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GEOPHYSICS

Normal Model of Electric Conductivity of the Baltic Shield Lithosphere and Its Geodynamic Interpretation

A. A. Zhamaletdinov[1], A. N. Shevtsov[2], and A. D. Tokarev[2]

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The problem of developing a normal model of the electric conductivity of the continental lithosphere is currently at the level of discussion, despite more than half a century of the deep electromagnetic sounding initiated by the experiments of A.P. Kraev and A.S. Semenov [1]. In the present paper, the normal model is understood as a model of electric conductivity of the lithosphere (shield and platform) free of the lateral influence of the Earth’s crustal conductors, marginal seas, and other objects of horizontal electric inhomogeneity. Such a model should reflect a one-dimensional distribution of electric conductivity at a particular depth, as it depends on the composition, thermodynamic state, and fluid regime of the Earth’s interior. Vanyan started the first systematic studies in this field [2, 3].

In order to develop a normal model in our work, we present the results of deep sounding with controlled sources on the Baltic Shield, supplemented by the magnetotelluric sounding (MTS) data from the Baltic Shield Electromagnetic Array Research (BEAR) experiment [4] and data from global geomagnetic observations [5]. The profiles and a map of the locations of the soundings are shown in Fig. 1. The points of the soundings were chosen within relatively uniform and poorly conducting blocks at a considerable distance from known crustal conductors. The main method employed in the research was sounding in the magnetohydrodynamic field (MHD-field) of the Khibiny source with a power of 40 MW (profiles Fig. 1, profiles I–III). The maximum depth of the sounding was 50–100 km at horizontal separations of 500–600 km. Frequency soundings using an EPS-67 automobile generator with a power of 29 kW [8, 9] and a *Zevs* [10] extremely low-frequency (ELF) antenna were applied to study the upper part of the Earth’s crust to depths of 10–15 km (Fig. 1, study areas 1–3). In 2003, the first tensor frequency soundings using two mutually orthogonal industrial power transmission lines (length 109 and 89 km) at distances of up to 270 km from the source were performed with support from the Russian Foundation for Basic Research. The upper part of the section was studied using DC vertical electric soundings (VES) with a separation between groundings AB of up to 16 km. The DC part of the soundings was performed at distances between the source and receiver of up to 100 km (Fig. 1, study area 1 and Khibiny-III profile) [6]. The total area covered by the soundings with controlled sources was approximately 0.5 mln km^2.

The resulting normal curve of the apparent resistivity and phase obtained from the sounding data with natural and controlled sources in the frequency range 10^6 to 10^{-6} Hz is shown in Fig. 2. The phase curve for soundings with controlled sources was obtained from the curve of apparent resistivity using Weidelt integral relations [11]. The phase for soundings with natural sources was obtained from the experimental data in [4, 5]. The left branch of the apparent resistivity curve in Fig. 2 in the frequency range 10^6 to 10^3 Hz was plotted by recalculating it into the frequency range of DC electric soundings. It can be seen that the curves of apparent resistivity in Fig. 2, measured with different types of sources under different geological conditions, repeat one another and continuously follow the particulars of the variation in properties over the geoelectric section virtually from the daytime surface to depths of 50–100 km, i.e., deeper than the thickness of the Earth’s crust.

We used the results of the BEAR experiment to evaluate the deeper depths [4]. The MTS curves measured within the limits of the most uniform and poorly conducting blocks are shown in Fig. 2. These are points B47 and B48 (the Karelian Megablock) and point B28 (the Central Finnish Block). The location and numbers of the points chosen for analysis are shown in Fig. 1. The minimum ρ_T curves, which are considered less dis-

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[1] *Institute of Terrestrial Magnetism, Ionosphere,*
and Radio Wave Propagation, St. Petersburg Branch,
Muchnoi per. 2, St. Petersburg, 191023 Russia;
e-mail: zham@az2608.spb.edu

[2] *Geological Institute, Kola Research Center,*
Russian Academy of Sciences, ul. Fersmana 14, Apatity,
Murmansk oblast, 184209 Russia

