History and state of the art of magnetotelluric studies of the lithosphere in Russia

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Geophysical **method of magnetotelluric (MT) sounding** is based on the use of the low-frequency electromagnetic (EM) field of the Earth to study its electric conductivity at various depths. The development of this method began in the 1950swith the pioneering works of A.N. Tikhonov (USSR), L. Cagniard (France) and T. Rikitake (Japan).

Andrey Tikhonov (fig. 1) began to study the theoretical problems of electrical exploration during the Second World War, already being a famous mathematician, corresponding member of the USSR Academy of Sciences. At that difficult time, the country needed oil, and he took part in electrical exploration for oil in Bashkiria. At that time, he proved the uniqueness theorem for solving the inverse problem of the DC resistivity method and laid the foundations for the theory of solving inverse (ill-posed) problems.

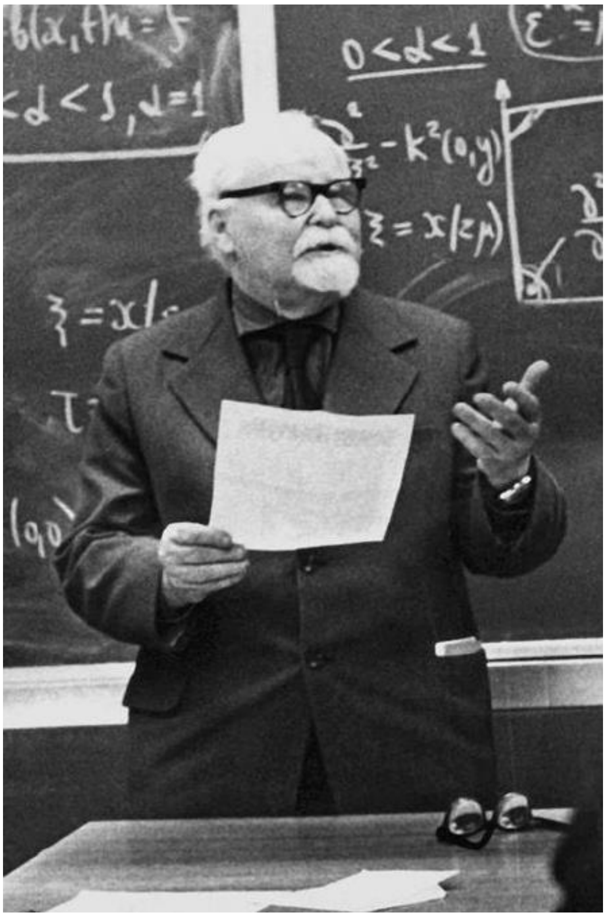

Fig. 1. Andrey Tikhonov (1906-1993).

In the postwar years, there was a rapid development of geophysical methods using alternate EM fields. The key work in this direction was an article by A. Tikhonov, published in 1950, in which he proposed to use the ratio between the orthogonal electric and magnetic components of the natural low-frequency field. Since then, the MT sounding method was developed both in the USSR and around the world.

In the institute "VNIGEOFIZIKA" in Moscow M. Berdichevsky and L. Vanyan were engaged in the development and implementation of EM methods. **Mark Berdichevsky** (Fig. 2) played a crucial role in the theoretical substantiation of the MT sounding method (in particular, he proposed using the impedance tensor [Z], which relates the horizontal vectors of the electric and magnetic fields), as well as in its application in Western Siberia and in other oil and gas promising regions of the USSR. Since 1969, M.N. Berdichevsky worked at the Lomonosov Moscow State University (MSU), where his scientific activity was associated with both the further theoretical development of magnetotellurics and its use to study electrical conductivity anomalies, identified in the continental consolidated crust of many regions, and related mainly to its fluidization and graphitization.

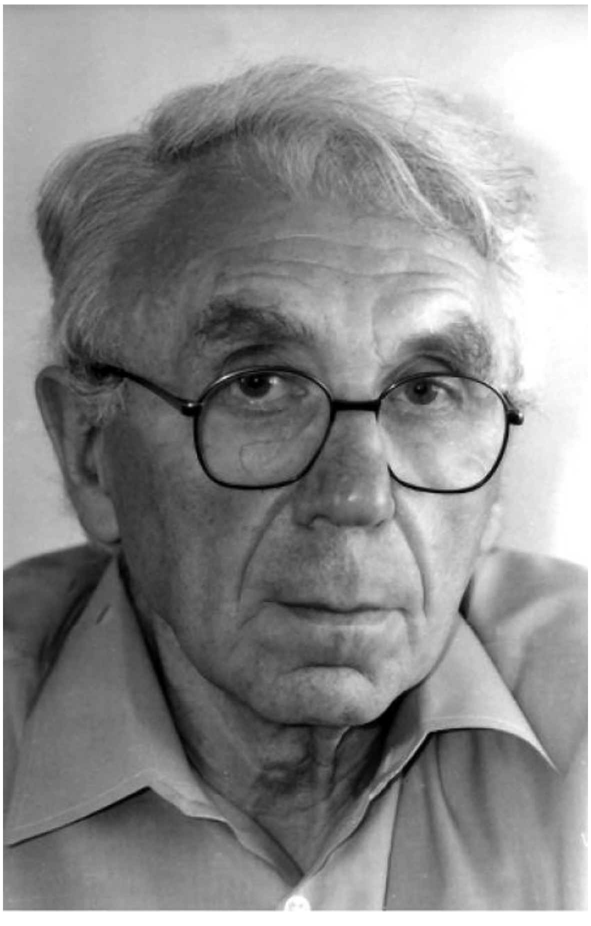

Fig. 2. Mark Berdichevsky (1923-2009).

Leonid Vanyan (Fig. 3) initially was primarily engaged in the development of EM sounding methods with a controlled source in the frequency or time domain. Later, in the field of his scientific interests was the application of the MT method to the study inhomogeneous conducting layer in the Earth's upper mantle (asthenosphere), associated with partial melting of the rocks. In the last years of the life L. Vanyan worked at the Institute of Oceanology, dealing with the use of EM methods with controlled and natural sources to study the Earth's crust and the upper mantle of the oceans.

Fig. 3. Leonid Vanyan (1932-2001).

