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COMBINED 2D INVERSION OF ELECTROTOMOGRAPHIC AND AUDIO-MAGNETOTELLURGIC SOUNDING DATA TO SOLVE MINING PROBLEMS

Viktor A. KULIKOV[1], Aleksandr E. KAMINSKII[2], Andrei G. YAKOVLEV[1]
[1] *Lomonosov Moscow State University*, *Moscow*, *Russia*
[2] «*Astra LTD*», *Saint-Petersburg*, *Russia*

Electrical methods of exploration are widely applied in prospecting and estimation of ore mineral resources. It is not always that geoelectrical models obtained in the course of interpretation of different types of electric and electromagnetic sounding are in line with each other. This leads to difficulties in geological interpretation of electrical exploration results. In single cases a geological model can be built that with great precision satisfies data from different electrical explorations, for instance, results of geometric and inductive electromagnetic soundings. For this purpose an algorithm of combined inversion of electrotomographic and audio-megnetotellurgic sounding data has been developed and implemented by A.E.Kaminskii in software ZondRes2D. Advantage of combined inversion has been shown for investigation of sections up till 400-500 m deep on synthetic models and actual field data.

***Key words*:** electrotomography, magnetotellurgic sounding, 2D inversion, mining electrical exploration

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Introduction. Electrical methods of exploration are widely applied in prospecting and estimation of ore mineral resources. In the latest years geometric sounding is usually carried out using method of electrotomography (ET), and leading methods of inductive sounding are audio-magnetotellurgic (AMT) sounding or near-field transient electromagnetic (TEM) sounding. Coordination of the results obtained with different means is one of relevant issues in modern mining electrical exploration.

For direct current methods (VES, ET) steadily definable geoelectrcial parameters are lateral conductivity of conducting layers $S = h/\rho$ and transverse resistance of high-ohmic layers $T = h\rho$. Using results of inversion, geometric mean of seam resistance is estimated: $\rho_m = \sqrt{\rho_l \rho_n}$, where ρ_l and ρ_n – resistance of layers along and across bedding.

For inductive low-frequency soundings (AMT, TEM) reliably definable parameters are total lateral conductivities S of low-ohmic layers and depth H to their upper edges. Strongest influence on the results in these methods comes from lateral rock resistance ρ_l.

Thus, geometric direct current sounding allows to get information about transverse resistance of high-ohmic layers, but is unreliable in estimating depth. Inductive sounding can estimate depth till the roof of conducting layers with good precision, but contains no data on resistance of high-ohmic layers. Complex use of two different types of sounding permits to expand the circle of geologic problems, from direct search for ore bodies to detection of indirect ore evidence [2, 6].

Algorithm of combined inversion of ET and AMT sounding data in the software ZondRes2D. Opportunities of combined inversion of electrotomographic and audio-magnetotellurgic sounding data have been realized in the software ZondRes2D by A.E.Kaminskii. The functions of the program permit to integrate different components of magnetotellurgic (MT) field with data from surface electrotomography (ET) in the process of selecting a model of electrical resistivity (ER).

The main problem in modern interpretation of different electrical exploration data lies in the mismatch between the scale of combined methods. This shows in the difference of effective volumes, covered by the field, as well as in different impact of electrical conductivity on the components of electrical and electromagnetic fields at macroscopic level. Besides, galvanic distortions and unequal influence of 3D objects on the results of measurements can complicate interpretation of field data.

In order to cope with galvanic effects in magnetotellurgic method, a technique of fitting static lags along with inversion resistance is used. To suppress «three-dimensionality» an additional weight parameter is introduced, which is chosen in accordance with earlier calculated parameter

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of asymmetry *skew*. In the easiest case, this parameter is inversely proportional to *skew*, which allows to decrease significance of MT-data, characterized by greater parameters of «three-dimensionality». Introduction of «penalties for three-dimensionality» along with using parameters of *skew* type for 2D inversion of 3D-distorted data is a tool widely applied in practice [1].

Newton least square method of iteration with regularization is used for solving an inverse problem. In case of inversion, each measurement has an individual weight, obtained in the course of processing, as well as a general one, which controls significance of this type of data (or component) in the general mis-tie. Thus, an opportunity emerges to increase the impact of certain type of data on the final ER model.

Functionality of the mis-tie consists of four parts: mis-tie in electrotomographic data, mis-tie in magnetotellurgic data, model smoothness, galvanic P-effect of MT-data. Two types of strict constraints are put on the latter component: minimization of the total of all lags and maximization of the lag (selected using graph analysis of apparent resistivities along the profile).

An option of mis-tie functionality of combined inversion has been used for effective MT impedance:

$$\Psi(m) = ||W_{\text{skew}}W_{\rho\text{MT}}(\rho^{\text{MT}} - \rho^{\text{MT}}(m) - \text{Sh}_{\text{st}}||^2 + ||W_{\text{skew}}W_{\varphi\text{MT}}(\varphi^{\text{MT}} - \varphi^{\text{MT}}(m)||^2 +$$
$$+ ||W_{\rho\text{ERT}}(\rho^{\text{ERT}} - \rho^{\text{ERT}}(m)||^2 + \lambda||W_{\text{m}}m||^2,$$

where W_{skew} – measurement weights, calculated in accordance with *skew* parameter; $W_{\rho\text{MT}}$ – measurement weights of effective MT apparent resistivities; ρ^{MT} and $\rho^{\text{MT}}(m)$ – logarithms of experimental and calculated data on effective MT apparent resistivities; Sh_{st} – galvanic P-effect in each point (in log), fitted in the course of inversion; $W_{\varphi\text{MT}}$ – measurement weight of phases of effective MT impedance; φ^{MT} and $\varphi^{\text{MT}}(m)$ – experimental and calculated phases of effective MT impedance; $W_{\rho\text{ERT}}$ – measurement weights of ET apparent resistivities; ρ^{ERT} and $\rho^{\text{ERT}}(m)$ – logarithms of experimental and calculated data on ET apparent resistivities; λ – regularization parameter; W_m – operator, responsible for model smoothness in the course of inversion; m – logarithm vector of section resistivities.

