The World's Largest Anomalies of Electrical Conductivity and their Nature - A Review

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Abstract: Geoelectrical parameters, structure and geologic-tectonic position of a number of largest anomalies of electrical conductivity on different continents of the planet Earth are analyzed against the background of published and some new experimental data. Criteria of dividing anomalies into fluid and electronically conducting varieties, and their relation with mineral deposits are considered.

In Memory of Sergey Kulik

Keywords: Electrical conductivity, crustal anomalies, graphite, fluid, magnetotelluric soundings.

1. INTRODUCTION

An important result of electromagnetic sounding that has been obtained on different continents is the establishment of a sharp electrical heterogeneity of the Earth's crust. Extended zones and belts of high electrical conductivity were found. By the formal (one-dimensional) interpretation the exposed anomalies manifest themselves in the form of so-called intermediate conductive layers in the Earth's crust interior. This property of the crustal conducting anomalies is of planetary scale of spreading. The depths of anomalously conductive objects vary from units to tens of kilometers. Their influence substantially limits the possibilities for studying electrical conductivity in deeper horizons of the upper mantle of the Earth. At the same, time crustal conductors are of special interest for fundamental and applied geology. They are indicators of physical state and geodynamic development of corresponding blocks of the lithosphere. The nature of electrical conductivity anomalies in the Earth's crust represents fundamental problem in the interpretation of the deep sounding data. Solution of the problem determines their role in studying the geological structure and composition of the Earth's interior. Two principal concepts of this problem are being developed at present: the electron-conductive and the fluid one.

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2. THE FLUID CONCEPT

Thermal dehydration observed in rocks of low metamorphic grade such as serpentinites and amphibole schist, is commonly accepted as the most probable mechanism of fluid formation at depth. The dehydration phenomenon in interpretation of the origin of crustal electrical conductivity anomalies was first described by Keller *et al*. [1] the example of two samples from a deep sea well in the vicinity of Puerto Rico. During heating of these samples, which had considerable porosity (up to 8%), their electrical resistivity decreased to 10^3 Ω m in the temperature range of 500 – 600°C. On further heating to 1000°C, the resistivity increased to 10^4 Ω m. The authors explained the obtained trend of temperature curves by the release of bound water and its subsequent evaporation. They supposed that if water evaporation were prevented by confining pressure, the resistivity could decrease to 10 Ω m at 800 – 900°C. In the subsequent years, the phenomenon of thermal dehydration was the most extensively studied by (Lyubimova & Fel'dman, 1974; Hyndman & Shearer, 1989; Vanyan, 1984 [2-4]).

At any interpretation of the mechanism of the liquid phase appearance, the fluid concept assumes that connected systems of pores filled with brine solutions exist in deep layers of the crust [5]. However, such an assumption contradicts data of petrology, according to which under deep conditions of granulitic facies metamorphism all free fluid (H_2O, CO_2) is intensely absorbed by the rock and enters into the composition of a crystal lattice [6]. Furthermore, the possibility of free fluid existence under shields and ancient

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platforms, i.e., under the conditions of thermodynamically equilibrium lithosphere, is doubtful since pores and cracks are closed up with depth due to lithostatic pressure, and fluids move upward, i.e., they are squeezed out toward the surface [7].

The dehydration can give rise to intermediate conductive layers only in tectonically active zones, where the thermal field is non-stationary, and where above-crystalline solutions can exist in the intercrystalline space of rocks at the boundaries of temperature fronts. Otherwise, in case of stable lithospheric plates it would be necessary to assume at least a two-layer division of the crust as in the work by Jones [8]. He assumed that the upper crust, being approximately 10 km thick, is moisture-impermeable on geological time scales, and the lower crust has a connected system of pores filled with fluid. Omitting further analysis of different approaches to substantiation of the fluid concept, let us mention the main conditions defining the limits of its applicability.

The first condition is related to the evaluation of the least possible value of electrical resistivity for a fluid-saturated rock(ρ_r). This can be computed with the Archie law [9].

$$\rho_r = \rho_{fl} / p^n$$

where ρ_{fl} is the resistivity of fluid in Ω·m, *p* is the volume porosity of deep matter, n varies from 1.5 to 2 depending on the rocks matrix. In crystalline rocks [10] uses *n*=2. The lowest average values of resistivity of brine solutions at depth lie in the range of 0.02–0.04 Ω·m, and the possible porosity in the crust according to the data from the Kola Super Deep Well even if seal failure effects are considered, does not exceed 0.015 of the rock volume at a depth of 10 km [11]. Thus, if one assumes n=2, the least permissible value of resistivity of fluid-saturated rocks at the low crust does not exceed 10-100 Ωm [12]. In Fel'dman & Zhamaletdinov [13] the estimate increases up to 1,000 Ω·m.

The second condition of the fluid concept is related to the depth of anomalies. The depth is determined by the minimum required temperature of rock dehydration, 500–600°C. In shields, this temperature corresponds to depths of 45–50 km, but in zones of recent activation and in the rift valleys, such temperatures are reached at depths of 10–15 km [14].

Finally, the third, completely qualitative conditioт is based on the assumption that the fluid anomalies should be characterized by smooth boundaries, weak spatial gradients of electric field, small or absent anisotropy, and large sizes comparable with the depth of anomaly occurrence.

If deep (crustal) anomalies of electrical conductivity do not fit to the framework of the above-mentioned conditions for the fluid mechanism, their nature is usually interpreted on the basis of the electron-conductive concept.

3. THE ELECTRON-CONDUCTIVE CONCEPT

Alexander Semenov, a professor at St. Petersburg University was the first who expressed the concept of electron-conductive origin of crustal anomalies of electrical conductivity [15,16]. He supposed that two possible types of electron-conductive objects could produce anomalies of electrical conductivity in the Earth's crust. The first type is connected with the appearance of ferromagnetic minerals (magnetite, titan-magnetite) in rocks at high temperatures. In this case, it should be supposed that the amount of electron-conductive minerals and the associated conductivity increase with depth, as temperature and metamorphic grade grow. This mechanism of electrical conductivity is not enough studied. It is based only on scarce experimental data pointing out on the increase of magnetization and electrical conductivity in certain rocks when they are exposed to high temperatures [17]. Also, the low electrical resistance is specific for ferriferous quartzites, which are abundant within iron-ore structures such as the Kursk magnetic anomaly, the Olenegorsk zone, the Krivoy Rog, etc. High electrical conductivity is sometimes specific for ultrabasic rocks due to the presence of thin inter-crystalline magnetite films [18].