The major role in the development of methods for solving forward and inverse problems of EM geophysics was played by **Vladimir Dmitriev**, a professor at MSU (Fig. 4). He solved, with the help of the method of integral equations, forward 2D and 3D problems of magnetotellurics, which made it possible to develop a theory of distortions of MT sounding curves in horizontally inhomogeneous media, and subsequently to solve 2D and 3D inverse problems. Of great importance in the latter case is the Tikhonov's regularization, which makes it possible to obtain a solution that is sufficiently detailed, and at the same time plausible, consistent with a priori information.

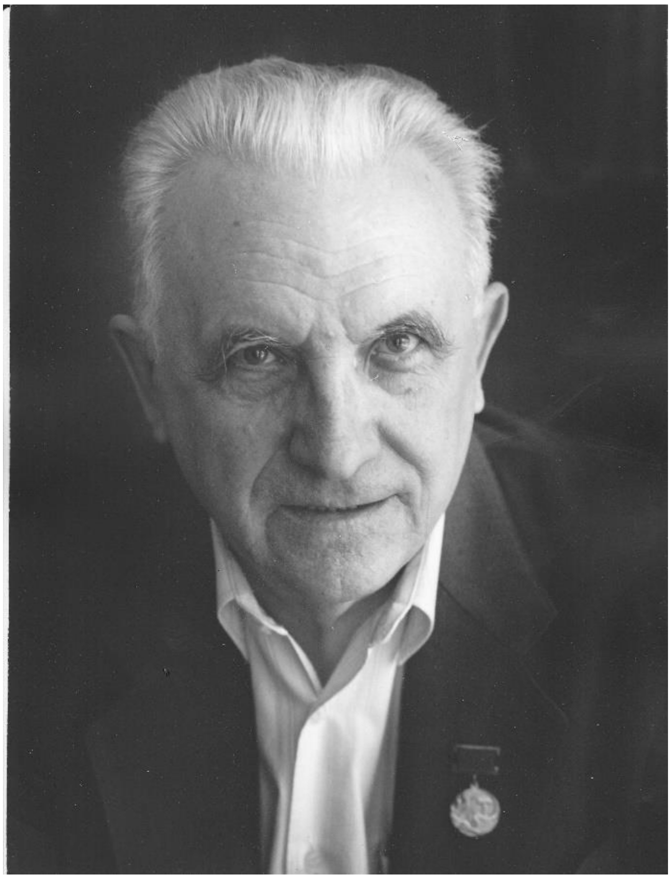

Fig. 4. Vladimir Dmitriev.

Fig. 5. Aida Kovtun (1929-2016).

At St. Petersburg University, studies of the natural EM field and, with its help, of the geoelectric structure of the lithosphere, were carried out for many years under the direction of **Aida Kovtun** (Fig. 5). She received, at the Borok Observatory, one of the first MT sounding curves. Later, using the MT method, a number of electrical conductivity anomalies in the crust on the Baltic Shield were investigated, and the method was implemented to solve many geological problems with different depths of exploration in the north-west of the country and in other regions.

The limited size of this paper does not allow us to introduce many other eminent geophysicists from the universities, research institutes and industrial organizations of the USSR, who were engaged in the development of MT method and its application to study lithosphere and solve exploration tasks. All-Union school-seminars on EM soundings were regularly held, where lectures by leading experts were given and new results obtained in the regions from the Carpathians to Kamchatka and from the Arctic to the Tien Shan were discussed.

