Geodynamics and Nature of the Conrad Boundary by Results of the Deep Electromagnetic Soundings and the Superdeep Drilling

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Abstract: Continental Earth's crust is subdivided into two parts – upper, brittle crust (namely geological) and low, ductile crust (namely physical). This idea has been investigated by many researchers on the base of seismical data, laboratory study of rock specimens at high thermo dynamic conditions and on the base of theoretical speculations [1, 2, 3]. In this presentation this idea is investigated on the base of the deep soundings with powerful controlled sources such as MHD-generator "Khibiny", industrial power transmitting lines (experiment "FENICS") and with taking into account results of superdeep drilling on Fennoscandian shield. The summary analysis of the obtained data allows to draw a conclusion that the upper part of continental crystalline earth's crust has a thickness of the order of 10-12 km. Its principal peculiarities are: the sharp horizontal heterogeneity of electrical properties, a wide range of variations of electrical resistivity from 10 till 10^4 Ohm·m, a high porosity, brittleness, and a presence of fluids (meteoric waters) that penetrate from the day time surface to the depths of up to 5-10 km. Upper crust is the most actively involved in geological processes. The low crust belongs to the depth interval from 10–12 to 35–45 km (up to the Moho boundary). It is remarkable by horizontal homogeneity of electrical properties and high electrical resistivity in the range of 10^5–10^6 Ohm·m, by the low porosity and increased ductility. Electrical conductivity of the low crust is mostly determined by influence of planetary physical–chemical parameters (pressure, temperature, and viscosity), phase transitions of substances depending on geodynamic peculiarities of evolution for different segments of the Earth crust. As an area of physical processes influence, the low crust is nearer by its origin to the upper mantle then to the geological Earth crust. The low and upper parts of the Earth crust are subdivided between each other by the boundary of the sharp increase of electrical resistivity at the depth around 10-12 km (so called Boundary of impermeability for DC currents, BIP zone). At the same depth the sharp increase of rocks solidity, viscosity has been met in the Kola superdeep hole. This transition zone between the upper and lower crust is related with hypothetic Conrad boundary predicted by seismic data by the stepwise increase of longitudinal waves from 6 to 6.5 km/s.

Keywords: lithosphere, Control source soundings, Geodynamics, Conrad boundary, Kola superdeep, Boundary of impermeability.

1. INTRODUCTION

The structure and volume of the Earth's crust are accepted to be linked to the position of the Moho seismic discontinuity, which was found by the stepwise growth of velocities from 7.5 to 8.0 km/s on average for longitudinal waves and from 4 to 4.5 km/s on average for transversal waves. Within continents, the Moho discontinuity is traced continuously in the relatively narrow range of depths (35–45 km) with rare sinks mostly beneath mountain ridges (down to 55–75 km). The Earth's crust consists of two parts – SIAL on the top and SIMA below. SIAL is of about 10-20 km thick. It consists of silicate (SiO_2) and alumina (Al_2O_3) matter existing in the shape of rocks like granite, schist and gneiss. SIMA is located below and consists of silicate, magnesium, mafic rocks such as basalts, diabase etc. Earth crust (SIAL and SIMA) is "floating" on the surface of the Upper Mantle. It is accepted that the Moho boundary subdivides them from the Upper Mantle. Numerous results of complex investigations show that the position of the Moho discontinuity is almost not related to the character of geological structures and only slightly reflects the relief of the day surface. Nevertheless, a certain geological meaning is attributed to it. The thickness of the Earth's crust and the transition boundary from the Earth's crust to the upper mantle are usually attributed to it. In the present article an attempt is made to present the structure of the continental Earth crust in a more precise manner based on the results of deep electromagnetic sounding with the use of powerful controlled sources and results of the Kola superdeep drilling.

The problem of super deep drilling of the continental crust was stated for the first time at a meeting in Paris in 1962; the necessity of direct study by drilling of the physical nature of the deep geophysical boundaries found by surface-based methods, first of all, by seismic survey, became clear. Approximately at the same time, two projects started in the United States-Moho and Apollo. The Moho project was aimed at reaching the

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most ancient rocks of the basaltic layer by drilling the oceanic crust from the *Glomar Challenger.* The other project, the Apollo program, as is known, was related to landing humans on the Moon, lunar core sampling, and transportation back to the Earth. In turn, the Soviet Union launched two programs: the Lunokhod automated missions, which was intended to collect lunar core samples, and the super deep continental drilling program that included drilling of ten super deep wells on the territory of the country. The Kola Super deep Well SG-3 was part of this extensive research into the composition and structure of the Earth's interior.

The location of the SG-3 drilling was determined by two aspects. The first reason was connected with its location on the territory of ancient Archean rocks of the Earth's crust in the northeastern Fennoscandian Shield. Due to erosional cut these rocks were exposed on the surface from the depth of about 10 km. They are represented, in particular, by granitic gneisses of the Kola Series and Murmansk block. The second reason was based on the deep seismic sounding (DSS) data. In accordance with these data the anomalously high position of the Conrad discontinuity (K1), was identified in the area of Pechenga structure, on the Kola Peninsula. The position of this boundary is usually attributed to a sharp growth of seismic wave velocity from 6.1 to 6.5 km/s. According to the DSS data, the K1 depth in the area of Pechenga is about 7 km [4] instead of 15-20 km in other territories. That makes an obvious advantage in this study. Therefore, to reach Conrad discontinuity became the central task of drilling the Kola well [5].

2. MHD-EXPERIMENT "KHIBINY"

MHD-experiment "Khibiny" was arranged near to the Kola super deep hole since 1976 [6, 7]. The electromagnetic soundings have been made on the territory of Eastern and Central parts of the Baltic shield (Kola-Karelian region, Northern Finland and Northern Norway). The most outstanding feature of the "Khibiny" experiment was the use of the sea area around Sredny and Rybatchy peninsulas as natural circuit for the current propagation (Figure **1a**). "Khibiny" installation is made of two (binary) magnetohydrodynamic (MHD) generators (Figure **1d**). Each of them consists of

