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RESULT OF COMBINING DATA FROM IMPULSE ELECTRICAL PROSPECTING AND AEROMAGNETIC PROSPECTING FOR GROUNDWATER EXPLORATION IN THE SOUTH OF YAKUTIA

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In 2014 in the south of Yakutia in the course of groundwater exploration works a complex of geophysical methods was tested: aeromagnetic and electrical prospecting was carried out using near-field transient sounding and electromagnetic sounding with induced polarization. Prospective structures for hydrogeological drilling are zones of discontinuous tectonic faults. In order to identify them, data from aeromagnetic and electrical prospecting were used. Results of drilling confirmed the presence of watered areas; however, analysis of obtained information allowed to come to the conclusion that the amount of water in the faults has no direct connection to electrical conductivity.

***Key words*:** electromagnetic sounding, induced polarizations, transient processes, aeromagnetic prospecting, magnetic susceptibility, groundwater

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In order to develop the industry of Eastern Siberia and to exploit oil and gas deposits of the region, it becomes a relevant task to carry out groundwater exploration for the supply of potable and technical water.

In 2014-2015 exploration and appraisal operations were carried out in Lensky region of the Sakha Republic (Yakutia) in the south-eastern part of the Central Siberian Plateau. Results of geophysical tests combined with geological and hydrogeological data were used to identify optimal location of hydrogeological wells.

According to geological and hydrogeological conditions, this territory belongs to the third category of difficulty due to permafrost, geological structure and Triassic trap magmatism. Groundwater resources are concentrated in subsoil areas confined to talik zones, spread out in an erratic manner but tending to zones of tectonic faults, as well as contacts of terrigenous rocks and intrusive trap formations [7].

Structural-tectonic mapping of the territory was based on results of decoded satellite images, data of aerovisual test and aeromagnetic prospecting. In the process of well location, results of two-dimensional survey interpretation were taken into account by way of shallow near-field transient sounding (NFTS) and detailed areal survey by method of electromagnetic sounding with induced polarization (EMS-IP), completed for three sections.

In order to identify zones of trap magmatism and to map tectonic faults, data from aeromagnetic survey were used; the works were carried out in 2006-2008 by GNPP «Aerogeophysica» with the distance between profiles approximately 500 m, terrain clearance 640-660 m, average terrain height around 390 m.

Interpretation of aeromagnetic data was carried out using software complex GelioSMI [6] and included following steps:

1. Calculation of anomalous component of the magnetic field T_a using robust filtering [4] to suppress high-frequency noises and to eliminate «pulling» effect (leveling), combined with filtering using principal component analysis [9].

2. Calculation of local component of the magnetic field T_B, which reflects development of discontinuous tectonics and trap magmatism in the sedimentary cover. Local component T_B has been obtained by excluding component T_R from T_a field. The former is determined by deep-seated heterogeneities of sedimentary cover and crystalline basement. The task has been completed using 3-D linear inversion of T_a magnetic field and defining components of total magnetization vector for parallelepipeds with horizontal dimensions 4000 × 4000 m and three layers in depthward direc-

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tion: 0-2000; 2000-5000 and 5000-9500 m. In these conditions, for the depth ranges of 2000-5000 and 5000-9500 m the effect of magnetic heterogeneities was taken for T_R component of the magnetic field. Implemented technology of inversion used an approach to solving ill-posed problems of high dimension [13] and break-point identification of the L-curve, reflecting dependence between standards of model parameters under consideration and standard of the field mis-tie [10]. Despite significant horizontal dimensions of the node, selected in order to obtain a stable solution, RMS mis-tie of the model field with the actual one amounted to 8.6 nT.

3. Suppression of magnetic heterogeneity effects from the basement and lower part of sedimentary cover in the local component $T_B = T_a - T_R$, whose influence has not been fully compensated due to significant horizontal dimensions of the node. For this purpose filtering using principal component analysis was applied, as well as directional filtering with robust multi-variable regression. As a result, local component T_L was obtained, which with great contrast reflects magnetic heterogeneities in the upper part of sedimentary cover, including linear anomalies related to disjunctive tectonics.