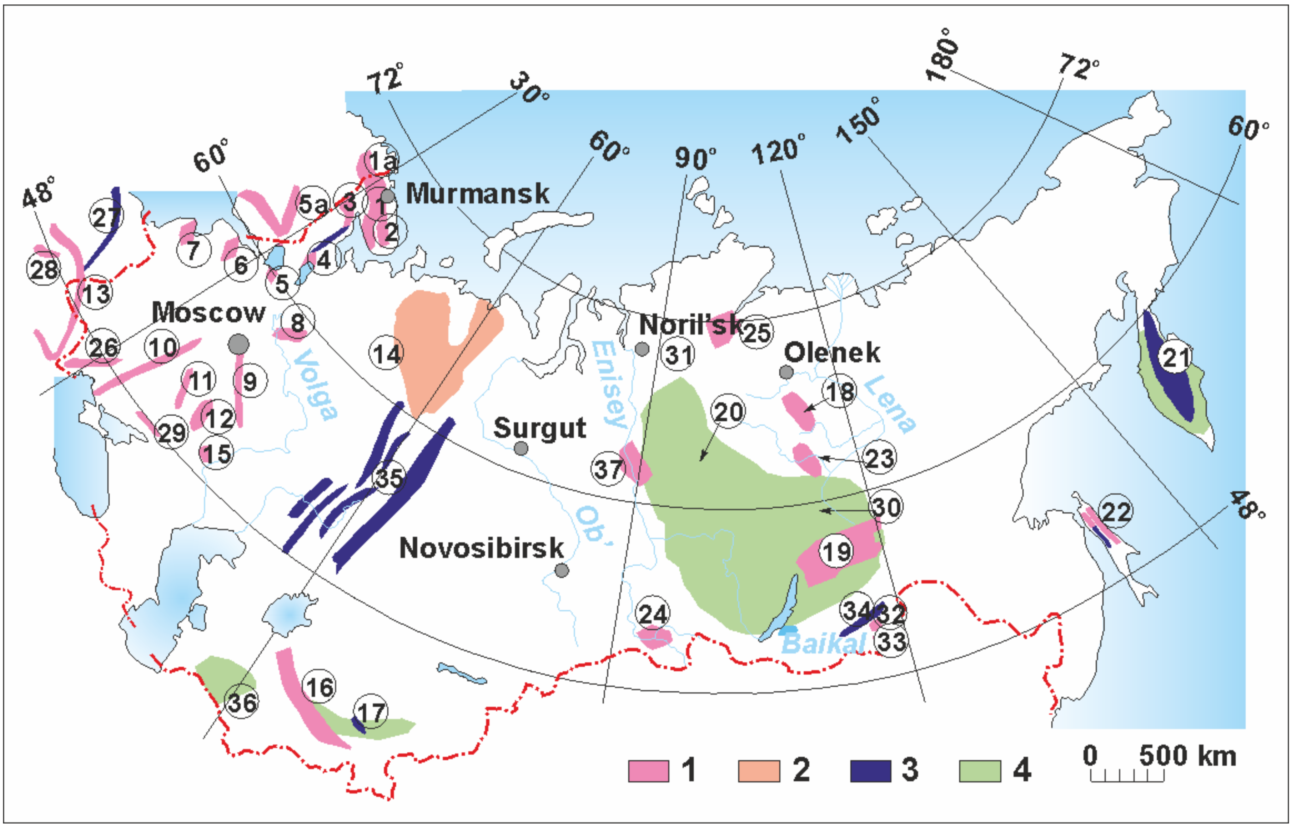

Fig. 6. Sketch map of crustal conductivity anomalies over the territory of the former USSR [Zhamaletdinov, 1996]. Crustal anomalies of presumably electron-conducting origin: 1 – linear high-conductive zones, 2 – vast high-conductive areas; crustal anomalies of presumably fluid origin: 3 – linear conductive zones, 4 – conductive areas.

It became necessary to systematize the obtained results of the studies of electrical conductivity anomalies in the Earth's crust. At the initiative of the country's leading scientists and on behalf of the USSR Ministry of Geology, the project was organized on **mapping the crustal conducting layer on the territory of the USSR** according to EM surveys data. The work was led by the Editorial Board of the map (chairman M. Berdichevsky, vice-chairmen - L. Vanyan and M. Zhdanov), which included representatives from more than 30 institutions.

Unfortunately, after the collapse of the USSR in the early 1990s, this work was interrupted due to lack of funding, and its main results remained unpublished. However, soon A. Zhamaletdinov compiled a sketch map of crustal conductivity anomalies, summarizing the obtained information (Fig. 6). It reflects the presumably dominant mechanism of conductivity (electron-conductive or ion-conductive).

The rapid technological development at the turn of the century led to the introduction of new measurement technologies and methods for data processing and interpretation. In the last decade, regional areal studies have been applied, combining deep (long-period) and exploration (broadband) MT soundings.

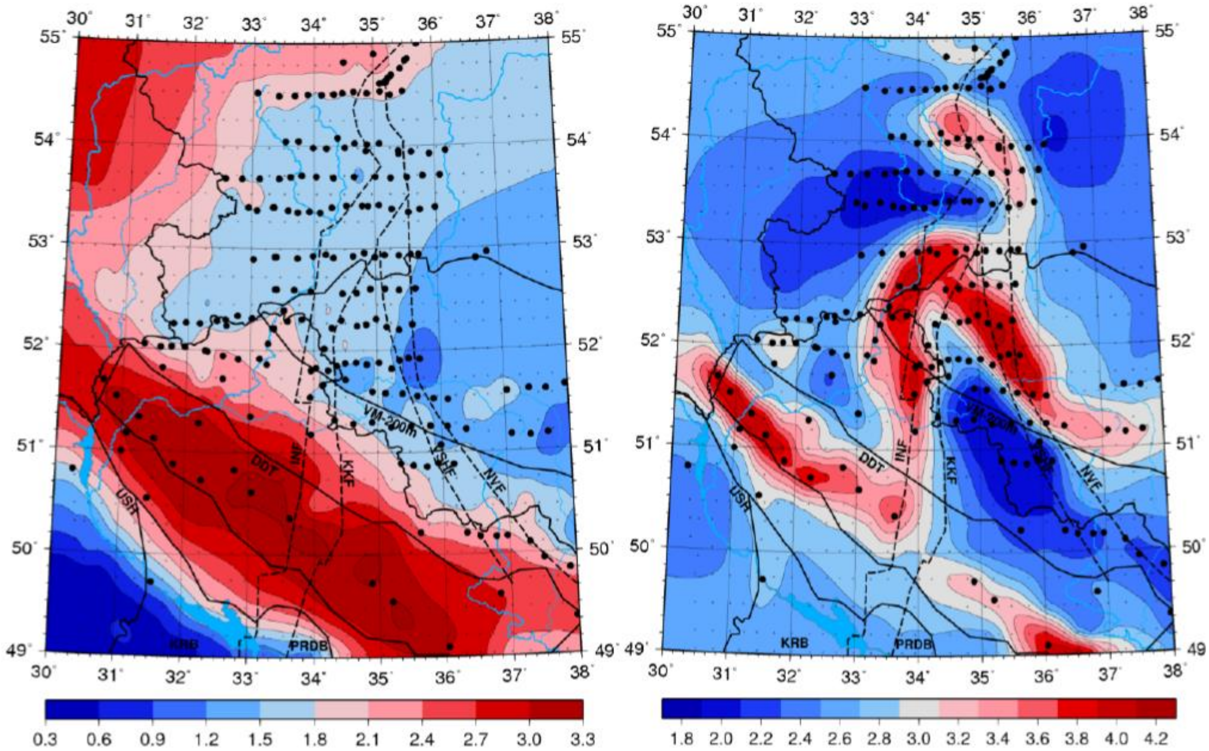

Fig. 7. Maps of longitudinal conductance (lg S) of the "sedimentary" layer (left) and "crustal" layer (right) obtained by quasi-3D inversion of horizontal magnetic tensor data at 400 s period, obtained in "Kirovograd" project [Varentsov et al., 2016].

An example of such research is the “Kirovograd” project, implemented on the initiative of Iv.M. Varentsov on the East-European Platform, in the western part of the **Voronezh anteclise**. Fig. 7 presents some of the results of this project in the form of conductance maps of the “sedimentary” and “crustal” layers. The first map clearly shows the Dnieper-Donets Basin (in the south-west), and the second - the Kirovograd (in the center), Kursk (in the east) and Baryatino (in the north) crustal anomalies. Interestingly, these anomalies of electric conductivity correlate with bright anomalies of potential fields, gravitational and magnetic.

New studies of the Ladoga crustal conduction anomaly in the northwest of the East-European platform, within the **Baltic shield**, were initiated by E.Yu. Sokolova. Fig. 8 shows a geoelectric cross-section of the Earth's crust along a profile intersecting this anomaly in the north-western Ladoga area. Recently, this anomaly was also investigated in detail to the south-east of Lake Ladoga. Probably, it marks the border of two platform blocks: the Late Archaean Karelian and the Early Proterozoic Svecofennian block.