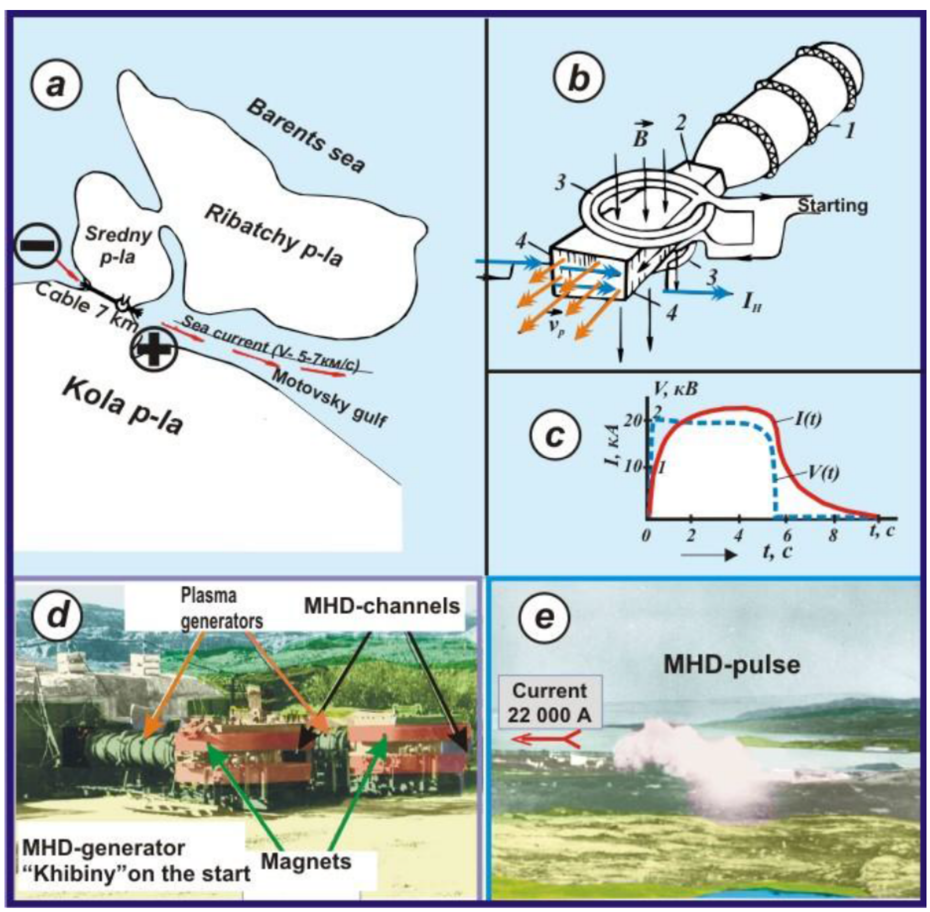

Figure 1: MHD-Khibiny installation. Explanations are given in the text.

plasma generator, magnet and MHD channel. The plasma generator uses solid fuel, which is mixed with ionized material. The stream of conducting “cold” plasma, with a temperature of 3000°C, flows through a MHD-channel with square cross section (Figure **1b**). The top and bottom walls of this channel are made of thermally insulating material; the vertical walls are covered by metallic material, playing the role of electrodes. Simultaneously with switching on the plasma generators, a battery of capacitors is discharged into the electromagnets of the generator causing a current of several thousands of Amperes to flow in the windings of the magnets. This creates a strong magnetic field braking the hot plasma stream (Figure **1e**). A Hall current appears flowing perpendicularly to both the plasma stream and to the magnetic field. When the current has reached its full value, one of the MHD-generators starts operating in the self-excitation mode feeding current into the solenoids of both MHD-generators. The power of the second generator is fed into the output circuit.

The output circuit consists of an aluminium cable, 7 km long and 160 tons in weight, immersed at its both ends in the sea on opposite sides of the isthmus between the Sredny and Kola Peninsula. Due to this arrangement the output resistance is rather low (0.095 Ohm) and the output current pulse can achieve the amplitude up to 22 kA at voltage 2 kV (Eig.1c), Although the voltage has a sharp front, the high inductance of the circuit (~ 0.05 H) causes the current to rise rather slowly (typical rise time: 1 s). The duration of the current pulse is up to 5-7 s. About 50% of the energy of the MHD-pulse is contained in the low frequency, around the first harmonic ~0.1 Hz.

The "Khibiny" generator produces, roughly saying two types of sources. The magnetic one is associated with approximately 80 percents of the total current that enters the sea water through the gulfs. This current diffuses into the sea with a velocity of 5-7 km/s. It is shown by the arrows on the Figure **1a**. Other (20%) part of the total current penetrates to the earth crust trough the sea bottom as galvanic mode and creates a source of electric type.

2.1. Block Structure of the Upper Earth Crust Electrical Conductivity

One from the first results of MHD-experiment is presented in the Figure **2** in the shape of block structure of the Earth crust longitudinal electrical conductivity $S = h/\rho$. The vertical thickness of blocks *h* is estimated at 10 km.

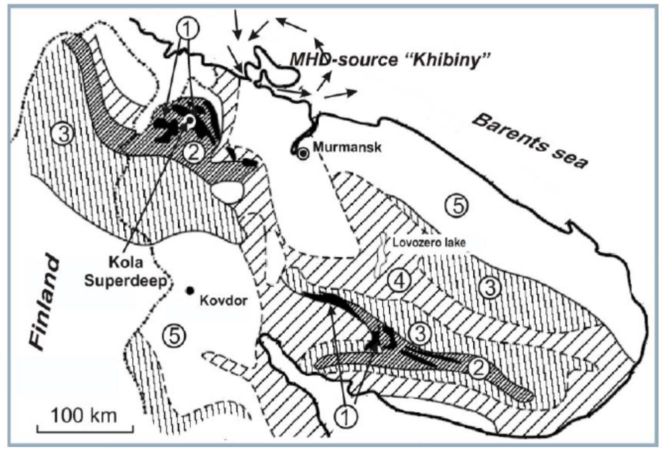

Figure 2: Scheme of the Earth’s crust longitudinal electrical conductivity S from results of MHD-“Khibiny” experiment.

Legend. Conductivity of blocks **1** – 1000 S and more, **2** – 20–100 S; **3** – 5–20 S; **4** – 2–5 S; **5** – 1-2 S and less.

Some blocks cover the area of up to dozens of thousands of square kilometers. Blocks with a weak conductivity (1-2 S) are characterized by the high resistivity (10^4-10^5 Ohm·m) and significant horizontal homogeneity. They are considered as, so called, “windows of transparency” favorable for carrying out the deep and super deep electromagnetic soundings of the lithosphere. Blocks of a high conductivity are sharply heterogeneous and produce distortions on results of the deep soundings. The nature of conductive blocks (crustal anomalies) is related to the presence of sulfide and carbon (graphite) bearing substance of biogenic origin [8-10]. They are conventionally identified as the “SC-layer” of Semenov. A scheme demonstrating distribution of electronically conductive crustal anomalies within the eastern part of the Baltic Shield, within the Russian territory and at all the world is presented in [11].