4. Calculation of robust standard deviation T_D in the field of local component T_L, which is characterized by excessive ruggedness in trap areas. To estimate this parameter, median absolute deviation (MAD) – characteristic, resistant to anomalous field outliers – was calculated in sliding windows of varying sizes (from

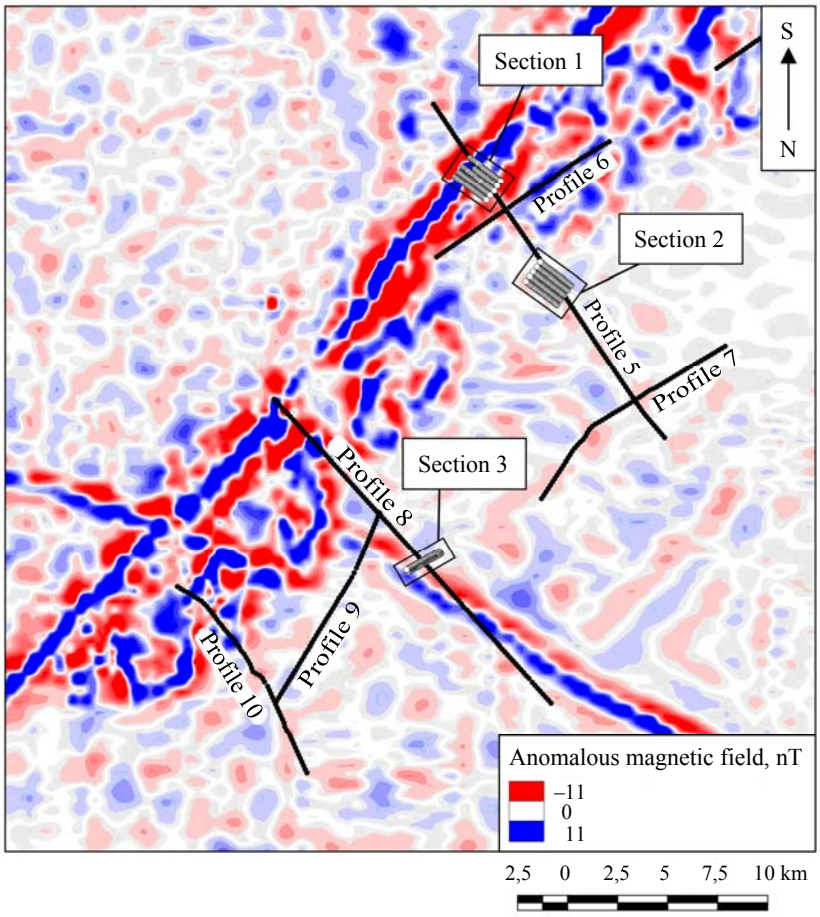


Fig.1. Scheme of profile construction for impulse electrical prospecting on the map of local field component T_L

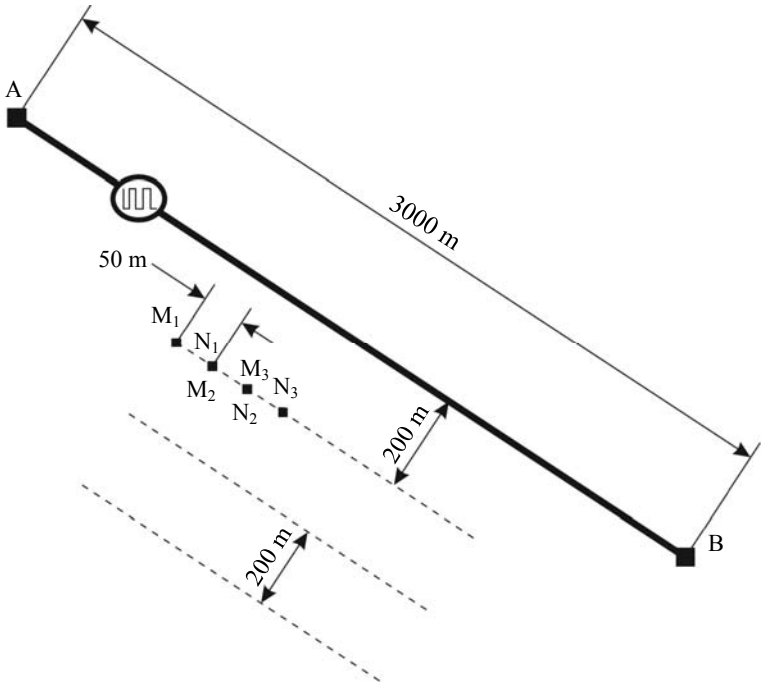


Fig.2. Scheme of conducting areal survey by EMS-IP method

2000 × 2000 to 5000 × 5000 m). The multitude of MAD solutions, obtained for windows of different sizes, was compacted in the field of the first principal component with subsequent inverse transformation into T_D. One of high-dispersion zones of the local component is situated within the license block. This zone is confined to the fault of north-eastern strike and characterizes the region of trap magmatism distribution.

