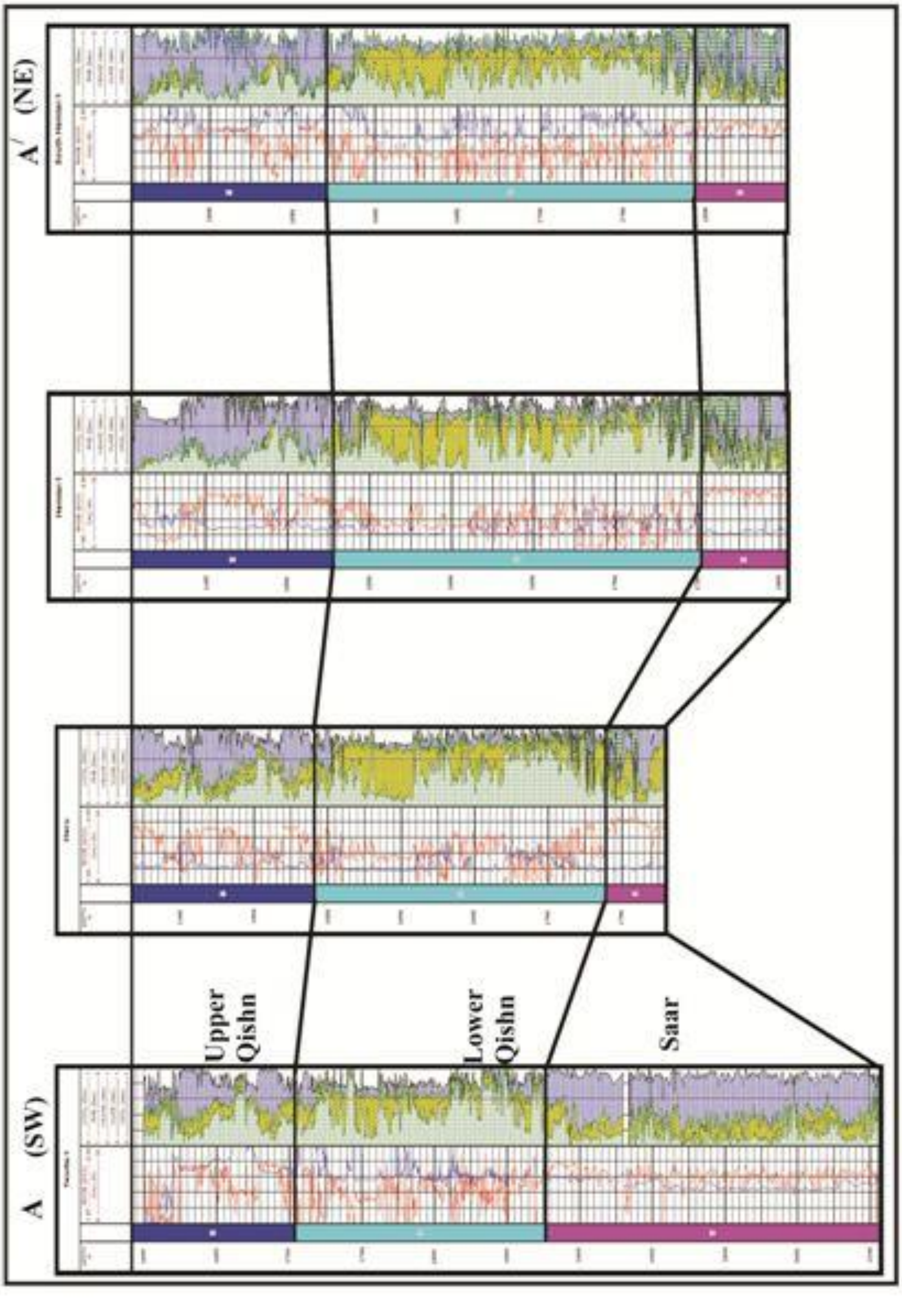

Fig. 6. Stratigraphic correlation line (A-$A^{/}$) through wells: Tawila-1, Haru-1, Hemiar-1, and South Hemiar-1 in the study area.

VI. Hydrocarbon Potentialities

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VI.1. *Lithological Identification*

The type and amount of each lithologic component for the Lower Cretaceous sequence was determined through different cross plots. These cross plots give a quick view about the rock and lithological contents in a qualitative way. Some of these cross plots give the amount of lithologic contents in a quantitative way. Such cross plots are NPHI-RHOB Matrix cross plots and GR-RHOB GR- NPHI cross plots.

VI.1.1 *Lithology Identification of North Camaal-1 Well*

A. *Lithology Identification of Qishn Formation*

a. Lithology Identification of Upper Qishn Carbonate Member

1- NPHI-RHOB Cross Plot Identification

The cross plot of NPHI-RHOB (Fig. 9) identifies carbonates (limestone and dolomite) from shale. The sandstone content is generally low as shown from the lesser plotted points along the sandstone line in this cross plot.

2- RHOB- NPHI Matrix Cross Plot Identification

The cross plot of NPHI-RHOB (Fig. 9) reflects the same picture of the above plot. The scattered plotted points show that the main lithology is carbonates (limestone and dolomite). The sandstone content is low as shown from the lesser-plotted points in the Quartz matrix zone in this cross plot.

3- GR-NPHI Cross Plot Identification

This plot (Fig. 9), which reflects the scattering of plotted points, indicates the variation of lithology of this rock unit. It shows that the points have a low GR and low NPHI indicating the presence of limestone and dolomite. Points that have a medium GR and medium NPHI reading indicate sandstone. On the other hand, points that have a high GR and high NPHI reading reflect the abundance of shale. It is clear that the main lithology is limestone and dolomite with shale and a little amount of sandstone.

4- GR-RHOB Cross Plot Identification

This plot (Fig. 9) illustrates the same as in the above plot except that the density of limestone and dolomite is larger than that of sandstone. Thus the points of limestone and dolomite are plotted in the left direction of the cross plot.

b. Lithology Identification of Lower Qishn Clastic Member

1- NPHI-RHOB Cross Plot Identification

The cross plot of NPHI-RHOB (Fig. 10) shows that the main lithology is sandstone with limestone, dolomite and shale. The sandstone content is generally high as shown from the highest -plotted points along the sandstone line in this cross plot, while the limestone and dolomite is low as shown from the lesser plotted points along the limestone and dolomite lines.

2- RHOB-NPHI Matrix Cross Plot Identification

The cross plot of NPHI-RHOB (Fig. 10) reflects the same picture of the above plot. The scattered plotted points indicate that the main lithology is sandstone with dolomite and limestone. The sandstone content is generally high as shown from the highest-plotted points along the Quartz matrix zone in this cross plot.

3- GR-NPHI Cross Plot Identification

This plot (Fig. 10), which reflects the scattering of plotted points, indicates the variation of lithology of this rock unit. The points, that have a low GR and low NPHI reading, indicate presence of limestone and dolomite, while the points that have a medium GR and medium NPHI reading indicate sandstone, and the points that have a high GR and high NPHI reading, reflect the abundance of shale. By comparison, it is clear that the main lithology is sandstone with limestone and dolomite and a few amount of shale.

