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ORIGINAL PAPER - PRODUCTION ENGINEERING

Integrated production logging tools approach for convenient experimental individual layer permeability measurements in a multi-layered fractured reservoir

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Abstract

Appropriate estimation of permeability is considered as one of the significant concerns of petroleum industries. Due to the growing demand for hydrocarbon fossil fuels in numerous industries, Petroleum Engineers always try to provide holistic and sustainable solutions to measure this parameter more accurately and to calculate the proper original oil in place (OOIP) and initial reserve. Hence, this accuracy estimation helps engineers whether the production and exploration operations are profitable or not and it might virtually eliminate the unnecessary expenditures. The term production logging tools (henceforth; PLT) involve a wide variety of measurement tools and many sensors. It, too, carries interpretation tools which evaluate the formation properties, in respect of the way PLTs would analyze the formation fluid movements inside and outside of the wellbore and subsequently estimate the production flow rate for each layer. On the other hand, it gives production and completion engineers the chance to investigate the appropriate efficiency of production and perforation processes to organize the remediation methodologies or preplan proper designing for modifying completion procedures which have based on the production logging tools interpretation. The purpose of this comprehensive research is to compare two different techniques (PLT and core analysis) of permeability measurement in a six-layered fractured reservoir and subsequently normalize each parameter to obtain the proper estimation. As a result, according to the evaluation of each technique, the amount of permeability in the layers 1, 2, 3, and 5 is relatively close to each other. Furthermore, regarding higher expenses of core analysis tests and the reliability of PLTs according to the results of this paper in the four out of six individual layers, Emeraude software by utilizing PLT interpretation could be a substitution and preferable methodology instead of core analysis measurements.

Keywords Production logging tools · Permeability measurements · Core analysis · OOIP · Reserve · Individual layers · Fractured reservoir

List of symbols

AOF	Specific productivity index, STB/day/psi/ft
B_o	Oil formation volume factor, BBL/STB
K	Permeability, md
M_u	Viscosity, Cp
P_{avg}	Average pressure in external borders, Psi
P_e	External borders pressure, Psi
PLT	Production logging tools
PI	Productivity index, dimensionless
P_{wf}	Wellbore pressure for flowing well, Psi
Q	Flow rate according to standard condition, STB/day
R_e	Distance from well center to external border, in
r_w	Well center distance to wellbore, in
S	Skin effect, dimensionless
Ø	Porosity, %
H_c	Hydraulic content, dimensionless
r_p	Assume radius pipe, ft

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Introduction

Permeability is the constant proportionality parameter in Darcy's law, which relates discharge (flow rate) and fluid physical properties (e.g., viscosity) to a pressure gradient which applied to the porous media (Adeboye et al. 2012;

Haro 2004; Rafik and Kamel 2017). The flow mechanisms pattern, especially in tight reservoirs like fractured reservoirs, should take into consideration. However, having said this, high amount of permeability will occasionally allow the reservoir fluids to move rapidly through rocks, and it utterly depended on the reservoir characteristics and other phenomena which significantly impact the permeability. Regarding the micro- or nanopores of these reservoirs, such parameters entailed fluid properties (e.g., fluid velocity) and pressure gradient which they exert a profound impact on the fluid mobilization in the cracks and subsequently lead to increase in the permeability. Thereby, the fluid flow in the small pores and these cracks is a bit different from the traditional Darcy's law in conventional reservoirs. Although some researchers believe that the phenomenon of low-velocity non-Darcy flow is the principal cause of fluid movement in the small pores, there are no comprehensive and systematic investigations to elaborate this issue appropriately. Furthermore, it needs to be more specific and accurate (Kaitna et al. 2016; Muljadi et al. 2016; Wang and Sheng 2017). Huang et al. (2013) proposed low-velocity non-Darcy flow schematically to show the considerable influence of pressure gradient and low velocity and consequently its impact on the fluid flow. As can be seen in Fig. 1 at a significant amount of pressure gradient, pressure gradient and fluid velocity have an increasing linear pattern, even though, in the small pressure gradient due to the absence of fluid flow, it has not any fluid velocity. Therefore, pressure gradient parameter and fluid velocity are considered as the principal factor in the fluid mobilization; in respect of the way, by increasing the pressure gradient rather than threshold pressure gradient (henceforth; TPG), the fluid would flow. Moreover, if the pressure gradient rises dramatically, the flow rate has a steep rise. Finally, it approximately seems a linear relationship as same as Darcy's law (Huang et al. 2016; Huang et al. 2013; Xiong et al. 2017). The proper amount of threshold pressure gradient is showed by PTPG. Prada and Civan (1999)