In order to examine geoelectrical structure of the upper part of the section and to identify water aquifers in it, electrical exploration by method of shallow NFTS was carried out, results of which were modified in software complex «Mars1D» [5] and interpreted with regard to aeromagnetic prospecting data. A fragment of profile grid is presented in Fig.1 (profiles 5-10 – survey by method of shallow NFTS, sections 1-3 – areal survey by EMS-IP method [2]). Curve adjustment was simultaneously carried out for both coaxial and distance-separated loops, which resulted in more reliable identification of permafrost rock (PFR) zones due to application of inductively induced polarization [3, 11].

To specify thickness of aquifers and boundaries of water seams, areal survey was carried out in three sections in the proximity of designed wells and mean gradient was set by EMS-IP method (Fig.2). This method allows to get full advantage of the information from transient processes, actuated by rectangular bipolar impulses from the grounded current source and registered by a multielectrode grounded receiver circuit [1].

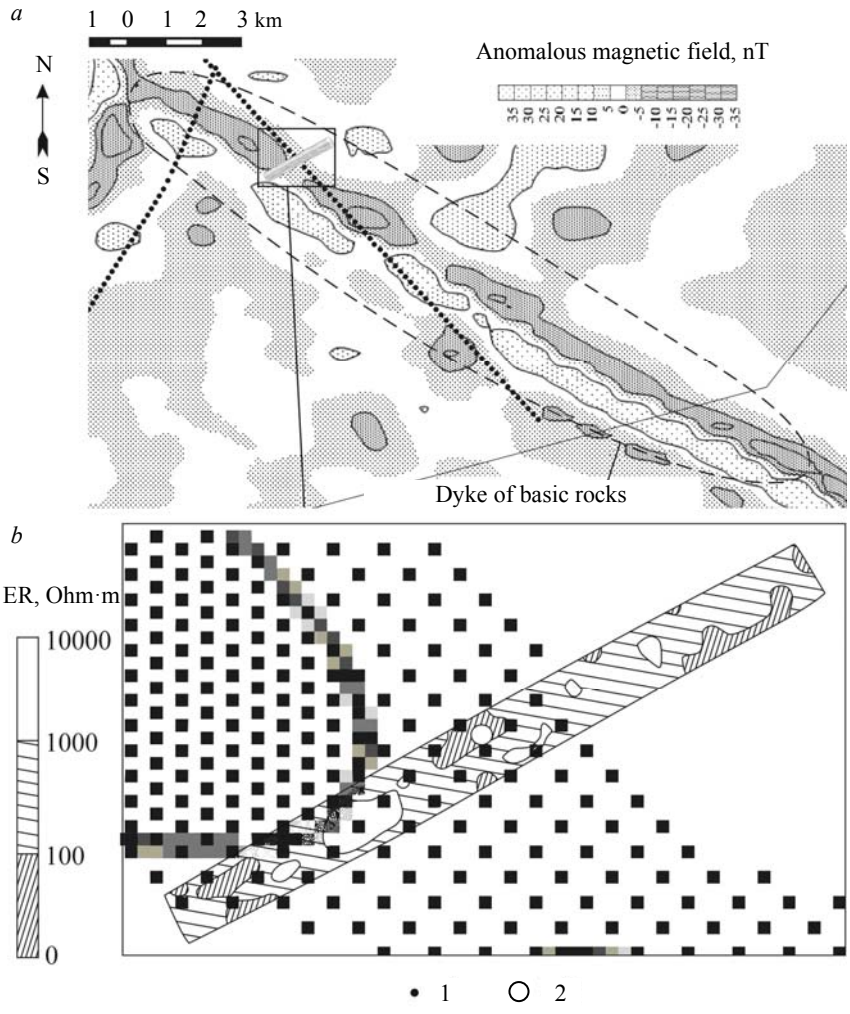


Fig.3. Scheme of the local field component T_L according to aeromagnetic prospecting (*a*) and an enlarged fragment with section 3 by EMS-IP method in the proximity of hydrogeological well (*b*)

