EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Kriosfera Zemli, 2020, vol. XXIV, No. 2, pp. 45–59 **http://www.izdatgeo.ru**

METHODS OF CRYOSPHERIC RESEARCH

DOI: 10.21782/EC2541-9994-2020-2(45-59)

THE STRUCTURE OF PERMAFROST WITHIN PARISENTO STATION (GYDAN PENINSULA) FROM GEOPHYSICAL DATA

D.S. Pankova[1,2], V.V. Olenchenko[1,3], L.V. Tsibizov[1,3], Y.K. Kamnev[4], A.N. Shein[3], A.I. Sinitskiy[4]

[1] *Novosibirsk State University, 2, Pirogova str., Novosibirsk, 630090, Russia; Pankova.geo@gmail.com*
[2] *St. Petersburg State University, Institute of Earth Sciences, 33-35, 10th Line V.O., St. Petersburg, 199178, Russia*
[3] *Trofimuk Institute of Petroleum Geology and Geophysics, SB RAS, 3, Acad. Koptyug ave., Novosibirsk, 630090, Russia; OlenchenkoVV@ipgg.sbras.ru*
[4] *Arctic Research Center of the Yamal-Nenets autonomous district, 73, Respublika str., Salekhard, 629008, Russia*

In this article the results of geoelectric survey investigations of permafrost in the area of Parisento station (Gydan Peninsula) are presented. According to the electromagnetic sounding data, the permafrost thickness is 210–300 m. Application of electrical resistivity tomography (ERT) has revealed, that massive ice stratum is characterized by extremely high electrical resistivity, exceeding million Ohm·m. It confines method's sensitivity below depths of 50–75 m. Fixing the depths of deep-lying conducting layers, determined by electromagnetic sounding, has insignificant effect on error of ERT inversion. However, the input of the layers with a fixed-by-depth electrical resistivity has lead to an improvement of the model for geological interpretation. It has been determined, that the massive ice between the Krugloye and Parisento Lakes does not have continuous distribution, as it was previously appeared according to drilling data. A linear area of low electrical resistivity has been identified, which is probably due to paleo-channel connecting the lakes in the past. By numerical simulation of thermal fields, a closed talik (up to the depth of 140 m) has been identified under Krugloye Lake, and an open one has been revealed under Parisento Lake. The influence of three-dimensional conductive heterogeneities, as a lake talik and a lake, on the electrical resistivity distribution in the two-dimensional and three-dimensional geoelectrical models has been considered.

Parisento station, permafrost, electrical resistivity tomography, transient electromagnetic sounding, resistivity, massive ice, lake, talik

INTRODUCTION

The Gydan Peninsula is one of the least developed and poorly explored areas. In order to realize the plans of environmentally safe industrial development of Tazovskiy District of Yamalo-Nenets Autonomous Okrug (YaNAO), it is necessary to assess the current state of permafrost, and to organize the monitoring of its transformation under the influence of climatic changes, as well as the human impact in all geographical subzones of the peninsula. That will allow to improve the design technology of field facilities and the systems of raw hydrocarbon transportation, situated in harsh engineering-geocryological conditions, to ensure their mechanical safety and reduce geotechnical risks by improving the efficiency of design decisions in the field of development of measures for the implementation of technologies for temperature stabilization of the foundation soils, geotechnical monitoring and other innovative technologies.

In 1970–1990s geocryological structure of the Yamal and the Gydan peninsulas was studied by the researchers from the Moscow State University (MSU) [*Badu, Trofimov, 1974*], the Production Scientific and Research Institute of Engineering Surveying in Construction (PNIIIS) [*Baulin, 1985*], the All-Russian Research Institute of Hydrogeology and Engineering Geology (VSEGINGEO) [*Anisimova, Kritsuk, 1983; Kritsuk, Polyakov, 1989*]. The overview and small-scale maps have been compiled. Geotechnical conditions of the Gydan Peninsula, including exogenous and geological processes and phenomena, have been described [*Trofimov et al., 1986*].

