Porosity and Permeability Measurements Integration of The Upper Cretaceous in Balad Field, Central Iraq

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Abstract

The corrected porosity image analysis and log data can be used to build 3D models for porosity and permeability. This can be much realistic porosity obtainable because the core test data is not always available due to high cost which is a challenge for petroleum companies and petrophysists. Thus, this method can be used as an advantage of thin section studies and for opening horizon for more studies in the future to obtain reservoir properties. Seventy-two core samples were selected and the same numbers of thin sections were made from Khasib, Sa’di, and Hartha, formations from Ba-1, Ba-4, and Ba-8 wells, Balad Oilfield in Central Iraq to make a comprehensive view of using porosity image analysis software to determine the porosity. The petrophysical description including porosity image analysis was utilized and both laboratory core test analysis and well log analysis were used to correct and calibrate the results. The main reservoir properties including porosity and permeability were measured based on core samples laboratory analysis. The results of porosity obtained from well log analysis and porosity image analysis method are corrected by using SPSS software; the results revealed good correlation coefficients between 0.684 and 0.872. The porosity range values are 9-16% and 9-27% for Khasib and Sa’di in Ba-1 Well, respectively; 10-21%, 9-25%, and 16-27% for Khasib, Sa’di and Hartha in Ba-4 Well, respectively; and 11-24% and 15-24% for Khasib and Hartha in Ba-8 Well, respectively according to petrographic image analysis. By using the laboratory core analysis, the porosity range values are 12-26% and 17-24% for Khasib and Sa’di in Ba-1 Well, respectively; 6-28% and 14-27% for Sa’di and Hartha in Ba-4 Well, respectively; and 17-19% and 15-24% for Sa’di and Hartha in Ba-8 Well, respectively. Finally, the well log analysis showed that the porosity range values are 11-16% and 7-27% for Khasib and Sa’di in Ba-1 Well, respectively; 4-18%, 21-26%, and 16-19% for Khasib, Sa’di and Hartha in Ba-4 Well, respectively; and 9-24% and 15-23% for Khasib and Hartha in Ba-8 Well, respectively. The permeability range values based on laboratory core analysis are 1.51-8.97 md and 0.29-2.77 md for Khasib and Sa’di in Ba-1 Well, respectively; 0.01-24.5 md and 0.28-6.47 md for Sa’di and Hartha in Ba-4 Well, respectively; and 0.86-2.25 md and 0.23-3.66 for Sa’di and Hartha in Ba-8 Well, respectively.

Keywords: Petrophysical properties; Petrographic image analysis; Porosity; Well logs

1. Introduction

Reservoir geology studies are important for exploration and field development plans (EDP and FDP). The hydrocarbon recovery factor of any reservoir is affected by the reservoir heterogeneities, and

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the distributions of porosity and permeability (Chen et al. 2014). Many studies have been conducted to evaluate the carbonate reservoirs and their pore types targeting the investigation of reservoir quality (Al-Jawad and Kreem, 2016; Al-Majid, 2019; Al-Qayim, 2010). The pore types are affected by the organic activities and post-depositional diagenesis process including dissolution, cementation, recrystallization, and replacement (Janjuhah et al. 2017). Different studies were done on the Khasib, Sa’di and Hartha formations. Al-Zaidy et al. (2013), Al-Jawad and Kareem (2016), Sadooni (1996, 2017), Mohammed (2018), Al-Majid, (2019), Al-Fandi et al. (2020), and Al-Haj (2020). These studies were focused on evaluating the Khasib, Sa’di, and Hartha formations by using sedimentological, petrophysical, and high resolution sequence stratigraphy in East Baghdad, Halifaya, Ahdab, Tikrit, and Samarra oilfields. No studies have been carried out on either the present study in Balad Oilfield except the study of Al-Qayim (2010) which was focused on microfacies analysis in Tikrit, Samarra, Balad, and East Baghdad oilfields. Based on available information, the reservoirs may be heterogeneous with limited information; thus, describing and evaluating their petrophysical characteristics might need exceptional approaches and techniques e.g. the fluids and movement of fluid (Becker et al., 2019). Balad Oilfield is one of the important oilfields in Central of Iraq which has been operated by the North Iraq Oil Exploration Company. This oilfield is situated in Salah Al-Din City and located nearly 65 km to the north of Baghdad (Fig. 1). The area is covered by the Pleistocene and recent sediments. These sediments consist of alluvial deposits and river terraces from silt and clay with intercalations of sand and gravel. The aim of present study is to evaluate the petrophysical characteristics of Balad Oilfield using an integrated approach of all available data including core data (porosity and permeability), well logs (gamma ray, density, and resistivity), and petrographic image analysis (PIA).

![Fig. 1. A) Location map; B) Enlargement view outlined in A marked Baghdad and Salah Al-Din provinces; C) Balad Oilfield, Central Iraq (Albeyati et al., 2021).](image-url)
2. Materials and Methodology

The Khasib, Sa’di, and Hartha formations from Ba-1, Ba-4, and Ba-8 wells within the Balad Oilfield in Central Iraq were selected to apply the approach of this study. The comparison between the core tested data and PIA obtained from thin sections data was used to determine the correlation coefficient (R) value and factors which can be used to correct the PIA data and log data on the base of available core test data.