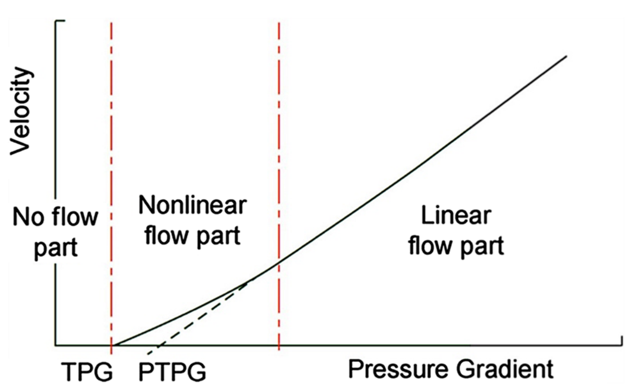


Fig. 1 A typical schematic of low-velocity Non-Darcy flow. (Reproduced with permission from Huang et al. 2013)

proposed their research based on the utilization of brine in the measurement of pressure gradient versus fluid velocity. They go on to argue that fluid mobility reduction causes to decrease the pressure gradient; that is to say that the higher value of rock permeability and higher amount of fluid velocity, the smaller amount of PTPG (Kundu et al. 2016; Prada and Civan 1999).

The amount of permeability in sandstone layers may change between less than one up to more than 50,000 milli-Darcy (mD). The average amount of this parameter varied in the range of ten milli-Darcy to thousands of milli-Darcy regarding the types of reservoir and interconnection between cracks and fractures. The concept of permeability measurement is of importance in detecting the fluid flow properties of a reservoir such as hydrocarbons and aquifers (Aigbedion 2007; Dale 1949; Denney 2007; Feng et al. 2017; Lee and Bauer 2016). The permeability measurements through a reservoir were first explained by an empirical correlation which was called Darcy correlation by utilizing the water flow rate through a sand filter in 1856 by Henry Darcy:

$$Q = \frac{KA}{L}(h_2 - h_1), \tag{1}$$

where Q is the volumetric flow rate through a sand pack, K is the constant proportionality parameter in Darcy's law, h_2, h_1 are the hydrostatic heads at the sand pack inlet and outlet, respectively, and A is the cross-sectional area. Later investigations determined that Darcy's law could be extended to other liquids and that the proportionality constant K could be replaced by $K/_\mu$, where K is the permeability of the rock and μ is the viscosity of the fluid flowing through the rock. With this modification, Darcy's law can be written in a form suitable for our experiment as:

$$Q = -\frac{0.00127KA}{\mu l}\Delta P, \tag{2}$$

where μ is absolute viscosity and ΔP is the pressure drop.

To calculate average permeability, weighted-average permeability, harmonic-average permeability, and geometric-average permeability techniques are derived from experimental evaluations (McCain et al. 2011). The method of calculating average permeability used in this research in the section of core analysis is weighted-average permeability. This averaging process is used to determine the average permeability of layered-parallel beds with different permeabilities. Dealing with the coherent diagenetic and depositional complexity of carbonated reservoirs is considered as one the main challenges of petroleum industries for several decades. Thereby, engineers try to find novel solutions by using harnessing technologies to reduce vast sums of money which they spent for measuring reservoir properties. Wireline logging tools may confidentially provide a reasonable solution for obtaining the proper value of porosity and fluid saturation; nevertheless, in the case of permeability measurements, it may be debatable. Furthermore, core plugs are not the best candidate tools to measure the characterization of fractured and vuggy intervals (Ali Ahmadi et al. 2013; Frash et al. 2016; Sullivan 2007). Evaluating the appropriate properties of each layered reservoirs is considered as the underlying issues of engineering and geological perspectives. Also, determining the proper value of these crucial parameters exerts a profound impact on the primary and secondary oil recovery procedures, where the different layer permeabilities may lead to differential depletion. There are a wide variety of applied techniques to estimate the amount of permeability in the layered reservoirs in which the most important ones are core analysis, sidewall samples, wireline logging correlations, NMR logs, wireline formation testers, drill stem tests (DST), and production logging tools (Amir Shah et al. 2017; Kading 1976; Qobi et al. 2000; Quintero et al. 1999; Sætrom et al. 2016).

