Scientific Journal for Damietta Faculty of Science **13**(3) 2023, 47-52
doi: 10.21608/SJDFS.2023.245746.1138
ISSN Print 2314-8594
ISSN Online 2314-8616

https://sjdfs.journals.ekb.eg/

Relative Permeabilities as Dynamic Petrophysical Parameters, Wafa Field, Ghadamis Basin, North West Libya

Ahmad M. K. Basal[1], Mohammad A. Sarhan[*1], Mostafa Gumaa Alfarog[1] and Ahmed Elbahrawy[1]

[1]Geology Department, Faculty of Science, Damietta University, New Damietta City, 34517, Egypt.

Received: 31 October 2023 /Accepted: 16 November 2023

[*] Corresponding author's E-mail: msarhan@du.edu.eg

Abstract

The Ghadames basin is the second-largest oil-producing basin in Libya. One of the gas and oil producers in the Ghadames basin is Al Wafa Field. The purpose of this investigation is to assess the Aouinet Uennin Formation (F3) "B" sandstone in the Al Wafa field, Ghadames Basin, Libya, specifically in the A37-NC169a well. The well-logging analysis revealed that the water saturation of the upper-most F3B sandstone is less than 30% reflecting its superior reservoir potentiality. The findings showed that the relative permeability to water as well as the water cut value equal zero while the relative permeability to oil is 100%, which confirm that this interval is at irreducible state. The applied J function technique approved the high-quality reservoir performance of F3B Upper Unit 1 with low computed J values (< 3.48) reflecting the low capillary pressure and the presence of mega- pores. The calculated irreducible water saturation is 22%, which matches the obtained core data.

Keywords: Ghadames Basin; Al Wafa field, Leverett "J" Function, Water Cut and Relative Permeability.

Introduction

The Ghadamis Basin is a large sag basin on the North African platform, extending over parts of Algeria, Tunisia, and Libya (Figure1). The basin was thought to have limited hydrocarbon potential prior to the 1990s because almost all of the 3.5 billion barrels of recoverable oil found had been found before 1965 (Van de Weerd and Ware, 1994; Echikh, 1998). The Libyan portion of the basin was the primary site of discoveries made in the 1970s and 1980s. However, in the 1990s, businesses like Anadarko and Burlington Resources spearheaded a new exploration campaign in Algeria that was primarily propelled by enhanced seismic acquisition and processing. As a result, an estimated 5.6 billion barrels of recoverable oil equivalent were found, mostly in sandstone reservoirs from the Devonian and Triassic periods (Echikh, 1998; Rusk, 2000). Understanding hydrocarbon generation and charge in the basin is essential to realizing the remaining potential because exploration in the Libyan portion of the basin has been less extensive.

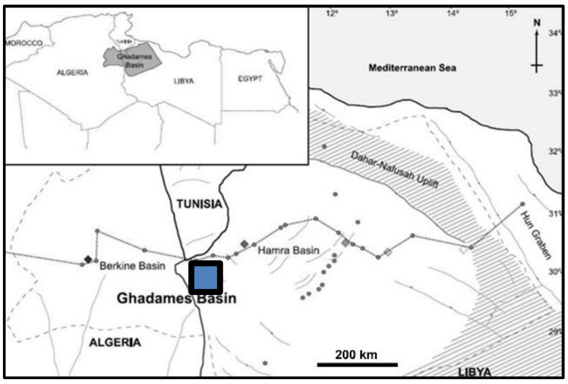

Figure (1): Map shows the location of Al Wafa field inside Ghadamis Basin, Western Libya (After, Underdown and Redfern, 2007).

The Paleozoic and Mesozoic sediments make up to 20,000 ft (Figure 2) of the Ghadamis Basin. A significant regional Hercynian (Permian-Carboniferous) unconformity divides the Paleozoic portion from the Mesozoic deposits. The petroleum systems in the basin have been directly impacted by erosion patterns and the topography that formed on the surface of this regional unconformity. These variables governed long-distance migration within the Triassic reservoirs, communication between the source and higher reservoirs, and the preservation of Paleozoic hydrocarbons. The late Silurian - Early Devonian reservoirs in the basin have a variety of structural and stratigraphic traps. Through channels found in a series of deltaic sediments, migration took place. Oil has seeped into Middle-Late Devonian reservoirs in the south, where these seals no longer hold. This study aims to evaluate the Aouinet Uennin Formation (F3) "B" sandstone in the A37-NC169a well of Al Wafa field Basin as a potential hydrocarbon-bearing reservoir in the Ghadames Basin.

