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Electromagnetic Soundings of the Sedimentary Cover and Consolidated Crust in the Transition Zone from the Moscow Syneclise to the Voronezh Anteclise: Problems and Prospects

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Abstract—The methods and results of electromagnetic soundings (EMS) performed in the transition zone from the Moscow syneclise to the Voronezh anteclise in the vicinity of the MSU geophysical base are considered. This base is located in the village of Aleksandrovka in the Yukhnov district of Kaluga area. The composite EMS curves characterizing rock complexes composing the sedimentary cover are constructed, and changes in these complexes within the specified transition zone are traced. The standard curves of magnetotelluric (MT) and magnetovariational (MV) soundings are constructed from the results of long-term measurements at the ALX observation point located at the Moscow State University's (MSU) geophysical base. The maps of thickness and total longitudinal conductance of the sedimentary cover are constructed from the results of interpretation of MT data obtained in the region. A conductor in the consolidated Earth's crust is identified within the Voronezh anteclise. Prospects for further investigations of the region are associated with the tracing of the crustal conductor within the Voronezh anteclise, as well as with the organization of an observatory at the MSU's geophysical base in order to perform long-term measurements of the electromagnetic (EM) and other geophysical fields.

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INTRODUCTION

The Moscow syneclise and Voronezh anteclise are the largest tectonic structures of the East European platform. In the region of their conjugation, the boundary between the sedimentary cover and the metamorphic basement smoothly subsides from south to north. At a distance of about 100 km, its depth increases from 500 to 1200 m. Such a thickness of sediments, on the one hand, gives no grounds for expecting much prospect for the oil- and gas-bearing potential characteristic of deeper sedimentary basins. On the other hand, the extraction of solid mineral resources, which are present in the basement, is not efficient here. Therefore, such transition zones are almost completely devoid of practical interest and are studied relatively scantily.

Investigations in a considerable part of the specified region are complicated by a high level of industrial EM interferences, and their largest sources are the Moscow–Vyazma and Moscow–Sukhinichi electrified (powered by direct current) railways. In addition, a substantial distorting influence is exerted by electrified railways powered by alternating current, numerous trunk pipelines, and power transmission lines.

At the same time, the transition zone under consideration is favorable for estimating the present-day possibilities of EM sounding methods for the study of the sedimentary cover and consolidated crust. Here, the sedimentary cover smoothly wedges out; however, not all its layers wedge out uniformly, which produces significant heterogeneities in the EM field structure. If the thickness of the high-resistivity complex in the middle part of the sedimentary cover decreases, galvanic coupling arises between its upper and lower low-resistivity parts, whereas the wedging-out of the lower sedimentary layers, ensuring the bulk of the integral conductance of the cover, increases EM responses associated with currents flowing in deep-seated crustal conducting structures. Under these conditions, it is possible to successfully study and compare the resolutions of different modifications of EM soundings.

The western slope of the Voronezh anteclise, which is characterized by a uniformly low longitudinal conductance of sediments [Sheinkman et al., 2003],

