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Electron-conductive sulfide- and carbon-bearing structures in the continental Earth's crust ("SC layer by Semenov")

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Abstract. The paper highlights the nature of electron-conductive graphite- and sulfide-bearing anomalies called "SC layer by Semenov" in honor of inventor of this phenomenon – professor of Saint Petersburg University Alexander Sergeevich Semenov. The electrical conductivity of the Earth solid crystalline cover called the lithosphere is determined by two factors to follow: the vertical change of the fluid regime, composition and thermodynamic state of rocks with depth and the horizontal heterogeneity caused by the "crustal" conductivity anomalies of electron-conductive nature mostly. Crustal anomalies strongly affect results of the deep soundings. The formal 1D interpretation presents these as "fictive" intermediate conductive layers at the depth of from a few up to tens of kilometres. Investigations on shields provide a more detailed analysis of their structure, geological position, and value at forecasting mineral resources.

Аннотация. В статье рассмотрена природа электронно-проводящих сульфидно-графитовых аномалий, которым присвоено название "SC-слой Семенова" в честь первооткрывателя этого феномена в природе – профессора Санкт-Петербургского университета Александра Сергеевича Семенова. Электропроводность кристаллической оболочки земли – литосферы – определяется двумя основными факторами. Первый из них – изменение по вертикали электрических свойств под действием таких факторов, как флюидный режим, состав горных пород и термодинамические условия. Второй фактор – горизонтальная неоднородность электрических свойств, обусловленная, прежде всего, широким распространением коровых аномалий электропроводности электронно-проводящей природы в составе сульфидно-углеродистых вулканогенно-осадочных образований. Коровые аномалии оказывают сильное влияние на результаты электромагнитных зондирований. При формальной, одномерной интерпретации они проявляются как промежуточные проводящие слои на глубинах от единиц до первых десятков километров. Исследования на щитах позволяют детально изучить их строение и геологическую природу.

Key words: electronically conducting rocks, Earth crust, Fennoscandian Shield, sulfide and carbon bearing rocks, conductivity structure
Ключевые слова: электронно-проводящие породы, земная кора, Фенноскандинавский щит, сульфидно-углеродистые породы, структура проводимости

1. Introduction

Geoelectrics, as well as other geophysical methods, is only sense-making and significant, when closely related with geology. The geoelectrical research is targeted at the properties of the electromagnetic fields and their distribution on the Earth. But the final result of the geoelectrical research should be tightly woven with the geological interpretation in close relation with the composition, structure and evolution of certain parts of the Earth. The insight into the Earth's deep electrical conductivity is provided by a combination of two concepts. On the one hand, it involves theoretical speculations grounded on a priori (physical, laboratory, etc.) data, which are at a researcher's disposal, and, on the other hand, experimental investigations are carried out using the deep electromagmetic sounding, profiling, mapping, etc.

The article highlights the nature of electron-conductive graphite- and sulfide-bearing anomalies called "SC layer" after Semenov and their spatial distribution in the Earth's crust. The electrical conductivity of the Earth solid crystalline cover called the lithosphere is determined by two factors to follow: the vertical change of the fluid regime, composition and thermodynamic state of rocks with depth and the horizontal heterogeneity caused by the "crustal" conductivity anomalies of electron-conductive nature mostly (*Zhamaletdinov*, 1990). Crustal anomalies strongly affect results of the deep soundings. The formal 1D interpretation presents these as "fictive" intermediate conductive layers at the depth of from a few up to tens of kilometres. Investigations on shields provide a more detailed analysis of their structure, geological position, and value at forecasting mineral resources (*Semenov*, 1970; *Zhamaletdinov*, 1980).

Electron-conducting rocks constitute a class of natural formations, which high conductivity is caused by the presence of minerals and mineral assemblages with high electronic conductivity sometimes tending to the metallic one. The common representatives are graphite- and sulphide-bearing gneisses and schists. The electron-conducting rocks occur mostly in the Proterozoic and Late Archaean complexes having undergone intense tectonic movements. They are minor or absent in the outcrops of the oldest Early Archaean protobasement (e.g., granite-tonalites of the Murmansk block) and in the youngest slightly metamorphosed Riphean rocks having formed in the sub-platform regime.

Fig. 1b illustrates the electron-conducting rocks distribution in the eastern part of the Baltic Shield according to (*Zhamaletdinov*, 1980; 1990; *Zhamaletdinov, Kovtun*, 1993). The inset-map (Fig. 1a) represents the crustal anomalies scheme for the Fennoscandian Shield after (*Pajunpaa*, 1984; *Rasmussen et al.*, 1985; *Korja*, 1993). The shading shows domains of reduced resistivity as derived from data of ground and airborne geoelectrics and the deep electromagnetic sounding with natural and controlled sources. Thick lines indicate the most conducting axial directions of the anomalous zones. The better the structure of the zones and bands of enhanced conductivity is studied, the more complicated it turns to be. In this respect, they possess features typical of fractal structures and can be represented as a system of percolating clusters by analogy of the structures of primarily sedimentary and volcanogenic rocks of iron formations (*Goryainov*, 1995).

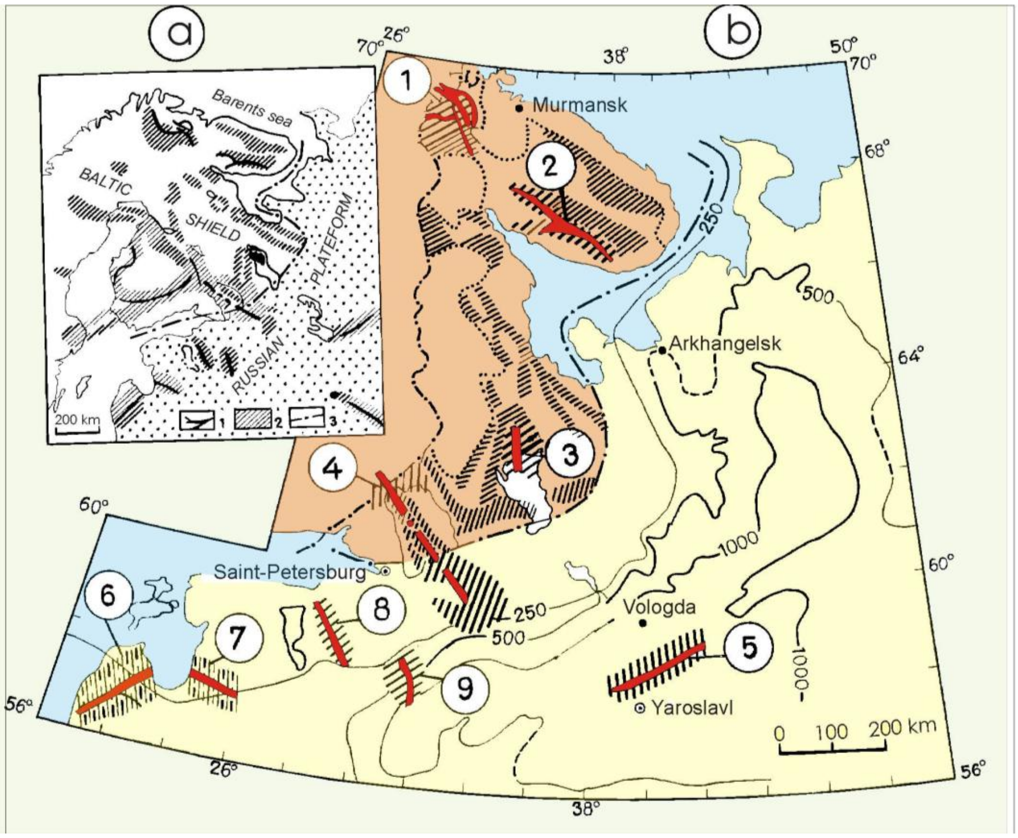

Fig. 1. Crustal anomalies of electrical conductivity on the western (a) and eastern (b) parts of the Fennoscandian Shield.

