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Interpreting Dual Laterolog Fracture Data in Fractured Carbonate Formation

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ABSTRACT: The estimation of fractures is key to evaluating fractured carbonate reservoirs. It is difficult to evaluate this kind of reservoir because of its heterogeneously distributed fractures and anisotropy. A three-dimensional numerical model was used to simulate the responses of the dual laterolog (DLL) in a fractured formation based on a macro-isotropic anisotropic model. Accordingly, a fast fracture-computing method was developed. First, the apparent conductivity of the DLL is linearly related to the porosity of the fracture and the conductivity of pore fluid. Second, the amplitude difference of the deep and shallow apparent resistivity logs is mainly dependent on the dip angle of the fracture. Then the response of the DLL to a formation with dip angle fractures is approximately depicted as a function of the bulk resistivity of the rock, the porosity of the fractures and the conductivity of fracture fluid. This function can be used to compute the porosity of fracture quickly. The actual data show that the fracture parameters determined by the DLL closely coincide with the formation micro imager log.

KEY WORDS: fracture, dual laterolog, carbonate rock, reservoir.

INTRODUCTION

The development degree of a fracture dominates the productivity of a fractured carbonate reservoir. Fractures are not only important storage space, but also favorable permeable channels. So fracture estimation is a key to evaluating fractured carbonate reservoirs (Luo et al., 2001; Wei et al., 2000). However, it is difficult to evaluate this kind of reservoir for the heterogeneity of fracture development and reservoir anisotropy. Fullbore formation micro image (FMI) provides credible well bore image data and can be used accurately to identify and evaluate fractures. However, its application is not as broad as a conventional log and it is expensive. Therefore, it is important and useful to identify fracture parameters with conventional log data. The dual laterolog (DLL) is sensitive to fractures due to its electric current focus, and it is favorable in computing fracture porosity. Sibbit and Faiver (1985) studied the DLL responses of one fracture with a dip angle of 0° and 90°, using a finite element model, and built a relation between DLL responses and fracture aperture in these two cases. Pezard and Anderson (1990) derived dual laterolog responses of fractures at any dip angle and provided a formula to compute quasi-horizontal and quasi-vertical fractures. Ouyang (1994) gave a semi-quantitative interpretation method of fractured limestone reservoirs based on a consideration of research into limestone reservoir fractures in China and abroad. Li et al. (1996) found a set of fast calculation formulae for fracture porosity with DLL apparent resistivity by numerical simulation.

Understanding the dual laterolog response characteristics of a fracture is a precondition to identifying fractures. Here, DLL response in macro-anisotropy fractured reservoirs is studied using the three-dimensional finite element method. According to the relationship between DLL responses of fractures and formation parameters, such as porosity, conductivity of liquid and basement rock conductivity, fracture parameters are computed fast and effectively.

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THEORETICAL FOUNDATION OF THE DUAL LATEROLOG RESPONSES OF FRACTURE

Fractures are mainly tectonic and sedimentogenic, according to their genetic classification. Tectonic fractures are intimately related to the fractured reservoirs and are favorable to their development. Generally, fractures are distributed heterogeneously in the fracturation zone due to tectonic stress, and the fractured formation is obviously anisotropic (Jiang et al, 2004; Yuan, 2000; Tan, 1987). So a parallel fracture model is used to simulate a fractured limestone formation as shown in Fig. 1, where σ_b and σ_f are the conductivity of block and liquid in fractures, respectively; h and d are the fracture aperture and the vertical distance between fractures, respectively; Ω is fracture dip, and the parallel fractures are equally spaced. Suppose that the fractures distribute over whole regions and the space between the fractures is small enough. Then electrical parameters would be considered macro-anisotropic. The electrical anisotropic characteristics of the equally spaced parallel fractures are considered to be the same as the macro-anisotropy medium (Li et al. , 1996). So the conductivity can be expressed as a tensor

