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Fracture Detection in the Carbonate Baba Formation, Bai Hassan Oilfield, Northern Iraq, Using Conventional Well Log Data

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Abstract

One of many lengthy, asymmetrical, and double plunging anticlines that make up the Foothill part of the Unstable Shelf Zone in northern and eastern Iraq is the Bai Hassan Oilfield. The absence of advanced fracture detection tools such as the Formation Micro Image (FMI) log and Televiewer tools used in boreholes has led to the follow of new methods to use common and ordinary well logging methods to investigate possible fractures in the reservoir. For fracture detection in the Baba Carbonate Formation in the Bai Hassan Oilfield, Northern Iraq, this study employs conventional well log data from two chosen wells (BH-101 and BH-078). Several applications have been combined, including the tri-porosity cross plot (M-N), secondary porosity calculation, natural gamma ray spectroscopy (NGS), dual laterolog - microspherical focused logs separation, and the cementation exponent (m) parameter, for detecting the fractured zones of the formation. The scatter of the sample points towards the secondary porosity field of the M-N crossplot was a preliminary indication for the existence of fractures in the studied sections. In various horizons of both studied wells, the Baba Formation has good secondary porosity that ranges from less than 1.0 to about 10%. Almost the entire formation has certain percentages of secondary porosity, especially in its middle and lower parts. An increase in the Uranium volume, as observed in some horizons from the U/K and U/Th ratios, coincides with the calculated secondary porosity values and supports those zones being fractured zones. The relative decrease in resistivities recorded by the resistivity logs in certain horizons also supported the suggestion that those intervals were fractured zones. The formation appeared to have cementation exponent values of 1.59 in the well BH-101 and 1.71 in the well Bh-078; both values are related to formations with fractures. It is vital and recommended that the procedure used in this study be applied to boreholes with image logs in order to calibrate the results and the reliability of the identified fracture zones.

Keywords: Baba Formation, Fractures, Bai Hassan, Well logs, Secondary porosity.

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الكشف عن الكسور في تكوين بابا الكاربوناتي في حقل باي حسن النفطي شمالي العراق بأستخدام معطيات الجس البئري

الخلاصة:

يقع حقل باي حسن النفطي في جزء أقدام الجبال من نطاق الرصيف غير المستقر في شمال العراق و يتكون من طية محدبة طولية غير متناظرة و ثنائي الغاطس. نظرا لعدم وجود المعطيات المستحصلة من الأجهزة الخاصة بالكشف عن وجود الكسور في الصخور الخازنة مثل مجس التصوير الدقيق للتكوين(FIM) و جهاز التلفاز البئري، فقد تم الأستعانة في هذه الدراسة بمعطيات المجسات التقليدية في سبيل التحري عن وجود الكسور في الصخور الخازنة لتكوين بابا الكاربوناتي و ذلك في بئرين مختارتين من ابار حقل باي حسن النفطي و هما (BH-101) و (BH-078). لقد تم تطبيق طرائق عديدة للكشف عن وجود الأنطقة الحاوية على الكسور في التكوين مثل أستخدام مرتسم (M-N) ثلاثي المسامية، أحتساب المسامية الثانوية، مجس مطياف گاما الطبيعي (NGS)، أنفصال منحني المقاومية لمجس اللاتيرولوگ المزدوج و مجس الكروي المبئور الدقيق، و معامل التسميت (m).

ان تبعثر النقاط على مرتسم M-N نحو منطقة المسامية الثانوية يدل بصورة أولية على وجود الكسور في التكوين، كما تم أحتساب نسب جيدة من المسامية الثانوية تراوحت بين أقل من 1.0 و 10% و قد تركزت الكسور في الجزء الأوسط و ألأسفل من التكوين. ان أزدياد حجم اليورانيوم نسبة لحجم البوتاسيوم و الثوريوم في ألأنطقة التي سجل فيها نسبة عالية من المسامية الثانوية يدل على وجود الكسور في تلك ألأنطقة. كما دعمت الهبوط في قيم المقاومية المسجلة لبعض ألأنطقة على وجود الكسور فيها. كما ان القيم المحتسبة لمعامل التسميت و البالغة 1.59 للبئر BH-101 و 1.71 للبئر BH-078 تدلان أيضا على ان التكوين يحتوي على التكسرات. من الأهمية بمكان أن تطبق طرق الكشف عن الكسور المتبعة في هذه الدراسة في أبار تملك معطيات مجس التصوير الدقيق للتكوين و ذلك لغرض المقارنة و التأكد من صحة نتائج الدراسة.

1. Introduction:

According to [1], up to 60% of the world's petroleum reserves are believed to be in naturally fractured reservoirs (NFRs), where the reservoir rock's fissures have a major impact on the flow of the reservoir fluid or are expected to do so.

Identification of the naturally fractured horizons within reservoirs is vital for best identifying productive zones. In the absence of modern Image logs or the borehole tele-viewer tool, the data from conventional wireline logs can be used to indirectly identify the fractured zones. The effect of the existed natural fractures on the rock properties and on the movability of the fluids can be sensed in different ways by the conventional well logging tools [2] [3] [4] [5]. The discontinuity resulting from the fractures has an impact on the density, porosity, and permeability of the rocks, which consequently will impact the records of most of the conventional logs such as the caliper, spontaneous potential, sonic, density, neutron, and resistivity. Some of those logging tools can aid in defining the fractured zones solely, while others can do so in combination. Attempts have been made by some authors not only to identify the existence of fractured zones based on the data from conventional logs but also to estimate the fracture density in the reservoirs [6].