The laboratory core analysis method obtained from Weber (1987) can be summarized by measuring porosity and permeability over a very small sample of rock using a laboratory mini permeameters. This instrument measures the rate of air flow from a small-diameter tube (approximately 1-mm aperture) into and through the rock. This air-flow rate can then be related to rock permeability through calibration. PIA is a common tool for studying and measuring the pores’ types and shape in addition to estimating the porosity values (Ehrlich et al., 1984; Anselmetti et al., 1998). One of the main goals of present work is to evaluate and estimate the pores’ types and shape as an indicator of reservoir features of the Khasib, Sa’di, and Hartha carbonate formations. To analyze the pores types and to estimate the porosity using PIA, 73 thin sections were prepared and made with blue epoxy at Egyptian Petroleum Research Institute (EPRI). This approach was used by Ehrlich et al. (1984) and Anselmetti et al. (1998). The image analysis system was completed in the EPRI. It consists of a Sony DXC-290, CCD color video camera mounted on an Olympus petrographic microscope, and then the camera was used to capture the images under plane and cross-polarized light (PPL and XPL). Then it is imported to a PC prepared with a graphics card. Inspection of the images through the microscope was focused on viewing and subsequent capture by the image analysis system (Fig. 2). The measurement procedures were analogous on all thin sections tested. The proportion of the summation of the pore spaces versus the space of the entire image which refer to the total optical porosity (TOP) will be displayed (Ehrlich et al., 1984). Ten images were taken from each thin-section. The porosity’s type and shape were estimated by averaging the results of the ten measurements for each sample. The image with the porosity rate that best fits the average porosity was further inspected and tabulated as it was the best typical model image of the thin sections (Anselmetti et al., 1998). A calibrated slide was observed under several magnifications and the superlative results for a wide range of measurement sizes were found to be 12.5 diameters. This exaggeration was accomplished with a 2.5X, 4X, and 10X. This exaggeration was exclusively used for this work (Anselmetti et al., 1998). The frequency distribution of the pores as well as the size and shape measurements allows quantitative analysis of carbonate rock.

Based on Choquette and Pray (1970) and Flügel (2004) classifications, the porosity in the image categorized into size and shape and listed in groups after determination of the aspect ratio and roundness factor. Then, the number of groups selected was indicated by the number of pore types in the sample. This study constructed to calculate the important petrophysical parameters needed for reservoir properties evaluation e.g. porosity (Φ), permeability, and water saturation (S_w). Calculation of the gamma-ray index (IGR) is the first step needed to determine the volume of shale (V_sh) for the Khasib, Sa’di, and Hartha formations in Balad Oilfield from a gamma-ray log (Asquith, 2012) by using the following equation:

\[ I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \]  

(1)

Where \( I_{GR} \) is gamma ray index; \( GR_{log} \) is the gamma ray log read at the desired depth and calculate the volume of shale; \( GR_{min} \) is the minimum read of gamma ray log at the clean part of shale (clean carbonate rocks); and \( GR_{max} \) is the maximum read of gamma ray log at the high content shale part. For Pre-Tertiary consolidated rocks, the equation becomes:
\[
V_{sh} = 0.33 \left[ 2^{2 \times T_{GR}} - 1 \right] \tag{2}
\]

Density log is one of the common logs that are used for porosity measurement by measuring the electron density. The instrument consists of one or more of a gamma ray radiation sources from a specified distance from the source. The emitted gamma rays collide with the electrons in the rock-unit causing in the loss of energy, some energy lost in the formation. The others that reach to the recipient counted as evidence of the density formation (Asquith and Gibson, 1982). The most important uses of the density log are to determine the evaporator minerals, determine the gas zones, and quantify the density of hydrocarbons (Asquith and Gibson, 1982). For calculating the porosity from density log, the Wyllie’s (1963) equation can be employed:

\[
\Phi_{D_{correction}} = \frac{P_{ma} - P_{b}}{P_{ma} - P_{f}} - V_{sh} \left[ \frac{P_{ma} - P_{sh}}{P_{ma} - P_{f}} \right] \tag{3}
\]

\(\Phi_D\) is porosity derived from density log; \(\rho_{ma}\) is matrix density in g/cm\(^3\) and recoup for carbonate rocks (2.710), dolomite (2.877), and anhydrite (2.977) (Asquith and Gibson, 1982; Asquith, 2012); \(\rho_b\) is the total formation density; and \(\rho_f\) is fluid density, where it is 1.1 for the salinity clay, 1.0 for fresh clay, and 0.7 for gas in g/cm\(^3\) (Asquith and Gibson, 1982; Asquith, 2012).