Production logging tools

Utilization of production logging tools in the horizontal and vertical wells is challenging regarding the deviation of the wells, complex conditions of the wellbore and multiple flow regimes. The first administration of production logging tools such as temperature, flowmeters, and density logging tools applied in the petroleum industries since the 1950s. In the coming decades, optimizing the well performances and managing the reservoir production are the most priorities of each company to provide the requirements to assess more contact with the production layers. Hence, the oil recovery factor has dramatically increased, and it gives engineers a chance to produce more volume of initial oil in place. As new production logging tools became available, interpretation methods evolved for the more complex flow conditions being encountered. These tools involved a series of records which illustrate the fluid behavior and nature of the reservoir during the production and injection procedures of an oil formation. Figure 2 shows the production logging tools components schematically (Frooqnia et al. 2011; Grayson et al. 2002; Hoffman and Narr 2012; Li and Zhao 2014; Plastino et al. 2017; Sullivan 2007).

One of the chief aims of production logging tools is to analyze and investigate the borehole performances like dynamic or static situation of a production well, measure the amount of productivity and injectivity index of zones or layers of a field, monitor the borehole inefficiencies by interpreting obtained logs, diagnose the effectiveness of stimulation or completion processes, and measure the physical condition of a well (Aghli et al. 2016; Al-Mulhim et al. 2015). Production logging tools are one of the leading operating services especially for cased-hole drilling, which entails

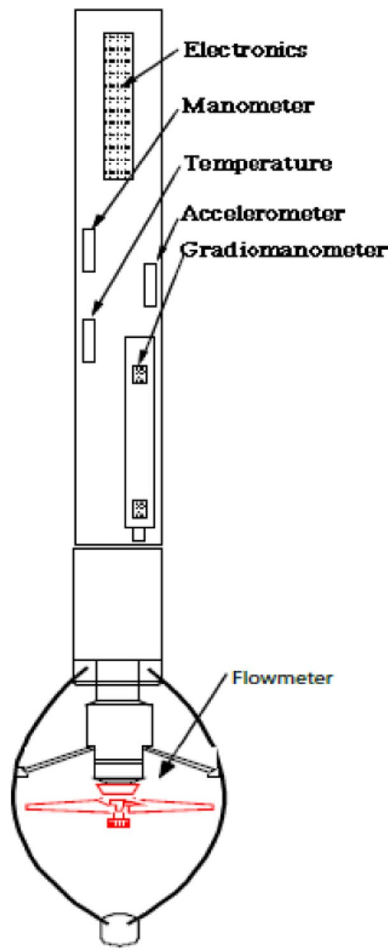


Fig. 2 Production logging tools components

monitoring the cement displacement, pipeline corrosion, and contacts. Moreover, it has been utilized in the setting of the packers, plug equipment, and perforation procedures. The most exceptional appeal of using production logging tools is to diagnose the problems which are caused by production operations such as leakage and occurring crossflow through the wellbore. There are many ways and techniques to obtain the measurement of the formation's fluid viscosity; however, it could be estimated by spinner flowmeter (a rotational blade which will turn when the reservoir fluid moves through the edges and past it). In ideal conditions, the rotational speed of the blade in revolutions per second (RPS) is proportional to the fluid velocity. Figures 3 and 4 show a schematic basis of two new production logging tools (Miklashevskiy et al. 2017).

Various types of production logging tools are listed below:

- Temperature logging
- Radioactive tracer logging
- Noise logging

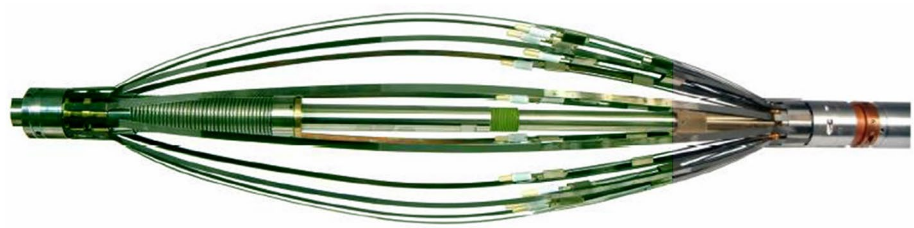


Fig. 3 General views of capacitance array tool (CAT)