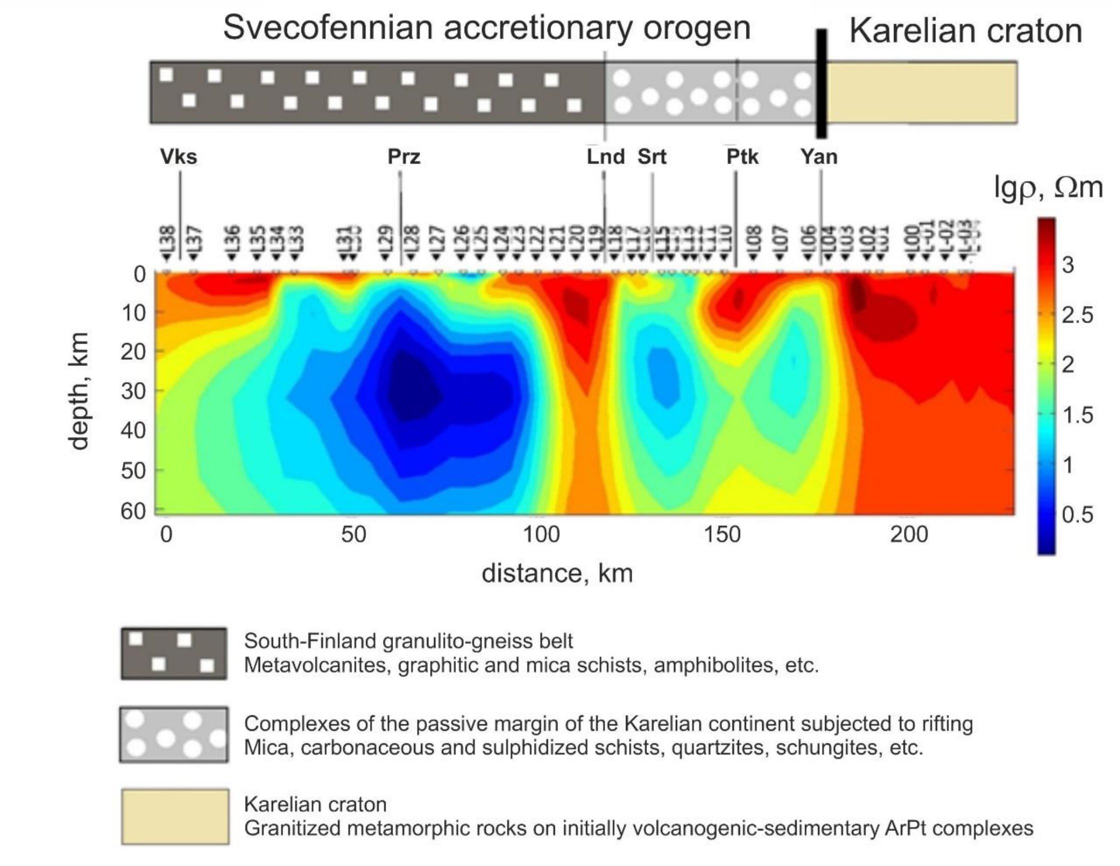

Fig. 8. “Vyborg-Suoyarvi” profile. Resistivity cross-section obtained by 2D inversion of transverse impedance, longitudinal impedance and tipper data. Tectonic structures and outcropping fault zones are also shown [Sokolova et al., 2016].

With the state support, a network of regional geophysical profiles is developed on the territory of Russia, ranging in length from a few hundred to the first thousand kilometers, through which MT soundings are performed with approximately 1 km step. Fig. 9 shows the resistivity cross-section constructed by the specialists of the North-West company using MT data along the 500-kilometer “Uralseis” profile, which starts on the East-European Platform and crosses the **Ural Mountains**. A conducting anomaly is located in the central part of the profile, apparently associated with deep watered faults. Large deposits of chromium and gold are confined to its surface outlets.