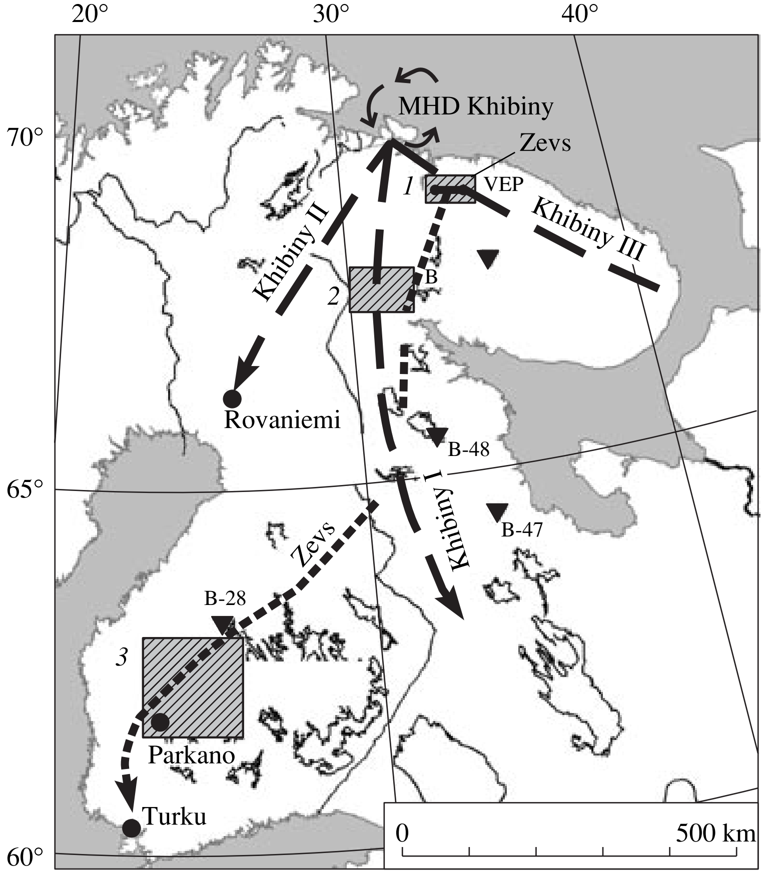

Fig. 1. Points and profiles of deep electromagnetic investigations with natural and controlled sources in the Baltic Shield. (Khibiny I–III) MHD sounding profiles; (ZEVS) the sounding profile with the Zevs ULF antenna; (CSAMT 1–3) frequency sounding regions; (VES) deep DC sounding region; (B28, B47, B48) points of the BEAR MTZ experiment.

torted by the horizontal inhomogeneity of the rocks, are shown in Fig. 2 for the chosen points of the MTS. The data of global soundings over the network of geomagnetic observatories are located in the lowest-frequency part of the diagram. An analysis of them is given in [5].

It is seen that the results from the soundings generally show satisfactory agreement with the natural and controlled sources. However, taking into account the significant instability of the MTS data caused by their high sensitivity to the lateral distortions and inhomogeneity in the source structure, further interpretation was done only on the basis of the results from soundings with controlled sources.

The inverse problem was solved using the method of effective linearization [8]. The resulting geoelectric section is shown in Fig. 3 in the form of a gradient model (curve *1*) and its step-like approximation (curve *2*). The bars show the confidence intervals determined by the initial data scattering.

The obtained normal section is a 5-layer model of the CNC type with three conducting layers. An interpretation of the nature of the evaluated layers is shown in Fig. 3 in the form of a structural-geodynamic column proposed by Nikolaevskii [12]. In this column, the upper part of the section is occupied by a region of reduced resistivity (*1*) that includes sedimentary moraine deposits 20–30 m thick and the upper disintegrated and water-bearing part of the crystalline basement cover having an average thickness of 100 m. The underlying layer of high resistivity (*2*) is crosscut by subvertical fractures and fissures filled with water solutions (fluids). Its average thickness is estimated at 2–3 km.