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In this study, the gathered data from the available conventional logs for the Oligocene reefal limestone of the Baba Formation in two selected wells of the Bai Hassan Oilfield has been used to identify the efficiently productive horizons resulting from the permeability enhanced by the existing natural fractures.

2. Study Area

In Northern Iraq, close to Kirkuk City, is the giant Bai-Hassan Oilfield (Figure 1). The field is located 35 kilometers north-west of Kirkuk City in the Dibbs area. Tectonically, the Bai Hassan structure is located in the Low Folded Zone according to [7] or the Makhul-Hamren Subzone according to [8], which is part of the Unstable Shelf Zone.

Iraqi Petroleum Company (IPC) found the field in 1953, and it has been on production since 1960. The Bai-Hassan structure is made up of two domes, Kithke in the southeast and Daoud in the northwest, which are divided by the Shahl saddle. The anticline of Bai Hassan has a longitudinal shape with asymmetrical dipping flanks and double plunging, which is generally in accordance with most of the structures in the Foothills region of the Unstable Shelf Zone in eastern Iraq (Figure 1).

The 40 km long by 3.8 km wide structure has a northwest to southeast trend. The noses plunge at over 5 degrees while the flanks dip by about 40 degrees.

Early wells' dipmeter data reveal local dips of more over 50 degrees that are almost certainly caused by faults. The Tertiary limestone formations used primarily in the field's production (known as the "Main limestone") are fractured and are similar to those found in the Kirkuk Oilfield. Production is also carried out in the Cretaceous Shiranish, Mauddud (Upper Qamchuqa), and Shu'aiba (Lower Qamchuqa) formations.

3. Stratigraphy of Bai Hassan Oilfield

Sadeq et al. [9] subdivided Bai Hassan Oilfield stratigraphically into eighteen major lithologic facies. The stratigraphic column of the field contains a lot of distinguished limestone beds of ages between Oligocene and Paleocene with different reservoir capabilities (Figure 2).

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Fig. (1): Location of Bai Hassan Oilfield [10]

The upper Miocene Age Upper Fars (Injanah) Formation covers most parts of the field, followed by the middle Miocene Lower Fars (Fatha) Formation, which overlaid either the lower Miocene beds of the Jeribe Formation or the Oligocene beds of Kirkuk Group, at which a basal conglomerate may exist. The interbedded anhydrites and limestones of the lower and middle Miocene ages are believed to act as the barrier cap rock for the accumulated hydrocarbons in the Tertiary reservoirs of the field.

The lower Eocene Jaddala Formation and the Paleocene Aaliji Formation, which are generally shaley limestones, both represent the cap rocks for the beneath Cretaceous reservoirs in both Kithke and Daoud domes of the field.

Sadeq [11]**,** during his study of the Tertiary reservoirs of the Bai Hassan Field mentioned that their thickness is ranging between 213 and 250m. He further subdivided the Oligocene formations in the field into two separate cycles with different facies belonging to environments ranging from back reef to reef-fore reef, and basin. Sadeq [11] more claimed that the first cycle consists of the dense limestone of the Shurau Formation (back reef), the limestone of the Sheikh Allas Formation (fore reef), and the Globigerinal limestone of the basinal Tarjil Formation. The second cycle, on the other hand, includes the Bajwan Formation (back reef) and Bajwan/Baba formations as the fore reef facies of the cycle.

Bellen originally identified the Baba Formation from Kirkuk oil well-109 in 1956. It is lithologically composed of porous dolomitized limestones, which have a chalky appearance,

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bedded, and massive when cropped out [12]. The formation was deposited in the fore-reef region of the Oligocene Basin's northeastern and southeasterly margins.

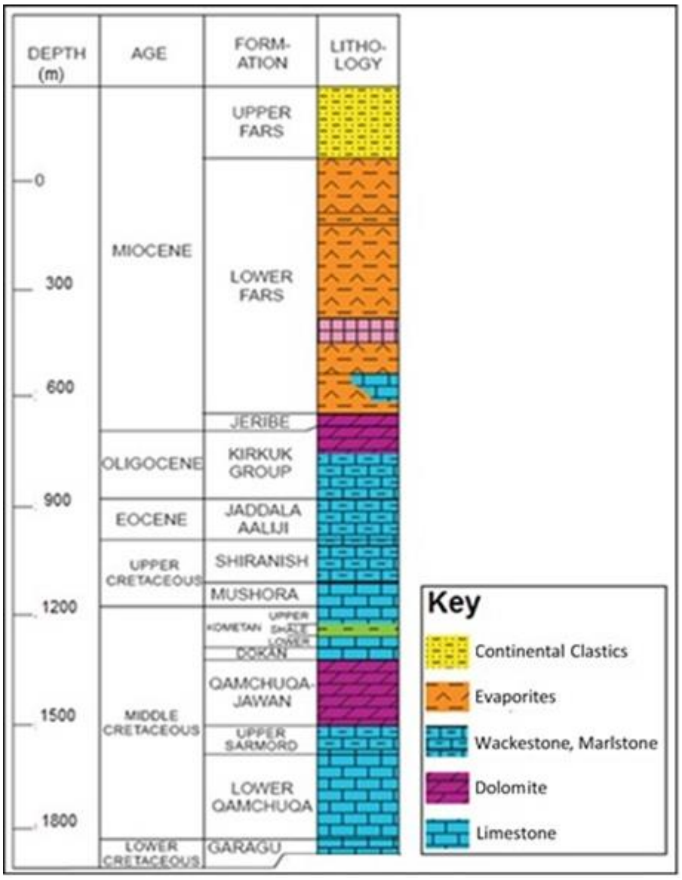

Fig. (2): General stratigraphic column at Bai Hassan Oilfield [11]

