Petrophysical properties of the Mamuniyat Formation for hydrocarbon potentiality in “A” Oil Field, NC115 Concession of Murzuq Basin, Libya

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Abstract

The Mamuniyat sandstones represent the main reservoir in the “A” Oil Field, NC115 Concession, Murzuq Basin of Libya. As a result, the primary objectives of the current work are to evaluate and define the Mamuniyat Formation’s petrophysical parameters using well-logging analysis. For this study, the available well-logging data from ten exploratory wells were provided. Several cross-plots were used to evaluate the lithologic constituents and fluid saturations in the form of litho-saturation cross-plots, and their output parameters were fed as inputs for Interactive Petrophysics (IP) software. According to the output results, the Mamuniyat Formation is primarily composed of sandstones with a few shales. These sandstones are generally fine- to coarse-grained, as indicated by the cross-plots, with a coarsening-upward sequence. According to the litho-saturation analysis, the Mamuniyat Formation is primarily oil-bearing with some levels of water-bearing sand. The petrophysical parameters derived from well-logging data agree with those derived from core sample analysis, demonstrating that the Mamuniyat Formation is a good reservoir.

Keywords Petrophysical parameters · Litho-saturation · Cross-plot · Mamuniyat · NC115 Concession · Murzuq Basin · Libya

Introduction

Libya is a country in the Maghreb region, located on the coast of the Mediterranean Sea in northeastern Africa, roughly between longitudes 10° and 25° E and latitudes 20° and 33° N. Its mainland covers an area of approximately 1,775,500 km² and is bordered to the east by Egypt, to the west by Algeria, to the northwest by Tunisia, to the south-east by Sudan, to the south by Chad, and to the southwest

by Niger (Fig. 1). Since the Paleozoic, Libya was exposed to many marine transgressions and regressions, resulting in the deposition of thick sections of a variety of continental and marine sedimentary rocks. Regional tectonic events such as the Caledonian, Hercynian, and Alpine played a significant role in shaping the geological and structural setting of Libya. They resulted in the formation of four major intracratonic basins, Ghadames, Sirt, Murzuq, and Al Kufra, which were separated by intervening uplifts and platforms (Nafusah, Gargaf, Tibesti, and Cyrenaica Platform) (Fello 2001).

The Murzuq Basin in southwest Libya is a massive Paleozoic intracratonic-sag basin with a ladle shape, covering more than 350,000 km². It is sandwiched between the Gargaf arch to the north and the Tibesti–Haruj uplift to the east, as well as to the southwest by the Precambrian Logger Massif of Algeria and Niger (Fig. 1). The basin is mainly filled with Paleozoic continental and marine sediments, with some Mesozoic and Cenozoic marine sediments. Murzuq Basin has several concessions with oil fields. In each field, some wells have been drilled to evaluate the hydrocarbon potential of the Cambro–Ordovician section described in

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Fig. 1 Map of Libya showing its major sedimentary basins and the location of the NC115 Concession and its oilfields. The boundaries of the basins are redrawn after Fello (2001)

the stratigraphic column (e.g., Mohamed 2016; Selim et al. 2014). The “A” Oil Field is a part of the NC115 Concession, which is located on the Murzuq Basin’s northwestern flank (Fig. 1). For this study, ten exploratory wells from the “A” Field were petrophysically analyzed.

The effectiveness of well-logging data in studying reservoir petrophysics has been demonstrated (Djebbar and Donaldson 2012). Well-logging data of the ten exploratory wells have been dedicated to define and evaluate the hydrocarbon potentialities of the Mamuniyat Formation

in the “A” Oil Field. The logs were subjected to a thorough analytical formation evaluation in order to delineate the lithologic constituents, petrophysical parameters, and fluid saturation parameters. Open-hole well-logging data includes caliper, electric resistivity, spontaneous potential, density, sonic, neutron, and gamma ray logs, while lithological data are represented by composite logs. In this study, the Schlumberger’s Interactive Petrophysics (IP) software was used.

