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GEOPHYSICS

Electromagnetic Sounding of the Kola Peninsula with a Powerful Extremely Low Frequency Source[1]

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Abstract—Experiment on electromagnetic sounding of the Kola Peninsula using unique mobile measuring complex of the low-frequency sounding was conducted, allowing to investigate a geoelectric section with a depth of several kilometers on distances up to 100 km from the stationary transmitting aerial. Excess on the order of amplitudes of the vertical component above the horizontal at all frequencies of sounding was registered in a number of points of measurements. This feature managed to be explained quantitatively by circulation of current on regional faults with the closure of current through the sea—before unknown galvanic coastal effect. Interpretation of the results of modeling and neural network solving of inverse problem essentially specifies the fault tectonics of the central part of the Kola Peninsula. Anomaly remote from the observation profile was found out—local pinch of a crustal conductive layer consisting of graphitized rocks and associated with the zone of overthrust.

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The level of geoelectric scrutiny of the Kola Peninsula is considered to be relatively good. Concentration on sounding of the Earth's crust by various methods using both natural and artificial electromagnetic field generated by the MHD generator [1] has played a special role in it. However the reached level of knowledge leaves much uncertainty by virtue of natural features of the region, such as prevalence of ionic and electronic conductors of different spatial scale among extremely resistive host rocks of the Baltic Shield, faults, graphitized bodies and unusually conducting structures of greenstone belt [2]. To reveal these uncertainties in recent years new opportunities of investigation due to development of technical means of sounding with powerful sources of extremely low frequency (ELF) range and interpretation methods based on the solution of integral equations (using computer clusters) and neural network approach have occurred.

The paper presents the results of the first, relatively small-scale experiment, realizing these opportunities in the central part of the Kola Peninsula near the stationary aerial (bipole) of the radio station "Zeus" with the purpose of studying fault tectonics and other conducting structures.

In April, 2009 on the Kola Peninsula experimental measurements of the three components of the magnetic field of ELF and lower ranges were executed. The work was carried out on pre-selected section of the Murmansk-Tumanniy highway located in latitudinal direction along the aerial of the ELF radio station "Zeus" at the distance of 15–25 km (Fig. 1). In eight points of the selected area measurements of two horizontal H_x, H_y, and vertical H_z components of the magnetic field generated by powerful stationary source were carried out.

The current (about 80 A) in the aerial was induced by a mobile, powerful, highly stable (frequency stability is not worse than 10^{-8}) generator in the frequency range from 0.01 up to 40 Hz [3].

Measurement of the full magnetic field parameters was conducted by a three-component induction magnetometer with digital system of registration and collection at frequencies: 0.094, 0.194, 0.382, 0.642, 0.942, 1.942, 3.822, 6.422, 9.422, 19.42, 38.23 Hz.

The error in determining the amplitudes of the components of the magnetic field (less than 1%) was provided by through calibration of measuring channels by means of specialized metrological equipment.

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[1] The article was translated in English by the authors.

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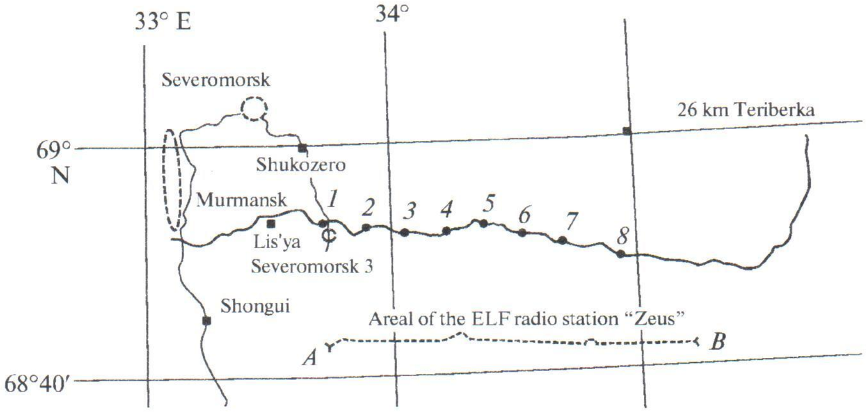

Fig. 1. Scheme of the experiment on the Murmansk-Tumanniy highway; here and on Figs. 2, 3 *1–8*—points of measurements.

