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

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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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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 $9 \times 6 \times 8$ 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.

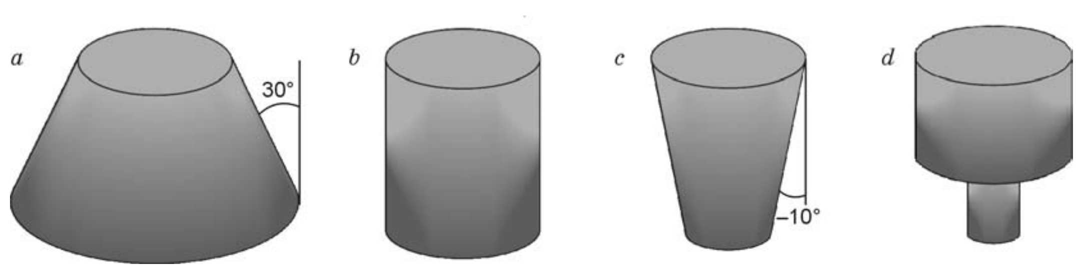

Fig. 1. Four types of modeled salt structures: *a*, truncated cone (inclination angle of the side wall of 30º); *b*, cylinder; *c*, inverted cone (inclination angle of the side wall of –10º); *d*, overhang.

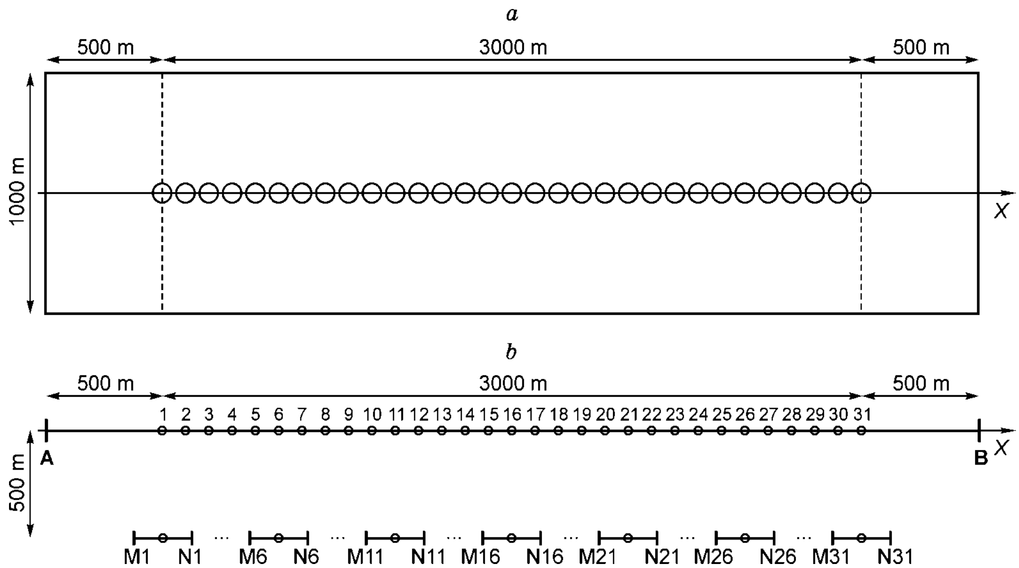

Fig. 2. Modeled geoelectric arrays: *a*, Qq-n; *b*, ABMN-n.

The ABMN-n array is the galvanic counterpart of the Qq-n array. The horizontal component of the electric field E_x is measured with a pair of MN electrodes moving along the AB transmitter line. The modeled line was 4000 m long, the working area 3000 m long, the receiver dipole 250 m long, the distance from the receiver dipole to the transmitter line (separation) was 500 m, and the measuring step was 100 m.

Mathematical modeling methods

Mathematical modeling of transient responses was performed using the Modem3D program (developed by M.I. Ivanov and I.A. Kremer, IPGG SB RAS (Ivanov et al., 2007, 2009)). The program is designed to calculate pulsed electromagnetic fields in complex three-dimensional conductive media, and is implemented as an integrated environment with a complete set of graphical functions for data entry, computation, and analysis of the calculation results. The problem of modeling of a transient electromagnetic field is solved using the vector finite element method on an unstructured three-dimensional tetrahedral space mesh. Integration over time was carried out with the second-order implicit Crank–Nicolson scheme.

