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A novel quantitative imaging method for oil-based mud: The full-range formation resistivity

Jianshen Gao [a,*], Jianmeng Sun [b], Yanjiao Jiang [c], Likai Cui [b], Pengyun Zhang [b], Jie Wu [a]

[a] Key Laboratory of Education Ministry for Photoelectric Logging and Detection, School of Electronic Engineering, Xi'an Shiyou University, Xi'an 710065, China
[b] School of Geosciences, China University of Petroleum, Qingdao 266580, China
[c] College of Earth Sciences, Northeast Petroleum University, Daqing 163318, China

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ABSTRACT

Oil-based mud cake with its high resistivity affects severely the quality of borehole microresistivity imaging and has limited the use of microresistivity imaging logging in oil-based mud environment. We have utilized an equivalent model of a resistor and a capacitor to emulate the electrical responses of the high-resistivity mud cake and the formation, respectively, and then developed the electrical coupling relationship between the mud cake and formation, including vertical coupling and parallel coupling. We used the coupling relationship with a formation model to measure both the apparent resistivity and apparent relative permittivity of the formation simultaneously. Furthermore, we have imaged two formation models, one low-resistivity and the other high-resistivity using the vertical and parallel coupling, compared with the standard images obtained in the water-based mud environment corresponding to the same formation models. We have found that the vertical coupling and parallel coupling conquering the bad effect made by oil-based mud cake, can measure quantitatively the resistivity of low-resistivity and high-resistivity formation, respectively, and describe qualitatively the relative permittivity of low-resistivity and high-resistivity formation, respectively. The joint use of the vertical and parallel coupling can deal with the full-range microresistivity imaging of formation.

1. Introduction

To obtain the fine scale formation features, the microresistivity logging has been developed since 1980s from the dipmeter technology (Lloyd et al., 1986; Ekstrom et al., 1986; Boyeldieu and Jeffreys, 1988). The physical principle of the initial microresistivity logging tools is similar to that of laterolog, i.e., the circuit can be equivalent to the series of resistivities encountered by the measuring currents (Griffiths et al., 2000). Shortly afterwards, the next generation microresistivity logging tools sprang up with higher borehole coverage (Safinya et al., 1991; Seller et al., 1994; Hansen and Parkinson, 1999; Chitale et al., 2004). These tools are all appropriate for water-based mud (WBM) with quite low resistivity.

However, compared with WBM, the use of non-conductive oil-based mud (OBM) can improve the drilling efficient and decrease the operation risks (Hilton et al., 2003) and is more suitable for most deepwater wells and many unconventional shale wells (Laronga and Shalaby, 2014). Due to the quite high resistivity of OBM (Patil et al., 2010), the images obtained by the tools mentioned above are blurry with low quality, resulting in restricted use of these tools in OBM. So it is imperative to find other ways to solve this difficulty.

In general, there are probably four ways developed to date. The first way is to research and develop a kind of conductive OBM that reserves the most original essential advantages (Laastad et al., 2000; Thaemlitz, 2004; Zanten, 2014), So it balances the both the effectiveness of the WBM microresistivity tools and advantages of OBM, but nevertheless this way is not economical. Another approach is to remove the high-resistivity mud cake. For example, Christie and Schoch (2007) modify the button electrodes to miniature spring-loaded scratcher knives, so the non-conductive mud cakes attaching the borehole wall can be cut off and the currents can flows into the formation. The third way is to improve the original WBM tools and make them suitable for the OBM under specific conditions (Laronga et al., 2011). Finally, the most common way is to establish other measuring methods in principle. Chen (2001), Cheung et al. (2001) and Martin et al. (2008) present the four-terminal measurement method respectively, and however, the imaging quality is affected seriously by the borehole wrinkles and the thickness of mud cake (Bloemenkamp, 2014). Lofts et al. (2002), Tabarovsky and Alexy (2004),

* Corresponding author.
E-mail address: gjs1109@126.com (J. Gao).

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Bespalov and Itskovich (2008), Bloemenkamp (2014) and Itskovich et al. (2014) provide methods, all of which can collectively called the capacitive coupling. However, more or less problems exist in them, such as the incompetence for quantitative or qualitative measurement in low-resistivity or high-resistivity formation. Our last work (Sun et al., 2016) attempts to obtain quantitative measurement and imaging of formation resistivity in OBM environment, but has not given full expression to our goals and appears un-completed.

All in all, due to effect of OBM layer's resistive and capacitive characteristic and formation's capacitive characteristic, the borehole micro-resistivity imaging in OBM environment is more difficult than that in WBM environment. In this paper we attempt to illustrate and extend our last work (Sun et al., 2016) deeply, furthermore, establish a quantitative imaging method for the full-range formation resistivity and qualitative imaging of relative formation permittivity simultaneously. In the following text, we first analyze an equivalent model of a resistor parallel with a capacitor to simulate the electrical responses of mud cake and formation, respectively, laying the foundation for the coupling methods adopted following. Subsequently, we establish the coupling relationship between the mud cake and the formation and formulate the apparent formation resistivity and apparent relative formation permittivity, not only for the low-resistivity formation but also for the high-resistivity formation. Finally, we demonstrate the validity of the coupling relationship using the low-resistivity and high-resistivity formation models, respectively.