Resistivity is the resistance of a matter against the electric current path determined between contrary faces of a unit cube of the matter at identified temperature. It is expressed in ohm.m, more frequently abbreviated to ohm-meter. The resistivity logs measure the resistivity of the fluid. Therefore, the fluid can be distinguished whether there is oil (high resistivity) or water (low resistivity). The formation water resistivity is calculated by the ratio method from the Asquith’s (2012) equation:

\[
R_w = \frac{(R_x \times R_{mf})}{R_{xo}} \tag{4}
\]

To correct the resistivity of mud cake (\(R_{mc}\)) and mud filtrate (\(R_{mf}\)), the different fluids can be used according to formation temperature using Arps’ (1953) formula:

\[
R_{w2} = R_{w1} \times \frac{(T_1 + 6.77)}{(T_2 + 6.77)} \tag{5}
\]

\(R_{w1}\) and \(R_{w2}\) are formation water resistivity at temperatures \(T_1\) and \(T_2\). The determination of rock resistivity (\(R_{xo}\) and \(R_x\)) based on the distance of invasion is divided into flushed zone resistivity (\(R_{xo}\)) and true (uninvaded) zone resistivity (\(R_x\)). The flushed zone resistivity (\(R_{xo}\)) was measured by microphysical focused log (MSFL). The correction of flushed zone resistivity (\(R_{xo}\)) depends on the calculation of the correction factor (\(C\)) which depends on the thickness of mud cake (hmc). According to Bateman and Konen (1978), the resistivity (\(R\)) is calculated from the basic formula:

\[
R_{xo} = \log_{10} \left[ \frac{R_{MSFL}}{R_{mc}} \right] \tag{6}
\]

Finally, the \(R_{xo}\) is corrected using the following equation:

\[R_{xo} = CR_{mcf}, \text{ where,} \]

\(C\) is correction factor, \(R\) is resistivity, and \(mcf\) is mud cake filtrate.

The uninvaded zone resistivity (\(R_x\)) was measured through deep induction log (IDL) and dual laterolog (LLD). The resistivity values are corrected for the borehole effect by using the following mathematical equations of Bateman and Konen (1978):
Where C is the correction factor which depends upon the hole diameter. The formation resistivity factor provides a useful and convenient way to clarify the nature of the pore structure of reservoir rocks. For determination of the formation resistivity factor (F) using Archie’s (1942) formula as follow:

\[ F = \frac{R_o}{R_w} \]  

(9)

The presence of shale in formation will cause to record a low resistivity log. Hilichie (1978) stated that “the most effect of shale in a formation is to reduce the resistivity contrast between oil or gas, and water”. Water saturation (S_w) is the proportion of pore volume in a rock which is engaged by formation water. It denotes a significant log analysis conception due to the fact that the hydrocarbon saturation of any hydrocarbon reservoir can be calculated by subtracting water saturation from the value one, where 1.0 = 100% water saturation. In the clean formation, the water saturation (S_w) of uninvaded zone is calculated by Archie’s (1942) formula:

\[ S_w = \left( \frac{a \times R_w}{\phi R_o} \right)^{1/n} \]  

(10)

In the flushed zone water saturation (S_w) and in clean zones, the water saturation of the flushed zone (S_w) can be used as an indicator of hydrocarbon movability and can be calculated by using the equation above. The determination of the fluid saturation either in the uninvaded zone (S_w) or in the flushed zone (S_w) facilitates, calculation of the hydrocarbon saturation, can be determined by using the following equation:

\[ S_h = 1 - S_w \]  

(11)

Fig. 2. Screen capture of image in color-separation style. The cursor was positioned on every pore (blue) pixels of that blue color in addition to extra pixels of that color in the image.
3. Results and Discussions

The core test data is not available for all wells due to its expensive cost; therefore, corrected PIA and log data can be used to build 3D models which can cover all the Balad Oilfield.

3.1. Petrographic Image Analysis

The results of the petrographic image analysis (PIA) summarized in Table 1. The Table 1 shows that the Khasib Formation porosity in Ba-1, Ba-4, and Ba-8 wells ranges between 9-16%, 10-21%, and 11-24%, respectively with an average of approximately 17%. The porosity types were intercrystalline and the porosity formed from the irregular distribution of early and late dissolution that resulted from the digenesis processes including vugs and channel porosity (Fig. 3).

Table 1. The result of the PIA from Sa’di, Khasib and Hartha formations, Balad Oilfield