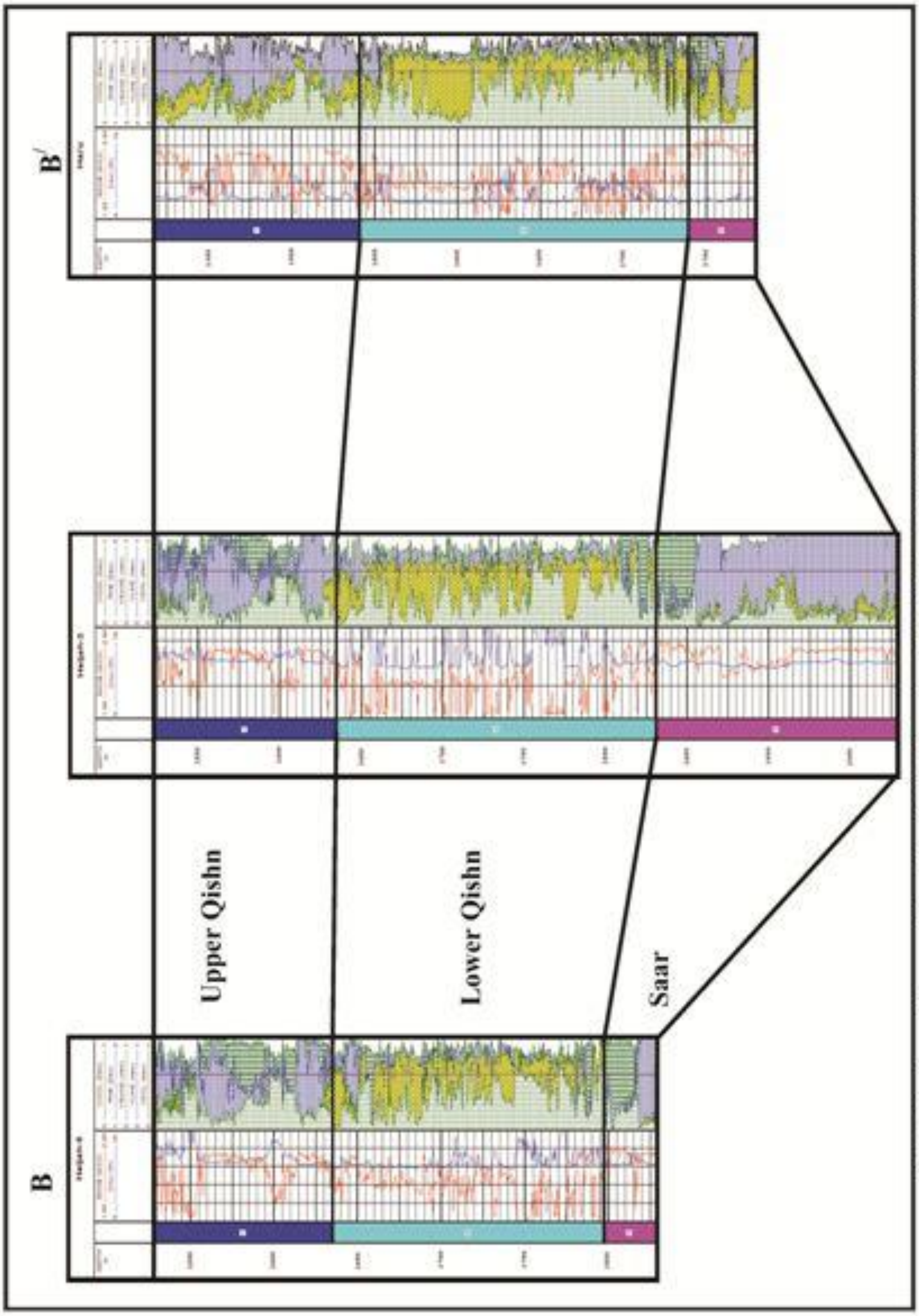

Fig. 7. Stratigraphic correlation line (B-B′) through wells: Heijah-5, Heijah-3, and Haru-1 in the study area.

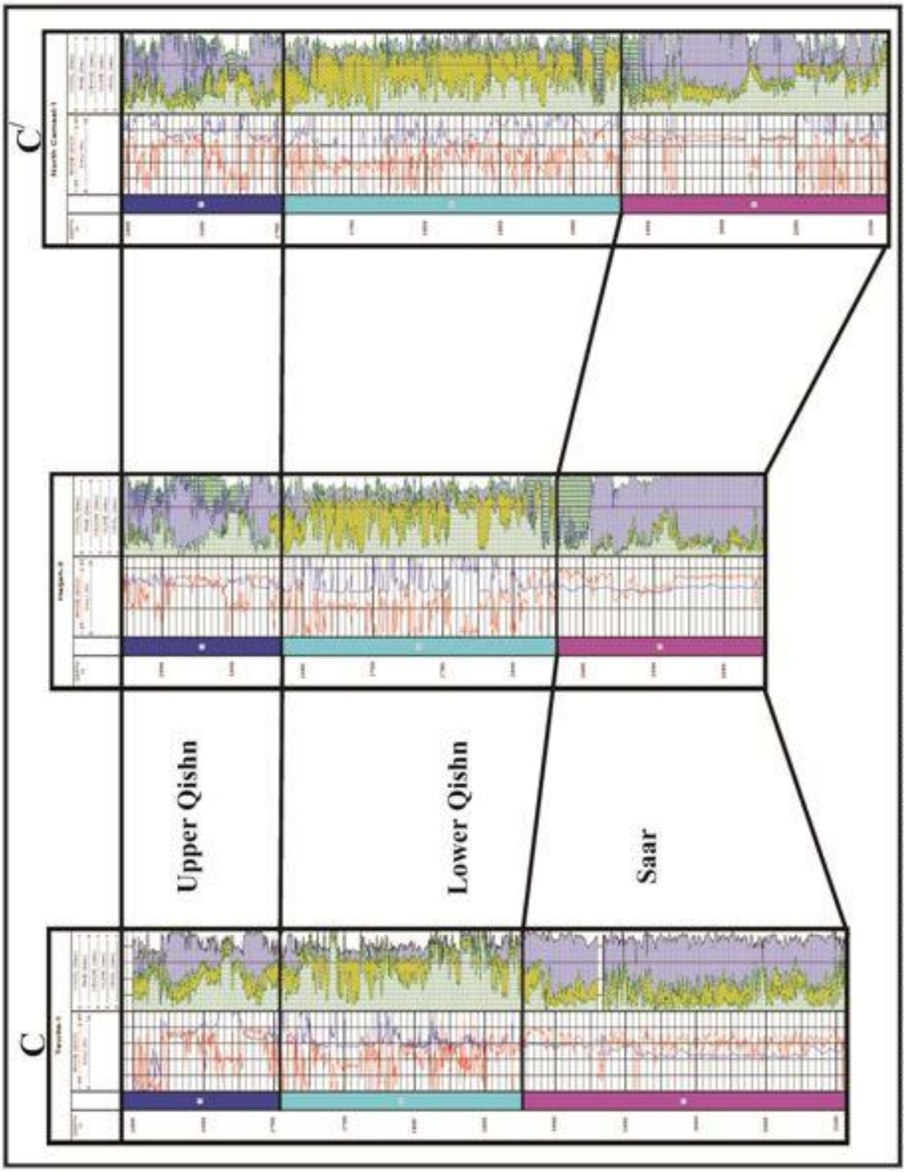

Fig. 8. Stratigraphic correlation line (C-C') through wells: Tawila-1, Heijah-3, and North Camaal-1 in the study area.

4- GR-RHOB Cross Plot Identification

This plot (Fig. 10) illustrates the same as in the above plot with three clusters as follows: the first cluster is a sandstone lithology (largest one) which has medium GR values and medium RHOB values. The second cluster is a limestone and dolomite (medium one) which has low GR values and high RHOB values. The third cluster is shale (small one) which has high GR values and low RHOB values.

VI.2. *Vertical Distribution of Hydrocarbon Occurrences*

The vertical distributions of hydrocarbon occurrences are shown through the litho-saturation cross plots. The litho-saturation cross plots are very important in well logging interpretation, for the illustration of the gross character of the petrophysical parameters, in terms of lithology fractionation and fluid saturation, such as water and hydrocarbon saturations. The formation analysis includes total porosity. Matrix content (sandstone, limestone and dolomite) and shale content in 100% scale. Moreover the caliper and density logs were presented in order to continuously check the reliability of the data encountered and their corresponding false petrophysical parameters analysis.

VI.2.1 *Litho-Saturation Cross Plot of the Lower Cretaceous of North Camaal-1 Well*

The studied interval of this well extends between 1594m and 2111m and constitutes the Upper Qishn, and Lower Qishn members and Saar Formation. The Upper Qishn Member is composed of limestone, dolomite, with shale and a few of sandstone. The Lower Qishn Member is composed mainly sandstone with limestone, dolomite, and shale. Saar Formation is composed mainly limestone and dolomite with sandstone. The average shale value is 17.8% while the average sandstone value is 1.7% and the average limestone and dolomite values are 65.1% at the Upper Qishn Member.

At the Lower Qishn Member showing the average of sandstone value is 51.6% while the average shale value is 18.8% and the average limestone and dolomite values are 29.6%. The Saar Formation showing the average shale value is 22.4% while the average sandstone value is 10.4% and the average of limestone and dolomite values are 67.2%. The average total porosity value is 16% at the Upper Qishn Member while at the Lower Qishn Member the average total porosity value is 18.7% and the Saar Formation the average total porosity value is 11.5%. The average calculated porosity values are 54.9% for water saturation and 45.7% for hydrocarbon saturation at the Upper Qishn. The average porosity values are 29.4% for water saturation and 70.6% for hydrocarbon saturation at the Lower Qishn. At the Saar Formation the average porosity values are 70.7% for water saturation while the hydrocarbon saturation is 29.3%.