Fig. 1a: 1 – axes of linear anomalies with longitudinal conductivity S > 1000 S; 3 – areas with enhanced conductivity S = 10-100 S; 7 – boundary of the Russian platform sedimentary cover.

Fig. 1b: Digits in circles indicate the largest anomalies of electrical conductivity (1 – Pechenga-Allarechka, 2 – Imandra-Varzuga, 3 – Onega, 4 – Ladoga, 5 – Ljubimskaja, 6 – Kuldino-Liepajskaja, 7 – Valmiero-Loknovskaja, 8 – Jhudskaja, 9 – Il'menskaja). These anomalies are briefly described below with some examples of experimental works and numerical modelling

2. The thin structure of electron-conductive rocks

The deep soundings the author performed on the Fennoscandian Shield and Russian Platform reveal their crustal conductive zones (under a sedimentary cover) being structurally and originally identical. Therefore, it would be reasonable to investigate the basement structure of conductor-accessible shields and outcrops. The common-most features of their structure are represented below on example of the investigations carried out on the Baltic Shield. In natural conditions graphite usually occurs fine-grained. It often appears in geological descriptions under the names of "carbonaceous matter" and "black pigmentation". It occurs in almost all types of primarily sedimentary metamorphic rocks, i.e. schists, gneisses, metadiabases, tuffs, amphibolites, etc. In a number of cases, e.g. biotite graphitic gneisses, two-mica schists, etc., graphite is one of basic rock-forming minerals. Here, its content is up to 5-10 %, sometimes 20 %.

In greenstone belts of low metamorphic grade, the carbonaceous matter is represented by black phillite-like shales mostly. Graphite in the shales is almost unrecrystallized. The carbonaceous matter penetrates the whole rock in the form of thinnest films and powdered impregnation with invisible separate grains, even at high magnification.

The origin of iron sulfides in metamorphic complexes is closely related with graphite. The latter is always associated with sulfides, whereas these can be observed with no visible graphite mineralization. Graphite-forming sapropel silts and blue-green algae are believed to contain sulfate-reducing bacteria in various proportions to the rest of the organic matter. In the long run, it has provided the formation of interlayered graphitic and sulfide-graphitic shales.

The electrical resistivity of sulfide-carbonaceous rocks depends on their structure. When they form a sustained network, the rock performs high conductivity. With no connection, the electrical conductivity of the rock weakly depends on the impact of electron-conductive minerals. Fig. 2 shows some examples of investigation of graphite rocks electrical conductivity. Fig. 2a represents a sulfide and graphitic shale. The thin layer indicated by a dashed line as NP divides the sample into two parts not connected with each other. The ideal electrical connection is observed all along either part, in spite of its inhomogeneously layered structure. This example shows the nature of electrical conductivity in rocks to be determined by primary conditions of sedimentation and composition of individual lamellas. The matter has syngenetically transformed into the electron-conductive one only when the organic (carbonaceous) matter accumulated and buried in the initial composition of the lamellas.

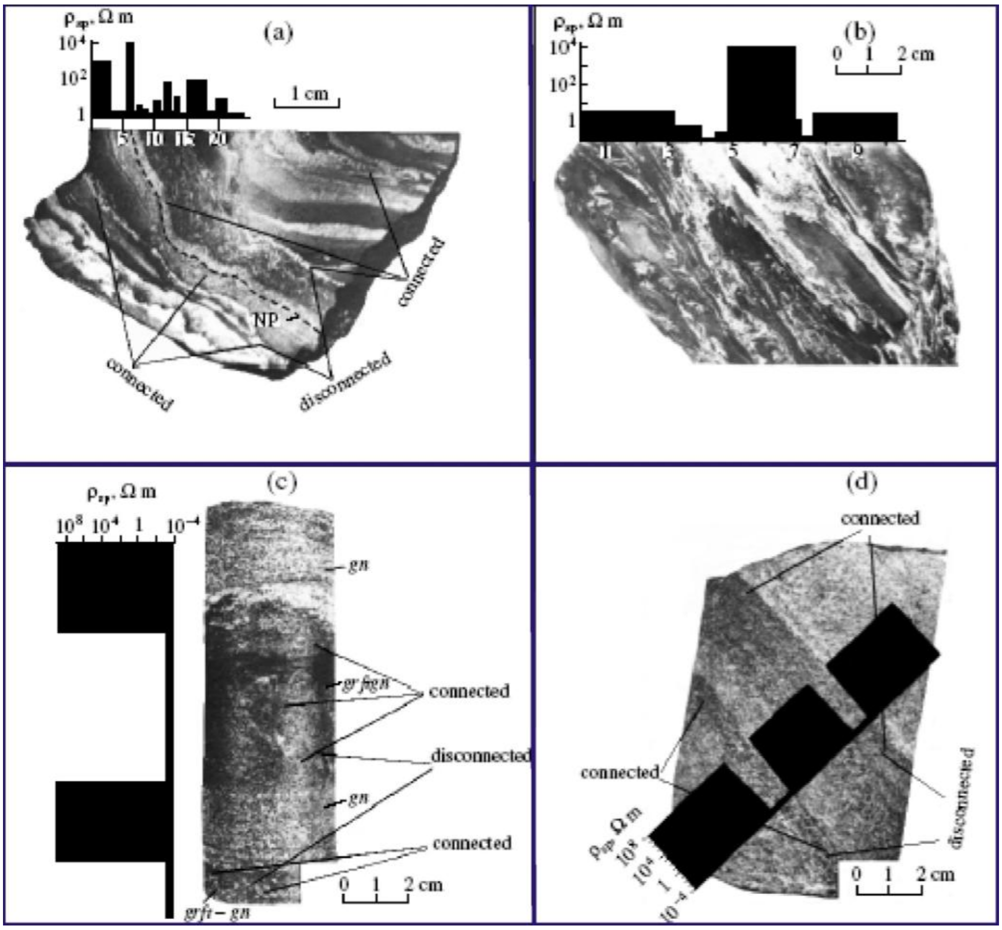

Fig. 2. Examples of the fine conductivity structure study on the samples of electron-conductive rocks. Legend: (*a*) and (*b*) – sulfide- and graphite-bearing black shales (fillites) of the Pechenga structure; (*c*) – biotite gneiss of granulitic series; (*d*) – two-mica schist of the Allarechensky region

In Fig. 2b, a light area with a thick impregnation of sulfides and high electrical resistivity can be distinguished in the black shale within the interval of 5-7 cm. The detailed study has revealed sulfide grains in it to be not connected with each other due to the coarse-grained structure of the enclosing material and the absence of graphite. In general, it affects the connection between grains owing to its plasticity. Figs. 6c and 6d display the samples of higher (granulite and amphibolite facies) metamorphic grade. Here, the resistivity of the conductive interlayers (up to 10^{-4} Ohm·m) is several times lower than that of black shales. The high conductivity of the former is attributed to greater graphitization degree of the carbonaceous matter. Here, graphite has a clear crystalline structure, the size of crystals is up to 2-3 mm. They are oriented towards the general schistosity of the rocks and characterized by the ideal electrical connection all along the interlayers. There is no connection between the latter. However, in terms of electric prospecting works, these interlayering systems deformed in subsequent tectonic movements act as continuous, inhomogeneously anisotropic conductors.

