

Numerical simulation of dual-laterolog measurements in the presence of dipping, anisotropic, and invaded rock formations

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Abstract

Modern hydrocarbon development techniques make extensive use of highly deviated and horizontal wells to maximize production and reduce drilling costs. However, many of the existing logging tools and associated interpretation procedures were originally designed for operation in vertical wells. Therefore, it becomes imperative that the response of conventional tools be properly understood when logging through highly deviated wells. In like manner, interpretation procedures need to be adapted for their accurate and reliable use in non-vertical wells. This paper undertakes the numerical simulation of dual-laterolog measurements acquired in 3D logging environments to appraise the reliability of measurement and interpretation procedures in non-conventional wells. Specifically, we consider the following borehole measurement environments: (1) dipping beds penetrated by vertical wells, (2) dipping anisotropic formations, and (3) multiple dipping anisotropic and mud-filtrate invaded formations. It is found that dual-laterolog measurements are chiefly sensitive to the horizontal resistivity even in the case of highly deviated wells. An increase of dip angle causes an increase of apparent resistivity due to the influence of vertical resistivity. In all cases, laterolog apparent resistivity readings will fluctuate between the horizontal resistivity and the geometric mean of horizontal and vertical resistivity. Shoulder-bed effects considerable increase with an increase of dip angle.

Introduction

Borehole dual-laterolog tools make use of a galvanic principle to probe the electrical resistivity of rock formations penetrated by a well. This type of resistivity tool is used when the electrical resistivity of the borehole is considerably lower than the resistivity of the probed rock formations. In a typical situation, where the well is vertical, the formation is horizontal and isotropic, and the tool is centered along the axis of borehole, dual laterolog measurements exhibit a relatively deep radial length of investigation. However, without the use of modeling it is difficult to predict how the same resistivity reading will behave if the aforementioned basic operating assumptions are not met.

Recently, reservoir exploration and development practices have increased the use of highly deviated wells to reduce drilling costs and improve production efficiency. This situation has spearheaded the interest of researchers and scholars alike to quantify whether standard borehole tool measurements enable the accurate assessment of electrical resistivity of rock formations penetrated by highly deviated wells in the presence of anisotropy. Moran and Gianzero (1979) investigated cross bedding anisotropic effects on point-source resistivity logging tools while Anderson et al.

(2000) examined cross-bedding anisotropic effects on induction instruments. Wang et al. (1999, 2001) analyzed 3-D cross-bedding anisotropic effects on dual-laterolog instruments. Most of these studies were carried out under the assumption that the electrical resistivity of the target bed was lower than the resistivity of the shoulder beds. In addition, only cases of three-layer formation models were considered in those publications.

In this paper, we consider specific rock formations models where the electrical resistivity of the target bed is both higher and lower than the electrical resistivity of its shoulder beds. We also consider the numerical simulation of dual-laterolog measurements in dipping layer formations. Finally, we consider the effects of variations of the vertical and horizontal resistivity on dual-laterolog measurement as a function of dip angle, anisotropy ratio, and radius of invasion of the probed rock formations.

Background

In a 3D cylindrical coordinate system, the electrical potential due to a laterolog DC source can be simulated with the equation

$$\nabla \cdot (\sigma \nabla u) = -I \delta(\rho - \rho_0, \phi - \phi_0, z - z_0), \quad (1)$$

where σ is the spatial distribution of electrical conductivity in the (ρ, ϕ, z) space, u is the electrical potential, δ is the Dirac delta function, and I is the impressed source current located at (ρ_0, ϕ_0, z_0) . Making use of a finite-element formulation to solve the above partial differential equation, we obtain the linear system of equations

$$AU = b, \quad (2)$$

Where A is the stiffness matrix, U is the electric potential to be solved at the nodes of the finite-element discretization domain, and b is the source term, given by $[0, 0, \dots, I, 0, \dots, 0]^T$. The entries of the latter vector are non-zero only at the source location. We make use of the above formulation to simulate the laterolog responses considered in this paper. Extensive numerical checks were performed to confirm the accuracy of the simulation procedure.

Formation Model

Figure 1 graphically describes the formation model considered in this paper. It consists of a vertical borehole penetrating a series of anisotropic beds dipping at a common arbitrary angle. The deviation angle, α , is the angle between the normal to the bedding plane and the borehole axis, whereas β is the angle between the bedding plane and the borehole axis. Both these angles are related

by $\alpha + \beta = \pi/2$. In Figure 1, r is the radius of borehole, R_m is the resistivity of the mud, R_{xo} is resistivity of the invaded zone, R_i is the radius of invasion radius, and R_v and R_h are the vertical and horizontal resistivity, respectively, of the virgin (uninvaded) zone.