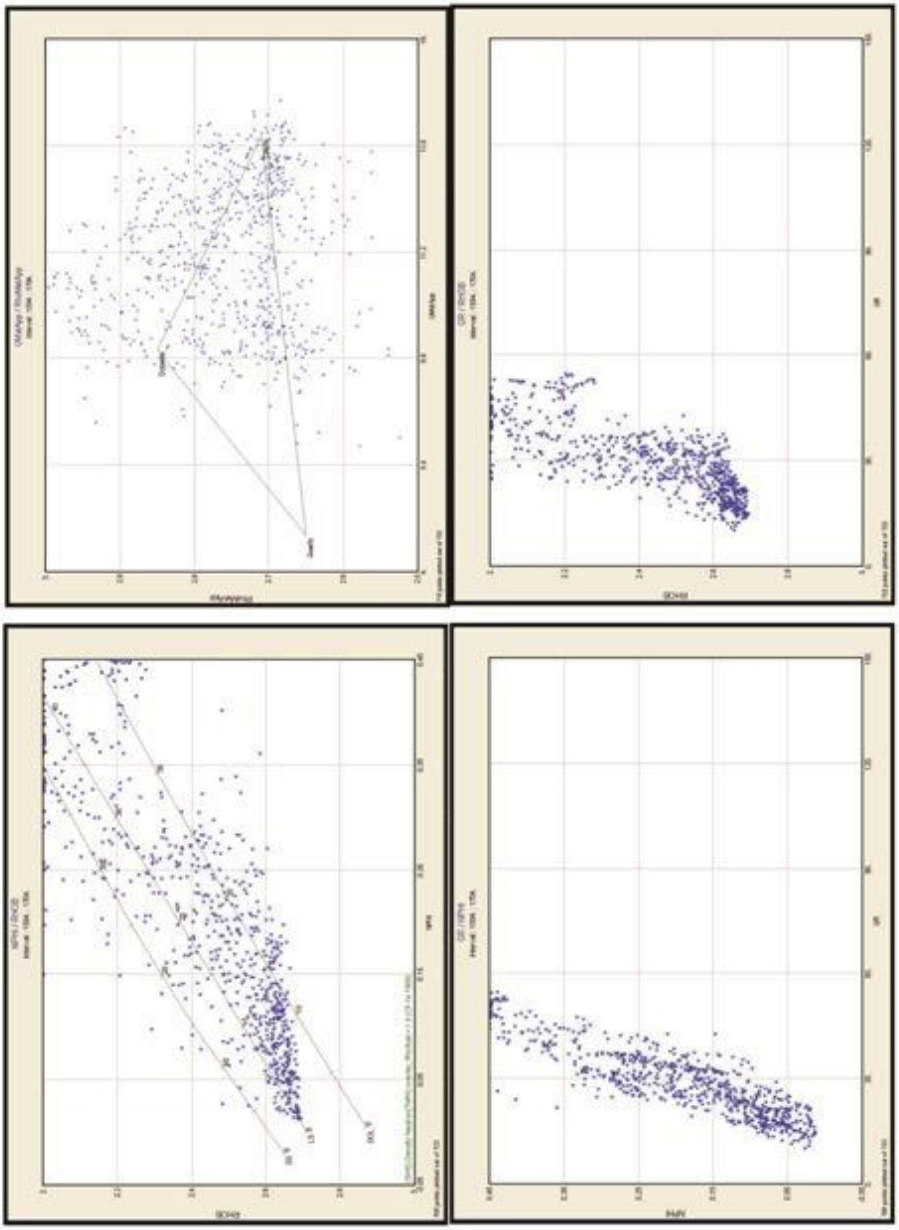

Fig. 9. Lithology identification of Upper Qishn Carbonate Member for North Camaal-1 well.

VI.2.2 *Litho-Saturation Cross Plot of the Lower Cretaceous of Camaal-4 Well*

In this well, the studied interval extends from 1568m to 2155m below sea level and represented by Upper Qishn, and Lower Qishn members and Saar Formation. The rock units are composed of limestone, dolomite, with shale and sandstone at the Upper Qishn Member. The Lower Qishn Member is composed mainly sandstone with limestone, dolomite, and shale. The Saar Formation is composed mainly limestone and dolomite with sandstone and shale. The average limestone and dolomite values are 81.7% while the average sandstone value is 10.9% and the average shale value is 7.4% at the Upper Qishn Member.

At the Lower Qishn Member showing the average of sandstone value is 50.4% while the average shale value is 6.8% and the average limestone and dolomite values are 42.8% that indicating clean sandstone. At the Saar Formation showing the average of limestone and dolomite values are 87.4% while the average sandstone value is 9.6% and the average shale value is 3.1% and showing a highly carbonates formation.

The average total porosity value is 13.7% at the Upper Qishn Member while at the Lower Qishn Member the average total porosity value is 22% and the Saar Formation the average total porosity value is 6.8%. The average calculated porosity values are 58% for water saturation and 42% for hydrocarbon saturation at the Upper Qishn Member. The average porosity values are 31.3% for water saturation and 68.7% for hydrocarbon saturation at the Lower Qishn Member. At the Saar Formation the average porosity values are 66.2% for water saturation and 33.8% for hydrocarbon saturation.

VI.2.3 *Litho-Saturation Cross Plot of the Lower Cretaceous of Haru-1 Well*

In this well, the Upper Qishn, lower Qishn Members and Saar Formation extend between depths 1417m and 1779m. The rock units are composed of limestone with shale and sandstone and a few of dolomite at the Upper Qishn Member. The Lower Qishn Member is composed mainly sandstone with shale and limestone, dolomite. The Saar Formation is composed mainly of dolomite and limestone with sandstone and low content of shale.

