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ScienceDirect

Russian Geology and Geophysics 58 (2017) 266–274

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

Physical and mathematical modeling of transient electromagnetic soundings over salt-dome structures

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Received 4 September 2015; received in revised form 25 February 2016; accepted 16 March 2016

Abstract

This paper presents the results of physical and mathematical modeling performed to evaluate the potential of transient electromagnetic sounding in areas of salt-dome tectonics. Two geoelectric arrays are considered: an array with an inductive source (a horizontal loop) and an array with a mixed-type source (a horizontal current line). It is shown that the transient electromagnetic method provides important information on the relief of the top of salt deposits.

Keywords: physical modeling; mathematical modeling; electromagnetic soundings; transient electromagnetic method; salt-dome structures

Introduction

Electromagnetic soundings with a controlled source are an important tool for shallow geophysical prospecting as well as for exploration of the upper crust. Electrical prospecting attempts to solve complex two-dimensional and three-dimensional problems. To validate various electromagnetic sounding techniques, researchers use a tool such as modeling. Modeling soundings over geological structures with known physical and geometrical parameters makes it possible to determine the advantages and disadvantages of various systems for transmitting and receiving electromagnetic fields. To answer the question about the potential capabilities of a particular geoelectric array, it is often sufficient to use the model structures of regular geometric shapes.

Physical modeling has long been the only tool for reproducing real electromagnetic soundings with controlled parameters of a three-dimensional medium. The start of work on physical modeling of electromagnetic soundings can be dated to the end of the 1950s. The development of the physical modeling technique occurred simultaneously with the development of electrical prospecting methods. Gradually two main directions of research took shape—tank modeling, in which models of geological structures are placed in a tank filled with an electrolyte solution simulating a conductive background medium, and modeling using metal models. A large amount of physical modeling of electromagnetic soundings using dipole sources in both the frequency and time domains has been performed by Kuznetsov in the Naro-Fominsk Branch of VNIIGeofizika in the 1970–1990s (Kuznetsov, 2002). The results of major foreign physical modeling studies are summarized in a review (Frischknecht, 1987). These studies have revealed important features in the operation of various electrical prospecting systems.

The development of software and algorithmic tools and computing capabilities in the last decades has brought mathematical modeling to the forefront (Nechaev et al., 2009; Newman et al., 1986; Shtabel' et al., 2014; Shurina and Epov, 2006; Trigubovich et al., 2009; Wannamaker et al., 1984; Ward and Hohmann, 1987). Nevertheless, analog (physical) modeling continues to be used to verify numerical calculations of electromagnetic field distribution in media with contrasting electrical properties (Ansari and Farquharson, 2014; Best et al., 1985; Farquharson et al., 2006) and to test new electrical prospecting methods (Kolesnikov and Skorokhodov, 2014; Macnae and Adams, 2011; Pellerin and Labson, 1994). It can be said that the implementation of a new method is rarely without previous physical modeling, despite the current potential of numerical calculation tools. For example, in the 2000s,

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1068-7971/$ - see front matter
http://dx.doi.org/10.1016/j.rgg.2016.03.017

the technology of direct hydrocarbon exploration using remote electromagnetic sounding with bottom stations (seabed logging) implemented by the EMGS Norwegian company established on the market of marine electrical exploration. In addition by being provided with a comprehensive theoretical foundation, supported by mathematical calculations, the technology was tested in a model experiment at the Research Center of Statoil in Trondheim, where a 9 × 6 × 8 m tank was built for this purpose (Løseth et al., 2008).

This paper presents the results of physical and mathematical modeling performed to evaluate the potential of transient electromagnetic sounding in areas of salt-dome tectonics. Physical modeling was conducted at the St. Petersburg State University and mathematical modeling at the Trofimuk Institute of Petroleum Geology and Geophysics (IPGG), SB RAS, in Novosibirsk.