Sufficient capacity of generating set and also relatively small distance from the source of radiation allowed to receive a good ratio of signal-noise in the experiment.

To measure the difference between the phases of the magnetic field components in the measurement point and of the current in the aerial of the source of radiation with an error less than 3% registration system of the gage measuring the magnetic field and the current were equipped with hardware binding to the universal time by signals of the satellite navigation systems GLONASS/GPS.

The integral equations method [4, 5] was used as the basic modeling tool. When solving problems by this method the following model is considered: horizontally homogeneous layered medium containing some anomaly, which conductivity is different from conductivity of the host medium. If conductivity of the medium inside of the nth layer is constant and equal to n then it is possible to calculate Green tensors $G_E(M, M_0)$, $G_H(M, M_0)$ of electric and magnetic types [4], that allows to pass to the vector integral equation for the electric field $\mathbf{E}(M)$ inside of anomalous area V:

$$\mathbf{E}(M) - i\omega\mu_0 \iiint_V (\sigma_a(M_0) - \sigma_n(M_0)) \times G_E(M, M_0)\mathbf{E}(M_0)dV_{M_0} = \mathbf{E}_0(M), \qquad (1)$$

where $\mathbf{E}_0(M)$—primary electric field, i.e. the field induced by those sources in the layered medium in the absence of the anomaly, $\sigma_a(M_0)$—conductivity inside of the anomaly, ω—circular frequency, $\mu_0 = 4\pi \times 10^{-7}$. Having solved this equation the electric field inside of the anomaly V is received. Knowing it, it is possible to calculate the electromagnetic field at all points under following conversion formulas:

$$\mathbf{E}(M) = i\omega\mu_0 \iiint_V (\sigma_a(M_0) - \sigma_n(M_0)) \times G_E(M, M_0)\mathbf{E}dV_{M_0} + \mathbf{E}_0(M),$$

$$\mathbf{H}(M) = i\omega\mu_0 \iiint_V (\sigma_a(M_0) - \sigma_n(M_0)) \times G_E(M, M_0)\mathbf{E}dV_{M_0} + \mathbf{H}_0(M),$$

where $\mathbf{H}_0(M)$—primary magnetic field.

For the numerical solving of the integral Eq. (1) it was used the method of collocations which consists of the following. We shall devide the anomalous area V into cells V_k, $k = 1, 2, \ldots, N$ which have the form of a parallelepiped, also we shall replace function $\mathbf{E}(M)$ in subintegral expression in (1) in each cell V_k with its value in the center of this cell M_k. Let's obtain the following system of the linear algebraic equations for the electric field in the centers of cells:

$$\mathbf{E}(M_n) - i\omega\mu_0 \sum_{k=1}^{N} \mathbf{E}(M_k) \times \iiint_{V_k} (\sigma_a(M_0) - \sigma_n(M_0))G_E(M_n, M_0)dV_{M_0} = \mathbf{E}_0(M_n).$$

To solve this system of linear equations the generalized iterative minimal residual method was used [4].

It was originally supposed, that it was necessary to model a rather small region, containing the profile of monitoring, but as it will be shown further, during research there appeared a necessity to model area with the horizontal sizes approximately 120 on 100 km. Discretization of integral equations for this region demanded nearby 8 million cells.

Calculations were performed on high-efficiency cluster of NRC "Kurchatov institute", by means of the software Pie3d, developed by the consortium CEMI.

Constructing a model using the method of integral equations consists of two consecutive stages: first the normal section is selected—horizontally homogeneous medium, and then anomaly is set. In our case the normal section was selected on the basis of known geophysical data [6], and the choice of normal section was specified by the coordination of calculations of a primary field with the results of experiment.

The main and unexpected feature of the results has appeared to be the excess on the order of the amplitudes of the vertical component of the magnetic field H_z above the horizontal observable at all frequencies. The example at one of the frequencies is shown on Fig. 2.