2.2. Conductive Channels in the Upper Earth Crust

The second by importance experimental result, directly concerned to the matter of the present work, is the discovery of sub horizontal conducting channels in the upper part of the Earth’s crust. The phenomena have been discovered firstly while performing of MHD-experiment “Khibiny” [10]. By division of the field generated by the Khibiny MHD source into galvanic and inductive components, it has been found that galvanic currents propagate on hundreds of kilometers in the upper of 10 km thickness layer of the Earth’s crust [12]. Galvanic currents gather in narrow alongated sulfide and carbon bearing structures (schists) and causes the effects of current conductive channels.

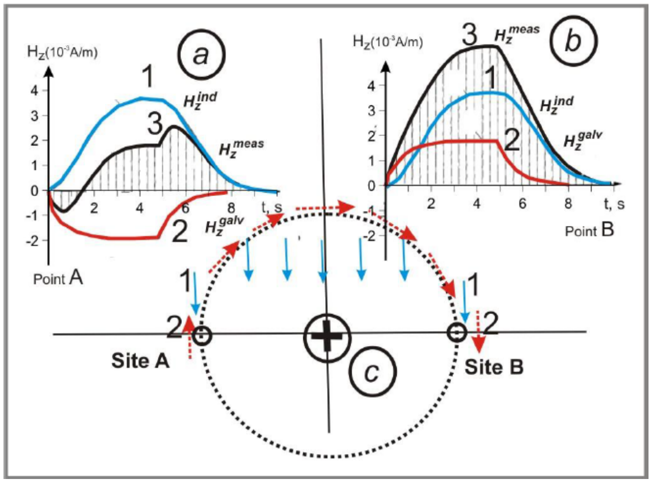

Figure 3: Synthetic scheme of magnetic fields of induction and galvanic tipe at the left (Figure 3a) and at the right (Figure 3b) sides from the current conductive channel signet by "+" in the Figure 3c.

Legend: Curves 1-3: **1** – magnetic field induced by sea currents of MHD source "Khibiny" (Hz^{ind}); **2** - magnetic field of galvanic origin Hz^{galv} created by the grounded current conductive channel; **3** – summary vertical magnetic field Hz^{meas} as a superposition of the Hz^{ind} and Hz^{galv}.

The synthetic sketch of superposition of magnetic fields of induction and galvanic nature of MHD-source "Khibiny" is given on the Figure **3**. It presents an example of the vertical magnetic component Hz registration at sites A and B situated symmetrically on opposite sides regarding to current conductor of endless length. Sign "**+**" indicates that the current flows away from observer (in our case, from the East to the West). Graphs 1 (Figure **3a** and **3b**) and blue arrows 1 (Figure **3c**) show the behavior of magnetic field Hz^{ind} produced by remote current streams in the sea. Since the velocity of current diffusion in the sea is low, respective electromagnetic signals of the magnetic source have flat frames in a low-frequency range. They penetrate the Earth's crust without responding to the heterogeneity of electric conductivity in the upper Earth's crust. Therefore, graphs H_z^{ind} on opposite sides of the conductor (Figure **3a** and Figure **3b**) are identical.

Amplitude of the vertical component of the magnetic field produced by currents at the sea can be approximated by the formula for the stationary vertical magnetic dipole

$$Hz^{sea}(t) = M/_{4\pi r^3}, \left[A/_m\right] \quad (1)$$

Where $M = Is(t) \cdot R^2$ is magnetic moment of the sea source, *Is(t)* is the current intensity at the sea, *R* is the radius of the magnetic loop (about 50 km), *r* is the distance between the centre of the loop and measuring site.

Graphs **2** (Figure **3a** and **3b**) reflect the behavior of the magnetic field Hz^{galv} produced by the endlessly long conductor with the current in the ground. The magnetic field of the galvanic nature Hz^{galv} has same shape of the on and off fronts as the fronts of the current in the source. It also has different polarity on opposite sides of the current. The polarity (direction) of the magnetic field Hz^{galv} is defined by the rule of the right hand. Amplitude of the field in the stationary state is found as

$$Hz^{galv}(t) = I^{galv}(t)/_{2\pi \cdot r}, \left[A/_m\right] \quad (2)$$

The produced curve of the vertical magnetic component Hz^{meas} is defined as a sum of fields of the induction and galvanic origin:

$$Hz^{meas}(t) = Hz^{ind}(t) + Hz^{galv}(t)\,. \quad (3)$$

Curves **3** indicate graphs Hz^{meas} in Figure **3**. Graphs Hz^{meas} on opposite sides of the conductor are shown to be absolutely different-looking. Their behavior, character and amplitude allow to trace the location of current-conductive channels. If we estimate the distance to the centre of the current-conductive channel and the distance from it to the reference point r^{galv}, we can easily define the net current of the galvanic origin in the conductor $Itot^{galv}$, using the ratio

$$Itot^{galv} = 2\pi \cdot r^{galv} \cdot Htot^{galv}, [A] \quad (4)$$

The total magnetic field $Htot^{galv}$ is given by the ratio (5, if three components of the magnetic field are measured:

$$Htot^{galv} = \sqrt{Hx^2 + Hy^2 + Hz^2}, \left[A/_m\right] \quad (5)$$

2D numerical modeling provides a better interpretation of results with estimates of bed position and the conductor length at the depth. The special "Magnet-2" program has been elaborated by V.E. Asming for this purpose [13]. This program allows detecting the magnetic field via summing a certain set of endlessly long horizontal current lines (DC) in a free half-space ignoring any impact of external currents. An interpreter device detects the amount and location of current lines in the 2D model on-line. An optimal solution of the inverse problem is solved automatically, when model and experimental data are adjusted with the least-square method.

Below at Figure **4*a*** the direction of galvanic currents from the MHD-source «Khibiny» is shown.

From the Figure **4a** it can be seen, that in the Imandra-Varzuga series (eastern structure) and in the Pechenga zone (western structure) currents run in opposite directions. That is an important evidence of their galvanic nature. The galvanic current intensity in the Pechenga structure, located closer to the source, is of about 40 A, and that in the Imandra-Varzuga zone is of 12.5 A. These values consist only tenths percents of the total current intensity of the MHD-generator amounting at 20 x 10^3 A. Nevertheless, that fact that the galvanic currents are found out in the conducting geological structures is important to gain a better insight into the model of electric conductivity in the basement of the Baltic Shield. It is thus clear that in the upper part of the earth's crust, in spite of absence of the sedimentary deposits and high resistivity of the exposed crystalline rocks, there are channels for ultralow-frequency, virtually direct current running in the horizontal direction over a distance of several hundred kilometres, not penetrating deeper than 10-12 km.