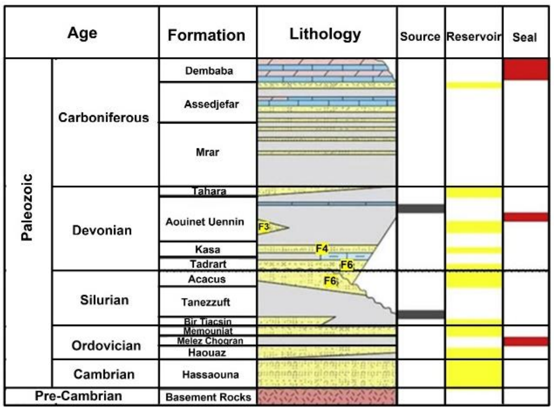

Figure (2): Stratigraphic column displays the petroleum system in Ghadamis Basin (modified after Bora & Dubey, 2015; Rusk, 2000).

Data and Methods

The available well log data for A37-NC169a Well are in the form of a suite of electric well logs which are represented graphically in five tracks (Figure3). Track one (depth ft), Track two (Stratigraphy unite studied Awaynat F3B), Track three (Gamma-ray, green color and Caliper blue color), Track four contain Latero Log Deep and Shallow resistivities (LLD and LLS, red and purple-blue colors) and Track five contain the following log curves: Neutron (NPHI, color), density (RHOB, red color), density correction (DRHO black color) and photo electric factor (PEF pink color). In addition to well logs, Routine Core Analysis (RCA) results as helium porosity and horizontal permeability are also available. The following sections represent the procedure followed for obtaining the dynamic F3B sandstone reservoir parameters by analysing and interpreting the data.

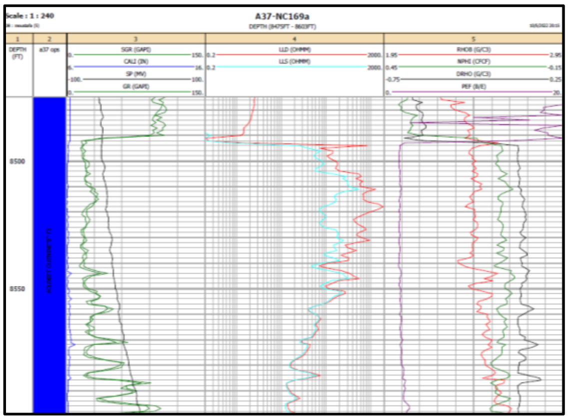

Figure (3): Well log suite available for F3B sandstone in A37-NC169a Well, Wafa Field, Ghadamis Basin, North West Libya.

Results and Discussion

Qualitative (Quick Look) interpretation of well logs

Figure (3) shows the visual examination of the different log curve shapes and their positions relative to each other, the entire interval can be segmented into three different units/ zones as follows:

The uppermost zone (Unit 1) occupies the interval between the depths of 8510-8540 Feet and is characterized by low Gamma Ray readings coupled with high positive resistivity separation (LLD>>LLS in track 4). This type of separation is considered a sign of permeability

presence. The sandstone nature of this unit is clearly seen in the magnitude of separation between Neutron on the right with respect to density and confirmed by the PEF reading of a typical quartz mineral of 1.98 (Track 5). The density correction curve ($\Delta\rho b$) reads around zero indicating excellent hole conditions and hence trusted log readings. The midway between neutron and density curves reads about 10% porosity on the neutron scale. The above quick look interpretation for this unit makes it an excellent candidate for further detailed investigation as a clean sandstone oil reservoir as will be displayed in this article.
The other two units will be excluded as they are not considered interesting as reservoir. Unit 2 (8550_8580 Ft) generally has lower resistivities with no separation (LLD=LLS) in addition to moderately higher Gamma Ray (i.e. shaly). Unit 3 (8580_8600 Ft) can be considered shale as the Gamma Ray gradually increases and reaches 135 API at the base. Also increasing PEF (2.3 b/e) confirms the shale nature of this unit.
It is of prime importance here to conduct a quick and simple form of the Archie model (1942) for Unit 1 as follows:

$$\mathbf{SW} = \sqrt{\frac{\mathbf{RW}}{\emptyset^2 \times \mathbf{RT}}} \qquad (1)$$

Where: Ø= 0.10 (neutron-density readings), R_W = 0.06 (Known from available core data), R_T = 150 (average LLD readings), Assuming m=2.

$$\mathbf{SW} = \sqrt{\frac{\mathbf{0.06}}{\mathbf{150*0.102}}} = 0.2\ (20\%)$$

The very low water saturation value for this unit indeed confirms the conclusion obtained above that this unit is very optimistic. In this respect, it is worth mentioning here that any justification or modifications for the assumed parameters m or n don't greatly alter the conclusion.