To improve the performance of the Modem3D program, the algorithms were parallelized, allowing efficient use of modern multicore processors. Parallelization was applied to vector-matrix arithmetic operations. In addition, for mass estimations, the program was adapted to run in the distributed computing system (GRID-system) and cloud environments implemented at the IPGG SB RAS (Mart'yanov et al., 2011). Testing for simple geometric objects and horizontally layered media has shown that the calculations are highly accurate for a large class of models (Shein, 2013).

The Modem3D program includes a graphical editor to construct three-dimensional models of computational domains, specify the electromagnetic properties of materials, and describe field sources. Generation of finite element meshes is performed automatically and can be edited manually on the basis of the results of mesh quality control. After constructing the spatial mesh of the medium, its constituent elements (subdomains) are assigned electrical resistivity values. The shape of the domain can be varied by partitioning the edge of the tetrahedron and shifting the vertices of the tetrahedra (changing their spatial coordinates). Complex objects for modeling can be constructed using a fine mesh. Also, after the model is created, boundary conditions are imposed on the outer surface of the computational domain. Figure 3 shows spatial mesh patterns of three-dimensional objects—a cylinder and a truncated cone with an inclination angle of the side wall of 30º.

The calculations are necessarily preceded by testing, for example, by comparison with programs based on different calculation algorithms. In this work, two types of tests of the Modem3D program were carried out using modeling of one-dimensional and three-dimensional geoelectric media. The calculations were compared with the UnvQQ and TEM_Line programs (developed by E.Yu. Antonov and M.I. Epov, IPGG SB RAS), (Antonov and Shein, 2008; Kozhevnikov and Antonov, 2006), which can be used to model pulse transient responses in horizontally layered conductive media and check the dimensions of the computational domain for defining boundary conditions. In addition, comparative calculations were made using other well-known programs for modeling electromagnetic fields in three-dimensional media: EFMAC (developed by N.V. Shtabel', IPGG SB RAS) and GeoPrep (developed by M.G. Persova and Yu.G. Soloveichik, NSTU, Novosibirsk). Test calculations were made for a truncated cone shaped object. Comparison with the EFMAC program was performed at the IPGG SB RAS, and comparison with the GeoPrep program by the Siberian Geophysical Research Development Company (P.Yu. Legeido). Comparison of the calculation results in both cases showed that the relative deviation of transient EMFs did not exceed 1%.

Figure 4 shows the results of comparing the signals calculated using the UnvQQ program (Fig. 4*a*) and the TEM_Line program (Fig. 4*b*) for a horizontally layered medium with calculations using the Modem3D program. As can be seen from the figure, the transient responses are in good agreement for most of the time interval (the relative deviation of the calculated EMF is less than 1%) except at the latest times greater than 4 s. This difference arises from the general reduction in the calculation accuracy at late transient times, typical of these programs.

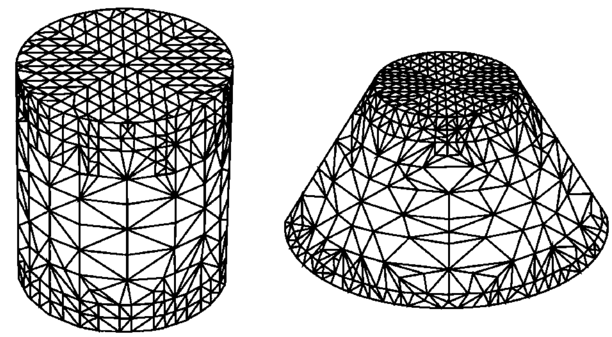

Fig. 3. Examples of the construction of unstructured tetrahedral meshes for modeling responses from three-dimensional objects: a cylinder and a truncated cone with an inclination angle of the side wall of 30°.