1 –NFTS pegs; 2 – hydrogeological well

Approach to measuring and processing transient process data, which combines robust regression analysis and inversion within the model of polarizable medium, enables to calculate not only apparent electrical resistivity (ER) of the model, but also frequency-dependent one. A distinctive feature of the method is a system of processing registration with minimal distortions of induction effect, which is considered a noisy signal in traditional IP methods. The approach applied to registration of transient processes imposes new conditions on the system of data retrieval. Correct recording is done with analog-to-digital converter with high-frequency sampling (no less than 100 kHz) and an adequate processing of primary data.

Development of a reference geoelectrical model for both methods of impulse prospecting (NFTS and EMS-IP) was done using logging results for deep-hole wells. Adjustment

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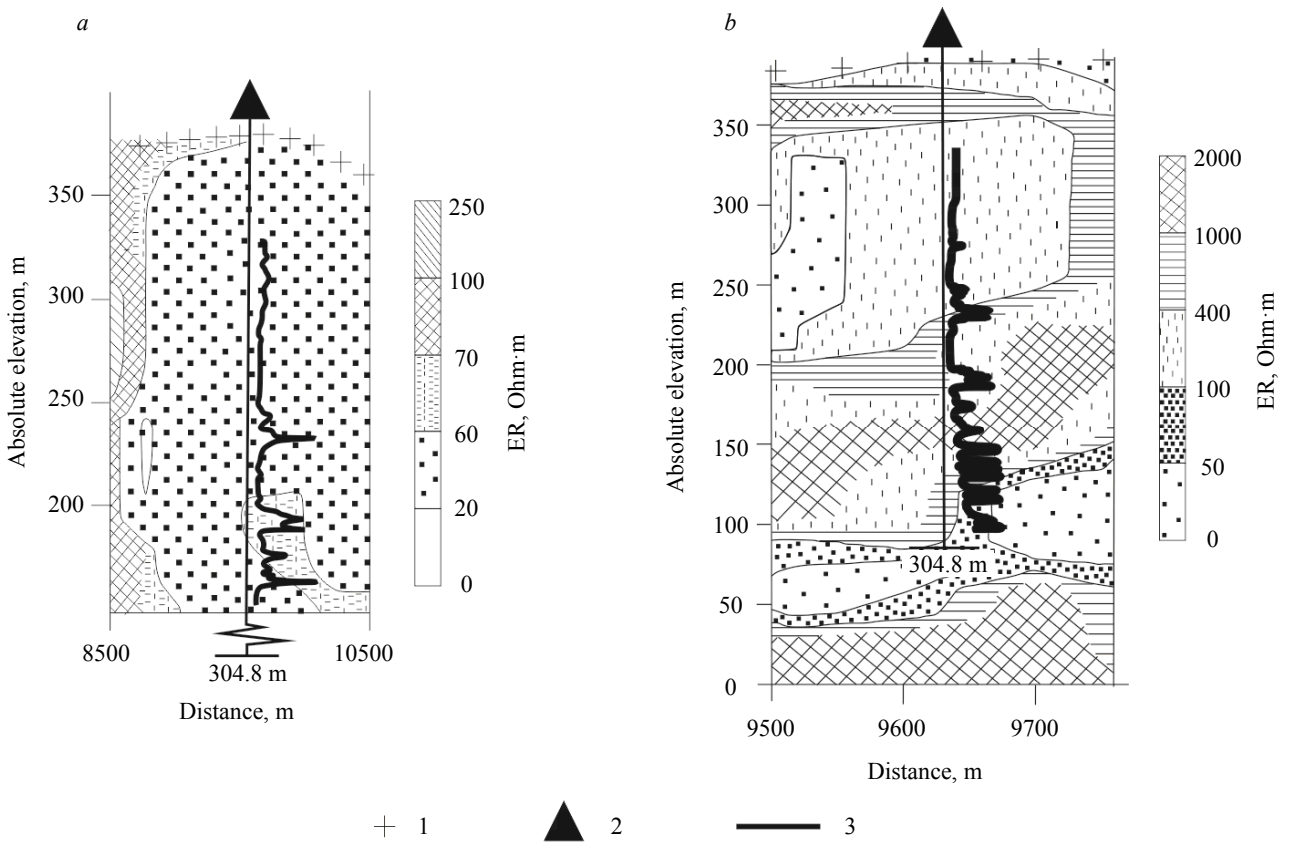


