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Acta Geophysica
vol. 55, no. ?, pp. ?-?
DOI 10.2478/s11600-006-0034-7

Magnetotelluric studies of the East-European Craton and adjacent regions

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Abstract

Magnetotelluric method is widely applied to study the Russian part of the East-European Craton, as well as the Caucasus and the Urals: several thousand soundings were performed during the last few years. Their periods range is approximately from 0.003 to 3000 seconds, which allows to study the sedimentary cover and the consolidated crust. Resistivity cross-sections along several regional profiles which run across the tectonic structures of the East-European Craton and the adjacent folded systems were obtained, mainly using 1D and 2D interpretational tools. MT investigations provided important information about the structure and reservoir properties of sedimentary complexes, the state of active geodynamic regions, the graphitization and fluid regime of the consolidated crust, and the permeable and fluid-saturated crustal zones.

Key words: magnetotelluric soundings, Earth's crust, electrical conductivity, East-European Craton.

1. INTRODUCTION

Electromagnetic (EM) geophysical methods (telluric current method, magnetotelluric sounding, frequency sounding, transient sounding) have been used in the USSR to study the deep structure of sedimentary basins and the consolidated crust since the 1950s. Tectonic schemes of the principal sedimentary basins of the USSR were constructed and several large hydrocarbon deposits were discovered using telluric currents method and magnetotelluric soundings, in combination with other geophysical methods. In the 1970s and 1980s, extensive magnetotelluric data characterizing the electrical conductivity of the Earth's crust were collected, and maps of crustal anomalies of electron-conducting and fluid origin were constructed. A review of major results obtained up to the 1990s is presented by Berdichevsky (1994). The review shows that there appeared a strong scientific community of researchers applying EM methods to study the Earth.

In the 1990s, because of economic difficulties, EM investigations were reduced. However, an abrupt expansion began in 2000 (Berdichevsky *et al*. 2002) which was caused by the depletion of established resources and by the increase of prices for hydrocarbons and other mineral resources.

Nowadays, EM methods, providing an exploration depth of more than 100 meters, are widely applied in Russia in three areas: regional exploration; oil and gas prospecting; and solid mineral prospecting. Regional surveys are conducted at the request of the Ministry of Natural Resources, while hydrocarbon and other mineral prospecting is mainly financed by private companies holding licenses for particular regions. During recent years the studies of the upper few hundred meters by means of the high-frequency (audio) magnetotelluric method have been developing rapidly. Audio-magnetotellurics proved to be one of the most efficient geophysical methods for the exploration of ore minerals and kimberlite pipes (Alekseev *et al*. 2004).

This paper focuses on regional geophysical surveys. They are performed in Russia along single profiles that are from a few hundreds to several thousand kilometers in length and run through deep boreholes. The locations of some of them are shown in Fig. 1.

Investigations along regional profiles give information about the deep structure of vast regions and help to solve such applied tasks as the prognosis of oil-and-gas content in sedimentary basins and the location of promising solid mineral zones. In active tectonic regions, data required to study geodynamic conditions and predict seismic activity is collected.

The integrated application of geophysical methods is characteristic for regional surveys. The combination includes CDP (Common-Depth-Point) seismic, EM, gravity and magnetic prospecting and other methods, such as geochemical ones. Seismic prospecting plays the leading role – in most cases it determines the location of geological boundaries rather precisely. Other methods, in particular EM, supplement this data with information about the physical properties of rocks, characterizing their lithology, fluid content, rheological state, etc.

The total length of regional profiles studied using EM methods each year is about 3000 to 4000 km, while the spacing between sites is 1–3 km. In the European part of Russia, surveys are mainly performed by the state enterprises "Spetsgeofizika", "GEON Centre" and "Kavkazgeolsyemka". Among private companies, the most active are "North-West" Ltd. and "CEMI" Ltd. In this paper we present some results obtained during the last few years by "North-West" Ltd. in cooperation with the organizations mentioned above and the Geological Faculty of Moscow University.

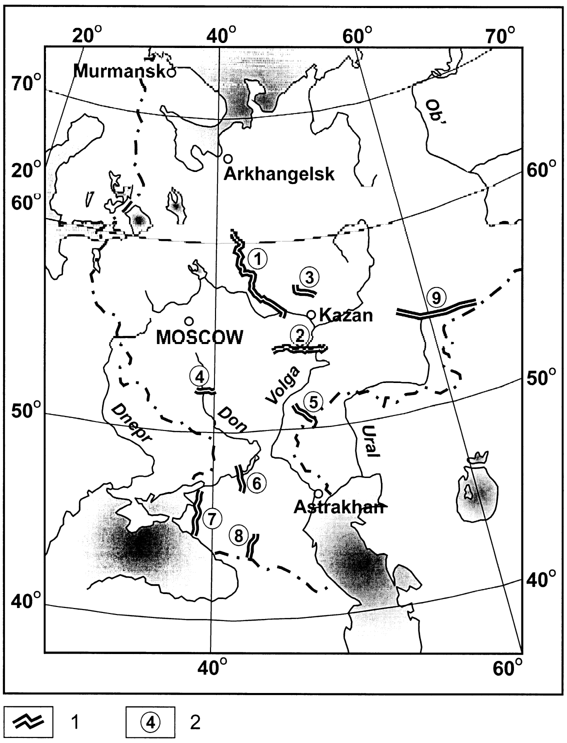

Fig. 1. Location map of the profiles considered in this paper: 1 – Soligalich aulacogen, 2 – Tokmov arch and Melekes depression, 3 – Kotelnich arch and Kazansko-Kazhimsky aulacogen, 4 – Voronezh anteclise, 5 – Pre-Caspian syneclise, 6 – Karpinsky swell, 7 – Western Caucasus forelands, 8 – Central Caucasus, 9 – “Uralseis” profile.