Fig. 4 General view of spinner array tool (SAT)

- Focused gamma ray density logging
- Unfocused gamma ray density logging
- Fluid capacitance logging
- Fluid identification logging in high-angle wells
- Continuous and full-bore spinner flowmeters
- Diverting spinner flowmeter

Some of the main applications of production logging tools are determination of well mechanical problems, analysis of the efficiency of completion processes, observation and monitoring of the profiles of production and injection scenarios, obtainment of the reservoir characteristics, and detection of cemented channels (Gan et al. 2016; Wilson 2016). According to the wide variety of logs which plotted in the Emeraude software, an empirical correlation for permeability estimation is described as Eq. 3. In this equation, fluid flow profile is considered for each meter ($h = 1$)(Galvao and Guimaraes 2017; Sullivan 2007; Williams 2016)

$$k_{\mathrm{plt}} = \frac{c * q_i * \mu_o * \beta_o}{(p_e - p_{\mathrm{wf}})}\left[Ln(\frac{r_d}{r_w}) + s'\right], \quad (3)$$

where C is the constant volume of the equation, q_i is obtained fluid flow from Emeraude software, μ_o is the viscosity, P_e is the external pressure, P_{wf} is the internal well pressure, S is skin factor, B_o is oil formation volume factor, r_d is depleted wellbore radius, and r_w is wellbore radius.

Although there is excellent petroleum company's interest, numerous investigations have been conducted about the considerable influence of production logging tools on the reservoir characteristics measurement, and many experimental evaluations are widely reported in literature to estimate the permeability, in this analytical study, we concentrate on the administration of production logging tools advancements and import the obtained data from its logs to the Emeraude software. Therefore, Emeraude software simulates the operating procedures and well logging data to estimate permeability in each layer individually, and then it compares with the permeability which obtained from core analysis for each section. Furthermore, according to the recent studies which are based on the simulations of reservoir behavior by production logging tools and how to analyze them accurately, this extensive evaluation from Emeraude software offers enormous opportunities for petroleum companies to simulate the reservoir models on the software instead of core analysis and subsequently, it virtually eliminates the unnecessary expenditures of core plugging, and it's outrageous expenses of laboratory investigations.

Methodology of work

Emeraude software

Emeraude software was one of the applied petroleum engineering softwares from Kappa Company to interpret logging data. One of the chief aims of this software is to analyze the production logging tools data and simulate production profile to estimate the permeability. Nowadays, especially logging service companies use this software for interpreting the different logs which have been taken from the wellbore, and it is also compared to the core data (Cui et al. 2016; Haoua et al. 2015). There are several production logging tools in the Emeraude software which any of them has a specific interpretation. For example, flowmeter log (CFB) is used to determine the reservoir areas, evaluate the well stimulation operations, and facilitate the calculation of absolute open flow (AOF) and selective inflow performance by estimating the permeability. Another significant log which is called temperature log is to determine the production and injection areas, investigate the procedure of making a fracture, and

Table 1 Perforation intervals

From the starting point of the perforated area (ft)	To ending point of the perforated area (ft)
6047.29	6059.15
6096.35	6114.92
6146.79	6158.57
6205.62	6216.43
6250.12	6263.51
6293.54	6298.32

detect gas entrance and movement of fluid flow at the back of the pipeline.

Field description

The studied field located in the Persian Gulf. In this oil field, six production wells and four water injection wells drilled. Production crude oil from this reservoir categorized in the high-quality crude with the number of 44 API, which has the similar potential with Brent crude oil. This reservoir was one of the geophysical reservoirs in this field which the subsequences of drilled sections or layers typically considered. There was not seen any fault during the drilling procedures that may cause duplication or elimination of geological layers. Geological properties of each layer are as below:

1. Hith Formation from the depth of 1757–1847 m (average thickness: 90 m)
2. Surmeh Formation from the depth of 1847–2534 m (average thickness: 687 m)

Perforation intervals enter into the Emeraude software. To obtain this interval, reservoir areas derived from geological wellbore data. Perforation intervals are provided in Table 1.

The fluid properties of this reservoir are demonstrated in Table 2.