Geologic setting

Figure 2 depicts a surface geological map of Murzuq Basin (Shalbak 2015). The stratigraphic succession of the basin and NC115 Concession, as well as their stratigraphic breaks according to the Repsol oil operations nomenclatures, is depicted in Fig. 3 (Fello 2001). The

basin is underlain by Precambrian high-grade metamorphic and plutonic rocks and Infracambrian low-grade metamorphic and unmetamorphic rocks of the Mourizdie Formation (Belaid et al. 2010). It is filled with a more than 3500-m-thick continental and marine sedimentary succession of Cambrian–Quaternary age (Thomas 1995).

The Upper Ordovician (Ashgillian) sandstones of the Mamuniyat Formation serve as the primary oil reservoir in the Murzuq Basin’s oil fields, with the Lower Silurian hot shales of the Tanezzuft Formation serving as the primary source and seal (Fig. 4) (Hassan and Kendall 2014). Lithostratigraphically, Fello (2001) and Fello and Turner (2004) subdivided the Mamuniyat sandstone facies according to depositional environment into three members: lower, middle, and upper member. The lower member is dominated by a shallow marine coarsening-upward sandstone sequence; the middle is a

Fig. 2 Murzuq Basin surface geological map (after Shalbak 2015)

Fig. 3 Stratigraphic column of NC115 Concession, Murzuq Basin, Southwest Libya, and the major tectonic events affecting it (modified after Fello et al., 2001)

ERA	PERIOD/SUBPERIOD		EPOCH	AGE (My)	TECTONIC EVENT	New ROO Terminology (IRC-based)			
65 CENOZOIC	Quaternary or Pleistocene		Holocene	0.01	Alpine	Quaternary			
			Pleistocene	1.64		Al Mahruqah Fm.			
	Tertiary	Neogene	Pliocene	5.2		& basalts			
			Miocene	23.3		Mazul Ninah Fm.			
		Paleogene	Oligocene	35.4		Bishima Fm.			
			Eocene	56.5		Surfah Fm.			
			Paleocene	65.0		Zmam Fm.			
			180 MESOZOIC	Cretaceous		Late Cretaceous	97.0	Austrian	Messak Fm.
Early Cretaceous	145.6	Taouratine Fm.							
Jurassic	Malam	157.1		Hercynian	Zarzaitine Fm.				
	Dogger	178.0							
	Lias	208.0							
Triassic	Late	235.0			Caledonian				
	Mid	241.1							
	Lower	245.0							
PALAEOZOIC	Permian					Zechstein	256.1		Taconic
				Rotliegendes		290.0	Tiguentourine Fm.		
	Carboniferous	Upper	Stephanian	303.0		Dembaba Fm.			
			Westphalian	318.0		Assedjefar Fm.			
		Lower	Namurian	332.9		Marar Fm.			
			Visean	349.5		"Lwr. Marar Fm."			
	Devonian	Tournaisian	Tournaisian	362.5		Awaynat Wanin			
			Late	377.4	Fm.				
			Middle	386.0	Quan Kasa/ Tadrart Fms.				
	325 P	Silurian		Early	408.0	Late Pan African	Akakus Fm.		
Wenlock-Prid				430.4	Tanezzuft Fm. Hot sh.mbr				
Liandoverian				439.0	Mamuniyat Fm.				
Ordovician		Upper	Ashgillian	443.1	Pan African		Tashgart / Melaz Shuqran Fm.		
			Caradocian	463.9			Ash Shabiyat / Hawaz Fm.		
		Middle	Llave./ Lland.	476.1			Hasawnah Fm.		
			Arenig	493.0					
Cambrian		Lower	Tremadoc	510.0					
			Upper	517.0					
			Middle	536.0					
4330	INFRACAMBRIAN		Lower	570.0					
			Algonkian	2500.0	Mourizdie Fm.				
4330	PRECAMBRIAN		Archean	4000.0	Pan African	Basement			

LEGEND	<div></div> Present in NC115	<div></div> Not Present in NC115	<div></div> Studied Formation
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LEGEND Present in NC115

Not Present in NC115

Studied Formation

fining-upward marginal marine sequence dominated with radioactive black shales with fine- to medium-grained sandstones and coarse-grained siltstones; and the upper member is made up of coarsening-upward fluvial sandstone sequence.