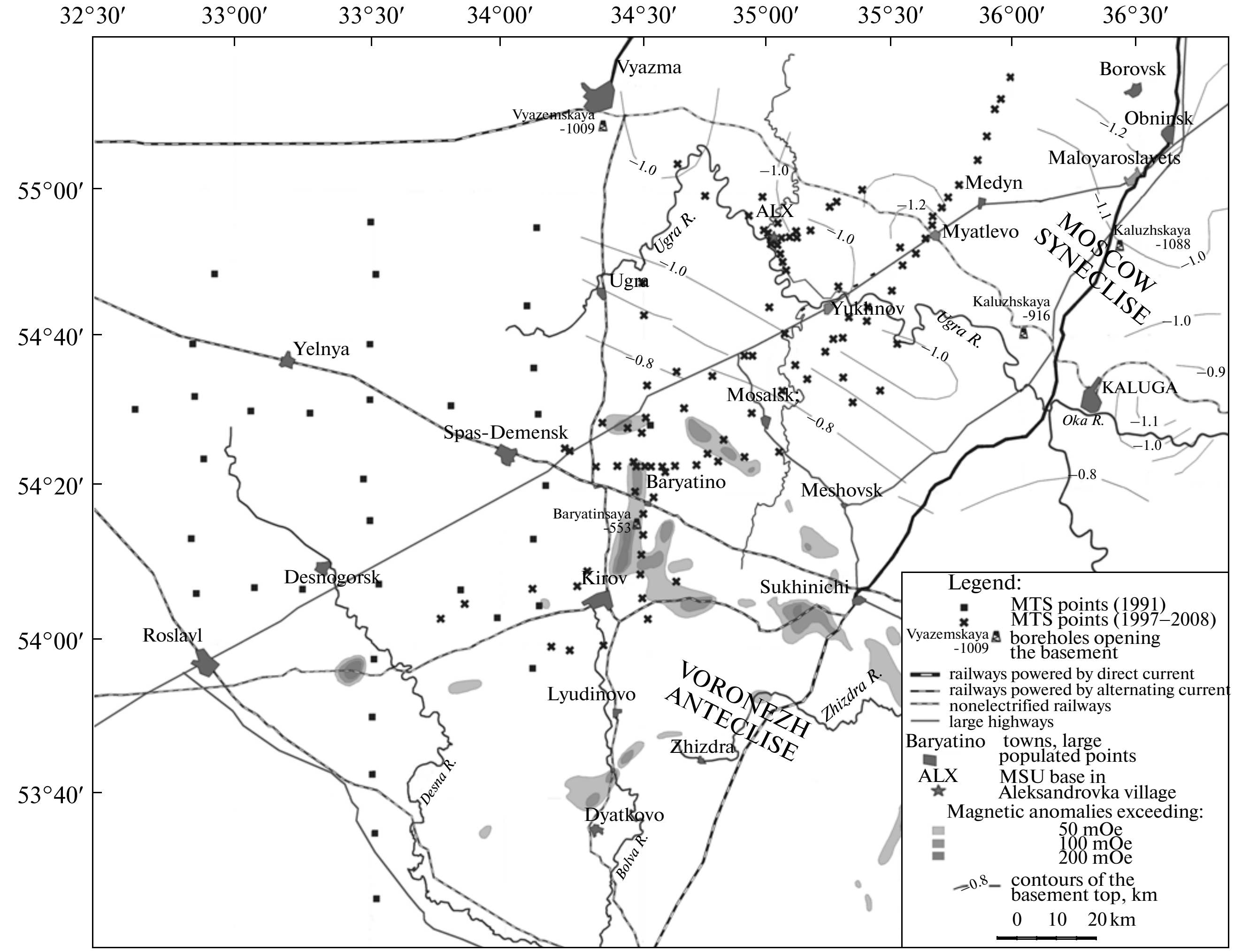

Fig. 1. Scheme of the region under investigation.

seems to be a convenient window for studying the deep geoelectric structure of the crust and upper mantle. However, such a study requires a rather complex system of EM soundings, including deep reference soundings and a denser observation network to control the variability of the surface conductivity. In order to overcome intense industrial EM interferences, the soundings must be synchronous.

This paper generalizes the results of a large series of EM soundings performed by the MSU Faculty of Geology and North-West Ltd in a rather wide vicinity of the MSU geophysical base located in the village of Aleksandrovka, Yukhnov district, Kaluga oblast. The field investigations were carried out during educational trainings of students-geophysicists of MSU, the Russian State University for Geological Exploration (RGGRU), and Dubna University, as well as in the course of geophysical works in the vicinity of the Smolensk nuclear power station (Fig. 1). The idea of including real scientific experiments for the study of the regional geoelectric structure in the program of students' practical works has proved very fruitful. The results of different methods of electromagnetic sounding (EMS), magnetotelluric sounding (MTS), frequency sounding (FS), time-domain electromagnetic sounding in the near zone (TEM), dipole electric sounding (DES), and vertical electric sounding (VES) are presented below. The prospects for further EM investigations in the vicinity of the MSU geophysical base and on the western slope of the Voronezh anteclise are discussed.

In the 1990s, EM observations were concentrated mainly in the northern part of the zone under consideration near the MSU's geophysical base. Methodological questions of the integrated interpretation of EMS data were investigated, and specific features of the geoelectric structure of the sedimentary cover were studied [Khmelevskoi et al., 1999; Kulikov et al., 1999]. As the soundings advanced southward, deep into the Voronezh anteclise, the integral conductance of the cover decreased by many times. An anomaly of the electric conductivity appeared in the MTS curves.

At the end of the 1990s–beginning of 2000s, soundings aimed at the study of this anomaly were performed near the village of Baryatino, Kaluga oblast [*Electric Prospecting* ..., 2005; Aleksanova et al., 2005], within the clearly pronounced Baryatino magnetic anomaly, and gravimagnetic investigations were simultaneously carried out there under the supervision of Professor of the RGGRU V.V. Brodovoi [Brodovoi et al., 2000; 2001]. It has been found that the magnetic anomaly is produced primarily by ferruginous qrtzites bedding in the upper part of the basement, whereas the electric conductivity anomaly is associated with deeper horizons of the crust.

Data of these observations are supplemented by the MTS data obtained at the Faculty of Geology of MSU in 1991 during the study of the geodynamic state of the region, where the Smolensk nuclear power station is located. These investigations were carried out under the direct scientific supervision of Prof. M.N. Berdichevsky. All subsequent investigations in the region are also associated with his name. Berdichevsky visited the MSU's geophysical base many times to get familiarized with the technology of the works and periodically estimated the results obtained. The accumulated MTS data were interpreted in accordance with the approaches proposed by him. This prehistory explains the appearance of this paper in the volume devoted to the memory of Berdichevsky.

TECHNIQUE OF ELECTROMAGNETIC SOUNDINGS

In order to study in detail the upper part of the structure (to about 200 m), we used the VES and TEM methods [*Electric Prospecting* ..., 2005]. A Shlumberger array (spacings up to 520 m), combined with an Astra transmitter and a MERI receiver (North-West Ltd), was used for observations by the VES method. Observations by the TEM method were carried out with the use of a one-loop array or a coaxial two-loop array (100 m× 100 m in size and larger); the works were performed with the TEM-Fast (AEMR Ltd.) or Tsikl (OOO Elta-Geo Ltd.) instrumentations.

For retrieving information about lower horizons of the sedimentary cover (down to 1000 m and deeper), we used the DES and FS methods. The UGE-50 transmitter, which produced a current of about 50 A in the transmitting line (500 m and longer), served as a source of the field. Observations were performed with the MERI instrument. When the DES method was used, transmitter-receiver spacings exceeded 10 km. The FS method was used for measuring the magnetic (H_z or H_y) and electric (E_x) components of the field in the frequency range 0.038–780 Hz.