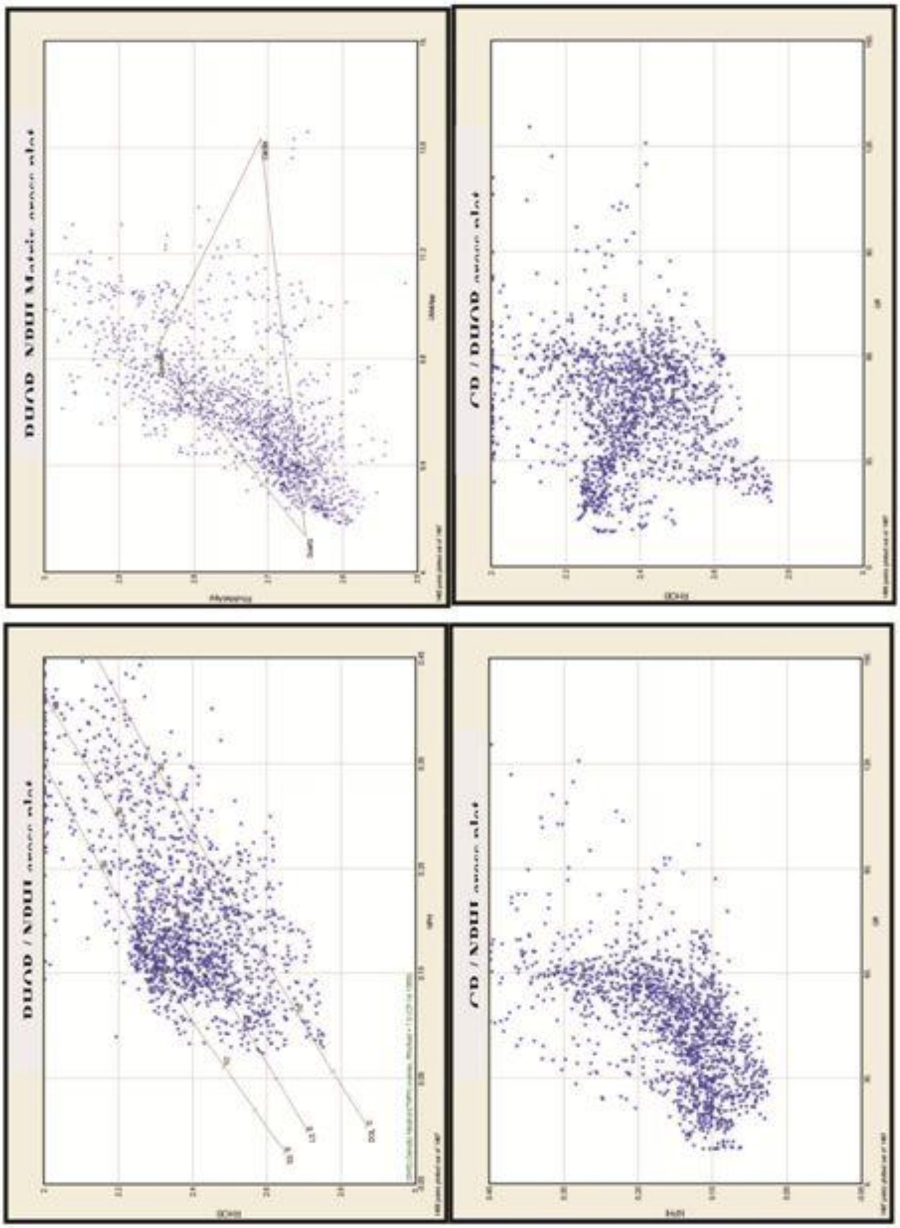

Fig. 10. Lithology identification of Lower Qishn Clastic Member for North Camaal-1 well.

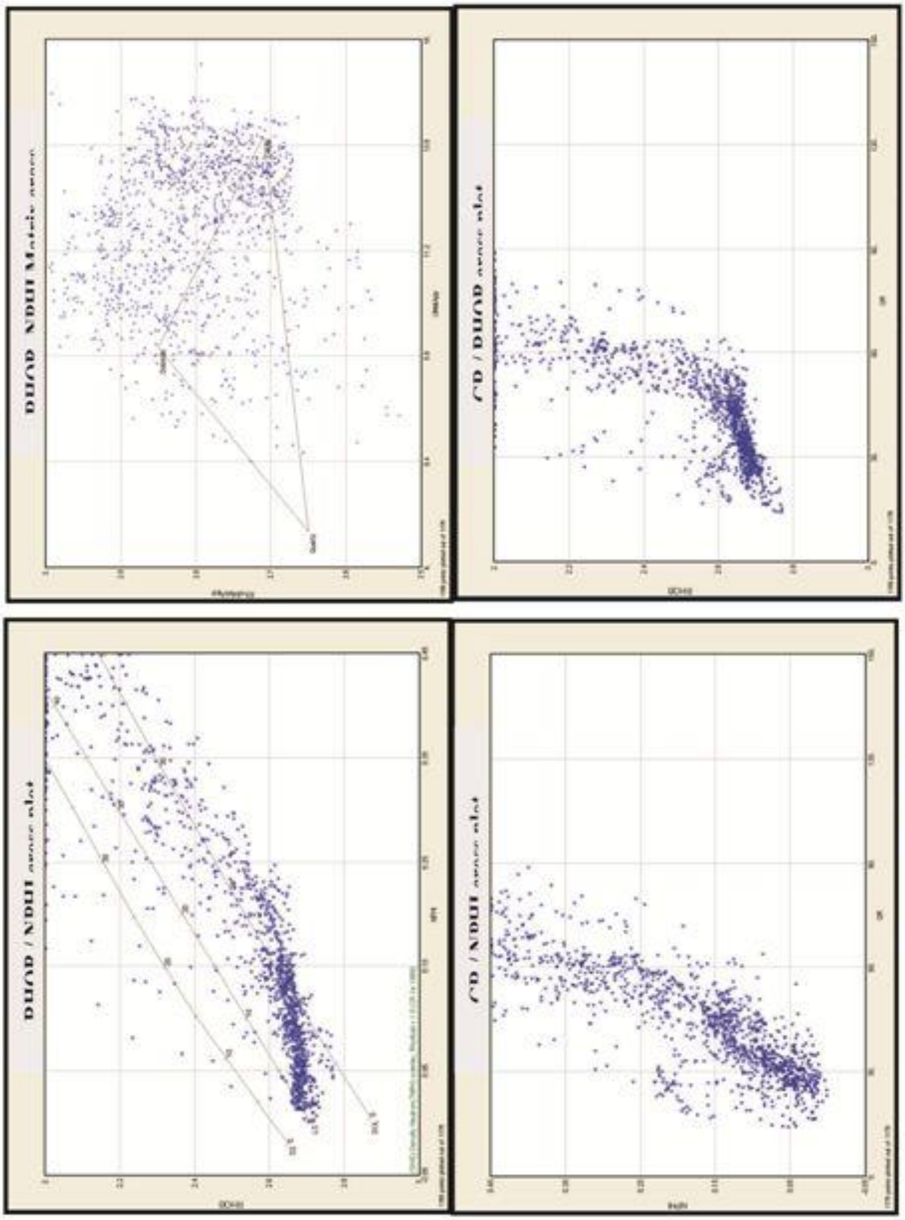

Fig. 11. Lithology identification of Saar Formation for North Camaal-1

The average limestone and dolomite values are 64.7% while the average sandstone value is 18.3% and the average shale value is 17% at the Upper Qishn Member. At the Lower Qishn Member showing the average of sandstone value is 48.8% while the average shale value is

21.6% and the average limestone and dolomite values are 29.6%. The Saar Formation showing the average of limestone and dolomite values are 71.4% while the average sandstone value is 24.4% and the average shale value is 4.2%. The average total porosity value is 14.3% at the Upper Qishn while at the Lower Qishn the average total porosity value is 21.3% The average calculated porosity values are 62.3% for water saturation and 37.7% for hydrocarbon saturation at the Upper Qishn Member. The average porosity values are 31.8% for water saturation while the hydrocarbon saturation is 68.16% at the Lower Qishn Member. At the Saar Formation the average porosity values are 75.6% for water saturation and 24.4% for hydrocarbon saturation.

VI. 2.4 *Litho-Saturation Cross Plot of the Lower Cretaceous of Heijah-5 Well*

The studied interval of this well extends between 1528m and 1828m and constitutes the Upper Qishn, and Lower Qishn members and Saar Formation (Fig. 12). The rock units are composed of limestone and dolomite with shale and a few of sandstone at the Upper Qishn Member. The Lower Qishn Member is composed mainly of sandstone with limestone, dolomite and shale. The Saar Formation is composed mainly of limestone and dolomite with shale and sandstone. The average limestone and dolomite values are 68.2% while the average shale value is 22.9% and the average sandstone value is 7.9% at the Upper Qishn. The average shale value reflects a high shaly-carbonate member. At Lower Qishn, the average sandstone value is 51.3% while the average shale value is 18.4% and the average limestone and dolomite values are 30.3%. At the Saar, the average of limestone and dolomite values are 73.2% while the average shale value is 15% and the average sandstone value is 11.8%. The average total porosity value is 14% at the Upper Qishn while at the Lower Qishn, the average total porosity value is 20.4% and the average total porosity value is 6% of the Saar Formation. The average calculated porosity value is 60.6% for water saturation while for the hydrocarbon saturation, the average value is 39.4% at the Upper Qishn Member. The average porosity value is 31.6% for water saturation while for the hydrocarbon saturation; the value is 68.4% at the Lower Qishn Member. At the Saar Formation, the average porosity value is 76.3% for water saturation and 23.6% for hydrocarbon saturation.

VI. 2.5 *Litho-Saturation Cross Plot for Lower Cretaceous of Tawila-1 Well*

In this well, the Upper Qishn, and lower Qishn members and Saar Formation extend between depths 1591m and 2106m (Fig. 13). The rock units are composed mainly of limestone with dolomite and sandstone and a few of shale at the Upper Qishn Member. The Lower Qishn Member is composed dominantly of sandstone with limestone and dolomite, and low content of shale. The Saar Formation is composed mainly of limestone with sandstone and a few of dolomite. The average limestone and dolomite values are 76.2% while the average shale value is 6.5% and the average sandstone value is 17.3% at the Upper Qishn. At the Lower Qishn, the average of sandstone value is 47.9% while the average shale value is 7.8% and the average limestone and dolomite values are 44.4%, which indicates clean sandstone. At Saar Formation, the average of limestone and dolomite values are high 80.4% while the average sandstone value is 17.7% and the average shale value is 1.9% which reflects a highly carbonate formation.