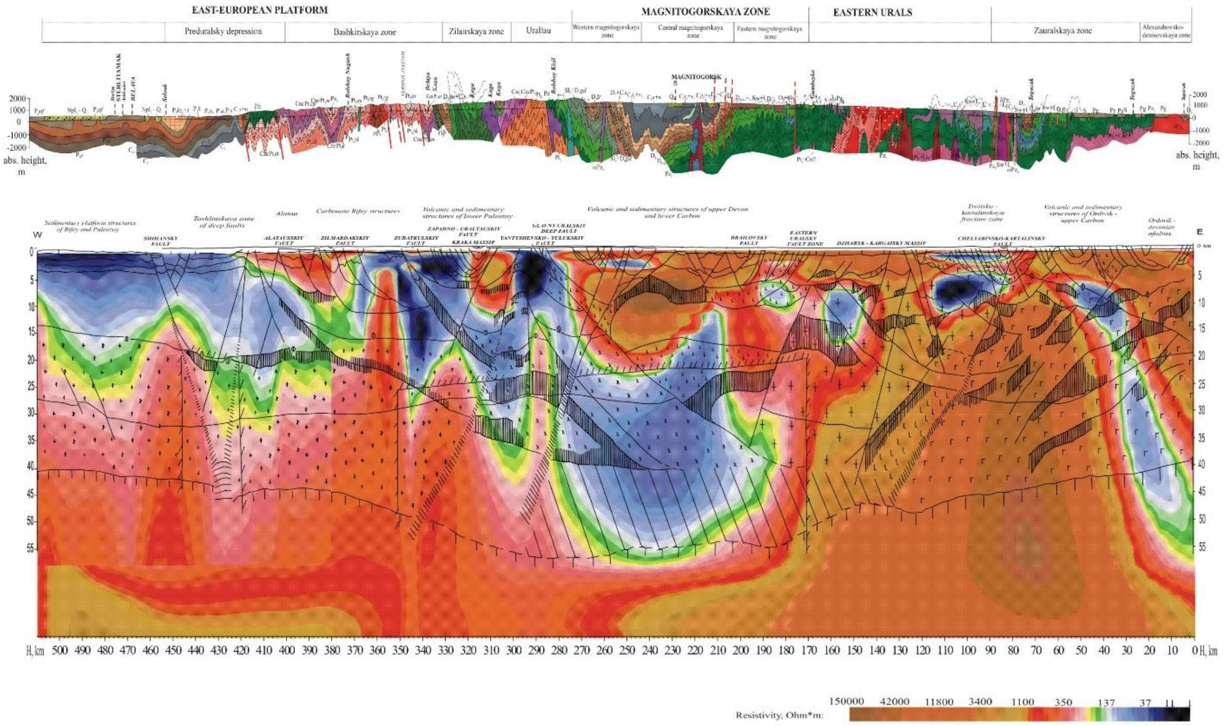

Fig. 9. “Uralseis” profile. Above – geological cross-section, below – resistivity cross-section of the Earth’s crust obtained by 2D inversion of MT data and the results of deep seismic sounding [Kulikov et al., 2003].

The 800 km long “1-SB” profile begins on the West-Siberian Plate, crosses the Yenisei tectonic belt and ends on the **East-Siberian Platform**. The deep resistivity cross-section along this profile (Fig. 10) was constructed by the specialists of the North-West company using MT data. Within the West-Siberian Plate, against the background of high conductivity of the sedimentary cover (1000 Sm), the details of the structure of the Earth's crust are not distinguishable. In the area of the Yenisei Ridge, a low-resistivity zone, the nature of which is controversial, is located beneath the near-surface resistive Proterozoic metamorphic rocks. On the East-Siberian platform in the middle crust a conductive layer with a resistivity of about 100 Ohm·m and a thickness of 10-15 km is clearly distinguished. The nature of its conductivity is probably related to the presence of fluids in the area of rock destruction at the depths of the transition from the brittle to ductile state. Interestingly, the position of the crustal conductor correlates with the largest Yurubcheno-Tokhomskoye oil and gas field in Eastern Siberia (a similar picture is observed in the area of the giant Romashkinskoye oilfield on the East-European Platform).

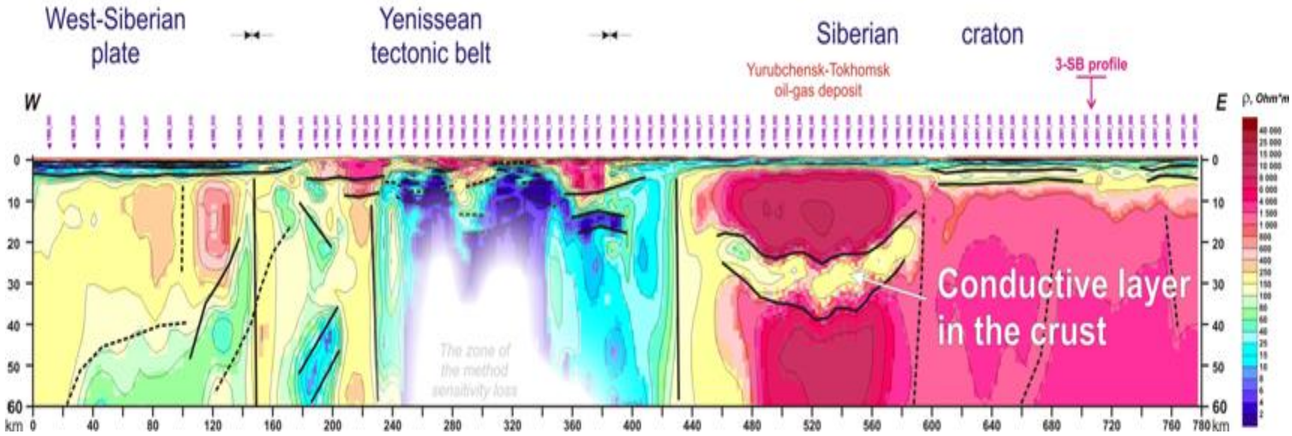

Fig. 10. "1-SB" profile. Resistivity cross-section of the Earth's crust obtained by 1D MT data inversion [Bubnov et al., 2007].

MT soundings are also successfully applied to study the sedimentary cover of ancient platforms and young plates. Fig. 11 shows a resistivity cross-section along profile IV of the "Rifey" project, 650 km long, crossing the **Moscow syneclise**, a large tectonic structure within the East European Platform [Bubnov et al., 2007]. The section, constructed using the data of drilling and seismic prospecting, shows the Soligalichsky aulacogen, which is a depression in the basement, and a genetically related uplift in the sedimentary cover. Due to the high-resistivity layer (screen), this uplift is clearly manifested in transverse impedance. At the same time, the longitudinal impedance carries information about the layers beneath the screen and makes it possible to reveal conductive Devonian, Vendian and Riphean rocks that are interesting in terms of their possible petroleum potential. Their thickness in the Soligalichsky aulacogen is estimated at 2–3 km, and their resistivity of a few Om·m indicates good reservoir properties. The resistive basement of the cross-section, consisting of the Archean-Early Proterozoic rocks, includes large blocks of different resistivities. On the slopes of the Moscow Syneclise, it is represented by highly resistive rocks of presumably Archean age, and in its central part - by more conductive, probably, Early Proterozoic rocks.

