PETROPHYSICAL PROPERTIES OF THE SILURIAN SANDSTONE RESERVOIR IN THE A STRUCTURE OIL FIELD, GHADAMES BASIN, WEST LIBYA

Muhend Milad[a, b] * Akhmal Sidek[c,d], Mohamed. H. Targhie[e], Majed Enfis[b], Najib Meftah Almukhtar Omar[f]

[a]Department of Petroleum Engineering, School of Oil and Gas, University of Zawia, Zawia, Libya

[b]Department of Petroleum Engineering, Al-Rifaq University, Tripoli, Libya

[c]Department of Petroleum Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia

[d]Institute for Oil and Gas (IFOG), Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[e]Geologist & Geology Engineering department, Mellitah Oil and Gas Company, Tripoli, Libya

[f]Chemical Engineering Department, Sabratha Faculty of Engineering, Sabratha University, Sabratha, Libya.

Graphical abstract
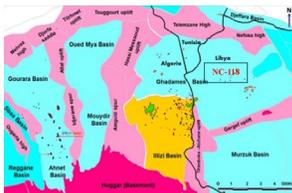
Abstract

The assessment of low-resistivity reservoir pay in the Silurian Sandstone Formation presents significant challenges and has far-reaching ramifications for field development plan. Therefore, this study attempts to analyse and examine the petrophysical properties of the Silurian Reservoir (Lower Akakus fm.) in the A Structure based on two well logs data (A1 and A2) located in the Block NC-118 at Ghadames Basin. There are numerous studies have been undertaken in the Ghadames Basin of West Libya; a few researchers have highlighted the challenges of reservoir pay in the Lower Akakus Formation. The comprehensive examination of the Silurian Formation is divided into five distinct sand units, namely sand 1, sand 2, sand 3, sand 4, and sand 5 (SS1, SS2, SS3, SS4, and SS5), arranged in a stratigraphic sequence from upper to lower Silurian. Employing advanced petrophysical analysis techniques and Techlog software, the lithological composition of each sand unit in the Silurian Formation was identified, revealing a predominantly sandstone reservoir interspersed with shale formations with an average shale volume ranging from 0.2% to 15%. Sand 1 has roughly 2% porosity, sand 2 and sand 3 have around 22% porosity, sand 4 has 17% porosity, and sand 5 has 15% porosity. Furthermore, the average water saturation within these sand units varies, with sand 1 registering approximately 60% water saturation, sand 2 indicating 72% water saturation, sand 3 displaying 62% water saturation, sand 4 revealing 17% water saturation, and sand 5 exhibiting 56% water saturation. Despite initial indications of low resistivity in the interval (L.A) from well test logs analysis, the subsequent well test results conclusively confirm the presence of oil in the Lower Akakus zone.

Keywords: Silurian formation, Petrophysical analysis, Techlog software, Well production test, Libya

1.0 INTRODUCTION

Energy Information Administration (EIA) has reported that Libya is among the globally recognized countries that produce oil and gas [1, 2]. In this study, the Lower Akakus reservoir was examined in the A Structure of NC118 Oil Field, located in West Libya's Ghadames Basin, is an intriguing case for development due to its unusual petrophysical features [3]. The A Structure represents a significant geological feature

within the Northwestern region of Libya. It is located approximately 250 km to the Southwest of Tripoli and 300 km to the Northeast of the renowned Wafa Field. Furthermore, the NC-118 block occupies a pivotal location on the northern flank of the Ghadames Basin in North-western Libya, which develops along a NE-SW direction across Algeria and Libya [4]. This basin is bounded by the following highs: Dahar and Garian to the South, Amguid el Biod to the West, and Tripoli-Asswada to the East (Figure 1).

