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Comprehensive evaluation of fracture parameters by dual laterolog data

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ABSTRACT

Reservoir quality and productivity of tight formations depend heavily on the degree of fracture development. In fact, hard and dense carbonate formations may not be considered as net pay without the presence of fractures that convey fluids towards the wellbore. The evaluation of fractures is key to effective reservoir characterization for purposes like well drilling and completion as well as development and simulation of fractured reservoirs. Although imaging technologies such as Formation Micro-Scanners and Imagers (FMS and FMI) provide useful information about fracture properties (i.e., dip angle, porosity, aperture, and permeability), they are very expensive and may not be available in all wells. In this work, fracture parameters are estimated using conventional dual laterolog (DLL) resistivity which includes shallow (LLS) and deep (LLD) responses. This technique is based on electrical resistivity anomalies resulting from the separation of shallow and deep laterolog curves. Fracture parameters that can be calculated by DLL include dip angle, aperture, porosity, permeability, and cementation factor. The accuracy of the parameters calculated using DLL data is validated by the results of FMI in a well in one of the Iranian fractured reservoirs. Contrary to the image logs, the conventional DLL is run routinely in all drilled wells. Therefore, if a reservoir has limited and insufficient data of image logs, as it is often the case, the DLLs can be used as a reliable replacement in the construction of fracture models. Furthermore, DLL has an advantage of deeper evaluation of fractures in comparison with the immediate borehole investigation of image logs.

1. Introduction

Naturally fractured reservoirs contain more than 50% of the known oil and gas reserves worldwide (Ahmed, 2010). These reservoirs are heterogeneous and anisotropic media consisting of matrix blocks and fractures. The ultra-low permeability matrix system acts as a source of fluids for fractures while the fracture network serves as the main pathway of the fluids towards production wells. Therefore, a qualitative and quantitative description of fractures and their spatial distribution is a key factor in effective reservoir characterization for purposes such as well drilling and completion as well as development and simulation of fractured reservoirs (Saboorian-Jooybari et al., 2012; Saboorian-Jooybari, 2015, 2016). Well test and image log data are used for quantitative description of fractures. However, the application of such data suffers from some shortcomings; on the one hand, image logs are not run in all of the drilled wells, and on the other hand, a well test interpretation gives average properties of the tested interval without providing a point-to-point quantitative description. There are also a number of tools that can describe the development of fractures qualitatively. A qualitative technique includes an analysis of mud losses, outcrops study, and petrophysical well logs anomalies. A summary of well logs and their corresponding anomalies resulting from the presence of natural fractures are presented in Table 1. In general, intersection of natural fractures with the borehole causes some anomalies in the well logs; these anomalies can be interpreted qualitatively. For example, it is expected to observe high neutron porosity, high slowness, and also low bulk density in front of an open fracture provided that the resolution of the logging tools is sufficiently high. It should be emphasized that all of the tools mentioned in the table only help detecting the fractures and do not provide any quantitative value for the parameters essentially required for construction of a discrete fracture network (DFN) and its subsequent import into numerical simulators. Additionally, because of their very shallow depth of investigations, these indicators may also detect the induced fractures. The only indicator in Table 1 which can be utilized for quantification of fracture parameters is the DLL response. Details of the applicability of laterolog measurements are presented below.

2. Dual laterolog

A dual laterolog (DLL) tool provides two types of resistivities with shallow (LLS) and deep (LLD) depths of investigation. In Fig. 1, the

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Table 1
Anomalies observed in conventional well logs due to response of an open fracture.

Abbreviation	Log name	Expected anomaly
CALIPER	Caliper	Sudden increase of borehole diameter
GR	Gamma-ray	Higher reading
RHOB	Bulk density	lower reading
CNL	Compensated neutron	Higher reading
DT	Sonic	Slowness increases
PEF	Photo-electric factor	Slightly increases
U	Uranium	Higher reading
TEMP	Temperature	decreases
DLL	Deep and shallow laterolog	Separation in the case of significant difference between mud and the formation fluids

focusing used by the (a) LLS and (b) LLD devices is illustrated schematically. Large separation between the shallow and deep laterolog measurements in fractured reservoirs was first observed by Rasmus (1981) as well as Boyeldieu and Winchester (1982). They indicated that the difference in resistivity measurements, which is because of the difference between conductivity of the invaded drilling mud and the displaced fracture fluid, is a function of the volume of mud losses during drilling. They assumed that the lost mud invades the fracture system leaving the low porosity and low permeability matrix almost free of the filtrate. This very simple assumption is supported by high capillary pressure in matrix in comparison with a nearby fracture (Sibbit and Faivre, 1985). This assumption is made in all discussions presented below. Recently, Shao-gui et al. (2010) used three-dimensional finite element method to simulate the response of array lateral log under different fracture parameter conditions and concluded that the array lateral log can be used in formation fracture evaluation.