The MTS method ensured the deepest investigations. The MTU-5 (Phoenix Geophysics Ltd.) and CES-M (Kruko Ltd) instruments were used. As a rule, observations were carried out during 12–15 night hours, and five components of the field were recorded. Since 2007, synchronous soundings have continued for two to three days each. The quality of MTS data in the region of the works most substantially depended on the proximity to electrified railways, especially those powered by direct current. The use of synchronous schemes of soundings makes it possible to reduce this dependence and approach such railways by a few tens of kilometers. At the same time, the EM field of the electrified railway carries certain information about the structure [Aleksanova et al., 2003].

As a result of the EMS data processing, we constructed apparent resistivity curves. When the MTS method was used, in addition to apparent resistivity curves, we also constructed phase curves and frequency dependences of the magnetovariational (MV) response (tipper).

COMPOSITE CURVES OF ELECTROMAGNETIC SOUNDINGS

Curves of the apparent resistivity qualitatively reflect changes in the resistivity with depth. In this case, the methods, which use the induction mode of the EM field, such as MTS, TEM, and FS with the magnetic field measurement, give an idea of the longitudinal resistivity of layers ρ_l [Vanyan, 1965]. The methods, which use the galvanic mode (VES, DES, and FS with the electric component at the galvanic excitation of the field) make it possible to obtain information about the transverse resistivity of layers ρ_n as well. According to these methods, the apparent resistivity depends on the rms resistivity of a sequence $\rho_m = \sqrt{\rho_l \rho_n}$.

The composite EMS curve consists of several apparent resistivity curves corresponding to different EMS methods and different components of the field [Khmelevskoi et al., 1999]. For constructing this curve, all of the apparent resistivity curves are related to one ordinate axis, whereas the abscissa axes for the methods based on direct current (geometric soundings) and the methods based on alternating current (induction soundings) are different. For the FS and MTS methods, the root from the period of oscillations ($\sqrt{T}$), and for the TEM method, $\sqrt{2\pi t}$, where t is the time of the field establishment, are plotted on the abscissa axis. For the curves obtained with the use of the VES and DES methods, the spacings $AB/2$ and R, respectively, are plotted on the abscissa axis.

In the construction of composite curves, the main problem is the coincidence of the axes corresponding to the methods based on direct and alternating currents. The axes are brought in coincidence by the marking horizons, i.e., by the layers, which manifested themselves in the sounding curves of both types. The axes $AB/2$ and R are moved parallel to the axes $\sqrt{T}$, and $\sqrt{2\pi t}$ and are scaled until the extremes corresponding to the chosen marking layers coincide.

In the region under investigation, three main sedimentary layers can be identified. The upper layer is represented by moraine and alluvial Quaternary (Q) deposits that are highly variable in plan. This layer is underlain by the high-resistance predominantly carbonate Upper Devonian–Lower Carboniferous (D_3–C_1) complex. Further, a conducting terrigenous complex composed of Vendian–Middle Devonian (V–D_2) rocks underlain by a high-resistance crystalline basement is present in the structure.

The composite EMS curves obtained at the margins of the Moscow Syneclise (near the village of Aleksandrovka) and the Voronezh anteclise (near the village of Baryatino) are presented in Fig. 2.

In the area around the village of Aleksandrovka, the DES and MTS curves in the region of the maximum associated with the high-resistance rocks of the Upper Devonian differ by one order of magnitude. This difference points to a strong macroanisotropy of this sequence. The main contributions to its longitudinal and transverse resistances are made by conducting clayey interlayers and high-resistance interlayers of gypsums and anhydrites, respectively. Nevertheless, the latter, representing a small fraction of the total thickness of the complex, due to their very high resistivity, make an enormous contribution to the total transverse resistance of the sequence (T), estimated by the quantitative interpretation at $2.5 \times 10^6\ \Omega\ m^2$.

In the Baryatino village area, the distinctions between the DES and MTS curves are not large, which is primarily explained by a smaller value of the transverse resistance ($0.6 \times 10^6\ \Omega\ m^2$). In addition, the lower most conducting part of the terrigenous complex composing the sedimentary cover base wedges out in this area. Therefore, the MTS curve does not descend below $10\ \Omega$ m.

The macroanisotropy can be also revealed during measurements of the electric and magnetic components of the field by the FS method with the galvanic excitation of the field [Kulikov et al., 1999]. In the area around the village of Aleksandrovka, the FS curve constructed from the component H_z gives a quantitatively true idea about the resistivity of the lower part of the cover and has a short ascending branch corresponding to the basement (whereupon the curve reaches the noninformative descending asymptote of the near zone). At the same time, the curve constructed from the component E_x rapidly reaches the horizontal asymptote of the near zone and becomes noninformative. In the area around the village of Baryatino, the FS curves constructed from different components are close in their information content. These curves virtually coincide within $\sqrt{T} = 0.5\ s^{1/2}$ and then reach the asymptotes of the near zone.

STANDARD MTS CURVES

Beginning from 2003, when MTS investigations were carried out in the region, the base five-component station (with the Phoenix MTU-5 instrumentation) was installed near the MSU's geophysical base. This station ensured the synchronous scheme of areal MT/MV soundings. The two-month records performed by the base ALX station in the summer of 2009 were processed to obtain the MTS and MVS standard curves (Fig. 3). The variant of data processing presented in the figure was obtained with the use of the PRC-MTMV system developed at the GEMRC IPE RAS [Varentsov et al., 2003; Varentsov, 2005]. During the data processing, for the suppression of local and regional industrial noise, we used multipoint schemes for estimating the impedance and tipper with reference to synchronous records of MV fields at the KIV observatory near Kiev and at field observation points located at distances of hundreds of kilometers to the south, in the vicinity of Zhizdra and Suzemka. A large volume of data and a fundamental graph of their processing made it possible to obtain good quality standardized results for periods of about 3 h.