Fig.4. Comparison of data from resistivity logging and geoelectrical sections: *a* – profile 8, NFTS; *b* – profile 13, EMS-IP

1 – pegs; 2 – hydrogeological well; 3 – RL curve

was realized within the framework of one-dimensional polarizable horizontally-layered model. To account for frequency dispersion, Cole-Cole dependence [8] was used, which allowed to calculate polarization properties of the section:

$$\rho(\omega) = \rho_0 \left[1 - \frac{\eta (i\omega\tau)^c}{1 + (i\omega\tau)^c} \right],$$

where ρ – ER; ω – frequency; ρ_0 – direct current ER; η – polarizability coefficient; i – imaginary unit; τ – relaxation time; c – index of power.

Inverse problem was solved using a set of minimization algorithms: Nelder – Mead method, also known as downhill simplex method [14], Levenberg-Marquardt algorithm [12] and principal axis method (PrAxis). For a correctly selected model this combination offers an opportunity to find absolute minimum position in multi-dimensional attribute space by means of stable and quick adjustment.

Refinement of results was done by secondary adjustment of curves after fixing certain parameters of the model basing on apriori geological and geophysical information. An original approach was used to suppress profile anomalies and to increase the quality of convergence at profile «crosses»; the curves were averaged in the ellipse with given axes. The averaging was carried out using a robust procedure, the weight assigned to the curve in the center of the ellipse was higher than the weights of adjacent curves.

As a result of NFTS and EMS-IP data interpretation, geoelectrical planes were identified in ER sections and zones of PFR development were highlighted in polarizability sections. PFR zones are characterized by ER values of 500-800 Ohm·m, polarizability up to 40 %, relaxation time around $1 \cdot 10^{-5}$ s and index of power $c = 0.9$. Traps have similar polarizability, but longer relaxation time ($\tau \approx 1 \cdot 10^{-3}$ s) and high resistivity (around 2000 Ohm·m). Aquifers have low resistivity (usually

lower than 50 Ohm·m) and make a contrast with surrounding rocks of higher resistivity (from 200 Ohm·m and higher).

From the viewpoint of water inflow, the most promising areas are disjunctive tectonic faults which in geoelectrical sections look like a subvertical low-ohmic region, correlated with fractures identified through the analysis of the local component of the magnetic field.

A promising area with decreased ER values was detected on one of NFTS profiles, at sharp angle intersecting a dyke of basic rock, allocated by magnetic prospecting data (Fig.3, *a*). Transverse to NTFS profile and the dyke, section 3 of areal EMS-IP survey was specified, in the center of which a hydrogeological well was drilled (Fig.3, *b*). In the process of comparing geoelectrical section of NFTS (Fig.4, *a*) and EMS-IP profiles (Fig.4, *b*) with resistivity logging (RL) data, high correlation with upper low-ohmic planes was observed. The bore log was represented by clay soils with argillite, limestone and dolomite underlays. At the depth of 310-358 m water inflow was detected, coming from cavernous plane corresponding to the area of increased conductivity in the geoelectrical section.