2. OBSERVATION TECHNOLOGY

The basic regional EM method is the magnetotelluric (MT) method. MT provides the largest exploration depth and is inexpensive and mobile, as it does not require an artificial field source. Different kinds of equipment are used for measurements. In the USSR, CES-2 receivers and their later modifications were applied. In the 1990s domestic CES-M, SGS, EIN, AKF and other kinds of equipment were widely used in Russia. Since 2000 regional MT surveys have usually been conducted by means of receivers produced by the Canadian company Phoenix Geophysics Ltd. This equipment is characterized by high sensitivity and broad dynamic range, unattended operation, synchronization using the GPS satellite system, reliability, and simplicity.

The magnetotelluric method is applied in three ways:

1. high-frequency (frequencies from 20000 Hz to 1 Hz, spacing between sites 1 km),
2. standard (periods down to 5000 s, 3 km spacing), and
3. low-frequency (periods down to 50000 s, 10 km spacing).

At observation sites, either all five components of the natural electromagnetic field (E_X, E_Y, H_X, H_Y and H_Z) or only the two electric field components (E_X and E_Y) are measured. In the latter case, magnetic field records taken at adjacent sites are used. Telluric lines 50–100 m long are used to measure electric field, magnetic field is measured using induction coils, sometimes additional low-frequency measurements by means of quartz magnetometers are performed. As a rule, a receiver at some reference site is operating synchronously with the receivers at a profile.

A difficult problem of MT soundings is connected with industrial electromagnetic inductive and galvanic noises. The inductive noise is caused by electric power lines. The galvanic noise, caused by current leakages from electrified railroads, is usually more intense. If resistive layers are present, producing gradual attenuation of the electric field when moving away the railroad, then this noise source influences the measurements performed several tens of kilometers away. Although railroads in Russia are powered by either DC or AC (50 Hz) current, in both cases a rather wide range

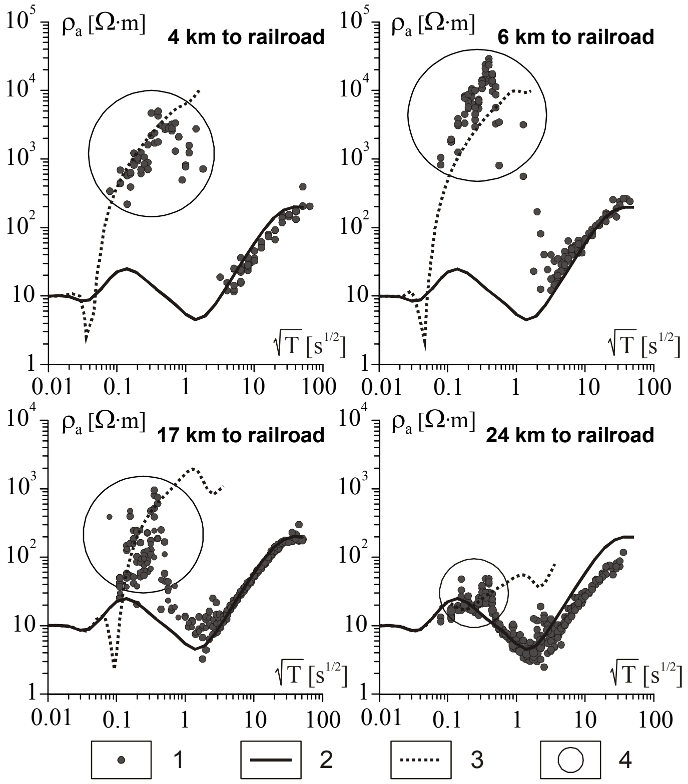

Fig. 2. Observed and modeled apparent-resistivity curves near the Moscow-Kazan electrified railroad. (1 – Observed curves, 2 – result of forward modeling using plane wave source, 3 – the same, using horizontal electric dipole as a source, 4 – zones where apparent resistivity is influenced by the electrified railroad field).

of frequencies is affected because intensity of current leakage varies with time. Figure 2 shows that near an electrified railroad, the galvanic noise caused by the electric circuit between the locomotive and the nearest power substation dominates the weaker MT signal at high frequencies. Note that this "noise" can be used to acquire information about resistive layers (Aleksanova *et al*. 2003). As the distance from the railroad increases, galvanic noise diminishes, and MT curves return to normal.

If industrial noise is very strong, then controlled-source measurements are performed. In most cases time-domain soundings with coaxial transmitting and receiving loops are used. Frequency-domain soundings, providing very high industrial noise immunity, are still seldom applied. They require large separation between transmitter and receiver, and if the medium changes significantly in this interval, then simplified (1D) approaches to data interpretation become inapplicable.

3. MT DATA PROCESSING, ANALYSIS AND INTERPRETATION

As a rule, MT data processing is performed in remote reference mode, allowing the suppression of uncorrelated noise. In addition, robust statistical approaches are used to increase the reliability of results. Rejection of data according to different criteria, such as dispersion relations between apparent resistivity and impedance phase, gives considerable improvement.