The obtained MT curves and induction vectors are shown in the directions of the measurements, because they correspond to the dips and strikes of the geological structures (the basement surface smoothly subsides from north to south), which is confirmed by the orientations of the real induction vectors indicating that the region of the maximum conductivity is located in the north (in the central part of the Moscow syneclise). The tipper anomaly caused by the conductivity contrast at the northern side of this syneclise at the 400-s period attains 0.5. The horizontal MV response (with respect to the KIV observatory) also contains a conspicuous anomaly in the northern main amplitude component [Varentsov et al., 2010] at periods equal to tens and hundreds of seconds, which reflects the effect

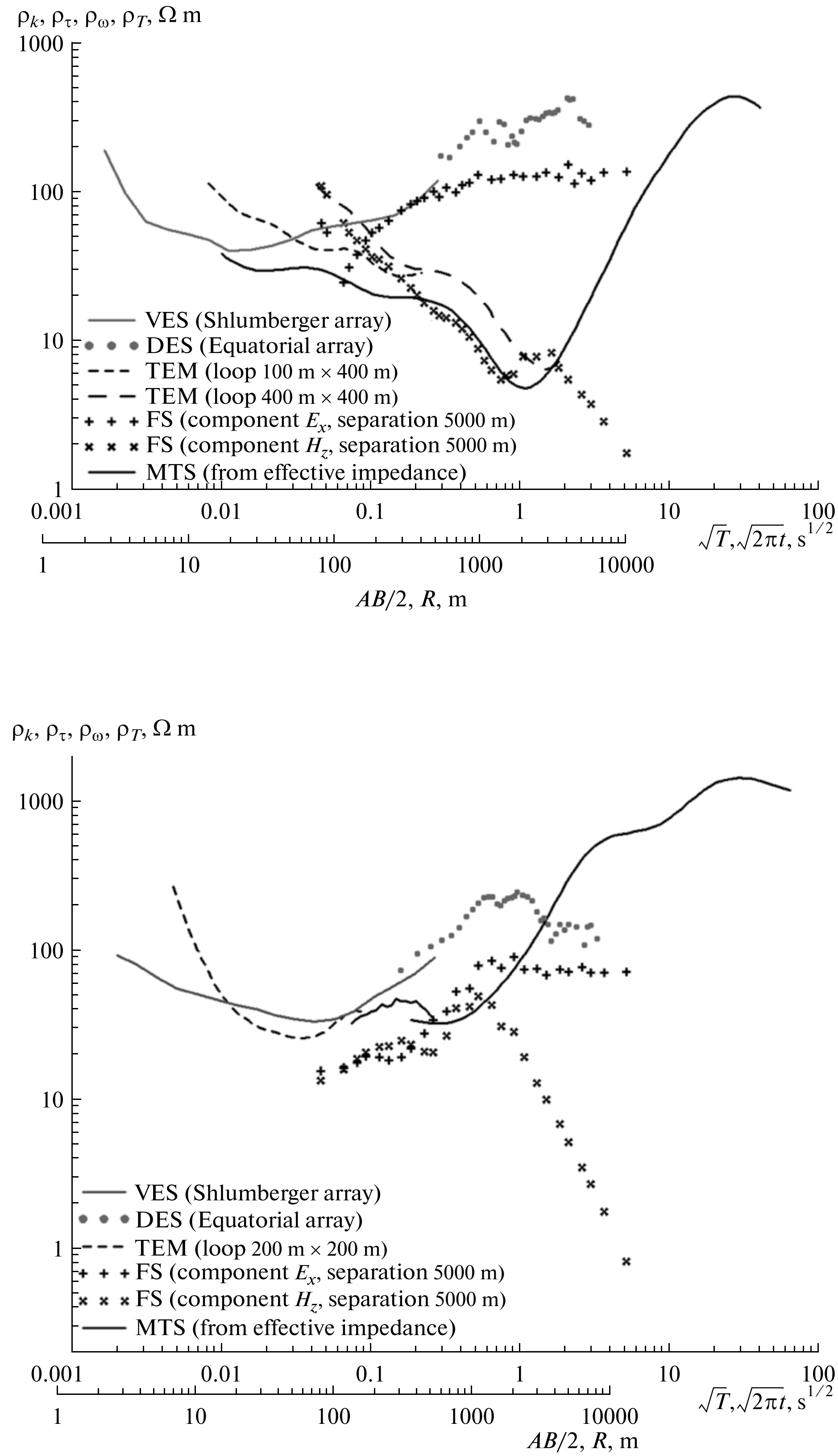

Fig. 2. Composite EMS curves obtained in the Aleksandrovka village (top) and Baryatino village (bottom) areas.