The A Structure was discovered in 1985 by drilling well A-1 crossing the so-called "A Structure," discovering five hydrocarbon layers in the Lower Akakus Formation of the Silurian age [6]. Different types of hydrocarbons were identified: gas condensate, saturation (or close to) oil, and under saturation oil. In 1995, an appraisal well A-2 was drilled at about 1.5 km south of well A-1 and confirmed the shape of the "A" structure of the oil-bearing formation, defining the area extent of the hydrocarbon, the oil gravity ranges from 34 to 40 API and the solution gas range from 540 to 3200 Scf/bbl [2, 7, 8].

The main objective study is to exploit well-logging data to unravel the secrets of the Lower Akakus reservoir, delve into its specific challenges and opportunities presented, and determine its potential as a productive oil reservoir. Furthermore, the aim is to better understand the vertical distribution of Lower Akakus reservoir facies variations across the study region.

The main method used in this study is to apply petrophysical analysis to two selected wells (A1 and A2-NC118) based on electrical logs. These logs include gamma-ray (GR), neutron (N), resistivity, density log, and sonic log, utilizing Techlog 2015 software. The goal is to determine the petrophysical properties of the Lower Akakus Formation, such as porosity, water saturation, and net pay. These properties will then be integrated with the well test results to facilitate a precise understanding and define the presence of hydrocarbons within the study intervals. By leveraging well-logging data and advanced analytical approaches, researchers aim to shed light on the reservoir's unique characteristics and provide significant insights for industry stakeholders looking to optimize production in this promising region. Figure 1 depicts the location map of NC118 for reference.
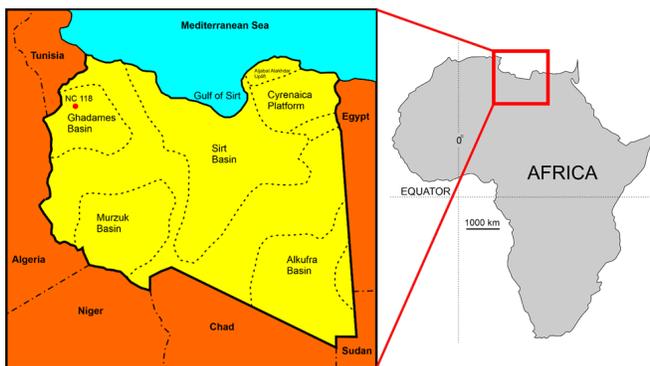

Figure 1 Location map of NC118 located in Ghadames Basin

2.0 REGIONAL TECTONIC SETTING

The Ghadames Basin, a large intracratonic basin on the North African platform, was formed during the early Palaeozoic era and covers an area of 350,000 km², straddling the borders of Libya, Tunisia, and Algeria. The Libyan portion, representing the basin's eastern flank and covering approximately 183,000 km², has served as a vital hydrocarbon province since the 1950s. It has been an important hydrocarbon province since the 1950s [9]. The main tectonic elements bounding the Ghadames Basin are the Dahar–Nefusa uplift to the north, the Gargaf arch to the south, partially bounded by the extension of Tihemboka uplift to the west, and the western flank of the younger Sirt Basin to the east. Many of these structural features were initiated in the late Precambrian Pan-African orogeny, with repeated reactivation of older structures occurring throughout the Phanerozoic. The basin contains up to 5,200 m [~17,000 ft] of Palaeozoic and Mesozoic sediments, with the Palaeozoic section being separated from the Mesozoic deposits by a major regional unconformity of Hercynian (Devonian-Carboniferous) age. This unconformity stands out as the basin's most prominent feature, marking the transition from the Palaeozoic sequence to the distinctly configured Mesozoic succession. The erosion patterns and topography developed on the surface of the regional unconformity play a crucial role in influencing the petroleum systems within the basin [10]. The Ghadames Basin is characterized by four major tectonic cycles, with the oldest Cambro-Ordovician cycle concluding with Early Caledonian tectonism. Subsequent cycles, including the Silurian, Devonian-Carboniferous, and Mesozoic, each ended with distinct epeirogenetic events.