Manual editing of impedance and tipper response function plays an important role. This stage is necessary because automated processing algorithms often do not allow to suppress the industrial noise or at least require a time-consuming adjustment of parameters. Manual editing is used to eliminate both outliers and stable branches of response functions caused by industrial field sources.

Another problem is connected with the distortion of MT curves by local near-surface inhomogeneities, producing uninterpretable geoelectric noise. This noise appears as a static shift of apparent-resistivity curves along the vertical axis. If we have a dense observation network, this noise can be reasonably decreased by the spatial smoothing of apparent resistivity at some period and further shift of apparent-resistivity curves to this smooth level. Another way to normalize MT curves is to adjust them to the levels of time-domain sounding curves obtained using a magnetic excitation and magnetic measurements of the EM field. If geoelectric noise is insufficiently suppressed, then the interpretation is performed with the priority of impedance phases and tipper, which become free from near-surface distortions with lowering frequency.

MT data interpretation is performed in terms of Tikhonov's theory of ill-posed problems. The most important stage of interpretation is the construction of an interpretational model, combining all possible inverse problem solutions. The interpretational model is based on *a priori* information about the medium and on MT data analysis. During data analysis, pseudo cross-sections of magnetotelluric and magnetovariational parameters, characterizing dimensionality of the medium, are constructed. In addition, we determine the principal values and directions of the impedance tensor and analyze impedance polar diagrams and induction arrows, showing the location and strike of resistivity structures. Impedance tensor decomposition methods, describing the relation between regional and local structures, are also applied.

As a result of data analysis, the acceptable dimensionality of inversion methods is determined: usually 1D or 2D. During regional investigations, 3D inversion methods are not applied, because observations are performed along separate profiles. However, to verify the reliability of 1D and 2D approaches, 3D modeling is used to study 3D effects and appropriate possible errors.

Data interpretation is usually performed in two stages. In the first stage, rough smoothed-structure inversion is applied. In the second stage, we deal with piecewise-uniform models to define the resistivity structure more precisely. All MT data components are used for interpretation, although their simultaneous inversion is not always effective because of their differing sensitivity to resistivity structures and differing robustness against 3D distortions. We suppose that in regions with complicated geoelectric conditions, better results can often be obtained using a succession of partial inversions (with tipper and impedance phases priority), although this approach is still rarely used in industrial surveys.

Interpretation is concluded by a geological and geophysical analysis of the resistivity models obtained. At this stage, EM results are considered together with other geophysical data. Specialists in the integrated application of geophysical methods as well as geologists are involved in this work.

4. CASE HISTORIES: EAST-EUROPEAN CRATON

We start the review with some results obtained at the East-European Craton, where a large number of MT soundings were performed within the last few years. In this region the following geoelectric complexes are present (from top to bottom):

1. Inhomogeneous Mesozoic–Cenozoic (rather conductive);

2. Upper Devonian–Carboniferous, including mainly carbonate rocks (resistive);

3. Mainly terrigenous, including Meso- and Neo-Proterozoic and Devonian rocks, saturated by mineralized water (conductive);

4. Metamorphic basement, consisting of Archean and Paleo-Proterozoic rocks (resistive).

New geoelectric information about the Moscow syneclise, the largest tectonic structure of the craton, was obtained along profile IV of the RIFEY exploration program (region 1 in Fig. 1). The profile length is 650 km, consisting of 160 MT sites. 1D interpretation of MT data, constrained by borehole and detailed seismic information about layer boundaries, was used to construct the resistivity cross-section (Fig. 3). It includes the basement depression — the Soligalich aulacogen and the superimposed

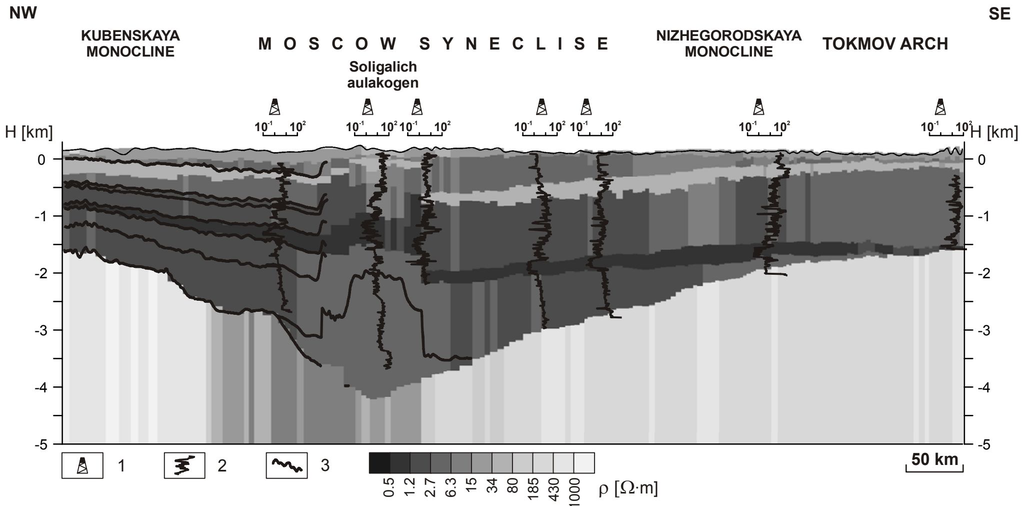

Fig. 3. Resistivity cross-section of the Moscow syneclise, profile IV of the "Rifey" program (1 – boreholes, 2 – electrical logging results, 3 – seismic boundaries).

