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Reservoir Quality, Structural and Sedimentological Study of the Upper Cretaceous/Lower Paleocene Kalash Formation, Rachmat Oil Field, Concession 13, Eastern Sirte Basin, Libya

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Abstract

In this research, the reservoir quality of the Kalash Formation (Upper Cretaceous/Lower Paleocene) within the Rachmat Oil Field, Concession 13, located in the eastern part of the Sirte Basin, was evaluated. The field, discovered in November 1976, has been producing from the Kalash Formation. The study focused on analyzing the reservoir quality concerning the structural geology and sedimentological characteristics of the Kalash Formation within the Upper Cretaceous level. The formation exhibits a diverse lithology consisting of limestone interbedded with dolomite. Logging data, including Gamma Ray (GR), Resistivity, Neutron, and Density logs, were employed in the analysis. Advanced analysis using Techlog and Surfer software was carried out to assess the

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petrophysical properties of five wells: L1-13, L2-13, DD1-13, DD2-13, and S1-**13.** The results revealed that the dolomite within the Kalash reservoir exhibited good quality, with porosity ranging from 5.5% to 13%. Structurally, the sedimentology of the Rachmat oil field is influenced by a legitimate closure, bordered to the west by a down-to-east normal fault intersecting the Hagfa Formation. The spatial relationship between wells L2-13, L1-13, and S1-13 at the Maastrichtian level indicates the presence of a reef at well L1-13, with L2-13 representing the back reef and S1-13 the fore reef area. The absence of hydrocarbons at the Cretaceous level in L2-13, which is up-dip relative to L1-13, suggests a geological barrier in the form of the fault separating the two wells, likely acting as a seal and hindering hydrocarbon migration.
Keywords: Reservoir Quality, Structural and Sedimentological System, Sirte Basin, Kalash Formation, Upper Cretaceous/Lower Paleocene, Rachmat Oil Field.

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دراسة جودة الخزان والجيولوجيا التركيبية والرسوبية لتكوين الكلاش من العصر الطباشيري العلوي الى الباليوسين السفلي، حقل راشمات النفطي، الامتياز 13، الجزء الشرقي من حوض سرت، ليبيا

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الملخص

تقيم هذه الدراسة جودة خزان تكوين كلش (الطباشيري العلوي/الباليوسين السفلي) داخل حقل راشمات النفطي، الامتياز 13، الواقع في الجزء الشرقي من حوض سرت. تم اكتشاف الحقل في نوفمبر 1976، وكان ينتج من تشكيل كلش. يركز البحث على تحليلات جودة الخزان، المتعلقة بالجيولوجيا الهيكلية والخصائص الرسوبية لتكوين الكلاش داخل المستوى الطباشيري العلوي، باستخدام الخصائص الفيزيائية البترولية للتكوين، والتي تظهر علم الحجر الليثولوجي المتنوع الذي يتكون من الحجر الجيري المترابط مع الدولوميت. حسنًا، تم استخدام بيانات التسجيل، بما في ذلك سجلات Gamma Ray و Resistivity و Neutron و Density. تم إجراء تحليل متقدم باستخدام برنامج Techlog و Surfer لتقييم الخصائص الفيزيائية البترولية لخمسة آبار. تشير النتائج إلى أن الدولوميت داخل خزان كلش يمتلك جودة جيدة، مع مسامية تتراوح من 5.5٪ إلى 13٪. من الناحية الهيكلية، تتأثر الرواسب في حقل نفط راشمات بإغلاق مشروع، يحده من الغرب صدع طبيعي من أسفل إلى شرق يتقاطع مع تكوين هاجفا. هذا يعني أن الكتلة 13 التي تم

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اختبارها جيدًا، بالإضافة إلى L1-13، في وضع الانخفاض. تشير العلاقة المكانية بين الآبار S1-13 L1-13 L2-13 على مستوى ماستريختيان إلى وجود شعاب مرجانية في L1-13 البئر، حيث تمثل L2-13 الشعاب المرجانية الخلفية S1-13 منطقة الشعاب المرجانية الأمامية. يشير غياب الهيدروكربونات عند مستوى العصر الطباشيري في L2-13، وهو انخفاض مرتفع بالنسبة إلى L1-13، إلى حاجز جيولوجي - على وجه التحديد، الصدع الذي يفصل بين هذين البئرين، والذي من المحتمل أن يكون بمثابة ختم ومنع هجرة الهيدروكربونات.