The comprehensive study at the Gydan Peninsula has been carried out in the vicinity of the Parisento station of VSEGINGEO, near the eponymous lake in the middle reaches of Yuribey River. The station was founded by V.A. Dubrovin in 1982 in order to organize monitoring of the cryogenic processes and phenomena dynamics in the undeveloped but prospective area. It represented a scientific station along with the landfills within which a stationary network

The English text is published as edited by the authors.

of reference plots had been deployed. During the operation of the station, the geocryological features of the region have been studied in detail, and such the climatic characteristics of the territory as air temperature, wind speed, snow depth and average insolation have been monitored. According to measurements carried out in three boreholes, the temperature regime of the upper part of the permafrost section have been determined up to the depth of 73.5 m, and the beds of massive ice, having thickness up to 32 m, have been drilled-in. The permafrost was studied by using such geophysical methods as vertical electrical sounding, high-frequency electric profiling and electrical well-logging.

In 1995, due to the termination of funding, research works within the station had been stopped, and the station itself had been mothballed. 20 years later, the government of Yamalo-Nenets Autonomous Okrug raised a question of the necessity to resume environmental monitoring of the permafrost zone before the intensive development of the North regions by the oil and gas producing companies. In August 2016 and in August 2017, the Arctic Research Center (Salekhard) organized comprehensive scientific expeditions to the Parisento station with the participation of specialists from the Trofimuk Institute of Petroleum Geology and Geophysics SB RAS (Novosibirsk).

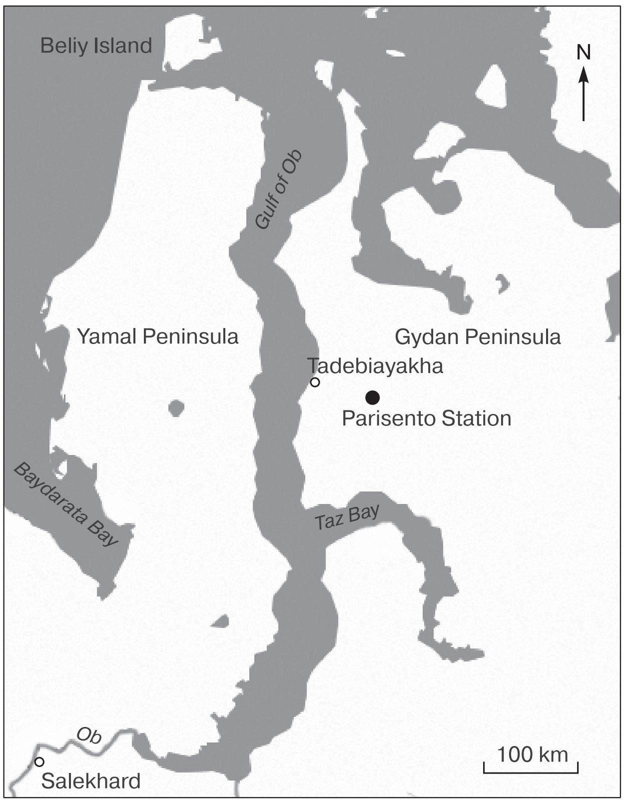

Fig. 1. Location map of the Parisento Station.

The main aim of the expeditions was to assess the current state of permafrost within the station according to geological, geomorphological and geocryological studies, as well as to obtain new information on the permafrost structure using modern geophysical technologies, which have been developed significantly over the past 20 years. Such geoelectrical methods as vertical electrical sounding in the modification of electrical resistivity tomography (ERT) and near-field time-domain electromagnetic (TDEM) sounding were applied in the research. Those methods are widely used in permafrost research, for instance, for detecting of massive ice beds [*Everest, Bradwell, 2003; Hauck et al., 2003*], delineation of the permafrost distribution area and determination of its thickness [*Hauck, Mühll, 2003; Olenchenko et al., 2011; You et al., 2013*], determination of active layer depths and talik thickness [*McClymont et al., 2013; Kozhevnikov et al., 2014; Fague et al., 2016*].