uplift in sediments (Bubnov *et al.* 2003). Due to the resistive layer, which resists the flow of transverse electric currents, this uplift strongly influences the transverse impedance data (TM mode). At the same time, the longitudinal impedance (TE mode) provides information about deeper layers and reveals conductive Meso- and Neo-Proterozoic and Devonian rocks. Their total thickness of rocks in the Soligalich aulacogen is about 2–3 km, and their low resistivity indicates good reservoir properties. The resistive basement consists of large blocks of different resistivity. On the sides of the Moscow syneclise, the basement is represented by resistive, probably Archean rocks. In the central part of the syneclise it is more conductive, possibly because Paleo-Proterozoic rocks are present here.

Figure 4 presents the resistivity cross-section of the Tokmov arch and the Melekes depression (region 2 in Fig. 1). Here the resistive crystalline basement lies at approximately 2 km depth. Due to *a priori* borehole and seismic data, quite a number of layers in the sedimentary cover were distinguished. It is notable that horizontal variations in the resistivity were discovered. The valuable information that supplements seismic data is that the resistivity diminishes from west to east, reflecting the increase in porosity and fluid mineralization.

The next example demonstrates the ability of the MT method to locate reefs in the junction zone of the Kotelnich arch and the Kazansko-Kazhimsky aulacogen (region 3 in Fig. 1). Here the integrated interpretation of seismic and MT data was performed to supplement with geoelectric parameters the cross-section based on seismic data. Within large lithological complexes, potentially productive of oil-and-gas, several zones presumably containing reef traps were revealed using seismic data. To verify and refine this result, variations of layer conductance determined using MT data

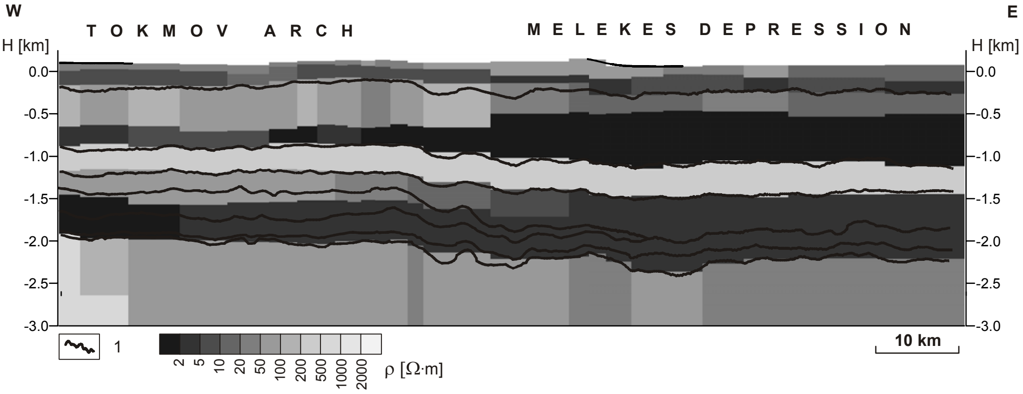

Fig. 4. Resistivity cross-section of the Tokmov arch and the Melekes depression (1 – seismic boundaries).

were studied. Figure 5 shows characteristic fragments of geological cross-sections predicted using seismic data, and graphs of conductance of the appropriate lithological complexes. In the layers between P_1 and C_2vr seismic reflectors, as well as between C_2vr and C_1jp reflectors, the conductive anomalies correlate well with supposed reefs. These anomalies are explained by the high porosity and permeability of reefs in comparison with host rocks.

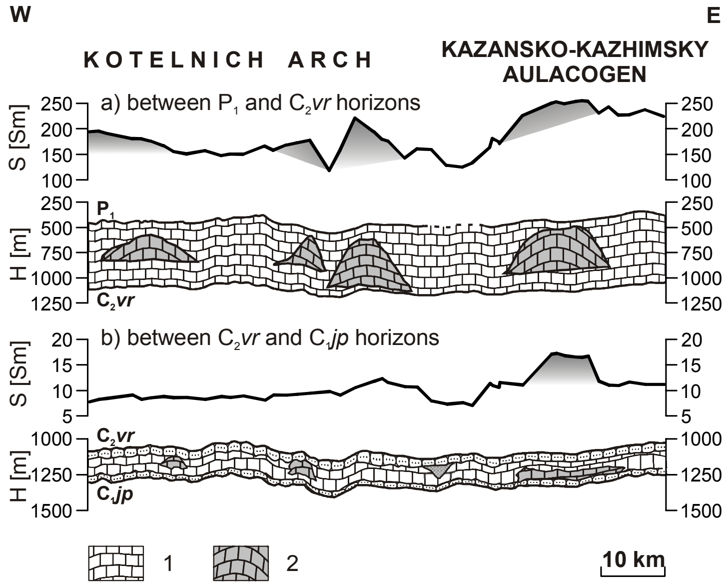

Fig. 5. Fragments of geological cross-section obtained using seismic data, and graphs of total conductance of the named layers: junction zone of Kotelnich arch and Kazansko-Kazhimsky aulacogen (1 – limestones, 2 – prospective reefs).

