On the study of the lithosphere temperature in Kola-Karelian region from the data of deep electromagnetic sounding

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ABSTRACT

A technique for assessing the temperatures of the Earth's crust and upper mantle based on solving the inverse problem of electromagnetic sounding for a two-phase model of rock electrical conductivity and taking into acccount laboratory data on rock electrical conductivity at high temperatures [Parkhomenko, Bondarenko, 1972] is presented and tested using the results of deep electromagnetic sounding with a controlled source and audio-magnetotelluric measurements of the FENICS-2007, 2009 and 2014 experiments. Soundings with natural and powerful controlled sources were performed within large, poorly conducting blocks of the lithosphere, the so-called "transparency windows", taking into account the influence of the "Earth-ionosphere" waveguide and of near-surface conductors (static shift). The apparent resistivity and impedance phase curves obtained have predominantly smooth variations along the observation profiles thus allowing interpretation within the framework of one-dimensional models. Temperature modeling was carried out assuming that within the upper part of the section (at depths less than 20-30 km), resistivity changes with depth largely due to the influence of porosity, permeability, and pore water content and salinity. For the depths exceeding 20-30 km, it is assumed that the resistivity of the lower part of the Earth's crust and upper mantle is affected, first of all, by the mineral composition of dry rocks, temperature and pressure. The vertical profile of mineral composition of the lithosphere was inferred from a priori geological estimates and superdeep drilling data. The temperature distribution over the depth is modeled on the basis of the heat balance equation (Shafanda et al., 1987). The calculated temperature models are compared with the model (Glaznev, 2003), built in the frame of complex interpretation of geophysical data without taking into account electromagnetic studies.

Ключевые слова: electrical conductivity, electromagnetic sensing, temperature, heat flux

INTRODUCTION

A unique multistage experiment FENICS-2007, 2009, 2014 and 2019 on the use of grounded sections of industrial power transmission lines as a controlled source of an electromagnetic field accomplished with measurements of the natural audio-magnetotelluric field and aimed at deep sounding of the lithosphere of the eastern part of the Fennoscandian Shield was carried out during the period of 2004 - 2019 by the research team from the Geological Institute, in close cooperation with colleagues from the Center for Physical and Technical Problems of the Energy of the North and with the support of the Russian Foundation for Basic Research, under the guidance of A.A. Zhamaletdinov.

FENICS experiments (Zhamaletdinov et al. 2011), as well as the frequency-domain soundings with dipole arrays in the Central Finland granitoid massif (Zhamaletdinov et al., 1998) and in Ensko-Kovdor block (Zhamaletdinov et al. 2017), and remote frequency sounding in the Murmansk block (Zhamaletdinov et al., 2019) before it, confirmed the applicability of the model of the "normal geoelectric section", first proposed in 1998 by Zhamaletdinov to explain the results of deep electromagnetic sounding of laterally homogeneous poorly conducting ancient blocks of the lithosphere of the Fennoscandian Shield.

TECHNIQUE

To determine the parameters of the crustal model from the solution of the inverse problem for electromagnetic data, e.g., from the conductivity model section obtained using both magnetotelluric (MT) and controlled source (CSAMT) data, taking into account assumed lithology and laboratory data for rock conductivity we use an approach based on the balance equation. We assume to be known boundary conditions on the surface: heat flux density $Q(0)=Q_0$ and temperature $T(0)=T_0$, and the dependence of thermal conductivity on depth and temperature, $\lambda(z)=\lambda_0(z,T)$. In this case, the resistivity is considered as a functional of the given boundary conditions, the function of thermal conductivity $\lambda(z)=\lambda_0(z,T)$ and temperature $T(z)$, which are adjusted in the process of minimizing the misfit functional for the measured values of the apparent resistivity logarithm $\lg \rho^1_{\omega j}$ and impedance phase

$\arg\left(Z^1_{\omega j}\right)$ for j-th frequency ω_j and solution for the direct problem:

$$S(\rho)=\sum_{j=1}^{N}\left(\lg\rho^0_{\omega j}(\rho)-\lg\rho^1_{\omega j}\right)^2+ \\ +\sum_{j=1}^{N}\left(\arg\left(Z^0_{\omega j}(\rho)\right)-\arg\left(Z^1_{\omega j}\right)\right)^2=\min \qquad (1)$$

Here $\rho^0_{\omega j}$ is apparent resistivity and $\arg\left(Z^0_{\omega j}(\rho)\right)$ is impedance phase, calculated for the geoelectric section $\rho(z,T)$. In the general case, for 2- and 3-dimensional observational data and, accordingly, for geoelectric models, the determinant of the impedance tensor matrix (matrix determinant) is used. The modulus and argument of this invariant are used to calculate apparent resistivity and phase, respectively.