Pickett Plot

The preliminary step before any detailed dynamic reservoir properties is to evaluate water saturation (S_W). This is based on the popular Archie Model (1942) and further modified to represent straight-line form when plotting porosity versus resistivity on log-log paper (Pickett, 1966). The Pickett plot for the main upper F3B clean sandstone reservoir (8510 – 8540 ft) belongs to Awaynat Wanin Formation in A37-NC169a is shown in Figure (4). The plotted points scattered below 30% Sw line reflecting clean oil production. Notice that also the quick look S_W calculations gave values below 30%, these water saturation values are considered the main input parameter for further any dynamic reservoir petrophysical parameters calculations as will be discussed below.

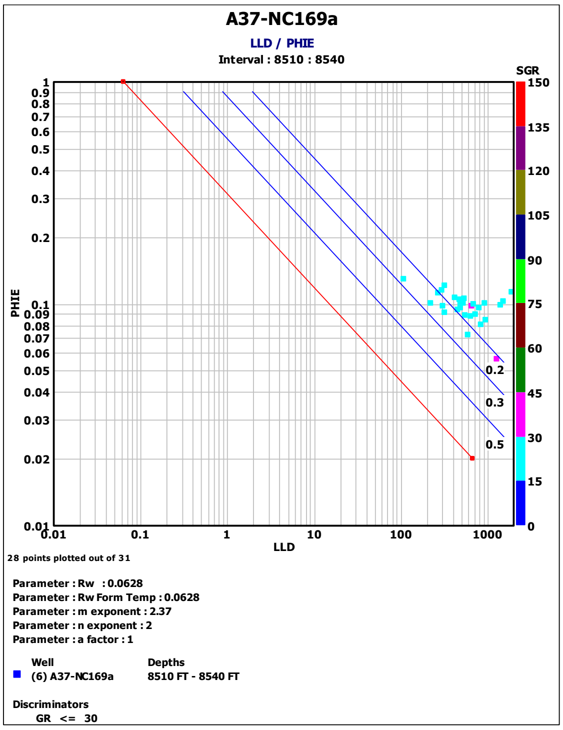

Figure (4): Pickett plot for F3B upper Unit 1reservoir zone (8510 to 8540 ft) in A37- NC169a well, Wafa field, Ghadames Basin North West Libya.

Relative permeabilities to water (Krw), oil (Kro) and Water Cut (WC)

The transmissivity of a fluid between the connected pores is referred to it as permeability (K). In cases where two immiscible fluids are present with each other, each fluid has its own movability known as relative permeability (K_r). In case of F3B reservoir, the relative permeability to oil (K_{ro}) and water (K_{rw}) have to be estimated to understand the dynamic flow of these fluids during production. Accordingly, this dynamic parameter is vital for evaluating any reservoir characterization. These two petrophysical parameters can be obtained as (Brock, 1986)

$$Kro = \left(\frac{0.9-SW}{0.9-SWirr}\right)^2 \qquad (2)$$

$$Krw = \left(\frac{SW-SWirr}{1-SWirr}\right)^3 \qquad (3)$$

Where: S_W = water saturation as deduced through Pickett technique (Figure4), S_{Wirr} = the irreducible water saturation and can be calculated for each point for graphical presentation as (Asquith and Gibson, 1982**)**:

$$\mathbf{Swirr} = \sqrt{\frac{\mathbf{F}}{\mathbf{2000}}} \qquad (4)$$

<u>Where:</u> F = the formation resistivity factor (=1/Φ^2).

The economic hydrocarbon production is mainly tied with the amount of water cut (**W.C**) associated with oil production. The less water cut corresponds to the more economic reservoir. This factor is controlled by the relative permeability to water (K_{rw}) and oil (K_{ro}) and irreducible water saturation (S_{Wirr}) as follows (Brock, 1986).

The water cut (**W.C**) is related to water oil ratio as follows:-

$$W.C = \frac{WOR}{1-WOR} \qquad (5)$$

$$WOR = B\left(\frac{KRW}{KRO}\right) \qquad (6)$$

The correlation between oil gravity (API) and the constant B are presented in Table (1) (Brock, 1986).

Table (1): Relation between oil gravity (API0) and the constant "B" in Equation (6) (Brock, J. 1986).

API^0 Gravity	B
14	50
19	20
27	10
35	5
45	2
>50	1.5*

***** extrapolated by the authors.
Brock, J.G. (1986): Applied Open-Hole Log Analysis, Volume 2, Gulf Publishing Company, Houston, Texas. 283P.