The main objectives of geophysical research carried out in the area of the Parisento station were to determine the permafrost thickness, and to define its structural features.

STUDY AREA

The Parisento station is located in the Tazovsky District of Yamalo-Nenets Autonomous Okrug, in the central part of the Gydan Peninsula, at the latitude of 70.1° N (Fig. 1). The nearest settlement is Tadebiayakha, which is situated in 64 km to the north-west of the station, on the coast of the Gulf of Ob.

The mean annual air temperature is –11.2 °C, according to the results of the regime observations of the VSEGINGEO in 1985–1990. The research area belongs to the zone of continuous permafrost distribution. Its thickness varies from 200 to 300 m, and the temperatures of frozen ground is up to –8 °C. The thickness of active layer varies significantly: from 55–65 cm (on polygonal peatlands) up to 170–180 cm (on bare-of-vegetation sandy deflation-flats). Ice content of the frozen ground can reach 90 %.

The surface of the Late Quaternary coastal plain with altitudes of 10–46 m occupies a dominant position in the topography around the Parisento station. The areas with high lake percentage (up to 40 %) are developed within the plain. Drained lakes basins (khasyreys) are usually confined to gently undulating landforms. Parisento Lake is the largest water body in the vicinity of the Parisento station. Its water surface size is 6 × 4 km and the maximum depth is 35 m. Krugloye Lake, smaller by the size, is located to the north of Parisento Lake, and Geofizicheskoye Lake is situated even more to the north of it. Massive ice bed, which has been drilled-in by boreholes, is the unique object within the Parisento station (Fig. 2). Its thickness according to the boreholes data is up to 32 m and the minimum temperature is –8 °C at a depth of

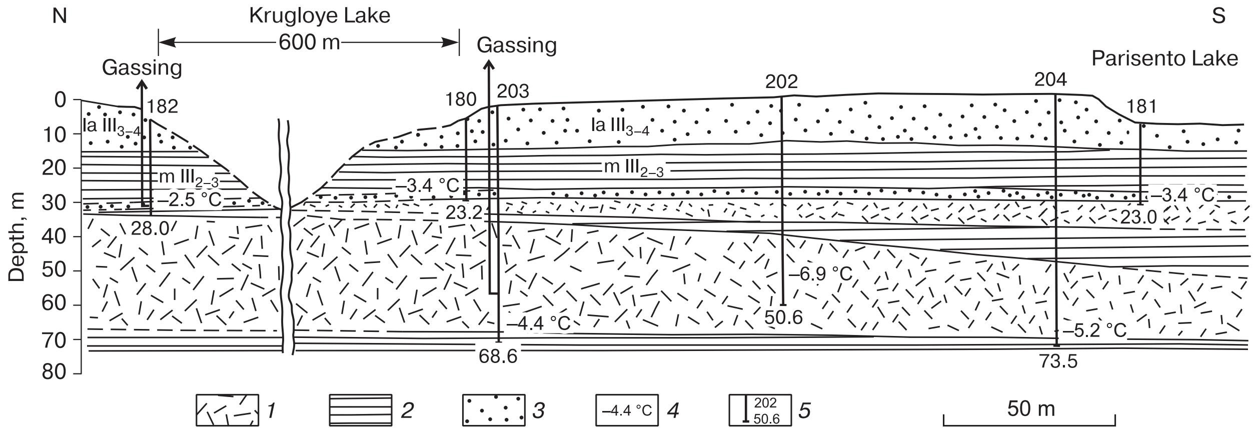

Fig. 2. Geological section of study site according to the VSEGINGEO data.

1 – ice; *2* – clay with inclusions of ice; *3* – frozen sand; *4* – permafrost temperature (°C); *5* – borehole, its number and depth (m).