The Taconic, Caledonian, Hercynian, Austrian, and Alpine tectonic events, particularly the Caledonian and Hercynian orogenies, have had a significant impact on the Murzuq Basin's tectonics and sedimentology (Belaïd et al. 2010). They divided the basin into various uplifts and

Fig. 4 North–south cross-section of Murzuq Basin (after Hassan and Kendall 2014). The location of the cross-section is plotted in Fig. 1

troughs of varying orientations, resulting in several major unconformities across the basin's sedimentary cover. The Caledonian tectonics caused a significant unconformity between Silurian and Devonian sequences. This unconformity reflects compressional tectonic movements that occurred during the Late Silurian to Early Devonian time (500–380 MA), when the main structural highs bounding the Murzuq Basin were reactivated (Davidson et al. 2000). It operated on an NW–SE axis (Klitzsch 1963) and resulted in the Silurian being overlooked along the Gargaf Arch in the basin's northern reaches (Fig. 2). The Hercynian compression caused by the Paleozoic collision of Gondwana and Laurasia affected the basin from the Late Carboniferous (Moscovian) to the Early Permian, spanning approximately 370 to 230 MA (Davidson et al. 2000). This event had a significant impact on Carboniferous sediment thickness where the Upper Carboniferous Tiguentourine Formation was lost due to erosion (Fig. 3). Aziz (2000) estimated a missing Carboniferous section in the NC115 block ranging from 1000 to 1800 m. Hercynian tectonism was perpendicular to Caledonian tectonism, resulting in a series of horsts and grabens (Klitzsch 1963). The dominant fracture trends in the Murzuq Basin's southwest are the Caledonian NW–SE within the pre-Silurian sediments and the Hercynian NE–SW within the Silurian–Devonian rocks (Tawadros 2011; Shalbak 2015).

Data analysis and processing

The well-logging data for ten exploratory wells (Fig. 5) were obtained in analogue form and then divided into zones every 0.5 feet and converted to digital form for computer processing. The anomalous peaks in the data were removed and corrected, as well as the environmental effects such as mud filtrate, hole rugosity, bed thickness, and invasion effects were reduced. These data are empirically and analytically integrated to validate the necessary petrophysical properties and hydrocarbon potentialities of Mamuniyat sandstones in the “A” Oil Field. Table 1 contains a list of abbreviations used in this study.

The data were processed to derive some of the petrophysical parameters, such as cementation factor (m), water resistivity (R_w), and matrix parameters (ρ_{ma} and ΔT_{ma}), using cross-plots (e.g., Hingle and Pickett cross-plots), and then fed them into the IP software for evaluating the Mamuniyat reservoir. The petrophysical parameters were then calculated using IP software, as described by Serra (2007) and Mohamed (2016). The shale volume (V_{shale}) was calculated using gamma ray log data. The weighted average neutron and density logs with shale correction were used to calculate porosity. The sonic log was used to calculate accurate primary porosity values. The connate water resistivity was then used to calculate the water saturation. The pay zone

Fig. 5 Locations of the wells employed in this study

petrophysical sums and averages were calculated using a V_{shale} cut-off of 38%, a porosity cut-off of 9%, and a S_w cut-off of 50%. These cut-off percentages were determined by inspecting the porosity versus V_{shale} logs and cross-plots.

The input data set as well as the output results deduced from the well-logging parameters using the IP software were displayed in the vertical zone-wise litho-saturation cross-plots. This is to assess the hydrocarbon potentialities of the formation based on the lithological and petrophysical parameters obtained from the IP software for each well separately. This plot is displayed in several tracks, as follows, from left

Table 1 List of the various abbreviations used in this study and their meanings

Abbreviation	Meaning
R_w	Formation water resistivity
R_o	Resistivity of rock 100% saturated with water
R_t	True resistivity of the formation and fluids
S_w	Formation water saturation
ρ_{ma}	Rock matrix density
ΔT_{ma}	Matrix interval transit time
ρ_b	Bulk density
V_{shale}	Fraction of shale in a sand formation
ϕ	Porosity
ϕ_n	Neutron-derived porosity
m	Cementation factor
a	Tortuosity exponent
n	Saturation exponent

to right: the first track contains logs of gamma ray, caliper, and spontaneous potential. It is followed by the horizon depths and tops in the second and third tracks, respectively. On the fourth track, there is a resistivity log. In the fifth track, the porosity logs are displayed. The output results are depicted in the last two tracks, which represent the effective porosity, oil, and water saturation, as well as the lithological identification analysis obtained from the IP software. It should be noted that the Mamuniyat Formation under consideration is oil-bearing, with no gas.