3. Conductivity anomalies of the Pechenga-Allarechka and Lapland blocks

In the 1930's, when a Finnish-Canadian company prospected the Pechenga region for Cu and Ni, an extended occurrence of conductive sulfide-carbonaceous rocks was established. Later, the region was explored with a complex of ground and airborne electrical surveys, including deep sounding with AB electrode spacing up to 20 km, telluric currents (TC), magnetotelluric sounding (MTS) and profiling (MTP) (*Vasin et al.*, 1981). Results of the geoelectric research provided a detailed mapping of the region structure.

The Pechenga structure general scheme is marked with zones of low resistivity of rocks. The thickest and most extensive zone is confined to the fourth tuff-sedimentary horizon of the northern flank. It consists of high carbonaceous phyllites and schists permeated by a great number of Ni-bearing ultramafic intrusions. That is why it is called the "productive" horizon. The phyllite-like schists of the productive horizon are observed for over 80 km from the Kuchin Tundra to the Norwegian border. Further, on the Norwegian territory, using the "Khibiny" MHD-source, the schists can be traced for other 20 km as a thin pinching-out layer (*Zhamaletdinov et al.*, 1995; *Velikhov et al.*, 1986). The integrated longitudinal conductivity in the central part of the productive horizon is about $2\text{-}3 \times 10^3$ S.

The southern part of the Pechenga structure is composed of volcanosedimentary horizons of the Porjitash zone. Prevailing here and in the northern Pechenga zone are sulfide-carboniferous phyllite-like schists and tuffites, which interstratify with small bodies of mafic-ultramafic rocks. However, these rocks are of no commercial interest. The southern Pechenga zone is of minor value for prospecting. The integrated longitudinal conductivity of the Porjitash zone, in comparison with the productive one, is a little bigger, i.e. about 5×10^3 S.

The "Khibiny" experiment with a 40 mW MHD-generator provides relevant information about the deep structure of the conducting zones (*Zhamaletdinov*, 2005). According to the data, they form monocline conducting plates, which plunging southwards and having no electrical connection. The zones dip southwards and become gradually gentle with depth. The zone is 1-2 km thick at the flanks of the Pechenga structure, and reaches 5 km in its central part.

The Porjitash zone is dislocated by a fault system. In the south it borders the older Late Proterozoic rocks of the Allarechka-Khihnayarvi zone and the Granulite Belt with common strip zones of high conductivity. The degree of the metamorphic rock transformation increases southwards from greenschist-amphibolite to granulite facies. The carbonaceous substance changes respectively. In the Pechenga structure rocks, carbon is finely dispersed. The specific electric resistivity of such rocks is usually no less than some fractions of ohmmeter.

In the rocks of the Lapland belt, the carbonaceous substance is metamorphosed up to crystalline graphite. The size of graphite crystals is 2-3 mm. The crystals are oriented along the general rock foliation. The resistivity of the graphite-bearing biotitic gneisses is about 10^{-4}-10^{-5} Ω·m. There is an ideal bond between the graphite grains and sulfide minerals (mainly pyrrhotite). In terms of the electrical surveying, the systems of such interlayers seem to be a single heterogeneous-anisotropic conductor.

The carbonaceous substance (2-3 % and more) is always virtually providing high conductivity for the country rock through the system of connected channels. Except massive ores, the sulfide mineralization effects rock conductivity only when graphite is present. Another important factor contributing to the increase of the rock conductivity is their tectonic reworking. The disjunctive dislocations of the sulfide-carbonaceous rocks are joint with conductor systems, which have formed under scaling, cleavage and metasomatism along with the origination of the secondary cutting conductivity zones.

4. Conductivity anomalies of the Pechenga, Allarechka and Lapland blocks

Figs. 3a and 3b present a geoelectrical section crossing the electrical conductivity anomalies of the Pechenga, Allarechka and Lapland blocks. The section is plotted by numerical 2D modelling of magnetotelluric sounding. MTS has been interpreted using TSAIS digital measuring automatic stations. The data have been processed with a program designed by V.Yu. Semenov (*Asming et al*., 1992). The numerical modelling has been performed using a program elaborated by *Vardanyantz* (1978). The initial model (Fig. 3b) has been selected basing on results of the MHD sounding (*Zhamaletdinov*, 1990).

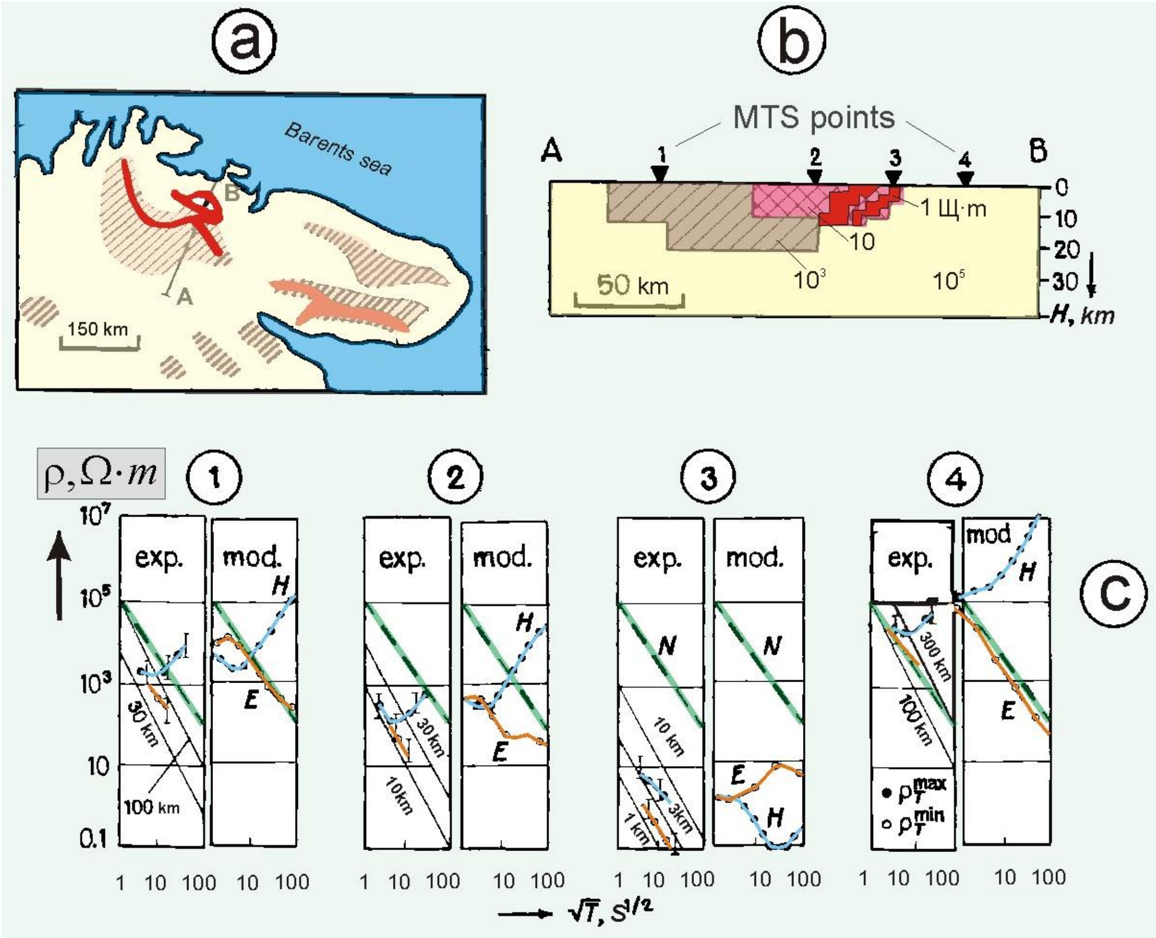

Fig. 3. Results of 2D modelling of the magneto-telluric sounding (MTS) data along AB profile crossing the Pechenga, Allarechka and Lapland blocks.
a – line AB at the scheme of the conducting zones; *b* – 2D model; 1-4 – values of electrical resistivity, 5 – position of MTS points; *c* – experimental (exp) and modelling (mod) MTS curves for points 1-4