The Alpine Orogeny, a key Mesozoic event, extended the northern boundaries of the basin, transforming it into a marginal sag basin [10]. The Palaeozoic deposits predominantly consist of non-marine and marine clastics such as conglomerates, sands, silts, and shales, accounting for over 95% of the total section. Conversely, Mesozoic deposits contain more carbonates and evaporites, while Cenozoic deposits are primarily made up of limestone and shale. The depositional environment during the Palaeozoic era reflected an interior, cratonic regime marked by shallow marine and non-marine conditions, whereas the Mesozoic era was characterized by a marginal platform regime.

3.0 STRUCTURE AND STRATIGRAPHIC OF STUDY AREA

The structure contour map of the Top Lower Akakus formation is displayed in Figure 2, the high structure in the central part of the study area then trends to low structure in the western part, also in the eastern part north part, in general, the region anticline structure
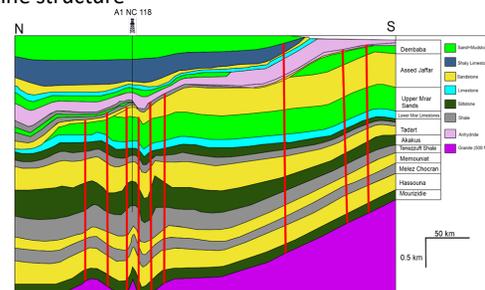

Figure 2 N-S cross section of "A Structure" in Akakus Formation with A1 NC118 well

The stratigraphic structure employed in this study is based on the final well reports, which detail the composition of Silurian strata within three separate formations. The series begins with the Bir Tlakshin Formation, also known as the Iyadhar Formation, which overlies the Atshan Saddle and is composed of fine to medium-grained quartzose sandstone similar to the Mamuniyat Formation. This sandstone layer is usually underlain by a dark grey to greyish-brown strong fissile shale. However, the Bir Tlakshin Formation may be lacking in areas with older structural highs because of an unconformity at the top of the Cambro-Ordovician epoch. Although it can reach thicknesses of more than 100 meters (328 feet), the average thickness is around 35 meters (115 feet). Moving upward, the Tanezzuft Formation is made up of a large concentration of grey to dark grey shales that range in thickness from 300 to 600 meters (984 to 1,969 feet). The upper portion contains intermittent siltstone and sandstone layers that transition into sands from the underlying Akakus Formation. The shales in the basin's northern portion have a high micaceous concentration and a largely metamorphosed look, whereas those in the southeast are more sandy in nature. The top boundary with the Akakus Formation shows a gradual shift from sandstone to shale units, resulting in a diffuse contact zone between the two formations. The formation and depositional environment of Ghadames Basin are depicted in Table 1

Table 1 Formation and depositional environment of Ghadames Basin

Era/Period	Formation/Group	Depositional Environment
Precambrian	Basement rocks	Not applicable
Cambrian to Ordovician	Tadrart Formation (Ordovician)	Shallow marine to fluvial
Silurian	Akakus Formation (Lower Silurian), Tanezzuft Shale	Marine transgression, deep marine
Devonian to Carboniferous	Tadrart and Tahara Formations (Devonian), Mrar Formation (Carboniferous)	Shallow marine to deltaic
Permian to Triassic	Ouargla Group (Permian)	Arid, marine regression
Jurassic to Cretaceous	Jurassic Sandstones and Carbonates, Cretaceous Units	Shallow marine, fluvial
Tertiary to Quaternary	Eocene Carbonates and Evaporites, Neogene and Quaternary Sediments	Shallow marine, continental

