Introduction

We focus on the real-time interpretation of resistivity logging-while-drilling (LWD) measurements for geosteering Bittar and Aki (2015); Sviridov et al. (2014); Seydoux et al. (2014). In presence of high-angle wells, discrepancies between apparent and actual resistivities are often large due to the presence of abnormal readings (such as "horns") associated to complex geometrical features on the formation Dupuis and Denichou (2015). For those cases, numerical inversion methods provide a precise quantitative estimation of the subsurface's resistivity distribution, enabling the identification and assessment of hydrocarbon-bearing formations.

In geosteering, interpretation of resistivity measurements has to be performed in real-time, and the use of general 3D inversion methods becomes prohibitively expensive. Rather, we follow the approach proposed over 20 years ago Meyer (1993) and still used by most oil companies based on a spatial dimensionality reduction of the given problem. Specifically, we decompose the original 3D TI formation in a sequence of stitched 1D models, as described in Ijasan et al. (2013). Then, for each logging position, we identify the corresponding 1D model, which can be rapidly inverted by using the semi-analytical solutions described in, e.g., Kong (1972).

Following the aforementioned approach, in Pardo and Torres-Verdín (2015); Bakr et al. (2016) we developed a fast inversion method of both co-axial and tri-axial LWD resistivity measurements. Among the main features of this approach, we emphasize that it was compatible with any commercial logging device with known antennae configurations, and it was able to deal with a large variety of 3D formations and multiple wells with possibly different logging instruments within each well.

In this work, we have extended the above inversion method to optimize also for the the bed boundary locations in addition to the horizontal and vertical layer resistivities. Synthetic numerical results illustrate the main advantages, limitations, and practical value of the proposed approach.

Minimization Problem

We first define the cost functional

\[ C^{(n)}(\rho) = \left\| H(\rho) - M \right\|^2_{l_2 W_M} + \lambda^{(n)} \left\| \rho - \rho_0^{(n)} \right\|^2_{l_2 W_{\rho_0}}, \]

where

- \( \rho = \sum_i \rho_i \chi_i(x) \) is the Transversely Isotropic (TI) resistivity tensor, \( \chi_i(x) \) are Heaviside functions defined over the domain occupied by the \( i \)-th layer, and \( \rho_i \) are the constant TI tensors corresponding to the resistivity value at the \( i \)-th layer,
- \( H(\rho) \) is the set of simulated measurement for \( \rho \), expressed in terms of the attenuations and phase differences,
- \( M \) is the set of actual (or synthetic) field measurements,
- \( l_2^{W_M} \) and \( l_2^{W_{\rho_0}} \) are weighted \( l^2 \) and \( L^2 \)-norms, respectively, where weights are selected to normalize the expected contribution of each term to the the global norms,
- \( \lambda^{(n)} \) is a regularization parameter that is selected automatically using a Singular Value Decomposition (SVD) and an L-curve algorithm, and
- \( \rho_0^{(n)} \) is an a priori distribution of \( \rho \).

At the \( n \)-th iteration of the inversion process, we minimize \( C^{(n)}(\rho) \) using one step of a Newton-Raphson algorithm. Initial a priori resistivity \( \rho_0^{(0)} \) is selected as the average of the input apparent resistivity logs, while \( \rho_0^{(i)} = \rho_0^{(i-1)} \) for \( i \geq 1 \). At each iteration, we minimize the above functional with respect to either
the resistivity values $\rho_i$ or an arbitrary number of user-prescribed bed boundary positions defining the support of $\chi_i(x)$. We alternate one minimization step in terms of resistivity values with another step in terms of bed boundary positions. Nonlinear constraints of the type $\rho_{\text{min}} \leq \rho \leq \rho_{\text{max}}$ and $z_i \leq z_{i+1} - z_{\text{min}}$ are imposed during the minimization process.

**Numerical Results**

Figure 1 shows validation results of the inversion algorithm. We consider co-axial LWD measurements acquired on a high-angle well that travels from a water-saturated rock into an oil-saturated sand. As shown on the sequence of iterations, the resistivity values of both layers and the boundary location converge to the exact solution. Nonetheless, by comparing panels (a) with (b), we observe that the convergence of the high-resistivity value is non-monotonic, indicating the highly nonlinear behavior of the cost functional with respect to the inversion variables.