MTS theoretical curves and experimental data (Fig. 3c) are well correlated. Notably, MTS has been carried out in different areas, which lie not exactly at AB profile. That is why the experimental and theoretical curves do not coincide completely. Nevertheless, the obtained results allow both explaining major features of maximum and minimum MTS curves and getting a sound idea about the structure of the crustal conductivity anomaly in the Precambrian crystalline basement. The most interesting thing is that the rocks (including electron conducting varieties) of the whole supracrustal complex extend at the depth of 10-15 km only, and the rock resistivity increases regularly from the north to the south as a result of the carbon volume content having rapidly reduced. Conversely, the specific electric resistivity of the carbon mineral assemblages decreases from the north to the south down to fractions of ohmmeter in the Pechenga rocks, and down to 10^{-4}-10^{-5} Ω·m in the rocks of the Lapland belt, which are metamorphosed at the granulite facies (Fi).

5. Conductivity anomaly of the Imandra-Varzuga zone

The Imandra-Varzuga zone has a rift origin and consists of the Low Proterozoic volcano-sedimentary rocks, which are compositionally and structurally similar to the Pechenga formation. The Imandra-Varzuga zone extends for 350 km in the latitudinal direction (Fig. 4a). It contains up to 10-12 volcano-sedimentary layers, some of them including sulphide- and carbon-bearing phyllites (black schists) enriched by pyrite-pyrrhotite mineralization mostly. The most widespread of these are traced in the Tominga Series section in the central part of the Imandra-Varzuga zone.

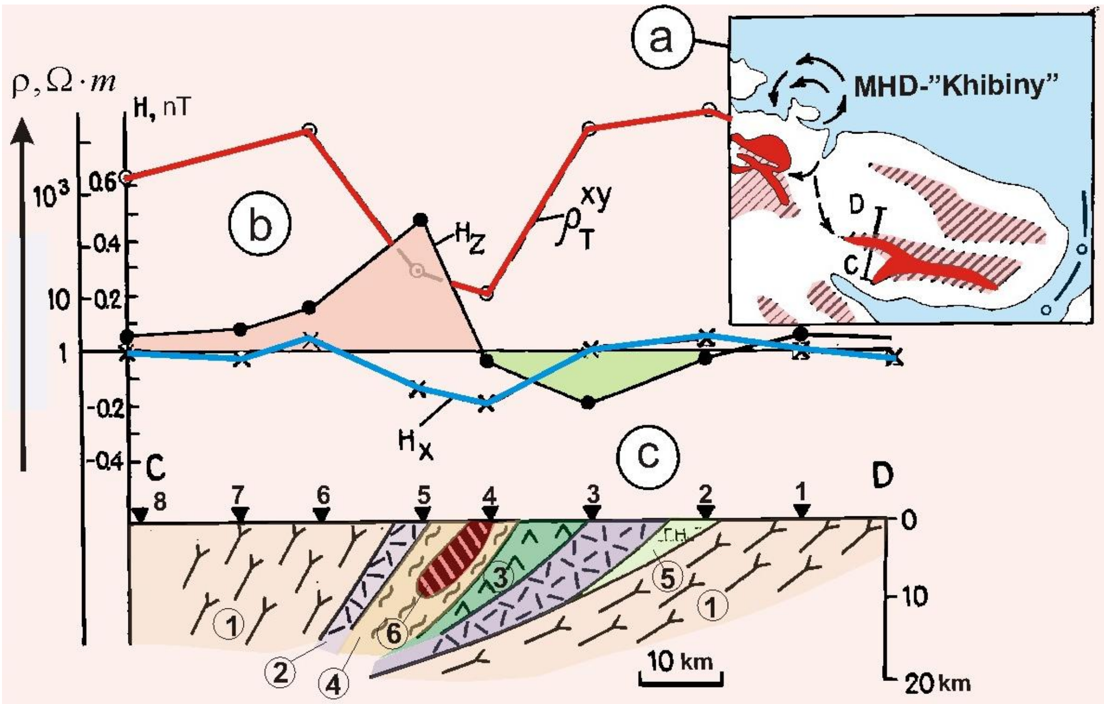

Fig. 4. Deep model of the Imandra-Varzuga structure according to the results of the "Khibiny" MHD-sounding.
a – location of the profile CD at the scheme of the conducting zones;
b – diagram of the electromagnetic field observed using the "Khibiny" MHD-source over the Imandra-Varzuga zone and geological-geoelectrical cross-section.
Legend (in circles): 1 – granite-gneiss of Lebyazhka; 2 – volcanites of Strelnya; 3 – effusives of Varzuga; 4 – schists and volcanites of the Tominga Series; 5 – gabbronorites of the Fedorov Tundra; 6 – location of the conductive channel

Fig. 4b illustrates the results of studying the Imandra-Varzuga zone deep structure at CD profile. Arrows in the upper part of Fig. 4a indicate the measurements implemented *in situ* using the "Khibiny" source (*Zhamaletdinov*, 1990). In the central part of the profile, over the Tominga Series formations, the electric and magnetic components of the field behave anomalously. H_z vertical magnetic component changes its sign from negative in the north to positive in the south. H_x horizontal magnetic field has the negative minima at the centre of H_z anomaly. These features denote that the anomalous galvanic current runs from the west to the east in the graphitic schists of the Tominga Series.

Thin arrows in Fig. 4a show the direction of the galvanic currents floating from the centre of the "Khibiny" MHD-source. It is clearly seen that the currents in rocks of the Imandra-Varzuga and Pechenga zones run in opposite directions. This is an important argument justifying their galvanic origin caused by conductive channels in the Earth's crust. The galvanic current intensity in the Pechenga conductive structure, which is closer to the source, is 40 A. In the Imandra-Varzuga zone it is 12.5 A. These values make up only tenths percents of the full current intensity of the MHD-generator of 20×10^3 A. Nevertheless, the fact of the galvanic currents being found in the conducting geological structures is essensial to gain a better insight into the model of the electrical conductivity of the Baltic Shield basement. Thus, it is clear that in the upper part of the Earth's crust, despite the absence of the sedimentary deposits and high resistivity of exposed crystalline rocks, there are channels for ultralow-frequency, virtually direct current running horizontally over a distance of hundreds kilometres.

The quantitative interpretation of the magnetic field (Fig. 4a) ascertains the extension of the conducting zone to the depth, which is estimated to be 10 km. This estimation corresponds with the results of the numerical modeling of MHD-signals using the technique of electromagnetic migration (*Zhdanov, Frenkel*, 1983) and with the results of magnetovariation profiling at the western flank of the zone (*Zhamaletdinov et al.*, 1980).