According to [12], the formation is middle Oligocene in age. A late Oligocene date is inferred from the abundance of faunal content [13] [14] [15] [16] [17] and [18].

[18] subdivided the Baba Formation in the well BH-25 of Bai Hassan Oilfield into three microfacies from bottom to top: fine to very coarse bioclastic foraminiferal packstone, fine bioclastic smaller foraminiferal packstone, and fine bioclastic smaller foraminiferal wackestone. On the other hand, [19] subdivided the formation in Kirkuk Oilfield into two microfacies, namely Limestone bearing larger foraminifera (Lepidocylina - Nummulites) packstone-wackestone microfacies at the lower and middle parts of the formation and Fossiliferous floatstone bearing larger foraminifera microfacies at the upper part.

[20] considered the Baba Formation (Unit B) as the main reservoir in the nearby Ismail Field. They concluded that matrix (primary) porosity is the main controller of the pore spaces in the formation, which showed very good porosities ranging between 17 and 19% as a result of dolomitization, whereas fractures represent only about 0.2–3.4% of the total porosity.

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4. Tectonic of study area

The structure of the Bai Hassan at the surface is largely flat, with minor dips of less than 10 degrees. According to [11], the current structure and its ensuing stratigraphy are the products of two very different tectonic periods. The Arabian and Eurasian plates' early pre-Tertiary rifting produced a graben system of basement fault blocks and normal faults, which were covered by a thick sequence of platform carbonates. The ancient Cretaceous seaway closed and shrunk as a result of compression, which began in the early Tertiary. As a result, carbonates and buildups related to the fore-reef and reef were deposited. The Zagros Fold Belt's current features, especially Bai Hassan, were developed as a result of folding and thrusting caused by continued shortening during the Miocene [21]. It's believed that this incident led to frack the cap rocks of the late Cretaceous and early Tertiary ages, allowing oil to move vertically into the carbonate reservoirs of the lithifying Tertiary. What was left of the ancient foredeep was filled up by Sabkha evaporites and continental clastics, locking the hydrocarbons in the anticline [11].

5. Data and Methodology

The available data for this study are generally conventional log data belonging to the North Oil Company (NOC), which thankfully permitted using them in this study.

5.1 Types of the available data

The data used in this study are from the conventional logs of the Baba Formation in the two wells BH-101 and BH-078 of the Bai Hassan Oilfield. The data are for the logs of natural and spectroscopy gamma rays, the porosity logs of sonic, density, and neutron, in addition to the resistivity logs. The data covered the formation between depths 1680 and 1760m (80m thickness) in the well BH-101 and between depths 1677 and 1713m (36m) in the well BH-078.

5.2 Research methods

The methodology followed in this study includes, firstly, preparing the available data towards detecting the fractured zones in the studied Baba Formation, and secondly, using the specific crossplots, diagrams, and curve crossovers through which the existence of fractures can be detected.

Preparation of the data includes, in addition to digitizing the logs, calculating shale volume

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from the gamma ray log data, converting the travel time (Δt) and bulk density (ρb) of sonic and density logs to sonic and density porosity, and finally correcting them (with the neutron porosity) from the effect of the shale content. The corrected porosity data, alone or in conjunction with the other data, are then applied to distinguish the fractured horizons within the Baba Formation in both studied wells. The necessary calculations and plots are done using Techlog 2015 and Excel softwares. As no image logs or detailed fracture study are available for the studied sections, the reliability and applicability of the followed research methods in this study are based on the published researches by different authors all global wide [2] [3] [4] [5] [22] [23] [6] [24] [25].

6. Results and Discussions

The direct recognition of fractures and microfractures can be done either in the borehole through the image logging tools and borehole televiewer or in the laboratory by examining the core samples. Indirectly recognizing in-situ fractured zones using conventional log data applied by different authors [2] [3] [4] [5] [22] [23] [6] [24] and [25].

6.1 Porosity logs

As open fractures contribute to enhancing effective porosity and provide easier passages for fluid to flow than matrix porosities do, advantages can be taken from the responses of porosity logs to fracture porosities for detecting fractured intervals. The three conventional porosity logs (sonic, density, and neutron) can be combined together when calculating the M and N parameters (Eqs. 1 and 2) in order to identify the lithology along with detecting the secondary porosity as proposed by [26] (Figure 3).

$$M = ((\Delta tfl-\Delta t) / (\rho b-\rho fl))* 0.01 \quad (1)$$

$$N = (\varnothing Nfl-\varnothing N) / (\rho b-\rho fl) \quad (2)$$

Where:

Δtfl: interval transit time in the formation fluid

Δt: interval transit time in the formation (from log)

ρb: formation bulk density (from log)

ρfl: fluid density (generally, 1.1 for salt mud 1.0 for fresh mud)

$\varnothing Nf$: neutron porosity of the fluid in the formation (usually 1.0)

$\varnothing N$: neutron derived porosity (from log)

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To make the M values consistent for simple scaling, a multiplier of 0.01 is employed.