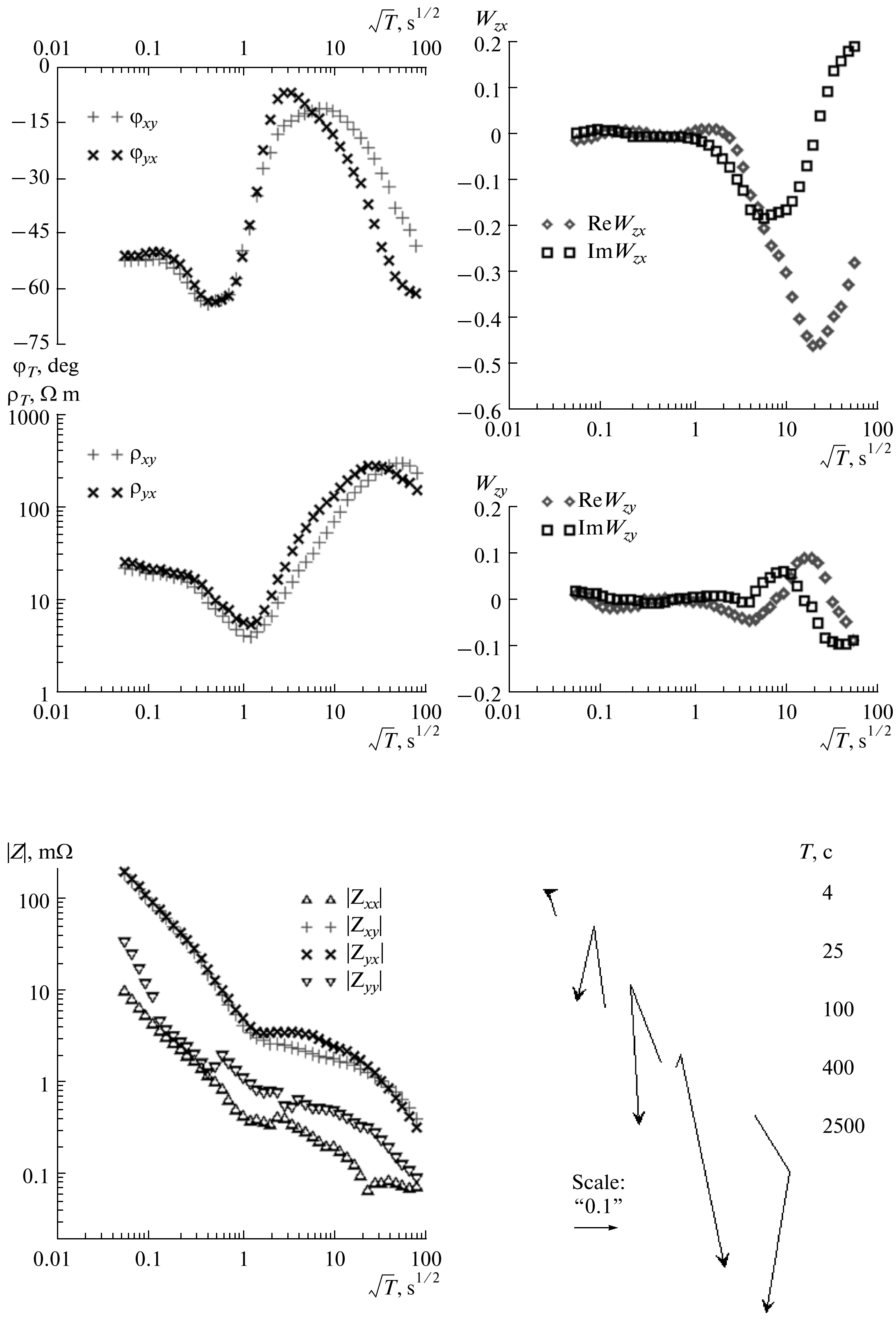

Fig. 3. MTS and MVS data obtained at the MSU geophysical base in Aleksandrovka village (ALX stationary point): MTS curves: phases of the main components of the impedance tensor, apparent resistivities, moduli of impedance tensor components (left-hand); and MVS data: real and imaginary parts of tipper matrix components and induction arrows at several periods (right-hand).