By minimizing the misfit, we determine the resistivity $\rho(z,T)$. Then, for a given lithology and laboratory data, we determine $T(z)$. To estimation of the fluids influence we use Archie low and linear low for fluids conductivity vs temperature t in upper crust (Vanyan, 1997):

$$\frac{\Delta\sigma}{\sigma_{18}}=\frac{\sigma-\sigma_{18}}{\sigma_{18}}=\alpha\left(t-18^0C\right) \qquad (2)$$

where $\alpha\approx 0.025$.

In lower crust and mantle Arrenius – Ioffe exponential low used for resistivity of the solid phase (the host rock) (Ioffe, 1974):

$$\rho=\rho_0\exp\left(\frac{E_a}{k_BT}\right). \qquad (3)$$

where ρ_0 is a factor, defined as the rock resistivity at T → ∞; E_a – activation energy of the ions carrying charge (in eV, 1 eV=1.602·10^{-19} J); kB – Boltzmann constant (k_B = 1.38·10-23 J/K); T is absolute temperature (K). That is, its logarithm is in direct proportion with reciprocal temperature:

$$\lg\rho=\lg\rho_0+0.434\cdot\frac{E_a}{k_BT} \qquad (4)$$

Since the factor in this expression (3) is a certain constant determined by the nature of electricity carrier ions, the dependence of the resistivity on temperature is usually depicted on a linear-logarithmic scale, as is shown in Fig. 1, which shows the average diagrams of the temperature dependence of the resistivity of acidic and basic-ultrabasic rocks of the Baltic Shield (Parkhomenko, 1965). The break of straight lines is caused by a change in the ion activation energies.

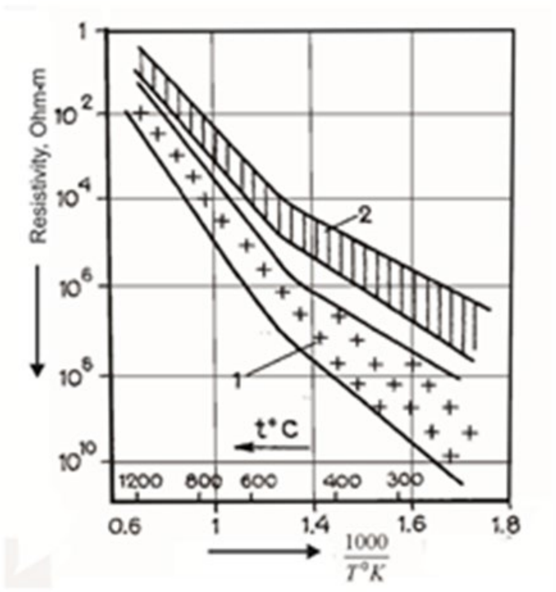

Figure 1. Averaged pattern of the electrical resistivity of dry rocks depending on temperature (Parkhomenko, 1965). 1 – acid rocks (granites), 2 – basic and ultrabasic rocks (peridotites, pyroxenites).

An approximation of the dependence between resistivity of the samples and temperature from (4):

$$\begin{cases}\lg(\rho)-\lg(\rho_{01})=0.434\dfrac{E_1}{k_B\alpha}\left(\dfrac{\alpha}{T}\right), & T>T_{12}\\[2ex] \lg(\rho)-\lg(\rho_{02})=0.434\dfrac{E_2}{k_B\alpha}\left(\dfrac{\alpha}{T}\right), & T\le T_{12}\end{cases} \qquad (5)$$

where T_{12} is the temperature of the change in the activation energy, and α is a scaling factor for the Earth's crust and upper mantle, it is convenient to use α = 1000. Note that according to (7), the parameters E_2 and $\lg(\rho_{02})$ are associated with ρ_{01}, E_1, and T_{12} values. From expression (5) we can find that

$$\lg(\rho_{02})-\lg(\rho_{01})=-0.434\frac{E_2-E_1}{k_B\alpha}\left(\frac{\alpha}{T_{12}}\right) \qquad (6)$$

The temperature can be expressed from (5) as a function of the resistivity:

$$\begin{cases}T=0.434\dfrac{E_1}{k_B\alpha}\left(\dfrac{\alpha}{\lg(\rho)-\lg(\rho_{01})}\right), & T>T_{12}\\[2ex] T=0.434\dfrac{E_2}{k_B\alpha}\left(\dfrac{\alpha}{\lg(\rho)-\lg(\rho_{02})}\right), & T\le T_{12}\end{cases} \qquad (7)$$

It is now possible to determine the parameters of the crustal model from the solution of the inverse problem for electromagnetic data, e.g., from the conductivity model section obtained using both magnetotelluric (MT) and controlled source (CSAMT) data, taking into account assumed lithology and laboratory data for rock conductivity.