The distribution of the sample points for the calculated M and N parameters for the Baba Formation (as shown in Fig.3) is clearly indicates the shift of an appreciable number of points towards the region of the secondary porosity.

Due to the fact that sonic porosity represents primary (matrix) porosity whereas density and neutron porosity represent total porosity (primary plus secondary), secondary porosity can be easily measured by subtracting corrected sonic porosity from shale effect from the corrected density and neutron from shale effect, or their combination porosity (Eq.3).

$$\text{Ø}sec = \text{Ø}NDcorr - \text{Ø}Scorr \quad (3)$$

Where:

Øsec: Secondary porosity

ØNDcorr: corrected neutron-density combination porosity

ØScorr: corrected sonic porosity

It’s worth mentioning that the calculated secondary porosity is not necessarily fractures only because vugs, voids, and channels are all secondary porosities that are also not sensed by the sonic log. The relationship between both mentioned porosities for the Baba Formation in BH-101 and BH-078 wells showed a lot of sample points of higher values of ØNDcorr than ØScorr indicating the possible existence of fractures as secondary porosity (Figure 4).

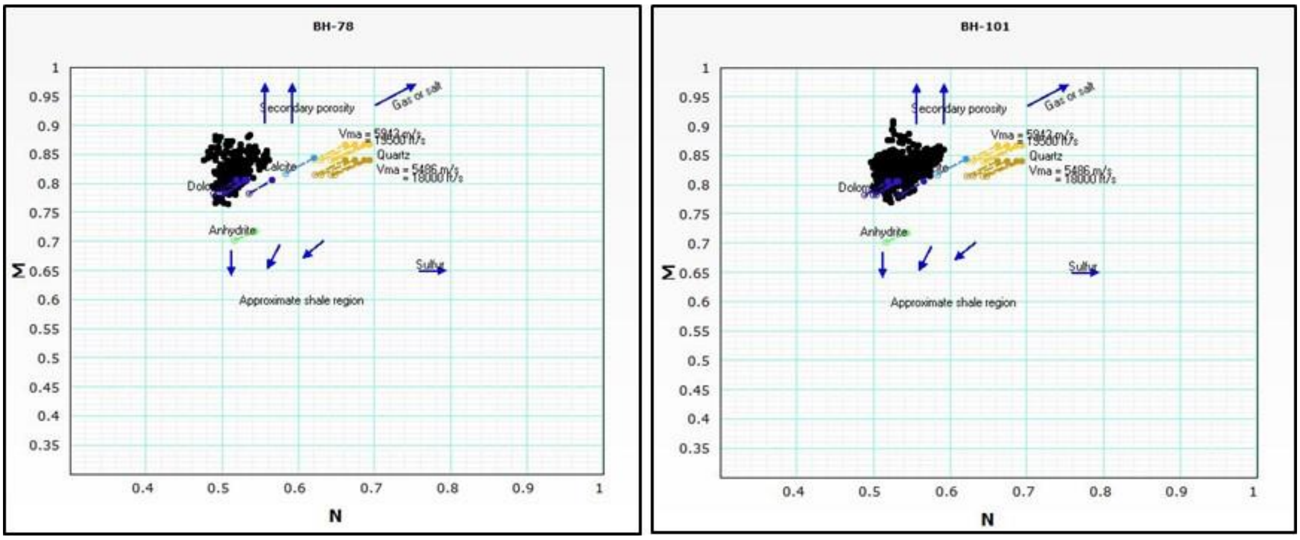

Fig. (3): M-N crossplot for the Baba Formation in the wells BH-101 and BH-078 showing shifting the sample points towards the secondary porosity region.

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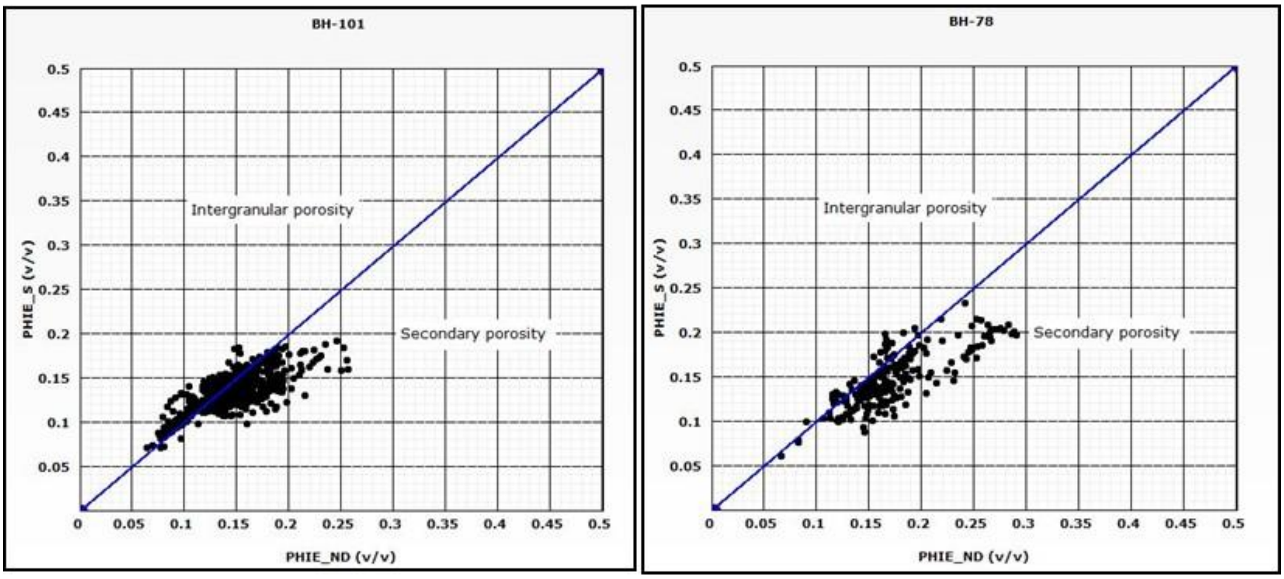