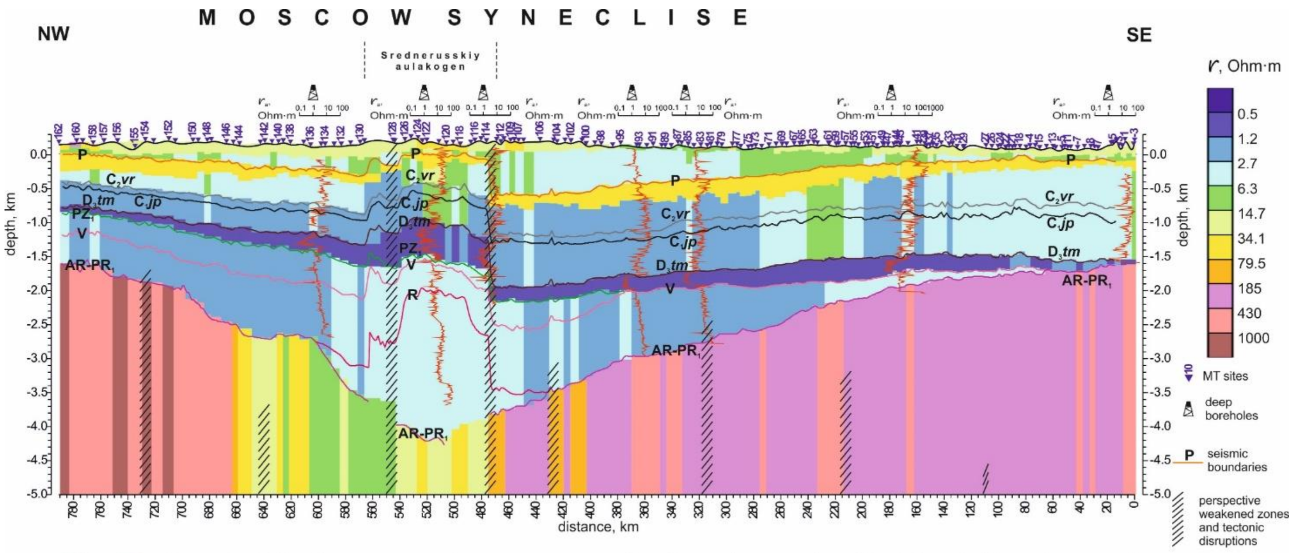

Fig. 11. Resistivity cross-section of the sedimentary cover obtained by 1D interpretation of MT data on the profile across the Moscow syneclise [Bubnov et al., 2007].

Fig. 12 shows a resistivity cross-section along a profile located in Western Ciscaucasia [Bubnov et al., 2007]. It runs from the Black Sea to the Scythian Plate, crossing the Caucasus Range and the Kuban Depression. The resistivity cross-section is complemented by seismic horizons. A remarkable feature of this cross-section is that a previously unknown trough is distinguished at the northern boundary of the Kuban Depression, filled with conductive rocks, presumably terrigenous formations of Jurassic age.

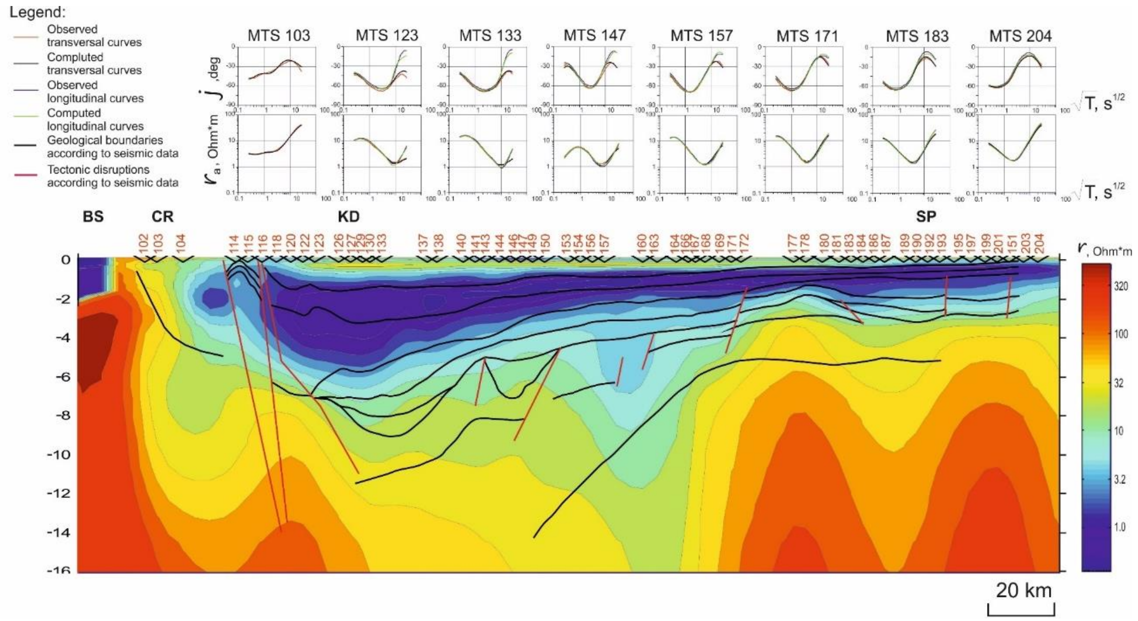

Fig. 12. Resistivity cross-section obtained by 2D MT data inversion and seismic boundaries along the profile from the Black Sea through the Caucasus Range, Kuban Depression and Skythian Plate [Bubnov et al., 2007].

The given examples show that on its development path, which took more than half a century, the MT method has gone from a laborious, rough way of detecting bright anomalies of the deep electrical conductivity to modern technology for constructing detailed resistivity models.

At present, the following **modifications of MT method** are applied, covering a wide **range of frequencies** and, accordingly, the **range of the studied depths** (Fig. 13). They are deep (low-frequency) MT sounding (frequencies 10^{-4}-10^{-2} Hz), exploration (broadband) MT sounding (10^{-3}-10^{2} Hz), near-surface audio MT and radio MT soundings (10^{1}-10^{4} Hz and 10^{4}-10^{6} Hz). The method of controlled-source frequency EM sounding provides increased accuracy, especially with strong industrial interference, which in some cases justifies its use instead of MTS.