The Akakus Formation is composed of three members: lower sand, middle shaly, and high sandy. The lowest part is made up of a thick sandstone/siltstone complex that is interbedded with shales. It contains light-coloured sandstone, light grey siltstones, and dark grey shales. The Middle Akakus shaly unit is distinguished by shales interspersed with thin beds of siltstones and firm sandstone layers, indicating a geographically extensive but relatively brief flooding event. The top of the Lower Akakus is well marked. The upper member has an irregular alternation of sandstones, siltstones, and shales, with the Akakus' total thickness ranging up to a maximum of approximately (unspecified length). The Middle Akakus acts as

an excellent regional top seal for the Lower Akakus reservoirs. It is important to note that measurements and specifications are deliberate and should be considered within the context of the entire proceedings, without revising the current designations. The Lower Akakus Formation, which consists of sandstone interbedded with shale, is the primary reservoir rock in the study region. The Lower Akakus Formation's lithofacies are classified, from bottom to top, as roughly five sandstone units, or ss1, sst2, sst3, sst4, and sst5, by the company's geologists. Since these units are the thickest, most prolific, and have the greatest extension throughout the study area, evaluation analysis of these units is made possible through regional integration of wireline logs and sample cutting descriptions. The following is a description of these units and representative lithofacies:

4.0 SEDIMENTOLOGY AND FACIES ANALYSIS

Based on a core study report, sedimentology and facies were investigated in two wells, A1 and A2-NC118. Four primary facies associations in the Lower Akakus sandstone were found by the investigation. Massive medium-fine-grained sandstones with trough cross-bedding were found in well A1 by core analysis, indicating deposition by unidirectional currents in a high-energy environment. Rare bioclasts, intraclasts, and shady streaks were also seen. Fine to very fine-grained sandstones in well A2-NC118 showed wave ripples, hummocky cross layering, and a profusion of shaly streaks. The main sedimentary formations were hidden by extensive burrowing, indicating that storm and wave action during low-energy periods was responsible for the deposition.

The presence of wave ripples, starving ripples, and a lot of burrowing in very fine-grained silty-shaly sandstones suggests a depositional environment impacted by different energy levels from wave action and quiet phases that are good for burrowing activity. Black shales, on the other hand, exhibit uncommon starved ripples and strong bioturbation, indicating a low-energy depositional environment with sporadic storms or wave activity. The vertical stacking pattern and the sedimentological facies described point to the presence of both wave action and unidirectional currents (tidal), indicating oscillations between lower-energy phases driven by relative sea level changes and high-energy times. This dynamic is most prevalent in physiographic settings that are flat, wide, and have low gradients. These settings allow for the rapid deactivation of the sandy system during sea level rises and the deposition of high-energy sandstone bodies during sea level falls. The ramp platform has a lot of bars that come together to form large sedimentary bodies of sandstone; these bodies may be organized in tabular sheets that span tens of kilometers. The finer-grained facies that are more common in offshore areas may lateralize these sedimentary formations.

5.0 PETROPHYSICAL STUDY

For the development of an oil and gas field, it is essential to locate and assess low resistivity in the bypassed pay of the lower Akakus reservoir[11]. Several causes contribute to low resistivity pay zones, and the issue of "low resistivity pay" is not

new[12]. Finding the source of this phenomena and conducting a petrophysical assessment of the low-resistance sand that contains hydrocarbons in lower Akakus sand deposits are critical tasks. This aids in understanding the reasons behind the lower Akakus sandstone reservoirs' low resistivity, as well as the process of performing a petrophysical investigation to determine precise petrophysical parameters, particularly water saturation. To comprehend the low resistivity phenomenon in sandstone and learn how to detect and assess it, an integrated workflow was provided and put into practice. The identification, characterization, and assessment of hydrocarbon-bearing low-resistivity rocks in Akakus sand reservoirs aim to understand rock types, how to conduct petrophysical analysis, and the low resistivity phenomenon in sandstone reservoirs. A comprehensive investigation employing petrographical, rock typing, and petrophysical techniques is carried out and utilized.

5.1 Determination of Rock Type

The rock type was determined using the density and neutron log cross plot. It is critical to classify the characteristics of each rock type in low-resistivity reservoirs in order to identify and comprehend the usual log response and petrophysical parameters of low-resistivity pay-bearing sand reservoirs.