الكلمات المفتاحية: جودة الخزان، النظام التركيبي والرسوبي، حوض سرت، تكوين الكلاش، حقل راشمات النفطي

1. Introduction

Rachmat oil field is situated on the upthrown side of the major Etel normal fault, positioned between the Hagfa trough in the east and the Beda Raguba high in the west. Located approximately 30 km north of the Ora oil field in Concession 13, this field was first discovered in November 1976 by the initial DD1-13 well (refer to Figure 1). The primary production comes from the Kalash formation, with additional output sourced from the M59 member of the Paleocene Beda Formation, totaling a cumulative production of 3,772,378 barrels. The secondary significant well, L1-13, represents a distinct reservoir between the L1-13 and DD1-13 pools. The Kalash reservoir exhibits the most promising potential for production in the Rachmat region, boasting two different types of lithology and reservoir quality, including porous rock with good permeability. The primary objective of this study is to assess the geology of the Rachmat oil field, examining the correlation between the structures of DD1-13 and L1-13, as well as the reservoir quality indicated by the Kalash Formation's thickness, lithology, and sedimentary environment influence on deposition. By integrating these findings with geological data, a deeper understanding of reservoir quality can be achieved.

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The study utilized data sets from Harouge Oil Company, comprising geological and petrophysical data, along with references to published papers. The primary methodology involved Petrophysical analysis of five designated wells (DD1, DD2, L1, L2, and S1-13) incorporating Electrical logs such as Gamma-ray, Neutron, Resistivity log, Electrical resistivity, Sonic log, and Formation tops. Software was employed to determine Petrophysical properties like Porosity, water saturation, and net pay for the Kalash formation, which were then integrated with geological data to assess reservoir quality in the research area.

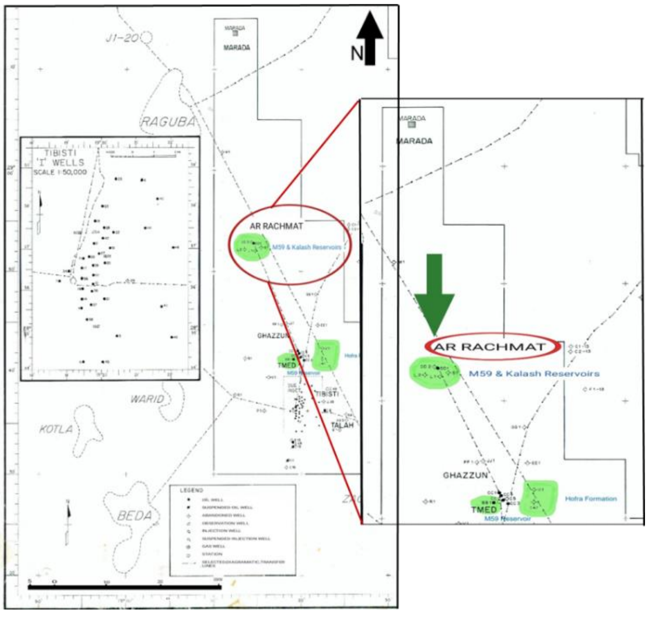

Figure 1: Location map of Rachmat oil field in concession 13 –Sirt Basin[1]

2. Geological Setting

The Sirt Basin, situated onshore in Libya, is delimited to the north by the Gulf of Sirt, to the northeast by the Cyrenaica Platform, to the southeast by the Jabal Al Dalmah Arch, to the south by the Tibisti Massif, to the southwest by the Murzuq Basin, and to the

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west by the Hun Graben [2-5]. Known as the region's youngest and most hydrocarbon-abundant basin, it covers approximately 600,000 km². The Sirte Basin represents a late Mesozoic and Cenozoic triple Junction continental Rift, which emerged during the late Jurassic Period due to tensional tectonic activities in the mid Mesozoic [6]. By the early upper Cretaceous (Cinomanian) era, the fundamental structural configuration of the Basin was established, characterized by a northwest elongated shape comprising northwest-southeast trending Platforms or uplifts (Horsts) and Troughs (Grabens), see Figure 2. Formed through intracratonic rifting, the Sirt Basin experienced episodes of stability and structural reversal phases. The basin gradually subsided during the Cretaceous and Tertiary epochs, particularly peaking in the Eocene period with the maximum subsidence rate [7].