2D inversion (Rodi and Mackie 2001) of MT data obtained in the Voronezh anteclise (region 4 in Fig. 1), where sediment thickness is small, revealed striking conductive anomalies in the consolidated crust (Fig. 6). Here the resistivity decreases to fractions of Ohm·m, allowing these anomalies to be explained by graphitization of Paleo-Proterozoic rocks. They are of practical interest as zones of probable ore mineralization. One of them is connected with the deep fault outlined according to geological data.

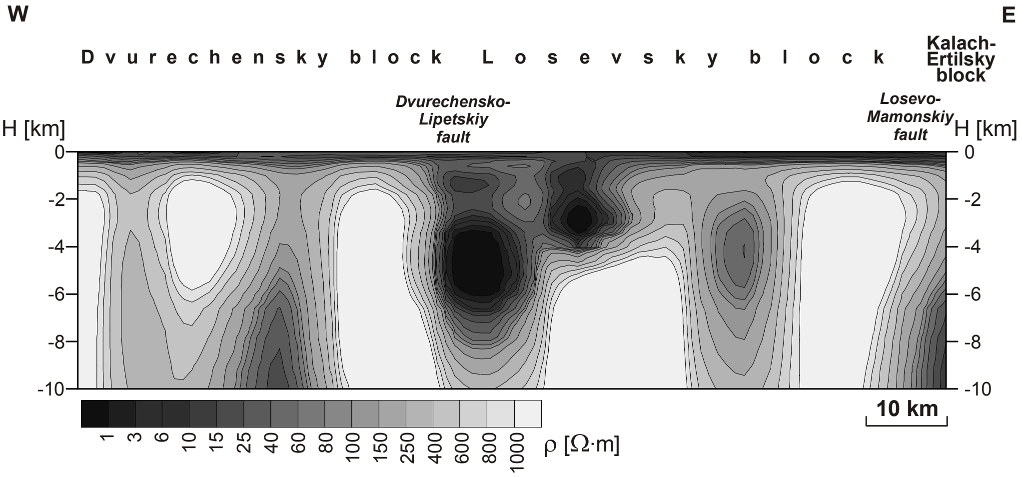

Fig. 6. Resistivity cross-section along the profile in the Voronezh anteclise.

Now we move to the northern part of the Pre-Caspian syneclise (region 5 in Fig. 1). This area is promising for hydrocarbons, and salt-dome structures are common there. Figure 7 displays the resistivity cross-section obtained using 2D inversion of MT data along one of the profiles oriented across the structures. In the conductive sedimentary cover, resistive salt domes, approximately 6 km thick, are easily seen. Their bottoms can form local oil and gas traps at a rather small depth, in terrigenous rocks above the salt layer. However, even more interesting are the areas of high and low conductance of the complex beneath the salt layer. Accordingly, they correspond to zones of mainly terrigenous and carbonate composition. Delineation of carbonate bodies in this complex is an important task, because in similar areas to the east, in Kazakhstan, such bodies contain large hydrocarbon deposits.

To conclude the review of recent MT investigations of the East-European Craton, we consider the result obtained at its southern flank in the Karpinsky swell area (region 6 in Fig. 1). The observations were performed along a 190 km profile comprising 71 MT sites (Berzin *et al*. 2005). On the basis of MT data and *a priori* geological and geophysical data analysis, the conclusion was reached of strong horizontal inhomogeneity of the medium. A large isometric near-surface depression, filled by sediments, is

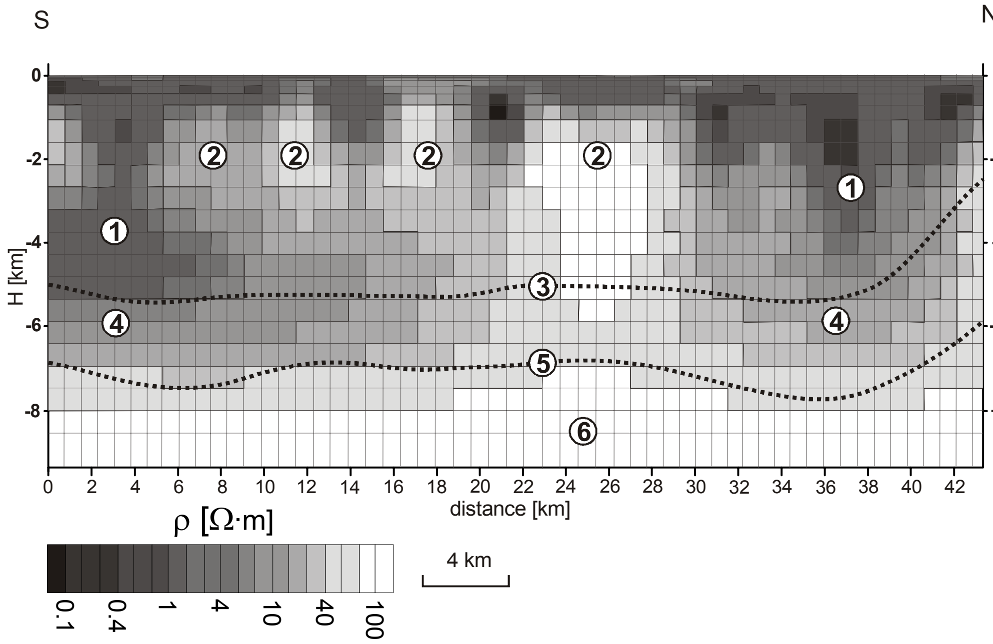

Fig. 7. Resistivity cross-section along the profile in the Pre-Caspian syneclise. (1 – Layer above the salt, 2 – salt domes, 3 – top of the layer below the salt, 4 – layer below the salt, 5 – basement top, 6 – basement).