To account for this fact, the normal section was chosen so that the ratio of the amplitudes $\frac{H_z}{H_x}$ was the greatest, thus horizontal components should not differ strongly from the average experimental. According to these criteria the following normal section was chosen: the top layer with conductivity of 10^{-4} S/m and thickness of 2 km underlained by the basis with conductivity of 10^{-5} S/m. For such section this ratio is close to 1.5. It is obvious, that observable anomalously high H_z can be explained only by taking into account the fault tectonics.

The results of calculations for various faults that intersect the profile or the local structures, located near the profile, have shown that they indeed increase the vertical component but not enough. It has been suggested that this kind of anomaly can be explained only by a large-scale structure. Such a ratio of vertical and horizontal components is typical for the magnetic field within a closed framework on which current circulates, that has allowed to put forward a hypothesis about existence of a similar structure. The analysis of the fault tectonics of the Kola Peninsula shown, that if to consider the flood of the faults in the Barents Sea similar "framework" consisting of the aerial, faults and the coastal zone really exists. Calculations for such model, located in the region with a diameter of about 100 km, shown, that the account of a similar framework allows to receive values of H_z close to experimental. Note that it is sufficient to take into account a relatively small coastal zone with width of about 20 km and depth 200–400 m.

Induction of powerful secondary fields by the current, canalizing along the coastal line (coastal effect) is well-known, however necessity of its account for sounding on land with a remote source is observed for the first time. And if classical coastal effect on land has the inductive nature, in our case its nature is galvanic.

The calculations considering closure through the sea allowed to receive good agreement with experiment for the component H_z, however calculated horizontal component H_x in this case exceeded the experimental more than twice. This ratio was observed also for the horizontal components of the primary field—it essentially exceeded the average experimental.

To reduce the primary field calculations with other sections were carried out, choosing them so that horizontal components were coordinated with experimental. It turned out that the agreement can be achieved, having added to the model a large enough conducting anomaly. When placing the anomaly to the south of the transmitting aerial it is possible to reduce essentially the horizontal component of the magnetic field with insignificant decrease of the vertical.

Thus, there appeared a problem of determining geometrical parameters of such body. To solve this inverse problem it was used neural network error backpropagation method [7]. A three-layer neural network was used. Direct distribution of the input signal representing values of the magnetic field components on such network took place from a layer to a layer. Thus each *i*th neuron of the next layer got the total signal from all *j*th neurons of the previous layer:

$$u_i^l = G\left(\sum_j W_{ij}^l x_j\right),$$

where u_i^l—output signal for *i*th neuron of the *l*th layer, G—transfer function of a neuron (e.g., hyperbolic tangent), W_{ij}^l—coupling coefficients between neurons of the layer $l-1$ and l, x_j—condition of the *j*th neuron of the $l-1$ layer.

"Correct" values of the neurons of the output layer match the values of the parameters of a two-dimensional geoelectric structure for the given training example. The total root-mean-square error for all training samples, which was required to be minimized, was a square of the difference between "correct" u_i^t and valid u_i values of output neurons and was equal to

$$Er = \sum_p \sum_i (u_i - u_i^t)^2, \tag{2}$$

where summation was carried out on all *p*th training samples for all the neurons of *i*th output layer. Coupling coefficients between layers of a network are those parameters which determine the magnitude of errors (2), therefore process of training consists in selection of the connection matrix for each pair of layers W_{ij} in order to minimize it. Coupling coefficients are set by the standard error backpropagation method using the calculated gradient of the error at each step for each pair of neighbor layers. This procedure is performed for the entire training series, and ends when a defined threshold accuracy eps($Er <$ eps) is achieved.

Unlike the procedure of training which demands many steps for passage of a signal on the network forward and back, procedure of recognition demands only one pass of a recognizable signal from the input to the output and is carried out with the coupling coefficients established at the training stage containing "rules of output."