5.2 The Neutron-Density Crossplot

The neutron-density crossplot is commonly used in the petroleum sector to identify lithologies and estimate porosity and matrix density. The apparent neutron porosity data are displayed against the bulk density readings for each zone. The matrix density values for pure lithologies are as follows: silica 2.65 g/cm3, limestone 2.71 g/cm3, and dolomite 2.87 g/cm3. These crossplots can be used to calculate lithology and porosity since they provide the highest resolution and are the most effective detectors of porosity across different lithologies. The crossplot clearly distinguishes between the lithologies of lime, dolomite, and sandstone. Before reaching any conclusions, the data must be corrected for the existence of shale and hydrocarbons. In wells with uneven walls or heavy drilling mud, the correlation between information density and lithology may not be evident, imposing limitations on the crossplot's utility. The cross plots in the research wells show that the lithology of the Lower Akakus Formation is sandstone interbedded with shale in all wells. Figure 3 depicts a cross plot for all sandstone units in wells A1-NC118.
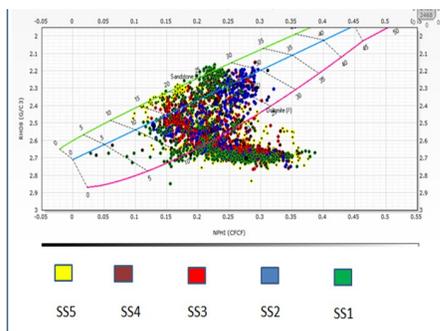

Figure 3 Neutron-density cross plot in well A1-NC118

5.3 Petrophysical Analysis

Petrophysical analysis was used to determine the reasons that induce low resistivity in sandstone reservoirs. Petrophysical analysis was used to specifically quantify reservoir quality. Petrophysical analysis determines three main parameters: shale volume (Vsh), effective porosity, and water saturation (Sw). These characteristics were estimated using the normal methodologies provided in the well-logging data.

5.3.1   Volumetric shale

The volumetric shale fraction was determined using the GR log. The volume of shale is estimated using the gamma-ray log indicated in the following equation.

VSH = (GRlog-GRmin)/(GRmax-GRmin) Equation 1

Where GR log denotes the gamma-ray reading (logging). GRclean: the minimal reading of a log. GRsh is the highest reading in a log. Vsh denotes the volume of shale (%).

5.3.2   Porosity calculation

Non-shale porosity was calculated using neutron density records whenever available. The total porosity values were determined by using the steps below:

Porosity from density log (ØD)

The density porosity (ØD) is determined from an equation below based on the rock type of the reservoir.

ØD = (ρbma - ρblog) / (ρbma - ρf)   Equation 2

Where: ØD =.Density porosity. ρb = Bulk Density, gm/cc (log). ρf = Fluid Density, equal 1gm/cc. ρbma = Matrix Density, equal 2.65gm/cc for sandstone

The neutron porosity has been determined directly from the neutron log. The total porosity is the average of the combined neutron and density porosity data for the water and hydrocarbon zones.

ØN-D= [(ØN²+ ØD²) /2]½   Equation 3
Where: ØN = Neutron porosity % (log). ØN-D =Total porosity

5.3.3   Formation Water Resistivity

The formation water resistivity was obtained from the Mellitah Oil and Gas Company, with an average salinity of 250,000 ppm and a temperature of 200 Fº see Figure 4. And, the RW was computed from the chart, and the result is 0.017 Ω.m.

Geologic Horizon	wt. (%)	NaCl Salinity (ppm)
Top Lower Acacus	22	220,000
Upper Shoreface	24	240,000
Sand 3	25	250,000
Sand 2	26	260,000
Sand 1	29	290,000

Formation	Average TVD (ft)	FOBP (psi)	Reservoir Pressure		Reservoir Temp	
			(Psi)	(bars)	(°F)	(°C)
Top Lower Acacus	9150	5575	3575	246.5	188	86.7
Upper Shoreface	9500	5854	3646	251.4	190	87.8
Sand 3	9750	6020	3730	257.2	193	89.4
Sand 2	9850	5888	3962	273.2	203	95.0
Sand 1	10030	5928	4102	282.8	208	97.8