Fig. (4): Sonic porosity vs. neutron-density combination for the Baba Formation in studied wells of BH-101 and BH-078

Figure 5 shows the detected possible fractured depth intervals in Baba Formation in wells BH-101 and BH-078. It's obvious that the Baba Formation contains a lot of possible fractured zones that contributed to increasing the total porosity by an average of about less than 1% to about 5%, and in a few horizons, the value reaches about 8-10%, especially in the well BH-078 in which the Baba Formation generally looks to be of relatively higher secondary porosity.

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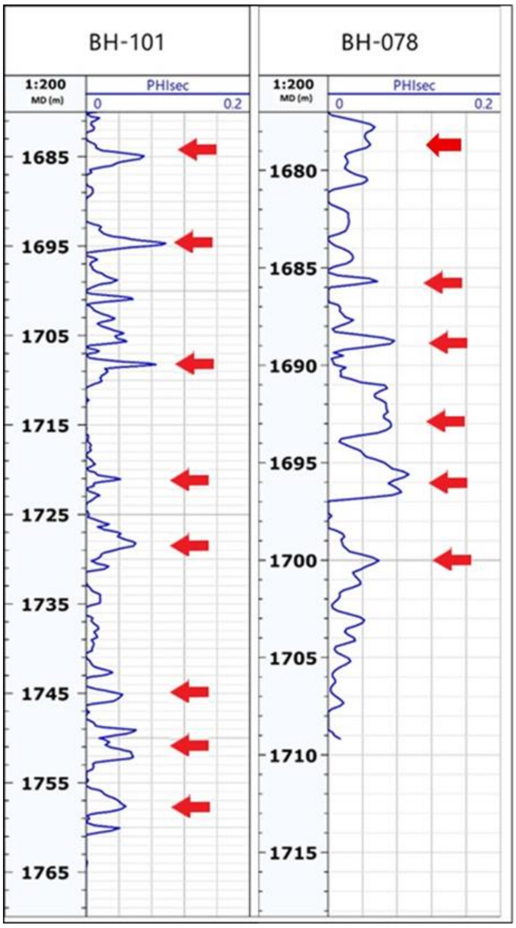

Fig. (5): The calculated secondary porosity (Øsec) showing the probable fractured zones in the Baba Formation in both studied wells of the study BH-101 and BH-078 (red arrows show distinctive possible fractured zones)

6.2 Spectral Gamma Ray Log (SGR)

Fractures play a more effective role in enhancing porosity and permeability in carbonate rocks than they do in sandstones. The SGR log can aid in recognizing the fracture system in the reservoir rocks by sensing the radiation emitted from the uranium precipitated in the fractures and fissures of the rock. When carbonate rocks are formed in reducing environments, uranium salts may precipitate in the fractures as a result of hydrothermal water circulation [27].

Fractured zones of high permeability can be detected using the SGR log when high concentrations of uranium exist with low concentrations of thorium and potassium, whereas clean reservoirs of accessory minerals are characterized by high uranium and thorium counts coupled with low potassium counts [28].

According to [2], because uranium is highly soluble in water, it is normally contained in groundwater, and increasing its concentration relative to the shale content might be an indication of the existence of natural fractures.

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the authors of [27] mentioned that in complex fractured systems with low concentrations of radioactive elements, the SGR curves are sometimes blurred, and it will be much better to recognize the fractured zones using the ratios of the uranium, thorium, and potassium to each other (U/K, Th/U, Th/K, and U/Ufree). In fact, the Th/U and U/K crossover curves are first and strongly recommended by [29], where the two curves are inversely proportional and fractured zones can be recognized when Th/U is less than U/K.

Figure (6) shows the Th/U and U/K ratios as crossover curves for the Baba Formation in the wells BH-101 and BH-078. The wider the separation between the two curves (U/K higher than Th/U), the higher the possibility of the existence of fractures. Indications for possible fractured zones can be noted in the well BH-101, especially in the middle and lower parts of the formation.

There is an acceptable match between the results of this method and the previously measured Øsec in well BH-101 (Figure 5). Regarding the case in well BH-078 (Figure 6), the lower part of the formation looks to have more possible fractured zones. There may be other kinds of secondary porosities, such as vugs and voids, in the middle and upper parts of the formation, which were previously detected in Figure (5).