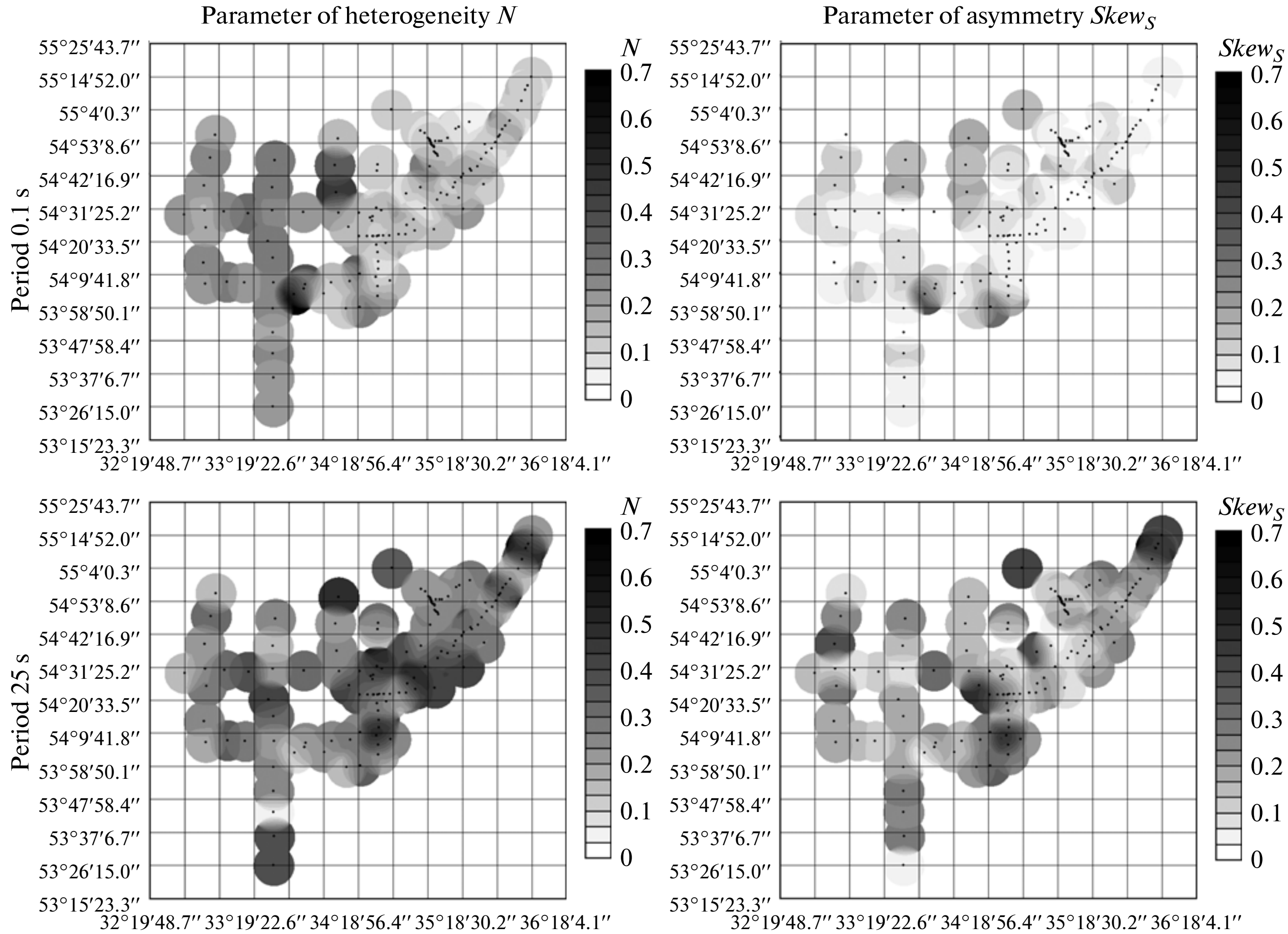

Fig. 4. Maps showing the parameters of heterogeneity *N* and asymmetry $Skew_S$ at the periods 0.1 and 25 s.

of concentration of sublatitudinal currents in the lateral part of the Moscow syneclise.

At the same time, the form of the obtained MTS curves is rather typical of horizontally homogeneous media. The phase curves and curves of the apparent resistivity constructed from the main components of the impedance tensor are close to each other, and the moduli of the main impedances (Z_{xy} and Z_{yx}) are by about one order of magnitude larger than the moduli of the additional components (Z_{xx} and Z_{yy}).

RESULTS OF INTERPRETATION OF MTS DATA

The MTS data obtained in 1997–2008 in the course of training–educational practical works, as well as in 1991 during the works in the area of the Smolensk nuclear power station (Fig. 1), were collected and systematized. The quality of their processing was estimated, and a part of the data was processed anew. Then, the structural analysis of these data, which serves as a necessary basis for the subsequent construction of the geoelectric model of the region, was performed. In particular, the maps showing the parameters of heterogeneity and asymmetry *N* and $Skew_S$ were considered [Berdichevsky and Dmitriev, 2009]. The small values of the parameter *N* at high frequencies and the increased values of *N* and $Skew_S$ at low frequencies point to the quasi-one-dimensional structure of the sedimentary cover and a more complex horizontally heterogeneous structure of the metamorphic basement (Fig. 4).

Further, we performed the one-dimensional interactive interpretation of the effective curves of the apparent resistivity and impedance phase (Fig. 5). Particular attention has been given not only to the minimization of discrepancies but also to the smoothness of the variations in resistivity and thicknesses of layers from one point to another, which corresponds to specific features of the geological structure of the sed-

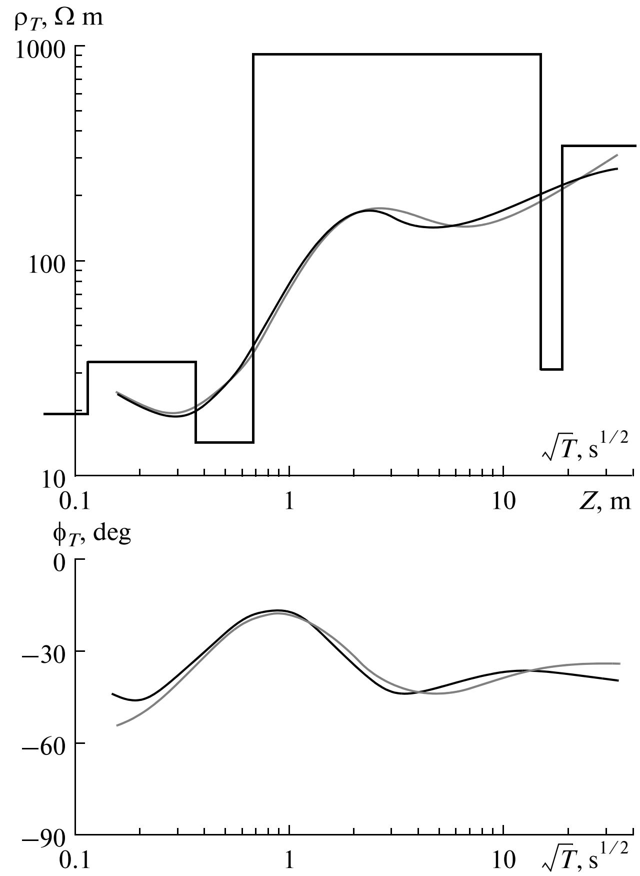

Fig. 5. Example of one-dimensional fitting of effective MTS curves of the apparent resistivity (top) and the impedance phase (bottom). Light lines are for observational data, and dark lines are for model data. The upper panel also shows the result of interpretation in the "pseudo-logging curve" form, i.e., as the dependence of the resistivity on depth.