| No. | Depth (m) | Well name | Formation | Pores Type             | Porosity % |
|-----|-----------|-----------|-----------|------------------------|------------|
| 1   | 1933      | Sa’di     | Intercrystalline | 19                     |
| 2   | 1934      | Vugs and Intercrystalline | 16         |
| 3   | 1936      | Intercrystalline | 11          |
| 4   | 1938      | Vugs and Intercrystalline | 24         |
| 5   | 1942      | Vugs and Intercrystalline | 21         |
| 6   | 1943      | Vugs and Intercrystalline | 20         |
| 7   | 1945      | Intercrystalline | 14          |
| 8   | 1961      | Intercrystalline | 27          |
| 9   | 1966      | Vugs and Intercrystalline | 9          |
| 10  | 1967      | Intercrystalline | 21          |
| 11  | 1972      | Intercrystalline | 22          |
| 12  | 1974      | Intercrystalline | 23          |
| 13  | 1989      | Vugs | 19          |
| 14  | 1991      | Vugs | 9           |
| 15  | 2007      | Vugs | 11          |
| 16  | 2009      | Vugs | 11          |
| 17  | 2485      | Vugs and Channel | 15          |
| 18  | 2486      | Vugs | 15          |
| 19  | 2488      | Vugs and Intercrystalline | 16         |
| 20  | 2490      | Vugs and Intercrystalline | 9          |
| 21  | 2493      | Vugs | 12          |
| 22  | 2497      | Vugs and Channel | 15          |
| 23  | 1971      | Intercrystalline | 24          |
| 24  | 1973      | Vugs and Intercrystalline | 25         |
| 25  | 1977      | Intercrystalline and Intergranular | 22         |
| 26  | 1985      | Intercrystalline | 16          |
| 27  | 1990      | Vugs and Intercrystalline | 27         |
| 28  | 1993      | Intercrystalline | 19          |
| 29  | 1995      | Intercrystalline and Intergranular | 21         |
| 30  | 2001      | Intercrystalline | 22          |
| 31  | 2003      | Intercrystalline | 23          |
| 32  | 2006      | Vugs | 19          |
| 33  | 2011      | Vugs and Intergranular | 18         |
| 34  | 2015      | Vugs and Intergranular | 21         |
| 35  | 2017      | Vugs | 22          |
| 36  | 2018      | Vugs | 22          |
| 37  | 2091      | Vugs | 18          |
| 38  | 2093      | Intercrystalline | 17          |
| 39  | 2096      | Vugs | 23          |
| 40  | 2099      | Vugs and Intergranular | 21         |
| 41  | 2103      | Vugs | 20          |
| 42  | 2172      | Vugs and Intercrystalline | 14         |
The Sa’di Formation porosity in Ba-1 and Ba-4 wells ranges between 9-27% and 9-25% (Table 1), respectively with an average of nearly 18%. The pore types are vugs and intercrystalline (Fig. 4). The Hartha Formation porosity in Ba-4 and Ba-8 wells ranges between 16-27% to 15-24%, respectively.

**Fig. 3.** Core photo from Khasib Formation, well Ba-4, Balad Oilfield (2526-2564 m). A) PPL photo; B) XPL photo showing the intercrystalline and vugs porosity; C) PPL photo; and D) XPL photo showing the vugs and channels porosity
with an average of about 21% (Table 1). The porosity types are vugs, intercrystalline, and channels. The porosity existing within the carbonate rocks was affected by recrystallization (Tucker and Wright, 1990) (Fig. 5). From above, it can be concluded that the Hartha Formation has the highest porosity values followed by Sa’di and Khasib formations, respectively. The possible reason is that the Hartha Formation is the most affected by the dissolution and diagenesis processes which were more than Sa’di and Khasib formations. Generally, the porosity types e.g. molded and vug represent environmental effect, because these two types can be described from or at the sequence boundary due to a slow rate of sedimentation (Morad et al., 2012). In addition to the fact that Khasib and Sa’di formations represent basinal facies which was characterized by slow rate of deposition (Al-Qayim, 2010). This could give ways to the diagenesis processes to enlarge the molded porosity at first to vugs and then to channel porosity (Asquith, 2012), while the intercrystalline porosity creation may be due to the effect of dolomitization on high surface area of basinal micrite supported facies.

Fig. 4. Core photo from Sa’di Formation, well Ba-1, Balad Oilfield (1933-2009 m). A) PPL photo; B) XPL photo shows the intercrystalline porosity; C) PPL photo; and D) XPL photo of the vugs porosity

Fig. 5. Core photo from Hartha Formation, well Ba-8, Balad Oilfield (1909-1921 m). A) PPL photo; B) XPL photo showing the intercrystalline porosity; C) PPL photo; and D) XPL photo showing the vugs and intercrystalline porosity
3.2. Laboratory Core Analysis

Laboratory core analysis includes several measurements with the objective of obtaining information about multiphase flow behavior. It gives detailed information about the distribution of oil, gas, and water in the reservoir; furthermore, the residual oil saturation and multiphase flow characteristics. However, the method is expensive and tedious, but it is still the most direct way of obtaining rock properties because the results from indirect methods like logs need to be calibrated against results obtained by core analysis. Laboratory core analysis attempts to extend the data provided by traditional measurements to be more representative of reservoir conditions. It is used to support log and well test data in gaining an understanding of individual well and overall reservoir performance. The main reservoir rock properties including porosity and permeability will be described in Table 2.