6. The Ladoga anomaly

The Ladoga conductivity anomaly has been first discovered by *Lazareva N.V.* (1967) during the magnetotelluric sounding along the 150 km-long Lahdenpohya-Sortavala profile. She has established no common low apparent resistivity values and irregular behaviour of the ρ_T curves there. Later, the region was investigated using the magnetovariation method. The anomaly centre has been estimated at the depth of 10 km (*Rokityansky*, 1981). The parameter $G = \sigma \times S$ (where σ – electrical conductivity in $\Omega \times m^{-1}$ and S-cross section of the anomaly in m^2) has been estimated as $10^9\ \Omega^{-1}\cdot$m. The correlation with the geological data and results of ground electrical survey has disclosed the Ladoga anomaly being correlated with by-surface rocks. The anomaly is confined to a set of long-living faults traversing the boundary between the large tectonic Karelian and Svecofennian blocks. North-westwards, the anomaly crosses, with some breaks, almost the whole of the Baltic Shield and passes to Gulf of Bothnia (Fig. 1a).

The Ladoga-Bothnian zone (LBZ) of enhanced electrical conductivity is confined to the Finnish belt, which is known for its commercial deposits of Cu, Ni and complex ores. On the Russian side of the zone there are Sn and pyrite deposits. All this evokes great interest in studying the deep structure of the zone. The Ladoga-Bothnian zone has been given the most extensive electromagnetic research using techniques of MT-AMT sounding by *A.A. Kovtun* (1989). According to the numerical modeling results, within the LBZ three conductivity centres have been discovered at the depth of 5-10 km. Presumably, the estimation defines the LBZ extension at the depth. The integral longitudinal conductivity is $1.5\text{-}2\times10^3$ S according to the MTS data. The parameter G is $2\cdot10^8\ \Omega^{-1}\cdot$m according to the Magnetometer Array Profiling (MAP) data (*Kovtun*, 1989).

7. Geoelectrical model along "White Sea-Umbozero-Kontozero-Barents Sea" profile

Fig. 5 shows a geological-geophysical section complied according to the deep geoelectrical investigations along the 300 km-long GH "White Sea-Umbozero-Kontozero-Barents Sea" profile. The inset of Fig. 5a indicates its location. The northern part of the profile (Barents Sea – Lake Umbozero area) is studied using the sounding with the "Khibiny" MHD-source (*Zhamaletdinov*, 1990). The southern part of the profile is examined with several techniques, e.g. the sounding with the "Zeus" ultra-low frequency antenna, audio-magnetotelluric sounding, vertical electric sounding and airborne geoelectrical prospecting (*Lyubavin et al*., 1999). Fig. 5b presents the resistivity diagram of the upper Earth's crust along the GH profile.

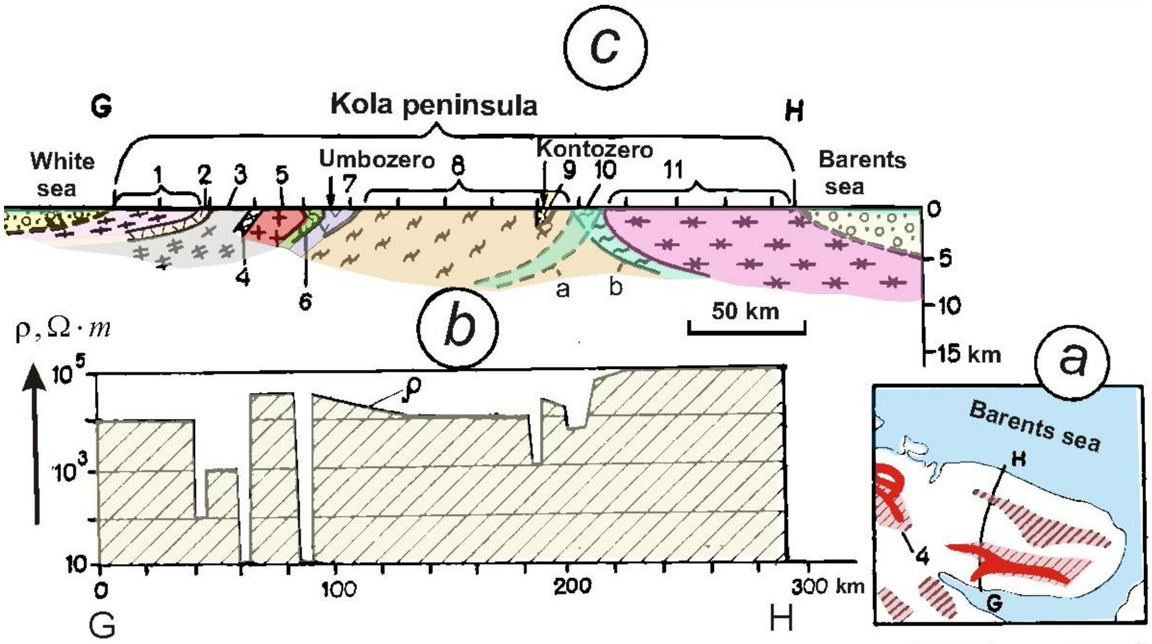

Fig. 5. Geoelectrical model along the "White Sea-Umbozero-Kontozero-Barents Sea" profile.
(a) – location of the profile; (b) – diagram of electrical resistivity of the Earth's crust along GH profile;
(c) – resulting geological cross-section.
Numbers indicate geological legend: 1 – Umba granulite; 2 – Porjeguba-Umba shearing zone; 3 – supracrustal formations; 4 – Kislaya Guba gneiss-ultrablastomilonite; 5 – Ingozero block; 6 – Tominga schist series; 7 – central Imandra-Varzuga zone; 8 – Central-Kola block; 9 – Kontozero sunken caldera; 10 – Kolmozero-Voronja zone; 11 – Murmansk block: a – location of the boundary between Murmansk and Central-Kola blocks according to data of MHD-sounding; b – the same according to geological data

In the northern part of the GH profile, the Murmansk block is characterized by high resistivity (over 10^5 Ω·m). At the southern boundary of the profile, in the resistivity reduces a little (10^4 Ω·m and less), which indicates the Kolmozero-Voronya zone being promising for REE (Rare Earth Elements). This zone marks the boundary between the Murmansk and Central-Kola blocks. According to the geological data, the boundary plunges gently to the south (*Pozhilenko et al.*, 2002). However, the MHD sounding gives no evidence to the conducting rocks below the granite-gneiss of the Murmansk block. This allows assuming that the Kolmozero-Voronya suture zone dips to the south at depth, while the Murmansk block granite-gneiss is not a thrust, but a basement for the Central-Kola block gneiss. Fig. 5c displays the two interpretations of the behaviour of the Murmansk block boundary at depth as two models *a* – after geological interpretation and *b* – after MHD-sounding interpretation.

About 15 km to the south from the Kolmozero-Voronya zone, a clear electrical conductivity anomaly is identified over the Kontozero ring structure (subsidence caldera) filled by sedimentary rocks. At the depth of over 1 km the sediments are substituted by alkaline rocks and nepheline syenite (*Pozhilenko et al*., 2002). The same electrical conductivity anomalies have been earlier registered in the Kovdor and Seblyavr alkaline intrusions, where they are related to the magnetite rocks (shtocks). It exposes the need to provide a more detailed study of the deep electrical conductivity of the Kontozero structure. It relates to the chance of finding mineral resources similar to those discovered in the Kovdor and Seblyavr alkaline intrusions.