General weights of inversion components are usually selected empirically, basing on two-three trial inversions. Due to varying metrics of different data components, attributing value to the regularization parameter λ can play a central role in the solution convergence. The algorithm utilizes wide-range linear search for optimal value of regularization parameter on every iteration.

For combined data inversion both effective impedances and TM/TE-modes can be applied. Feasibility of using effective impedance in 2D MT-inversion of 3D-distorted data has repeatedly been examined in domestic and foreign publications [7], including its eligibility for mining problems [1, 3]. Opportunities of combined inversion of electrotomographic and radio-magnetotellurgic sounding data in software ZondRes2D have previously been reviewed for solving problems of engineering geophysics [2]. In the current paper we estimated potential of new inversion to solve mining problems where the depth of research amount to hundreds of meters and unconventional electrotomographic devices are utilized.

Testing the algorithm of combined inversion on synthetic models. Testing of combined inversion has been carried out on a range of synthetic models imitating ore objects of different sizes and configurations. The paper contains selective testing results, demonstrating that combined inversion of AMT sounding and ET can lead to a significant increase in resolving power of electrical exploration methods.

In the course of modeling for ET method we have used asymmetrical axial array with a long current circuit AB [5]. Such array is used for deep electrotomographic measurements (300-500 m). The length of current circuit AB = 500 m, length of receiving line increased by the range from 20 m for small spans to 200 m for large ones. Spans *AO* vary from 50 to 1200 m. Distance between sounding points is 40 m. Described array permits to investigate both small and great depths at constant length of current dipole. For small spans, as the influence of remote current electrode is insignifi-

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cant, it corresponds to three-electrode Schlumberger array, for large spans it functions as a traditional dipole axial array, for mid spans it is an asymmetrical four-electrode array. Spans, lengths of receiving lines and distance between sounding points have been fashioned in such a way that, while the array moves along the profile, electrodes of receiving and current lines are repeatedly used at different spans.

Calculation of magnetotellurgic parameters to solve the direct problem has been carried out at 20 frequencies in the range from 1 to 10000 Hz, which corresponds to conventional working range of audio-magnetotellurgic sounding [4].

At the first stage two direct 2D problems have been estimated using software ZONDMT2D and ZondRes2D. We have examined vertical, horizontal and inclined conducting bodies of simple shapes, as well as more sophisticated models imitating actual ore deposits of various types. Some models have been complicated by adding geoelectric heterogeneities in the upper part of the section. At the second stage inversion has been carried out, separately for MT-parameters and ET data. At the last stage combined inversion of electrical exploration data. Inversions at all stages have been carried out on a starting semi-space model with ER = 1000 Ohm·m. For ET method the quality of fitting is characterized by mis-tie between the curves of apparent resistivity ($\rho_к$). For inversion of MT-data the quality of fitting is defined by mis-ties between curves of apparent resistivity and impedance phase for TM-mode (ρ^H, φ^H), TE-mode (ρ^E, φ^E) or for effective curves (ρ^{eff}, φ^{eff}). Fitting mis-ties are presented on relevant figures.

Depth of ore formations in calculation models has not exceeded 600 m with thickness varying from 50 to 200 m. Surrounding media was a homogenous space with resistivity 1000 Ohm·m. Resistivity of ore bodies amounted to 100 Ohm·m. Insignificant contrast between ore bodies and surrounding rocks from the viewpoint of resistivity reflects actual insignificant drops in ER, characteristic of rocks with ingrained or vein-disseminated mineralization.

Model of horizontal conducting body. When a conductor with thickness of 100 m and length of 500 m is located in homogenous semi-space at the depths of 100-400 m, its boundaries and resistivity can very well be obtained using either ET or AMT sounding data.

Adding to the model a surface conducting layer with thickness of 50 m and resistivity of 50 Ohm·m, imitating quaternary sediments will decrease sensitivity of MT-parameters to deeper conductors. Anomaly-forming bodies are detected using inversion, but their shape and electrical properties are retrieved incorrectly, especially horizontal dimensions. In the model Fig.1.**1** horizontal conducting bodies sized 500 × 100 m are located at different depths from the surface (depth of the upper edge ranges from 150 to 250 m). Compared to magnetotellurgic inversion (Fig.1.**2**), carried out using six components (TM-, TE-modes and tipper), and ET inversion (Fig.1.**3**), results of combined inversion allow to retrieve boundaries of all bodies with greater precision, especially in case of their relatively shallow occurence (Fig.1.**4**). Deterioration of the results with further immersion of objects is related to limited applicability of the electrotomographic array from the viewpoint of depth.

Horizontal conducting seam is a basic model for ore deposits of such type, e.g., magmatic liquation deposits. Sulphide copper-nickel ores in deposits of this type are formed in the bottom part of differentiated intrusions. Ores can be represented both by continuous sulphide bodies and vein-disseminated mineralization. Total thickness of mineralization zones can reach dozens of meters. Electrical resistivity of continuous ores equal several Ohm-meters, for regions of ingrained mineralization – dozens Ohm-meters.

Model in Fig.2.**1** imitates such a deposit. Ore-bearing intrusion is located at the depth 50 m and has a trapezoid shape. Maximal thickness of intrusion is 150 m, width – 1 km. Electrical resistivity of surrounding rocks – 1000 Ohm·m, ER of intrusion rock is higher and reaches 5000 Ohm·m. At the base of intrusion lies a horizontal conducting seam 30 m thick and 700 m long – a plane of sulphide mineralization. Intrusion is overlapping with surface conducting layer, which thickness equals 50 m and resistivity amounts to 70 Ohm·m. Upper conductor imitates conducting quaternary sediments.