In this review, most attention is focused to the second Semenov's idea that connects crustal conductors with electron-conductive graphite and sulfide-bearing rocks. He proposed this view already in his interpretation of the first super deep sounding in the Gulf of Finland [19]. In contrast to A.P. Kraev's opinion, A.S. Semenov proposed to explain the apparent resistivity decrease in sounding curves by the influence of graphite and pyrite–pyrrhotite rocks in the upper crust [20].

4. OVERVIEW OF THE MAJOR ELECTRICAL CONDUCTIVITY ANOMALIES IN RUSSIA AND THE ADJACENT TERRITORIES

In order to check and substantiate the Semenov's electron-conducting concept, the structure and geological position of graphitic and sulfide-graphitic rocks were investigated by the example of Precambrian formations in the Baltic shield. Electrical conductivity of graphite-bearing crystalline rocks was studied on different scales, from microscopic objects to large regional structures. The deep structure of graphitic formations and their influence on the results of electromagnetic sounding were studied in experiments with natural and controlled sources [21]. Apart from the Baltic shield, experimental investigations were performed in the Central Russia, in the Ukrainian crystalline shield, in the eastern Baikal, Kazakhstan, and on Sakhalin. Results of these works, as well as the generalization of many data obtained by other authors, made it possible to compile a schematic distribution of crustal electrical conductivity anomalies in Russia and adjacent territories (Figure **1**). Anomalous objects are displayed in Figure **1** as the electron-conducting and fluid ones. This subdivision is based on the quantitative and qualitative criteria considered in the previous sections, as well as on the conclusions of the investigators who found and described crustal anomalies.

The majority of crustal anomalies in Figure **1** was discovered by methods of magnetotelluric sounding (MTS), magnetometer array study (MAS) and telluric currents (TC). Alongside, some objects (15, 17, 18) were found during soundings from powerful controlled sources. The *scheme* shown in Figure **1** is not comprehensive. It was compiled using those materials that we managed to collect. Therefore, the blank (white) areas should only be considered as the regions, for which information is not available. However, the northwestern part of Russia is an exception. The survey grid here is quite dense, and blank spots here represent the crust of high resistivity, where conductivity anomalies are absent.

Figure **1** shows that crustal anomalies of fluid origin mainly occur in the eastern part of Russia. They are characterized by moderate values of resistivity (hundreds of Ω· m) and have an isometric or slightly extended form with obscure contours. The best-known anomalies of this type include Kopet Dagh (22 in Figure **1**) [24], Siberian (29, 33) [25] and Kamchatka (39) [26].

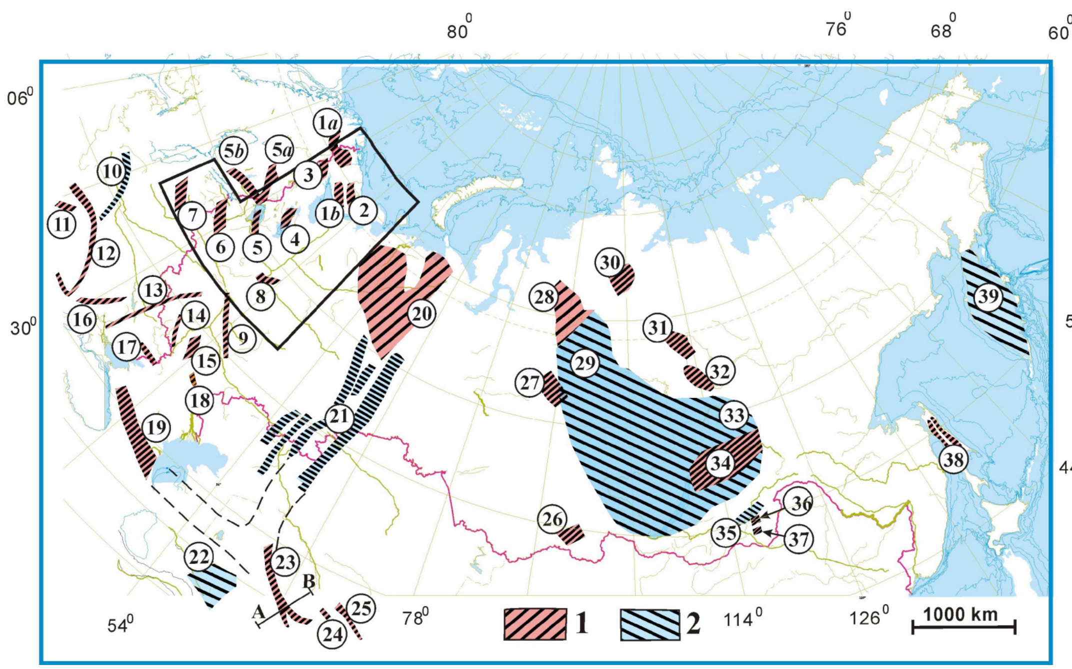

Figure 1: Schematic map of crustal anomalies of electrical conductivity over Russia and the adjoining regions [22,23].

Composed by A.A. Zhamaletdinov from data obtained by Adam A., Berdichevsky M.N., Derlyatko Ye.L., Dubrovsky V.G., Fainberg E.B., Feldman I.S., Kovtun, A.A., Krasnobaeva A.G., Kulik S.N., Moroz Yu.F., Nikiforov V.M., Podlovilin E.S., Poltoratskaya O.L., Rokityansky I.I., Shapiro V.A., Sheinkman A.L., Van'yan L.L., Zhamaletdinov A.A.