Simulation Results

Dipping and anisotropic formations with high-resistivity shoulders

Figures 2a through 2d show the simulated dual-laterolog measurements across the three-layer formation model described in Figure 1. The thickness of the central bed is 2 m and the dip angles are 30 and 60 degrees. Shoulder-bed resistivities are larger than the resistivity of the center bed. In Figures 2a and 2b, the central layer is assumed electrically isotropic, whereas in Figures 2c and 2d the same layer is assumed electrically anisotropic. The assumed anisotropy ratio is equal to 5. We make the following remarks about the simulation results described in Figure 2:

1. Apparent electrical resistivities change with a change of the dip angle. Presence of electrical anisotropy in the central bed exacerbates this effect.
2. The characteristic “horns” appearing in the shallow laterolog curves are sharper than those of the deep laterolog curves.
3. Compared to shallow laterolog readings, deep laterolog readings are more sensitive to variations of shoulder-bed resistivity.
4. The apparent resistivity in the central bed increases from a value slightly higher than R_h to a value somewhat lower than $\sqrt{R_h R_v}$ as the dip angle increases from 0 to 60 degrees.
5. Shallow laterolog readings are similar to deep laterolog readings except for minor fluctuations near bed boundaries. In addition, shallow laterolog readings vary slightly across the central bed. The difference between the deep and the shallow apparent resistivity logs may be attributed to shorter conduction paths for the shallow laterolog array than for the deep electrode array.

Dipping and anisotropic rock formation with low-resistivity shoulders

Figure 3 shows the simulated dual-laterolog readings across the three-layer formation shown in Figure 1 for the case of low-resistivity shoulder beds. The resistivity of the shoulder beds is 1 Ohm-m. In Figures 3a and 3b, the central layer is assumed electrically isotropic (resistivity equal to 5 Ohm-m). However, in Figures 3c and 3d the central layer is assumed electrically anisotropic with horizontal and

electrical resistivities equal 5 Ohm-m and 50 Ohm-m, respectively. Compared to the case of high-resistivity shoulder beds, we observe that dual-laterolog readings are chiefly influenced by the horizontal resistivity even in the case of high dip angles. Deep laterolog readings are the most affected by variations of shoulder-bed resistivity. We also notice that a measurable difference between the laterolog readings simulated for the case of isotropic and anisotropic electrical resistivity regardless of dip angle. The shallow laterolog readings remain the most sensitive to presence of electrical anisotropy.

Dipping and anisotropic rock formations in the presence of invasion

In cases where (a) dip angle, (b) presence of electrical anisotropy, and (c) invasion are all part of the rock formation model, the response of laterolog tools is not trivial to understand. Generally speaking, invasion will cause the readings to exhibit an apparent resistivity closer to that of the invasion zone. An increase of dip angle will exacerbate shoulder-bed effects making the readings closer to those of the resistivity of the shoulder beds. An increase of dip angle in the presence of electrical anisotropy will exacerbate the influence of the vertical resistivity.

Figure 4 shows dual-laterolog readings simulated across the three-layer model shown in Figure 1. These simulations were performed to assess the simultaneous influence of dip angle, anisotropy ratio, and invasion radius on laterolog readings. The thickness of the central bed is 1.5 m, the radius of invasion is 0.2 m, the resistivity of the invaded zone is 2 Ohm-m, the horizontal resistivity of the virgin zone is 5 Ohm-m, the vertical resistivity of the virgin zone is 50 Ohm-m, and the resistivity of the shoulder beds is 1 Ohm-m. Figures 4c and 4d show the simulated deep laterolog and shallow laterolog readings, respectively. Comparison of the above simulations to those reported in Figure 3 indicates a similar overall behavior of the simulated resistivity curves. However, a measurable variation of the simulated apparent resistivity logs is observed when invasion is included in the rock formation model.

Example of Multiple Beds

Practical logging situations often include multiple dipping beds that exhibit electrical anisotropy and are subject to mud-filtrate invasion. It is not easy to assess, by simple inspection and intuitive arguments, the relative influence of these three factors on dual-laterolog measurements. Numerical modeling is the best alternative to approach such interpretation problems. In this section, we provide an example intended to appraise the relative effects of dip

angle, electrical anisotropy, and presence of invasion on dual-laterolog readings across multiple beds.