3. Quantification of fracture parameters

3.1. Fracture dip angle

Field measurements of DLL indicate that the deep resistivity (LLD) of a fractured formation may be higher or lower than the equivalent shallow resistivity (LLS). According to the finite element modeling of the DLL measurements, Sibbit and Faivre (1985) concluded that the positive separation of LLS and LLD ($R_{LLD}>R_{LLS}$) can occur in sub-vertical (a dip angle > 60°) fractures, whereas the negative separation ($R_{LLD}<R_{LLS}$) in some intervals can be attributed to the presence of sub-horizontal fractures (a dip angle < 60°).

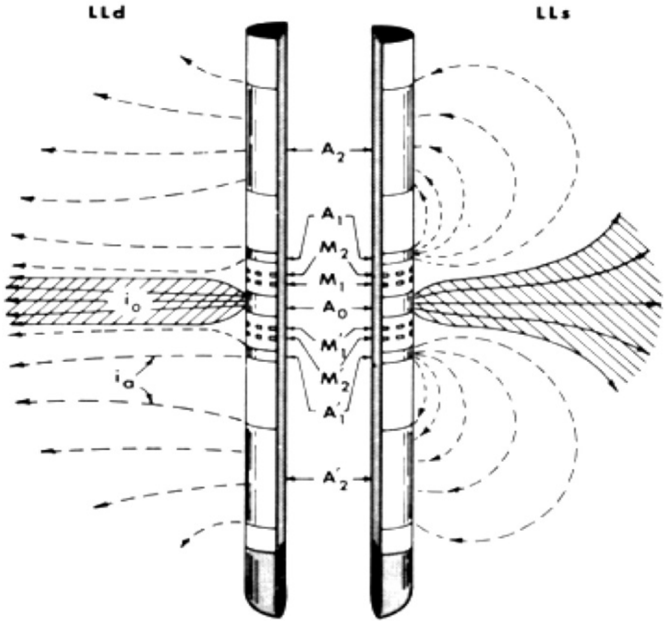

Fig. 1. Sketch of a dual laterolog (DLL) tool (after Schlumberger, 1991).

3.2. Fracture porosity

The first attempt to estimate porosity of a medium on the basis of electrical properties was made by Archie (1942). He experimentally found a power relationship between the total porosity of the formation and the electrical resistivity of a non-shaly formation and the formation water as:

$$\phi^m = \frac{aR_w}{R_t S_w^n} \tag{1}$$

where ϕ is the total porosity in fraction, m is Archie's cementation factor, a is the dimensionless tortuosity factor (mostly unity value), R_w is the formation water resistivity in $\Omega\cdot$m, R_t is the formation resistivity in $\Omega\cdot$m, S_w is the water saturation in fraction, and n is the saturation exponent. Assuming that the matrix blocks of formations are not affected by the mud invasion, Boyeldieu and Winchester (1982) developed Archie's equation to calculate fracture porosity from the DLL responses as:

$$\phi_f^{m_f} = R_m\left(\frac{1}{R_{LLS}} - \frac{1}{R_{LLD}}\right) \tag{2}$$

where ϕ_f is the fracture porosity in fraction, m_f is the cementation exponent of a fracture, R_m is the drilling mud resistivity in $\Omega\cdot$m, and R_{LLD} and R_{LLS} are the resistivities measured by the deep and shallow laterologs in $\Omega\cdot$m, respectively. This technique suffers from two main shortcomings. Firstly, although Boyeldieu and Winchester (1982) assumed a value of 1.5 for m_f, the value may vary between 1 and 2 depending on the size, wall thickness, and tortuosity of the fracture. Secondly, this equation fails to estimate the fracture porosity of sub-horizontal fractures with negative separation of LLS and LLD. Pezard and Anderson (1990) extended the work of Boyeldieu and Winchester (1982) by developing an analytical model of fractured rocks. Their analytical approach led to the following equations for porosity estimation of horizontal and vertical fractures, respectively:

$$\phi_{fh} = R_m R_{LLD}\left(\frac{1}{R_{LLD}^2} - \frac{1}{R_{LLS}^2}\right) \tag{3}$$

$$\phi_{fv} = 2R_m R_{LLD}\left(\frac{1}{R_{LLS}^2} - \frac{1}{R_{LLD}^2}\right) \tag{4}$$

These equations are used in this paper to calculate fracture porosity.

3.3. Fracture aperture

The analytical approach of Pezard and Anderson (1990) led to the following equations for aperture estimation of horizontal and vertical fractures, respectively:

$$b_h = \frac{R_m}{1.2\times 10^{-7}}\left(\frac{1}{R_{LLD}} - \frac{1}{R_b}\right) \tag{5}$$

$$b_v = \frac{R_m}{4\times 10^{-7}}\left(\frac{1}{R_{LLS}} - \frac{1}{R_{LLD}}\right) \tag{6}$$

where b is the fracture aperture in μm, R_b is the maximum resistivity of the nearby non-fractured rock, and the other parameters are defined as above.