Interpretation of deep directional resistivity measurements in high-angle and horizontal wells

V. Puzyrev[1], C. Torres-Verdin[2], and V. Calo[1,3]
[1]Curtin University, Western Australian School of Mines, Department of Applied Geology
[2]The University of Texas at Austin, Department of Petroleum and Geosystems Engineering
[3]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Mineral Resources

Summary

Interpretation of resistivity measurements acquired in high-angle and horizontal wells is a common problem in formation evaluation since these wells are widely used by the oil and gas industry to maximize contact with the producing formation. We present an efficient parallel three-dimensional inversion of the electrical resistivity from deep directional borehole electromagnetic induction measurements. The method utilizes full three-dimensional simulations which place no restrictions on the symmetry of the subsurface models and spatial distribution of electrical resistivity, and supports arbitrary well trajectories. To achieve fast forward modeling of triaxial induction problems with multiple transmitter-receiver positions we employ a parallel direct solver. The inversion algorithm uses a gradient-based approach whose accuracy is improved by using a preconditioner and the Wolfe conditions to achieve an optimal step length. Numerical examples for several challenging synthetic scenarios confirm the feasibility of full 3D inversion-based interpretations in practical time frames. Thus, we plan to integrate resistivity measurements with seismic amplitude data to improve petrophysical and fluid interpretations.

Keywords: Inversion, parallel, deep directional resistivity, borehole induction, reservoir monitoring.

Introduction

The oil and gas industry continuously adopts new technologies to improve the efficiency of well placement. High-angle (HA) and horizontal (HZ) wells of the increased lateral length have become common with the recent advancements in drilling technology. Given the limitations of the current electromagnetic (EM) technologies such as logging-while-drilling, new monitoring and exploration methods have been introduced recently. A new generation of deep directional resistivity (DDR) tools provides accurate estimations of various petrophysical properties of producing rock formations and has an improved depth of investigation of more than 30 m from the wellbore (Seydoux et al., 2014; Dupuis and Denichou, 2015). This technology several times exceeds the coverage of conventional tools and offers an unprecedented opportunity to map the near-wellbore formations.

Conventional modeling methods developed for vertical wells are not suitable for interpretation of DDR measurements in HA/HZ wells. A full three-dimensional (3D) inversion is required to process DDR data in complex geologic media. However, one of the main practical limitations of this approach is its high computational cost. Since the tool is moving in the well, a large number of transmitter and receiver positions (in the range of thousands for a long HA/HZ well) must be considered. Multiple 3D modeling methods of multicomponent borehole EM induction logging measurements have been developed during the past decades (Newman and Alumbaugh, 2002; Hou et al., 2006 among others). However, the size of these problems has been often considered excessively large to be solved in real time in practical applications, preventing the widespread use of full 3D inversion in borehole data interpretation. Many of the published borehole induction modeling methods took advantage of the axial symmetry of formation geometry. In the context of DDR measurements, Thiel et al. (2016) presented a fast 2D inversion that employed point-wise 1D forward simulations for interpretation in real time.

With the development of high-performance computing methods and the increase in availability of computer resources, fast 3D inversion of geophysical dataset no longer poses a serious challenge. For a local dataset it can be performed on a workstation or small cluster in an acceptable time frame. In particular, recent advances in parallel direct solvers have allowed us to incorporate them in the inversion scheme for accurate and efficient simulations of multiposition and multicomponent DDR measurements in complex reservoir formations.

Methodology

We solve a regularized nonlinear minimization problem with the following quadratic error functional

$$\phi(\mathbf{m}) = \|\mathbf{F}(\mathbf{m}) - \mathbf{d_{obs}}\|_2^2 + \lambda \mathbf{R}(\mathbf{m}), \qquad (1)$$

where $\mathbf{F}(\mathbf{m})$ is the forward problem mapping, $\mathbf{d_{obs}}$ is the observed data vector, $\mathbf{R}(\mathbf{m})$ is the stabilizing functional that ensures well-posedness of the nonlinear inverse problem, and λ is the Lagrange multiplier. We employ the preconditioned nonlinear conjugate gradient method to minimize the misfit between the simulated and observed data. The data gradient is efficiently calculated using the adjoint method to avoid the explicit calculation and storage of the Jacobian. The expensive matrix factorization is performed only once for each frequency at the beginning of each iteration and then it is applied in forward and adjoint solves throughout this iteration.
Preconditioning for inversion is used to optimize its convergence and improve detection of deeper targets by preventing their shielding by shallower ones (Puzyrev and Torres-Verdin, 2016). As a criterion for optimal step length, we employ the Wolfe conditions. To improve the computational efficiency, we use a hybrid MPI/OpenMP parallelization scheme, which is well-suited for modern multicore architectures.

Numerical example

We have applied the inversion scheme to two main application scenarios: reservoir monitoring and exploration. Figure 1 shows a 3D synthetic reservoir model with two zones where an early water breakthrough is expected. The main goal of the monitoring is to detect these zones and thus diminish the chance of water breakthrough. Resistivities of fluid saturated rocks are chosen according to Archie's equation and vary from 1.2 to 90 Ohm-m in this example.
180 positions of the triaxial induction source have been considered in this example, resulting into 540 modeling tasks. While this number would pose a serious challenge for iterative schemes, the main limitation of using a direct solver in 3D problems in not the number of sources, but rather the size of the resulting linear system. The model shown in Figure 1 was discretized into 220 x 120 x 80 cells resulting into approximately 6 millions of unknowns in the forward problem. The number of model parameters to be determined by inversion is approximately 1.1 million. For a system of this size, the computational effort for forward and backward substitutions for each of the 540 right-hand-sides is much smaller than the cost of the matrix factorization. The inversion was finished in about 30 hours of CPU time using one computational node equipped with 16 Intel Xeon cores per frequency.

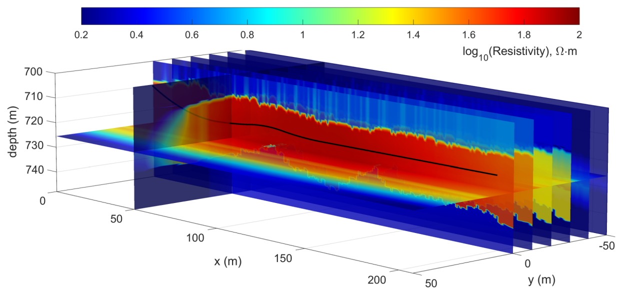

Figure 1: Illustration of the reservoir monitoring scenario.

The oil-water-contact and both water breakthrough zones have been successfully detected during the inversion. In the presentation, we will show inversion results for various source-receiver offsets and their density, and discuss the optimal inversion parameters for both scenarios under consideration.

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