The average total porosity value is 15% at the Upper Qishn Member while at the Lower Qishn Member, the average total porosity value is 20.5%. At Saar Formation, the average total porosity value is 9.2%. The average calculated porosity values are 55.7% for water saturation and 44.3% for hydrocarbon saturation at the Upper Qishn Member while the average porosity values are 37.2% for water saturation and 62.8% for hydrocarbon saturation at the Lower Qishn Member. At Saar Formation, the average porosity values are 53.3% for water saturation and 46.7% for hydrocarbon saturation.

VI.3. Horizontal Distribution of Hydrocarbon Occurrences

The lateral distribution of hydrocarbon occurrence can be studied and explained through a number of porosity and saturation gradient maps. These maps are constructed for petrophysical parameters (total and effective porosities, water saturations) for the Lower Cretaceous sequence to complete the picture of hydrocarbon potentialities in the study area. The weighted-average-determined petrophysical properties, for the Lower Cretaceous sequence, in the studied wells, have been calculated.

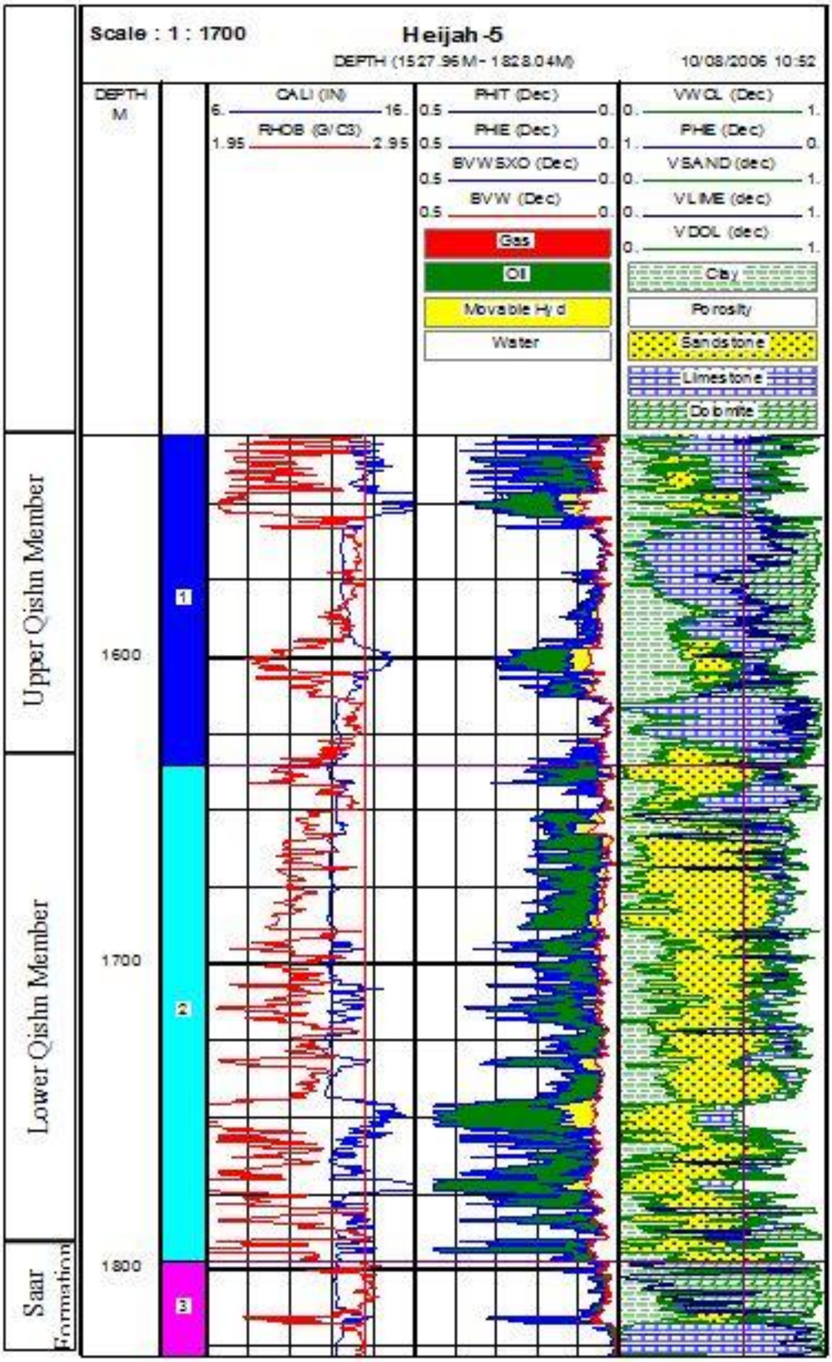

Fig. 12. Litho- saturation cross plot of the Lower Cretaceous for Heijah-5 well.

VI.3.1 *Porosity Gradient Maps*

For the evaluation of the reservoir rocks of the studied rock units, a set of iso-porosity maps (total and effective porosities) were constructed to follow the distribution of the implied types of porosity in the study area.

VI.3.1.1 *Total Porosity Distribution Maps*

a. Total Porosity Distribution Map for Upper Qishn Member

The total porosity distribution map of the Upper Qishn Member (Fig. 14) in study area shows variation in porosity values from minimum value (13.4%) at Heijah-3 well to maximum value (16%) at North Camaal-1 well. This map shows that the total porosity increases toward northwestern, east and southwestern parts of the study area but decreases at northeastern part of the study area.

b. Total Porosity Distribution Map for Lower Qishn Member

The distribution of the total porosity in the Lower Qishn Member shows variation in porosity values from minimum value (18.7%) at North Camaal-1 well to a maximum value (24.3%) at Heijah-2 well. This map shows that the total porosity increases toward central, eastern, and northeastern parts of the study area while decreases toward northwestern, and southwestern parts of the study area.

c. Total Porosity Distribution Map for Saar Formation

The distribution of total porosity in the Saar Formation in the study area shows variation in porosity values from a minimum value (5%) at Heijah-3 well to a maximum value (11.5%) at North Camaal-1 well.

VI. 3.1.2 *Effective Porosity Distribution Maps*

a. Effective Porosity Distribution Map of the Upper Qishn Member

The effective porosity distribution map of the Upper Qishn Member (Fig. 15) shows variation in porosity values from a minimum value (9.5%) at Heijah-3 well to a maximum value (14.5%) at Tawila-1 well. This map has nearly the same configuration and trends as in the total porosity distribution map. It shows that the effective porosity increases toward northwestern, east and southwestern parts of the study area but decreases at central part of the study area.