Analytical cross-plot technique

The values of the matrix parameters (ρ_{ma} and ΔT_{ma}) were calculated using Hingle's cross-plot, the oldest resistivity versus porosity cross-plot method. Figure 6 depicts a specific example for well A1. The top line represents the resistivity of water-filled rock (R_o) with $S_w = 1$. $S_w < 1$ is represented by the other lines, which decrease clockwise. The intersection of the R_o line and the scale of the x -axis in porosity units determined the matrix parameters. The results showed that the average ρ_{ma} value is 2.66 gm/cc and the ΔT_{ma} value is 55 $\mu\text{s/f}$. The points located between the lines ($S_w = 100\%$ and $S_w = 50\%$) primarily represent water-bearing zones. The hydrocarbon-bearing zones have mostly been found below the 25% water saturation line. Pickett's cross-plot (Pickett 1966) is, on the other hand, another efficient common method to use. The true resistivity (R_t) is observed to be a function of porosity (ϕ), water saturation (S_w), and cementation factor (m) in this technique (Fig. 7). In this study, it

Fig. 6 Hingle cross-plot of Mamuniyat formation at A1-NC115

was used to help determine the formation water resistivity (R_w), water saturation, and cementation factor by plotting the porosity with deep resistivity values on two-by-three cycle log-log paper.

At 100% water saturation, the intersection of S_w line with the horizontal axis represents a $*R_w$. The cross-plots revealed that the average value of R_w is 0.32 $\Omega \cdot m$, which is consistent with the core sample data obtained from the Repsol company (Selim et al. 2014). It was also discovered that the average value of m was 1.9 (slope of 100% S_w line), which is consistent with well-logging data. The average saturation exponent value ($n = 1.75$) was obtained directly from the cores obtained from the

Repsol company. The water-bearing zones represent the Mamuniyat Formation's lower part and are concentrated between lines S_w 100% and 25%; on the other hand, the hydrocarbon-bearing zones represent the formation's upper part and are concentrated around the 25% water saturation line.

A dia-porosity ρ_b/ϕ_n cross-plot has been plotted for all wells to study the lithologic facies and their grain size analysis from well-logging data, revealing that the lithologic facies consist primarily of sandstones (Figs. 8 and 9). According to the relationship between porosity and water saturation, this sandstone is coarsening upward from the lower to upper parts of the Mamuniyat reservoir (Fig. 10). The

Fig. 7 Pickett plot for Mamuniyat Formation for A10-NC115 well, “A” Oil Field

Fig. 8 A dia-porosity ρ_b/ϕ_n cross-plot for Mamuniyat Formation at well A5-NC115, “A” Oil Field

information from well-logging data mentioned above were used as input parameters for the IP software to deduce the petrophysical parameters in the form of litho-saturation cross-plots, which will be discussed next.

The litho-saturation analysis of Mamuniyat Formation

The Mamuniyat Formation's petrophysical parameters have been calculated. The parameters considered include shale volume, porosity, and water and hydrocarbon saturations, which change from borehole to another. Their percentages

have been discussed for a few selected wells for illustration purposes only, as follows:

The calculated shale volume varies from well to well, but a few intercalations are generally found. It ranges from 0.2 to 17.7% with a weighted value of 5.4% in well A1 (Fig. 11); effective porosity varies between 10.3 and 15.6% with a weighted value of 12.5%, water saturation varies between 23.7 and 99.6% with a weighted value of 75%, and oil saturation varies between 1 and 63.9% with a weighted value of 25%. As shown in the litho-saturation cross-plot, the vertical distribution of these data shows that the Mamuniyat Formation's upper part is the most effective zone for hydrocarbon saturation (Fig. 11).