Figure 4 Water salinity and temperature

Accurate water saturation values were difficult to determine, yet necessary for identifying hydrocarbon dispersion in a low resistivity sand reservoir. Thus, the water saturation computation method was used in low-resistivity sandstone reservoirs. The log data from all four wells were interpreted qualitatively. Water saturation is computed using the Archaic equation.

$$Sw = \left[\frac{a \, x \, Rw}{\Phi^m \, x \, Rt)}\right] 1/n \qquad \text{Equation 4}$$

Sw=

Where: Ø= Total Porosity (%), m = Cementation factor, equal 2. Rt = Formation resistivity, Ω.m. n = Saturation exponent, equal 2. a = is the Archi factor and equals 1. Rw=is the formation water resistivity 0.017 Ω.m.

6.0 RESULTS AND DISCUSSION

The well logging interpretation of wells A1 and A2, NC 118, in the Lower Akakus Formation, demonstrates that the GR log response is constantly less than 75 API, whereas resistivity values are consistently less than 12 ohm-meter in clean sandstone units SS1, SS2, SS3, and SS5. Furthermore, the neutron-density log curves do not show a clear separation, indicating high-density log values. The cross plot of the neutron-density logs identifies the major lithology in the Lower Akakus Formation, revealing that sandstone is the primary rock type, with some shale present.

6.1 Low resistivity Pay

The explanations for the low resistivity phenomenon are divided into two categories, as shown in Figure 5. The first group comprises reservoirs with high real water saturation but producing water-free hydrocarbons. According to Edo Pratama, the process responsible for the high water saturation is most commonly described as microporosity. The second category includes reservoirs where the calculated water saturation is higher than the actual water saturation. The presence of conductive minerals such as clay minerals and pyrite in clean reservoir rock is thought to be the source of the high water saturation. Clay minerals are conductive minerals due to their high cation exchange capacity (CEC), with illite having the greatest CEC value of approximately 26.6-69.0 meq 100 g–1. In sandstone containing clay minerals, there is a decreasing resistivity value. The ability of clay minerals to combine with or

bind to water is one factor associated with the decreasing low resistivity value, as stated by Edo Pratama (2017). Another factor causing a decreasing resistivity is the presence of iron minerals, particularly pyrite.

The presence of pyrite in rock formations can lead to higher density log readings compared to the matrix density, typically sand. This discrepancy is attributed to the high-density nature of pyrite, with a value of approximately 5.0 g/cc (Rider, 2002). Moreover, dry pyrite exhibits a resistivity range between 0.03 and 0.8 Ωm, influencing the observed low resistivity readings. In the study area, the lower resistivity logs in sandstone layers resulting from water saturation exceed the actual water saturation levels determined through water sample analysis.

Within the petrophysical domain, the lower Akakus Formation poses a unique challenge in interpretation due to the presence of sodium chlorite. This mineral significantly impacts petrophysical parameters, posing difficulties in determining water saturation as it affects electrical measurements (Resistivity Logs). Research on the lower Akakus Formation suggests that the 'n' value (saturation exponent) in the water saturation formula varies between 1.4 and 1.8 when Chlorite is present, contrasting with the usual value of 2. The calculated water saturation values in petrophysical analyses were higher than the observed SWI determined from well-testing results, a finding that has been consistently validated.
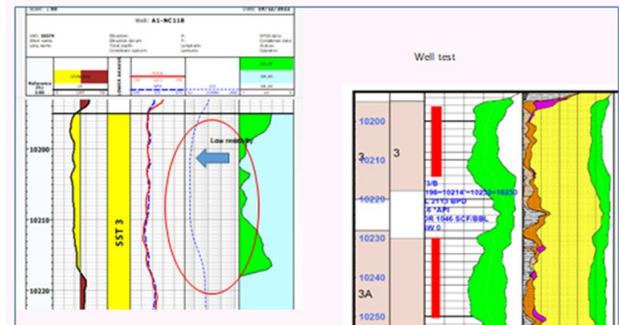