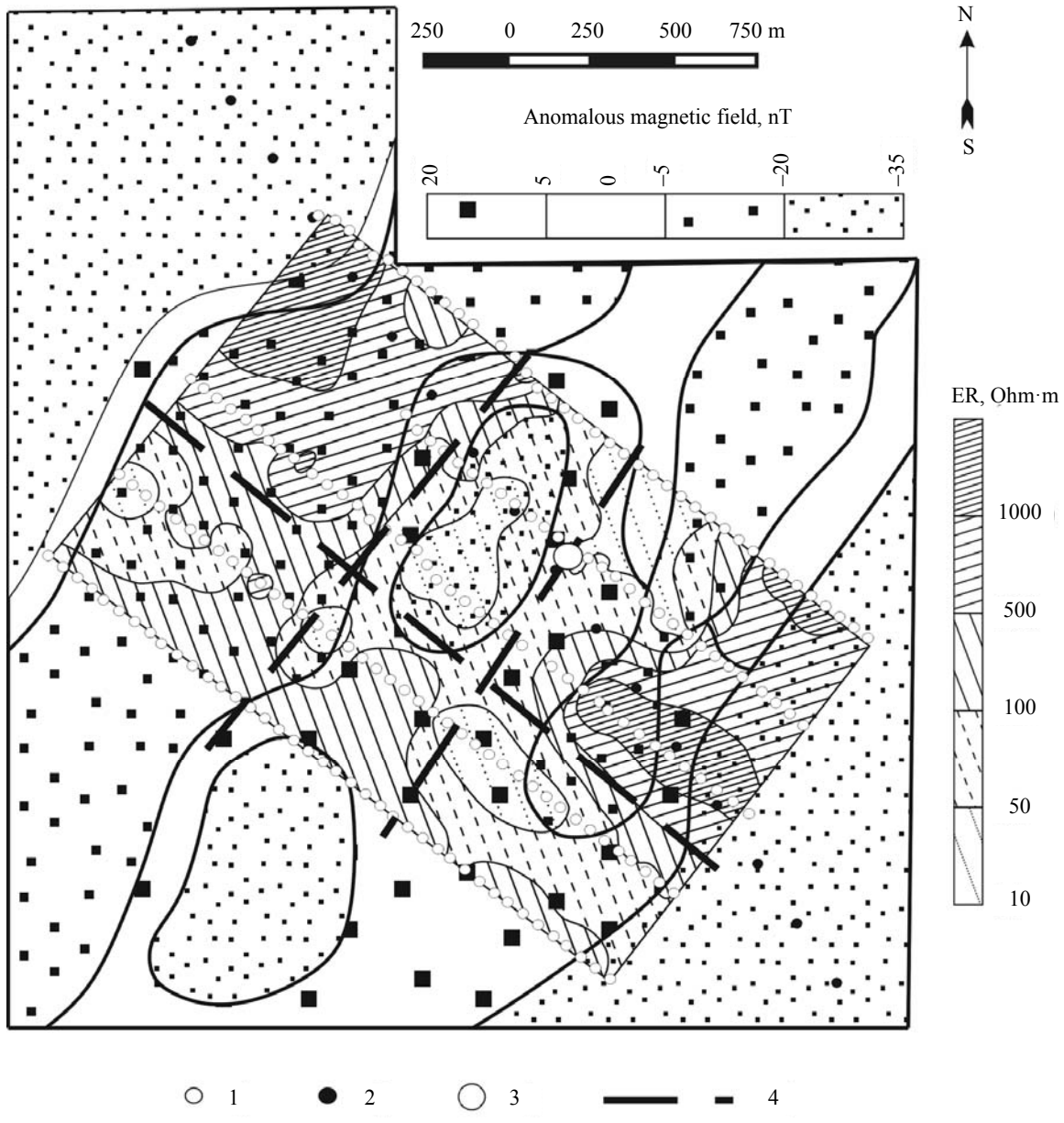


Fig.5. Scheme of the local field component T_L according to aeromagnetic prospecting and ER in the section 1 in the proximity of hydrogeological well