During the Oligocene to Miocene epochs, the existing structural components of the Sirt Basin consist of numerous NNW-SSE oriented depressions of grabens interspersed with intervening horsts. These features include the Hon Graben Waddan Platform, Maradah (Al-Hagfa) trough, Ad Defa Waha Zelten Platform, Ajdabiya trough, Amal-an Nafurah platform, Maragh trough, and Cyrenaica platform aligned from west to east [8]. The sedimentary processes were influenced by both tectonic and eustatic forces, leading to localized high rates of sedimentation, with the distribution of distinct lithologies being controlled by paleotopographical variations characterized by ridge-and-trough configurations. The oil field under investigation can be divided into three paleogeographic zones depicted in Figure 3: 1) the northern area characterized by predominance of peri-reef sediments, 2) the central region dominated by protected middle shelf deposits, and 3) the southern area comprising dolomitized inner platform sediments that may have experienced intermittent emergence. Lateral changes in facies distribution are evident across the region, with argillaceous strata being most concentrated in the central area. Discontinuities exhibit a prominent development in the southern region, gradually diminishing in occurrence towards the northern area as the sediment sequence thickens. The majority of these discontinuities are linked to transient terrestrial exposure in the southern region, characterized by localized dissolution processes within the northern formations. These discontinuities serve as indicators of interruptions in sedimentation, with associated processes that hold the potential to enhance the reservoir capacity of underlying sediments [8]. The Heira Formation encompassed the irregular pre-existing paleotopography, addressing challenges in correlation and variable thickness within this lithological unit. Sedimentation within the area is influenced by a series of tectonic phases, resulting in localized high sedimentation rates. During the Paleocene period, shallow carbonate deposits formed on the crests, while argillaceous carbonates and marls accumulated in the basins. The deposition of carbonate units continued to be influenced by the presence of paleotopographic crests and basins, as well as the minor reactivation of NW-SE faults associated with the rift activity. The Mabruk carbonate reservoir member comprises a limestone sequence deposited in shallow marine environments, transitioning laterally and vertically into shale compositions.

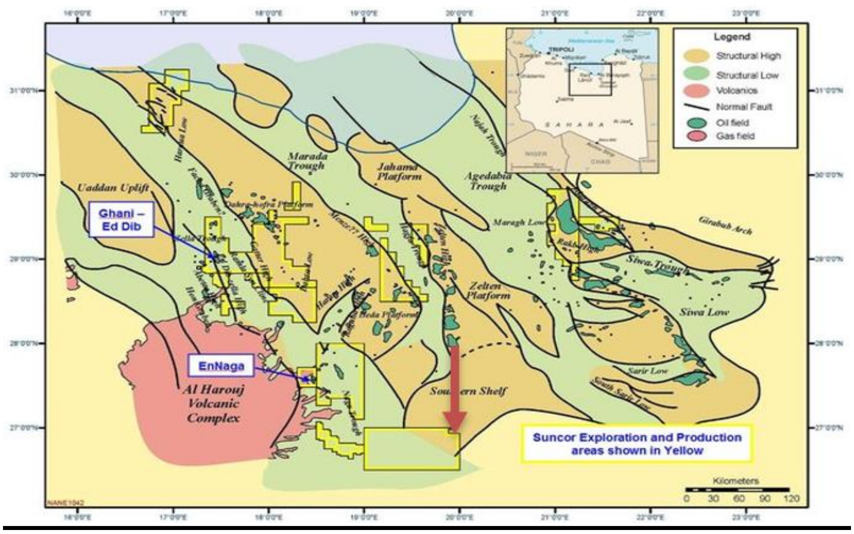

Figure 2: Sirt Basin major structural features, location of study area marked by red arrow [9, 10]

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3. Geological Setting of Rachmat Oil Field

The Rachmat field is located on the upthrow side of the major Etel fault trending northwest-southeast. Structural cross section. Figure 3 shows the structural style of the Rachmat field. A normal fault of up to 120’ vertical displacement separates the Rachmat**,** field from the dry hole S1-13. This fault intersects the Zelten formation in well DD1-13 at 4,050’ subsurface. A normal fault trending north-south with about 150’ of throw separates L2-13 from L1-13 at the Kalash level. There is a direct relationship between the structure and development of the reservoir facies in the Rachmat area. The Hofra formation, M59 member, and lower Beda are paleo-structural reservoirs. However, the Kalash formation has stratigraphic structural elements [1].