To test the neural network simulated data base was divided into two samples: training and testing. After

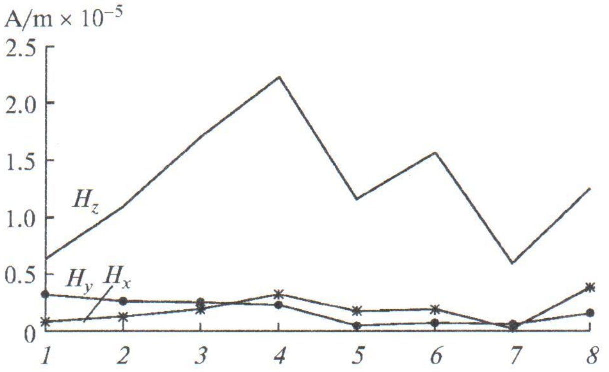

Fig. 2. Experimental values of the magnetic field at the frequency 3.822 Hz.

training the network on a testing sample the quality of recognition was verified.

Geoelectric inhomogeneity of crustal conductor type of trapezoid form was characterized by following geometric parameters, which were to be defined: depth of the upper boundary of the crustal conductor Z_1, depth of the lower boundary of the crustal conductor Z_2, length of the upper boundary of the crustal conductor in the north-south direction L_1 and the length of the lower boundary of the crustal conductor in the north-south direction L_2. Thus, number of output neurons of the three-layer neural network which was defined by the given parameters, was 4. The hidden layer of a neural network contained 40 neurons.

To train the neural network 256 models with different values of each of the geometrical parameters were calculated.

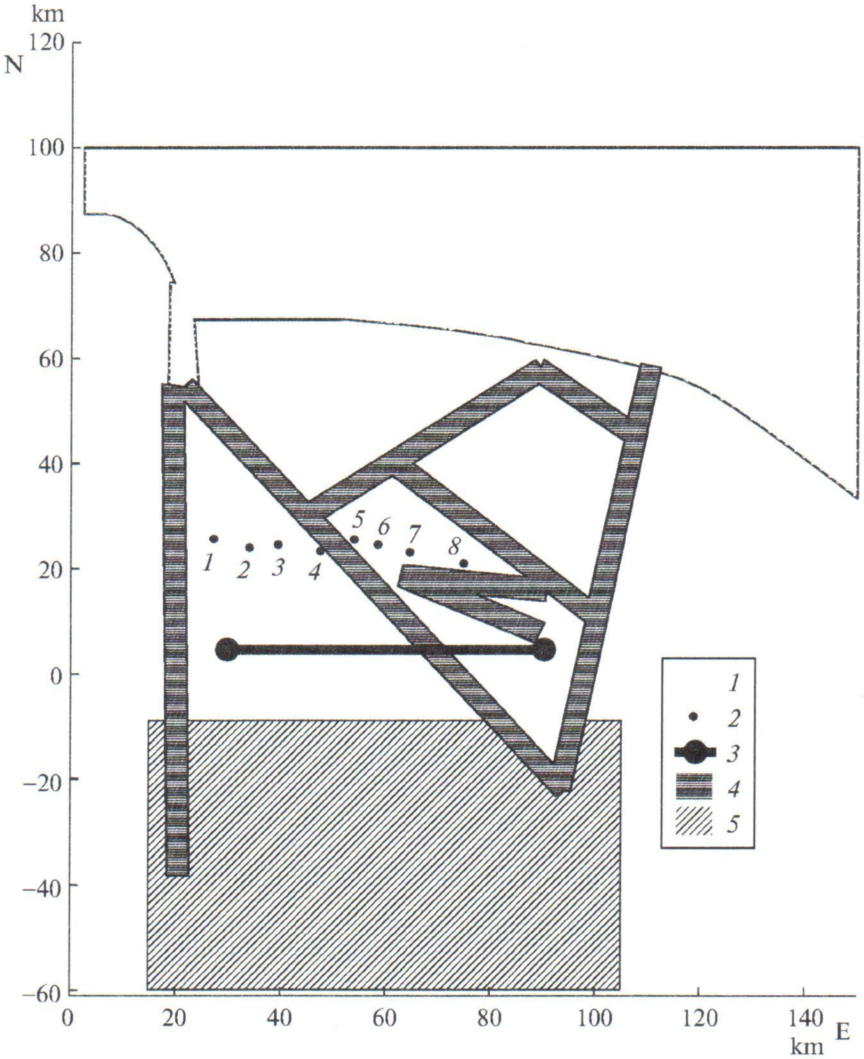

Fig. 3. The result of solving the inverse problem in the plan: *1*—sea, 2 S/m; *2*—receivers; *3*—source; *4*—faults, 1 S/m; *5*—crustal anomaly, 1 S/m.