Physical modeling method

In physical modeling of electromagnetic soundings, we should adhere to the criterion of electromagnetic similarity, according to which the relations between the geometrical parameters of the array, medium, and electromagnetic field (the wavelength in the frequency domain and transient response parameter in the time-domain) must remain invariant in the transformation from nature to model (Berdichevskii et al., 1987; Frischknecht, 1987). For transient electromagnetic soundings (TEM soundings), the electromagnetic similarity criterion takes the form

$$t\rho/L^2 = \text{const}, \tag{1}$$

where t is the time after the current is switched off (transient period, delay), ρ is the electrical resistivity of the medium, and L is the characteristic size. If this requirement is satisfied, the model and field transient response curves have the same shape, i.e., they can be superimposed by changing the time and amplitude scales. Thus, a reduction in the geometry in the laboratory can be compensated in two ways: by decreasing the transient period and by decreasing the electrical resistivity of the medium. The decrease in the dimensions in modeling is determined by the geometric similarity ratio $k = L_m/L_n$, where L_m is the characteristic size of the model and L_n is the characteristic dimension in nature.

Physical modeling of transient electromagnetic soundings was performed using Tsikl commercial equipment (made by the Tsikl-Geo company, Novosibirsk). Electrical line soundings were modeled in a 4 × 4.5 m electrolytic tank filled with a 20% solution of NaCl, representing the sedimentary layer. From the results of direct-current conductivity measurements, the electrical resistivity of the salt solution was ρ = 0.050 ± 0.002) Ohm·m.

Note that the use of ABMN-n technology under field conditions is motivated primarily by the attempt to minimize the displacements of the cumbersome transmitter line. In model measurements, this is not a problem, while the constancy of the array configuration, including the depth of immersion of the electrodes and the wire arrangement improves the quality of the data obtained. In this regard, it was decided not to reproduce ABMN-n measurements in the physical modeling, but use an ABMN stationary equatorial

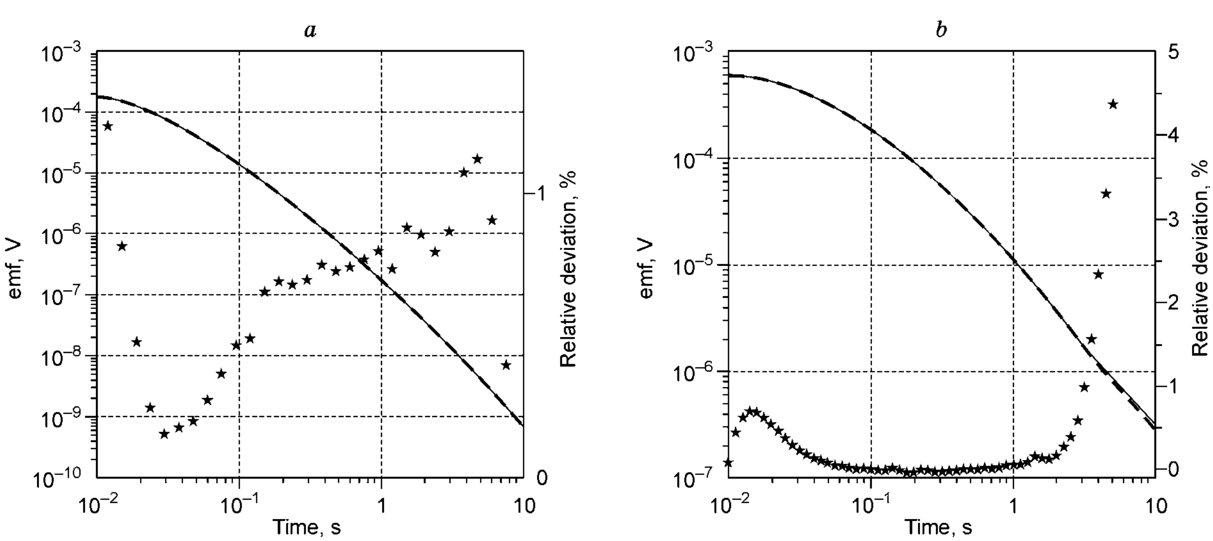

Fig. 4. Results of test calculations of the EMF for a horizontally layered model using the Modem3D program (solid lines) and the following programs: *a*, UnvQQ (dashed curve), Qq array; *b*, TEM_Line (dashed curve), AB-MN array. Asterisks denote the relative deviations of the transient responses (%).