| No. | Well name | Formation | Depth (m) | Air Permeability (md) | Porosity % | Grain density g/cc |
|-----|------------|-----------|-----------|-----------------------|------------|-------------------|
| 1   | Ba-1       | Sa’di     | 1933      | 0.53                  | 19         | 2.692             |
| 2   | Ba-1       | Sa’di     | 1934      | 0.29                  | 17         | 2.694             |
| 3   | Ba-1       | Sa’di     | 1942      | 1.79                  | 23         | 2.693             |
| 4   | Ba-1       | Sa’di     | 1943      | 0.99                  | 23         | 2.693             |
| 5   | Ba-1       | Sa’di     | 1966      | 0.45                  | 17         | 2.707             |
| 6   | Ba-1       | Sa’di     | 1974      | 2.77                  | 24         | 2.693             |
| 7   | Ba-1       | Sa’di     | 1989      | 0.82                  | 19         | 2.694             |
| 8   | Ba-1       | Sa’di     | 1991      | 0.51                  | 17         | 2.704             |
| 9   | Ba-1       | Sa’di     | 2007      | 1.95                  | 23         | 2.702             |
| 10  | Ba-1       | Sa’di     | 2009      | 2.21                  | 25         | 2.695             |
| 11  | Ba-1       | Sa’di     | 2327      | 8.97                  | 25         | 2.695             |
| 12  | Ba-1       | Khasib    | 2336      | 3.99                  | 23         | 2.695             |
| 13  | Ba-1       | Khasib    | 2338      | 5.32                  | 21         | 2.702             |
| 14  | Ba-1       | Khasib    | 2338      | 4.48                  | 26         | 2.702             |
| 15  | Ba-1       | Khasib    | 2341      | 1.51                  | 21         | 2.704             |
| 16  | Ba-1       | Khasib    | 2346      | 1.65                  | 21         | 2.701             |
| 17  | Ba-1       | Khasib    | 1971      | 1.12                  | 18         | 2.692             |
| 18  | Ba-1       | Khasib    | 1973      | 0.49                  | 17         | 2.694             |
| 19  | Ba-1       | Khasib    | 1990      | 6.47                  | 27         | 2.693             |
| 20  | Ba-1       | Khasib    | 1995      | 1.91                  | 22         | 2.693             |
| 21  | Ba-1       | Khasib    | 2006      | 4.14                  | 27         | 2.693             |
| 22  | Ba-1       | Khasib    | 2017      | 1.27                  | 20         | 2.693             |
| 23  | Ba-1       | Khasib    | 2018      | 0.28                  | 14         | 2.694             |
| 24  | Ba-1       | Khasib    | 2091      | 1.66                  | 20         | 2.704             |
| 25  | Ba-1       | Khasib    | 2093      | 1.97                  | 20         | 2.702             |
| 26  | Ba-1       | Khasib    | 2103      | 4.29                  | 21         | 2.695             |
| 27  | Ba-1       | Khasib    | 2104      | 3.65                  | 23         | 2.695             |
| 28  | Ba-1       | Khasib    | 2116      | 3.91                  | 24         | 2.699             |
| 29  | Ba-1       | Khasib    | 2117      | 1.53                  | 19         | 2.696             |
| 30  | Ba-1       | Khasib    | 2125      | 0.23                  | 14         | 2.701             |
| 31  | Ba-1       | Khasib    | 2133      | 1.23                  | 18         | 2.694             |
| 32  | Ba-1       | Khasib    | 2134      | 1.36                  | 19         | 2.690             |
| 33  | Ba-1       | Khasib    | 2140      | 0.72                  | 13         | 2.705             |
| 34  | Ba-1       | Khasib    | 2141      | 0.92                  | 12         | 2.694             |
| 35  | Ba-1       | Khasib    | 2143      | 0.01                  | 6          | 2.693             |
| 36  | Ba-1       | Khasib    | 2182      | 4.53                  | 25         | 2.686             |
| 37  | Ba-1       | Khasib    | 2187      | 24.5                 | 28         | 2.689             |
| 38  | Ba-1       | Khasib    | 1909      | 0.71                  | 18         | 2.702             |
| 39  | Ba-1       | Khasib    | 1910      | 3.66                  | 24         | 2.696             |
| 40  | Ba-1       | Hartha    | 1915      | 3.46                  | 22         | 2.693             |
| 41  | Ba-1       | Hartha    | 1921      | 0.23                  | 15         | 2.707             |
| 42  | Ba-1       | Hartha    | 2444      | 2.25                  | 17         | 2.692             |
| 43  | Ba-1       | Hartha    | 2447      | 0.86                  | 17         | 2.693             |
| 44  | Ba-1       | Hartha    | 2452      | 1.36                  | 19         | 2.697             |
| 45  | Ba-1       | Hartha    | 2458      | 2.06                  | 19         | 2.695             |

Table 2. Laboratory core analysis of the Hartha, Khasib and Sa’di formations in Balad Oilfield
The analysis was done on core interval samples selected from Khasib, Sa’di, and Hartha formations in Ba-1, Ba-4, and Ba-8 wells within Balad Oilfield. The analysis was provided by the EPRI. The results display that the Khasib Formation porosity and permeability in well Ba-1 range between 12-26% and 1.51-8.97 md (Table 2), respectively with an average porosity of 18.5% and average permeability of 5.24 md. The Sa’di Formation porosity and permeability results in Ba-1 range between 17-24% and 0.29-2.77 md (Table 2), while in Ba-4 Well range between 6-28% and 0.01-24.5 md (Table 2), and in Ba-8 range between 17-19% and 0.86-2.25 md (Table 2), respectively. The average porosity and permeability for the Sa’di Formation in the three studied wells were 18.5% and 5.11 md, respectively. The Hartha Formation characterized generally by high value of porosity and permeability due to its location at the boundary of new sequence package. Therefore, it is characterized by vug porosity. The second reason is that the Hartha Formation consists of grain supported reef facies (Sadooni, 2017); thus, the formation has high values of the both porosity and permeability (Asquith, 2012). The Hartha Formation porosity and permeability in well Ba-4 range between 14-27% and 0.28-6.47 md (Table 2), while in Ba-8 they range between 15-24% and 0.23-3.66 md (Table 2), respectively. The average porosity and permeability for the Hartha Formation in Ba-4 and Ba-8 wells is 20% and 2.65 md, respectively. A commonly observed trend is the increase of permeability with porosity increase.