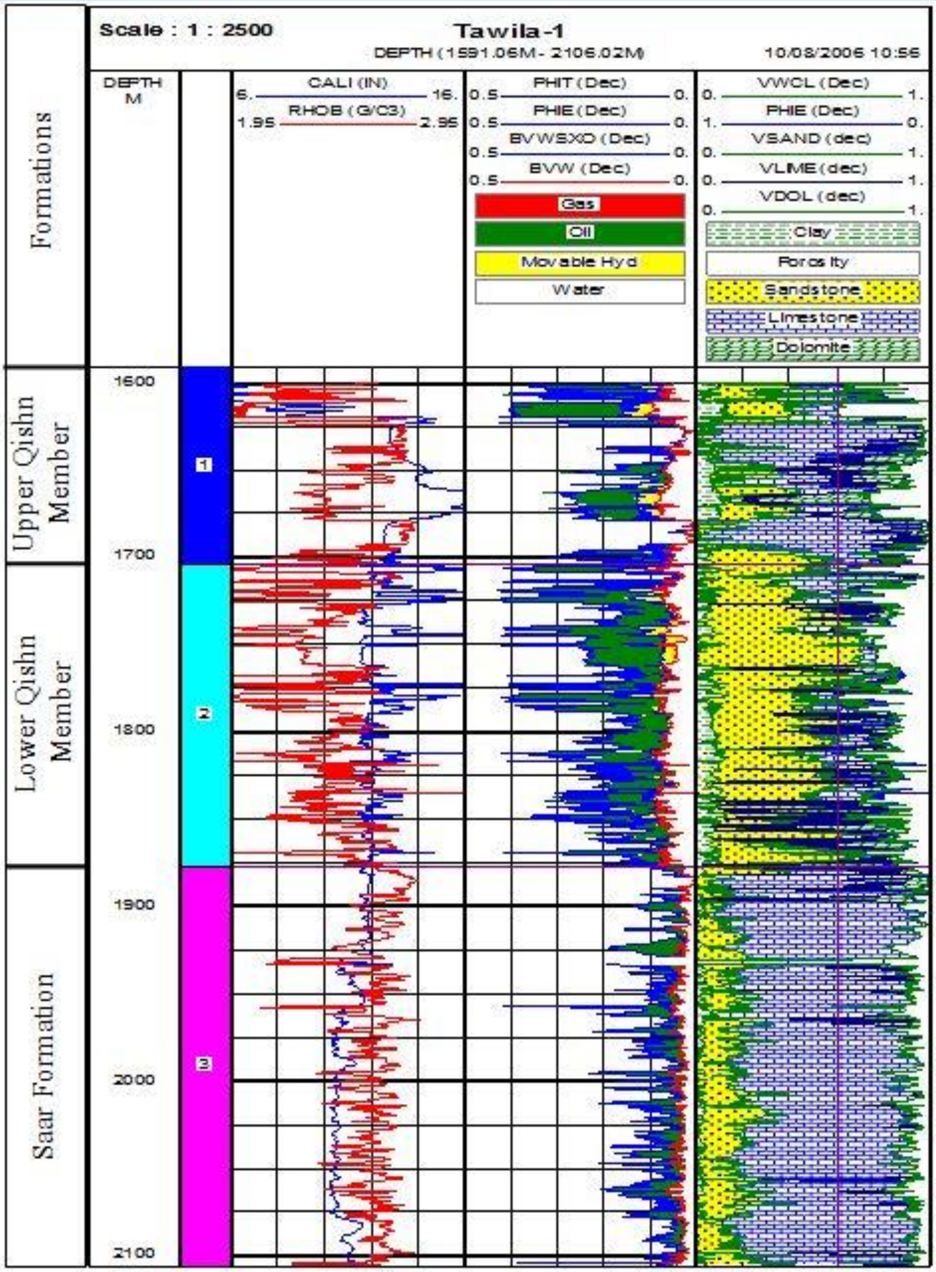

Fig. 13. Litho- saturation cross plot of the Lower Cretaceous for Tawila-1 well.

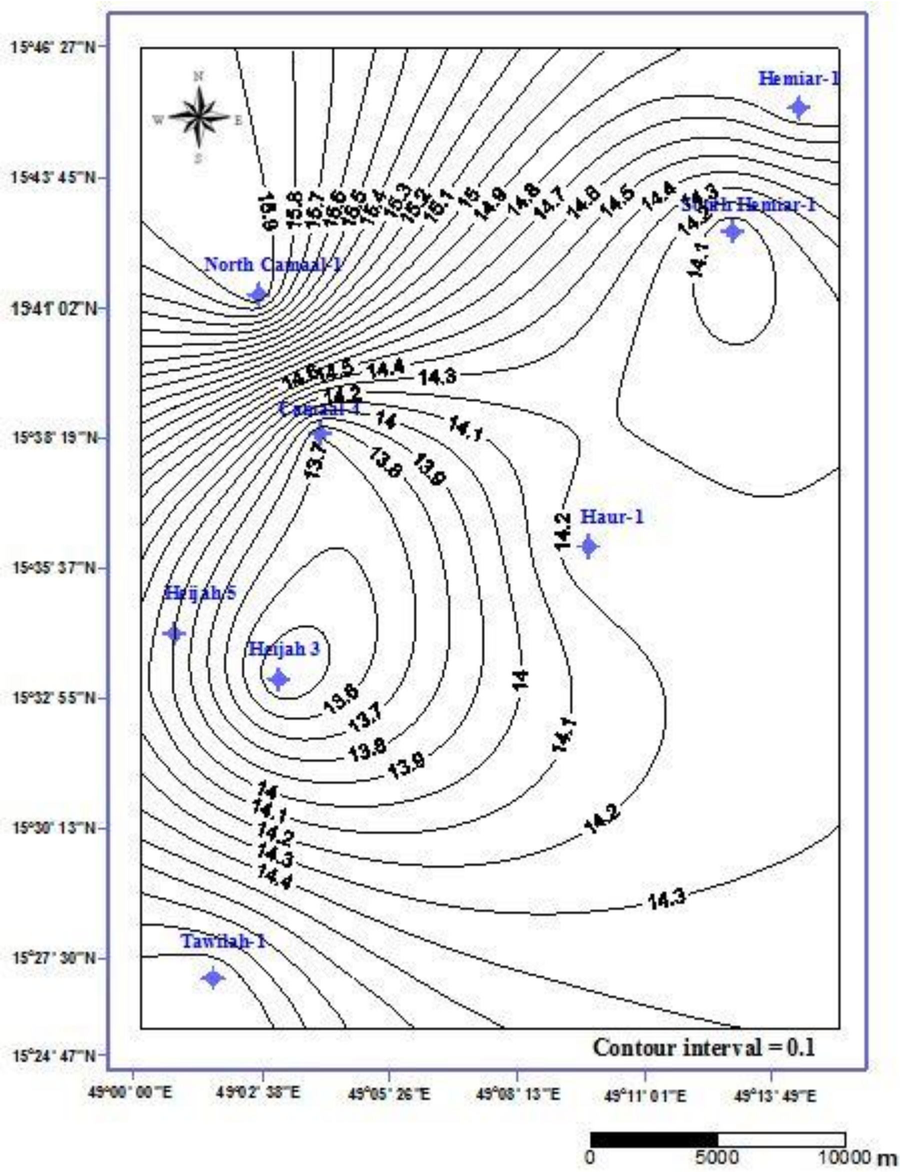

Fig. 14. Total porosity distribution map of the Upper Qishn Member in the study area.

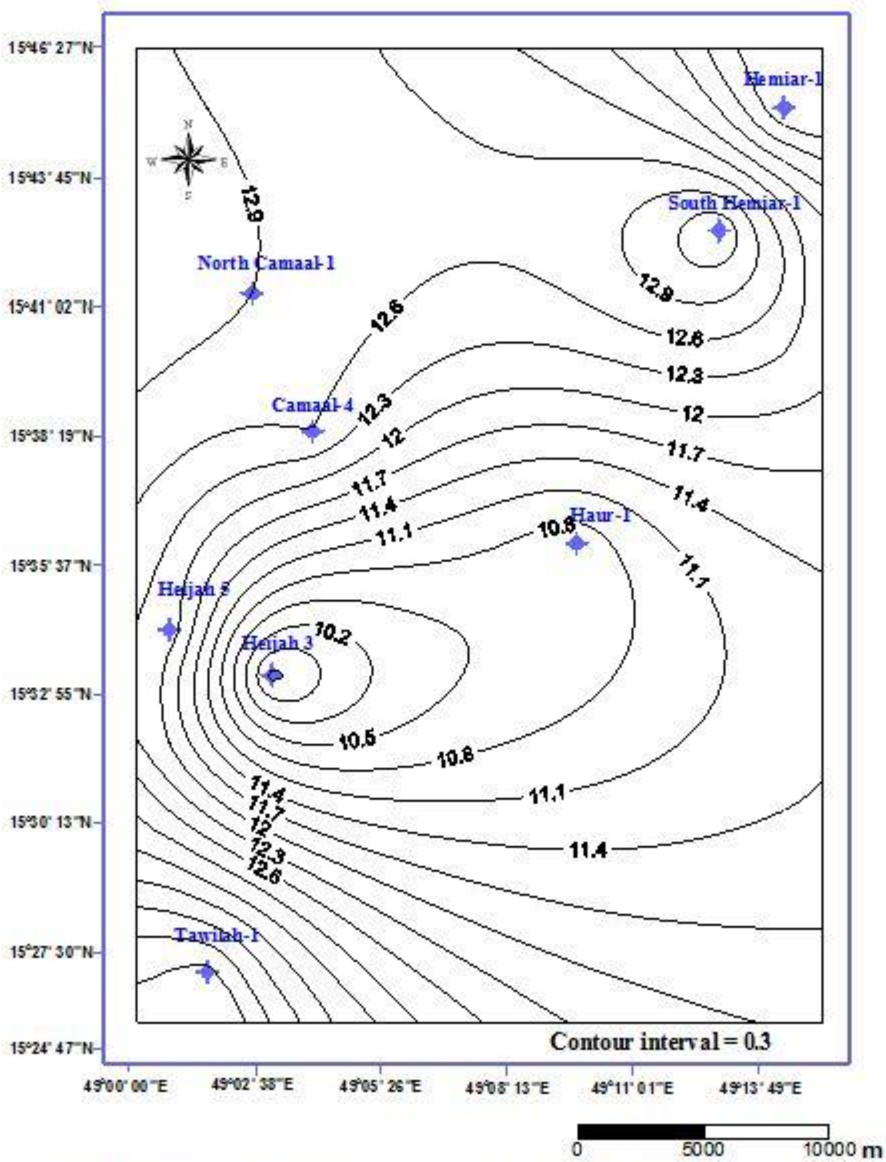

Fig. 15. Effective porosity distribution map of the Upper Qishn Member in the study area.