Legend 1: – electron conductive anomalies; 2 – fluid conductive anomalies.

Names of crustal anomalies (numbers in circles): 1*a* - Lapland Pechengsky; 1*b* – Imandra-Varzugsky; 2 – Keiv'sky; 3 - Tiksheozersky; 4 - Onezhsky; 5 – Ladozhsky; 5*a* - Bothnian; 5*b* - South Finland; 6 - Chudskaya; 7 - Baltic; 8 - Vologodsky; 9 – Tambovsky; 10 - North-German; 11 – Pannonian; 12 - Carpathian; 13 – Kirovogradsky; 14 – Kursky; 15 – Vorontsovsky; 16 – Izmail-Poltavsky; 17 – Donbassky; 18 – Frolovsky; 19 – North-Caucasian; 20 - Timano-Pechorsky; 21 – Urals; 22 - Kopet Dagh; 23 – South Tien Shan (Muruntausky); 24 – Fergansky; 25 – Talasso-Fergansky; 26 – Minusinsky; 27 – Tungussky; 28 – Noril'sky; 29 – Central Siberian; 30 – Khatanga; 31 – Anabarsky; 32 – Viluysky; 33 – East Siberian; 34 - Bodaibinsky (Baikal rift zone); 35 – Mongolo-Okhotsky; 36 – Undinno-Baleysky; 37 – Kurunzulaysky; 38 – Sakhalinsky; 39 – Kamchatsky.

4.1. The Urals-Tien Shan Electrical Conductivity Anomaly

Bow-shaped electrical conductivity anomalies of the supposed fluid origin extend along the Urals (21) [27]. Further to the south, they are connected by dashed lines (Figure **1**) *via* the Aral Sea (where observations are absent) with the South Tien Shan (same is Muruntau) anomaly (23), the origin of which is defined as electron-conductive (graphitic) one [24]. Shapiro [27] considers that the whole described system of electrical conductivity anomalies, extending as an arched band of total length of about 3,500 km (Figure **2**), is a continuous marginal belt formed owing to collision at the boundary of a Devonian continent that overrode the Ural and South Tien Shan ancient ocean.

The original interpretation of the geological history of the Tien-Shan metamorphic formations proposed in [28] is consistent with this point of view. Bakirov [28] paid special attention to an unusual interlayering (mixing) of two geological formations observed along the Tien Shan arc, sharply different in their genesis: rocks of ophiolitic association (basic and ultrabasic rocks and eclogites) produced by oceanic crust metamorphism, and rocks of primarily sedimentary origin (gneisses, graphitic schist) produced by continental crust metamorphism. A geodynamic model explaining the genesis of these formations is shown in Figure **2**.

It is supposed (see Figure **2**, left panel) that the oceanic crust (2) in the process of subduction carried (pulled) along with it, to a depth of 60–130 km, sedimentary formations (4) deposited at the passive margin of the continent (Figure **2a**). At the final stage of development (Figure **2c** and **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 was then squeezed out to the surface along the suture of the collided continents.

The above hypothesis based on a large body of mineralogical and petrological investigations, allows one to satisfactorily explain the coexistence of the interlayered, primarily igneous and primarily sedimentary rocks subjected to high-temperature and high-pressure metamorphism. These formations are abundant in graphitic schist containing carbon of organogenic origin. The character of the Tien Shan conductivity anomaly traced over a distance of more than 1,000 km along its strike, is associated with this carbon. The estimated longitudinal conductivity of the anomaly vary from 300,000 Sm to 10,000–15,000 Sm depending on the approach to inversion.

Thick crustal conductors of electron-conductive origin are found in the Paleozoic basement of Siberia. They are traced as a band from the north to the south (Figure **1**) and include the so-called Khatanga (30), Anabar (31), Vilyui (32), and Baikal (34) zones. The last one comprises a system of units with conductivity of 10,000 – 15,000 Siemens. At present, there are many direct and indirect evidences that these anomalies are connected with carbonaceous and graphitic schist accompanied by sulfide mineralization [29,30].

The Anabarsky and Vilyuisky anomalies, according to recent data, nearly join one another and embrace an area of about 250,000 km^2. Their depths of occurrence

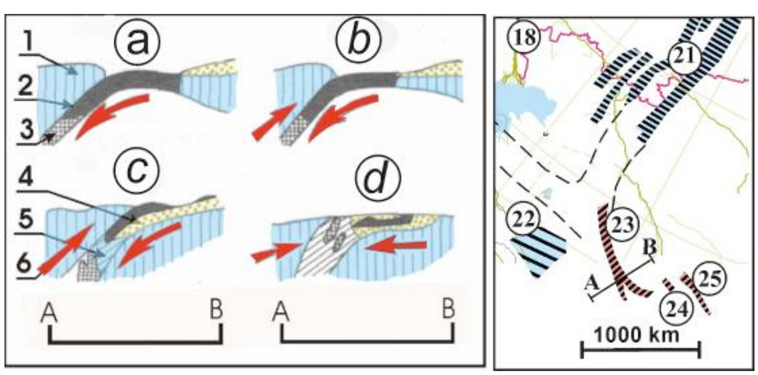

Figure 2: Model of forming eclogite-bearing metamorphic complexes and associated graphite-bearing shales in the South Tien Shan (Muruntausky) anomaly of electrical conductivity [24,28].

Letters in circles: (a, b) subduction stages; (c, d) obduction stages, squeezing out of the material upwards at the boundary of colliding plates.

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:

vary from 1.5–2.0 km at the south slope of the Anabarsky shield to 10–15 km in the Vilyuisky syneclise. The longitudinal electrical conductivity of the local conductive bodies irregularly varies from 5,000 to 80,000 S. The majority of these spatially coincide with intensive manifestation of kimberlite magmatism of mid-Paleozoic age. It is believed that the sources of kimberlite magma could lie at depths of 3–15 km. The heat flows associated with the existence of magma sources at small depths could facilitate the transformation of organic matter in sedimentary basins into graphite and diamond. The latter statement is based on certain experiments substantiating the idea of the organic nature of diamond [31], as well as on the facts of spatial coincidence of diamond-bearing kimberlite bodies with the regions of wide development of graphitic bodies not only in Yakutia but also in South Africa and other regions.