Figure **4б** illustrates results of the current conductive channel study on the example of the Imandra-Varzuga zone along the profile CD shown at Figure **4a**. The Imandra-Varzuga zone is a riftogene structure composed by the Lower Proterozoic volcano-sedimentary rocks, which are similar in composition and structure to the Pechenga formations (on the west in Figure **4a**). Imandra-Varzuga extends for 350 km in the latitudinal direction (Figure **4a**) and contains up to 10-12 volcano-sedimentary layers, some of which include phyllite-like rocks (black schists), enriched by organic carbon and sulfide (pyrite-pyrrhotite) mineralization. In the central part of the profile CD, over the formations of Tominga series, electric and magnetic components of the MHD field manifest anomalous behavior. The vertical component of the magnetic field H_z changes the sign over the conductive body. Horizontal magnetic field H_x has negative minimum over the anomaly. Ai these features denote that the galvanic current flows from the west to the eastwards in the graphitic schists of the Tominga series.

The quantitative interpretation of the magnetic field (Figure **4a**) ascertains the extension of the conducting zone to the depth, which is estimated to be 10 km. This estimation agrees well with the results of the digital calculation [14], with numerical modeling MHD-signals using the technique of electromagnetic migration [15] and with the results of magnetovariation profiling at the

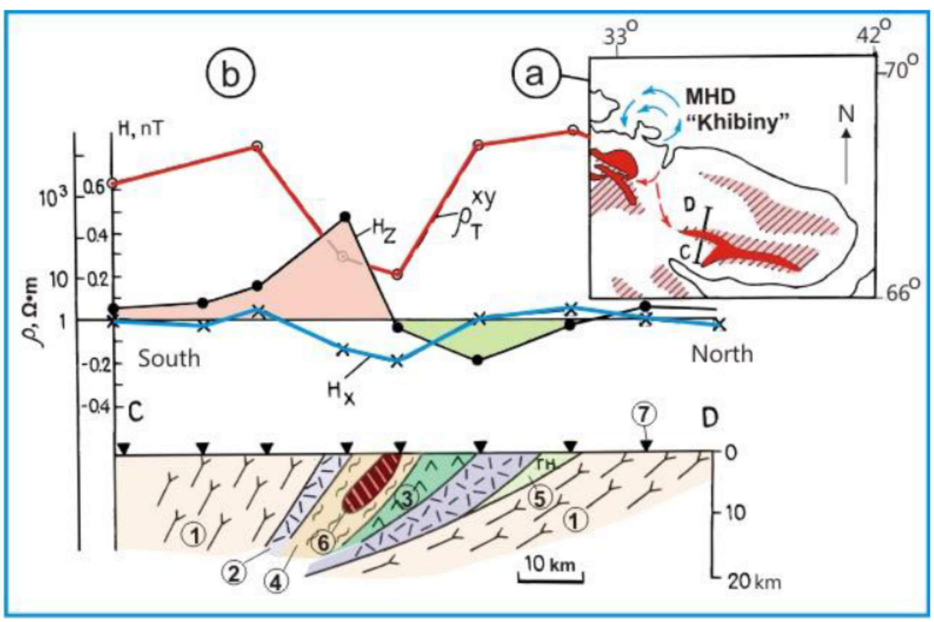

Figure 4: The view of the sea currents (blue arrows) and galvanic currents (red arrows) propagation in the Barents sea and on the Kola peninsula from MHD source "Khibiny" (**a**) and the example of current conductive channel study over the Imandra-Varzuga structure along profile CD (**b**).

Legend. **1** – granite-gneiss; **2** – volcanites; **3** – effusives; **4** – schists and volcanites of the Tominga Series; **5** – gabbro-norites; **6** - current conductive channel.

western flank of the Imandra-Varzuga zone [16]. It is important to emphasize that the current strength estimated by circulation of the magnetic field varies slightly along the directions of the conducting channels. The current in them does not penetrate deeper than 10 km due to the high transversal resistance of the insulating basement.

3. FENICS EXPERIMENT AND ELECTRICAL PROPERTIES OF THE LOW EARTH CRUST AND UPPER MANTLE

The presented above results of MHD-experiment “Khibiny” as many others controlled source soundings were still insufficient to obtain a complete view of the lithosphere structure by geoelectric survey data, despite the great volume of the works made. The “trouble spot” of all the deep controlled source soundings both in Russia [17, 6] and abroad [18-21] was the use of one polarization of the primary field. This did not enable to estimate the possible influence of regional anisotropy and horizontal heterogeneity of the low medium on the observation results. The mentioned difficulties had been overcome by carrying out the international experiments FENICS-2007, FENICS-2009 and FENICS-2014 [22] on the deep sounding with the use of two mutually orthogonal grounded electric lines (industrial power lines) of 109 and 120 km length. The use of two mutually orthogonal polarizations of the primary field made it possible to illuminate the deep structure of lower half space at two directions. The scheme of FENICS experiment is illustrated on the Figure **5** on the example of researches implemented in 2007.

The abbreviation FENICS means “Fennoscandian Electrical conductivity from Natural and Induction Control source Soundings”. The FENICS soundings were carried out at distances up to 825 km between transmitter and receiver in the frequency range of 0.1–200 Hz. Generator “Energy-2” of 200 kW power served as the source of current [23]. Successful measurements of FENICS signals have been made also in Barensburg (Svalberg) at distance of 1300 km from the source.

FENICS soundings were undertaken for to solve the following tasks.

1. For to demonstrate the existence of a so-called normal (standard) geoelectrical section for the Fennoscandian shield and for to specify its parameters.

2. For to study the properties of a transitional zone between upper Earth crust (brittle), and lower one (ductile) one in a range of depths of 10–30 km by the complex solution of an inverse problem based on the frequency (induction) and remote (galvanic) sounding modes.

3. For to investigate the anisotropic properties of a lithosphere of the Fennoscandian shield by measuring the electroconductivity of the earth’s crust in the field of two mutually orthogonal polarizations of the primary field.

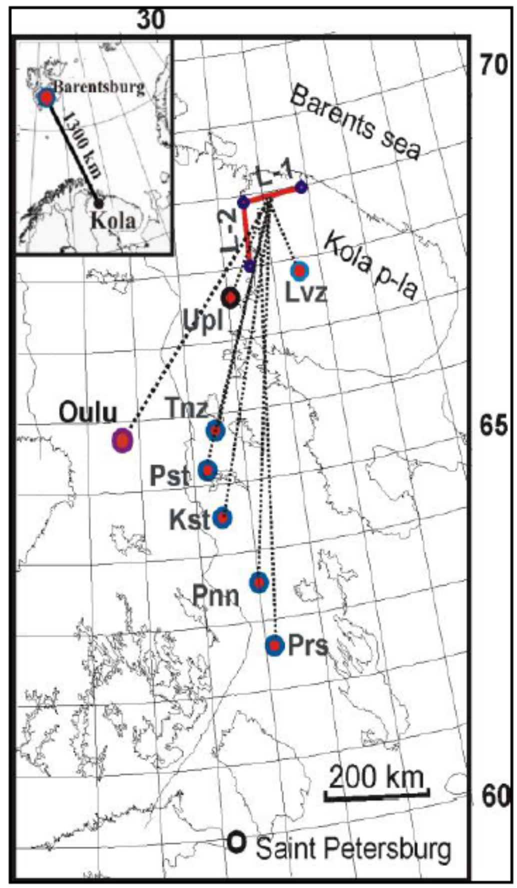

Figure 5: The scheme of FENICS-2007 experiment on the deep sounding with the use of two mutually perpendicular power lines L1 and L2.