The values of the Poisson's ratio (v) for the Baba Formation in Figure 6 generally show values less than 0.25. According to [30], Poisson's ratio, which is a dimensionless value reflecting rock strength, ranges between 0.1 and 0.45.

Rocks with a Poisson's ratio between 0.1 and 0.25 are easier to fracture, whereas rocks with high values such as 0.35 to 0.45 have a higher resistance to fracture. Thus, the existence of fractures in the Baba Formation is not out of the ordinary; additionally, zones with a lower Poisson's ratio show a relatively higher possibility for more intense fracturing and this is so clear in the well BH-101, especially in the middle part of the formation between depths 1727 and 1740m.

No clear indications about the existence of fractures can be observed from the record of the caliper log. Generally, enlargements occur in borehole sections where fractures exist, which can be sensed by the pads of the caliper log. The relatively small bit size used in drilling (5.98 inch) is may be the reason behind strong collapse of the borehole wall.

6.3 Resistivity logs

The conventional resistivity logs are helpful in indirectly recognizing fractured horizons. In any permeable fractured zone invaded by the drilling mud filtrate, the result is a reduction in

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the resistivity of the flushed zone to be nearly the same as the resistivity of the drilling mud. In the case of fractures filled with saline water, the resistivity decreases in the invaded zone, while in the case of fractures filled with hydrocarbons, the resistivity in the invaded zone becomes close to the resistivity of the formation [31]. The nature of the separation between the curves of the Dual Laterolog (DLT) and Microspherically Focused Log (MSFL) are used by different authors to detect fractured zones in reservoirs [4] [32] and [25].

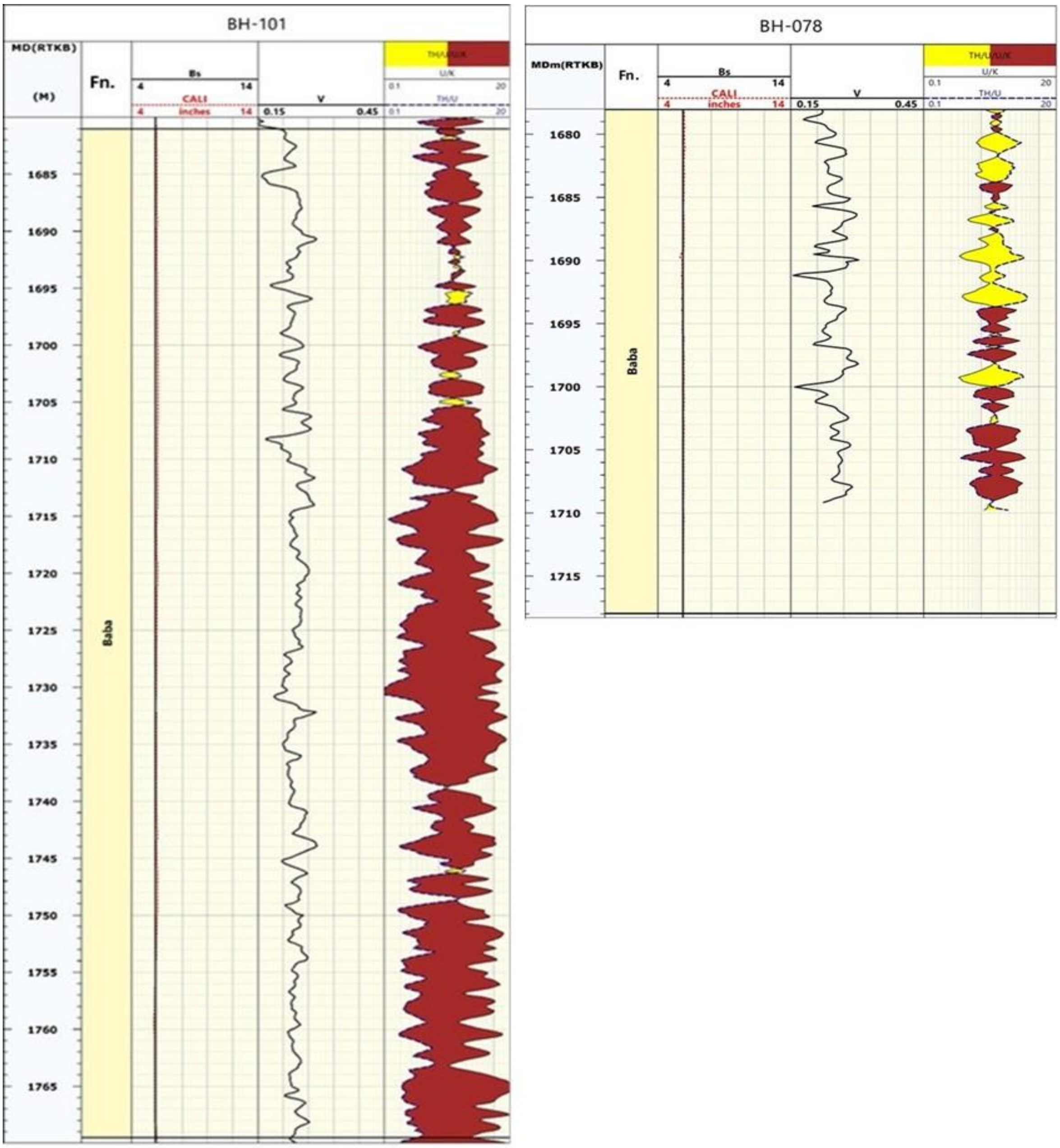

Fig. (6): The crossover of the Th/U and U/K curves, Poisson's ratio, and Caliper log record for the Baba Formation in BH-101 and BH-078 wells (The brown color are possible fractured intervals)

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The MSFL tool records high resistivity value across low permeability zones and it records observable low values across fractured zones [25].