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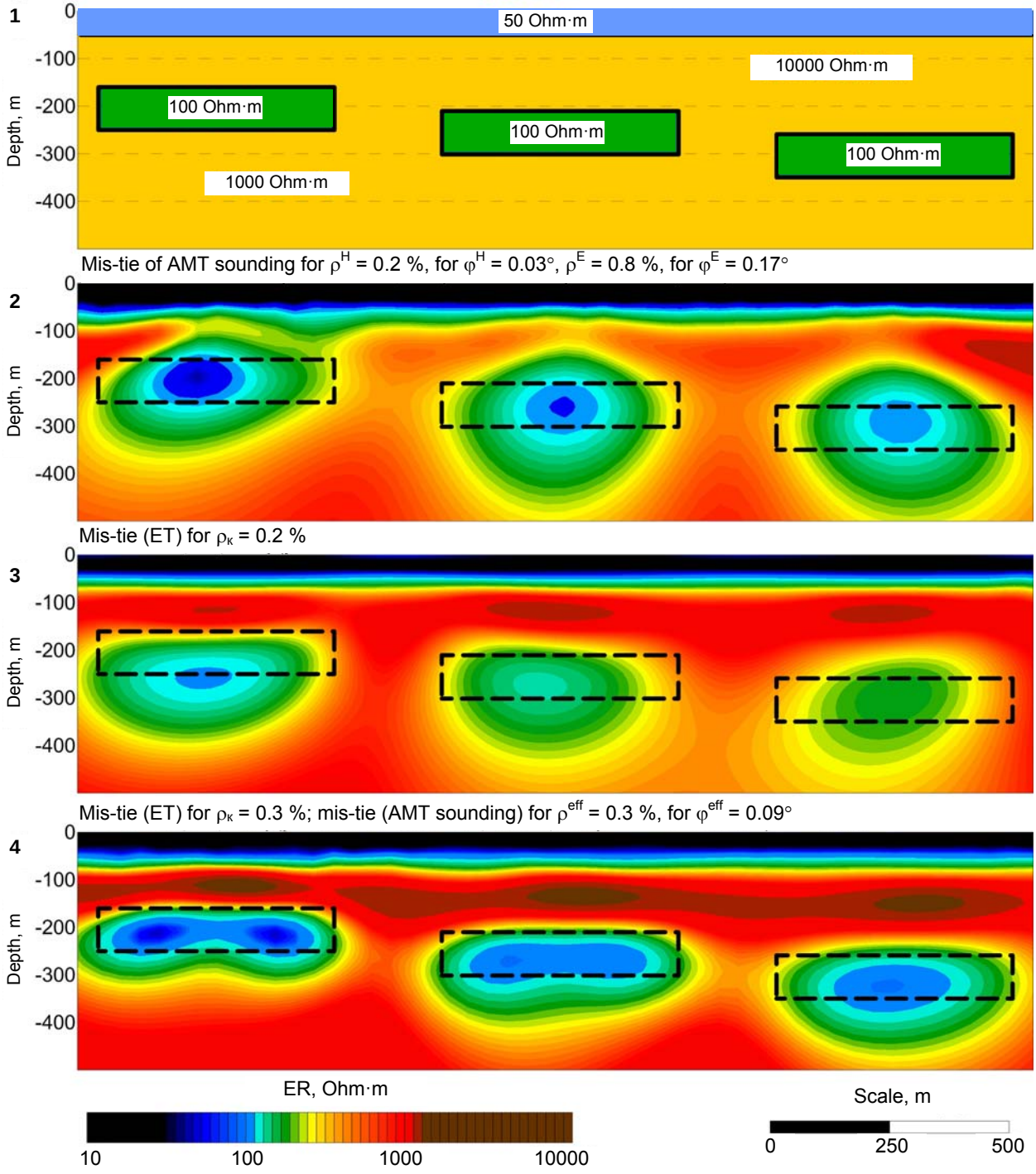


Fig.1. Synthetic model 1 of horizontal conducting layer

1 – initial model; **2** – result of data inversion for AMT sounding (bimodal impedance and tipper); **3** – result of data inversion for ET; **4** – result of combined data inversion for ET and AMT sounding

As a result of bimodal inversion of magnetotellurgic impedance, in the center of the model we get an area with a slightly decreased ER, which can wrongly be attributed to the increase of thickness of surface conductor (Fig.2.**2**). High-ohmic body of intrusion does not appear in the final model, carried out using inversion of TM-data. A deep conductor is better revealed in case of bimodal impedance and tipper inversion, though its boundaries do not match the initial model (Fig.2.**3**). Inversion of ET data is an effective tool to define boundaries of high-ohmic intrusion (Fig.2.**4**), but the latter totally screens the conductor. Combined inversion of ET and AMT sounding data produces the closest result to the initial model: boundaries of high-ohmic intrusion are defined with great precision, however, the depth of occurrence and thickness of the ore body are slightly overestimated (Fig.2.**5**).