Fig. 9 A dia-porosity ρ_b/ϕ_n cross-plot for Mamuniyat Formation at well A35-NC115, “A” Oil Field

Fig. 10 S_w vs ϕ showing upward coarsening sequence, for Mamuniyat Formation at A12-NC115, “A” Oil Field

The determined shale volume of the well A10 (Fig. 12), on the other hand, varies between 0.1 and 4.5% with a weighted value of 1.3%. The effective porosity varies between 5.5 and 18.3% with a weighted value of 13.5%, the water saturation varies between 4 and 80% with a weighted value of 55%, and the oil saturation varies between 7.3 and

85% with a weighted value of 45%. The litho-saturation cross-plot shows that the middle and lower parts of Mamuniyat are the most productive zones for hydrocarbon occurrence (Fig. 13).

While the litho-saturation cross-plot of well A24 reveals that the calculated shale volume varies between 0.1 and 12%

Fig. 11 Litho-saturation for Mamuniyat Formation, A1-NC115 well, “A” Oil Field

with a weighted value of 9%, the effective porosity varies between 5.0 and 14% with a weighted value of 11.6%, the water saturation varies between 3 and 44% with a weighted

value of 40%, and the oil saturation varies between 8 and 75%, with a weighted value of 60%. As shown in the litho-saturation cross-plot from the hydrocarbon potentiality, the

middle part is the most effective zone for hydrocarbon content (Fig. 13). There is no evidence to differentiate the petrophysical parameters in one part of the Mamuniyat Formation from another; they vary from well to well but generally

reflect good reservoir rocks. As shown in the litho-saturation cross-plot, the total thickness of the Mamuniyat reservoir varies from well to well, indicating that this field may be structurally controlled.

Fig. 12 Litho-saturation for Mamuniyat Formation, A10-NC115 well, “A” Oil Field

Fig. 13 Litho-saturation for Mamuniyat Formation, A24-NC115 well, “A” Oil Field

Discussion

The primary goal of this research is to investigate the petrophysical parameters and hydrocarbon potentials of

the Mamuniyat Formation in the “A” Oil Field, NC115 Concession, Murzuq Basin. The oil is stored in the Ordovician Mamuniyat reservoir and sourced from the hot shales of the Silurian Tanezzuft Formation (Craik et al. 2001).

Fig. 14 Distribution maps of the effective porosity (a) and oil saturation (b) in “A” Oil Field

Ten exploratory wells have been chosen for this field. The cross-plot output results show lithological facies that are mostly sandstone with a little shale. This sandstone is coursing upward. Hingle's cross-plot was used to calculate the matrix parameters (ρ_{ma} and ΔT_{ma}). The Pickett cross-plot, on the other hand, has been used to calculate R_w and m . The findings of these cross-plots are highly consistent with the findings of the core sample analysis. This agreement highlights the cross-plots' high reliance in the absence of core sample data. For each well, the dia-porosity ρ_b/ϕ_n cross-plots have been plotted. They stated that the lithologic facies is primarily composed of sandstones. Hingle's cross-plot revealed that the average values of ρ_{ma} and ΔT_{ma} are 2.66 gm/cc and 55 μ s/f, respectively. Pickett cross-plots revealed that the average value of R_w is 0.32 $\Omega \cdot m$. All of the above-mentioned parameters are consistent with those derived from the core sample data collected by the Repsol Oil Operation. The calculated petrophysical parameters show a valuable reservoir because the weighted effective porosity values reached up to 19%, which is relatively high. At well A23i, effective porosity values generally increase northward (Fig. 14a). Furthermore, the weighted values of hydrocarbon saturation percentages have a maximum value of 60%, which increases toward the north at well A23i and

to the south east at well A24i (Fig. 14b). The low shale volume reflects the high quality of this reservoir. The well-logging data and calculated petrophysical parameters indicate that this reservoir is primarily oil-bearing, with some sandstone levels saturated with water.

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Declarations

Conflict of interest The authors declare no competing interests.

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