Legend: Upl, Tnz, Pst, Kst, Pnn and Prs – receiving sites in Russia; Oulu - receiving site in Finland.

Location of the receiving points was selected taking into account the geological structure of the region. They were situated within the distribution of the most ancient granite rocks of Archaean age (areas “5” in Figure **2**), differing by high resistivity and uniformity of a structure in comparison with the younger volcanogenic–sedimentary complexes.

Spectral processing of primary data were implemented by A.N. Shevtsov [24] on the base of calculating the relations of spectral densities of autocorrelation and cross correlation functions of stationary random processes using the Wiener–Khintchine theorem [25-27].

The main results of the “FENICS” experiments are presented on the Figure **6** by the apparent resistivity curves (Figure **6a**) and vertical sections resulting from the inversion problem decision (Figure **6b**). For three sites (Tnz, Kst and Pnn) the data are calculated for two polarizations induced by lines L1 and L2 (Figure **5**).

The inversion itself was carried out using three different methods, namely, based on the method of effective linearization (MEL) [28], the controlled transformation technique [29], and the standard fitting method. The latter turned out to be the most efficient for bimodal interpretation. All inversions were carried out with the use of the phase data. The phases were calculated from the apparent resistivity curve in accordance with the Weidelt formula and played a supportive role as an indicator of smoothness of the apparent resistivity curve.

One-dimensional resistivity cross sections yielded by inversion are shown in Figure **6-b**. The bimodal inversion using both polarizations of L1 and L2 fields was carried out for three sites where the signals from L1 and L2 power transmission lines (Tng, Kst, Prs) were measured. The agreement between the results of the bimodal inversion and the experimental data measured with two quasi orthogonal polarizations of the primary field is an important argument in favor of the homogeneous (one dimensional) structure of the deep electric conductivity of the lithosphere of Eastern Fennoscandia.

The general analysis of the results of deep electromagnetic soundings carried out in the scope of the FENICS-2007 experiment allows us to make the three following main conclusions.

1. There is complete agreement (in shape and in amplitude) between the apparent resistivity curves, measured over the eastern part of the Baltic shield on the 700 km long submeridional profile.

2. There is a coincidence (within 10–20% error) of the apparent resistivity curves calculated from the electric component and from the input impedance as well as the apparent resistivity curves measured with latitudinal and meridional polarizations of the primary field within the wave zone.

3. There is an agreement between the experimental and theoretical estimates of the boundaries of the wave zone and its manifestations in the apparent resistivity curves CSMT sounding with the axial and equatorial arrangement of the current and receiving lines. Taken together, the aforementioned analysis suggest the main conclusion that the deep structure of the electric conductivity distribution in the lithosphere (Low Earth crust and Upper Mantle) of the eastern part of the Baltic shield is characterized by substantial horizontal homogeneity (stratification) of the electric properties within the depth range from 15–20 to 50–70 km. This conclusion contradicts the multiyear experience of the magnetotelluric data that point out on the high heterogeneity of the deep electrical properties of the Low Earth crust and Upper mantle of the Fennoscandian shield [30-33].

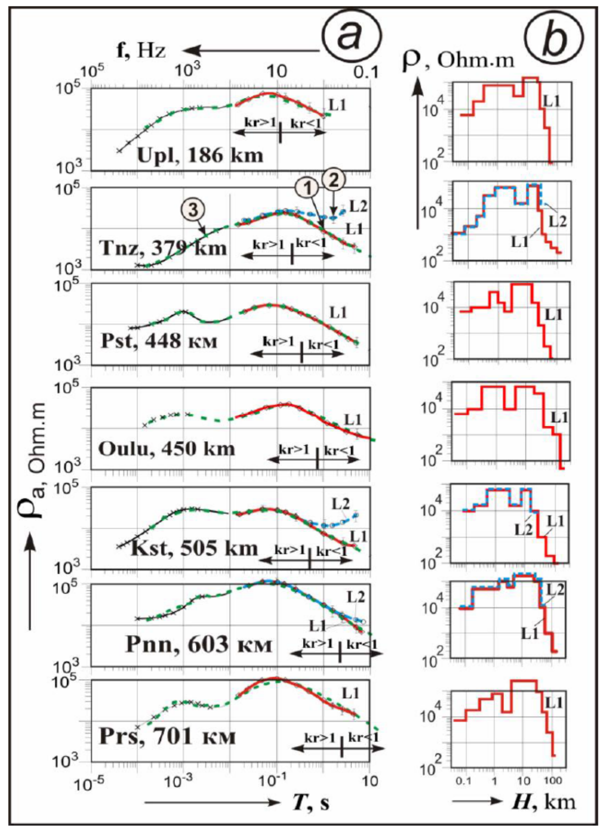

Figure 6: Results of FENICS-2007 experiment.

Location of transmitters (L1 and L2) and receiving sites is shown on the Figure 5.
Legend: (**a**) Apparent resistivity curves for lines L1 and L2. Digits in circles: **1** – theoretical (modeling) curve for the line L1, **2** – same for the line L2, **3** – theoretical frequency sounding curve recalculated from DC sounding. (**b**) 1D vertical sections obtained from the inversion results with lines L1 and L2.

4. GEODYNAMICAL INTERPRETATION OF THE EARTH CRUST AND UPPER MANTLE ELECTRICAL CONDUCTIVITY

The so called “normal” electrical section of lithosphere for the Baltic Shield (in the absence of the influence from electronically conductive rocks) following from presented above results of electromagnetic soundings with powerful controlled sources is given in the Figure **7-a** alongside with its geodynamical interpretation given in the Figure **7-b**. The geodynamical interpretation is followed from the model of V. Nikolaevsky [1], presented on the Figure **7-c**, **d**.