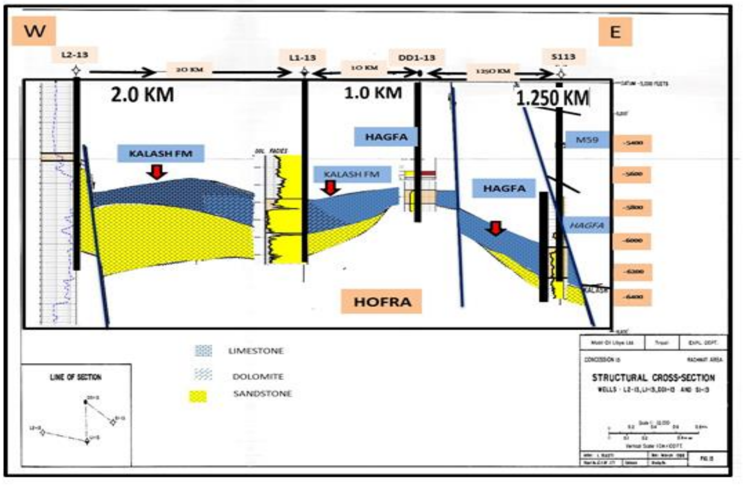

Figure 3: Structural cross section shows the structural style of the Rachmat field

4. Reservoir Quality Based on Petrophysical Analysis

The Petrophysical analysis applied for four selected wells located at the Rachmat oil field by using Techlog 2015 software, starting by loading the electrical logs including GR, Neutron, Density, sonic, and resistivity logs, also formation tops have been loaded to identify all the zones in area study, then sorted the logs and submit the cut-

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off parameters, then calculations and results carried out as layouts and tables.

4.1 Determination Volume of Shale

There are many different methods to determine the volume of shale (Vsh); the basic methods of shale volume determination use the following indicator GR.In this study only the gamma-ray log was used to determine the shale Contents in the Kalash Formation reservoir in four wells only, shale volume indicator. The simplest procedure is to rescale the gamma-ray between its minimum and maximum values (in one consistent geologic zone consisting of both clean and shale) from 0% to 100% shale. The gamma-ray (vsh) is defined as a relationship between (GRmin) and (GRmax), and the formula can be written as: vsh= (GRlog –GR clean)/(GR sh – GR clean)…….Eq. (.1)

Vsh: is the volume of shale (API). GR log: is the Gamma-ray reading on the log. GR clean: this is the minimum reading on the log. GR sh: is the maximum reading on the log.

4.2 Porosity Determination

Porosity logs neutron and density logs are used to determine the density porosity (ØD) and the total porosity (ØN-D) of the Kalash Formation reservoir**.**

4.3 Density Porosity

The density porosity (**ØD**) was determined based on the type of reservoir rock from Equation 2

ØD = (pbma- pblog)/(pbmax- pfl)……………Eq(.2)

Where: ***ρb*** **=**bulk Density, gm/cc (**log**). ***ρfl*** **=**Fluid Density, (**equal 1.1 gm/cc**). ***ρb ma*** **=**Matrix Density, **equal 2.71** gm/cc (for limestone)**. *ØD*** **=**Density Porosity**.**

figure 4 summarizes the average effective porosity in the study area, which ranges from 5.2% in well L1-13- to a high effective porosity of 13.5 in well DD1-13

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Well Name	Average Porosity (%)
L1-13	5.2
L2-13	7
DD1-13	13.5
DD2-13	8
S1-13	6.1

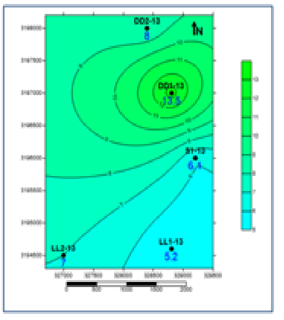


Figure 4: Porosity map of the study area by Surfer software

4.4 Determination of water Saturation (SW)

In petrophysical terms, water saturation (SW) can be defined as the fraction of a rock's pore space that is filled with water. When the water saturation is less than 100%, hydrocarbons are typically present. Water saturation calculations based on resistivity logs in clean (non-shaly) formations with uniform intergranular porosity adhere to Archie's water saturation equation. Table 2 presents a summary of water saturation values in the research area, ranging from 4.5% in well L1-13 to 66% in well L-13, as illustrated in the water saturation map depicted in Figure 5.