Production rates of each fluid at the surface are shown in Table 3 statistically.

Core analysis

For a start, the reservoir divided into six layers which had different permeability up to each section into 268 samples. According to this classification, six cores were taken from the layers, and the average permeability had been obtained for six cores in Table 4. To measure average permeability, the amount of this parameter is calculated in each layer in Table 4.

Table 2 Fluid properties of this reservoir

Fluid type	Water, oil, gas
Gas specific gravity	1.162
N_2%	2.37
Co_2%	1.08
H_2S%	0
Z	From Beggs and Brill, constrained Eq.
Oil specific gravity	0.855 sp gr
GOR	$420.19\ {ft^3}/{bbl}$
P_b	From Petroski and Farshad Eq.
R_s	From Petroski and Farshad Eq.
B_O	From Standing Eq.
C_o	From Vasquez and Beggs Eq.
Water salinity	2.5E+6
R_{sw}	From Katz Eq.
C_w	From Dodson and Standing Eq.

Table 3 Production rates of each fluid at the surface

Type of fluid	Flow rate	Unit
Water	498	STB/D
Oil	518	STB/D
Gas hydrocarbons	90	Mscf/D

Table 4 Amount of average permeability of each layer

Layer no.	Average permeability (mD)
Layer 1	122.3755195
Layer 2	146.78836
Layer 3	113.96074
Layer 4	84.36438766
Layer 5	142.9324114
Layer 6	39.63111259

Permeability measurements by using Emeraude software

The amount of skin effect due to the well production is assumed zero. The amount of flow rate is calculated from Darcy equation in the Software. External and internal wellbore radii were 4.5 and 2.25 inches, respectively. The software calculated the amount of viscosity via PVT data like bubble point pressure. The amount of permeability measurements by Emeraude Software is demonstrated statistically in Table 5.

To achieve more sustainable and reliable data, it needs to rearrange the core data efficiently; in respect of the way, by removing 7 percent of the high and low

Table 5 Amount of permeability measurements by Emeraude software

Layer no.	Permeability by Emeraude software (mD)
Layer 1	76.419
Layer 2	106.812
Layer 3	72.51
Layer 4	55.84
Layer 5	99.12
Layer 6	10.434

Table 7 Estimated flow rate from Emeraude software (bbl/D)

Layers	Estimated flow rate from Emeraude software
Layer 1	– 312.985
Layer 2	427.407
Layer 3	716.844
Layer 4	– 76.212
Layer 5	– 46.277
Layer 6	1.858

Table 6 Comparison of permeability between two techniques after correcting core data analysis

Layers	Average permeability of each layer	Permeability measurements by Emeraude software
Layer 1	70.521	76.419
Layer 2	98.51	106.812
Layer 3	61.94	72.51
Layer 4	78.651	55.84
Layer 5	92.35	99.12
Layer 6	21.514	10.434

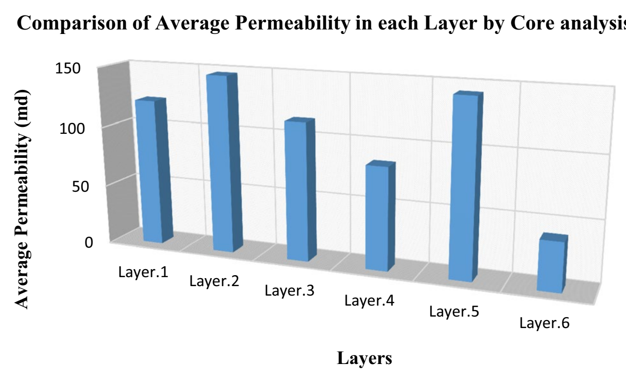


Fig. 5 Amount of average permeability of each layer

permeability from the received cores, core permeability intervals could be arranged between 0.12 and 370 mD. The reason for this elimination is that during the core plugging, the cores would be crushed from the bottom and top of the cores in the equipment, so to obtain appropriate results from core analysis, we assumed the right section of each cores which are not damaged. Furthermore, due to the laboratory investigation report from these cores, the percentages of damages for cores are calculated averagely about 5–10 percent, and we assumed the average number of 7 percent for them. Consequently, those permeabilities ranged out of these intervals would not be accepted and would not play a significant role in the calculation and should be negligible. It would be noticed that the reservoir may be produced from the permeable layer which has been omitted from the measurements. Thereby, regarding lack of image logs through the well logging, it would be assumed that these layers do not have a critical role in the productivity rate. This issue is, too, considered as one of the restrictions of using production logging tools in the carbonated reservoirs. The comparison of permeability between two techniques after correcting core data analysis is explained in Table 6.