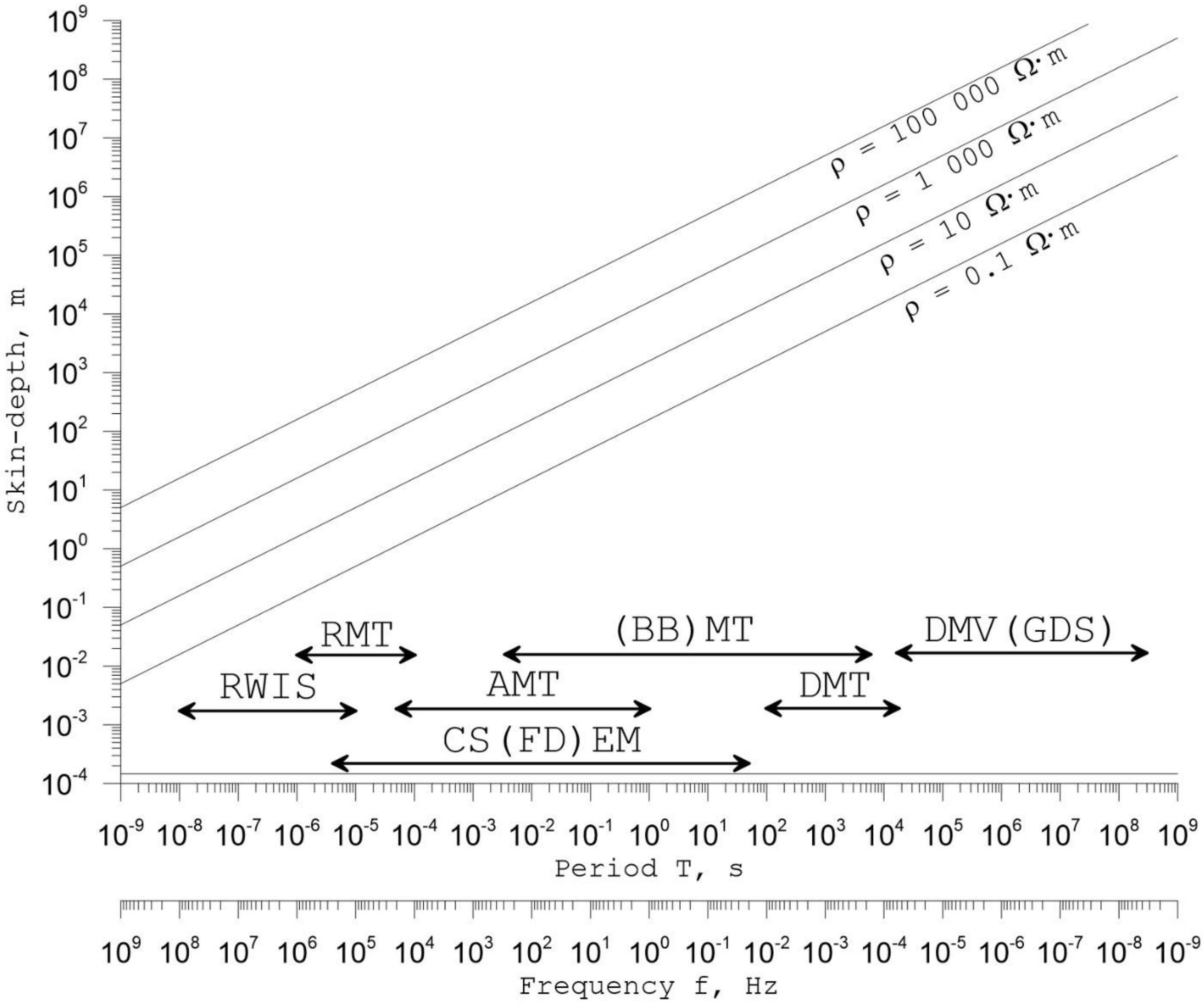

Fig. 13. Frequency ranges of EM sounding methods and appropriate exploration depth (skin-depth) for different values of homogeneous medium resistivity.

The investigation depth of EM sounding is usually considered as the skin-depth, at which the field decays in e ≈ 2.7 times. The skin-depth h_δ (m) is related to the resistivity of the medium ρ (Ohm·m) and the period of field oscillation T (s) according to the formula: $h_\delta = \sqrt{10^7 \cdot \rho \cdot T}/(2\pi)$. Fig. 13 shows the dependence of the skin-depth on the period for the four values of medium resistivity. The horizontal lines show the approximate frequency ranges of the EM methods. Half of the methods are magnetotelluric: RMT, AMT, (BB)MT, DMT. At long periods, they are supplemented by deep magneto-variational (or geomagnetic depth) sounding (DMV or GDS). Among the methods using artificial sources, the most high-frequency is the radio-wave interference sounding RWIS, then follows the controlled-source frequency-domain EM sounding CS(FD)EM. Low-frequency EM methods (not taking RWIS into account) cover the range of periods from about 10^{-6} to more than 10^8 s, which, with medium resistivity of 10 Ohm·m, corresponds to the depth range from a few meters to a thousand kilometers.

Fig. 14 shows the general **graph of modern MT research** (deep, exploration, shallow). Let's briefly consider its elements.

I. Survey design. Geological and geophysical information is collected, prior models are compiled, mathematical modeling of expected anomalies is carried out. The availability of observation sites and the level of industrial noise are evaluated. As a result, the optimal observation technology is chosen.

II. Field observations. Initially, maintenance work is carried out to prepare the equipment (calibration, identity test, etc.). The main part of the survey consists of measurements in observation sites. The result of this stage is a geophysical data set, which is one of the most valuable results of both academic and exploration studies.

III. Data processing. On this stage transfer from time series of field components to frequency domain is performed, and complex-valued components of magnetotelluric and magnetovariational matrixes [Z], [W], [M], [T], independent from the source, are obtained. An important feature of data processing is industrial noise depression, performed using remote reference data by means of statistic methods.

IV. Data analysis and interpretation.

1). Evaluation and depression of near-surface distortions. Methods of sounding curves normalization (static shift correction) and data decomposition (estimation of transfer functions, robust to near-surface distortions) are applied.

2). Evaluation of dimensionality and strike of resistivity structures. Pseudo cross-sections of invariant parameters, maps of polar and vector diagrams are analyzed. Main structures are localized, their elongation is estimated, as well as (for 2D inversion) their strike. As a result, strategy of further interpretation is selected.

3). Formation of a dataset of inverted components. For 1D inversion, the invariant determinant Zdet component is often chosen. For 2D inversion, the data is rotated to the main directions, usually averaged along the profile, in this case the observation sites position is projected onto the profile of the corresponding azimuth.