Well Name	Average water saturation (%)
L1-13	4.5
L2-13	66
DD1-13	28.4
DD2-13	50.6
S1-13	34

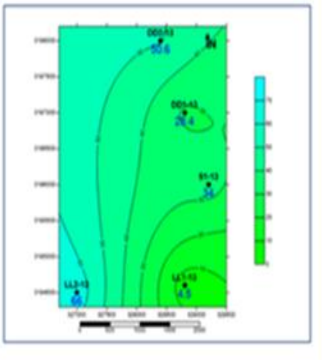
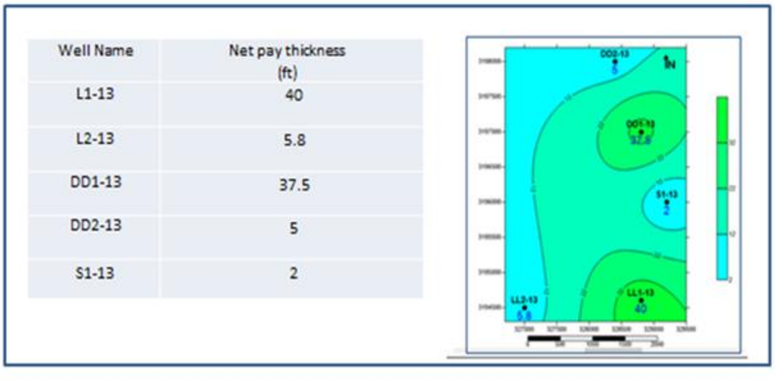


Figure 5: Average water saturation map of the study area by surfer software

4.5 Net Pay thickness

The Net pay thickness of the reestablished Netts intervals having porosity less than or equal to the cut-off porosity (8%) and having water saturation greater than the cut-off water saturation (50%). To determine the net reservoir, the porosity of the established net sand must be calculated figure 6 shows a summarized Net pay thickness and map of Net pay thickness in the study area ranging from 2 ft in well S1-13- to 40 ft in well LL1-13.



Well Name	Net pay thickness (ft)
L1-13	40
L2-13	5.8
DD1-13	37.5
DD2-13	5
S1-13	2

Figure 6: Net pay thickness map of the study area by surfer software

5. Petrophysical Analysis Results

In this section, the results of the petrophysical analysis will be presented individually for each well, for a more detailed idea about the nature of the reservoir.

Well DD1-13 is the main one of the acquired wells, as it was the first well to be drilled in the area, it was also the well in which the formation tops were provided. The well was drilled to test the hydrocarbon potential of the Kalash Formation, it penetrated the top Kalash at a depth of 6172 feet and the thickness of the unit59 feet figure (7), well DD1-13 The result of petrophysics analysis of the Kalash reservoir in this well was started to determine of shale volume by use GR log only by equation before, the volume of shale in this well figure (8) shows the average volume of shale (green color represent the volume of shale) the volume of shale is high where GR is high and average of volume of shale. The second calculation is porosity by neutron and density logs are used to

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determine the total porosity (ØN-D) of the Kalash Formation reservoir. The first determines the density porosity (ØD based on the type of reservoir rock from the Equation and the neutron porosity. They determine the net pay thickness. The net pay thickness of the reservoir denotes intervals characterized by porosity equal to or lower than the cut-off porosity (9%) and water saturation exceeding the cut-off water saturation (50%). The net pay result in this well (highlighted in red to indicate the net pay zone) depicts an average net pay thickness of approximately 46 feet. Well DD2-13 was drilled to assess the hydrocarbon potential of the reef sediment in the Kalash Formation. It encountered the upper sand layer at a depth of 6301 feet with a thickness of 175 feet. The petrophysical analysis of the Kalash reservoir in this well commenced by determining the shale volume solely using the GR log by means of an equation. The average shale volume (indicated in green to represent shale volume) is elevated where the GR reading is high, averaging around 4.8%. Subsequently, porosity was calculated using neutron and density logs to ascertain the total porosity (ØN-D) of the Kalash Formation reservoir. The density porosity (ØD) was initially determined based on the reservoir rock type utilizing a pre-existing equation.