b. Effective Porosity Distribution Map of the Lower Qishn Member

The distribution of the effective porosity in the Lower Qishn Member shows variation in porosity values from a minimum value (16%) at North Camaal-1 well to a maximum value (21.5%) at South Hemiar-1 well. This map shows that the effective porosity increases toward central and northeastern parts of the study area but decreases toward east at Haru-1 well, northwestern, and west parts of the study area.

c. Effective Porosity Distribution Map of Saar Formation

The distribution of the effective porosity in the Saar Formation shows variation in porosity values from a minimum value (3%) at Heijah-5 well to a maximum value (8.6%) at Tawila-1 well. This map shows that the effective porosity increases toward northwestern, east and southwestern parts of the study area while decreases toward northeastern part of the study area.

VI.3.2 *Water Saturation Distribution Maps*

a. Water Saturation Distribution Map of the Upper Qishn Member

The distribution of water saturation map in the Upper Qishn Member shows variation in water saturation values from a minimum value (54.9%) at North Camaal-1 well to a maximum value (62.3%) at Haru-1 well. Generally the water saturation increases toward east, and central parts of the study area while decreases toward northeastern, northwestern, southwestern, and west parts of the study area.

b. Water Saturation Distribution Map of the Lower Qishn Member

The water saturation map of the Lower Qishn Member (Fig. 16) shows variation in water saturation values from a minimum value (29.4%) at North Camaal-1 well to a maximum value (37.2%) at Tawila-1 well. This map shows that the water saturation distribution increases toward south, and central parts of the study area but decreases toward northwestern part of the study area.

c. Water Saturation Distribution Map of Saar Formation

The distribution of the water saturation in the Saar Formation shows variation in water saturation values from a minimum value (52%) at South Hemiar-1 well to a maximum value (76.3%) at Heijah-5 well. Generally the water saturation distribution increases toward central to east, and northwestern parts of the study area while decreases toward northeastern, west, and southwestern parts of the study area.

VI.4 *Overview of Present Work on Hydrocarbon Habitat*

The physical entities of hydrocarbon habitat are consisting of the source rock, reservoir rock, seal rock and trap. The Masila area can be considered as oil province since the exploration work is focused on the following targets:

- About 90% of the reserves are found in the Lower Qishn Clastics Member of the Qishn Formation.
- The fractured Cambrian granitic basement rocks are present in area.
- Additional targets are clastic and carbonate rocks ranging from Late Jurassic to Early Cretaceous age (Saar Formation).

VI.4.1 *Source Rocks*

In the Masila area, the principal source rock is the Madbi Formation (Canadian Oxy Company, 2001; and PEPA, 2004). The Madbi source rock is mainly of laminated organic rich shale. Geochemical studies performed in the Masila rift basin had indicated the presence of two types of kerogen (I, II) with different percentages of total organic carbon (TOC) and Vitrinite Reflectance (Ro). It represents a good quality, oil prone source rocks, deposited in a marine anoxic environment with Kerogen of type-I (Algal Sapropel) and type-II (Waxy Sapropel). It achieved oil maturity in the Early Cretaceous.

VI.4.2 *Reservoirs*

Potential reservoir rocks are widely distributed throughout the geological section of the Masila basin:

- Basement and weathered basement produced hydrocarbon from fracture pores (Canadian Oxy Company, 2001; PEPA, 2004).
- Kohlan Formation sandstones.
- Saar Carbonates with reservoir and additional Clastic reservoirs have been encountered in the Saar Formation (Canadian Oxy Company, 2001; PEPA, 2004).
- The main reservoirs targets in the Masila basin are Lower Cretaceous, Qishn Clastic Member of the Qishn Formation (Canadian Oxy Company, 2001; PEPA, 2004).
- In addition to potential reservoir, the Qishn Carbonate Member of the Qishn Formation is another target.

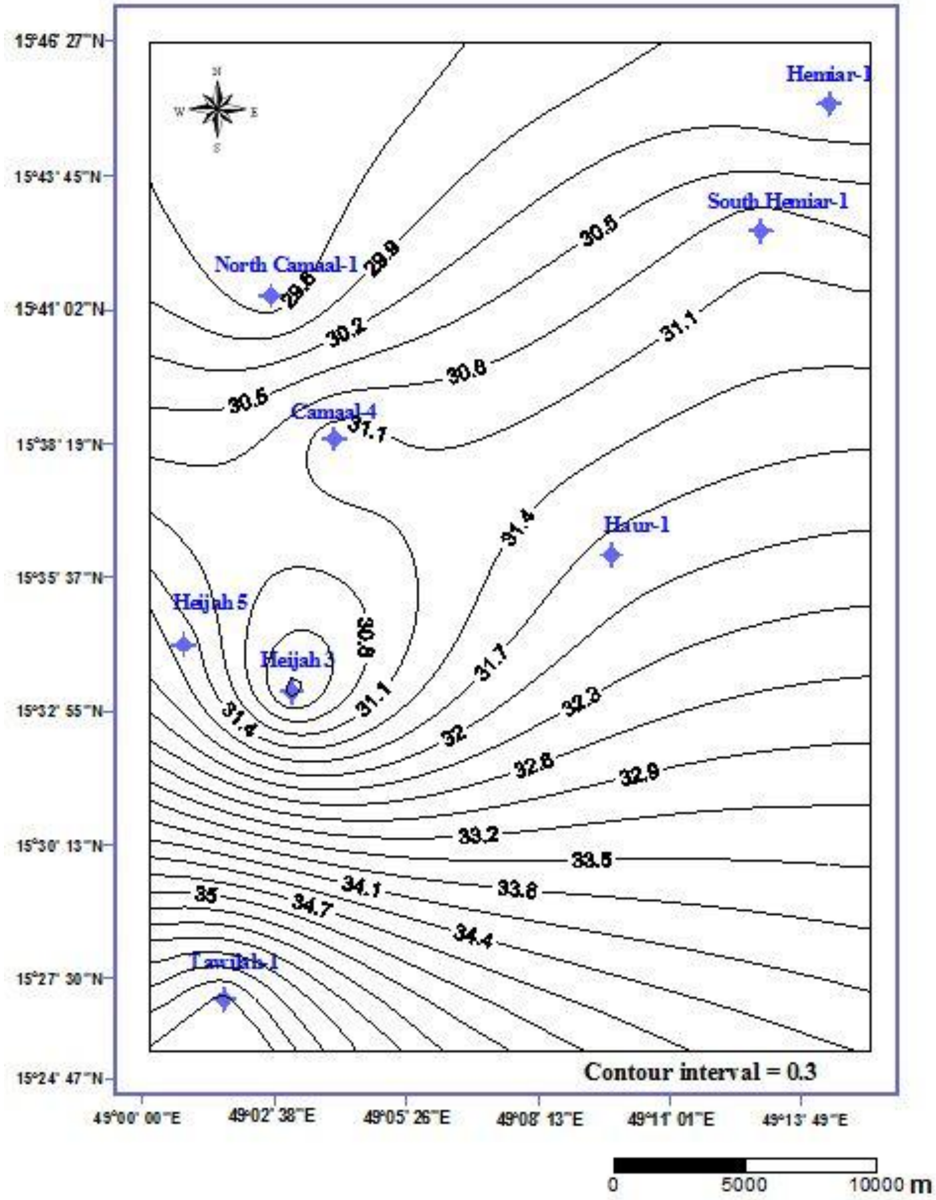

Fig. 16. Water saturation distribution map of the Lower Qishn Member in the study area.