Formulation of the problem

Seismic prospecting is the main geophysical method used in hydrocarbon exploration. Electrical prospecting is an auxiliary method, but, in some geological settings, it makes a substantial contribution to subsurface studies. Thus, in areas of salt-dome tectonics, it is difficult using seismic methods to map the first reflector (top of salt deposits) for depth imaging of subsalt boundaries. This difficulty is due to the fact compositionally inhomogeneous salt structures and interdome troughs are composed of rocks with similar velocity characteristics. Therefore, they are hardly distinguishable in time seismic sections and hence are not considered in imaging subsurface sections of subsalt deposits. In an electromagnetic field, these structures are manifested quite differently. The significant difference in electrical resistivity (ρ) between the rocks composing salt domes (ρ = 200–20,000 Ohm·m) and suprasalt sequences in through zones (ρ = 2–10 Ohm·m) is responsible for their good differentiation in integrated geoelectric parameters. Therefore, electrical prospecting has long been successfully used for subsurface imaging in areas of salt structures, in particular, in the Caspian region. The transient electromagnetic sounding method using different arrays is employed most often for this purpose. Recently, oil companies involved in oil exploration in subsalt deposits have expressed growing interest in evaluating the potential of electrical prospecting for mapping the top of salt structures. Within the framework of the procedure development for field electrical exploration under these geological conditions, it was required to examine the sensitivity of various electromagnetic systems to variations in the relief of the top of salt structures. The problem was solved in an integrated using mathematical and physical modeling.

The base model was chosen to be a homogeneous sedimentary layer 4 km thick with an electrical resistivity of 2 Ohm·m, which lies on a relatively poorly conducting basement with an electrical resistivity of 100 Ohm·m (these parameters are typical of the subsurface of the Caspian depression). The effect of salt structures of different geometrical shapes and sizes (Fig. 1) present in the sedimentary section on the transient signal was modeled. The electrical resistance of salt was assumed to be 200 Ohm·m. In the mathematical modeling, the model also included subsalt deposits (ρ = 50 Ohm·m), but their presence has little effect on the results.

Studies of the subsurface to a depth of several kilometers require strong field sources with a considerable momentum, whose geometric dimensions are also several kilometers. Deployment of such systems in field conditions is very laborious, so that it is common to use sounding techniques that can be referred to as "fixed-source techniques"—measurements with the field source at the same position are made at many points to provide the desired coverage of the study area; then the source is moved to a different location and the process is repeated. In this paper, we consider two geoelectric arrays which have found wide application in field practice: the Qq-n array with an inductive source (horizontal loop) (Ugarova et al., 1977) and the ABMN-n array with a mixed-type (conductive-inductive) source (current horizontal line). The arrays are shown schematically in Fig. 2. Measurements using the Qq-n array are made along the long axis of the transmitter loop, and the rate of change in the vertical component of the magnetic induction dB_z/dt is measured using inductive sensors. The dimensions of the modeled loop are 4000 × 1000 m, the length of the profile inside the loop is 3000 m, and the measuring step is 100 m. After completion of the measurement cycle in the transmitter loop, it is moved parallel to its long axis so as to provide at least 10% overlap. Thus, the sounding and profiling modes are combined. Primary results of the measurements can be represented as time sections—sets of transient signal curves plotted along the profile for fixed time delays.

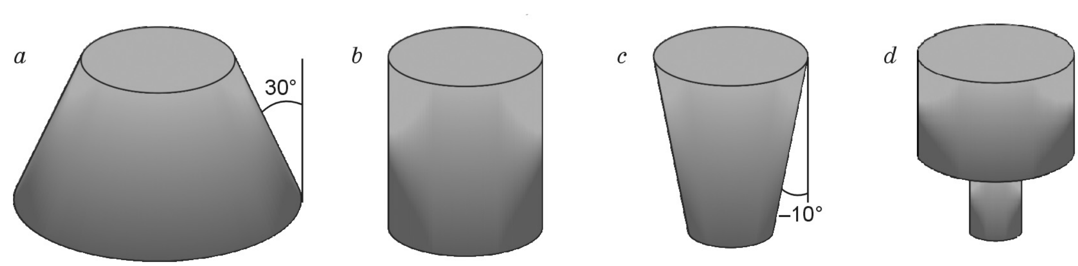

Fig. 1. Four types of modeled salt structures: *a*, truncated cone (inclination angle of the side wall of 30°); *b*, cylinder; *c*, inverted cone (inclination angle of the side wall of –10°); *d*, overhang.