Figure 5 shows a five-layer formation model that contains three anisotropic shale beds and two isotropic sand beds. The horizontal and vertical resistivity of the shale beds is 1 and 5 Ohm-m, respectively. In one of the sand beds the radius of invasion is 0.6m while in the remaining sand bed the radius of invasion is 0.3 m. The resistivity of the invaded and virgin zones is 10 and 20 Ohm-m, respectively. Both beds are assumed electrically isotropic.

Figure 6 shows the deep and shallow dual-laterolog readings simulated across the formation model shown in Figure 5. Figure 6a graphically describes the radius of invasion for each bed and Figure 6b describes the resistivity of the invaded and virgin zones for each bed. Figures 6c and 6d show the simulated deep and shallow laterolog readings, respectively, for 30- and 60-degree dip angles.

The following observations stem from inspection of Figures 6c and 6d:

1. Dip angles lower than 30 degrees have no appreciable effect on the simulated laterolog readings. Significant effects due to dip angle are observed when the latter reaches 60 degrees.
2. The effect of dip angle on laterolog readings is more significant for anisotropic thin beds than for anisotropic thick beds.
3. Shoulder bed effects can be appreciable in the presence of electrical anisotropy.
4. Presence of invasion causes the simulated apparent resistivities to approach the resistivity of the invaded zone, R_{xo} . The deeper the invasion, the more pronounced this effect becomes.

Conclusions

The following conclusions stem from the work reported in this paper:

1. Dip angle, shoulder beds, invasion, and anisotropy may cause significant effects on dual laterolog readings. It is difficult to predict these effects from physical intuition; full 3D numerical simulation is necessary to quantitatively assess their relative influence on laterolog readings.
2. For the case of vertical boreholes and horizontal beds, electrical anisotropy has a marginal effect on laterolog readings. However, this effect is unique in the sense that it entails visible "horns" near the bed boundary.

3. When a relative dip angle exists between the borehole and the beds, "horns" disappear and the apparent resistivity curves become relatively smooth.
4. An increase of dip angle causes the vertical resistivity of formations to significantly contribute to dual-laterolog measurements. Moreover, the measured apparent resistivity across anisotropic beds is slightly higher than the theoretical limit of R_h for small dip angles, and lower than the theoretical upper limit of $\sqrt{R_h R_v}$ for large dip angles.
5. Shallow laterolog readings behave similarly to deep laterolog readings. However, shallow laterolog readings may exhibit more visible "horns" than deep laterolog readings. Shallow laterolog readings exhibit less sensitivity to shoulder-bed effects than deep laterolog readings because of their shallower radial length of investigation.

References

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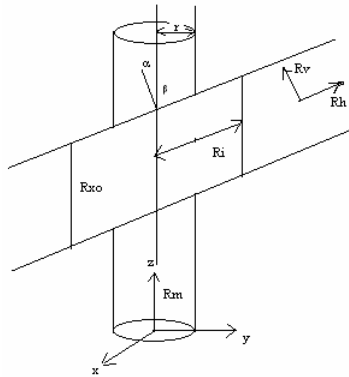


Figure 1. Description of the assumed rock formation model. The x - y - z coordinate system is chosen with the z -axis aligned with the borehole axis.

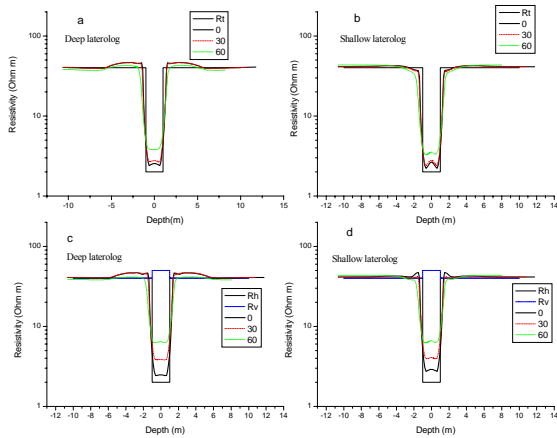


Figure 2. Comparison of dual-laterolog readings simulated for the cases of isotropic and anisotropic formations. Figures 2a and 2b show deep and shallow laterolog readings, respectively, simulated for the case of an isotropic layer, respectively. Figures 2c and 2d show deep and shallow laterolog readings, respectively, simulated for the case of an anisotropic layer (anisotropy ratio equal to 5). The diameter of the borehole is 0.2 m and the resistivity of the mud is 0.1-Ohm m.