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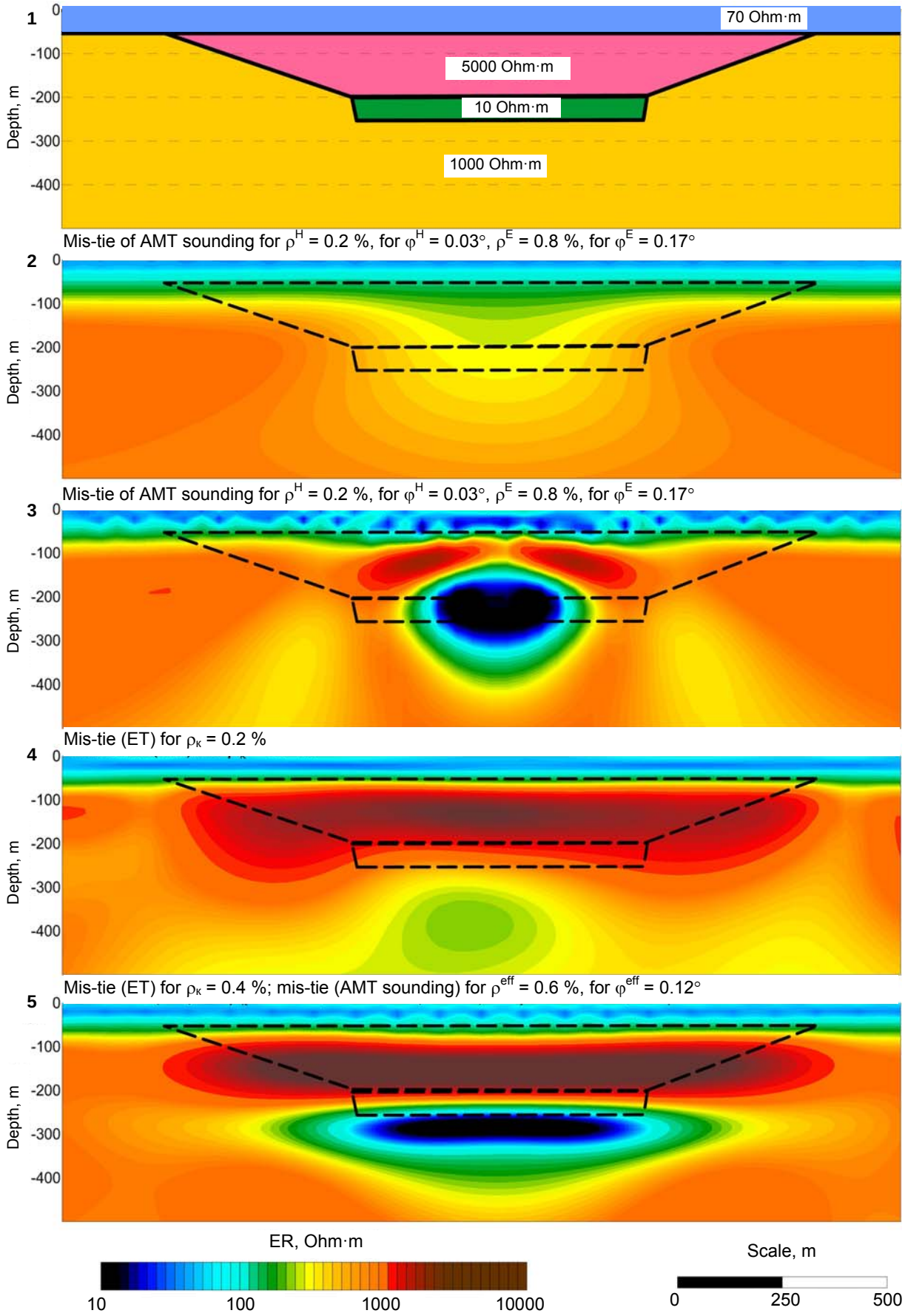


Fig.2. Synthetic model 2 of high-ohmic intrusion with a conductor in the base

1 – initial model; **2** – result of data inversion for AMT sounding (bimodal inversion); **3** – result of data inversion for AMT sounding (bimodal impedance and tipper); **4** – result of data inversion for ET; **5** – result of combined data inversion for ET and AMT sounding

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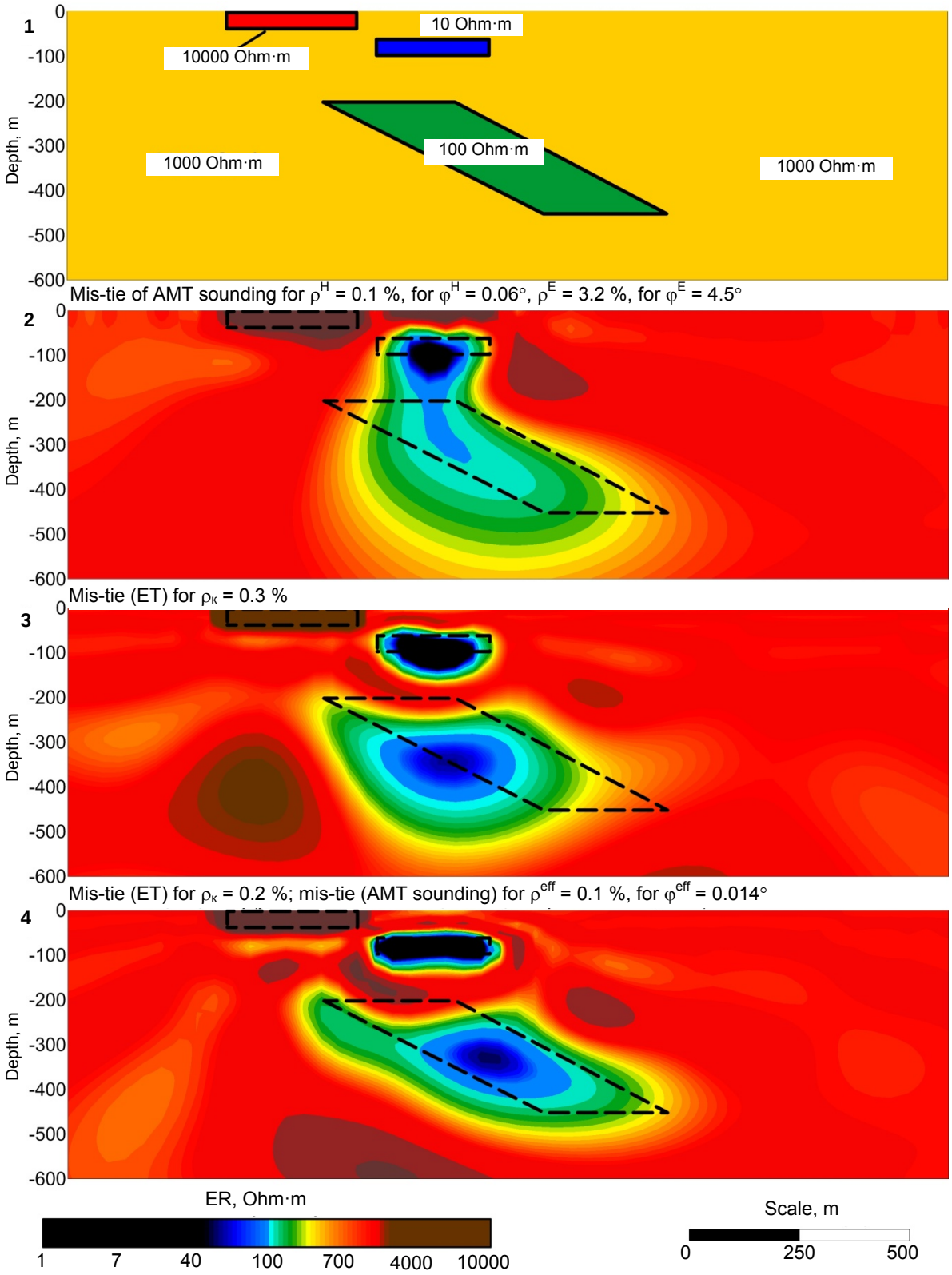