1 – EMS-IP pegs; 2 – NFTS pegs; 3 – hydrogeological well; 4 – fault lines

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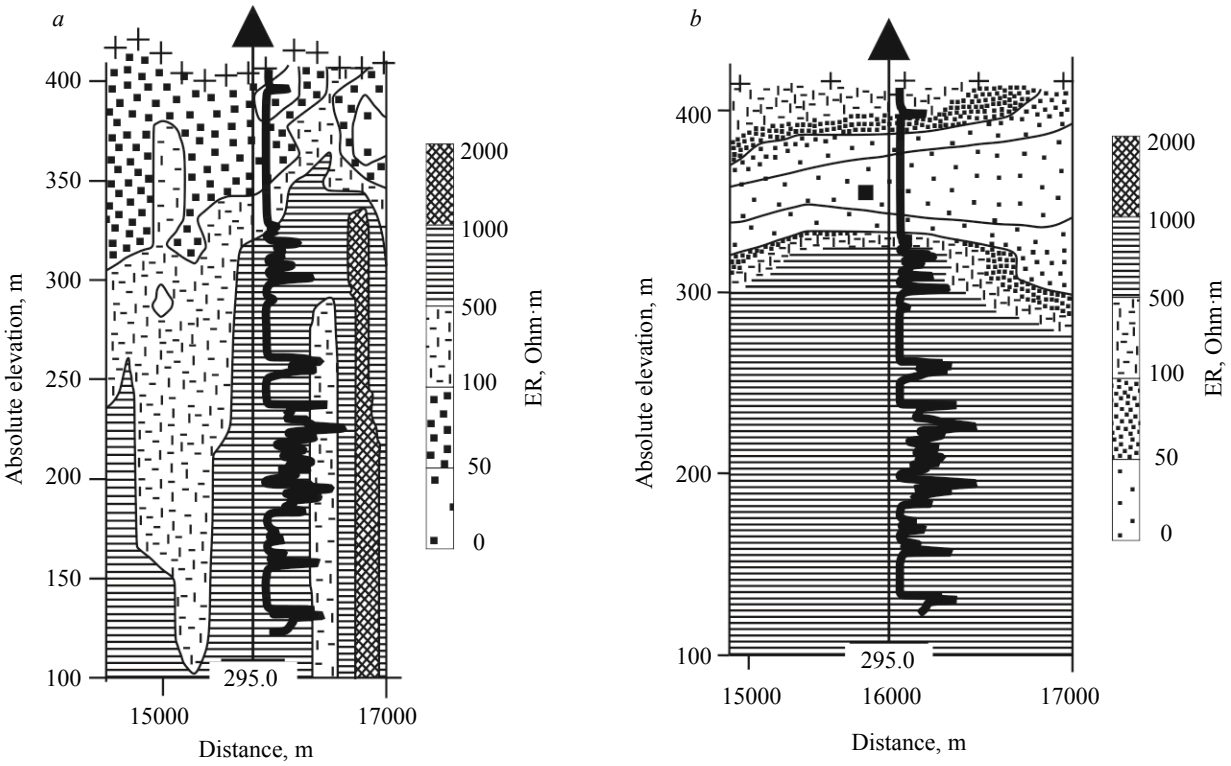


Fig.6. Comparison of data from resistivity logging and geoelectrical sections: *a* – profile 5 (PFR); b – profile 4 (EMS-IP)

Legend: see Fig.4

Another section of areal EMS-IP survey (number 1) is located at the core of anticline structure (Fig.5). Judging by the intensity of local anomalies of the magnetic field, detected by magnetic prospecting, and high ER values, obtained through NFTS data inversion (Fig.6, *a*), this territory contains trap intrusions. The aim of areal EMS-IP survey was in localization of a watered zone with excessive fissuring within this trap intrusion. A low-ohmic plane, identified through EMS-IP inversion at the depth of 50 m, correlates with magnetic field variations, which allows to specify location of the fractures (Fig.6, *b*). Subsequently, a hydrogeological well was posed in one of detected fracture zones, with supposed absence of PFR and presence of fissure-vein groundwater at the depths up to 300 m. The drilled well gave a good influx and confirmed the presence of fissured watered zone in the dolerites. Position of low-ohmic plane in the upper part of the section is confirmed by resistivity logging to high precision. One more low-ohmic watered plane, detected by EMS-IP method, is located below 400 m, and therefore predicted inflow is only possible from the upper aquifers.

Conclusions

Integration of data from remote sounding, aeromagnetic prospecting and electromagnetic sounding enabled early-stage detection of tectonic fault zones, outlining of trap intrusion bodies, assessment of PFR development features. Comparison of test results for underground water inflow with resistivity logging data and results of electromagnetic sounding inversion did not allow to trace a stable dependence between electrical resistivity of rocks and the amount of water in them. Apparently, it can be explained by the fact that even small amounts of high salinity groundwater significantly change total electrical resistivity of the seam. Nevertheless, application of geophysical meth-

ods at the exploration stage results in a substantial increase in overall efficiency of prospecting due to specification of structural, tectonic and geocryological conditions and consequently permits to save up significant amount of funds on exploration drilling.

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