$$\boldsymbol{\sigma}=\begin{bmatrix}\sigma_{xx} & 0 & \sigma_{xz}\\ 0 & \sigma_{yy} & 0\\ \sigma_{zx} & 0 & \sigma_{zz}\end{bmatrix} \tag{1}$$

where $\boldsymbol{\sigma}$ is the tensor of formation conductivity. Each parameter is depicted as follows

$$\sigma_{xx} = \sigma_b + \phi_f\sigma_f\cos^2\Omega \tag{2}$$

$$\sigma_{yy} = \sigma_b + \phi_f\sigma_f \tag{3}$$

$$\sigma_{zz} = \sigma_b + \phi_f\sigma_f\sin^2\Omega \tag{4}$$

$$\sigma_{xz} = \sigma_{zx} = \phi_f\sigma_f\sin\Omega\cos\Omega \tag{5}$$

where ϕ_f is fracture porosity. In a given well bore condition, the dual laterolog responses of a fracture are mainly affected by fracture porosity, conductivity of fluid in the fracture, fracture dip and the conductivity of the rock block. Generally, the depth of mud invasion is very great in a fractured formation. Therefore, the block conductivity is far less than the conductivity of the invasive liquid. In a certain circumstance, the block conductivity has little fixed effect on electric characteristics of rock.

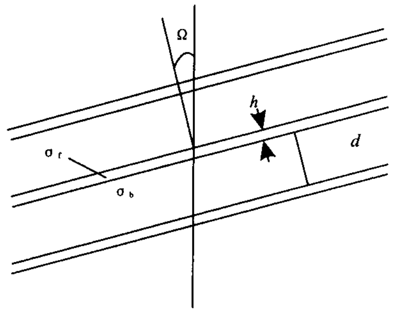
The function of the DLL response in a fractured reservoir needs to be continuous and smooth, which meets the condition as following

$$\nabla\cdot(\boldsymbol{\sigma}\nabla\Phi)=0 \tag{6}$$

where Φ is the function of potential distribution. On the surface of constant voltage and constant current electrode, Φ meets the first boundary condition, and is a given constant and an unknown constant, respectively. For the surface of constant current electrode E_A, Φ meets the second boundary condition, $\iint_{E_A}\sigma\frac{\partial\Phi}{\partial n}dS=I_A$, where n is border normal; I_A is current of current electrode A. For the insulation boundary surface, $\frac{\partial\Phi}{\partial n}=0$. For the fractured formation, equation (6) is usually solved numerically. With a three-dimensional finite element method, it is transmitted to rooting the extreme value of a function, which is depicted as follows

$$F(\phi)=\frac{1}{2}\iiint_{\alpha}\sum_{i,j=1}^{3}\left[\sigma_{ij}\frac{\partial\Phi}{\partial\xi_i}\frac{\partial\Phi}{\partial\xi_j}\right]dxdydz-\sum_{E}I_E\Phi_E \tag{7}$$

where σ_{ij} is element of conductivity tensor of formation; $\xi_1=x$, $\xi_2=y$, $\xi_3=z$, Φ_E and I_E are the voltage and current of electrode E, respectively, and α is the three-dimensional region excluding the electrode system, which is actually subdivided to 56 088 tetrahedron elements. Equation (7) is quickly resolved with the frontal solution method (Zhang, 1984).



gure 1. Plane model of fracture.

DUAL LATEROLOG RESPONSES IN THE FRACTURED FORMATION

Influence of the Fracture Porosity and Liquid Conductivity on Dual Laterolog Responses

As shown in Fig. 2, the corrected dual laterolog apparent conductivity increases the product of fracture porosity and conductivity of liquid, and they are positively proportional under an arbitrary dip angle if the mud invasion is infinitely deep. Here, D_h is well bore diameter; σ_m is mud conductivity; σ_{LLDC} and σ_{LLSC} are respectively corrected DLL apparent conductivity, which are the subtraction values between DLL apparent conductivities, and the block conductivity.

Influence of the Dip Angle of Fracture on Dual Laterolog Response

The difference between the deep and shallow

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