superimposed on regional elongated (quasi-2D) structures. In this case, quasi-longitudinal (TE mode) impedance suffers from galvanic distortions that are much larger than the effect of deep structures. On the other hand, quasi-transverse (TM mode) impedance has a low sensitivity to deep structures, although it contains information about shallow ones. In this situation, the deep conductive anomalies were studied using tipper data, which is weakly distorted by the influence of isometric near-surface inhomogeneities and quite sensitive to deep conductive structures.

The cross-section obtained by means of 2D inversion of tipper and transverse impedance data is shown in Fig. 8. The cross-section includes two conductive zones. The upper conductor, constructed using transverse impedance, occurs at approximately 1 km depth. These are terrigenous Cretaceous and Cenozoic sediments, mainly clays. Beneath them are more resistive, mainly carbonate rocks. The lower conductor occurs at a depth of about 15 km. It probably represents the southeastern extension of the Donbass conductivity anomaly (Rokityansky *et al.* 1989), covered by thick young sediments. The total conductance of this anomaly is several thousand siemens, and it can be associated with the presence of both electron-conducting minerals and increased fluid content.

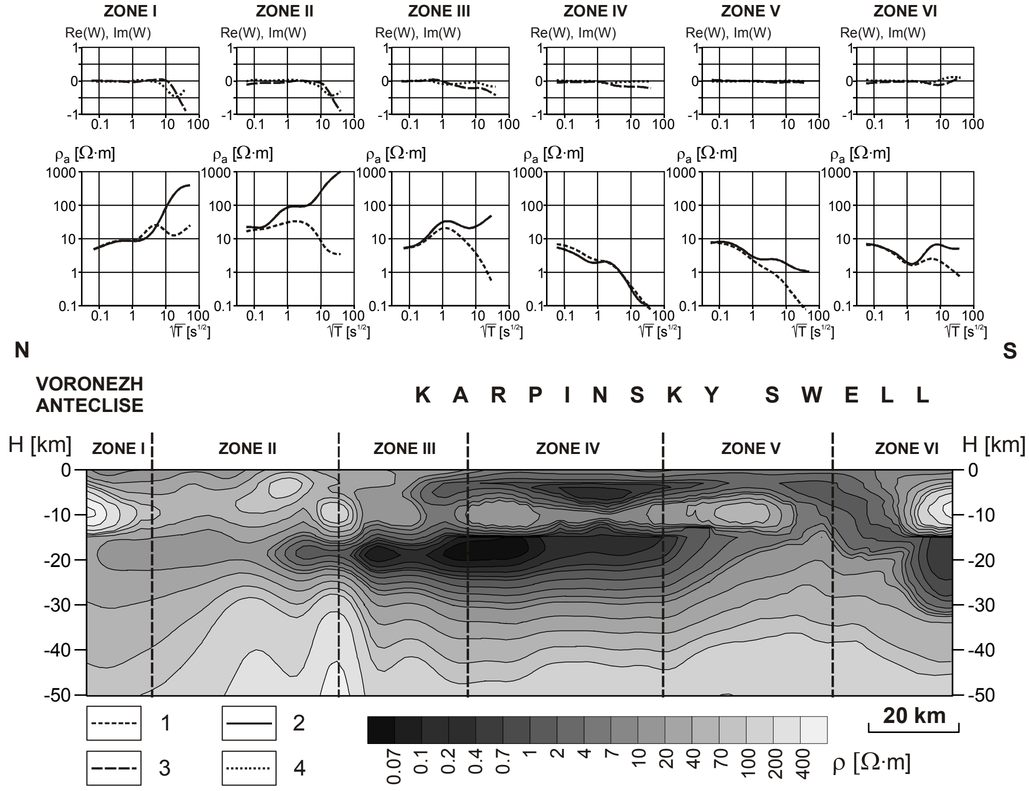

Fig. 8. Typical interpolated MT curves and resistivity cross-section of the Karpinsky swell. Six zones of conformal sounding curves are shown (1 – ρ_{XY}, 2 – ρ_{YX}, 3 – Re(W_{ZY}), 4 – Im(W_{ZY})).

5. CASE HISTORIES: CAUCASUS AND THE URALS

In the Greater Caucasus Mountains and in the Caucasus forelands, MT measurements were recently conducted along 10 profiles whose total length is about 2000 km. Consider the profile in Western Caucasus forelands. It stretches from the Black Sea to the Scythian plate, crossing the Caucasus Mountains and the Kuban depression (region 7 in Fig. 1). Figure 9 displays a geophysical cross-section along the profile, based on 2D MT data inversion results and seismic data. Its remarkable feature is that at the northern border of the Kuban depression, an unexpected deep trough filled with conductive (supposedly terrigenous Jurassic) rocks was revealed.