The normal section on the Figure **7-a** is represented in the form of a gradient model (curve 1) and its layered approximation (curve 2). The resulting section is a five layered “KHK”_type model with three conductive layers. Interpretation of the nature of the found layers is given in the Figure **7-b** in the form of a structural geodynamic column, after V.N. Nikolaevskiy [1]. The upper part of the section (1) is composed of conductive sedimentary deposits (moraine) and a moist part of the roof of the crystalline basement. A layer of high resistivity (2) with subvertical faults and cracks filled with water solutions (fluids) lies below. The average thickness is estimated at 2–3 km. In the depth interval from 2 to 10 km, the intermediate conductive domain (3) is identified, with a decrease in resistance from about 10^5 Ohm·m to about 10^4 Ohm·m. The cause of this decrease in resistivity is related to fluids of meteoric (surface) origin that penetrate into depths along the cracks and faults flattening with depth. This layer has a dilatancy diffusion nature and is identified as the “DD layer.” Below the DD layer electrical resistivity of the earth crust increases again up to 10^5–10^6 Ohm·m.

The boundary of the sharp increase of electrical resistivity at the depth around 10-12 km is called as Boundary of impermeability for DC currents (BIP zone). This is transition zone between upper crust (brittle) and lower crust (semi ductile) followed by the sharp increase of electrical resistivity of rocks from 10^4 to 10^5-10^6 Ohm·m. We attribute it to the Conrad boundary. Below, at the next section this supposition is compared with the data of the Kola super deep drilling.

5. KOLA SUPERDEEP WELL SG-3

Location of the Kola super deep well is shown on the Figure **8**. The choice of this place for the deep drilling has been determined by two aspects. The first reason was connected with location of this site on the territory of spreading of ancient Archaean complexes of the Earth’s crust in the northeastern Fennoscandian Shield. Due to erosion the upper part of Archaean rocks were elevated here from the depth of about 10 km and exposed on the day surface They are represented, in particular, by granitic gneisses of the

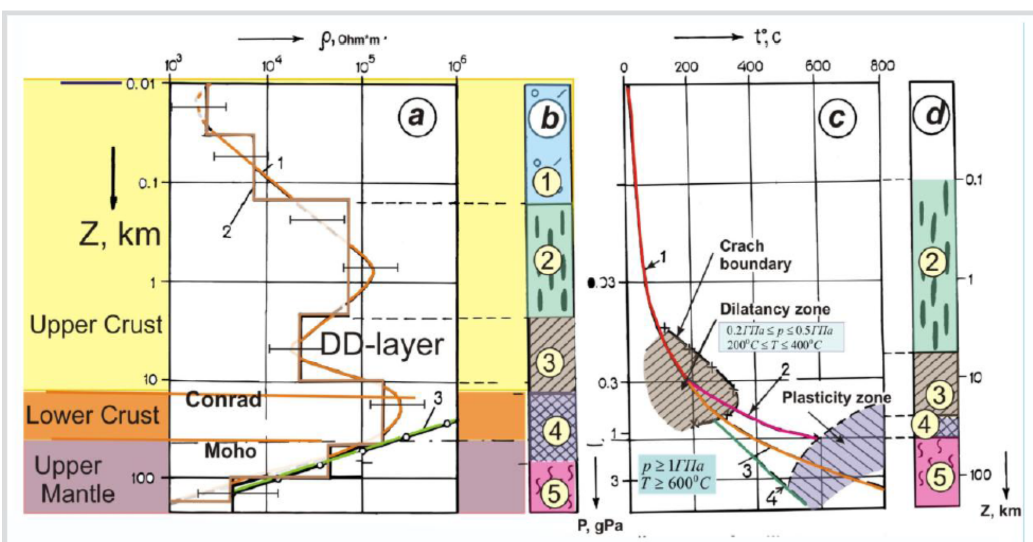

Figure 7: Geodynamical interpretation of the Earth Crust and Upper Mantle electrical conductivity.

Legend: ***a*** – normal electrical section of the continental Earth crust (1 – gradiental model, 2 – stepwise model, 3 – laboratory model). ***b*** – geodynamic column, following from “a” – digits in circles – 1 – moraine, 2 – brittle crust with subvertical fractures, 3 – same with listric (flattening) fractures, 4 – semiductile zone, 5 – ductile zone. ***c*** - phase diagram of a dilatancy and plasticity zones after [1]. 1- temperature in the Kola superdeep, 2, 3, 4 – extrapolation of the Kola superdeep temperature to the depth: 2 – by [34], 3 – by [35], 4 – by [36]. ***d*** - geodynamic column, following from “c”.

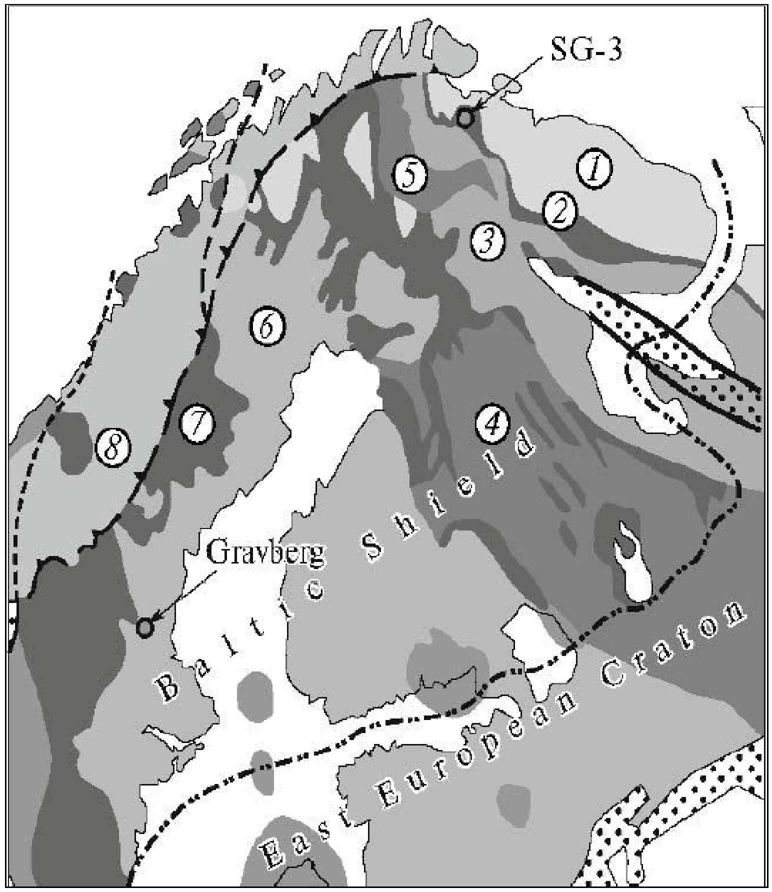

Figure 8: Location of the Kola Super deep well SG-3 and the deep well Gravberg on the Fennoscandian Shield.

Legend: 1-5 - Archean complexes (**1** - Murmansky block; **2** - Greenstone complexes; **3** - Kola gneisses; **4** - Karelian megablock; **5**- Granulitic belt); **6-7** - Proterozoic complexes (**6** - Svecofennides; **7** - Gothnian granites); **8** – Paleozoic Caledonidian complex.