The depth interval from 2–3 to 10 km includes an intermediate conductive region (*3*), where resistivity decreases from $2 \cdot 10^5$ Ohm m to approximately $2 \cdot 10^4$ Ohm m. (This conductive layer was distinguished for the first time.) The nature of the decline in resistivity is related to the penetration of meteoric fluids deep into the rock. We assume that the intermediate conductive layer has a dilatant-diffusive nature. Therefore, it can be termed the DD layer. This idea is conventional in character, since the distinguished region cannot be determined as a conductive layer in the usual geometric sense. The DD layer has an extremely inhomogeneous structure with significant scattering in power and specific resistivity. The resistivity of the layer changes in different regions of investigation in the interval $3 \cdot 10^3$ to $3 \cdot 10^4$ Ohm m. The longitudinal conductivity of the

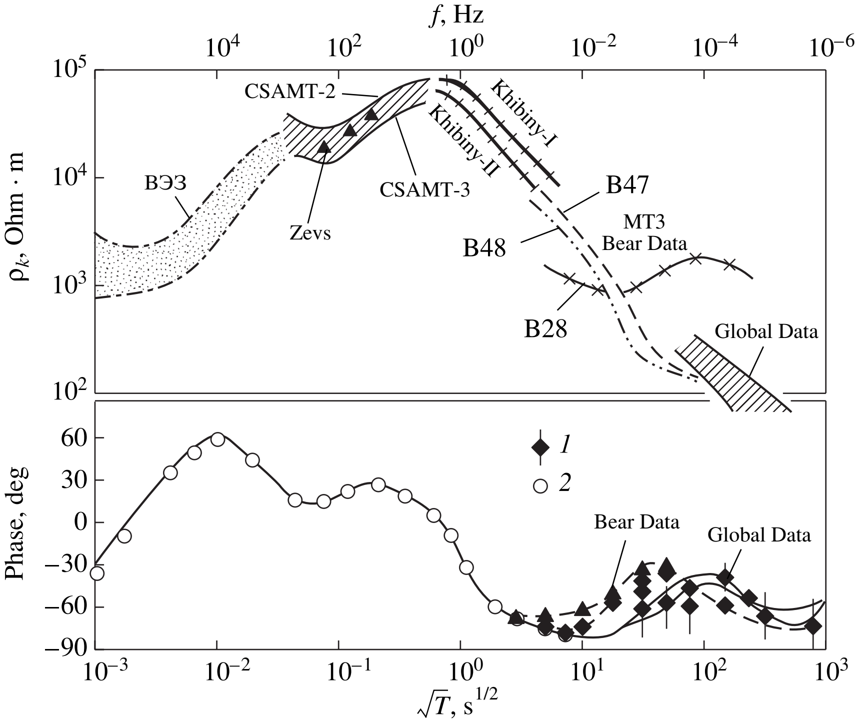

Fig. 2. Composite diagram of the curves of apparent resistivity and phase based on results of deep electromagnetic sounding with natural and controlled sources in the Baltic Shield. (*1*) Measurements; (*2*) calculation.

layer changes from 0.3 to 1–2 S. The nature of the mentioned scatterings is mostly explained by the sharp horizontal inhomogeneity of the parameters of the conductive layer rather than by the ambiguity of the inverse problem solution.

It is important to note that the intermediate conductive DD layer is not manifested during DC soundings even at larger separations (up to 100 km or more). The DD layer must be considered together with the upper poorly conducting layer. Together they reflect the general features of the transition from subvertical fractures to flattening subhorizontal ones within the upper 10-km layer of the Earth's crust.

Continuing the consideration of the normal geoelectric section in Fig. 3, we may note that an increase in the specific electric resistivity of the rocks of up to $2 \cdot 10^5$ Ohm m is observed in zones deeper than 10 km. The thickness of the poorly conductive part of the lithosphere is estimated as 60–80 km. The mean value of the transversal resistivity is approximately 10^{10} Ohm m^2. An exponential drop in resistivity is observed in the deeper zone. By extrapolating the obtained section, we can suppose that the drop in specific resistivity to 100 Ohm m needed for the appearance of the partial melting zone in the asthenosphere [2] can be observed at a depth of 250–300 km.