Results

Rayakoski – Vidlitsa geothermal profile (Fig. 2) extending in submeridional direction through the Karelia-Kola section of the Fennoscandian Shield was constructed using the data of the FENICS-2009 and 2014 experiments, as well as information on the heat flow (Mitrofanov et al., 1998) by comparing the results of one-dimensional inversion at each of the points of the profile.

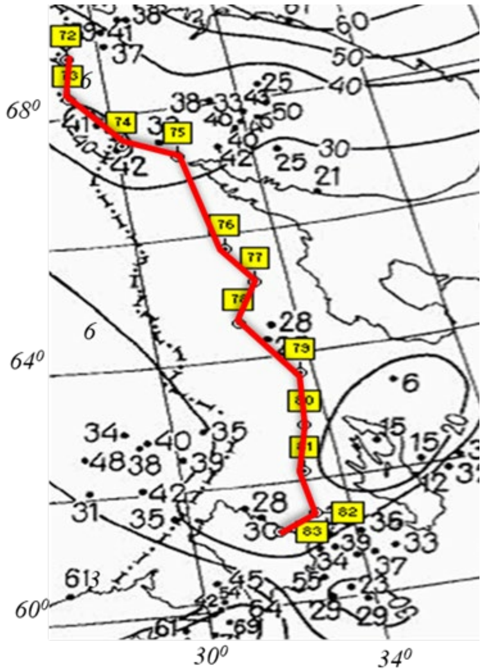

Figure 2. Rayakoski (point 72) - Vidlitsa (point 83) profile (red line). Points with a number indicate position of the receiving station and value of heat flow (mW/m^2).

Figure 3 shows the results of the inversion of the electromagnetic sounding data of the FENICS-2009 experiment in Rayakoski point (point 72) nearly Kola Super deep hole SDH-6. The models of geoelectric cross-section with a different number of layers. The resistivity of layers was calculated from temperature dependance from depth. Black line is result of Molochnov-Viet transformation of the CSAMT and MT data. The temperature vs depth, estimated by iterations of the conjugate gradient method. The temperature dependance for these models are presented in figure 4.

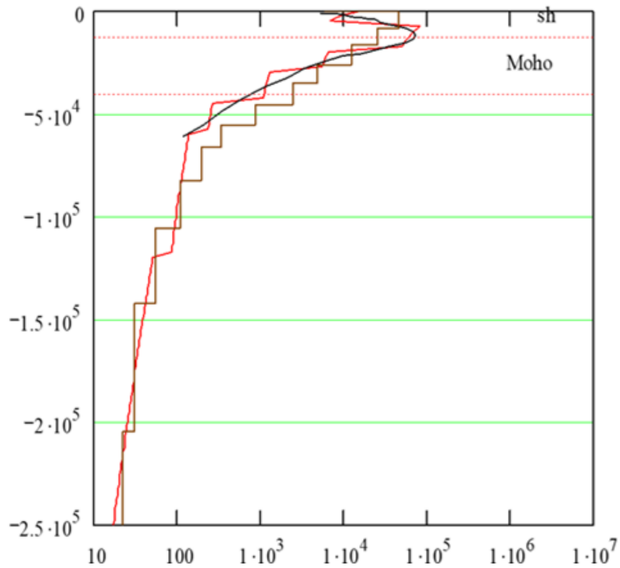

Figure 3. Result of inversion of electromagnetic soundings at the Rayakoski point – resistivity (horizontal axis) vs. depth (vertical axis). Deep levels sh = 1.2 · 10^4 m, Moho = 4 · 10^4 m. The geoelectric section was approximated by models with a different number of layers.