According to core data available, F3B sandstone reservoir has 0.75 gm/cc oil density. The required oil gravity in this case will be calculated as:

$$API = \left(\frac{141.5}{\rho b}\right) - 131.5 \qquad (7)$$

The calculated API is 57 (i.e >50) corresponds to B equals 1.5 (as extrapolated by the authors).

Leverett J-Function

Leverett (1941) introduced a model through which porosity, permeability and capillary pressure were merged into one equation as follows:

$$\mathbf{Jsw} = \frac{\mathbf{Pc}}{\boldsymbol{\sigma}\,\mathbf{csc}\,\boldsymbol{\theta}} * \sqrt{\frac{\mathbf{K}}{\emptyset}} \qquad (8)$$

<u>Where:</u> J = dimensionless Leverett function, P_c = capillary pressure (psia), σ = interfacial tension (dyn/cm), k = permeability (md), ϕ = porosity (fraction).

The applications of the above-described techniques on Awaynat Wanin Formation (F3) "B" in A37-NC169a well, give the following results:

Figure (5) represents the graphical relation between S_W versus S_{Wirr} (Equation 2). The plotted points landed on and around 100% ~ 1K_{ro} indicating that the oil is the only expected fluid, which will be produced. However, Figure (6) contains a number of lines representing relative permeability to water (Equation 3) ranging from 0 to 0.1. The plotted points confirm water-free oil production as they are located on and around the zero line. Figure (7) represents a graphical form of Equation (5). The plotted points for the study F3B reservoir consider additional confirmation for the excellent quality performance as the water cut reaches zero.

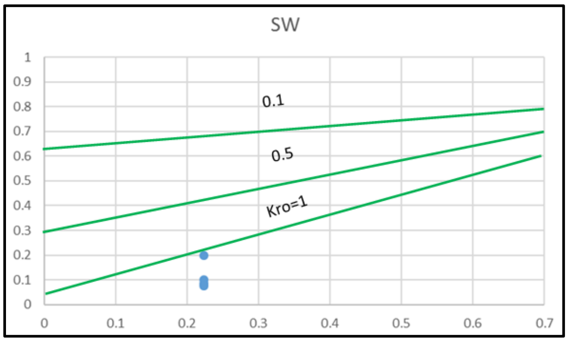

Figure (5): Irreducible water saturation (Swirr) (horizontal axis) versus water saturation (Sw) (vertical axis) cross-plot (after Asquith and Gibson, 1982) for determining relative permeability to oil (Kro) for upper unit 1 for Awaynat Wanin Formation (F3) "B" in A37-NC169a well sandstone reservoir.

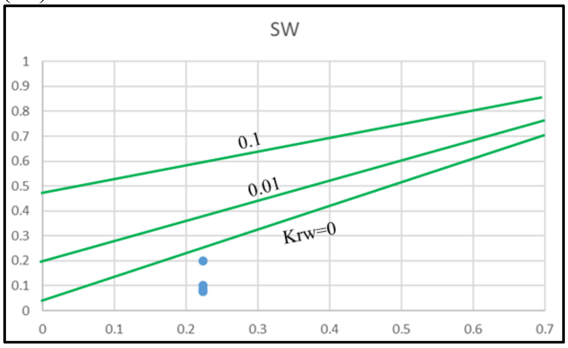

Figure (6): Irreducible water saturation (Swirr) (horizontal axis) versus water saturation (Sw) (vertical axis) cross-plot (after Asquith and Gibson, 1982) for determining relative permeability to water (Krw) for upper unit 1 for Awaynat Wanin Formation (F3) "B" in A37-NC169a well sandstone reservoir.

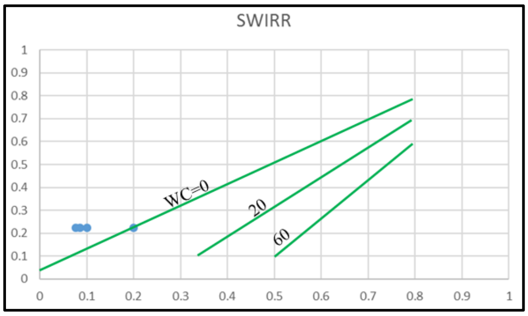

Figure (7): Irreducible water saturation (Swirr) (vertical axis) versus water saturation (Sw) (horizontal axis) crossplot (after Asquith and Gibson, 1982) to determine the water-cut percentage for upper unit 1 for Awaynat Wanin Formation (F3) "B" in A37-NC169a well sandstone reservoir.