The dilatancy mechanism, which probably governs the nature of the DD layer, is defined as the irreversible expansion of polycrystalline aggregates during shear dislocations [12]. The shear conditions deep in the Earth are explained by the simultaneous action of lithostatic pressure and tangential stress. Shear tensions deep in the Earth appear due to a more rapid increase in the horizontal component of rock pressure with depth as compared to the lithostatic vertical component. The shear conditions lead to rock failure within the Earth. The failure boundary is shown in the phase diagram in Fig. 4. The boundary defines the following *PT* conditions of the dilatancy zone:

$$0.2\ \text{HPa} \le p \le 0.5\ \text{HPa}, \quad 200°\text{C} \le T \le 400°\text{C}. \qquad (1)$$

According to these conditions, the dilatancy (or fracture flattening) zone occupies the depth range 5–17 km on the Nikolaevskii column (Fig. 4). In our column, obtained from the analysis of normal geoelectric section, the dilatancy zone occupies the 2–3 to 10 km depth range; i.e., it is located significantly higher in the section (Fig. 3).

On the Nikolaevskii column, a lower fissuring and pseudoplasticity zone is located below the dilatancy zone in the 17 to 40 km depth range (Fig. 4). This region, also defined as the half-brittle state zone of the Earth's crust, is bounded from below by the Moho surface. According to [12], the Moho boundary is underlain by the region of the true plastic state of granite gneisses determined by the following thermodynamic conditions:

$$p \ge 1\ \text{HPa}, \quad T \ge 600°\text{C}. \qquad (2)$$

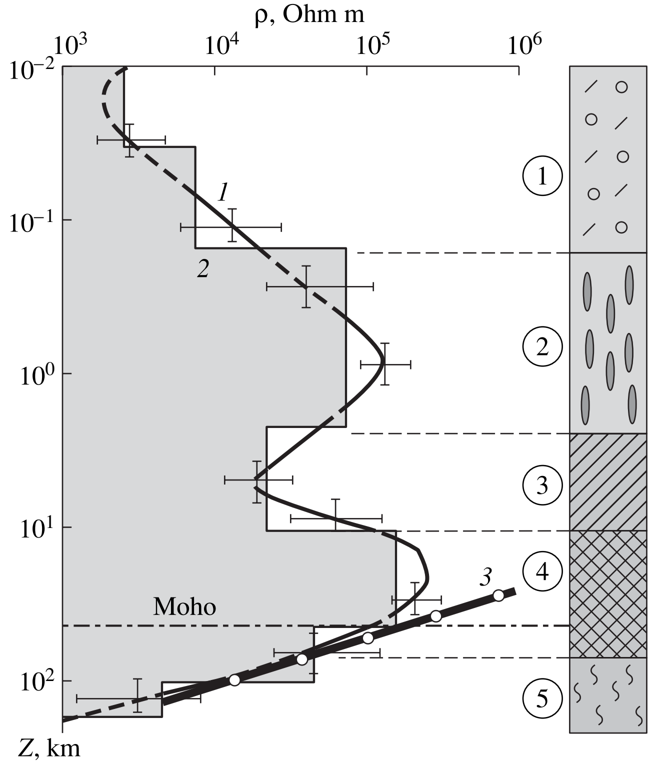

Fig. 3. Normal electric section of the Baltic Shield lithosphere and its interpretation in the form of a structural geodynamic column. (*1*) Gradient model of geoelectric section; (*2*) the same, but for a layered model; (*3*) a model of the section based on laboratory data. Numerals in circles: (1) water-bearing moraine and cover of the crystalline basement; (2) upper brittle part of the lithosphere with subvertical fractures; (3) the same, but with inclined and subhorizontal fissures (dilatancy zone); (4) middle pseudoplastic part of the lithosphere; (5) lower lithosphere (plasticity zone).