Fig.3. Synthetic model 3 of inclined conductor with surface heterogeneities

1 – initial model; **2** – result of data inversion for AMT sounding (bimodal inversion); **3** – result of data inversion for ET; **4** – result of combined data inversion for ET and AMT sounding

Model of inclined conducting body. Inclined orientation is characteristic of many ore deposits. Those can be skarn bodies adjacent to exocontact granitoid intrusions, areas of sulphide mineralization in porphyry-copper deposits etc.

Inclined conducting bodies of simple shapes in homogenous semi-space can easily be defined by separate methods of electrical and electromagnetic soundings. But presence of a conducting

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surface layer or local surface heterogeneities (especially of low resistivity) decrease the quality of MT-parameter inversion (Fig.3.**1**). In the final models local surface bodies merge with deeper objects (Fig.3.**2**), and the results of electrotomography present them as isometric bodies of round shape (Fig.3.**3**). In such cases combined inversion significantly increases the quality of final results (Fig.3.**4**).

Model 4 has features, characteristic of porphyry-copper deposits with an area of heightened ER in the center due to secondary silification of the rocks and narrow conducting zones framing central stockwork and imitating areas with sulphide mineralization (Fig.4.**1**).

On the general, the model can be well retrieved using inversion of MT-impedance and tipper (Fig.4.**2**). In the center there is a zone of heightened resistivity belonging to a high-ohmic body, lateral areas of reduced resistivity can also be seen. However, the width of these areas is much greater than in the model and amounts to several hundreds of meters instead of 50 m, and ER significantly exceeds resistivity of conducting layers in the starting model.

Results of ET-data inversion produce boundaries and resistivity of high-ohmic zone close to the initial model (Fig.4.**3**). Boundaries of conducting layers are retrieved insufficiently, merge with the upper layer and can hardly be read from the results of inversion.

Combined inversion produces a more balanced model (Fig.4.**4**), which better corresponds to the initial one. Still resistivities of lateral conductors are overestimated, and the boundaries of central high-ohmic body are retrieved imprecisely.

Increasing depth of IP method based on combined inversion of AMT sounding and ET. Demonstrated earlier examples were related to estimation of one physical parameter of the rock – electrical resistivity. Using results of combined inversion of geometric and inductive soundings, one can improve depth and sensitivity of yet another method of electrical exploration – method of induced polarization (IP), which gives us additional parameter of the media – electric polarizability.

IP method utilizes the same installations as resistivity method. To examine horizontally-heterogeneous media standard methods and approaches of electrotomography are used. As mentioned earlier, one of the drawbacks of ET method is limited depth of investigation, which depends on the maximal span of the array. Larger arrays mean significantly higher costs of exploration.

When abnormal conductivity and polarizability of minerals have the same origin, a starting model for IP-data inversion can be same as used in ER estimations. Such approach is quite acceptable for ore objects, because presence of sulphide minerals in the rocks reduces resistivity and increases polarizability. Combined inversion of ET and AMT sounding, compared to separate inversion of electrotomographic data, permits to build ER model for greater depths. Using this model as a starter one for IP-data inversion, we can increase the depth of polarization model as well.

An example of this approach applied to modeling data is demonstrated in Fig.5. Homogenous non-polarizable semi-space with resistivity 1000 Ohm·m at the depth of 400 m contains a conducting and polarizable body with thickness 100 m, width 500 m, resistivity 10 Ohm·m and polarizability 10 % (Fig.5.**1**). In the surface part a 50-meter layer with high resistivity – 5000 Ohm·m – has been added.

Great depth of conductor occurrence and presence of a surface isolator significantly reduce abilities of electrotomography to determine location and electrical properties of the body. Area of reduced resistivities as a result of ET data inversion only provides vague information about position of the center and about depth of the conductor (Fig.5.**2**). Polarization model has small deviations from baseline values, fitting into actual measurement error (Fig.5.**3**).

Combined inversion of ET and AMT sounding permits to retrieve boundaries and resistivity of the deep conductor with great precision, and basing on obtained ER model (Fig.5.4) – its polarization properties (Fig.5.**5**).

Example of combined inversion of ET and AMT sounding for field data. Pyrite-polymetallic deposit Signalnoye is situated in Leninogorsk mining region of Rudno-Altai mineragenic zone.

