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



The limited size of this paper does not allow us to introduce many other eminent geophysicists from the Geophysical method of magnetotelluric (MT) sounding is based on the use of the low-frequency universities, research institutes and industrial organizations of the USSR, who were engaged in the electromagnetic (EM) field of the Earth to study its electric conductivity at various depths. The development of this method began in the 1950s with the pioneering works of A.N. Tikhonov (USSR), L. 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 Cagniard (France) and T. Rikitake (Japan). given and new results obtained in the regions from the Carpathians to Kamchatka and from the Arctic to Andrey Tikhonov (fig. 1) began to study the theoretical problems of the Tien Shan were discussed.



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 (illposed) problems.

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.

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

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. 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.

Fig. 6. Sketch map of crustal conductivity anomalies over the territory of the former USSR [Zhamaletdinov, 1996]. Crustal anomalies of presumably electronconducting origin: 1 – linear highconductive zones, 2 - vast highconductive areas; crustal anomalies of presumably fluid origin: 3 – linear conductive zones, 4-conductive areas. ■ 1 ■ 2 ■ 3 ■ 4 0 500 km

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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 ionconductive).



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].

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.

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.



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.,

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 crosssection 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. 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].

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. DEEP GEOELECTRIC CROSS-SECTION



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. 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]

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



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

[Bubnov et al., 2007].

Depression and Skythian Plate



Fig. 5. Geoelectrical cross-section along the profile from the Black sea to the Skythian plate. BS - Black sea, CR - Caucasus range, KD - Kuban depression, SP - Skythian plate.

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.

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

medium resistivity.

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 (lowfrequency) 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.

The investigation depth of EM sounding is usually considered as the skin-depth, at which the field decays in e \approx 2.7 times. The skin-depth h_{δ} (m) is related to the resistivity of the medium o (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.



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Frequency f, Hz

rvey design: modeling of the anomalous responses
ervations: acquisition of time series of field components
sing: obtaining frequency-dependent matrixes [Z], [W], etc.
ession of near-surface distortions: data normalization/decomposition
ality (elongation) and strike of resistivity structures: analysis of invariant values, polar and vector diagrams
2D medium 3D medium
Data rotation, sites projection
Prior model construction, if near-surface part is 1D – construction of near-surface part using 1D inversion
2D inversion 3D inversion
Interactive correction of 2D or 3D model
model, evaluation of 3D effects
↓ ↓ ,
Calculation of sensitivity to model elements
↓ ↓
cal and geological interpretation of resistivity model

Fig. 14. Common graph of magnetotelluric survey.

The results of MT method application in deep interior and exploration studies can be formulated as follows.

. 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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