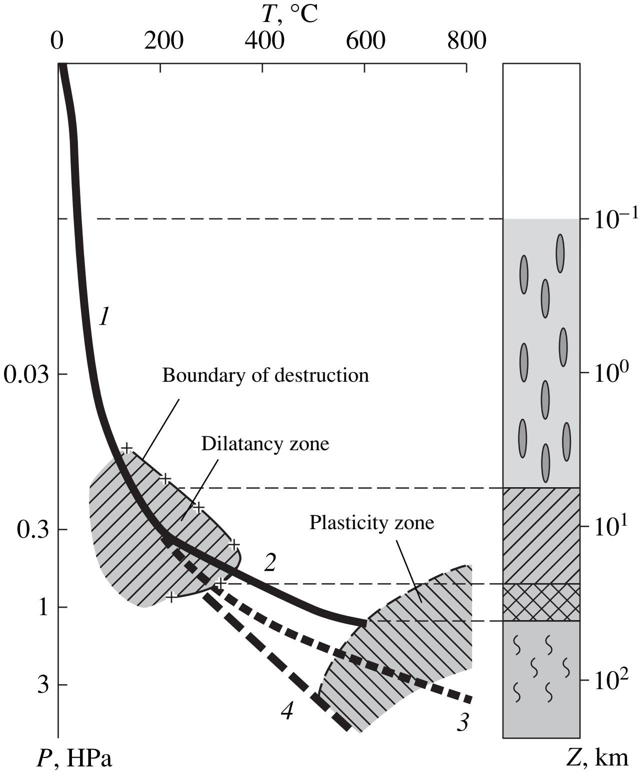

Fig. 4. Temperature interpretation of the results of deep electromagnetic soundings at the phase surface of dilatancy and plasticity zones (according to [12]). (*1*) Measured temperature curve SD-3; (*2*) extrapolation of temperature curve SD-3 to a depth (based on [13]); (*3*) the same, but with the consideration of the electromagnetic sounding data; (*4*) temperature curve based on data from [Valle, 1951]. Notations on the structural geodynamic column are the same as in Fig. 3.

The location of this boundary was based on the extrapolation of the Kola Superdeep Borehole 3 (SD-3) temperature curve to point 580°C at a depth of 40 km (Fig. 4, curve *2*) [13]. However, a comparison of the normal geoelectric section of the Baltic Shield with the results from laboratory investigations [14] (in Fig. 3, curves *1* and *3*) shows that their best coincidence is observed if we assume that the temperature at the Moho boundary does not exceed 400°C in the conditions of the Baltic Shield. In this case, the extrapolation of the temperature evolution of curve SD-3 takes the form shown by curve *3* in Fig. 4. According to condition (2), the upper edge of the plasticity zone would descend to a depth of ~80 km, where the data from deep electromagnetic soundings suggest a temperature of ~600°C.

Thus, the results of our analysis of the normal geoelectric section in the eastern part of the Baltic Shield, based on a comparison of controlled-source sounding data and data from the Kola Superdeep Borehole, demonstrate their good agreement with the main points of the theory of dilatant fissuring suggested by Nikolaevskii. However, one can see differences between the experimental and theoretical data in the estimates of the manifestation of dilatancy and plasticity zones. In particular, according to the experimental data from deep soundings, the dilatancy zone is located 3–5 km above the theoretical estimates. It is possible that this difference is caused by the influence of lunisolar stresses. In any case, it is noteworthy that the location of the dilatancy zone (the DD layer) coincides with the depth of the development of maximum variations in the electric conductivity of the Earth's crust caused by lunisolar tidal stresses [15]. This allows us to suggest that it is the lunisolar diurnal tides that provide the energy resource needed for the dilatancy and descent of fluids along the tectonic zones against the lithostatic pressure driving the moisture to the daytime surface.

Solving the question of the above differences is of great importance with regard to the fundamental problems of Earth physics and requires additional experimental and theoretical studies.

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