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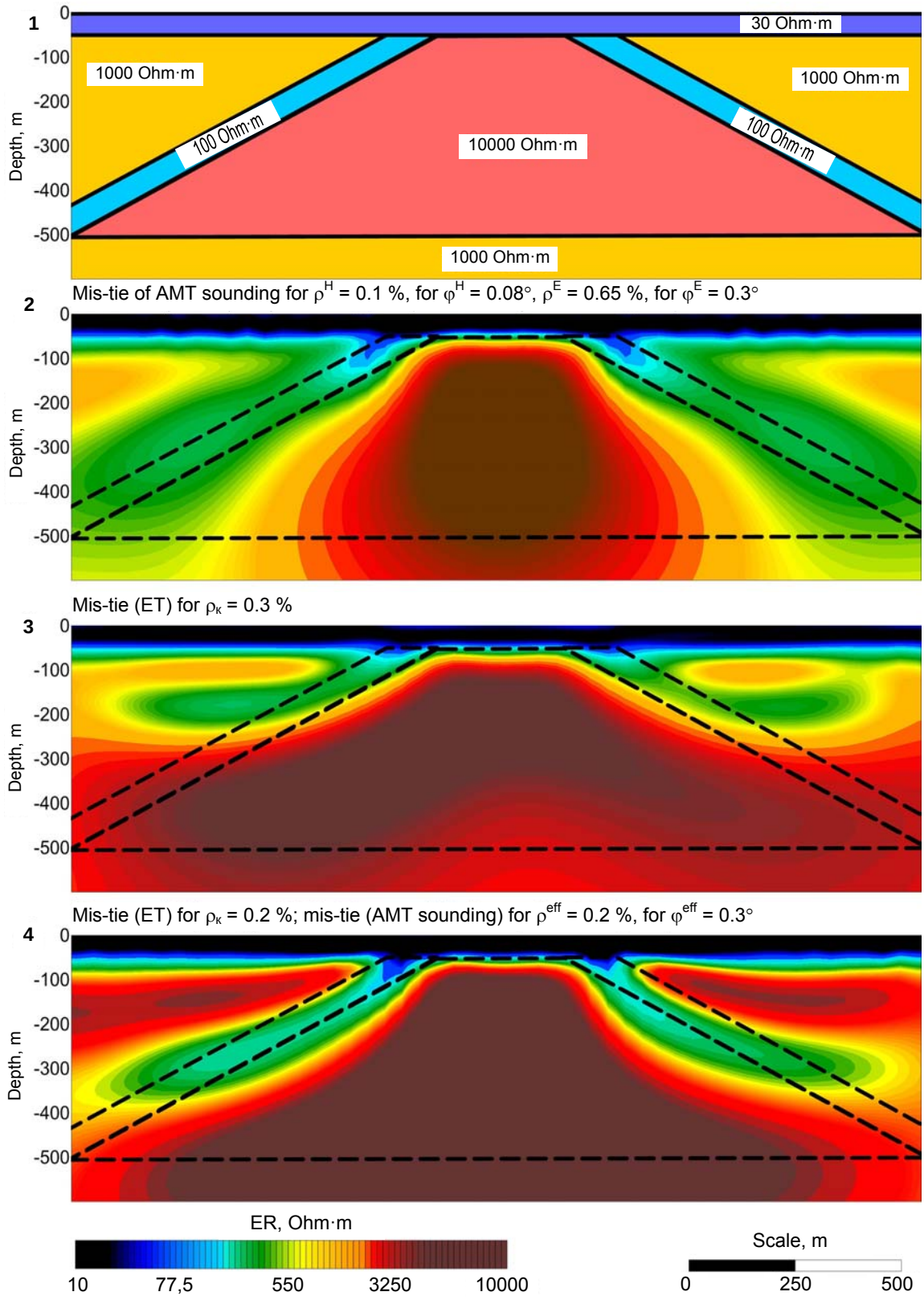


Fig.4. Synthetic model 4 of porphyry-copper deposit

1 – initial model; **2** – result of data inversion for AMT sounding (bimodal impedance and tipper); **3** – result of data inversion for ET; **4** – result of combined data inversion for ET and AMT sounding

The deposit is located in allochthon of a large transpressional fault, along which Mid-Devonian igneous-sedimentary rocks are overlapping aleurolite-silstone depth of terrigene formation. The rocks are striking NW 300-320°, dipping at a high angle, mostly monoclinal, SW 65-85°.

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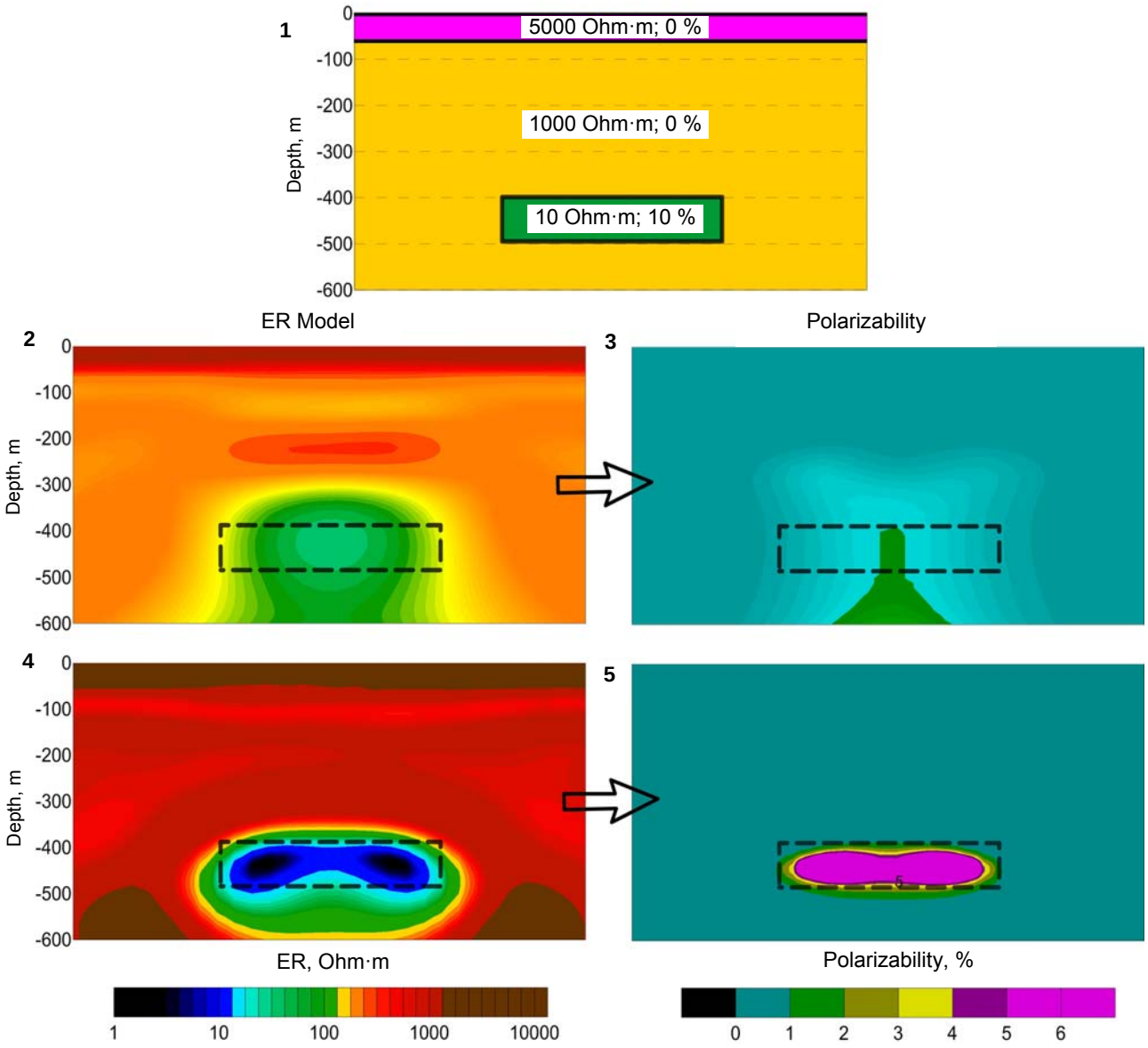