array which moves as a single unit during profiling. In profiling using ABMN-n technology, the change in the array geometry as the MN line approaches the current electrodes significantly affects the measured signal. However, this effect is taken into account in processing the results of actual field measurements by averaging data obtained at the same coordinates of the receiver line, but at different positions of the transmitter line. This procedure smoothes the changes in the signal measured at the same point due to the different positions of the current electrodes relative to geoelectric inhomogeneities. In measurements with a fixed array geometry, averaging is not required, and at the same time, the anomalous response and the overall anomaly pattern are maximally close to those obtainable using ABMN-n technology.

In the model experiments, the measuring system was placed on a Penoplex plate to ensure the permanence of the contact conditions of the electrodes with the electrolyte. The plate was moved by means of an elastic cord over the electrolyte surface and could be rigidly fixed at any point of the profile with an accuracy of 1 mm. The current electrodes were made of brass, and the E_x component was measured using a three-electrode array with ERP-102 platinum electrodes.

The coefficient of geometric similarity of the array was 1:10,000, i.e., an electrolyte layer 40 cm thick corresponded to a sedimentary layer 4 km thick. In accordance with (1), the transient period in nature (t_n) and in the model (t_m) for this array are related as $t_m = 4 \times 10^{-7}\ t_n$. The use of a special transmitter with a small current cutoff time reduced the start time of the measurement of the transient process to 0.2 μs. The upper limit of the measuring range was determined by the time of decay of the transient signal to the level of polarization of the electrodes and was equal to 7 μs. Thus, this array allowed recording the late stage of the transient process that in nature corresponded to a delay interval of 0.5–17.5 s. The performance of the modeling apparatus developed on the basis of Tsikl commercial equipment are similar to those obtained in the specialized system developed earlier at the Naro-Fominsk Branch of VNIIGeofiziki (Deshitsa and Kuznetsov, 1981).

Models of salt structures for tank modeling were made of a cement-sand mixture and expanded clay. According to their electrical properties, the resulting models and the bottom of the tank are insulators. However, since in nature the contrast in electrical conductivity between, on the one hand, the basement rock and salt structures and, on the other, the sedimentary rock is 1.5–2 orders of magnitude, the use of nonconductive models for physical modeling is quite justified.

Before the measurements over the models, we obtained a map of the tank, which allowed us to estimate the effect of its finite dimensions on the measurement results at different time delays.

Estimates show that tank modeling of soundings using standard equipment with an inductive source is practically unfeasible. In the later stage, the signal of the Qq array over a conductive bed, which in this case can be approximated by an S plane, decays as t^{-4} and rapidly reaches the noise threshold. To raise the signal level, it is common to increase the number of turns in the receiver and transmitter coils, but this enhances the effect of the interturn capacitance and increases the contribution of the transient oscillation process, which distorts the useful signal. Another way is to shift the operating range to longer times by increasing the scale of the model L_m, but this cannot provide a significant increase in the coefficient k. An alternative to tank measurements for modeling TEM soundings with the Qq array is the use of metal models. The low electrical resistivity of metals allows the measurement range to be shifted to longer times by two or three orders of magnitude and thus separate the operating range and the interval of maximum manifestations of internal transient processes in the working circuits.

Metal models for the physical modeling of TEM soundings with an inductive source were fabricated by sand casting. The material of the model was AK-7 casting aluminum alloy, which modeled sedimentary rocks. The geometric similarity ratio in this case was 1:100,000, i.e., 1 cm in the model corresponded to 1 km in nature. The models were $40 \times 30 \times 4$ cm plates. The resistivity of the aluminum alloy evaluated from longitudinal conductivity of the plate was $\rho = (7.4 \pm 0.3) \times 10^{-8}$ Ohm·m. The cuts simulating the salt structures shown in Fig. 1*c*, *d* were produced in the center of the models by means of inserts of appropriate configuration, which were added to the mold during casting. Cuts with inclination angles of 0° (cylinder) and 30° were made after the measurements on models with an angle of –10° by additional milling cut of the metal.