imentary cover. In the southwestern part of the region, a deep conducting anomaly clearly manifests itself in the MTS curves. The used approach to the interpretation allowed us to obtain a smoothed averaged image of this anomaly.

The results of the interpretation were used for constructing the maps showing the bedding depths of several horizons, as well as the total surface conductances of the upper part of the structure, sedimentary cover, and crustal conductor. In the map showing the depths to the basement, the subsidence of the latter toward the northeast is noted (Fig. 6a), and in the map showing the total conductance of the sedimentary cover, its lowest values (less than 50 S) are observed in the southeastern part (Fig. 6b). Only at this place, can we identify with certainty the deep crustal conducting zone at a depth of about 15 km (Fig. 6c) with the longitudinal conductance up to 100 S (Fig. 6d).

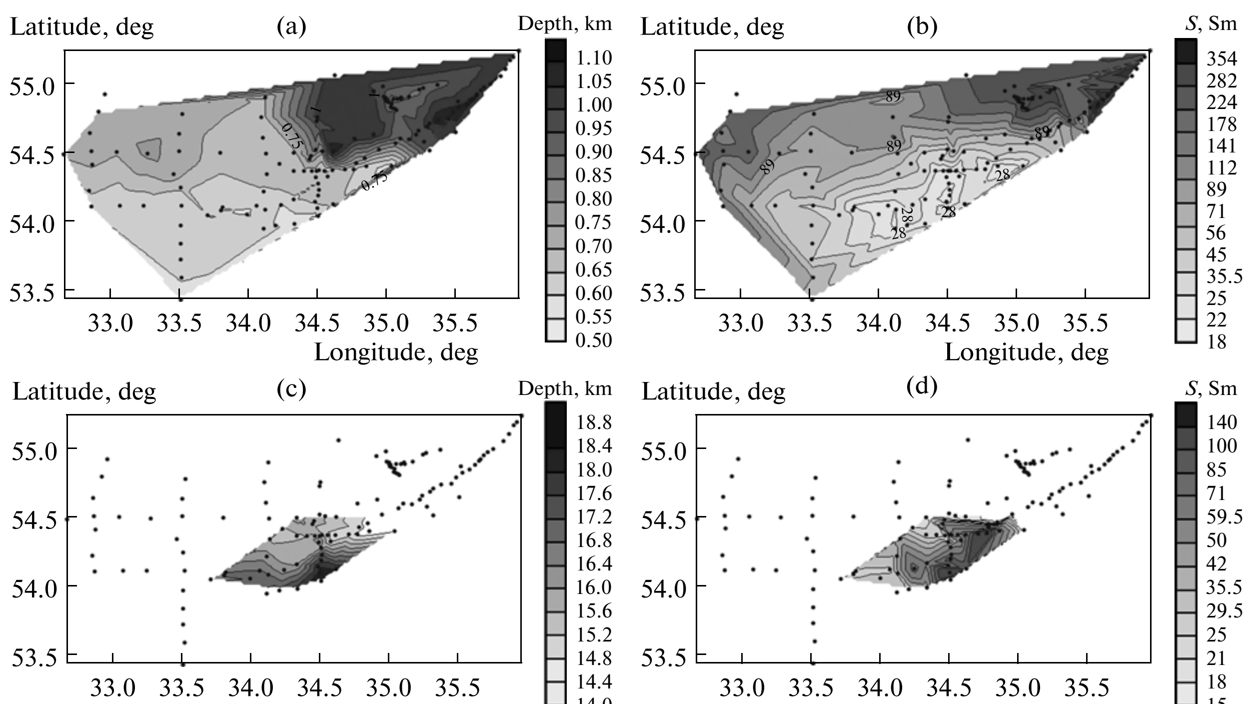

Fig. 6. Maps constructed as a result of the interpretation of MT data: (a) depth to the crystalline basement; (b) total longitudinal conductance of the sedimentary cover; (c) depth to the crustal anomaly of electric conductivity; and (d) total longitudinal conductance of the crustal anomaly.