The southern part of the profile is marked by a clear Imandra-Varzuga electrical conductivity anomaly. Its deep structure has been described above. However, it should be noted that the southward dip of the structure beneath the Ingozero granite has been established using the MHD-sounding (Fig. 4d). This conclusion contradicts the geological and test drilling data, which suppose its northward dip. The contradiction is explained by the dipping inversion ("storm-like" structure). The same phenomenon can be observed in the Kolmozero-Voronya zone, southern frame of the Pechenga structure and contact zone of the Shuoni-yarvi granite dome.

In the extreme southern part of the GH profile, there is an amazing object requiring some extra study. It is the Porjeguba-Umba zone of the Proterozoic thrust gently plunging southwards, according to the data of the electrical survey (Fig. 5c, zone 2). The airborne electric survey has revealed the zone to be traced at the surface for over 200 km as a latitudinal bow-shaped band composed of a set of echelon-like contiguous conductivity zones (*Lyubavin et al.*, 1999). The thrust nature is suggested to be determined by the development of the Tanaelv-Kolvitsa rift and an associated relatively close linear basin with the ocean crust (*Balagansky et al*., 1998). It is supposed that the closure of the basin has completed by the collision 1.9-2 Ga ago and has been accompanied by the NNE-trending compression.

8. The conductivity anomalies of the Baltic Shield southern frame

Digits 4-9 of Fig. 1b indicate the crustal anomalies of the southern frame of the Baltic Shield. They are determined directly under the sedimentary cover and have the electron-conducting nature. The parameters of the crustal conductivity anomalies in the eastern part of the Baltic Shield are compiled in the Table.

Table. Parameters of crustal conductivity anomalies in the eastern part of the Baltic Shield and its southern frame

Anomaly		Geometric parameters, km				Conductivity		Electr.
№	Name	Width D	Length L	Upper depth $h_{в.к.}$	Lower depth $h_{н.к.}$	S, S·m^{-1} (by MTS)	G, S·m (by MAP)	Resist. ρ, Ω·m
1.	Pechenga	2-20 км	80	0	5-15	$(5\text{-}7)\cdot10^3$	–	0.1-1
2.	Imandra-Varzuga	2-50 км	350	0	10	$(3\text{-}5)\cdot10^3$	$7\cdot10^7$	1-5
3.	Zaonezhsky	120	130	0	1-2	10^3	–	1-10
4.	Ladoga	160	1000	0	5-10	$2\cdot10^3\text{-}10^4$	10^9	1-10
5.	Lyubimsky	40-60	240	2	15	$5\cdot10^3$	10^9	0.8
6.	Kuldigo-Leipa	140-200	160-200	2	15	$(0.7\text{-}1)\cdot10^3$	$3\cdot10^8$	–
7.	Valmiero-Loknovsky	70	160-200	1	15	$(0.5\text{-}1)\cdot10^3$	$4\cdot10^7$	13
8.	Chudsky	60	250-300	1	8-15	$(2\text{-}4)\cdot10^3$	$(4\text{-}6)\cdot10^8$	–
9.	Ilmensky	100	80-100	2	8-15	$5\cdot10^3$	$9\cdot10^8$	–

The parameters of the anomalies in the table are given in circles in Fig. 1b. The parameters of the anomalies 1-2 are provided after (*Zhamaletdinov*, 1990; *Zhamaletdinov et al.*, 1980); anomalies 3-4 – after

(*Rokitynsky*, 1985); anomalies 5-9 – after (*Kovtun, Sheinkman*, 1993). The lower depth of all anomalies for the southern frame of the Baltic Shield is also 15 km and less as for the Kola-Karelian anomalies.

9. Conductivity anomalies on the territory of Russia and its neighboring countries

Along with the investigations on the Fennoscandian Shield, the author has spent several field seasons working on the Voronezh crystalline block of Central Russia, Ukrainian Shield, eastern Baikal zone, Kazakhstan and Sakhalin for several field seasons. Results of these works and compilation of some data obtained by other researchers permitted the author to construct a scheme of the distribution of crustal electrical conductivity anomalies in CIS and adjoining areas (Fig. 6). The distribution has been used to divide anomalous objects according to their origin, i.e. the electron-conductive or fluid ones. This division is based on the quantitative and qualitative criteria and conclusions of the investigators, who have found and described crustal anomalies. The scheme shown in Fig. 6 is incomprehensible. It is confined to the materials the author managed to collect. The majority of crustal anomalies have been defined using the methods of magnetotelluric sounding (MTS), magnetovariational profiling (MVP), telluric currents (TC), etc. Also, a number of objects (12, 15, and 29) have been found using the sounding with controlled power sources. The author has had no experimental data for the whole territory; therefore, open fields should only be considered the regions with no information on. However, the northwestern part of Russia, where the density of investigations is great, is an exception. Here open spots represent the anomaly-free, poorly conductive crust. With Fig. 6 one can gather the crustal anomalies of fluid origin occurring in the eastern CIS mainly. They have moderate values of resistivity (tens and hundreds of Ω m) and an isometric or slightly extended form with indistinct contours. The best-known anomalies of this type are the Kopet Dagh (36), Siberian (20, 30) and Kamchatka (21) ones.

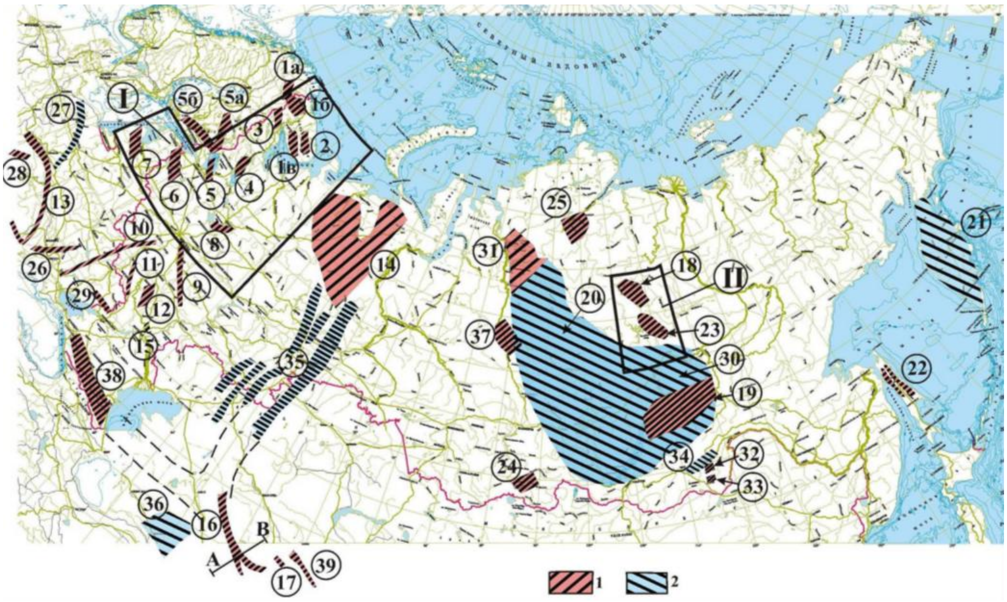

Fig. 6. Crustal anomalies of electrical conductivity over the territory of CIS and the adjoining regions. Elaborated by A.A. Zhamaletdinov after data of M.N. Berdichevsky, L.L. Van'yan, V.G. Dubrovsky, A.A. Zhamaletdinov, A.A. Kovtun, A.G. Krasnobaeva, S.N. Kulik, Yu.F. Moroz, V.M. Nikiforov, E.S. Podlovilin, O.L. Poltoratskaya, I.I. Rokityansky, E.B. Fainberg, I.S. Feldman, V.A. Shapiro, and A.L. Sheinkman.