The Timano-Pechersky (20), Minusinsky (26) Tungussky (27), Norilsk (28),, and anomalies also belong to crustal anomalies of the electron-conductive (graphitic) origin confined to the Paleozoic basement. The Timano-Pechersky anomaly occurs at the boundary between Paleozoic and Precambrian. The relation of the above-mentioned conductors to graphitic deposits is established on the basis of sharp heterogeneity of the anomalies, extremely low resistivity of layers (0.1–1.0 Ω m), absence of correlation between their position, and thickness of sedimentary cover, as well as on the basis of geological and drilling data revealing carbonaceous-graphitic matter in the ascending areas of crustal conductive layers, immediately beneath the sedimentary cover [32]. Mineral deposits (ores, hydrocarbons) correlate with some of these anomalies.

The Sakhalin anomaly (38 in Figure **1**) is of special interest. It consists of two linear zones extending along the northern part of the island in accordance with the strike of the main tectonic elements in the basement overlain by thick sedimentary cover. The origin of the anomalies is usually defined as fluid [33]. However, such an interpretation does not agree with the character of the thermal field, which has a monotonous distribution throughout the Sakhalin territory with average values of heat flow within 40 –50 mW/m^2. Directly in the anomalous region, within its southern part, even a decrease in the geothermal gradient from 20 to 10– 15C/km is observed. In Figure **1**, we show the Sakhalin anomaly as being electron-conductive. Apart from the above-mentioned considerations, the basis for this concept was formed by the results of electrical conductivity measurements performed on rocks from carbonaceous shale outcrops of the Susunaysky uplift situated in the continuation of the eastern anomalous band. In terms of appearance and composition, these rocks slightly differ from quartz–chlorite–carbon schist, which were studied in the Baltic shield to show reduced resistivity of a few hundred Ω·m. It is believed that these rocks being located beneath the sedimentary cover, may under the conditions of high degree metamorphism (amphibolitic or greenschist facies) acquire high electronic conductivity and produce the observed magneto-telluric anomaly.

4.2. The Precambrian Basement

Crustal electrical conductivity anomalies associated with the Precambrian basement are most widely distributed within the West-European plate (Figure **1**). The largest of them is the Kirovograd anomaly (13 in Figure **1**). The anomaly intersects the Ukrainian crystalline shield and extends in the meridional direction for more than 600 km. The anomaly is established and traced by magnetometer array profiling [34]. Its maximal occurrence depth is evaluated as 25–30 km.

In 1978, frequency soundings with a controlled source were carried out in the central part of the Kirovograd anomaly [35]. That work, in which I also took part, was aimed at more accurate determination of the sectional structure above the epicentre of the anomaly. The 5-km long transmitting dipole AB was arranged in parallel to the strike of the anomaly, and displaced 20 km to the east of the axis. The spacing reached 40 km to the maximum. Measuring traces of soundings were oriented transverse to the anomaly, on both sides of it. The results of formal data interpretation permitted one to clearly distinguish a conductor at a depth of 5–7 km in the epicenter zone of the MVP anomaly.

The authors offered two possible variants of interpretation of the data obtained. The first variant supposed that the detected conductor is not connected with the Kirovograd anomaly itself, which is located deeper, has fluid origin, and is due to the non-stationary heat flow that has not yet reached the surface [34]. According to the second variant proposed by the author of the paper, the conductor detected by frequency sounding is the upper part of the Kirovograd anomaly and seems to represent an ancient rift filled with volcanogenic-sedimentary strata with interlayers of sulfide-carbonaceous rocks extending directly under the sedimentary cover. Traces of these rocks were detected in the regional basement from geological data. A similar conductivity anomaly was found by Enenshtein [36] in the Vinnitsa region by frequency sounding and was interpreted as a conductive layer inside the basement at a depth of 4- 5 km. However, it was later established that this layer is connected with graphitic formations in the basement roof beneath the sedimentary cover.

The Frolovsky anomaly (18 in Figure **1**) gives an example of a crustal conductor in the Precambrian basement extending to the bottom of the sedimentary cover. This anomaly was found from the deep soundings with the use of the 800 kV Volgograd–Donbass DC electric power line [37]. Longitudinal electrical conductivity abruptly arises over the anomaly from 120-150 S up to 2,000 S. The more-than-tenfold increase in electrical conductivity cannot be explained by the sedimentary cover effect since its thickness continues to smoothly decrease in the northwest direction. The Frolovo anomaly is spatially confined to the Upper Proterozoic basement, which consists of primary-sedimentary rocks. According to drilling data, carbonaceous graphitic formations are widely developed in these rocks. Flowing oil seepage from the Devonian horizon occurring directly on the basement roof was met in the anomaly region at a depth of 2.8 km. This fact is principally important because it allows one to suppose, in accordance with the idea of "hydrocarbon breathing" [38] i.e., that fossils in primarily sedimentary formations of the basement in the process of their transformation into graphite could supply hydrocarbons into overlaying sedimentary strata.

