Journal of Applied Geophysics 100 (2014) 1–13

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Numerical simulation and fracture evaluation method of dual laterolog in organic shale

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ARTICLE INFO

Article history:
Received 15 May 2013
Accepted 21 October 2013
Available online 30 October 2013

Keywords:
Dual laterolog
Fracture identification
Numerical simulation
Three-dimensional finite element method (3D FEM)
Fracture porosity

ABSTRACT

Fracture identification and parameter evaluation are important for logging interpretation of organic shale, especially fracture evaluation from conventional logs in case the imaging log is not available. It is helpful to study dual laterolog responses of the fractured shale reservoir. First, a physical model is set up according to the property of organic shale, and three-dimensional finite element method (FEM) based on the principle of dual laterolog is introduced and applied to simulate dual laterolog responses in various shale models, which can help identify the fractures in shale formations. Then, through a number of numerical simulations of dual laterolog for various shale models with different base rock resistivities and fracture openings, the corresponding equations of various cases are constructed respectively, and the fracture porosity can be calculated consequently. Finally, we apply this methodology proposed above to a case study of organic shale, and the fracture porosity and fracture opening are calculated. The results are consistent with the fracture parameters processed from Full borehole Micro-resistivity Imaging (FMI). It indicates that the method is applicable for fracture evaluation of organic shale.

1. Introduction

Fractures are key channels and important space for gas or oil flow in shale formations, which play important roles in organic shale exploration (Karl-Heinz and James, 1984; John, 2002). Geophysical well logging can continuously measure a series of physical parameters of the formation along the borehole. The primary objectives of the wireline logging include reservoir identification, hydrocarbon estimation in situ, and formation evaluation. Dual laterolog is suitable for high resistivity formation, and can be used to identify the fluid and locate the fractures (Richard, 2012; Darling, 2005). Because the oil- and gas-bearing shale reservoirs are located in hydrocarbon source rocks, the resistivity are higher than regular shale. Thus, dual laterolog is selected for fracture identification and evaluation of oil/gas shale instead of induction log. In fact, dual laterolog was often used to identify the fractures in carbonate formation, and it could also evaluate fracture parameters quantitatively. Sibbit and Faivre (1985) first applied finite element method (FEM) to calculate dual laterolog responses. The characteristic of low-angle and high-angle fractures was studied and analyzed. In high-contrast formations like carbonate formation, namely, the resistivity of the target formation is much higher than resistivity ($R_t \gg R_m$) of the mud or surrounding bed, the dual laterolog responses dependent on four parameters including resistivity of the formation blocks, the resistivity of the invading fluid, the invasion length, and the fracture opening. With a few simplified assumptions, the dual laterolog measurement may be used to determine the fracture opening through solving the inverse problem. Philippe and Roger (1990) derived some response formulas of dual laterolog under an arbitrary angle and calculated dual laterolog responses of the formations with quasi-vertical and quasi-horizontal fractures (Philippe and Roger, 1990). Li et al. (1997) also used FEM method to simulate the dual laterolog responses in carbonate formations with inclined fractures. He also constructed a series of function relationships between dual laterolog and fracture porosity, fluid conductivity, and the resistivity of the formation blocks, which was proved effective for fracture identification in carbonate formations (Li et al., 1996, 1997; Li, 1998). Deng et al. (2005, 2006) applied the method to study fractured carbonate and tight sandstone formations, and established a series of equations to estimate fracture porosity and fracture angle (Deng et al., 2005, 2006). Fan (2002) applied the same method to study volcanic rocks, which was proved helpful to identify the fractures. Generally, the researches mentioned above were applicable to fracture identification because the resistivity of these formation

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http://dx.doi.org/10.1016/j.jappgeo.2013.10.006

blocks is so higher. However, for the organic shale whose resistivity may be lower than carbonate, tight sandstone and volcanic reservoirs, the previous methods cannot be used directly. Therefore, a new approach for organic shale should be studied to estimate its fracture parameters such as fracture porosity and fracture opening. It is necessary to use conventional logs for the fracture identification and evaluation using conventional logs in shale reservoirs.

According to the characteristics of fractured shale formations, we set up various fractured shale models with different fracture widths, fracture spacings (distance between two fractures), fracture angles, and fracture numbers. We also study three-dimensional finite element method (3D FEM) to simulate dual laterolog responses in different models. Then, a variety of characteristics are described and analyzed. Through a number of numerical simulations of shale models with different base rock resistivity and fracture openings, the corresponding equations in various cases are constructed, respectively, which can be used to calculate fracture porosity accurately. Finally, a case study is introduced and discussed, and the fracture porosity and fracture opening calculated from dual laterolog match well with that from Full borehole Micro-resistivity Imaging (FMI).