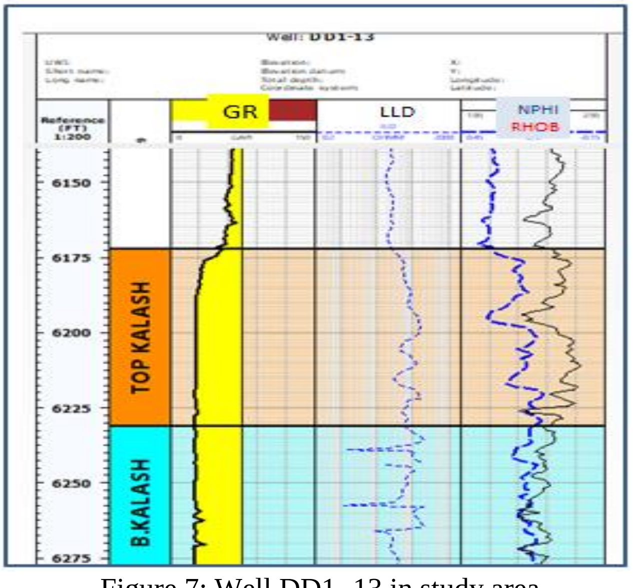

Figure 7: Well DD1 -13 in study area

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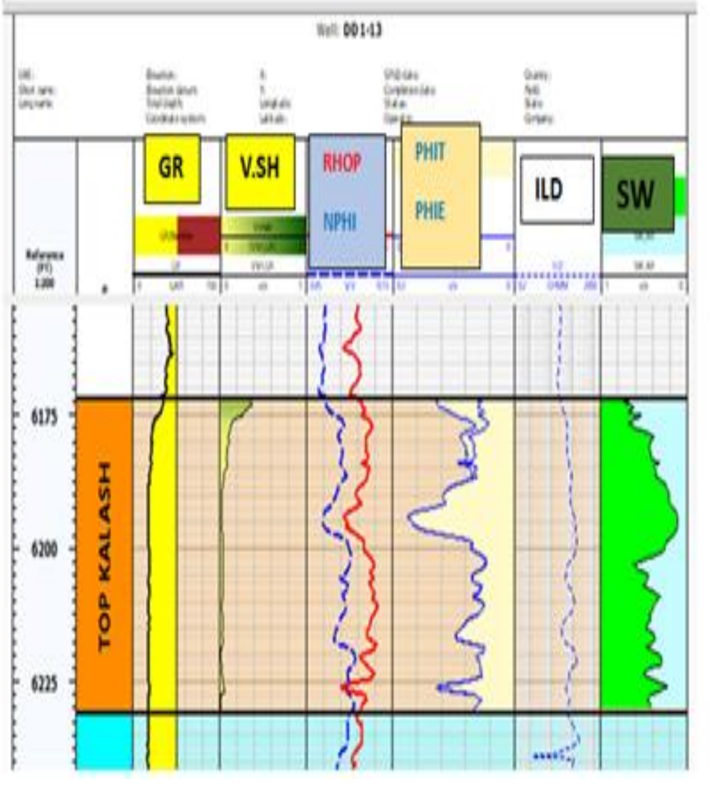

Figure 8: Show average porosity result of well DD1-13

Following this, the neutron porosity was directly derived from the neutron log. The total porosity corresponds to the average of the combined neutron and density porosities after the removal of shale porosity, resulting in an average effective porosity of approximately 10.2% in this well. Water saturation was determined based on Archie’s water saturation equation, resulting in water saturation values in this well (depicted in green for the oil zone and blue for water saturation) averaging at 4.1%. The net pay thickness was then assessed, representing reservoir intervals with porosity equal to or less than the cut-off porosity (9%) and water saturation greater than the cut-off water saturation (50%). The petrophysical results of the well are depicted in Figure 9.

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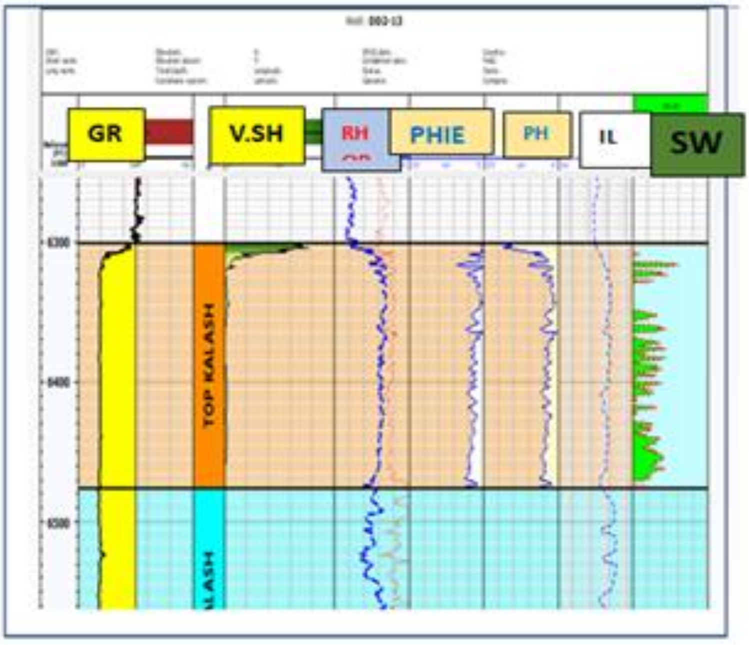