Fig.5. Synthetic model 5 of horizontal conducting and polarizable layer

1 – initial model; **2**, **3** –result of data inversion for ET (2 – ER model, 3 – polarizability model); **4**, **5** – result of combined data inversion for ET and AMT sounding (4 – ER model, 5 – polarizability model)

Mining zone is confined to NW-trending split, accompanied by a zone of increased cleavage and hydrothermal-metasomatic rock modifications, with intensive pyritization and nested-vein-disseminated mineralization of copper pyrite, sphalerite and galenite. Width of zone of intensively modified rocks amounts to 200-250 m, length – over 1 km. Zone of increased cleavage and intermediate seritization is spread much wider and has dimensions 350 × 1500 m.

Complex operations of electrical exploration by methods of ET and AMT sounding have been carried out for 2500 m-long profile cross-secting the ore zone.

For implementation of ET method an axial array «dipole – dipole» has been used. Array parameters: current line AB = 660 m, spans – from 15 to 1740 m, receiving line MN = 10÷400 m. Profile step in ET method was 50 m. Audio-magnetotellurgic sounding has been carried out using equipment «Phoenix Geophysics» in the mode of five-component survey with reference point over 100 m.

Depth of investigation for ET array in current geological section approximated 500 m. On ER model, obtained in the result of data inversion from ET (Fig.6.**1**), the deposit is clearly distinguished in the central part of the profile as sub-vertical area of low resistivity (< 30 Ohm·m). One more zone of reduced ER is detected 300 m NE from identified ore bodies and corresponds to the zone of metasomatites according to drilling data.

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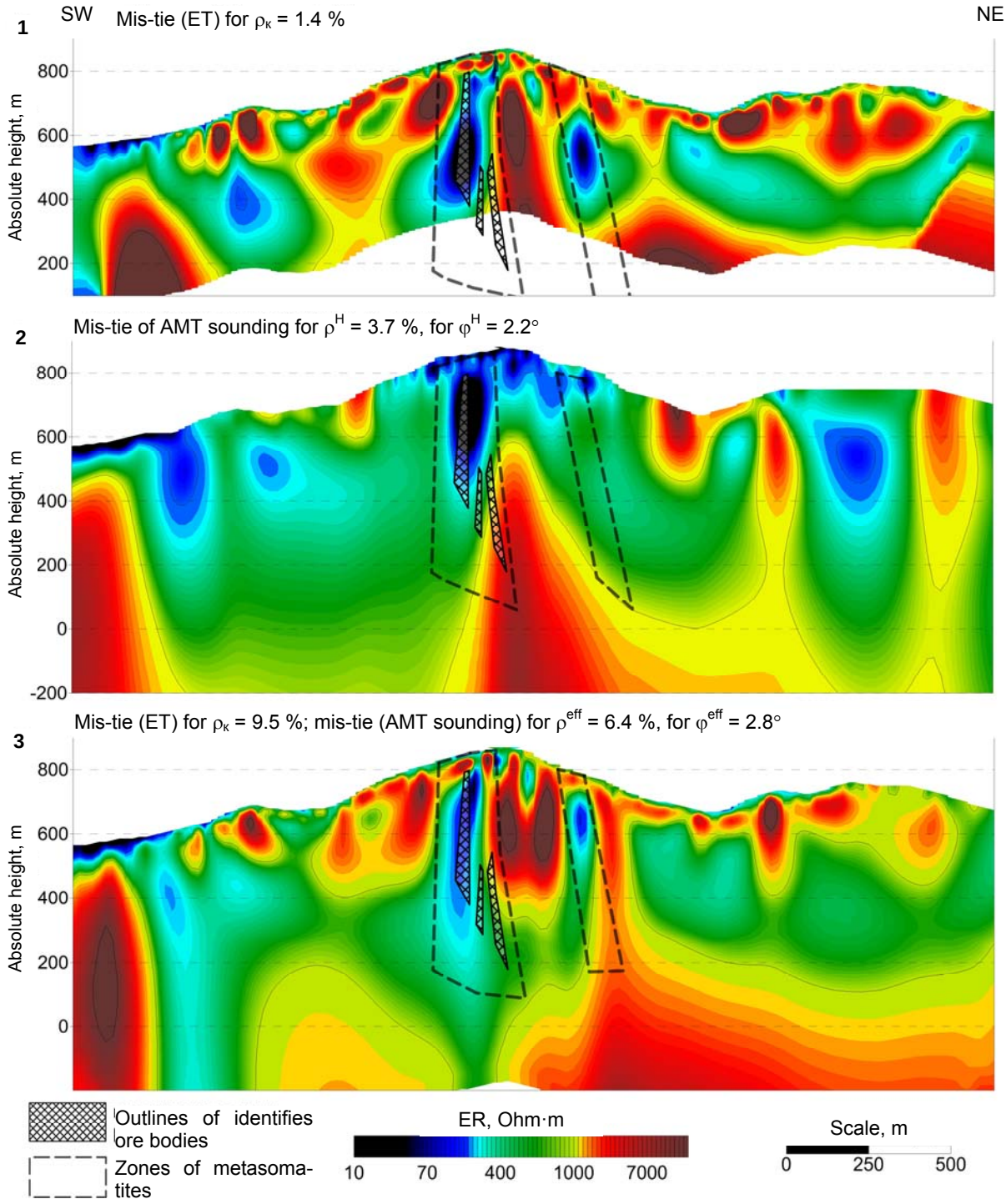