Figure (7) shows the resistivity recorded by DLT and MSFL for Baba Formation in both wells of the study (drilled with fresh water base mud) along with the density and neutron porosity logs.

Taking into consideration that the Baba Formation in the well BH-101 has an average hydrocarbon saturation (Shc) of about 58% and in the well BH-078 about 37.4%, the separation between the curve line representing the resistivity of the flushed zone (Rxo) recorded by MSFL and the curve line representing the true resistivity (Rt) recorded by the LLD in the well BH-101 is less than that in the well BH-078. In the flushed zone, the resistivity of the hydrocarbon or brine-filled facture is comparable due to the invasion of the low resistivity mud filtrate [31], but in this study, the used drilling mud in both wells is of fresh water base, which means the flushed zone is invaded by high resistivity mud filtrate. Accordingly, fractured zones will show a relative decrease in the records of both MSFL and LLD in hydrocarbon-bearing zones with almost the same resistivity value.

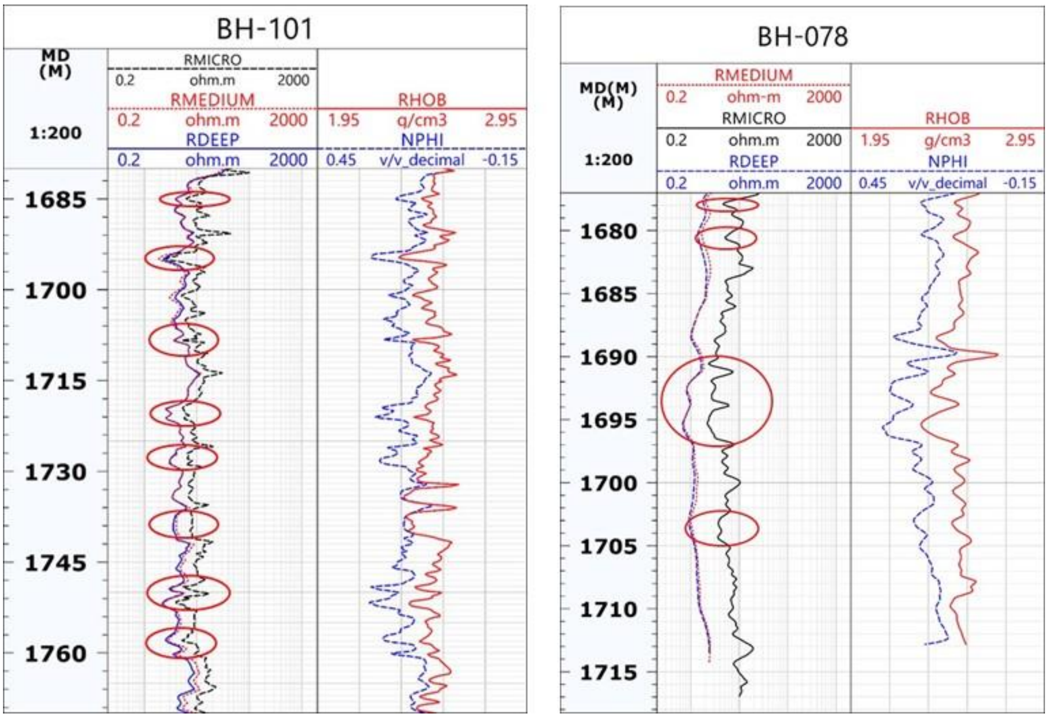

Fig. (7): The record of the resistivity (DLT and MSFL), Density and Neutron logs for the Baba Formation in BH-101 and BH-078 wells (red circles are possible fractured zones)

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In water-bearing zones, the same relative decrease occurs but with a lower recorded resistivity value by the LLD log. It is worth mentioning that reduction in the resistivity record by both MSFL and LLD are comparable with zones at which secondary porosities where detected (Fig.5). The mentioned possible fractured zones have been signed-in red circles in figures 10 and 11. The mentioned fractured zones showed a noticeable increase in the recorded ØN (NPHI) which may be as a result of filling the fractures with mud filtrate (high hydrogen index). The recorded relatively low bulk density (RHOB, ρb) values at the same zones may also support the possibility of the existence of open fractures.

6.4 Cementation exponent (m)

The cementation exponent, or factor (m), is a parameter in the equation known generally as Archie's law for calculating water saturation (Sw). The conductivity of the reservoir rocks saturated with hydrocarbons is impacted by this exponent (in addition to the saturation exponent, n). In fact, the water and hydrocarbon saturations estimated by Archie's equation are quite sensitive to this range of variability in m values. The cementation exponent values typically range between 1 and roughly 5 [33].

As the connectivity between the pore spaces becomes less, the cementation exponent's value rises. Cementation exponents in fractured reservoirs often have values of less than 2, but m values in reservoir rocks with low porosity but a well-developed fracture network may be close to 1.0 [34] [33].