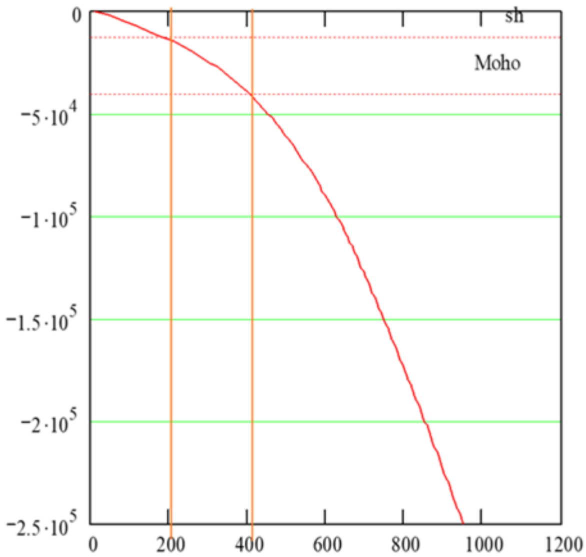

Figure 4. The thermic section for models from figure 3. Temperature t (^{0}C) (horizontal axis) vs depth (vertical axis)

Discussion

The geothermal estimations for profile of Rayakoski – Vidlitsa from electromagnetic data in north part well agree with results of complex interpretation from (Glaznev, 2003) and Kola SDH-6 temperature measurements. But in south part for points from 78 to 83 we have significant discrepancy. See figure 5 (at end of article). It possible connected with influence of the deep anomalies of conductivity in this region.

Conclusions

The work presents an algorithm for assessing the temperature vs. depth patterns using a-priori information on changes in electrical conductivity with depth (based on the results of electromagnetic soundings) and electrical conductivity and rock composition at depth (based on laboratory data and geological assumptions). The solution to the problem is illustrated by the example of calculations performed for two types of geoelectric section - "normal" and "anomalous". Information on electrical conductivity was obtained from the results of electromagnetic soundings with industrial power transmission lines (FENICS experiment) and from measurements of the magnetotelluric field in various parts of the Fennoscandian Shield.

Acknowledgments

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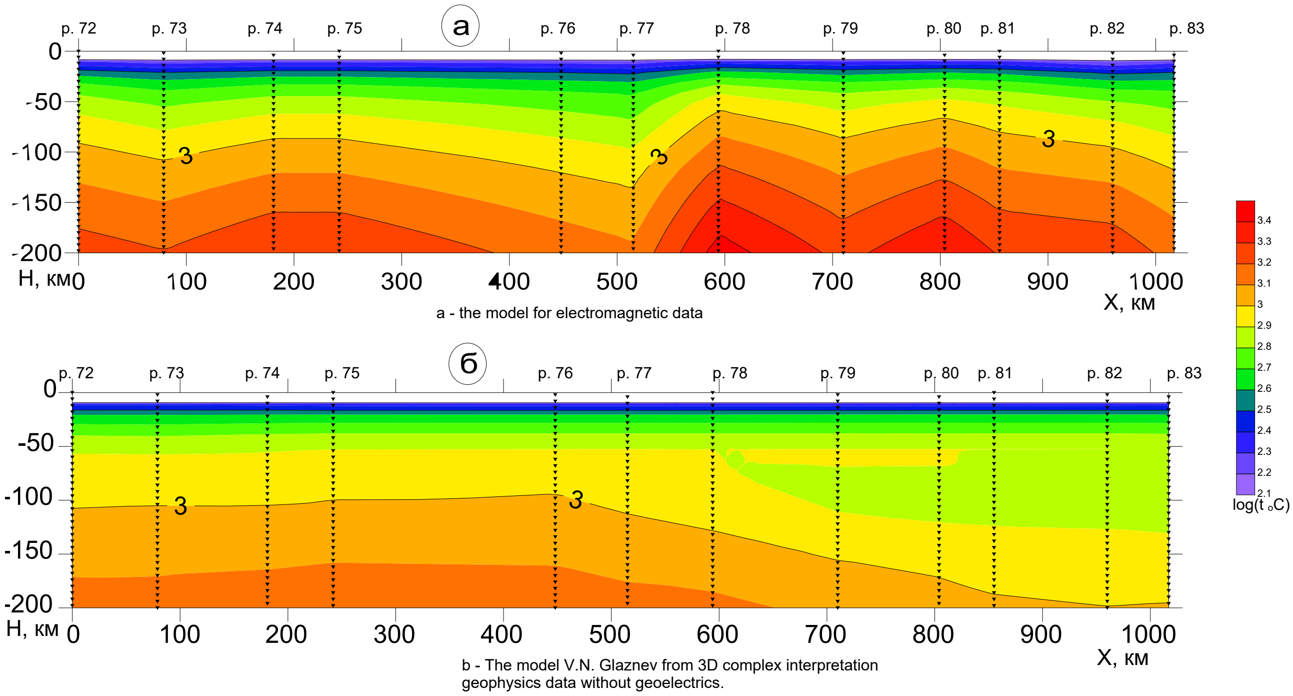

Figure 5. Geothermal profiles of Rayakoski - Vidlitsa. a – according to the results of inversion of the data of electromagnetic soundings and heat flow, b – according to the model of Glaznev (2003).