The measuring range of transient signals on the metal models was 20 μm–20 ms. Since, in this case, the measurement time on the models and in nature are related as $t_m = 2.7 \times 10^{-3}\ t_n$, the corresponding interval in field measurements is 7.4 ms–7.4 s.

The measurements were made using multiturn coils simulating a 4000×1000 m rectangular transmitter loop and a receiving inductive sensor moved along the long axis of the transmitter loop. Exact positioning of the coils was achieved using a specially developed fastening system, which allowed the receiver and transmitter coils to be placed at any point on the surface of the plate with an accuracy of about 0.1 mm during measurements in the profiling mode. Special studies of the effect of the sizes of the coils and winding thickness on the measured transient signal showed that these factors can be neglected at transient times exceeding 1.3 ms, which corresponds to 0.5 s in actual measurements.

Modeling results

In the first phase of this work, we carried out mathematical and physical modeling of TEM soundings using models of single salt structures (see Fig. 1) occurring at different depths to assess the sensitivity of the two geoelectric arrays to changes in the dimensions and shape of these structures. The thickness of the sedimentary layer remained constant and equal to 4 km. The results were represented in the form of time sections of the normalized anomalous field δU, defined as $(U - U_0)/U_0$, where U is the transient signal in the presence of an anomalous object and U_0 is the transient signal over the homogeneous sedimentary layer. The spatial scale in the plots for the physical and mathematical modeling is the same and corresponds to actual measurements.

Figure 5 shows time sections δU for the Qq-n array over a truncated cone with a taper angle of 30º. The depth of the top edge of the object is 500 m, the height of the cone is 3500 m, and the diameter of the upper base is 3000 m. The time section obtained from the results of physical modeling is

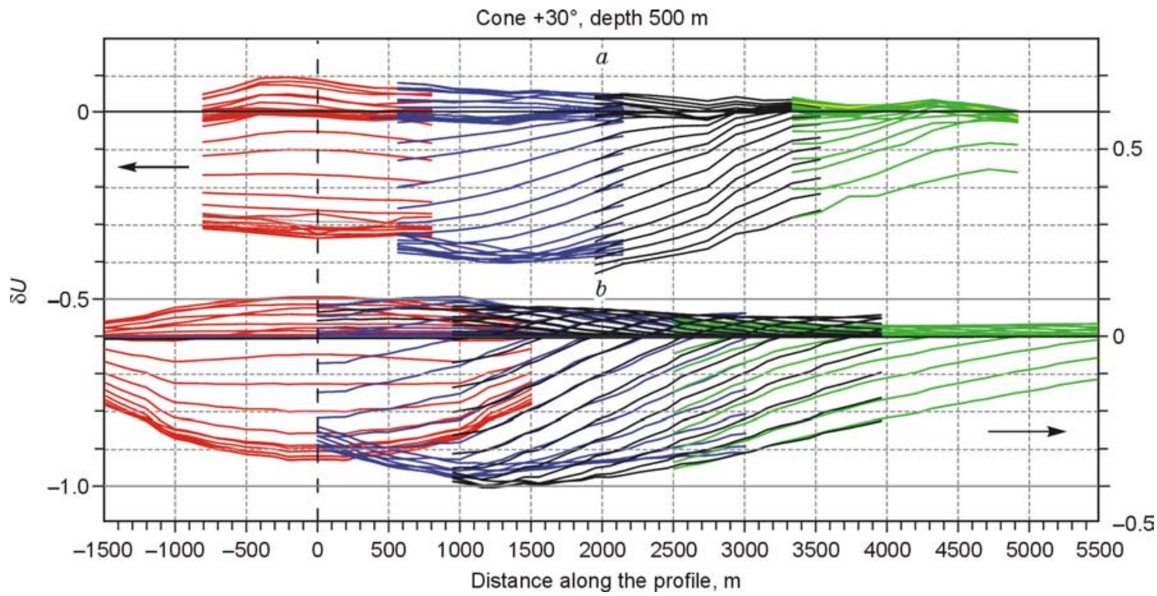

Fig. 5. Time sections δU for the Qq-n array over a cone with an inclination angle of the side wall of 30º from the results of: *a*, physical modeling; *b*, mathematical modeling. Delay range from 7.4 ms to 3.7 s.