Fig.6. Signalnoye deposit

1 – result of data inversion for ET; **2** – result of data inversion for AMT sounding (bimodal inversion); **3** – result of combined data inversion for ET and AMT sounding

According to results of bimodal inversion of AMT sounding data with tipper, ER section is generally more conducting (Fig.6.**2**). The main ore body is definitely visible on the geoelectrical model, but its thickness is slightly overestimated.

The most balanced model, obtained from the results of combined data inversion from AMT sounding and ET, contains both high-ohmic areas, related to quartzite bodies and gabbro-diorite dikes, and also conducting zones, related to ore bodies of the deposit and areas of sulphide mineralization (Fig.6.**3**). Judging by results of combined inversion, both zones of hydrothermally modified rocks merge at the depth of around 600 m.

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Conclusions. Result, presented in this paper, demonstrate significant advantages that we obtain using combined inversion of geometric direct current methods and electromagnetic inductive sounding to solve mining problems. Electrotomography as a direct current method has advanced sensitivity to high-resistivity objects and permits to define boundaries of intrusions, silification areas, dikes and other high-ohmic bodies with higher consistency. ET method is aimed at investigating heterogeneous geologic media, i.e. majority of existing ore provinces. Main disadvantage of this method is limited depth of investigation. Increasing spans lead to problems of different kinds, such as: growth of source power and lengths of current and receiving lines, transition to lower frequencies and, as a result, increasing duration of measurements to satisfy near zone conditions etc.

Depth of magnetotellurgic methods is only limited by recording time in the measurement point. Audio-magnetotellurgic range is usually enough to reach the depth of several hundred meters – first kilometers. Recording duration in this mode does not exceed 1h. MT-parameters have advanced sensitivity to conducting objects and do not get screened by high-ohmic layers. Magnetotellurgic inversion can be carried out using different independent parameters, so that they complement each other and narrow the region of equivalent solutions to the inverse problem.

When abnormal conductivity and polarizability of minerals have the same origin, data inversion for induced polarization can be carried out using a starting ER model. Such approach is quite acceptable for ore objects, because presence of sulphide minerals in the rocks reduces resistivity and increases polarizability. Combined inversion of ET and AMT sounding, compared to separate inversion of electrotomographic data, permits to build ER model for greater depths. Using this model as a starter one for IP-data inversion, we can increase the depth of polarization model as well.

REFERENCES

1. Varentsov Iv.M., Kulikov V.A., Yakovlev A.G., Yakovlev D.V. Possibilities of Magnetotellurgic Methods in Geophysical Exploration for Ore Minerals. *Fizika Zemli*. 2013. N 3, p. 9-29 (in Russian).

2. Kaminskii A.E., Erokhin S.A., Shlykov A.A. Joint 2D Inversion of Electrical Resistivity Tomography and Radio/Audio Magnetotellurgic Data. *Geofizika*. 2015. N 4, p. 32-39 (in Russian).

3. Andreeva E.V., Bobachev A.A., Varentsov Iv.M. et al. Combination of Geophysical Methods for the Purposes of Exploration of Copper-Nickel Ores on the Objects of MMC «Norilsk Nickel». *Razvedka i okhrana nedr*. 2006. N 8, p. 71-79 (in Russian).

4. Kulikov V.A., Yakovlev A.G. Practical Application of Magnetotellurgic Methods in Orebody Geophysics. *Razvedka i okhrana nedr*. 2011. N 3, p. 26-33 (in Russian).

5. Kulikov V.A., Bobachev A.A., Yakovlev A.G. Application of Electrical Resistivity Tomography in Deep Mining Prospecting. *Geofizika*. 2014. N 2, p. 39-46 (in Russian).

6. Electrical Exploration: Guidelines for Electrical Exploration Practice. Ed. by V.K.Khmelevsky, I.N.Modin, A.G.Yakovlev. GERS Moscow, 2005, p. 311 (in Russian).

7. Pedersen L.B., Engels M. Routine 2D Inversion of MT Data Using the Determinant of the Impedance Tensor. *Geophysics*. 2005. Vol. 70(2), p. G33-G41.

***Authors*: Viktor A. Kulikov**, *Doctor of Geological and Mineral Sciences*, *Associate Professor*, *vic@nw-geophysics.ru* (*Lomonosov Moscow State University*, *Moscow*, *Russia*), **Aleksandr E. Kaminskii**, *Head of Interpretation Group*, *kaminae@yandex.ru* («*Astra LTD*», *Saint-Petersburg*, *Russia*), **Andrei G. Yakovlev**, *Candidate of Physics and Mathematics*, *Associate Professor*, *mail@nw-geophysics.com* (*Lomonosov Moscow State University*, *Moscow*, *Russia*).

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