10 m. Taking into account the fact that massive ice bed has been stripped by a limited number of boreholes, the boundaries of its distribution remain to be uncertain. A description of the sediments at the borehole 204, located at a distance of 15 m from the edge of the Parisento Lake scarp is presented below:

0.0–15.9 m – light-gray sand, obscurely-layered, the bedding is due to the presence of plant residues, interlayers of clay, ice, peat, sandy loam ; the ground is frozen from a depth of 0.6 m; there are sections (up to 1 m in thickness) of pure ice;

15.9–27.8 m – obscurely-layered and varved, icy clay (loam); there is pure ice in some intervals;

27.8–30.3 m – fine sand to silty sand with isometric inclusions of ice and bands of sandy loam and clay;

30.3–36.7 m – mostly pure and transparent ice, with sparse inclusions of dark gray clay and sandy loam;

36.7–48.05 m – dark gray to black clay, mostly homogeneous, cross-bedded due to interlayers of lighter clay and silty loam, sometimes with separate ice lenses; from a depth of 42.2 m, the ice content increases sharply;

48.05–70.2 m – mostly clear and transparent ice, with a lot of air bubbles and the inclusions of clay;

70.2–73.5 m – icy dark gray clay; deeper than 72.0 m, the ice content decreases, the clay acquires a greenish tint and some plasticity (probably due to increased salinity).

METHODS

Such geophysical methods as near-field time-domain electromagnetic sounding (TDEM) and vertical electrical sounding in the modification of electrical resistivity tomography (ERT) have been applied in two study sites (Fig. 3).

The Site I is located between the Krugloye and Geofizicheskoye lakes. The TDEM method measurements have been performed on a 65 × 65 m network inside ten transmitter loops 200 × 200 meters in size, using Fast-Snap equipment (NPK Sibgeosystems LLC, Russia). The PDI-50 induction sensor with an effective moment, which is equivalent to a loop of 50 × 50 m in size, has been used as a receiver. It was installed inside each transmitter loop with a uniform

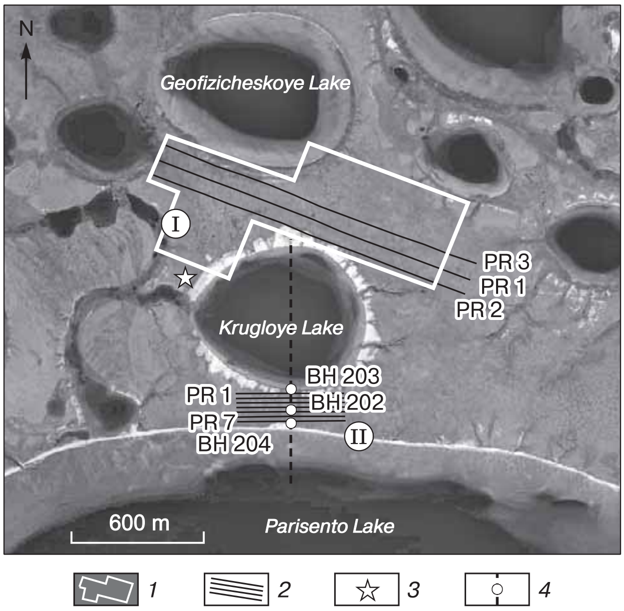

Fig. 3. Layout of the geophysical prospecting profiles:

1 – contour of the near-field time-domain electromagnetic sounding area; *2* – profiles of the electrical resistivity tomography method; *3* – Parisento Station; *4* – the line of geological section through boreholes and position of boreholes 202, 203, 204; I, II – number of study site.

mesh. A similar technique of electromagnetic sounding is effective in area studies. Furthermore, when the size of the generator loop is 200 × 200 m, the effect of the induced polarization of the upper part of the section on the transient process is minimized. The contour of the study area by means of the TDEM sounding method is displayed in Fig. 3. The subsequent quantitative interpretation of the TDEM sounding data has been carried out using the TEM-IP program, developed at the Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences (IPGG SB RAS) [*Antonov et al., 2014*]. The inverse problem of electromagnetic sounding has been solved within the framework of a one-dimensional horizontally-layered model without taking into account the induced polarization of the upper part of the section with high ice content. The weak influence of the upper layers on the process of electromagnetic field formation was noted already at 0.04 ms as a low-amplitude minimum on the electromotive force (EMF) curve (or a small maximum on the apparent resistivity curve). Therefore, before interpretation, the field formation curve had been cut off to the EMF values for a time of 0.1 ms, as well as in the noise areas at the "tails" of the curves after a time cutoff of 50 ms. The error in approximating of the experimental curve to the theoretical dependence for the upper icy part of the section was 1–3 %. The multi-electrode electrical prospecting station Skala-48, developed at IPGG SB RAS, was used for measurements by the ERT method. Further data processing was performed with using the programs Res2Dinv and Res3Dinv (Geotomo Software) [*Loke, 2009*].