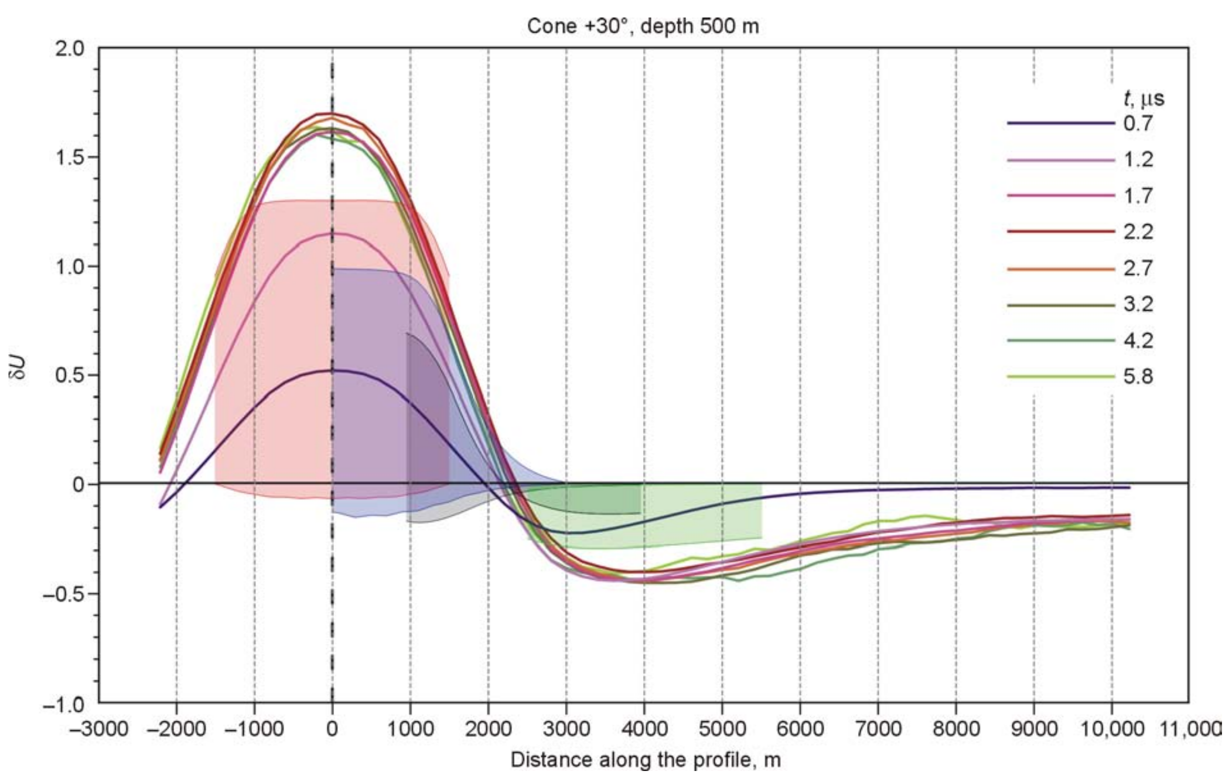

Fig. 6. Time sections δU for the mixed-source array over a cone with an inclination angle of the side wall of 30º. Coloring corresponds to the results of mathematical modeling of the ABMN-n array field for different positions of the transmitting line (delay range of 1 ms–10 s). Contour lines are obtained from the results of physical modeling of the ABMN equatorial array of the (delay range of 0.7–5.8 µs; corresponds to an interval of 1.75–14.5 s in nature).