Sandstone reservoir rocks have cementation exponent values ranging between 1.5 and 2.5, while values between 2.5 and 5 are commonly related to carbonated reservoir rocks where their pore spaces are not well connected [35].

In this study, the picket plot method is used for determining the cementation exponent value for Baba Formation in both wells of study (Figures 8 and 9). The determined values of 1.59 and 1.71 for the formation in the wells BH-101 and BH-078, respectively, indicate the existence of fractures in the formation. Based on the spherical and fracture porosity chart (SatOH-2) proposed by [34] and using the average total porosity of 14.2% and cementation exponent value of 1.59 for the Baba Formation in the well BH-101, fractures represent about 0.7% as an average of the total porosity.

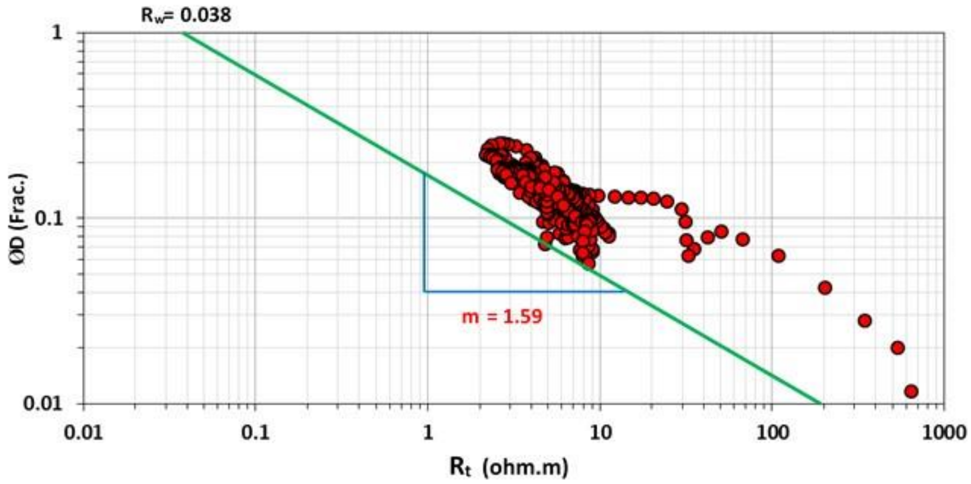

Fig. (8): Picket plot method for determining cementation exponent (m) for the Baba Formation in the well BH-101

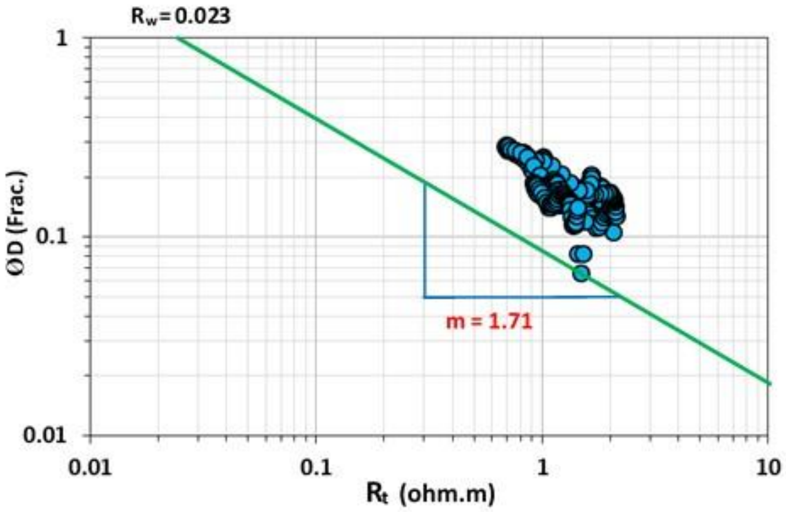

Fig. (9): Picket plot method for determining cementation exponent (m) for the Baba Formation in the well BH-078

For the well BH-078, an average total porosity of 17.1% and a cementation exponent value of 1.71 are used, from which an average amount of fracture porosity equal to 0.5% of the total porosity is measured.

7. Conclusions

The Baba Formation in the wells BH-101 and BH-078 contains naturally fractured horizons, at which fractures represent part of the secondary porosity of the formation.

The data from the porosity logs indicated the existence of possible fractured zones in different parts of the formation, with values ranging from less than 1.0 to about 10% in some horizons.

The Th/U and U/K ratios derived from the SGR log also approved the existence of a lot of

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possible fractured intervals, especially in the middle and lower parts of the formation in well BH-101. The location of the zones that showed significant secondary porosity values in the formation was approved by the data of the LLD and MSFL when relatively low resistivity values were recorded.

Baba Formation has a cementation exponent value of 1.59 and 1.71 in the wells BH-101 and BH-078, respectively, indicating a fractured formation in which fracture porosity amounts are generally representing 0.7% of the total porosity of the formation in the well BH-101 and 0.5% of the total porosity of the formation in the well BH-078.

As most of the conclusions in this study are based on detecting fractured zones in the Baba Formation, calibrating the results is vital for approving the reality of the conclusions. Accordingly, it is highly recommended to calibrate the output of this study with any future executed image logging, or at least support the results of this study with additional data from the photoelectric effect (Pe) log, the self-potential (SP) log, the rate of penetration (ROP), mud loss, and formation tests.

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