VI. 4.3 *Seal Rocks*

In the study area, the seal rocks cover the main reservoir (Qishn Clastic) and are represented by the Qishn Carbonate and Harshiyat Shale. The total thickness of carbonates and shales ranges from 40 to 200 m with 150 m thick around the central and Southern part of the basin .The Saar Carbonate reservoirs are sealed by shale and carbonate beds within Saar. Meanwhile, Saar Clastics are sealed by the intra-formational massive shales and overlying carbonates. The Kohlan sandstone and fractured basement reservoirs are sealed by the shales of the Madbi Formation or carbonates of the Shuqra Formation.

VI. *4.4 Traps*

The majority of oil fields discovered in the Masila basin are associated with the structural traps but potential stratigraphic traps exist. Extensional tectonics related to Late Jurassic phase of rifting has resulted in structural traps and the most common of these are:

1. Fault – bounded horst blocks.
2. Tilted fault blocks. (Beydoun and Sikander, 1992)

Traps developed during, and associated with earlier phases of rifting, are commonly modified, and in many cases, closures are enhanced by fault reactivation during younger phases of rifting in the studied Masila and neighboring areas (Beydoun, *et al.* 1996).

Summary and Conclusions

1. The Mesozoic basins of Yemen vary spatially and temporally from the west to the east of the country. The interior rifts of the western and central areas are oriented NW-SE. The Sayun-Masila Basin and Jiza'-Qamar basins are oriented progressively more east-west. The extensional Basin Phoenix extends 140º and is a possible extension to the west of al Masila Basin. It is a large asymmetric graben with strata dipping and thickening to the southwest with an estimated 3 km of Upper Jurassic-Lower Cretaceous syn-rift strata showing phases of footwall fan progradation. The earliest syn-rift strata within the Masila basins are early to mid Kimmeridgian in age with a maximum subsidence occurring in the Kimmeridgian and Tithonian.

2. Highly detailed reservoir properties from log analysis were augmented by similarly detailed seismic and stratigraphic correlations,

and integrated together in a 3D geological model and reservoir simulator to provide an accurate historical and predictive model for production optimization.

3. In the fields of Masila block, the Early Cretaceous marine Qishn Formation provides both the reservoir sandstone and an overlying sealing tight limestone unit. The largest hydrocarbon volumes are reservoired in sands of the Qishn Formation sands of Barremian-Aptian age that have produced considerable rates of oil with little dissolved gas and are sealed by tight limestones of the Qishn Formation. The Qishn Formation comprises shallow shelf to fluvio-deltaic sandstones in central and western Yemen and is likely to be equivalent to the lower fluviatile sandstones of the Tawilah Group of western Yemen and to the east it becomes more carbonate rich and passes into the purer carbonate facies of the Mahra Group (Beydoun, 1997).

4. The Madbi shale is the source for the Masila block fields which are located over horsts that comprise the Masila Terrace. The largest hydrocarbon volumes are reservoired in the Qishn Formation sands (Barremian Aptian)**.** The absence of the Sab'atayn salt from the Masila basin provides a direct migration pathway from the Late Jurassic Madbi source to the Early Cretaceous sands (Qishn Formation). The fault network of the reservoir defines the interrelationship between the faults, such as truncations, intersections, and lateral extensions. The internal zonation of Masila reservoir, based on sequence stratigraphic analysis and lateral correlation across the reservoir, is sub-seismic. The structural model of the Masila area shows the relationships between the major fault and selected horizons in the basin: pre-fault top of basement; syn-fault tops of the Upper Qishn and Lower Qishn members and Saar Formation.

5. Quantitative analyses of well logs were carried out for the Lower Qishn Clastic reservoir encountered in the selected eight wells in the study area. The reservoir evaluation that represents the main task in the present work is conducted to evaluate the petrophysical parameters needed for formation evaluation. It includes determination of shale volume, porosities (total, and effective), lithology identification (sand, and carbonates), and fluid saturation (water, and hydrocarbon) for the studied formations using the Interactive Petrophysics software (IP). The results of well log analysis were used in the evaluation of the hydrocarbon potentialities of the study area.

6. Porosity analyses of the investigated reservoir for the studied wells concluded that the total porosity ranges from 18% to 24.3% while the effective porosity ranges from 25% to 18%. The permeability of this reservoir range from 375 to 103 md. Meanwhile, the water saturation values range from 29% to 37%, whereas the hydrocarbon saturation has a match with water saturation in a reverse relationship. Hydrocarbon occurrence decreases, whereas water saturation increases.

7. The lithology of the investigated reservoir indicates that the main lithology is composed mainly of sandstone with shale and carbonates. From petrophysical parameters, it is concluded that the reservoir has high hydrocarbon saturation and containing many pay zones. The integrated interpretation of the open-hole log data helped in the determination of the total and effective porosities, fluid saturation and Lithology identification for Qishn and Saar Formations in the studied wells at the Masila area. The utility of cross-plots between the implied petrophysical parameters facilitates the lithology identification. By this way, the Qishn Formation is composed mainly of sandstone with limestone and dolomite, and Saar Formation is composed mainly of limestone and dolomite with shale and low content of sandstone. Hydrocarbon saturation of Qishn Formation is higher in value when compared with that of Saar Formation.

8. From petrophysical parameters, it is concluded that the reservoir has high hydrocarbon saturation and contains many pay zones. Meanwhile, the water saturation values range from 29% to 37%. On the other hand, the hydrocarbon saturation has a match with the water saturation in a reverse relationship*; i.e.* the hydrocarbon occurrence decreases, where as water saturation increases.

9. The utility of cross-plots between the implied petrophysical parameters facilitates lithology identification. By this way, the Qishn Formation is composed mainly of sandstone with limestone and dolomite, and Saar Formation is composed mainly of limestone and dolomite with shale and low content of sandstone in the studied wells.

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الاحتمالات الهيدروكربونية وخصائص خزان تتابعات الكريتاوي المبكر بحقل نفط المسيلة باليمن

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المستخلص. تعتمد مواصفات خزان النفط على دراسات تكاملية للجودة، والمميزات الكيفية والكمية للبيانات والمعلومات المتاحة، بأسلوب ومنهاج مترابط ومتناسق، بغرض وصف ومعرفة خصائص الخزان، عند مواضع آباره المحفورة. فبالنسبة للخزانات البترولية تعتمد خصائص الخزان على عملية تكامل البيانات السيزمية (الزلزالية) مع مختلف المعلومات الأخرى، ومع بيانات سجلات الآبار إلى حد كبير، بطريقة متناسقة لرصد وتعيين خصائص المكمن، اعتمادا على البيانات السيزمية إلى حد كبير.

تضم المدخلات الأساسية لعملية دراسة خصائص المكمن كلا من الإطار الجيولوجي، وبيانات سجلات الآبار، والبيانات السيزمية (ثنائية، وثلاثية، ورباعية البعد) وبيانات الضخ الإخبارية للآبار، بالإضافة إلى أي بيانات أخرى، يمكن مضاهاتها مع الخصائص الصخرية مثل: المسامية، والنفاذية، والتشبع، والسمك، والسحن الصخرية.

إن هدف دراسة خصائص المكمن محل البحث (خزان الكريتاوي السفلي بحقل نفط المسيلة باليمن) هو تقييم الهيدروكربونات في النطق المسامية الموجودة بتتابعات الكريتاوي المبكر، من خلال

ثمانية آبار، موزعة لتغطي الخزان محل الدراسة، ومن خلال مسح سيزمي ثنائي وثلاثي البعد. وقد تم الأخذ في الاعتبار أثناء عملية تقييم المتكون، السمات الجيولوجية لتقنية تقييم المتكون، وكذا قيم المعاملات البتروفيزيائية. تشمل بيانات سجلات الآبار الأساسية كلا من:

1. Spontaneous potential (SP), 2. Caliper (CL), Deep (LLS, LLD), and Shallow (MSFL) resistivity logs, 3. porosity tools (Density, Neutron and sonic), 4. litho-density (PEF) 5. Gamma-Ray (GR). كما تم استخدام علاقات بيانية متنوعة مثل Rho-PHIN (Density-Porosity), Rho-DTN (Density-Sonic), M-N (Cementation-Saturation) للتعريف الصخري للمتكونين محل الدراسة (متكون الكشن Qishn Formation ومتكون السار Saar Formation) في الآبار المدروسة. وقد سمح هذا التقييم للمتكونين من خلال المعاملات البتروفيزيائية، باستنتاج أن المتكونين بهما تشبع مرتفع بالهيدروكربونات في المنطقة محل الدراسة، ويحتويان على العديد من النطاقات المنتجة.