![Figure 1](image1.png)

(a) Iter. 1  
(b) Iter. 5  
(c) Iter. 9  
(d) Iter. 21

Figure 1: *Four selected iterations of the inverse method showing the convergence of the resistivity values of two different layers and the bed boundary location. Synthetic measurements were simulated using a co-axial commercial LWD tool operating at 2 MHz placed on an 89° deviated well.*

Figure 2 describes superb inversion results for tri-axial measurements acquired on a TI formation. In particular, the inversion process is capable of automatically detecting the correct bed boundary locations of the original synthetic model. Only small discrepancies on the resistivity values are observed on the thinnest layers.

Figure 3 is based on a more realistic reservoir model. Panels (a)-(b) describe the subsurface model and the well trajectories. Panels (c)-(f) show the inversion results on the vertical wells at two different iteration numbers. We observe significant variations in resistivity and bed boundary locations between the results obtained at iteration 29 —panel (c)— with those corresponding to iteration 44 —panel (d)—. However, these large variations only have a minor impact on the logs, reflecting the ill-posedness of the inversion problem. Panel (g) displays the initial inversion results along the geosteering well, which are extrapolated from the partially inverted vertical wells results. Panel (h) shows the final inverted results on the geosteering well, providing an outstanding description of the actual reservoir configuration along the well trajectories. The entire inversion process took 15 minutes on a laptop equipped with a 3 GHz dual-core processor.

**Conclusions and Future Work**

We described a rapid 1.5D based inversion method for the estimation of resistivity values and bed boundary locations. This method can be employed to invert co-axial and/or tri-axial borehole resistivity measurements acquired with commercial logging instruments on a large variety of 3D formations. Inversion results provide a precise and quantitative estimate of the formation electrical properties that is especially useful to interpret abnormal apparent resistivity logs. Thus, the presented method constitutes a
Figure 2: Four selected iterations of the inverse method illustrating the convergence of horizontal and vertical resistivity values and bed boundary locations on an anisotropic formation. Synthetic measurements were simulated using a tri-axial commercial LWD tool operating at 2 MHz placed on an 82° deviated well.

A semi-automatic algorithm that enables to recover bed boundary locations and resistivity values.

As future work, we shall extend this method to the case of deep and extra-deep azimuthal borehole resistivity measurements. To that end, we shall incorporate 2.5D simulations to model logs in geometrically-complex areas of the formation.

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References


Figure 3: Panels (a)-(b): Description of the reservoir model and well trajectories. Panels (c) and (e): Results after a preliminary inversion of the exploratory and offset well measurements. Panel (g): Initial formation model along the geosteering well trajectory obtained from an extrapolation of the results shown in panels (c) and (e). Panels (d), (f), and (h): Final inversion results.

TITLE: 1.5D BASED INVERSION OF LOGGING-WHILE-DRILLING RESISTIVITY MEASUREMENTS IN 3D FORMATIONS

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SUMMARY: This manuscript describes an extension of a computer method developed for the fast inversion of logging-while-drilling (LWD) resistivity measurements Pardo and Torres-Verdin (2015); Bakr et al. (2016). The method enables to simultaneously invert measurements recorded at different wells using possibly different commercial LWD co-axial and tri-axial logging instruments. The original three-dimensional (3D) transversely isotropic (TI) reservoir is approximated by a sequence of several "stitched" one-dimensional (1D) TI sections. Then, multiple 1.5D semi-analytical solutions are employed for simulation and inversion.

The key novel contribution presented here is the ability to invert also for bed boundary locations in addition to the previously available inversion of horizontal and vertical resistivity values.

Numerical experiments performed over numerous synthetic examples show that in most of the considered realistic 3D synthetic formations, the inversion method enables to properly recover the formation model composed of resistivity values and bed boundary locations from measurements acquired at multiple wells. Thus, it provides a useful method to properly interpret LWD resistivity measurements, especially in the presence of abnormal readings such as horns, which are prone to misinterpretation.

We are currently working on the extension of this method to the case of deep and extra-deep azimuthal resistivity measurements.