Kola Series and Murmansk block (Figure **8**).

The second point to the choice of the SG-3 place is based on results of the deep seismic sounding (DSS). According to DSS data in the area of Pechenga structure the K1 depth (Conrad boundary) is about 7 km [4] instead of 15–20 km in other territories. That makes an obvious advantage in the project. Therefore, the task to reach the Conrad discontinuity became the central topic of drilling of the Kola well [5].

However, instead of the expected Conrad discontinuity at this depth (6.8 km), the base of the volcanogenic sedimentary Pechenga complex was found. According to the DSS data, this boundary was expected to find at a depth of 4 km. Comparison of the predicted and found geological boundaries is shown in Figure **9** by columns 1and 2.

Drilling of the SG_3 was led by D.M. Guberman and V.S. Lanev and lasted for more than 20 years (from 1970 until 1992). The task was to reach a depth of 15 km. For this purpose, the unique Uralmash_15000 drilling platform was manufactured. In total, four well shafts were drilled and all finished with breakdowns, which occurred nearly at the same depths, about 12 km, with 5% scatter (Figure **9**, section 3). The expected Conrad discontinuity with its supposed change of rock composition from SIAL to SIMA was not found in any well shaft of SG_3.

Throughout the whole extent of the Achaean part of the section (from 6.8 to 12.262 km depth) the composition of rocks consists of granite and gneisses of the Kola Series with some amphibolites interlayer's. Correlation of expected and actual sections is shown in Figure **9**-(**3**). It also shows positions of multi-well drilling and depths of four wells bottoms (1, 2, 3, 4).

Among the officially discussed causes of breakdowns, material fatigue, high temperature at the shaft bottom, insufficient funding, and other reasons were mentioned; but the main cause was not mentioned. However, the men who did the drilling spoke about it many times in personal communications with the author. They attributed the cause of

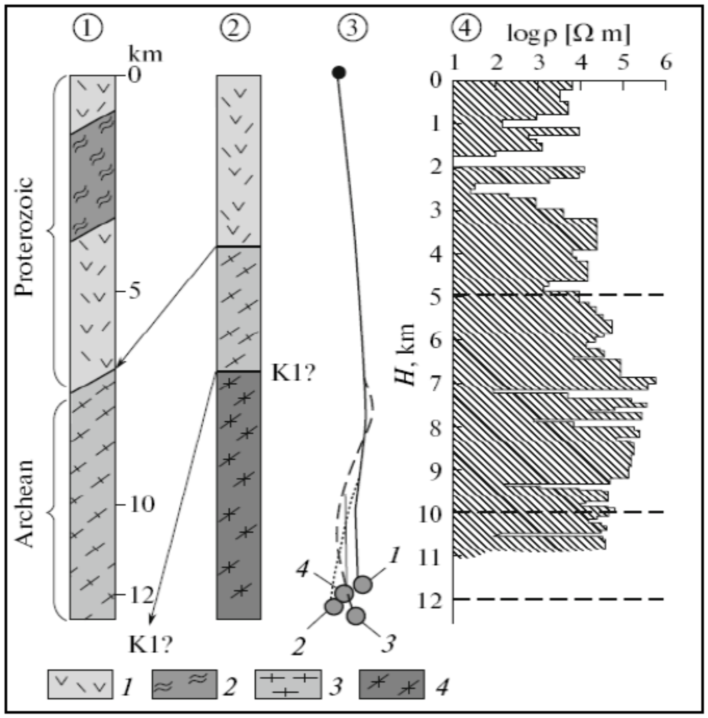

Figure 9: The sections of the Kola Superdeep well SG-3.

Digits in circles **1** – the found geological section, crossed by SG-3; **2** - the beforehand predicted geological section based on the deep seismic sounding DSS data. K1 –Conrad boundary location supposed from DSS data; **3** – four boreholes of SG-3 and the stopping points (circles 1-4); **4** - electric logging data of SG-3.
Legend: **1** – volcanogenic cover; **2** – sedimentary cover (phyllites, schists); **3** - Archaean granitic gneisses (SIAL); **4** – supposed (but not reached) basaltic layer (SIMA).

breakdowns to the sharp change in the physical state of rocks in the vicinity of 12_km depth, due to the rock transition from a relatively easily drillable cracked state in the depth interval of 7–11 km to “solid as a glass” rocks at about12 km depth. This is why the drilling tool rotated rapidly at the shaft bottom, not breaking the rock, and when it rose to the surface it appeared to be flowing. To overcome this problem, a percussive rotary drilling technique had to be applied; *i.e*., the drill line was picked up and dropped down. This required an especially high skill, because the 12-km drill line was a spring stretched by 40 m. It must not be freely deposited on shaft bottom-in this case, the drilling tool and turbine would be destroyed.

6. SUPPOSED NATURE AND LOCATION OF THE CONRAD BOUNDARY

Based on the information given in the above sections and in a new data of tensor frequency soundings the model of the two layered structure of the continental crust was developed [37]. According to this model, the upper 10 to 15 km stratum of the Earth’s crust is characterized by widespread conducting fault structures, the presence of brittle zones, and a generally lower resistivity due to the common distribution of electron conducting sulfide- carboniferous rocks and the presence of fluids that drain the supra structure. The lower crust, conditionally confined at the bottom by the Moho discontinuity, is characterized by high resistivity and horizontal homogeneity of the electrical properties. An important peculiarity of the upper crust is the presence of the intermediate conducting layer of dilatance-diffusion nature (the so-called DD layer) in the depth interval 2–5 to 7–10 km (Figure **7a**) [38]. The reduction in the apparent resistivity in the diagram of SG3 lateral electrical logging (Figure **9**, column 4) in the depth range 7–10.5 km is attributed to the existence of the DD layer. For the purposes of illustration, the summary diagram of logging at two super deep wells, SG3 and Gravberg, is presented on the Figure **10**.

The Gravberg well in Sweden is of 7 km in depth and drilled in homogeneous granitic gneiss rocks. We used its data instead of a logging diagram of the anomalously conducting rocks of the Pechenga effusive sedimentary complex, which lies in the depth interval 0–6.8 km in columns 1 and 4 (Figure **9**). Figure **10** shows the curves of longitudinal (ρl) and transverse (ρn) resistivity. The ρl curve is recalculated from the apparent resistivity curves of lateral logging (LL) for the current running along the rock bedding; ρn, for the current running mostly across the rock bedding. It can be seen that sections of both SG3 and Gravberg wells agree well, despite of significant (nearly 1000 km) distance between them (Figure **8**).