Figure 9: Show petrophysics result of well DD2-13

Well L1-13 was drilled in order to assess the hydrocarbon potential of the Kalash Formation. It successfully reached the upper sand layer at a depth of 6280 feet with a thickness of 196 feet. The petrophysical analysis of the Kalash reservoir in this well began by determining the shale volume using the GR log equation exclusively. Figure 10 illustrates the average shale volume in green, with an average effective porosity of approximately 8%. Water saturation was determined based on Archie's method, where green indicates the oil zone and blue represents water saturation. The calculation of net pay thickness involved identifying intervals with porosity equal to or less than the cut-off porosity of 10%, water saturation exceeding the cut-off value of 50%, and permeability greater than 100 md. The average net pay thickness was approximately 40 feet. Similarly, **Well-S1-13** was drilled to explore the hydrocarbon potential of the Kalash Formation, encountering the top reservoir layer at a depth of 6640 feet with a thickness of 44 feet as depicted in Figure 11.

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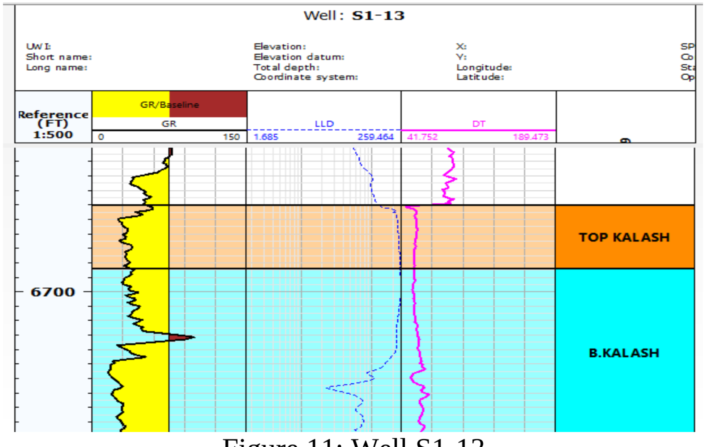

Figure 11: Well S1-13

The petrophysical analysis of the Kalash reservoir in this well commenced with the assessment of shale volume through the implementation of the GR log exclusively through an equation. The shale volume in this well was determined to be 11.4%. Subsequently, porosity was calculated to be 11.4%, average water saturation at 21.7%, and the net pay thickness was ascertained. The average net pay thickness is reported as 147 feet, as illustrated in Figure 12.

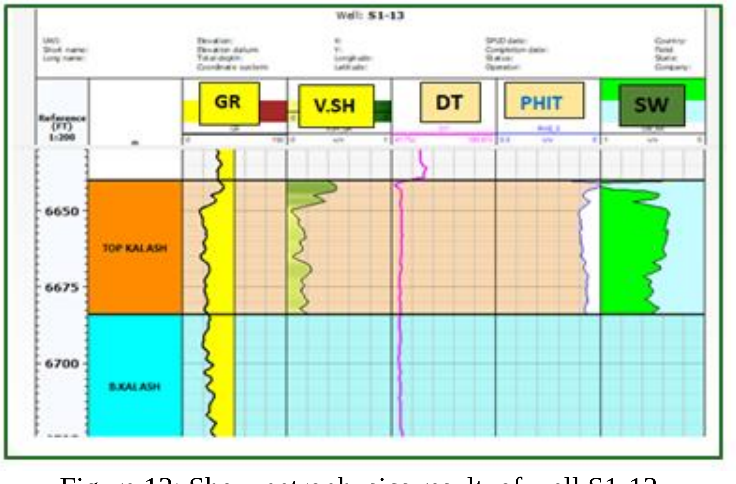

Figure 12: Show petrophysics result of well S1-13

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6. Structure Relates to Reservoir Depositional Facies

Based on the available well data, a strong correlation exists between the structure and reservoir facies development within the study area, with the reservoir exhibiting stratigraphic and structural trap elements. The Kalash Formation demonstrates significant potential, particularly when situated within a high structure (Palae-high structure), where increased leaching of carbonate rock promotes porosity development. Conversely, locations within low-structure areas tend to exhibit limited porosity, forming tight porosity zones. In DD1-13, the Kalash reservoir displays superior quality, characterized by favorable porosity and permeability trends aligned in a North-South orientation and extending southeast towards well L1-13. This reservoir primarily comprises dolomite with moderate porosity and an absence of porous limestone. Variability in the thickness of the Kalash reservoir is observed. The drilling operation aimed to target the Beda structure's summit, a lower Paleocene reef indicated by seismic interpretations. However, the outcome revealed a smaller structure, positioned on the upthrown side of a fault that separates wells S1-13 and L1-13. Well S1-13 is situated in the eastern-central region of concession 13, approximately one-kilometer northeast of well L1-13, having been drilled on the downthrown side of a northwest-striking fault believed to be associated with the Raguba-Etel high zone.