The calculated Leverett J function (Equation 8) at different water saturations for F3B reservoir in the study field (Table 2) is based on the following parameters needed: σ=47.4 ϴ=0 (core data). The capillary pressure (P_c) is not available therefore; Pittman (1992) model was applied using core porosity and permeability. The graphical presentation for the tabulated values above is displayed in Figure (8). The resulting curve greatly resembles that of P_c versus Sw but with a more accurate and definite description of the study reservoir. Through this figure, the high-quality reservoir is seen where 40% S_W is reached at only 10 J function corresponding to low P_c. In another word, the reservoir is homogeneous with large pore throat radios and higher permeabilities.

Table (2): Calculated Leverett J function (Equation 8) for F3B upper unit 1 reservoir in A37-NC169a, Ghadamis Basin, Wafa Field, North South Libya.

SW%	J	SW	J
90	5.18	55	8.28
85	5.88	50	9.03
80	6.47	45	10.35
75	6.95	40	12.30
70	7.33	35	15.02
65	7.76	30	20.06
60	8.17	25	30.485

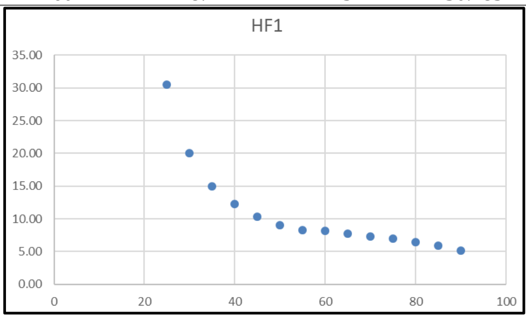

Figure (8): Water saturation (horizontal axis) versus Leverett J function (Vertical axis) for upper unit 1 for Awaynat Wanin Formation (F3) "B" in A37-NC169a well sandstone reservoir.

Conclusions

The Quick Look technique represents the first step for locating the most optimistic zones to be exposed for detailed studies for (F3) "B" interval in A37-NC169a well sandstone reservoir A37Wafa Field, Ghadamis Basin, South East Libya. The Upper Unit 1 of F3B Formation has excellent reservoir characterization hence it has water saturation (**S_W**) less than 30% on Pickett Plot. Relative permeability to oil (**K_{ro}**) and water (**K_{rw}**) in addition to Water Cut (**W.C**) considered the vital petrophysical parameters for evaluating F3B reservoir in the study well. According to these parameters, the study reservoir is at an irreducible state hence **K_{ro}** is 100%, **K_{rw}** and **Water Cut** is zero. Application of Leverett **J-**function model confirmed the high-quality performance of F3B Upper Unit 1 reservoir in the study well. The low computed **J** values (maximum 3.48) reflected low capillary pressure corresponding to large (**Mega**) pore radios of excellent quality. The **SW-J** curve shape for this Unit 1 greatly resembles that of **SW-Pc** but with a more accurate description of the reservoir performance during production. It also gives Irreducible Water Saturation (**SWirr**) to be 22% which nearly coincides with that obtained through core analysis.

Acknowledgment

The authors are grateful to the National Oil Corporation Petroleum of Libya and the Mellitah Oil & Gas B.V. Company for providing the geophysical data presented in this work.

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الملخص العربي

عنوان البحث: النفاذية النسبية كمعلمات بتروفيزيائية ديناميكية، حقل الوفاء، حوض غدامس، شمال غرب ليبيا

أحمد محمد كمال بصل[١]، محمد عبد الفتاح سرحان[١]، مصطفى جمعة الفاروج[١]، أحمد البحراوي[١]
[١] قسم الجيولوجيا – كلية العلوم – جامعة دمياط - مصر

يعتبر حوض غدامس ثاني أكبر حوض لإنتاج النفط في ليبيا ويعد حقل الوفاء أحد منتجي الغاز والنفط في حوض غدامس. الغرض من هذا البحث هو تقييم الحجر الرملي لتكوين عوينات وانن في حقل الوفاء بحوض غدامس. كشف تحليل تسجيلات الابار للبئر محل الدراسة أن تشبع الماء في الحجر الرملي العلوي أقل من ٣٠٪ مما يعكس إمكانات الخزان العالية. أظهرت النتائج أن النفاذية النسبية للماء وكذلك قيمة قطع الماء تساوي صفر بينما النفاذية النسبية للنفط ١٠٠٪ مما يؤكد أن هذه الطبقة في حالة انتاج للبترول بدون ماء مصاحب.