This process is responsible for the spatial coincidence of the crustal conductor of graphitic nature with oil accumulations in the overlapping sedimentary cover. Similar spatial relations are also observed in the regions of the Timano-Pechera (20), Vilyui (31), Sakhalin (38), and other anomalies. Nevertheless, definitive correlation cannot take place here since the conditions for hydrocarbon accumulations are determined by a large number of other factors, which

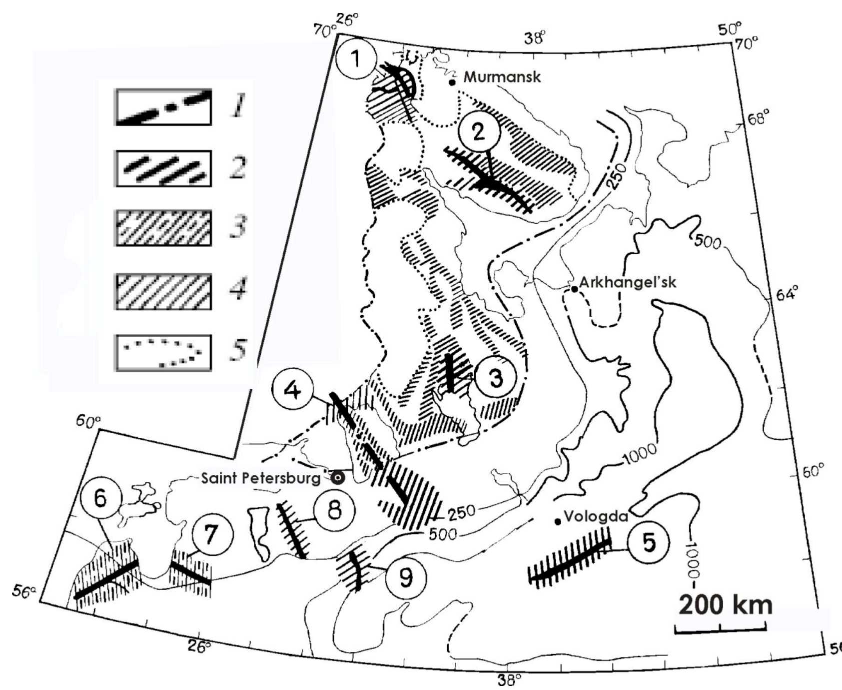

Figure 3: Crustal conductivity anomalies of the Eastern Baltic shield and Russian platform [22] Zhamaletdinov, 1996].

Legend:

1 - linear zones, **S** ≥1,000S;

2 – broad zones, S ≥ 1,000S*;*

3 – same, **S=**100÷1,000S*;*

4 – same, **S=**1,000S *;*

5 - resistive crust (**S** <0.2 *S*).

Names of anomalies with S≥1,000S: 1- Pechenega–Allarechensky, 2- Imandra-Varzugsky, 3- Onezhsky, 4- Ladozhsky, 5- Lyubimsky, 6- Kuldino–Liepaysky, 7- Valmiero-Laknovsky, 8- Chudsky, 9- Il'men'sky.

cannot be accommodated within the framework of the developed *scheme*. In particular, great role belongs to the migrating ability of hydrocarbons. This phenomenon was described in detail by Karagodin [39] the example of giant oil deposits in West Siberia that migrated along the vertical and lateral from bituminous deposits of the deep-seated Bazhenov formation.

As a conclusion to the review, the schematic map of crustal electrical conductivity anomalies in the eastern part of the Baltic shield and in the northwest of the Russian platform is shown in Figure **3** by the data [23,40].

All conductors included in the *scheme* are defined as electron-conductive ones associated with graphitic and sulfide-graphitic rocks. Their upper edges approach either the surface (on the shield), or a zone beneath the sedimentary cover base (on the Russian platform). The conductors themselves are divided into two types. The first type is represented by narrow extended zones (bands) of conductivity described as two-dimensional ones. As a rule, they are characterized by high longitudinal conductivity **S** of thousands of Siemens and more. Their axes are shown by bold lines.

The second type of conducting structures in the Earth crust consist of broad regions of reduced resistivity in the basement. Their estimated **S** values vary from tens of Siemens up to a thousand Siemens and more. Weak anomalies of tens of Siemens are distinguished only for the shield and are not detected beneath the sedimentary cover. Intensive band-like anomalies are distinguished with equal certainty both on the shield and beneath the platform cover. One of them, the Ladozhsky anomaly of black carbonaceous schist and pyrite–pyrrhotite rocks (5 in Figure **3**) has been traced continuously from the shield territory to the platform under the sedimentary cover. In the northwest, in the Finland territory, the anomaly runs across the Mikkeli copper–nickel ore-body and then forks into the northwestern and western branches (5*a* and 5*b* in Figure **1**). The northwestern branch (5*a*) forms the Ladoga–Bothnian zone (so-called “Colour belt” of Finland), and the western branch (5*b*) runs parallel to the Gulf of Finland toward Sweden. Crustal anomalies distribution in the central Fennoscandian Shield is summarized in [41]. Occurrence depths of the most conductive parts of crustal anomalies at the Baltic shield territory and on the northwest of the Russian platform vary from a few units to 10–15 km [23].

5. OVERVIEW OF THE MAJOR ANOMALIES OF ELECTRICAL CONDUCTIVITY ON SEPARATE CONTINENTS

Extended for hundreds and thousands of kilometers anomalies of high electrical conductivity are found on all continents. They may be the result of early or recent tectonic processes, the boundaries of continental blocks or the signs of the oldest biogenic life on the Earth, or many other kinds of geological and organic activity [22,23,42-45].

5.1. The American Continent

The clearest manifestation of the geoelectric heterogeneity of the Earth - North American anomaly of high electrical conductivity (1 in Figure **4**), which is located in the Great (Central) Plains [45]. This electric anomaly has been detected by measurements of geomagnetic variations. It stretches from southeastern Wyoming along the northern boundary of the Canadian Shield along the regional geological fault, which is studied in Lake Slave [46,47]. There is assumption that the anomaly goes further to the east, to the pool of the Hudson Bay. It lies within a region that stands out in the work [48] as the Proterozoic array. Kemfildem and Gough [47] suggested that the electrical anomaly of the Great Plains points out on the boundary of a Proterozoic plate.

At the end of the 1960s in the western United States has been found an anomalous behavior of horizontal (latitude) and the vertical components of geomagnetic field with periods of 32.5, 50, 60 and 89 min [49,50]. Somewhat later, in the eastern and central parts of the Great Basin and the Colorado Plateau area, three profiles magneto-telluric soundings were measured. According to these data, to the west of the above-described anomalies of the Great Plains, an intensive conductivity anomaly is revealed (2 in Figure **4**). They are traced along the Bitterroot and Wasatch ridges and further to the Cascade Mountains [34]. On the basis of the data obtained by Schmucker [46], a conductivity anomaly is revealed on the Pacific coast in the valleys of the Sacramento and San Joaquin, in the intermountain valley between the Coastal Range and the Sierra Nevada, as well as under the Sierra Nevada mountain range. Further to the south, the anomaly goes to the Gulf of California (3 in Figure **4**).