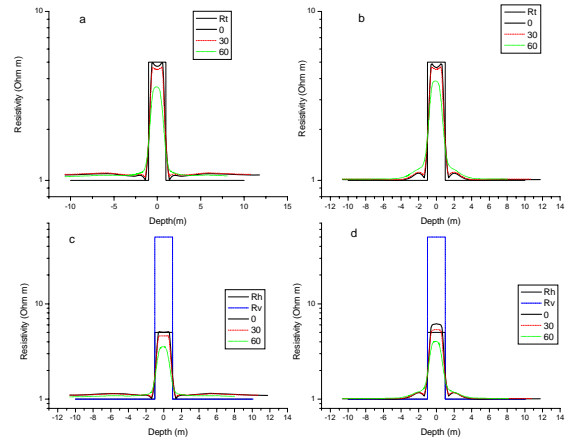


Figure 3. Comparison of dual-laterolog readings simulated for the case of isotropic and anisotropic dipping formations. Figures 3a and 3b show the simulated deep and shallow laterolog readings, respectively, for the case of an isotropic layer. Figure 3c and 3d show the simulated deep and shallow laterolog readings, respectively, simulated for the case of an anisotropic formation. The diameter of the borehole is 0.2m, the borehole resistivity is 0.1 Ohm-m, and the anisotropy ratio is equal to 5.

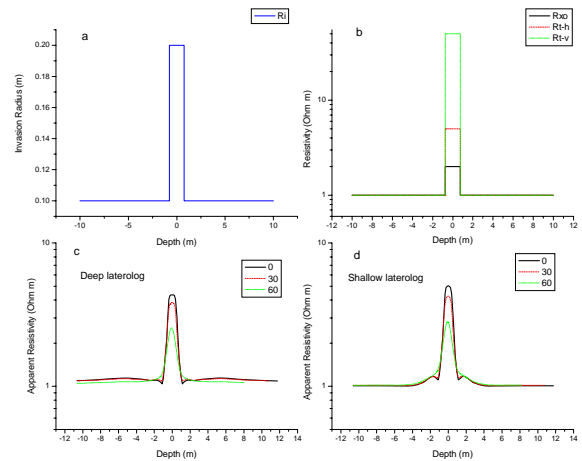


Figure 4. Comparison of dual-laterolog readings simulated for the case of a dipping and invaded electrically isotropic layer. The thickness of the layer 1.5 m, the radius of invasion is 0.2 m, and the resistivity of the invaded zone is 0.2 Ohm-m. The horizontal and vertical resistivity of the central formation is 5 and 50 Ohm-m, respectively.

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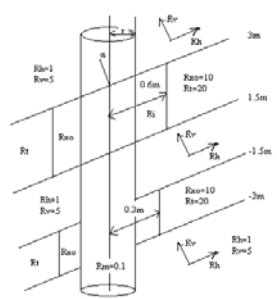


Figure 5. Description of a five-layer formation model that includes three electrically anisotropic shale beds and two isotropic sand beds. The borehole radius is 0.1m, and the borehole resistivity is 0.1-Ohm m.

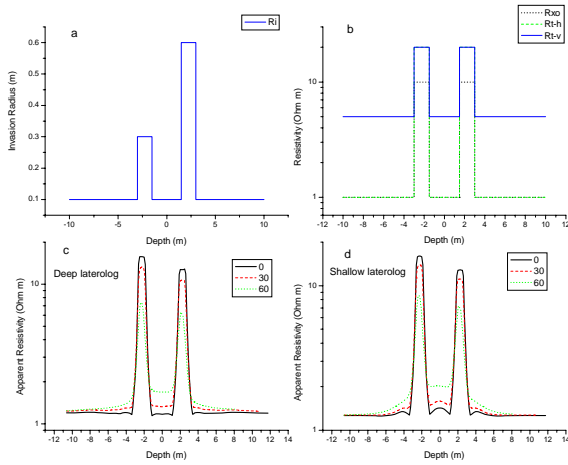


Figure 6. Deep and shallow dual-laterolog measurements simulated for the five-layer formation model shown in Figure 5. Figures 6a shows the invasion radius for each bed and Figure 6b shows the resistivities of the invaded and virgin zones for each bed.