The cross plot of porosity versus permeability (Fig. 6) demonstrate a positive log-linear correlation of increasing permeability with increasing porosity from all studied core samples of Khasib, Sa’di, and Hartha formations within Balad Oilfield. The association of porosity with permeability emphasize on the existence of vugs, intercrystalline, and channel porosity types. This result reveals very good to excellent matching with the obtained results by PIA method in this study due to faraway location of all represented values of permeability versus porosity from Y axis.
3.3. Well Log Analysis

Wire line logging is performed after an interruption or the termination of drilling activity, and is thus distinguished from drilling-logs (Serra, 1984). Log interpretation is the process by which these measurable parameters are translated into the desired petrophysical parameters. Well log examination is the main performance for every well to disclose the reservoir rock units amongst the entirely drilled intervals. Their conventional uses in hydrocarbon exploration are to correlate zones and assisting the structure and isopach mapping. Well logs are the main tools that can be used to describe physical rock features including lithology, porosity, pore geometry, water saturation, and permeability. They are used to recognize pay zones; define depth and thickness of pay zone; differentiate oil, gas, or water from each other in a reservoir; and evaluate the reserved petroleum capacity. Gamma ray log is used for determining the volume of shale effect (more than 10%) to correct all data obtained from well logs viz. density and resistivity logs to data visualization the three reservoirs of Balad Oilfield (Khasib, Sa’di, and Hartha formations) from Ba-1, Ba-4, and Ba-8 wells (Table 3 and Figs. 7, 8, and 9). The Khasib Formation shale volumes in Ba-1, Ba-4, and Ba-8 wells range between 1-3%, 2-17%, and 1-15% with an average of 6.5% (Table 3); the porosity values range between 11-16%, 4-18%, 9-24% and with an average of 13.7% (Table 3); and the water saturation expanses range between 92-98%, 31-97%, and 47-68% with an average of 72.2%, respectively (Table 3).

The shale volume of Sa’di formation in Ba-1 and Ba-4 wells ranges between 1-18% and 1-1% with an average of 4.5% (Table 3); the porosity values range between 7-27% and 21-26% with an average of 20.3% (Table 3); and the water saturation ranges between 5-58% (average 21.3%) and 67-76% (average 70.9%) (Table 3). The Hartha Formation shale volumes in Ba-4 and Ba-8 wells are 1% for both with an average of 1% (Table 3); the porosity values range between 15-19% (average 18.9%) and 15-23% (average 19.5) (Table 3); and the water saturation amounts range between 26-58% and 32-51% with an average of almost 47%, respectively (Table 3).

Table 3. Gamma ray, density, and resistivity logs data of the Hartha, Khasib and Sa’di formations