Figure 5 Low resistivity log in well A1-NC118

7.0 CONCLUSION

The integration of well log analysis and well test results was applied to evaluate the Lower Akakus Formation within the A Structure oil field, located in Block NC-118 in the western Ghadames Basin. Using available logging data from two wells (A1 and A2), the study yielded the following key findings:
1. The average shale volume ranges from 3.2% to 32.68%, porosity varies between 9.1% and 20.6%, and water saturation spans from 8.7% to 99%.
2. Formation water analysis indicates high salinity, with sodium chloride concentrations ranging from 220,000 to 290,000 ppm.
3. Despite low-resistivity indications from well log analysis, well test results confirm the presence of oil in the Lower Akakus zone.

Acknowledgement

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1]   M. Milad, R. Junin, A. Sidek, A. Imqam, and M. Tarhuni, 2021, "Huff-n-Puff Technology for Enhanced Oil Recovery in Shale/Tight Oil Reservoirs: Progress, Gaps, and Perspectives," *Energy & Fuels,* 35(21): 17279-17333. DOI: 10.1021/acs.energyfuels.1c02561.

[2]   M. Milad, R. Omran, N. M. A. Omar, and M. Enfis, 2024. "Predicting Waterflooding Performance IN A-NC186 Oil FIELD," *African Journal of Advanced Pure and Applied Sciences (AJAPAS).* 251-258.

[3]   D. Hallett and D. Clark-Lowes, 2017. *Petroleum geology of Libya*. Elsevier,

[4]   P. Turner and K. Pelz, 2017 "Development of an Upper Triassic-Lower Jurassic Evaporite Basin on the Saharan Platform, North Africa," in *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins.* 581-599. Elsevier.

[5]   M. A. Albaghday, M. Targhi, and M. Milad, 2024, "Reservoir Quality, Structural and Sedimentological Study of the Upper Cretaceous/Lower Paleocene Kalash Formation, Rachmat Oil Field, Concession 13, Eastern Sirte Basin, Libya."

[6]   Z. B. Abdulhafid, I. Aldukali, and A. Saad, 2022. "Cement logs evaluation Ghadames Basin,(Al Wafa Gas field), case study, Libya," *Journal of Pure & Applied Sciences,* 21(4): 145-150.

[7]   A. M. Basal, M. A. Sarhan, M. G. Alfarog, and A. El Bahrawy, 2023."Relative Permeabilities as Dynamic Petrophysical Parameters, Wafa Field, Ghadamis Basin, North West Libya," *Scientific Journal for Damietta Faculty of Science,* 13(3): 47-52

[8]   M. Milad *et al.*, 2023. "Experimental investigation of bypassed-oil recovery in tight reservoir rock using a two-step CO2 soaking strategy: Effects of fracture geometry," *Upstream Oil and Gas Technology,* 11: 100093.

[9]   K. Echikh, 1998. "Geology and hydrocarbon occurrences in the Ghadames basin, Algeria, Tunisia, Libya," *Geological Society, London, Special Publications,* 132(1): 109-129.

[10]   M. Hallett, 2002. "Blepharospasm: recent advances," *Neurology,* 59(9): 1306-1312

[11]   I. D. Wibowo, A. Prawesti, S. Sobani, L. I. Saputra, T. Maulana, and M. Luciawaty, 2019. "Unlocking Low Resistivity Pay as New Reservoir Backbone for Mature Field Redevelopment Strategy: A Case Study of Alengka Field, Offshore North West Java," in *SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition*, D011S001R002, DOI: 10.2118/196559-ms.

[12]   L. Gao, R.-H. Xie, L.-Z. Xiao, S. Wang, and C.-Y. Xu, 2022. "Identification of low-resistivity-low-contrast pay zones in the feature space with a multi-layer perceptron based on conventional well log data," *Petroleum Science,* 19(2): 570-580.