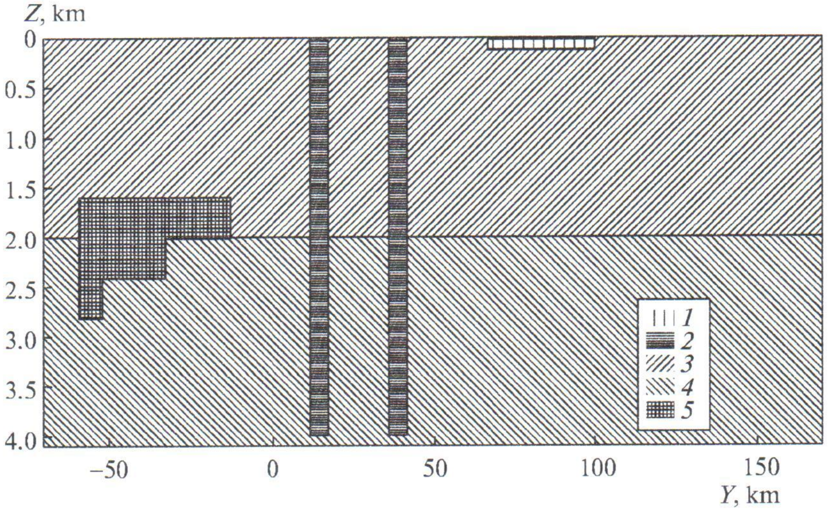

Fig. 4. The result of solving the inverse problem in the meridional section: *1*—sea, 2 S/m; *2*—faults, 1 S/m; *3*—10^{-4} S/m; *4*—10^{-5} S/m; *5*—crustal anomaly, 1 S/m.

Threshold accuracy of training has been defined as 0.15.

After determining the optimal structure of the neural network testing was conducted, namely, some of the models were removed from the full training sample in order to verify on these models the interpolation properties of the neural network. It has been shown, that relative error of testing for Z_1 and Z_2 was no more than 27 and 29% respectively, and for L_1 and L_2 no more than 45%.

After testing the neural network, recognition (inversion) on real data was carried out and following values of parameters were received. The depth of the upper boundary of the crustal conductor Z_1 was equal to 1.68 km, depth of the lower boundary the crustal conductor Z_2 was 2.75 km, length of the upper boundary of the crustal conductor in the north-south direction L_1 was 53.4 km and the length of the lower boundary of the crustal conductor in the north-south direction L_2 was determined by the value of 1 km.

To check, root-mean-square errors over all components of the magnetic fields between real data and each of models of training sample have been calculated. Minimum error value was found for the model with the following parameters: Z_1: 2 km, Z_2: 3 km, L_1: 60 km, L_2: 0 km. Thus, additional confirmation of correct estimation of parameters was received.

On Figs. 3 and 4 the final result of the inverse problem is shown. Position of the conducting body at the boundary of the layers of the normal section is an important indication for the geological interpretation.

Detected conducting body occupies the eastern part of the Kola-Norwegian block including gneisses and amphibolites of the Kola-Belomorsky complex (upper archaea). According to [2], the part of this block covered by the model has high electrical conductivity. This is where the greenstone belts alternating with layers of gray gneiss are common [8]. In this region also intense gas and bitumen manifestations are found [9]. The possibility of formation graphitic compounds under these conditions was described in [10]. Even at 1% volume content of graphitic matter its electron-conducting films at grain boundaries in rocks can lower the overall resistance of rocks by several orders [11] and form this conducting body. Body position in the zone of thrusting explains its pinch to the north.

Thus, experiment has shown, that fault tectonics played the basic role in formation of anomalous field. Explanation of the unusually large amplitudes of the vertical magnetic field components is for the first time observed galvanic coast effect. Besides, the amplitudes of all components are affected by a remote deep conductive inhomogeneity. Its geometric parameters are determined by solving the inverse problem and allow to interpret it as a pinch of a crustal layer consisting of graphitized rocks.

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