2. Measurement principle

2.1. Tool structure and working process

The structure of OBM electrical imaging tools is similar to the framework of the imaging tools for WBM, which is showed in Fig. 1(a). At the bottom of the tool, there are several pads distributing symmetrically around the mandrel. In the center part, an insulating cover, in which there are some other functional parts, for example, the navigator and connection, acts as an insulating medium between the pads and the top part of the tool. When the tool is logging, the pads is pushed to the sidewall by the backup arms driven usually by a hydraulic device.

In this paper, we employ an imaging tool with six pads and the structure of pads is showed in Fig. 1(b). An array of button electrodes arranged in two rows staggered up and down, are mounted in the center part of the pad. The number of button electrodes is twenty five, in which one row is thirteen and the other one is twelve. A bucking ring surrounds the button array and is insulating to the button electrodes. Other than placed conventionally at the top of the tool, two return electrodes are mounted symmetrically at the two ends of the pad similar to the construction adopted by a previous work (Bloemenkamp, 2014), which can reduce the influence of OBM on measurement. When working, every button electrode and the bucking ring emit currents with a certain supply frequency, and the currents penetrate the mud cake, flow in the formation and finally return to the return electrodes at the two ends of the pad. When the tool moves in borehole, the currents of button array are recorded that are used to scale the resistivity distribution of the sidewall.

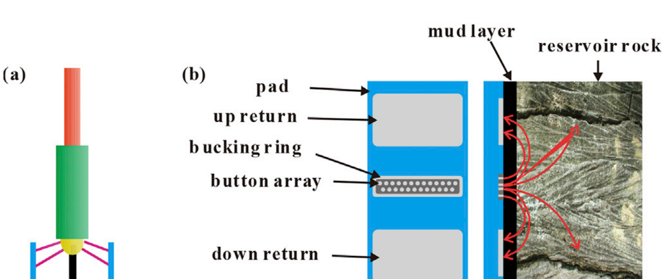

Fig. 1. The structure of OBM electrical imaging tools and current flow. (a) The whole structure. (b) Pad structure and current flow.

2.2. Physical principle

Based on Fig. 1(b), we divide the physical process of the electrical current flow into two parts, and one occurs in the mud cake, the other in formation. Because of the so high resistivity of OBM, the supply frequency of current must be large enough to make the current break through the mud cake and flow into formation. In this case, the physical process in mud cake can be equivalent to the parallel of a resistor and a capacitor, and the same equivalent maybe also adopted in formation (Fig. 2). In Fig. 2, r_m, r_f, c_m, and c_f represent the resistance of mud cake, the resistance of formation, the capacitance of mud cake and the capacitance of formation, respectively. However, the most difficult and important keypoint is that how to formulize the relationship between the two parts. Here, we call the relationship the coupling and express it with a symbol $\boldsymbol{F}$ seen in Fig. 2. The coupling, although unknown, depicts the electrical interaction between the mud cake and formation and we discuss it significantly in detail following.

When a current emitted by a button electrode with the frequency f passes through the mud cake, the total impedance $\overrightarrow{Z_f}$ of the parallel of r_m and C_m can be expressed as

$$\overrightarrow{Z_m} = \frac{1}{r_m^{-1} + j\omega C_m} \tag{1}$$

where ω, j are angular frequency, imaginary unit $\sqrt{-1}$, respectively. The superscript "→" means that the impedance of the mud cake is a complex vector and can be divided into two parts, one real part and the other one imaginary part. ω can be written as

$$\omega = 2\pi f \tag{2}$$

where π is circumference ratio *pi*.

Usually, the cross-sectional area of a button electrode, and the thickness of the mud cake are very small compared with the whole body zone. So we treat the mud cake between the button electrode and formation as a cylinder and the expressions following is satisfied.

$$r_m = R_m \frac{L_m}{S_{button}} \tag{3}$$

$$C_m = \frac{\varepsilon_m \varepsilon_0 S_{button}}{L_m} \tag{4}$$

where R_m, L_m, S_{button}, ε_m, ε_0 are the OBM resistivity, the thickness of the mud cake, the cross-sectional area of a button electrode, relative permittivity of the mud cake and vacuum permittivity, respectively.

Substituting equations (2)–(4) into equation (1), yields

$$\mathrm{Im}\left(\overrightarrow{Z_m}\right) \Big/ \mathrm{Re}\left(\overrightarrow{Z_m}\right) = -\omega R_m \varepsilon_m \varepsilon_0 \tag{5}$$

where "Re", "Im" means the real part and imaginary part of a complex vector, respectively, i.e., $\mathrm{Re}(\overrightarrow{Z_m})$, $\mathrm{Im}(\overrightarrow{Z_m})$ mean the real part of mud cake, the imaginary part of mud cake, respectively. Based on equation (5), it can be known that the larger frequency, the larger absolute value of

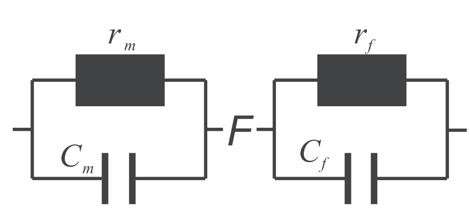

Fig. 2. Equivalent model for OBM electrical imaging principle.