1 – Crustal anomalies of the electron-conductive origin, 2 – anomalies of the fluid origin.

Names of crustal anomalies (digits in circles): (1) Pechenga-Varzuga; (1a) Lapland; (2) Keivskaya; (3) Tiksheozerskaya; (4) Onega; (5) Ladoga; (5a) Bothnian; (5b) South Finlandian; (6) Chudskoe; (7) Baltic; (8) Vologda; (9) Moscow-Tambov; (10) Kirovogradsky, (11) Dneprovo-Donetskaya; (12) Vorontsovskaya; (13) Carpathian; (14) Timano-Pechorskaya; (15) Frolovskaya; (16) Tien Shan; (17) Fergana; (18) Anabar; (19) Bodaibinskaya (Baikal rift zone); (20) Siberian; (21) Kamchatka; (22) Sakhalin; (23) Vilyui; (24) Minusinskaya; (25) Khatangskaya; (26) Izmail-Poltava; (27) North-German; (28) Pannonian; (29) Donbass; (30) East-Siberian; (31) Noril'sk; (32) Undino-Baleiskaya; (33) Kurunzulaiskaya; (34) Mongolia-Okhotsk; (35) Ural; (36) Kopet Dagh; (37) Tungusskaya; (38) Severo-Kavkazskaya; (39) Severo-Ferganskaya

10. The Urals-Tien Shan electrical conductivity anomaly

The band-like electrical conductivity anomalies of the supposed fluid origin extend along the Urals (35) (*Shapiro*, 1988). Southwards, they are connected by dashed lines (Fig. 6) via the Aral Sea (where observations are absent) with the Tien Shan (or Muruntauskaya) anomaly (16), which origin is considered electron-conductive (*Babadzanov et al*., 1986). Later, this point of view has been justified by the Muruntavsky superdeep hole. At the depth of about 7 km the well crosses graphite deposits.

V. Shapiro (1988) believes, that the system of the electrical conductivity anomalies, stretching as an arched band for about 3500 km, (16) and (35) anomalies in Fig. 6, is a continuous marginal belt formed owing to a collision at the boundary of the Devonian continent that overrode the Ural and South Tien Shan palaeo-ocean. An original interpretation of the geological history of the Tien Shan metamorphic formations by *A. Bakirov* (1984) is consistent with this point of view (Fig. 7). A. Bakirov has paid special attention to an unusual interlayering (mixing) of two geological formations observed along the Tien Shan arc, sharply different in their genesis. These are the rocks of the ophiolitic association (basic and ultrabasic rocks and eclogites) produced by oceanic crust metamorphism and the rocks of primarily sedimentary origin (gneisses, graphitic shales, and quartzites) produced by the continental crust metamorphism. Fig. 7-I shows location of the anomaly and Fig. 7-II shows the geodynamic model explaining the genesis of these formations. The oceanic crust (2) is supposed to have pulled along with it during the subduction at the depth of 60-130 km, sedimentary formations (4) deposited at the passive margin of the continent (Fig. 7-IIa,b). At the final stage of development (Figs. 7-IIc,d) metamorphosed (graphitic) sediments (5) mix with eclogites (3) formed at depth by oceanic crust recrystallization. A specific "pasty mass" (by Bakirov's definition) formed from this mixture had then squeezed out to the surface along the suture of the collided continents. The presented hypothesis, which is based on a profound mineralogical and petrological research, allows explaining the coexistence of the interlayered primarily igneous and sedimentary rocks subjected to the high-temperature and high-pressure metamorphism. These formations are abundant in graphitic shales containing carbon of organogenic origin. The character of the Tien Shan conductivity anomaly traced over more than 1000 km along its strike is associated with this carbon. The longitudinal conductivity of the anomaly varies from 300000 S to 10000-15000 S by different estimates.

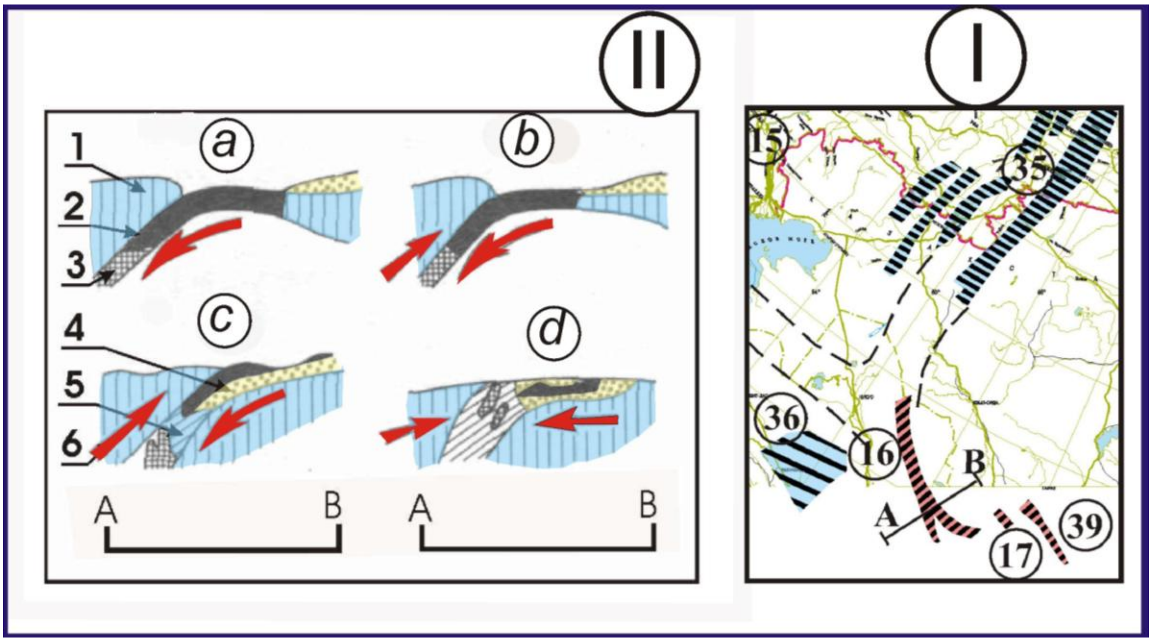

Fig. 7. Model of formation of the eclogite-bearing metamorphic complexes and associated graphite-bearing shales in the South Tien Shan anomaly of electrical conductivity (*Bakirov*, 1984).
Digits in circles: I – location of Tien-Shan conductive anomaly and AB profile crossing it.
II – scheme of subduction-upduction movements.
Legend: (1) continental crust; (2) oceanic crust; (3) eclogites; (4) sediments of the passive continent margin; (5) metamorphosed sediments containing organogenic graphite; (6) directions of driving forces at different stages of the collision zone development: (a, b) subduction; (c, d) squeezing out of the material upwards at the boundary of colliding plates (upduction)

11. Discussion

Interpreting the nature and origin of sulfide-graphitic formations is important for elaborating a geological explanation of crustal electrical conductivity anomalies. Two incompatible approaches to the problem have been elaborated. The first one is based on the assumption that carbon, in all its forms on the Earth's surface, has been produced at the expense of the Earth's degassing from the upper mantle (*Paterson*, 1978). In this case, graphite as an element resistant to thermal and chemical actions should penetrate throughout the crust and the major part of the upper mantle, forming through-thickness current-conductive channels.