In [51] the position of Mesozoic thrust faults in western Nevada has been investigated. The border of Paleogene-Neogene tectonic movements coincides with the position of the North American Great Plains

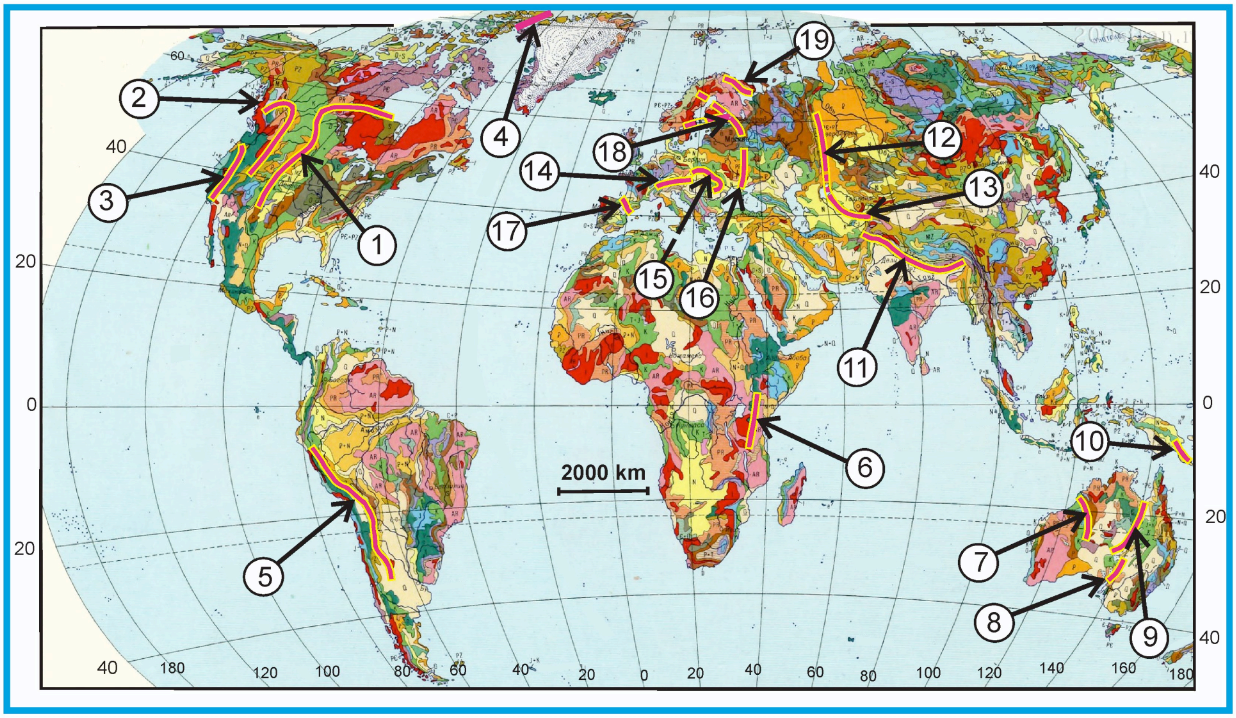

Figure 4: Largest anomalies of electric conductivity of the world.

1 - North American; 2 - Bitterroot-Cascade Mountains; 3 - Sierra Nevada; 4 - North Greenland; 5 - Andean; 6 - Kenya, 7 - Carpentaria; 8 - Flinders; 9 - South-West Queensland; 10 - New Guinea; 11 - Trans-Himalayan; 12 - Urals; 13 - South Tien Shan; 14 - Alpine-Pannonian; 15 - Carpathian; 16 - Kirovogradsky; 17 - Pyrenees; 18 - Ladoga-Bothnian; 19 - Polmak-Pechenga-Imandra-Varzuga.

anomaly, and the Cascade anomaly in the western United States, extending to the east along the ridges of the Bitterroot and the Wasatch, coincides with the Jurassic-Cretaceous thrust faults. Gilluly [51] indicates that the thrust faults and tectonic activity are associated with the meridional movements. Direct manifestations of latitude contractions are absent here. Scale of the tectonic movements on the east from the west coast of North America exceeded 1,500 km up to the southern boundary of the Rocky Mountains.

In South America, in the Andes, according to [52,53], there is an anomaly of electrical conductivity found to extend along the coastline of the Pacific Ocean for more than 2,500 km (5 in Figure **4**). Brasse *et al*. [52] conducted a long-period geomagnetic sounding in the Central Andes, including measurements on the high plateau of Altiplano. Anomaly is detected at a depth of about 10 km. It is assumed that the high conductivity caused by fluids formed as a result of metamorphism in the Andes, and the partial melting of the substance in the Altiplano. The fault system, controlling the Andean anomaly of conductivity, corresponds to the subduction zone of the oceanic Nazca plate beneath the South American continental plate.

5.2. Africa

In Central Africa, in the area of the Kenyan rift, an anomaly of increased conductivity in the Earth's crust was found during the magneto-telluric and magnetometer array survey [54] (6 in Figure **4**). The upper edge of the conductor is at a depth of 25 km. Note that in the mid-1970s on the southern extension of this anomaly, experiments were conducted on deep electromagnetic sounding of the lithosphere with the use of 1,250 km long industrial power line DC "Cabora Bassa" [55]. The results of these studies established a conductor at a depth of 10-20 km. It is possible that the nature of the conductor is also associated with the effect of the proposed extension to the south of the Kenyan conductivity anomaly.

