Recent advances on the inversion of deep directional borehole resistivity measurements

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SUMMARY

We describe our latest developments on the inversion of subsurface electrical resistivity from deep directional borehole resistivity measurements. Two different methods are introduced for fast inversion of tri-axial induction measurements with multiple transmitter-receiver positions. The first one approximates transversely isotropic (TI) formations with a sequence of "stitched" 1D planarly layered TI sections, which efficiently approximates the solution via 1.5D simulations. The second method uses a pixel-based inversion approach and employs full 3D modelling of borehole EM induction with either an iterative or a direct solver. This enables the inversion of spatial distributions of electrical resistivity of any complexity without restrictions on the symmetry of the models. Numerical examples for several challenging synthetic conditions confirm the accuracy and efficiency of the developed algorithms.

Key words: electromagnetic methods, tri-axial induction, logging while drilling, inversion.

INTRODUCTION

High-angle and horizontal wells are commonly used by the oil and gas industry to improve exposure to hydrocarbon-bearing zones. The interpretation of resistivity measurements acquired in these wells is an essential problem of formation evaluation since electrical resistivity is highly sensitive to both porosity and hydrocarbon saturation. Recent deep directional resistivity (DDR) tools enable the reliable estimation of petrophysical properties of rock formations at depths of investigation of more than 30 m from the wellbore (Dupuis et al., 2014; Seydoux et al., 2014). This significantly extends the spatial coverage of conventional logging-while-drilling (LWD) tools. In parallel, the complexity of DDR measurements limits their direct interpretation and requires new modelling and inversion methods for DDR data acquired in high-angle and horizontal wells. Real-time data interpretation typically uses continuous inversion of local 1D layered resistivity models. Lateral changes in the formations present in the DDR measurements are ignored by the 2D inversion, which only provides a longitudinal cross-section of the 3D reservoir structure. This limits geosteering decisions concerning lateral reservoir heterogeneities, such as faults (Thiel and Omeragic, 2018).

Inversion methods for induction logging tools typically consider either parametric or pixel-based approaches (Liang et al., 2011). The former is usually preferred since the number of parameters to be optimized is significantly smaller compared to the pixel-based inversion. Forward simulations for real-time geosteering inversion usually employ 1D or 2D approximations, which take advantage of the axial symmetry of formation geometry. The main advantage of these methods is their high computational efficiency. Nevertheless, while inverting in practical time frames, these methods are insufficient for reliable interpretation of DDR measurements in the presence of lateral reservoir heterogeneities. In complex geological formations, to interpret DDR measurements, we require full 3D modelling and inversion. The main practical limitation of such inversion is the high computational cost of the 3D modelling, which, in turn, is affected by the large number of transmitter and receiver positions (usually in the range of thousands for a tool moving in a long well). This motivates the development of a set of numerical algorithms where an appropriate inversion method can be selected automatically from the measurements.

PROBLEM FORMULATION

The inverse problem is formulated as a regularized nonlinear minimization problem with the following quadratic cost function

$$\phi(\mathbf{m}) = \frac{1}{2}\left\|\mathbf{D}\left(\mathbf{F}(\mathbf{m}) - \mathbf{d}_{\mathrm{obs}}\right)\right\|_2^2 + \frac{1}{2}\lambda\mathbf{R}(\mathbf{m}). \tag{1}$$

Here, $\mathbf{F(m)}$ is the forward problem mapping, $\mathbf{d}_{\mathrm{obs}}$ is the vector of DDR measurements, $\mathbf{R(m)}$ is the stabilizing functional that ensures well-posedness of the nonlinear inverse problem, and λ is a Lagrange multiplier. The borehole induction forward problem is described by the wave double curl equation for the unknown electric field

$$\nabla\times\nabla\times\mathbf{E} + i\omega\mu_0\sigma\mathbf{E} = -i\omega\mu_0\mathbf{J}_s - \nabla\times\mathbf{M}_s, \tag{2}$$

which is obtained from the time-harmonic Maxwell´s equations in the diffusive regime. The simulation of DDR tri-axial induction is a computationally challenging task due to a large number of transmitter positions at different locations along the well trajectory.