The results of our investigation are more consistent with the second point of view, which is based on the idea of the initially sedimentary, biogenic origin of graphite (*Sidorenko, Sidorenko*, 1975). According to this concept, in its infancy the Earth saw a dramatic change of geological processes accompanied by the origination of atmospheric, hydrospheric and photosynthetic bacteria. At that time (3.0-3.5 Ga), the organic life appeared and started to actively develop. It intensively proceeded to shallow water basins, where organic matter accumulated and was buried. Simultaneously, these regions sank and were subjected to disjunctive tectonic movements, erosion phenomena and sedimentation. The deep metamorphism resulted in the elimination of volatiles and structural rearrangement of substance. Fossils rich in hydrogen sulfide transformed into peculiar interlayered members of sulfide-graphitic rocks. After its bio-geochemical and volcanic activity, the described zone of great geological transformations was called supracrustal, or the one occurring on the primary crust at the earliest, nuclear stage in the Earth's development. The primary crust, defined as the Lower Archaean protobasement, is characterized by a surprisingly monotonous, homogeneous structure and the absence of mineral deposits in appreciable concentrations.

The presented scheme of graphite formation in the crust is confirmed by the results of our investigation. Also, it is proved by the fact that electron-conductive sulfide-graphitic formations are always observed within supracrustal, volcanogenic-sedimentary formations. They occur conformably with horizons of initially sedimentary rocks and as their component reflect lithologic-stratigraphic features of the corresponding geological formations. The general scheme of the spreading electron-conductive (graphitic) crustal anomalies in planetary scale based on experimental data is consistent with the biogenic-sedimentary concept of the graphite origin either. These anomalies include gigantic conductive inclusions, or cover formations, sometimes occuring as faults, overthrusts, or riftlike structures on the irregular surface of the most ancient sialic crust formed in the Earth's infancy.

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References

Asming V.E., Zhamaletdinov A.A., Semenov V.Yu., Tokarev A.D. Experience of MTS data processing on the Baltic Shield. *Physics of the Solid Earth*, N 4, p.102-106, 1992.

Babadzhanov T.P., Basov M.D., Gatina R.M. The Ural-Tien Shan anomaly of electrical conductivity. *Bulletin AS USSR, Physics of Earth*, N 6, p.79-90, 1986.

Bakirov A.B. The Tien Shan endogenic geological formations. Part 2. *Frunze, Ilim*, 250 p., 1984.

Balagansky V.V., Glaznev V.N., Osipenko L.G. Early Proterozoic evolution of the NE Baltic Shield: Terrain analysis. *Geotectonics*, N 2, p.16-28, 1998.

Goryainov P.M. Nonlinear tectonics. *Apatity, KSC RAS*, 44 p., 1995.

Klabukov B.N. Background and abnormal electrical conductivity of the Earth crust in Karelia. *Physics of the Solid Earth*, N 4, p.72-77, 1996.

Korja T. Electrical conductivity distribution of the lithosphere in the central Fennoscandian Shield. *Els. Science Publishers B.V. Amsterdam. Precambrian Research*, v.64, p.85-108, 1993.

Kovtun A.A. Structure of the crust and upper mantle in the NW part of the Eastern Europe Platform according to the data of magnetotelluric sounding. *Leningrad, Publishing House, LSU*, 284 p., 1989.

Kovtun A.A., Sheinkman A.L. Southern frame of the Baltic Shield. Structure of lithosphere in the Baltic Shield. *M., MGK RAS*, p.71-76, 1993.

Lazareva N.V. Some features of the natural electromagnetic field in the southern slope of the Baltic Shield. Problems of geophysics development. *L., Nedra*, Iss. 6, 1967.

Lyubavin L.M., Zhamaletdinov A.A., Pozhilenko V.I. Structure of the SE Kola Peninsula according to the results of the airborne and ground electrical sounding. *Geophysics*, N 3, p.53-62, 1999.

Pajunpaa Kari. Magnetometer array studies in Finland – determination of single station transfer functions. *Geophysics*, N 55, p.153-160, 1984.

Paterson D. Methane from the bowels of the Earth. *New Sci*., v.78, N 1109, p.896-898, 1978.

Pozhilenko V.I., Gavrilenko B.V., Zhirov D.V., Zhabin S.V. Geology of the ore districts in the Murmansk region. *Apatity, MPR RF*, 359 p., 2002.

Rasmussen T., Zhang P., Pedersen L. Preliminary results from magnetotelluric measurements along Fennolora profile. The development of the deep geoelectric model of the Baltic Shield. Part 2. *Oulu Dep. of Geoph., Univ. of Oulu*, Report 8, p.307-327, 1985.

Rokityansky I.I. Inductive soundings of the Earth. *Kiev, Naukova dumka*, 296 p., 1981.

Semenov A.S. Nature of the electrical conductance of the ancient crystalline basement. *Bulletin SPbGU*, N 12, p.12-26, 1970.

Shapiro V.A. The Ural-Tien Shan anomaly of electrical conductivity. *USSR AS Reports*, v.299, N 3, p.598-602, 1988.

Sidorenko Sv.A., Sidorenko A.V. Organic matter in Precambrian sedimentary-metamorphic rocks. *M., Nauka*, 165 p., 1975.

Vasin N.D., Novitsky G.P., Suvorov E.A. The results of magnetotelluric profiling and telluric current method for the Northwestern Kola Peninsula. *In: Geophysical Investigations in the Baltic Shield, Proceedings LSU*, v.39, p.102-107, 1981.

Vardanyants I.L. Calculations using the method of networks for magnetotelluric fields in two-dimensional inhomogeneous media: Parts 1 and 2. *Vopr. Geofiz.*, Issue 27, p.36-40, 1978.

Velikhov E.P., Zhamaletdinov A.A., Bel'kov I.V. Electromagnetic studies on the Kola Peninsula and in Northern Finland by means of a powerful controlled source. *Journal of Geodynamics*, N 5, p.237-256, 1986.

Zhamaletdinov A.A. Electron-conducting structures of the NW Kola Peninsula and their influence on results of the deep soundings of the Earth Crust. *Berlin, Geod. Geophys. Veroff*., p.207-223, 1980.

Zhamaletdinov A.A. Model of electrical conductivity of continental lithosphere. *Sci. Rep. of SPb State University, Problems of Geophysics*, N 438, v.38, p.115-129, 2005.

Zhamaletdinov A.A. Model of the lithosphere electric conductivity based on investigations with controlled field sources (Baltic Shield, Russian Platform). *L., Nauka*, 159 p., 1990.

Zhamaletdinov A.A., Kovtun A.A. Sketch of the Baltic Shield electric conductivity. Parameters of a normal section. Structure of the lithosphere of the Baltic Shield. *M., MGK RAS*, p.86-88, 1993.

Zhamaletdinov A.A., Kulik S.N., Pavlovsky V.I., Rokityansky I.I., Tanachev G.S. Anomaly of short-period geomagnetic variations over structure Imandra-Varzuga (Kola Peninsula). *Geofiz. Zhurnal, Naukova Dumka*, v.2, N 1, p.91-96, 1980.

Zhamaletdinov A.A., Ronning J.S., Lile O.B. Geoelectric investigations with the "Khibiny" source in the Pechenga-Pasvik area. *In: Geology of the eastern Finnmark-western Kola Peninsula region. Eds. D. Roberts, O. Nordgulen. Geological Survey of Norway, Special publication N 7. Trondheim*, p.339-348, 1995.

Zhdanov M.S., Frenkel M.A. The solution of the inverse problems on the basis of the analytical continuation of the transient electromagnetic field in the reverse time. *J. Geomagn. and Geoelec.*, v.35, p.747-765, 1983.