5.3. Australia

The longest conductivity anomaly in Australia is found in the Gulf of Carpentaria. The anomaly extends inland to meridional direction over a distance of 1,000 km (7 in Figure **4**). This anomaly was discovered in 1997 as a result of magnetometer array and magneto-telluric research [56]. The conductor exists in the earth's crust at a depth of about 10 km beneath the sedimentary cover. The Carpentaria anomaly is also recorded by gravity and aeromagnetic data. According to seismic data this area is characterized by sharp changes in the propagation velocity of seismic waves.

In [56] a hypothesis is proposed that the conductivity anomaly in Australia - Carpentaria (7), Flinders (8) and South-West Queensland (9) correspond to the continental seams and represent fundamental markers indicating a particular relationship of lithospheric blocks. They are the main Precambrian elements of the Australian Plate. The greatest one is the Mount-Aiza unit well known by deposits of zinc, lead, gold and copper. According to 3D seismic tomography, it has been detected a significant difference between the craton and the eastern regions separated by a conductivity anomaly of Carpentaria. It is possible that some of these changes could be due to the temperature effects of Neogene volcanism in the eastern region of Australia, and the high seismic velocities on the shield related to the variability of the chemical composition of the lithosphere. It is believed that the Pacific plate is being introduced to the southeast under the Australian plate, forming in the lower crust and upper mantle advection of cold material. This, in turn, leads to radioactive heating and appearance of free fluids. The last ones increase the electrical conductivity of overlying geological structures [57].

5.4. Eurasian Continent

Two large areas of the northwestern part of India were investigated by the areal magnetometer array observations in 1979-1980 [58] and also by magnetotelluric profiling. The results of studies have revealed an elongated region of high electrical conductivity, which are referred to as Trans-Himalayan anomalies (11 in Figure **4**). In the crust of the Asian continent, this anomaly is one of the most powerful and extended structures. It is mostly located at a depth of 10-20 km, and only in Kangmar craton, it comes close to the earth's surface. According to the electromagnetic profile traversing, the north rift of Yadong-Gulu, an area of high conductivity extends beyond the rift [59]. Integrated seismic and electro-magnetic studies in Tibet have shown that it is possible to assume the existence of zones of partial melting in the lower crust. These data allowed the authors [59] to propose a concept of the displacement of the middle part of the earth's crust from the Indian shield on the Eurasian plate. Nearly the same conclusion was made by Gilluly, [51], who states that the main Himalayan Ridge is composed by rocks of similar origin as the Indian shield.

In Taiwan, the MTS method was used to detect a 100-km long and 20-km wide conductivity anomaly, extending from the northwest to southeast [60]. In the Sanyi-Puli area, it is extended by a high seismic activity zone.

The southern part of Scotland from coast to coast is detected to accommodate an anomaly in geomagnetic variations corresponding to a crustal conductor at a depth of 4-12 km. It coincides with a negative Bouguer gravity anomaly [61].

The boundary between the Paleozoic Hercynides of Central Europe and the Paleogene-Neogene Carpathian Mountains is characterized by significant contrast in electrical conductivity of the Earth crust. The northeast contact of Hercynides and Archaean system of the East European platform is well known as the Trans-European Tesseir-Tornquist suture zone (TESZ). The suture had been noticed by the North-German-Polish anomaly in geomagnetic variations. This regional structure is characterized by high electrical conductivity in the middle mantle. In a wide region (ca. 15° to 40° E), the conductivity is increased to 100 thousand Siemens [62].

5.5. Alpine System Conductive Zones

Dashed line in Figure **4** denotes an offset of the Tien-Shan conductivity anomaly to the west, towards the Caspian Sea and to the Caucasus. Analysis of the published data [63] led to the conclusion that the crustal conductivity anomalies of graphite origin are observed along the whole Alpine folding system. The carbon bearing formations of "black schist" are traced by I. Feldman in the North Caucasus as a conductive layer, hollow dive to a depth of 10-20 km [64]. Adam [63] proposes to associate the nature of crustal conductivity anomalies Alpine collision zone (12-17 km depth) and its extension to the east, in the region of Lake Balaton (14 in Figure **4**, depth of 5-9 km) with black graphitic schist. According to Rokityanskii [34], the nature of strong conductivity anomaly in the Pyrenees (17 in Figure **4**) is also related with graphite.

One of the largest conductors in the chain of the Alpine orogeny (after the Tien Shan area) is the Carpathian conductivity anomaly extending along the inner arc of the Carpathians for more than 1,000 km (12 in Figure **1**, 15 in Figure **4**). Firstly, the anomaly has been discovered in the last century [63,65,66]. For almost half a century, it is the topic of active research and debate on its structure and nature. The nature of

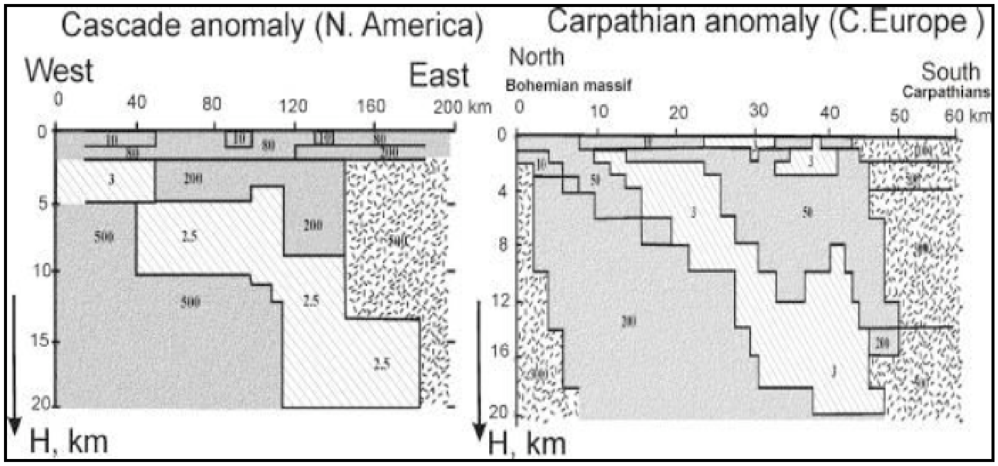

Figure 5: An example of 2D interpretation of conductivity anomalies of the Cascade area (2 in Figure **4**) and Carpathian foredeep (15 in Figure **4**) [66].

the anomaly is interpreted by most researchers as associated with changes of fluid and temperature conditions on the border of subduction plates of lithosphere. The depth of the anomaly varies from 10 to 20 km according to different authors. However, the fluidic concept, in the application to the nature of the Carpathian anomaly faces formidable contradictions. First of all, they are connected with the need to assume the existence of rather high temperature (500-600° C) at relatively shallow depths, from 5-7 to 10-15 km. It should also be added that position axis of the anomaly is inconsistent with the contours of the anomaly of heat flux density [67].