| No. | Depth (m) | Well name | Formation | Volume of shale (%) | Porosity % | Water saturation % |
|-----|-----------|-----------|-----------|---------------------|------------|-------------------|
| 1   | 1933      | Ba-1      | Khasib    | 12                  | 15         | 31                |
| 2   | 1934      | Ba-1      | Khasib    | 14                  | 17         | 24                |
| 3   | 1936      | Ba-1      | Khasib    | 12                  | 18         | 21                |
| 4   | 1938      | Ba-1      | Khasib    | 18                  | 22         | 10                |
| 5   | 1942      | Ba-1      | Khasib    | 15                  | 21         | 8                 |
| 6   | 1943      | Ba-1      | Khasib    | 14                  | 21         | 8                 |
| 7   | 1945      | Ba-1      | Khasib    | 12                  | 27         | 5                 |
| 8   | 1961      | Ba-1      | Khasib    | 15                  | 23         | 28                |
| 9   | 1966      | Ba-1      | Khasib    | 13                  | 15         | 36                |
| 10  | 1967      | Ba-1      | Khasib    | 17                  | 18         | 19                |
| 11  | 1972      | Ba-1      | Khasib    | 8                   | 7          | 58                |
| 12  | 1974      | Ba-1      | Khasib    | 4                   | 24         | 18                |
| 13  | 1989      | Ba-1      | Khasib    | 1                   | 21         | 14                |
| 14  | 1991      | Ba-1      | Khasib    | 1                   | 20         | 20                |
| 15  | 2007      | Ba-1      | Khasib    | 5                   | 18         | 20                |
| 16  | 2009      | Ba-1      | Khasib    | 7                   | 14         | 21                |
| 17  | 2485      | Ba-4      | Hartha    | 1                   | 12         | 98                |
| 18  | 2486      | Ba-4      | Hartha    | 1                   | 16         | 92                |
| 19  | 2488      | Ba-4      | Hartha    | 1                   | 13         | 92                |
| 20  | 2490      | Ba-4      | Hartha    | 1                   | 12         | 98                |
| 21  | 2493      | Ba-4      | Hartha    | 3                   | 11         | 98                |
| 22  | 2497      | Ba-4      | Hartha    | 2                   | 13         | 98                |
| 23  | 1971      | Ba-4      | Hartha    | 1                   | 17         | 63                |
| 24  | 1973      | Ba-4      | Hartha    | 1                   | 25         | 24                |
| 25  | 1977      | Ba-4      | Hartha    | 1                   | 23         | 27                |
| 26  | 1985      | Ba-4      | Hartha    | 1                   | 24         | 30                |
| 27  | 1990      | Ba-4      | Hartha    | 1                   | 20         | 32                |
| 28  | 1993      | Ba-4      | Hartha    | 1                   | 20         | 45                |
| 29  | 1995      | Ba-4      | Hartha    | 1                   | 22         | 35                |
Through the average results of the shale volume, porosity, and water saturation of the three reservoirs, the Hartha Formation has the least shale volume (1%), and this finally reflected on the relativity of higher porosity average (19.2%) with the lowest water saturation ($S_w$), 47%. This is due to higher hydrocarbon saturation in wells Ba-4 and Ba-8. So, it can be considered that Hartha Formation has the most promising hydrocarbon accumulations in the Balad Oilfield, followed by Khasib and Sa’di formations. This is due to Hartha Formation containing grain supported rocks (Fig. 5) in addition to its dominant reef facies, while the Sa’di Formation represents the basinal facies and the Khasib Formation represents ramp facies (Al-Qayim, 2010).
Fig. 7. Petrophysical calculations of the Ba-1 Well, Balad Oilfield including density derived porosity (Phi), shale volume (Vsh), water saturation (Sw), and hydrocarbon saturation (Sh)

3.4. Correlation the Petrophysical Analysis Data

The petrophysical analysis techniques of the reservoirs could be categorized into three groups: 1) petrographic image analysis (PIA) of the thin sections; 2) core tested plug samples; and 3) well logs calculations. The integration of the results obtained from these analyses has been done to build up a complete picture of the Khasib, Sa’di, and Hartha formations within the Balad Oilfield by determining the main features for each given horizon. The statistical processing by using Statistical Package for the Social Sciences (SPSS) software program through using an available porosity as one important from two petrography factors to determine the correlation coefficient (R) and fundamentals of test statistics e.g. F test and T test. In Ba-1 well, the results of correlated core porosity with predicted log porosity that were obtained from SPSS software represented by formula equation (1a) (Tables 4, 5 and Fig. 10a) showing good correlation coefficient ($R^2 = 0.826$), and (Std. Error = 0.115). The result from correlated core porosity with the measured petrographic image porosity represented by formula equation (1b) (Tables 4, 5 and Fig. 10b), the correlation coefficient ($R^2 = 0.872$) and (Std. Error = 0.103), indicated good correlation coefficient with the neglected error as its clear from F and T tests.
Fig. 8. Petrophysical calculations of the Ba-4 Well, Balad Oilfield including density derived porosity (\( \Phi \)), shale volume (\( V_{sh} \)), water saturation (\( S_w \)), and hydrocarbon saturation (\( S_h \)).

Table 4. Model summary of the core and predicted porosity in wells Ba-1, Ba-4, and Ba-8

| Model | R  | R Square | Adjusted R Square | Std. Error of the Estimate | R Square Change | F Change | Df1 | Df2 | Sig. F Change |
|-------|----|----------|-------------------|--------------------------|----------------|----------|-----|-----|--------------|
| 1     | 0.909\textsuperscript{a} | 0.826 | 0.818 | 2.18174 | 0.826 | 95.088 | 1 | 20 | 0.000 |
|       | 1 | 0.934\textsuperscript{b} | 0.872 | 0.8865 | 1.87460 | 0.872 | 135.891 | 1 | 20 | 0.000 |
|       | 1 | 0.883\textsuperscript{a} | 0.780 | 0.775 | 2.44158 | 0.780 | 145.584 | 1 | 41 | 0.000 |
|       | 1 | 0.827\textsuperscript{b} | 0.684 | 0.676 | 2.92997 | 0.684 | 88.565 | 1 | 41 | 0.000 |
|       | 1 | 0.910\textsuperscript{a} | 0.828 | 0.815 | 1.48073 | 0.828 | 67.184 | 1 | 14 | 0.000 |
|       | 1 | 0.902\textsuperscript{b} | 0.814 | 0.801 | 1.53639 | 0.814 | 61.408 | 1 | 14 | 0.000 |
Fig. 9. Petrophysical calculations of the Ba-8 Well, Balad Oilfield including density derived porosity (Phi), shale volume (Vsh), water saturation (Sw), and hydrocarbon saturation (Sh).