2. Numerical simulation of dual laterolog

2.1. Fractured shale model

The shale has complex composition, and usually includes clay, quartz, feldspar, calcite, pyrite, and other mineral components. The structure is mostly laminated. The effective porosity is very small and its permeability is extremely low. From the current exploration results of organic shale group from some basins in America and China, the resistivity of the organic shale ranges from 50 to 9000 Ω m, as shown in Fig. 1. The resistivity of some organic shales can be as high as tens of thousands Ω m. Silica and calcite-rich shales often exhibit brittle behavior. These brittle minerals are favorable and helpful for propagation and extension of fractures, which not only increases reservoir space, but is also important to elevate the permeability. When there are more quartz and calcite contents, it becomes more brittle, and more fractures would be induced, which indicates that the reservoir quality is better (Karl-Heinz and James, 1984; John et al., 2005).

In this study, we assume that there is one inclined fracture in shale reservoir and it goes through the borehole, which is illustrated in Fig. 2. The resistivity of shale is given as R_t, the resistivity of mud is given as R_m, the fracture opening is h and the fracture angle is α (the angle ranges from 0° to 90°), the fluid resistivity in the fracture is denoted as R_f. In the radial zone, the model consists of borehole, mud cake, and shale zone. In this study, no mud invasion is considered. As more fractures are added into the model, another parameter D_f, the distance or spacing between two fractures, must be considered.

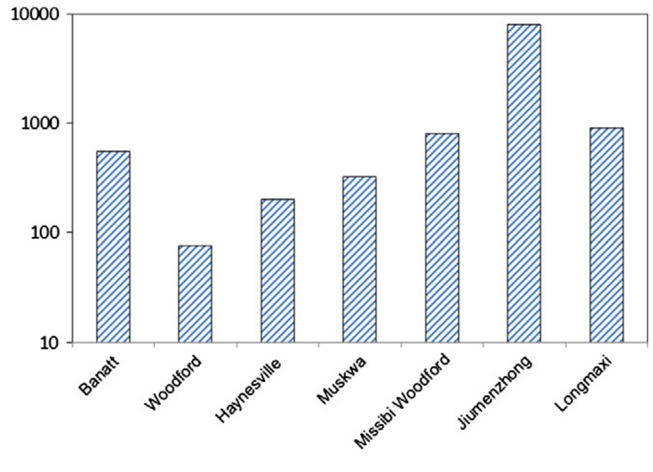

Fig. 1. The resistivity of shale formations in some basins.

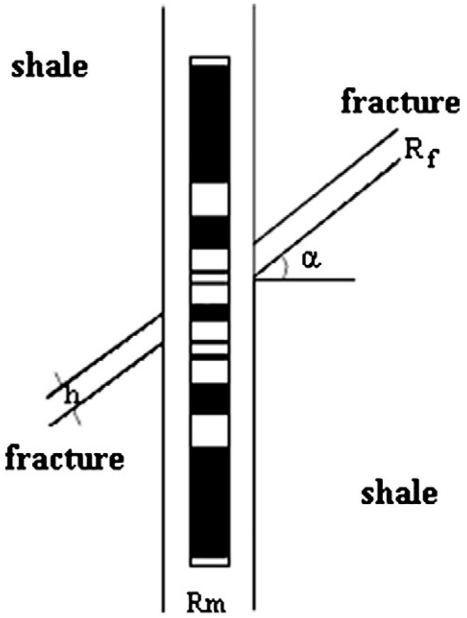

Fig. 2. Shale formation model with a single fracture.

2.2. Numerical simulation theory

The supply current in dual laterolog is regarded as steady as the direct current (DC), the potential function $u(x,y,z)$ in the space position (x,y,z) satisfy the following equation (Zhang, 1986; Chew et al., 1991)

$$\nabla^2 u = 0. \tag{1}$$

The boundary conditions should be considered in the different region boundaries, and there are three boundary conductions such as boundary between electrode and mud, boundary between electrode and insulation, and radial infinite boundary (Chew et al., 1991; Zhang, 1986; Wang et al., 2000).

On the surface of the constant-voltage electrode and at the infinite boundary, the potential function $u(x,y,z)$ satisfies complete restraint conditions, namely, $u(x,y,z)$ equals a known constant on the surface of constant-voltage electrode, and $u(x,y,z)$ equals zero at the infinite boundary. Whereas, on the surface of the constant-current electrode, the potential function $u(x,y,z)$ satisfies incomplete restraint conditions, that is, $u(x,y,z)$ is an unknown constant.

On the surface of the constant-current electrode,

$$2\pi\sigma_m \int_{C_A} r \frac{\partial u}{\partial n} dS = I_A, \tag{2}$$

where σ_m is the mud conductivity, S/m; I_A is the current intensity of the constant-current electrode A, which is known; n is the exterior normal of the boundary of solution region, the integration is carried out on surface of constant-current electrode.

On the insulated boundary surface,

$$\frac{\partial u}{\partial n} = 0.$$