In Stanley [68] and [69] it is proposed to interpret the nature of the Carpathians anomaly from the position of the electron-conductive concept. According to geological data [70], graphite-bearing rocks are widely spread in the Marmoroschsky schist zone, spatially coinciding with the position of the Carpathian conductivity anomaly axis from Rakhov to Uzhgorod at the area of the Western Carpathians. Alexander Ivliev sampled carbon-bearing rocks for laboratory tests [69]. The test results have showed high electronic conductivity of rocks with resistivity ranging within 0.1 to 2 Ω·m. Further to the West from Rachov, the crystalline schist of the Peninian ridge zone (similar to Marmoroschsky graphite-containing zone) extend along the axis of the Carpathian anomaly for almost 1,000 km. Zhamaletdinov (2005) [69] scrutinized the features of the Carpathian anomaly manifestation on the basis of numerical modeling of MT data and complex analysis of other geophysical data. The research justified the nature of the Carpathian anomaly from the viewpoint of the electron-conductive concept, and drew a parallel with the South Tien Shan anomaly with regard to the geodynamic interpretation of its nature. Figure **4** according to [68], shows an example of two-dimensional interpretation of the Carpathian anomaly (15 in Figure **4**) in comparison with the conductivity anomaly of the Cascade zones in North America (2 in Figure **4**). The paper substantiates the fact of graphitic nature for both conductivity anomalies.

6. DISCUSSION

The above analysis indicates exceptional prevalence of conductivity anomalies in the earth's crust all over the world. They cover a wide range of age groups - from intensively deployed and metamorphosed rocks of the Late Archaean, Proterozoic and Paleozoic to relatively weakly metamorphosed rocks of the Mesozoic. With increasing volume of experimental data of deep soundings and level of the research detail, it becomes clear, especially by the example of the Baltic shield, that "contamination" of the earth's crust at the expense of existing anomalies of electrical conductivity is so high that it becomes “normal” whereas areas of the earth's crust with homogeneous (lateral) structure and high resistivity rarely accommodate anomalies.

In many cases, according to the formal (1D) interpretation of soundings data, the crustal anomalies are defined as intermediate sub-horizontal conductive layers that occur at depths from a few up to a few tens of kilometers. However, it is more correct to interpret them as inclined zones of conductivity, which exist under the sedimentary cover, under the trap field or under younger effusive-sedimentary complexes.

Conductivity anomalies of fluid nature are mainly observed in the areas of young volcanism and in collision zones. Fluids commonly associate also with regional lowering of resistance in the upper mantle at depths of 110-140 km as observed within the vast Siberian anomaly (29, 33 in Figure **1**). The nature of the most part of crustal conductivity anomalies finds convincing explanation from the position of the electron-conductive concept developed by Semenov [15] confirmed in the works of Adam, Stanley [63,66,68] and many other researchers. Electron-conductive structures in the earth's crust are presented by sulfide-carbonate formations. Sulfide-carbonaceous formations in the crust are characterized by the heterogeneously anisotropic structure of electrical conductivity in all volumes, from microscopic to the sizes of large regions. In order of increasing scales, they can be divided into a number of gradations in the form of structures fitting into each other, from finest microscopical current-conductive channels and intercalations to conductive fields and networks embracing territories of tens and hundreds of thousands of square kilometers.

Elucidation of the nature and origin of sulfide-graphitic formations is an important issue in determining a viewpoint on the geological interpretation of crustal electrical conductivity anomalies. Two mutually exclusive approaches to this problem have been developed. The first is based on the assumption that carbon, in all its forms on the Earth's surface, was produced at the expense of the Earth's degassing from the upper mantle [71]. 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 based on the idea of the initially sedimentary, biogenic origin of graphite [38]. According to this concept, at an early stage in the Earth's evolution, an abrupt change in the character of geological processes took place in connection with the appearance of atmosphere, hydrosphere and photosynthetic bacteria [72]. Since then (3.0–3.5 billion years), organic life has appeared and begun its active development. It proceeded most intensively in shallow water basins, where organic matter accumulated and was buried. Simultaneously, these regions sank and were subject to disjunctive tectonic movements, erosion, and sedimentation. The deep metamorphism resulted in elimination of volatiles and in structural rearrangement of substance. Fossils, rich in hydrogen sulfide were transformed into peculiar interlayered members of sulfide-graphitic rocks.

The described zone of great geological transformations due to bio-geochemical and volcanic activity was called suprastructure, or a zone occurring on the primary crust at the earliest, nuclear stage in the Earth's development. The primary crust, defined as the Lower Archean primary basement, is characterized by a surprisingly monotonous, homogeneous structure and by the absence of mineral deposits in appreciable concentrations.

The *scheme* presented of graphite formation in the crust is confirmed by results of our investigation and, first of all, 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, being their component, reflect lithologic-stratigraphic features of the corresponding geological formations.

The general *scheme* of spreading electron-conductive (graphitic) crustal anomalies on the planetary scale following from experimental data is also consistent with the biogenic-sedimentary concept of graphite origin. These anomalies include gigantic conductive inclusions, or cover formations. We provisionally have allocated to this area as sulfide-carbon layer ("SC-layer" by Semenov). "SC-layer" sometimes observed in the form of faults, overthrusts, or rift structures on the irregular surface of the most ancient lower Archaean crust formed at the earliest stages of the Earth's evolution.

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