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Joint inversion of induction and galvanic logging data in axisymmetric geological models

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Abstract

We have developed a computational algorithm for joint inversion of array induction and galvanic data in 2D models. It is based on a finite-difference solver and nonlinear minimization and is designed to develop realistic geoelectric models of complex fluid-saturated formations. The algorithm is tested and verified on noisy synthetic induction and galvanic data. The obtained 2D inversion results are compared with those corresponding to the traditional 1D radial approach. The developed algorithm was used to conduct joint 2D inversion of VEMKZ and BKZ logs from the Fedorovskoe and Vostochno-Surgutskoe oil fields in the E–W striking Ob' River area.

Keywords: joint inversion; electrical logging; VEMKZ; BKZ; axisymmetric model; electrical resistivity

Introduction

In recent years, the global development and operation of new types of hydrocarbon reservoirs with complex geological structure has led to a significant complication and extension of the range of well logging problems. This, in turn, necessitates the improvement of hardware systems and methodical support for processing and interpretation of well logging data. Among the new import-substituting technologies for logging oil and gas wells is the SKL hardware system, which, along with the main commonly used geophysical methods, incorporates induction and galvanic logging methods (Epov et al., 2010). Using this system saves tripping time, and simultaneous measurements eliminate the need to match log depths. Electrical logging methods have found application at all stages of construction of oil and gas wells—from geosteering to reaming (Epov et al., 2015; Kayurov et al., 2014).

The development of new hardware systems for exploration of oil and gas deposits leads to the necessity to design software and algorithmic means aimed at increasing the reliability of quantitative determination of parameters of heterogeneous reservoirs. Improving the accuracy of evaluating the reservoir saturation from electrical logging is particularly important in this case. One way to do this is to employ realistic interpretation models. These models should include a description of the complex spatial distribution of the electrophysical parameters of the geological model and take into account various physical effects. However, their employment is only possible with the use of numerical simulation and inversion when solving multidimensional problems of computational electrodynamics.

Traditionally, the reservoir saturation pattern is determined from induction and galvanic logging data based on analysis of the radial electrical resistivity profile determined within the scope of a 1D cylindrically layered model (Epov and Nikitenko, 1993). The radial resistivity distribution pattern is due to the displacement of formation fluids by mud filtrate and the change in salinity in the near-wellbore zone during formation drilling. However, when interpreting in formations of limited thickness, characterized by an inhomogeneous invaded zone and depth-variable oil content, it is necessary consider the effect of overlaying and underlying rocks. In addition, the presence of conductive shale and high-resistivity (compacted sand and carbonate) thin layers commonly found in reservoirs leads to significant inaccuracies in determining the resistivity

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and subsequent unreliable estimates of fluid saturation. To avoid this, it is necessary to use an axisymmetric interpretation model which takes into account both the radial and vertical resistivity distributions (Epov et al., 2013; Mikhaylov and Glinskikh, 2015; Nikitenko et al., 2015).

Integration of well logging methods is widely used to improve their efficiency in exploration of complex oil and gas reservoirs (Kneller and Potapov, 1992; Mezzatesta et al., 1994; Rabinovich and Tabarovsky, 2001; Shanjun et al., 2007; Yang, 2001). Due to the different sensitivity and resolution of induction and galvanic logging measurements, the integration of these methods improves the reliability of resistivity determinations. Joint inversion of electrical logging data provides an integrated geoelectric model. The construction of a consistent interpretation model narrows the region of ambiguity (or equivalence) in determining the model parameters, which is due to the different physical principles of field excitation and signal measurement and the different influence of the parts of a medium on the recorded signals. It is known that conductive regions have a greater influence on induction signals, whereas resistive ones on galvanic signals.

The use of an integrated interpretation model to examine different physical processes provides more accurate evaluation of the properties of reservoirs. For example, an integrated geoelectric and hydrodynamic model of the near-wellbore zone has been widely applied for an integrated petrophysical interpretation of electrical logging data. Subsequently, the need for further consideration of geomechanical properties has led to the development of a multidisciplinary approach based on an integrated electro-hydrodynamic and geomechanical model (Yeltsov et al., 2014). In addition, joint inversion of induction and galvanic logging data makes it possible to study the various effects involved in the propagation and interaction of electromagnetic fields with the medium. That is, it becomes possible to study in detail the frequency dispersion of the resistivity and electrical macroanisotropy of rocks, which have recently attracted considerable interest, in particular, for deviated and horizontal wells (Epov et al., 2010; Nikitenko et al., 2016). Their consideration in well logging data interpretation necessitates the use of specialized software.

There are various approaches to the solution of computational problems of electrical logging using axisymmetric geological models. Forward problems have been solved by numerical-analytical and approximate methods (Epov and Nikitenko, 1993; Glinskikh et al., 2013a,b, 2014; Tabarovsky and Rabinovich, 1998). These methods have found widespread use as they allow developing fast algorithms for data processing and inversion. Due to the complication of electrical logging models and the rapid development of computational methods for electrodynamic problems, grid methods are preferred. Of these, finite-difference and finite-element methods are most widely used to simulate electromagnetic fields in inhomogeneous media (Epov et al., 2007; Surodina and Epov, 2012). However, solutions of multidimensional problems in full statement for processing and interpreting large volumes of field data are very resource intensive and have therefore found only limited use. Significant advances in this area have been made possible through the development of computer information technologies and multiprocessor computation systems. It has become feasible to use computationally intensive operations for practical purposes of data processing and interpretation, which will significantly improve the accuracy of determination of geoelectric parameters and the reliability of the results of interpretation based on the data of a suite of well logging tools.

This paper presents an algorithm for joint numerical inversion of high-frequency electromagnetic logging (VEMKZ) and lateral logging (BKZ) data on axisymmetric geological models and the results of its application on synthetic and field data. It should be noted that the developed algorithm can be easily adapted to the numerical inversion of data of electrical logging tools with induction, galvanic or mixed induction-galvanic types of signal generation and measurement.

Computational inversion algorithm

The basic interpretation model is a 2D axisymmetric geoelectric model which describes the penetration of a horizontally layered section by a vertical well with the formation of invaded near-wellbore zones (Fig. 1). The axisymmetric model includes a sequence of layers with plane parallel horizontal boundaries penetrated by a vertical cylindrical well. In the near-wellbore zone of each of the layers, there may be two zones—an invaded zone and a low-resistivity annulus—and in some cases, an additional flushed zone. They are separated from each other, from the borehole, and the formation by coaxial-cylindrical boundaries. Each of the regions of the geoelectric model is characterized by its own resistivity.

The developed joint inversion algorithm is based on grid finite difference algorithms for numerical simulation of induction and galvanic data for media with axial symmetry (Surodina and Epov, 2012). Numerical solutions of forward problems after finite difference discretization are reduced to systems of linear algebraic equations (SLAE) with large sparse matrices, which are solved using well-known direct and iterative methods.

The main features of the numerical simulation algorithms are as follows. Numerical 2D simulation of galvanic logging data reduces to the solution of the Poisson equation. Using a conservative difference scheme reduces the problem to a SLAE, which is symmetrized and then solved by the conjugate gradient method. Due to the ill-conditioning of the SLAE, it is preconditioned using Hotelling's algorithm (Labutin and Surodina, 2013). The solution of the forward 2D problem of induction logging reduces to the solution of the Helmholtz equation. The obtained SLAE is solved using the COCR iterative method (Sogabe and Zhang, 2007), also with preconditioning. The developed algorithms for solving forward problems have been carefully verified, tested, and validated on a large number of realistic geoelectric models.