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ScienceDirect

Russian Geology and Geophysics 57 (2016) 1111–1117

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

High-frequency induction logging in deviated and horizontal wells: geosteering and inversion

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Received 4 June 2015; accepted 24 September 2015

Abstract

The study focuses on processing methods for high-frequency induction data from deviated and horizontal wells. Simulation of electromagnetic fields with analytical algorithms is used to study how the resistivity of rocks above and below the well influences the acquired data. The simulations show that the contribution of under- and overlying layers into the recorded responses is considerable and depends on resistivity contrasts between the layers and on the position of logging arrays relative to the layer boundaries. This fact has to be taken into account when estimating true resistivity of reservoirs and when inverting induction logs from horizontal wells for reservoir characterization. The method is applied to oil- and water-saturated reservoirs in West Siberia, which contain high-resistivity impermeable layers leading to overestimation of apparent resistivity. Due regard for the effect of these layers in inversion of induction logs provides high-quality resistivity estimates.

Keywords: induction logging; geosteering; resistivity model; resistivity; phase shift; amplitude ratio

Introduction

Success of oil and gas production from complex reservoirs lies with extended reach of ever more hardly accessible pay zones due to advance in drilling technologies, including deviated and horizontal wells. High-technology works increased in 2014, though the total amount of production drilling decreased relative to the previous year. The number of horizontal wells drilled by *Lukoil* in 2014 was 22.3% more than in 2013, and *Gasprom* increased this number by 4.8 times (From quantity to quality, 2014). Exhaustion of conventional reservoirs urges further progress in horizontal drilling and its broader use.

Drilling horizontal wells and choosing perforation intervals require reliable knowledge of reservoir properties. Such knowledge can come from geophysical data acquired in open holes and while drilling (LWD), including resistivity logging by galvanic (dc) and induction instruments. In the latter case, induction logging, including that with high-resolution high-frequency induction isoparametric logging systems (HFIL, or VEMKZ and VIKIZ according to the Russian abbreviation) provides reliable and informative results. Since 1997 it has become an essential element in characterization of reservoirs in West Siberia.

Like many logging methods, high-frequency induction isoparametric logging was originally designed for vertical holes (Epov and Antonov, 2000). The conventional data processing techniques fail to allow for the factors that affect logs from horizontal and deviated wells but are absent from those of vertical wells. These effects arise because strongly deviated (high-angle) and horizontal wells are parallel to layer boundaries or cross them at small angles, and the resistivity of the involved rocks interferes with the collected responses. Furthermore, the lines of the electric field induced by the transmitter in inclined logging systems cross layer boundaries, which are actually resistivity interfaces. Thereby, the responses become subject to the effect of the resulting electric charges, with their density proportional to the interface-orthogonal electric field component, which in its turn depends on the field angle to the layer boundary. Correspondingly, the responses can have different patterns as a function of inclination even for the same resistivity model (Gorbatenko and Sukhorukova, 2014).

HFIL responses from deviated or horizontal wells are processed using specially designed forward algorithms (Cheryauka, 1996; Epov, 1979; Epov et al., 2007; Glinskikh et al.,

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1068-7971/$ - see front matter
http://dx.doi.org/10.1016/j.rgg.2016.06.010

2013a,b; Labutin and Surodina, 2013; Surodina and Epov, 2012; Tabarovsky, 1975). Testing of these algorithms demonstrated that the processed HFIL data provide highly reliable results in horizontal holes. Proper use of the software is ensured by algorithmic and survey techniques based on analysis of HFIL responses from deviated and horizontal wells (Epov et al., 2014a, 2015; Nikitenko et al., 2014; Gorbatenko and Sukhorukova, 2014).

We discuss forward modeling of synthetic HFIL responses and inversion and of data acquired by 1.4 and 2.0 m long inclined arrays (Epov et al., 2014b) from deviated and horizontal wells. The calculations are performed with reference to resistivity values typical of West Siberia. The wellbore and invasion effects on the measured parameters are neglected because horizontal wells are often drilled with biopolymer-based muds which reduce resistivity in limited zones and affect only the responses of short sondes or arrays (Gorbatenko and Sukhorukova, 2014). The latter fact has been proven by finite-difference and finite-element simulations with regard to the wellbore and invasion effects (Epov et al., 2007; Labutin and Surodina, 2013; Surodina and Epov, 2012). Short-sonde responses are used to divide reservoirs into zones, to investigate the wellbore vicinity, to estimate the depths to interfaces and layer resistivities, and to account for contributions of under- and overlying rocks to the responses (Yeltsov et al., 2014).

Effect of rocks below a horizontal well

Horizontal drilling often strips thin reservoirs. In this case, successful geosteering and characterization of reservoirs from their resistivity require knowledge of distance to host rocks above and below the target reservoir. Therefore, one of logging objectives is to estimate the maximum distance from the sounding point to the reservoir boundaries at which the responses become sensitive to the overlying and underlying rocks (Epov et al., 2015).