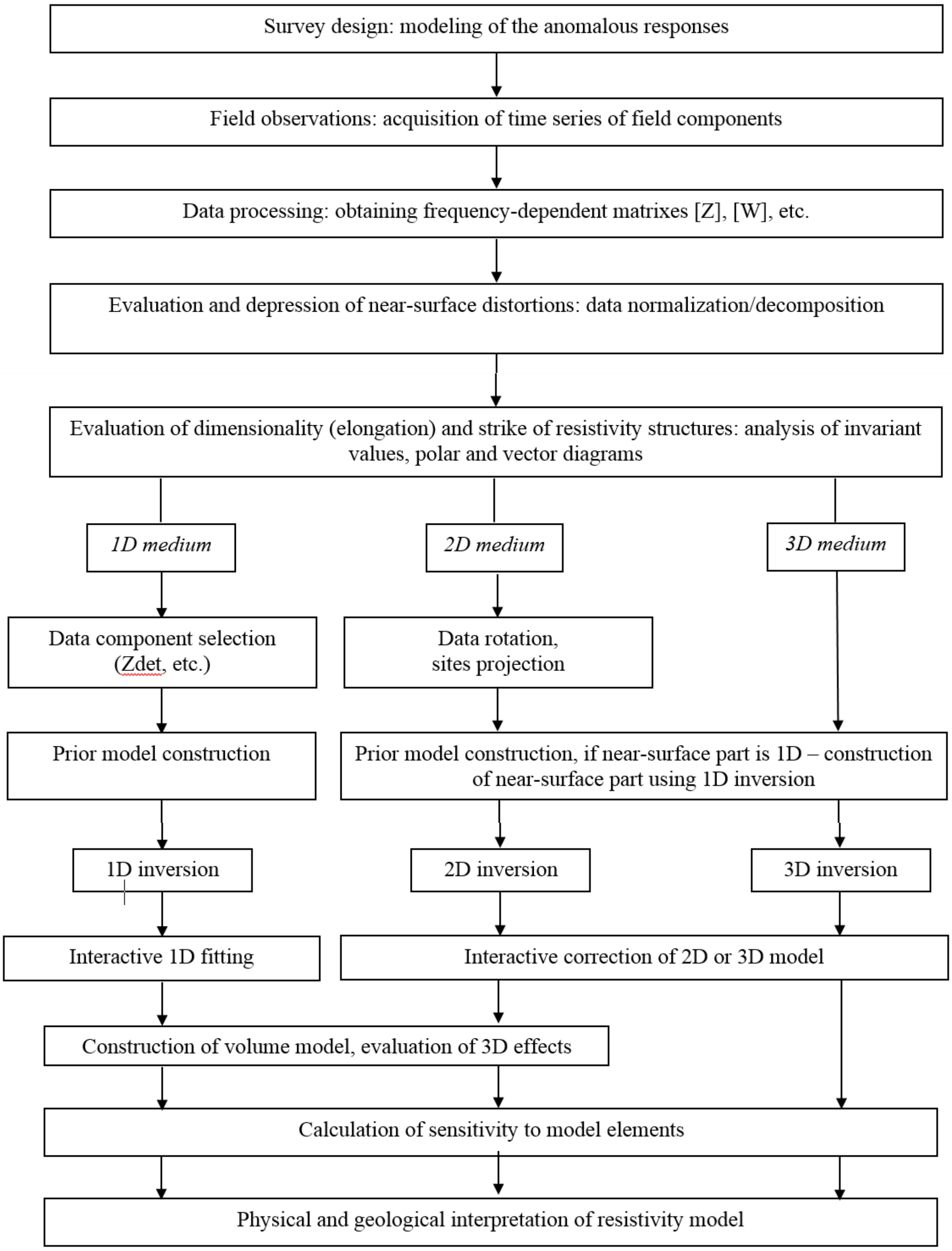

Fig. 14. Common graph of magnetotelluric survey.

4). Prior model construction. The grid in vertical and, depending on the selected dimensionality, horizontal direction(s) is created. Based on the available information, a priori resistivity values are specified. If the near-surface part of the section is characterized by 1D structure, then for 2D or 3D inversion the result of 1D interpretation of the near-surface part can be included in the prior model.

5). Automatic data inversion. A resistivity model is constructed that is consistent with the observed data and is close to a prior model. Part of the model parameters can be rigidly or semi-rigidly fixed. Most often, a smoothed-structure inversion is applied, although other types of solution stabilization are also used.

6). Interactive model correction. При 1D интерпретации применяется широко и часто без предварительной автоматической инверсии, обеспечивая простой учёт априорной информации о глубинах залегания границ. При 2D и 3D трудоемка и применяется реже, но позволяет получить наглядную генерализованную модель для дальнейшего истолкования.

If 1D interpretation is applied, such correction is widely used and often without prior automatic inversion, providing a simple account of a priori information about the depths of the boundaries. In case of 2D or 3D interpretation, interactive correction is laborious and is used less often, but it allows to get a demonstrative generalized model for further geological interpretation.

7). Evaluation of three-dimensional effects. It is performed on the basis of 3D modeling in case of areal observations and application of 1D and 2D inversion methods. In single profile studies if 1D inversion is used, then two-dimensional effects can be evaluated by means of 2D modeling.

8). Estimation of sensitivity to model elements. Variants of the resulting model are created by exclusion of key elements of this model (their resistivities are replaced with background values). The appropriate misfit increase demonstrates the necessity of the considered element in the resulting model.

9). Geological interpretation. Resistivity model is analyzed in complex with other geological and geophysical information by the interpreter together with experts in the field of the geological problem being solved. The conclusions on the solution of this problem are made.

In the most common sense, **the results of MT method application** in deep interior and exploration studies can be formulated as follows.

1. Most extended anomalies of electrical conductivity in the consolidated earth's crust mark the ancient or modern boundaries of crustal blocks, these zones are favorable for increased heat and mass transfer and participate in the formation of geodynamic activity. The ratio of the contribution of electron-conducting minerals and the contribution of fluids to the conductivity of anomalies for tectonically stable regions is higher than for active ones. In the latter, anomalies are also present, which are due to the melting of rocks and may not be associated with tectonic boundaries.

2. Several practical geological problems, characterized by different types of studied objects, scales and depths of the study were solved: identification of oil and gas prospective structures, delineation of different mineralization areas, exploration of geothermal zones, survey for the construction of facilities, groundwater exploration.

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