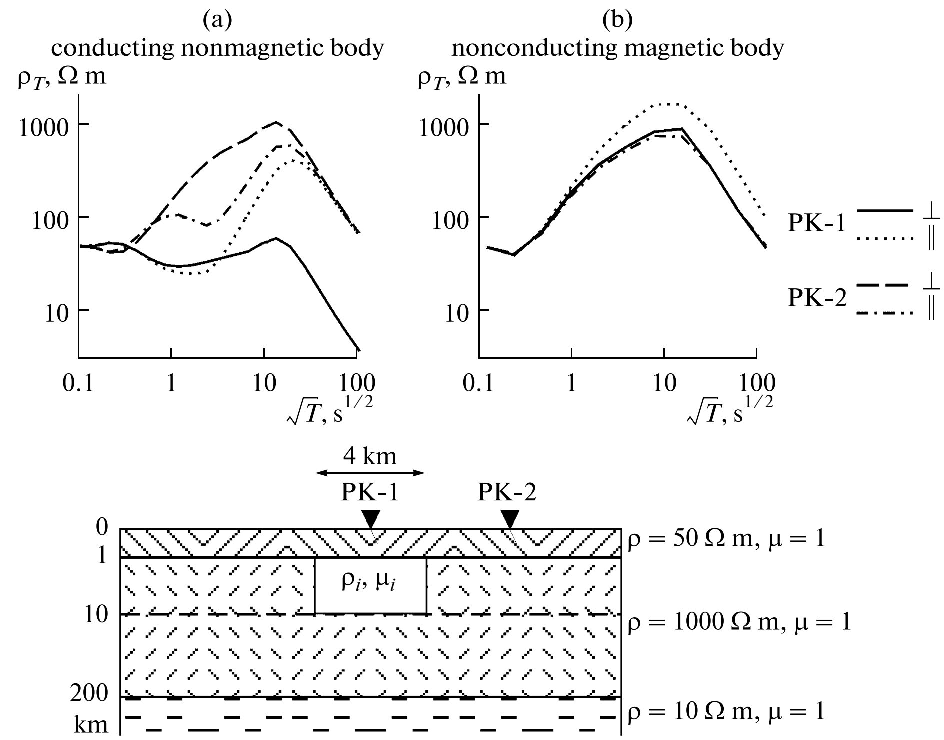

Fig. 7. Results of the two-dimensional modeling of the influence of electric conductivity and magnetic permeability anomalies on MTS curves: the geoelectric model (bottom) and the results of calculations for two variants (a) $\rho_i = 10\ \Omega$ m, $\mu_i = 1$, and (b) $\rho_i = 1000\ \Omega$ m, $\mu_i = 3$ (top). The observation points (PK-1 or PK-2) and directions (across or along the anomaly), to which the curves are related are indicated on the right.

CONCLUSIONS

The investigations carried out resulted in the study of the main features of the geoelectric structure of the sedimentary cover in the region. In the transition zone from the Moscow syneclise to the Voronezh anteclise, where the thickness of the sedimentary cover changes approximately twofold, the total transverse resistance T of its middle (high-resistance) part and the total longitudinal conductance S (caused mainly by the underlying sequence) decrease by about fivefold. Thus, in the area around the village of Aleksandrovka, the values of T and S are equal to about $2.5 \times 10^6\ \Omega\ m^2$ and 200 S, whereas in the area around the village of Baryatino, they are $0.6 \times 10^6\ \Omega\ m^2$ and 40 Sm.

The conducting anomaly in the middle part of the crust is stably recognizable only in the part of the region, where the conductance of the sedimentary cover is 50 S and less. In order to answer the question whether this anomaly continues beneath the Moscow syneclise, high-precision observations are necessary (which is problematic due to the high noise level), as well as the passage to more complex models of the medium and the careful inclusion of a priori information.

One more question arising in relation to specific features of the geoelectric structure of the region is the influence of the magnetic permeability on the results of EM soundings. The relative magnetic permeability μ_{rel} of ferruginous quartzites, which produce the Baryatino magnetic anomaly, attains values 2–3. The preliminary 2D mathematical modeling showed (Fig. 7) that the μ_{rel} anomaly in the upper part of the basement weakly affects the longitudinal and transverse impedances. The presented example demonstrates only a small overestimation of the longitudinal impedance values directly over the anomaly. The electric conductivity anomaly yields a much stronger effect than the magnetic permeability anomaly. The influence of μ_{rel} anomalies on the tipper and magnetic tensor must be investigated additionally.

Since 2007, the regional program of EM soundings has received a new impetus for its further development: supported by the Russian Foundation for Basic Research (RFFI) (project nos. 07-05-00437a, 08-05-00327a, 09-05-00466a), scientists from MSU, GEMRC IPE RAS, and Institute of Oceanology (IO) RAS began systematic investigations on the western slope of the Voronezh anteclise from the MSU's geophysical base to the Ukrainian frontier. These investigations are performed with the use of new synchronous techniques ensuring obtaining stable MT and MV responses in spite of the high level of industrial

EM interferences. Synchronous observations are performed with reference to the ALX stationary MV point at the MSU's geophysical base and the KIV geomagnetic observatory near Kiev.

The first results of synchronous soundings [Varentsov et al., 2009; 2010] indicate that the Baryatino crustal anomaly of electric conductivity is connected with the brighter Kirovograd crustal anomaly, which is well studied on the Ukrainian shield and continues northward deep into Russia along the meridians 34° and 35°E. In cooperation with scientists of the Institute of Geophysics, National Academy of Sciences of Ukraine, a complex geophysical study of the Kirovograd anomaly in the north of Ukraine and the southwest of Russia began with the support of the grant of the RFFI–UKR_F 09-05-90439a.

The organization, within the Innovational educational program of MSU, of a pavilion for long-term geophysical observations and a parametric borehole has served as an additional impetus for new directions of geoelectric investigations in the region. The pavilion was equipped with magnetovariational, telluric, and seismic stations, which will activate investigations of the deep structure and geodynamic processes. A borehole 300 m deep drilled with a complete core sampling and intended for the training practice in logging ensured the reliable and detailed information necessary for the interpretation of the EMSs of the upper part of the sedimentary cover.

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