The estimated flow rate from Emeraude software is demonstrated in Table 7. In some areas, the obtained flow rate from Emeraude software was negative. The cause of this issue could be the occurrence of latitude flow between two productive layers or may be caused by high fluid velocity. This parameter might rotate the butterfly tools reversely.

Results and discussion

1. As can be seen in Fig. 5, the amount of permeability in the layers 2 and 5 are the highest (approximately 140 mD). It revealed that these layers had played the significant role in the production rate of the well. The lowest permeable area belonged to layer 6; it is just under 40 mD. On the contrary, by increasing the depth, the permeability of the reservoir would be decreased.
2. The amount of estimated permeability by Emeraude software is demonstrated in Table 5. It has the same pattern as core data analysis by increasing the depth. It has been provided in Fig. 6.
3. The comparison of estimated permeability from both methodologies is plotted in Fig. 7. In all the layers, the amount of permeability has more than the amount of permeability which was obtained by Emeraude software. In the layers 3 and 4, these amounts are nearly close

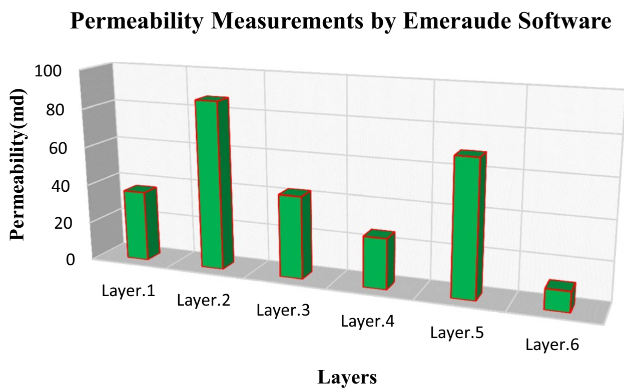


Fig. 6 Permeability measurements by Emeraude software

together. Thereby, it needs to normalize the gathering data by eliminating the 7 percent of high and low permeabilities from each layer.

4. After normalizing and reducing the unnecessary data, it demonstrates that the amount of permeability in both methods in the layers 1, 2,3, and 5 is being relatively close to each other for both techniques. Therefore, regarding high expenditures of core analysis in the laboratory, production logging tools would be preferred to predict permeability. On the contrary, layers 4 and 6 have differences between two methods. Its comparison is plotted in Fig. 8.