The longitudinal and transversal resistivity curves in Figure **10** are compared to the results of frequency electromagnetic (ρ_{FES}) and vertical electromagnetic (ρ_{VES}) soundings. The intermediate conductive layer is clearly discernible in the section built from frequency electromagnetic sounding results (ρ_{FES}), while it is absent in the vertical electromagnetic sounding ρ_{VES}. The most important peculiarity in Figure **10** is the coincidence of the ρ_{FES} minimum and the descending segment of the longitudinal resistivity curve ρ_l in the SG3 logging diagram for the depth interval 7–10 km. However, the section of vertical electromagnetic sounding (ρ_{VES}) agrees with the transverse logging curve ρ_n. Such behavior is explained by the main role of the poloidal mode in frequency sounding, and this mode is sensitive to the horizontal, longitudinal conductivity of rocks. In contrast, during direct current vertical electrical sounding (VES) the lower half space is excited at the expense of the toroidal mode, which is directed mostly across the horizontal bedding [39].

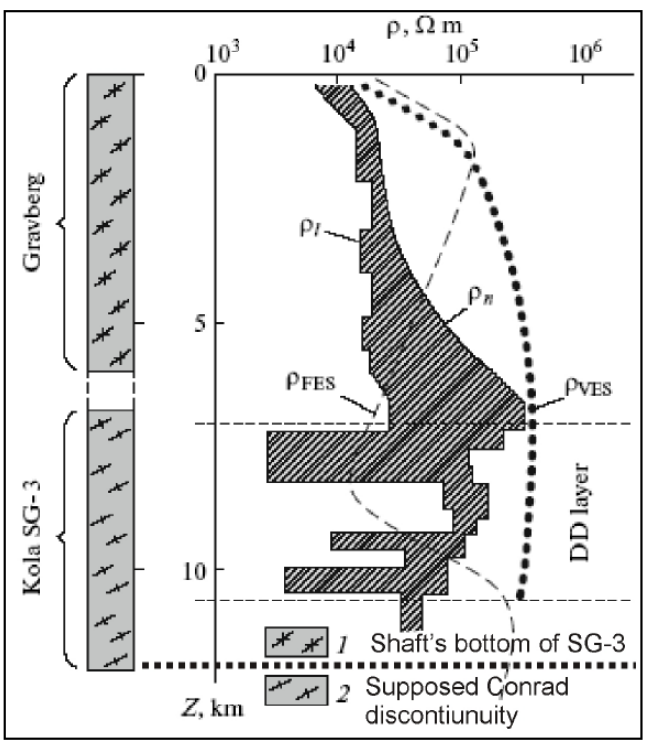

Figure 10: Longitudinal (ρ_l) and transversal (ρ_n) resistance curves from electrical logging in the SG3 and Gravberg super deep wells, comparing to results of control source frequency electromagnetic sounding (ρ_{FES}) and DC vertical electrical soundings (ρ_{VES}). The location of wells is shown in Fig. 8.

Legend: **1** - granitic gneisses; **2** - granitic gneisses with amphibolite interbeds.

The geodynamical interpretation of the SG3 logging results and the electromagnetic sounding data is given in Figure **7** and **10**. The phase diagram of the dilatance and ductility zones, in accordance with the model by V.N. Nikolaevskii [1] is shown in Figure **7-b**. According to this model, the dilatance mechanism is defined as an irreversible increase in volume of polycrystalline aggregates during shearing. The shear conditions in depth are explained by the simultaneous effect of lithostatic (vertical) and tangential (horizontal) stresses. Shear phenomena leading to the appearance of free porous spaces in depth can be explained by the more rapid increase in the rock pressure's horizontal component in a certain depth interval, in comparison to the lithostatic, vertical component. In Figure **7b**, the column of the structural geodynamical interpretation is given for the results of electromagnetic sounding using powerful controllable sources, in the form of a generalized "normal" electrical section (Figure **7a**), based on the results of deep soundings using a car generator and industrial power lines (FENICS experiment) [22, 39].

7. DISCUSSION

The general analysis of the data presented above suggests the following conclusion. The deep soundings using the controllable sources indicate that there is a zone of sharp increase in resistivity in the Earth's crust in the depth range of 10–12 km and this zone marks the boundary between the upper brittle and lower quasiductile crust. Remarcable, that at the same depth interval (about 12 km) four shafts of the Kola Super deep well SG-3 stopped because of worsening of drilling conditions. Four accidents happened at this depth due to a sharp increase in rock strength. So we can make the conclusion that the "impermeability boundary" established by the data of drilling at the SG-3 superdeep well at a depth of about 12 km can be considered as the Conrad discontinuity. In this case, the nature of the hypothetical Conrad discontinuity should not be related to the change in the rock chemical composition from aluminosilicate (SIAL) to substantially magnesian (SIMA) as supposed by gelogy, but to the change in the physical state of the rock from brittle to viscous properties. The cause of the increase in viscosity (strength) of rocks at the Conrad discontinuity can be related to the bigger role player by the vertical, lithostatic pressure in the lower crust due to elimination of tangential stresses existing in the upper crust and leading to dilatance in the depth range from 2–3 to 10 km.

CONCLUSIONS

The general analysis of the data presented above suggests the following conclusions.

1. The deep controlled source soundings indicate in the Earth's crust in the depth range of 10-12 km a zone of sharp increase of resistivity. We name it as boundary of impermeability (BIP zone) for galvanic DC currents.

2. BIP zone divides Earth crust on the upper (brittle) and lower (ductile) parts.

3. The upper part of the Earth crust of 10-12 km thickness is heterogeneous. Crustal conductors of sulfide and graphite nature and an intermediate conductive layer of fluidal, dilatancy-diffusion nature (DD-layer) in the depth range of 2-10 km are widely distributed. The average resistivity of the upper (brittle) crust is of about 10^4 Ohm.m.

4. The low crust of 20-30 km thickness is of high resistivity (10^5-10^6 Ohm.m) and is horizontally homogeneous. It can be depicted by the “normal” electrical section after FENICS experiment. It can be named as compaction zone having semi-ductile properties.

5. The "BIP zone", established by CS soundings, coincides with the boundary of “irresistibility” that has been met in the Kola super deep hole SG-3. At the depth interval 11-12.6 km four breakdowns occurred in four shafts of the Kola super deep well SG3. The main cause of these breakdowns is attributed to the worsening of drilling conditions due to a sharp increase in rocks strength, rocks viscosity.

6. The cause of the increase in viscosity (strength) of rocks can be explained by transition zone between brittle and ductile states of the earth crust related to the bigger role player by the vertical, lithostatic pressure in the lower crust due to elimination of tangential stresses existing in the upper crust and leading to dilatance in the depth range from 2–3 to 10 km.

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