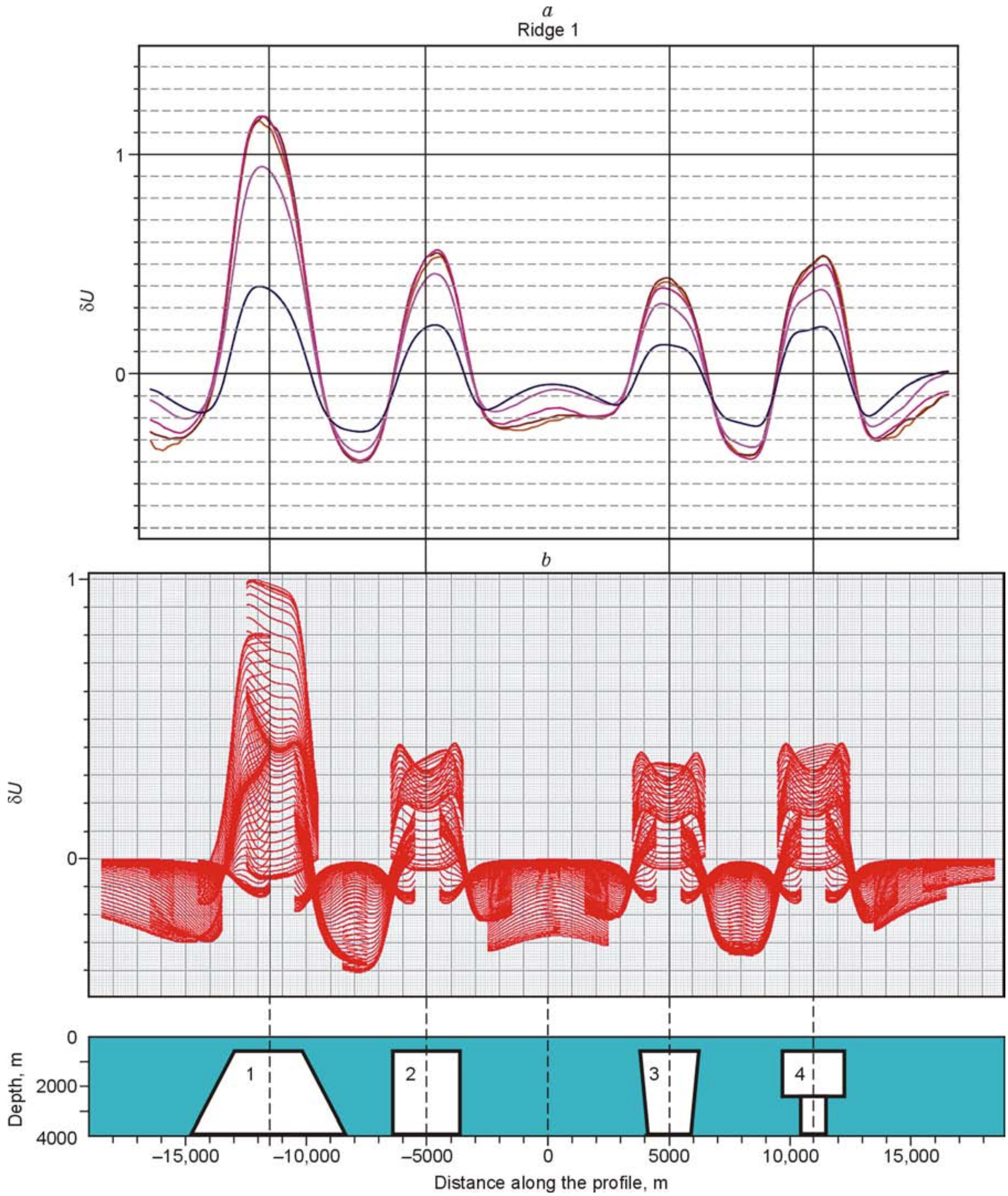

Fig. 7. Time sections δ*U* for the mixed-source array over the Ridge 1 model from the results of: *a*, physical modeling of the ABMN equatorial array field (delay range of 0.7–2.7 µs; corresponds to an interval of 1.75–6.75 s in nature); *b*, mathematical modeling of the ABMN-n array field (delay range of 1 ms–10 s). *1–4*, types of salt structures.

shown in Fig. 5*a*, and that obtained from the results of mathematical modeling in Fig. 5*b*. The profile passed over the center of the cone. Contour lines of the anomalous field obtained at different positions of the transmitter loop are shown in different colors. The working domain in the physical modeling was slightly less than 3000 m because of the finite dimensions of the receiver coil.