Fig. 7 Comparison of permeability between two techniques

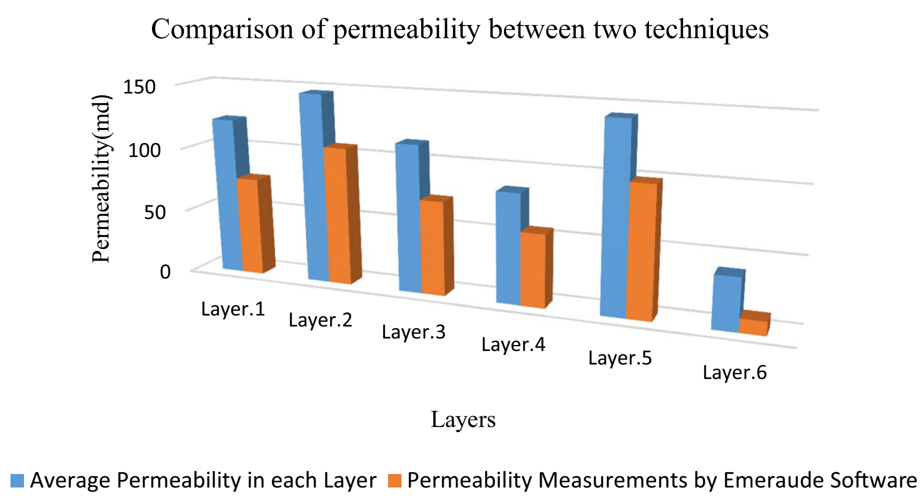
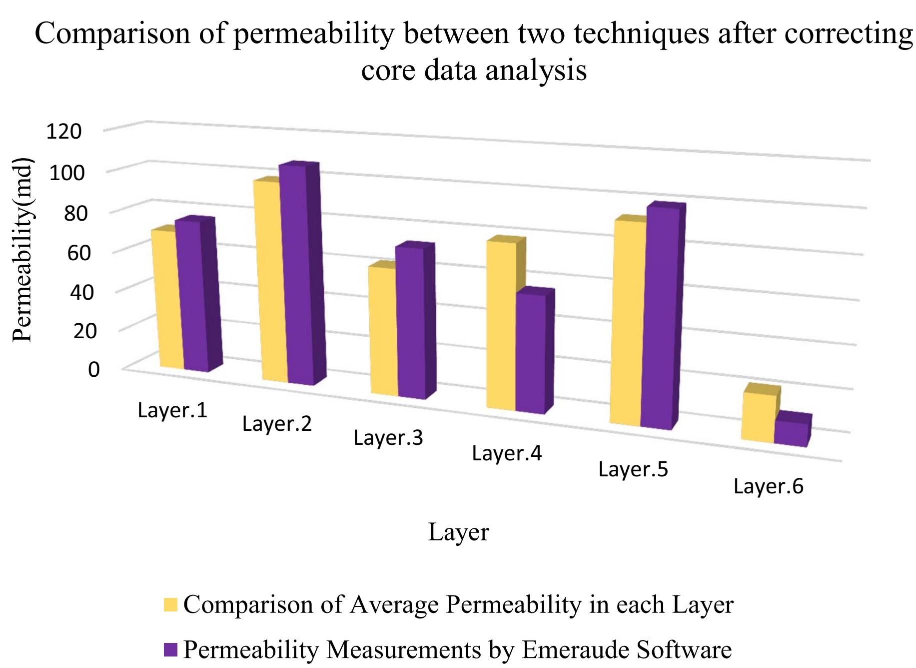


Fig. 8 Comparison of permeability between two techniques after correcting core data analysis



Parameters would severely affect the results of PLT

One of the significant parameters which play a vital role in the permeability measurements is external borders pressure. External reservoir borders at different depths have various pressures. It obtains the more appropriate quantities which they matched with core analysis, and the average pressure is assumed in the calculations. The accurate and efficient way to measure average pressure is selecting inflow performance (henceforth; SIP). Also, average pressure has an adverse effect on the permeability, and by increasing average pressure, permeability would decrease. Due to the results of SIP, it is evident that when the productivity index (PI) is very low, the PLT is not preferable for permeability measurements and core analysis would be the best choice. The second significant parameter is the bottom hole pressure, which exercises a dominant influence on the permeability; to dramatically increase the permeability by raising the bottom hole pressure. Hence, this parameter should be taken into account throughout the logging procedures, and its changes should be recorded accurately. The other parameters such as fluid properties (e.g., viscosity, oil formation volume factor, etc.) except pressure gradient and fluid velocity have less impact on the permeability measurements and should be negligible.

Conclusion

Using production logging tools has some possibilities like a homogeneous reservoir, single-phase flow, and the stable system should appear on the reservoir system. One of the chief aims of production logging tools is to eliminate the small-scale non-homogeneity principals of cable logs. Moreover, it calibrates their homogeneity extremity. This technique could enroll as depth interval detection in those layers which have more permeability regarding immediate alterations in the well flow logs. Therefore, these inefficiencies may not be illustrated by core plugs and cable logs. The most extraordinary appeal of production logging tools is to obtain the appropriate vertical dispersion of the reservoir layers, which helps to the accurate explanation of flow units in the reservoir. In the areas with a low volume of flow rate or low productivity index, it would not be preferred to utilize production logging tools instead of core analysis. Production logging tools have been more reliable and better results when the flow rate does not low enough regarding rotation of the tools.

Suggestions and future research

1. We highly recommend investigating more wells and fields to get proper evaluations from them.
2. During the use of production logging tools, it would be better to apply FMI and VSP tools to obtain more accurate data.
3. By using MATLAB software regarding the appropriate artificial network algorithms to simulate the proper way of fluid mobilization, it would be achieved an analytical model for estimating the amount of permeability in fractured reservoirs which facilitate the petroleum industries to foster a deeper understanding of reservoir fluid characterization.

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