1.5D inversion

In some geological formations, borehole resistivity measurements can be efficiently simulated using a sequence of 1D models (Figure 1). The dimensionality of the problem in this case can be reduced from 3D to 1.5D (Bakr et al., 2017). The method assumes a sequence of 1D models based on planarly layered transversely isotropic formations with parallel bed boundaries, penetrated by arbitrary well trajectories.

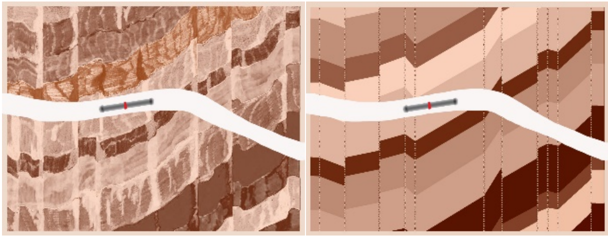

Figure 1. Real geological model (left) and its 1D approximation (right). Each formation column has an independent dip value.

The main advantage of this 1.5D inversion approach is its high computational efficiency. The method is suitable for fast estimation of spatial distributions of resistivity in practical time frames.

3D Inversion

For formations that exhibit a high degree of geological complexity, we apply the full 3D pixel-based inversion, which improves the quality of inversion at the cost of increasing its computational effort. In this case, for minimization of (1), we employ the nonlinear conjugate gradient (NLCG) method preconditioned by the depth rescaling (Puzyrev et al., 2018). Its accuracy is further improved by using the Wolfe conditions to determine an optimal step length to perform the model update. The data gradient is calculated using the adjoint method, which allows us to avoid the explicit calculation and storage of the Jacobian matrix. The method is parallelized using a hybrid MPI/OpenMP scheme. Depending on the number of source positions in the well, we use either a standard (batch) NLCG, where all sources are solved at once using a parallel direct solver, or a mini-batch NLCG that employs iterative solvers and processes a new subset of sources at each iteration. Due to data redundancy, the latter approach often allows for faster simulations.

NUMERICAL RESULTS

The performance of the 1.5D inversion scheme is illustrated with a synthetic example consisting of a reservoir monitoring during production. We are sensitive to large depths of investigation associated with DDR tools, which are beneficial for the dynamic location of the oil-water contact (OWC), estimation of the thickness of an oil column, and detection of early water breakthroughs.

Figure 2 shows the true synthetic model of a reservoir and the results of the 1.5D inversion using different borehole EM measurements. The resistivities of the fluid saturated rocks are chosen according to Archie's equation and vary from 0.4 to 100 Ohm-m. We observe that the best results are obtained when we consider both short LWD and long DDR Geosphere measurements and account for moving bed boundaries. In this case, the OWCs have been successfully detected along the entire well trajectory.

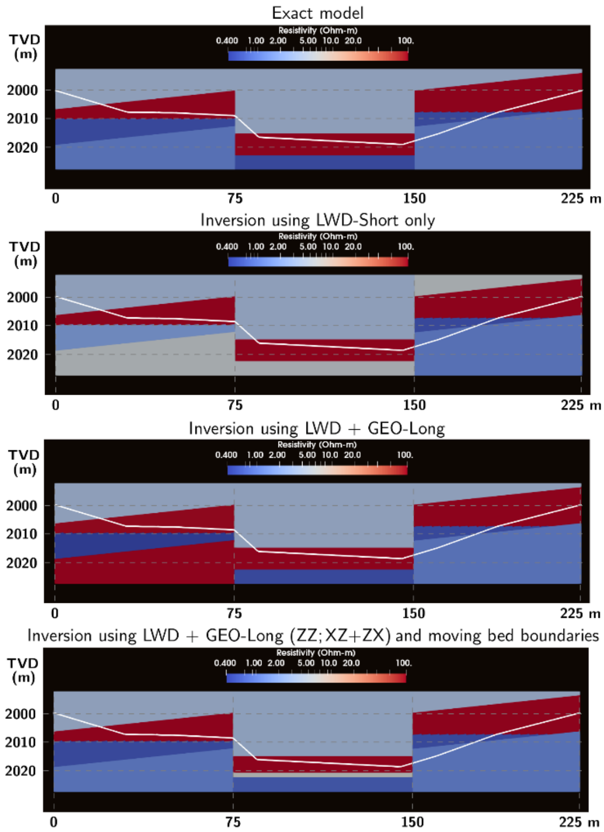

Figure 2. Original reservoir model (top) and inversion results obtained with the 1.5D method and different measurements.