Fig. 10. Correlation coefficient between (a) core and predicted porosity and (b) cores and measured petrographic image from well log in Ba-1 Well.
In Ba-4 Well, the result of correlated core porosity with predicted log porosity represented by formula equation (2a) (Tables 4, 5 and Fig. 11a) \( R^2 = 0.780 \), and (Std. Error = 0.082) showing good relation. The result from correlated core porosity with the measured petrographic image porosity represented by formula equation (2b) (Tables 4, 5 and Fig. 11b), the correlation coefficient \( R^2 = 0.684 \) and (Std. Error = 0.098) showing fair relation. In Ba-8 Well, the result of correlated core porosity with predicted log porosity represented by formula equation (3a) (Tables 4, 5 and Fig. 12a) showing good correlation coefficient \( R^2 = 0.828 \) and (Std. Error = 0.117). The result from correlated core porosity with the measured petrographic image porosity represented by formula equation (3b) (Tables 4, 5 and Fig. 12b), the correlation coefficient \( R^2 = 0.814 \), and (Std. Error = 0.158) indicated good correlation coefficient.

Table 5. Coefficients of the core and predicted porosity in wells Ba-1, Ba-2, and Ba-8

| Model | Unstandardized coefficients | Standardized coefficients | t  | Sig.  |
|-------|-----------------------------|----------------------------|----|-------|
|       | B                    | Std. Error | Beta |       |       |
| Ba-1  | (Constant)           | 1.349      | 2.047 | - 0659 | 0.517 |
|       | Logs                | 1.120      | 0.115 | 0.909  | 9.751 | 0.000 |
|       | a. Dependent Variable: Core Core = 1.1196 Logs – 1.349………………..1a |
| Ba-4  | (Constant)           | - 1.893    | 1.760 | - 1.075 | 0.295 |
|       | Image               | 1.198      | 0.103 | 0.934  | 11.657| 0.000 |
|       | a. Dependent Variable: Core Core = 1.1979 Image – 1.8926………………..1b |
|       | (Constant)           | 0.010      | 1.569 | 0.006  | 0.995 |
|       | Logs                | 0.989      | 0.082 | 0.883  | 12.066| 0.000 |
|       | a. Dependent Variable: Core Core = 0.9895 Logs + 0.0099………………..2a |
|       | (Constant)           | 0.667      | 1.936 | 0.345  | 0.732 |
|       | Image               | 0.924      | 0.098 | 0.827  | 9.411 | 0.000 |
|       | a. Dependent Variable: Core Core = 0.924 Image + 0.6673………………..2b |
| Ba-8  | (Constant)           | 1.065      | 2.219 | 0.840  | 0.639 |
|       | Logs                | 0.957      | 0.117 | 0.910  | 8.197 | 0.000 |
|       | a. Dependent Variable: Core Core = 9.565 Logs + 1.0652………………..3a |
|       | (Constant)           | - 4.772    | 3.058 | - 1.561 | 0.141 |
|       | Image               | 1.239      | 0.158 | 0.902  | 7.836 | 0.000 |
|       | a. Dependent Variable: Core Core = 1.2389 Image – 4.7717………………..1b |
4. Conclusions

The results of the correlations between the petrophysical analysis, the PIA method and core analysis revealed good correlations with negligible standard errors; therefore, the PIA method can be recommended to use in determining the approximate values of porosity as an advantage that can be obtained from thin sections studies. The porosity range values in Ba-1 Well are 9-16%, 12-26%, and 11-16% for Khasib Formation; 9-27%, 17-24%, and 7-27% for Sa‘di Formation by using the petrographic image analysis, laboratory core analysis, and well log analysis, respectively.

The porosity range values in Ba-4 Well are 10-21%, 12-26%, and 11-16% for Khasib Formation; 9-25%, 6-28%, and 21-26% for Sa‘di Formation; and 16-27%, 14-27%, and 16-19% for Hartha Formation by using the petrographic image analysis, laboratory core analysis, and well log analysis, respectively. The porosity range values in Ba-8 Well are 11-24% and 9-24% for Khasib Formation by using the petrographic image analysis and well log analysis, respectively. The porosity range values are 17-19% for Sa‘di Formation by using laboratory core analysis. The porosity range values are 15-24%, 15-24%, and 15-23% for Hartha Formation by using the petrographic image analysis, laboratory core analysis, and well log analysis, respectively.
The integration of PIA, well logs, and core analysis revealed that the Hartha Formation has the most promising hydrocarbon reserves in Ba-1 and Ba-4 wells, followed by Sa‘di and Khasib formations. The Ba-8 Well shows that the Khasib Formation has the majority of reserved hydrocarbon where this formation has low water saturation value, while Sa‘di Formation was fully saturated by water. The permeability range values based on laboratory core analysis are 1.51-8.97 md for Khasib Formation in Ba-1 Well; 0.29-2.77 md, 0.01-24.5 md, 0.86-2.25 md for Sa‘di Formation in wells Ba-1, Ba-4, and Ba-8, respectively; and 0.28-6.47 md and 0.23-3.66 md for Hartha Formation in Ba-4 and Ba-8, respectively.

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