Let us also consider the profile in the central part of the Greater Caucasus, crossing the Elbrus mountain (region 8 in Fig. 1). The resistivity cross-section (Fig. 10) clearly displays the transition from the folded belt of the Greater Caucasus to the Scythian plate and the associated gradual increase of sediment thickness (Arbuzkin *et al*. 2003). Within the limits of these tectonic structures, the Hercynian basement is

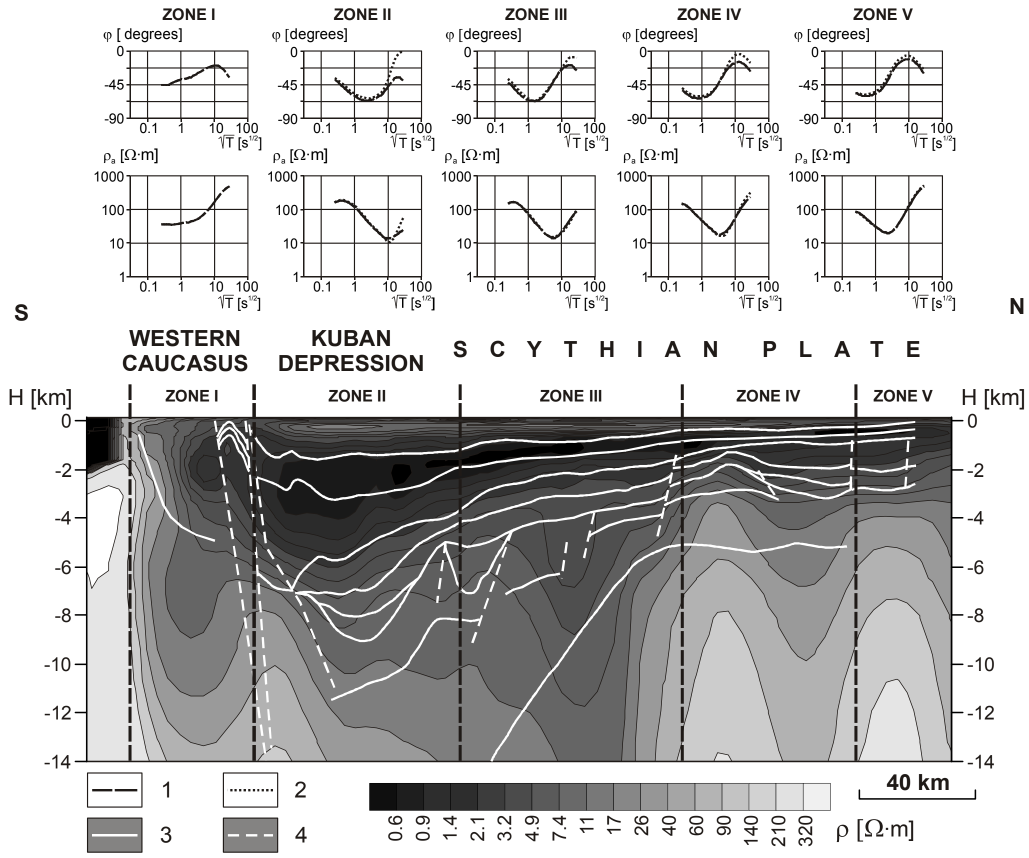

Fig. 9. Typical MT curves and resistivity cross-section of the Kuban depression and zones (1 – Observed TE curves, 2 – observed TM curves, 3 – geological boundaries according to seismics, 4 – tectonic disruptions according to seismics).

heterogeneous, and the most complicated geoelectric situation is observed in the tectonic block of the Greater Caucasus. Known tectonic disruptions are seen as conductive zones, possibly because they are fluid-saturated. A small conductive anomaly at 2–8 km depth beneath the Elbrus volcano is interpreted as a magma chamber; at approximately 30 km depth another conductive anomaly was revealed, possibly connected with the magma center.

In the Southern Urals, a regional MT survey was conducted along the 510 km "Uralseis" profile (region 9 in Fig. 1). Measurements at 500 sites were performed (Kulikov *et al.* 2005). Three domains were marked out in the resistivity structure of the Southern Urals: Western Ural, being a part of the East-European Craton edge; Eastern Ural, formed by Paleozoic volcanic and Plutonic basic and ultrabasic complexes; and Trans-Ural, which is part of the Kazakhstan Caledonian plate. According to MT data 2D inversion results, the Earth's crust is resistive beneath the East-European Craton and the Kazakhstan plate, and conductive between them (Fig. 11).