Phase shift ($\Delta\varphi$) and amplitude ratio (A_2/A_1) change near layer boundaries (resistivity interfaces), and the distance at which this change becomes detectable is proportional to the array length and depends also on inclination (hole angle to the interface). Long-sonde responses change farther from the interface than those of short sondes, and the change is slower for inclinations about the right angle. We choose 0.5° as a reliably detectable change in phase shift $\Delta(\Delta\varphi)$ at a measurement error of 0.2°–0.3°. HFIL responses from horizontal holes often bear quasi-periodic oscillations caused by local heterogeneities in rocks or variations in hole diameter (rugosity), but these oscillations have short periods controlled by drilling technologies (Gorbatenko et al., 2013). Therefore, approaching layer boundaries are detected from changes in average signal values.

As an example, we consider a two-layer model (Fig. 1, top left panel) with the resistivities ρ_1 and ρ_2 in the upper and lower layers, respectively, and the distance Z from the sounding point to the layer boundary. The phase shift change $\Delta(\Delta\varphi)$ for a long array (DF20, 2 m, 0.875 MHz) parallel to the layer boundary is calculated relative to phase shift $\Delta\varphi$ in a homogeneous formation with the resistivity ρ_1 of the upper layer, where the well is located, assumed to be 5 and 50 Ohm·m, as in typical formations of West Siberia. The resistivity of the lower layer ρ_2 is assumed to be 0.5 to 5000 Ohm·m in different models, to have the ρ_2/ρ_1 ratio from 0.1 to 100. The ρ_2/ρ_1 ratio and the distance Z vary along the x and y axes, respectively (Fig. 1).

If the upper layer is low resistive (5 Ohm·m), the change $\Delta(\Delta\varphi)$ under the effect of the lower layer exceeds 0.5 at a distance 1.0–1.4 m to the interface and at $\rho_2/\rho_1 > 1.1$ ($\rho_2 >$ 5.5 Ohm·m), as well as at Z from 1.8 m to 2.3 m and ρ_2/ρ_1 > 7 or 8. At a lower resistivity ratio of $\rho_2/\rho_1 < 0.45$, the effect of the lower layer, as negative $\Delta(\Delta\varphi)$, becomes notable at a distance within 0.5 m from the interface, while notable positive $\Delta(\Delta\varphi)$ appears at Z from 0.2 m to 0.9–1.1 m. The phase shift change exceeds 0.5° at a distance of 0.0 m to 0.6–0.8 m at a resistivity contrast (ρ_2/ρ_1) of 0.5 to 0.9, but remains within measurement error at greater ρ_2/ρ_1 from 0.9 to 5.5.

At $\rho_2/\rho_1 > 10$, there are two Z ranges approaching the interface, which increase slowly as the resistivity contrast increases. The change $\Delta(\Delta\varphi)$ exceeds 0.5° at approximately equal distances Z to the interface within the resistivity contrasts ρ_2/ρ_1 from 0.1 to 1.0 and from 1.0 to 10.0, but it is smaller and alternates between positive and negative in the range of smaller resistivity ratios.

Note that the phase shift in a two-layer formation can equal that of a one-layer formation in some zones, for instance, at distances from 1.1 m to 1.4 m at $\rho_2/\rho_1 < 1$ and from 1.3 m to 1.7 m at $1.0 < \rho_2/\rho_1 < 100.0$ in the case of $\rho_1 = 5$ Ohm·m. Therefore, the array depth matters more than the magnitude of variations in the measured parameters.

In the case of a more resistive upper layer, $\rho_1 = 50$ Ohm·m (Fig. 1), $\Delta(\Delta\varphi)$ near the layer boundary is much less than in the previous model: within 4°. At $\rho_2/\rho_1 > 3$, the change $\Delta(\Delta\varphi)$ is always negative and exceeds 0.5° at a greater distance Z than in the model above: 1.3 m against 1.2 m at $\rho_2/\rho_1 = 3.0$; 1.7 m against 1.4 m at $\rho_2/\rho_1 = 10.0$; and 1.9 m against 1.5 m at $\rho_2/\rho_1 = 100.0$. At the resistivity ratio ρ_2/ρ_1 < 0.6, the distance to the layer boundary is likewise longer than in the previous model: $Z = 1.5$ m at $\rho_2/\rho_1 = 0.1$ and $Z =$ 1.0 m at $\rho_2/\rho_1 = 0.4$; at a greater ρ_2/ρ_1 from 0.6 to 1.4, $\Delta(\Delta\varphi)$ is less than 0.5.

Reservoirs in many oil and gas fields can include a thin resistive layer between two thick layers (Fig. 1, right panel), which affects interpretation results if its presence and parameters are unknown *a priori*. The effect of a thin (0.2 m) high-resistivity (100 Ohm·m) layer shows up at any distance to its top and at any ρ_2 if the upper layer is low-resistive ($\rho_1 =$ 5 Ohm·m). The phase shift change $\Delta(\Delta\varphi)$ exceeds 0.5° at different distances to the thin layer depending on the resistivity ratio: about 1.5 m at $\rho_2/\rho_1 = 0.1$; 1.3 m at $\rho_2/\rho_1 = 1.0$; 1.4 m at $\rho_2/\rho_1 = 10.0$; and 1.5 m at $\rho_2/\rho_1 = 100.0$. The region of small $\Delta(\Delta\varphi)$ disappears at weak resistivity contrasts. On the other hand, if the contribution of the lower layer to the response were zero, the $\Delta(\Delta\varphi)$ contour lines would be straight and their position would correspond to the model with $\rho_1 =$