Figure 3 shows the synthetic model used for the hydrocarbon exploration condition, where we aim at detecting and delineating the hydrocarbon-bearing sandstones from low-resistivity formations and shales. The model is based on the Moab fault zone geology (Utah, USA) and contains a pressure seal that splits the reservoir. Due to this complex geological setting, interpretation of DDR measurements acquired in the high-angle well requires 3D inversion.

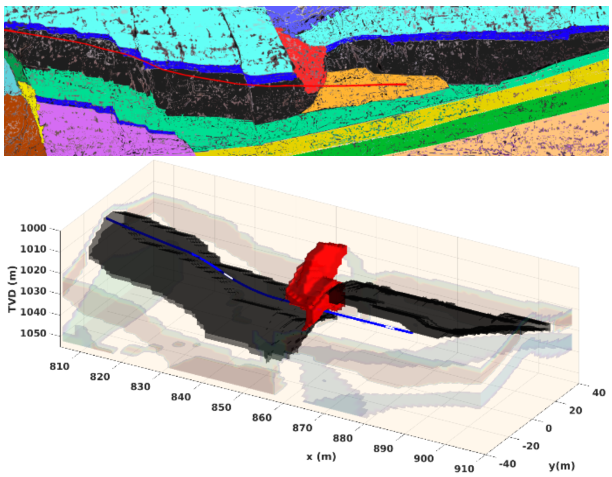

Figure 3. The "Moab fault" exploration condition. The original geological model (top) and its approximation with

3D Cartesian grids (bottom). The pressure seal is shown in red.

In Figure 4, we show 3D inversion results using two receivers located at offsets of 20 and 40 m from the transmitter. In this example, we utilize 3 frequencies, which are logarithmically spaced in the 7-15 kHz range and 70 positions of the tri-axial induction source in the well, which leads to 210 modelling tasks per frequency. The number of resistivity parameters to be determined by inversion is approximately 0.2 million. Both the conductive pressure seal and the resistive reservoir layer are successfully detected.

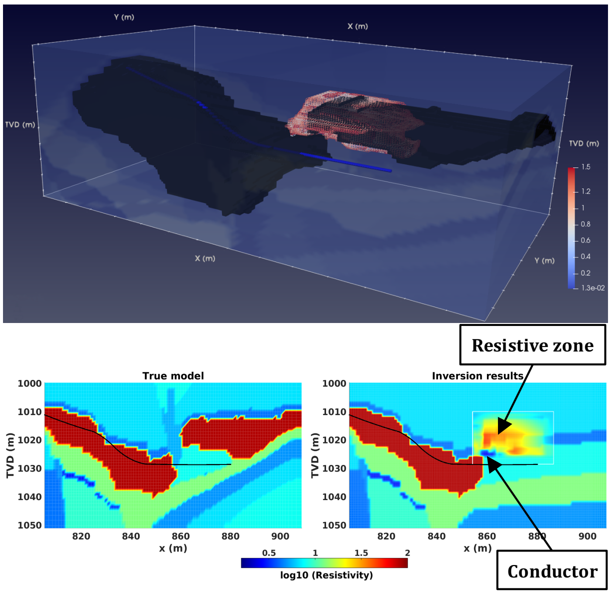

Figure 4. Top: Inversion results for the reservoir (red) versus the true model (black). Bottom: cross section of the true model (left) and inversion results (right). The starting model for inversion does not include information about the horizontal coordinate beyond 858 m (identified with a white line).

CONCLUSIONS

We developed new computational tools for efficient and reliable inversion of spatial distributions of electrical resistivity from DDR measurements. Depending on the complexity of the surrounding formations, we can select between: (a) fast 1.5D methods, useful for rapid estimation of the resistivity distribution around the well to assist in real-time operations planning and (b) a more computationally demanding 3D inversion.

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