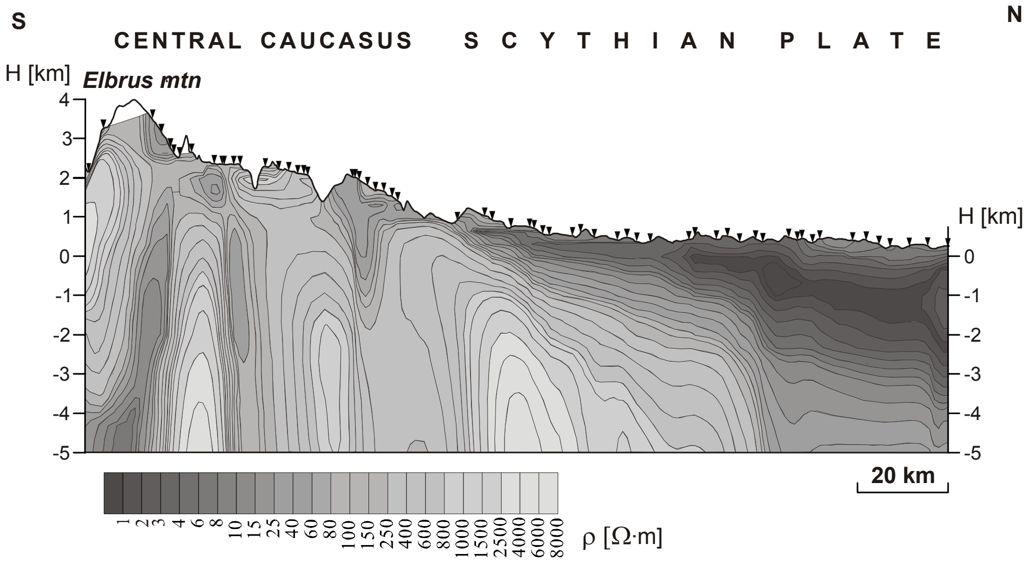

Fig. 10. Resistivity cross-section along the profile in Central Caucasus.

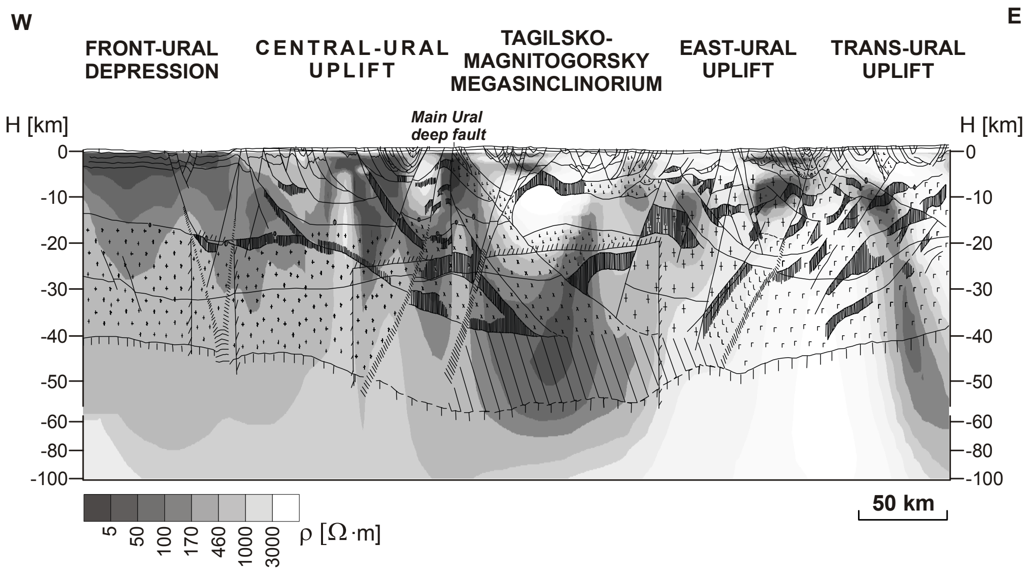

Fig. 11. Resistivity cross-section of the Southern Ural along "Uralseis" profile (smooth gray-scale structures) and the results of seismic data interpretation (Moho boundary and structures with sharp boundaries inside the crust).

The Southern Urals shows a divergent structure. In its western part, nappes and thrusts moved westwards, and in the eastern part they moved eastwards. The most striking conductivity anomalies are associated with the Main Ural Fault and the Zuratkulsky, Zapadno-Uraltaussky and Kartalinsky Faults. Here the resistivity of rocks goes down to a few Ohm·m, probably characterizing their fluid saturation. Chrome and gold deposits of the Magnitogorskaya metallogenic zone occur in areas where these deep faults rise to the surface. In the Magnitogorskaya and Trans-Ural zones, crustal conductive layers were also revealed. A conductor in the first zone occurs at 15–25 km depth; it is about 30 km thick and its conductance is above 1000 siemens. A crustal conductor of the Trans-Ural zone dips eastward from the Kartalinsky Fault, its conductance exceeding 150 siemens.

6. CONCLUSIONS

MT investigations essentially expand the existing ideas about the structure and geodynamics of the Earth's interior, based on the results of drilling and seismic, gravity and magnetic studies. MT investigations provide unique information about the structure and reservoir properties of sedimentary complexes, the state of active geodynamic regions, the graphitization and fluid regime of the consolidated crust, and the permeable and fluid-saturated crustal zones.

Currently, the generalization of all the electromagnetic data obtained in the European part of Russia is being performed. Maps of sediment conductance and other parameters of large sedimentary complexes and lithospheric conductive layers are being constructed (Sheinkman *et al*. 2003, Feldman *et al.* 2005).

Acknowledgements. The authors wish to acknowledge A.V. Lipilin, Head of the Department of ROSNEDRA Federal Agency, for the support of regional electromagnetic explorations. We are also grateful to I.S. Feldman, A.K. Suleimanov, V.V. Belyavskiy and other leading experts of industrial geophysical companies for fruitful collaboration, as well as to V.A. Kulikov, E.V. Andreeva, A.G. Morozova, D.A. Alekseev and other specialists of North-West Ltd. for taking part in the studies considered. The scientific effort of authors from Moscow University was supported by RFBR (project 05-05-65082). One of the authors (P.Yu.P.) also thanks INTAS for their support (project 03-55-2126).

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Received 2 March 2006
Accepted 15 September 2006