The anomaly has the plus sign at early times and the minus sign at late times. Maximum of the anomalous field is observed at late times over the edge of the top of the truncated cone (1500 m from the center), and the magnitude of the anomaly is 40%. The anomalous field decreases away from the salt dome.

Figure 6 shows the results of physical and mathematical modeling of transient electromagnetic soundings over the same anomalous object using the mixed-source array. Individual contour lines of the anomalous field based on the results of mathematical modeling of the ABMN-n array are not shown in the figure; time sections δ*U* for different positions of the transmitter loop are shown by different colors in the interval between the contour lines corresponding to the maximum and minimum of the anomalous field. The same figure shows the contour lines δU obtained from the results of physical modeling for different time delays. The tank measurements, in contrast to the numerical calculations, were performed for fixed array geometry (ABMN equatorial array), so that one continuous contour line was obtained for each delay. The maximum distance of the array from the center of the dome in the physical modeling was increased to 10,000 m. It is evident that at late times, the influence of the anomalous object remains marked even at this distance. The magnitude of the anomaly is maximal over the center of the salt dome and is 130% based on the results of mathematical modeling and 170% based on the data of physical modeling. Obviously, the mixed-source system responses more strongly to the presence of a poorly conductive object than the inductive array since the field of the horizontal electric dipole contains, in addition to the TE mode, the TM mode, which is absent in the field of the horizontal loop.

In the second phase of the work, we performed modeling of transient profiling over models of salt ridges—structures consisting of several objects of simple shape—to determine their mutual influence upon exposure to an electromagnetic field. Figure 7 shows time sections of the normalized anomalous field over the Ridge 1 model consisting of salt structures of the four types presented in Fig. 1. The height of all objects was 3500 m, their depth was 500 m, and the diameter of the upper base 3000 m. Mathematical modeling was carried out for the ABMN-n array with the transmitter line moving consistently, with some overlap, along the profile, and physical modeling was performed for continuous profiling with the ABMN equatorial array.

The modeling showed that the magnitude of the anomaly from a nonconductive object simulating a salt dome depends on the depth to the top edge of the object (decreases with the immersion of the object) and, as a first approximation, is determined by the area of the vertical cross section of the object through its center. Maximum anomaly is observed over model 1. Thus, the physical modeling showed electrical prospecting is a highly informative method for studying salt structures with positive inclination angles of the walls.

In general, the presence of a nonconductive body in the subsurface leads to an increase in the transient signal in the case of array location over the center of the body and to a decrease in the signal in the immediate vicinity of the nonconductive object. Both effects are caused by a change in the induction current pattern in the vicinity of the salt dome. The first effect is due to an increase in the density of current lines over the top edge of the object, and the second effect to their expulsion from the region of high electrical resistivity. Also there is a noticeable decrease in the anomalous signal over the object from the side of another nearby nonconductive object, due to which the anomalies become asymmetric. In particular, when considering the contour lines of the anomalous signal over models 3 and 4, it is clear that despite the same cross-sectional dimension of the objects, they differently affect the anomalous field of each other. This is because in the pattern of the contour lines of the normalized anomalous field, the depth of the negative wings of the anomaly from model 4 is greater than that from model 3. This effect is manifested at later times, when the field propagates to a greater depth, indicating that in the case of negative wall inclination angles of the salt structures, the transient signal of the electrical line carries information about the geometry of their lower part, and these data can be used to refine seismic data.

Conclusions

The mathematical and physical modeling of transient fields of two arrays (inductive and mixed-source) showed that the AMNB-n array is more efficient for determinig the shape and size of salt structures than the Qq-n array. The geoelectric environment of the Caspian depression is favorable for the use of the transient electromagnetic method, which can be an important complement to seismic methods in mapping the relief of the top of salt deposits. In this case, even relatively complex variations in the geological structure of the salt bed (negative inclination angles of the walls of salt domes, hangovers) are reflected in the recorded signal, but their identification requires the development of a special technique.

The studies have shown and that the Tsikl commercial equipment can be successfully used for physical modeling of transient electromagnetic soundings. Given the possibility of developing complex analog models of geological structures, physical modeling retains a high potential for solving methodological problems of electrical prospecting.

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