The thickness of the Kalash reservoir in well DD1-13 measures approximately 44 feet, with indications of fault-related section disruption. The Cretaceous sediment in this well is comparatively thinner than that in wells S1-13, L1-13, and L2-13. The gradual thickening of the Maastrichtian Kalash formation from L1-13 to S1-13 may have been attributed to eastward step faulting towards the trough axis, interrupted by slightly thicker deposition at L1-13, resulting in a 26-foot section thickness increase. This phenomenon can be attributed to reef growth surpassing sedimentation along the flanks. In well L1-13, the Kalash reservoir comprises 156 feet of white to light tan dolomite, characterized by medium to coarsely crystalline structure. There is a sudden facies transition over a short lateral distance between well L1-13 and S1-13, where the dolomite

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rock in L1-13 signifies reef or carbonate buildup, while S1-13 represents fore-reef or open-water limestone facies due to its offshore deeper water location. Well L2-13, situated 2 kilometers to the west of L1-13, revealed only traces of brown, micro-crystalline, argillaceous dolomite with thin beds of argillaceous limestone.

The majority of the Cretaceous section in L2-13 consisted of porous, wet sandstone. Being positioned higher on the flank of the Beda/Raguba high, L2-13 exhibited a thinner stratigraphic section compared to L1-13, with every unit being thinner except for the Cretaceous layer. This observed change in facies from dolomite and sandstone to predominantly sandstone led to a 50% increase in thickness. The dolomite buildup at L1-13 suggests shallow water carbonate deposition, contrasting with the transition to clastic sediments at L2-13.

The DD2-13 was drilled 600 meters Northwest of DD1-13 drilled in limits of the Rachmat structure (Hofra high), the target of the well was the Paleocene reef as well DD1-13 the result of the well was lower than DD1-13 about 137 feet and no reef was found and porous dolomite is absent, the facies distribution changes due to fault controlling deposition. The DD2-13 was drilled 600 meters Northwest of DD1-13 drilled in limits of the Rachmat structure (Hofra high), the target of the well was the Paleocene reef as well DD1-13 the result of the well was lower than DD1-13 about 137 feet and no reef was found and porous dolomite is absent, the facies distribution changes due to fault controlling deposition.

The geological history of the region during the Maastrichtian period suggests the presence of a narrow ridge at well locations L1-13 and S1-13, which likely extended in a northerly or northwesterly direction, separating the Hagfa Trough from a depression to the west at well L2-13. The sedimentation of the Kalash Formation commenced with subsidence towards the eastern region along the fault's hinge zone, leading to a transgression by the Maastrichtian Sea.

The inundation in the study area was relatively shallow, as evidenced by the fauna remains. Favorable conditions for reef development were present along the fault's hinge zone, resulting in

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the formation of carbonate structures at well L1-13, while normal marine limestone was being deposited in the fore reef. The gradual thickening of the Maastrichtian Kalash Formation from well L2 to S1-13, reaching a thickness of 26 feet, can be attributed to the continuous growth of the reef, which outpaced sedimentation in the surrounding areas. Subsequent rapid subsidence occurred during the Danian period, leading to the deposition of limestone from the Kalash Formation in wells L1-13 and S1-13. This subsidence persisted into the Paleocene and early lower Eocene periods, characterized by the rapid eastward thickening of marine sediments toward the Hagfa trough. The subsidence may have been triggered by fault movements towards the eastern section, converging towards the trough's exit.

7. Conclusion

The well S1-13 was drilled on a legitimate structure with closure to the western boundary, delineated by an east-to-west normal fault. This fault intersected the Hagfa formation, resulting in the up-thrown block 13 being tested by the well, as well as placing L1-13 in a down-dip position. The interrelation among wells L2-13, L1-13, and S1-13 at the Maastrichtian stratum indicates the development of a reef at L1-13, with L2-13 representing the back reef and S1-13 depicting the fore reef area. The absence of hydrocarbons at the Cretaceous level in L2-13, situated up-dip from L1-13, signifies the presence of a barrier between the two wells, with the fault serving as a sealant that impeded hydrocarbon migration.

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