In the Site I, the ERT method soundings have been implemented on three profiles of 1425 meters long with the measurement spacing along the profile of 10 m. The distance between the ERT profiles was 65 m. The sequence of the electrode connecting corresponded to the pole-dipole arrays with a maximum span between the current electrodes A or B and the center of the receiving line MN equal to 430 m.

The Site II was located between the Krugloye and Parisento lakes, where in the 1990s a boreholes-profile had been driven, and the thick massive ice bed had been drilled-in. In that site, the ERT soundings have been carried out on 7 profiles of 470 m long each, the distance between profiles was 25 m, the measurement spacing was 10 m, and the pole-dipole array was applied.

The wet surface of the tundra provided a low level of grounding resistance, and the absence of industrial electromagnetic interference made it possible to obtain high-quality data. The current strength in the AB circuit was 10–40 mA, and the voltage at the receiving electrodes varied from 4 to 5000 mV. The instrumental error of one measurement of the apparent resistivity at maximum electrode spacing, calculated by the Skala-48, did not exceed 0.2 %. The scheme of the electrotomography profiles arrangement is demonstrated in Fig. 3.

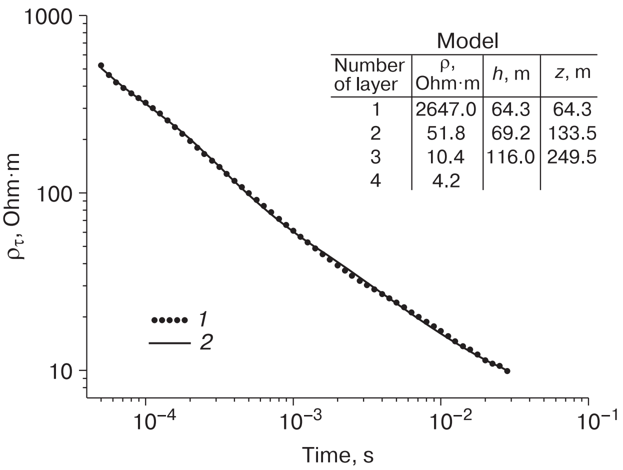

Fig. 4. Experimental (*1*) and theoretical (*2*) curves of apparent resistivity at the near-field time-domain electromagnetic sounding point No. 501, and corresponding one-dimensional models of section.

See explanations in the text.

RESULTS

The solution of the inverse problem for the TDEM method data has been carried out in the framework of the three-layer, four-layer, five-layer, and six-layer models. As a result, it has been determined that the four-layer model of a medium, combining the equivalent layers of more complex models, is optimal. Figure 4 shows an example of the experimental and theoretical curves of apparent electrical resistivity (ρ_τ) and the one-dimensional geoelectric model corresponding to the theoretical curve, including the resistivity of each layer (ρ), thickness (h), and roof depth (z). The mean-square error of selection, in that case, was 3 %.

In the model, layer No. 1 of high resistivity includes the sediments represented by sands and massive ice. Its thickness is estimated at 64 m, which is consistent with the drilling data (Fig. 2). Layer No. 2 with a resistivity of 51.8 Ohm·m is interpreted as frozen loam. At a depth of 133 m, the resistivity of the sediments decreases to 10.4 Ohm·m, which the authors attribute to an increase in the salinity of loams. In the base of the section, at a depth of 249.5 m, layer No. 4 stands out with a very low resistivity of 4.2 Ohm·m. It is assumed that the boundary between layer No. 3 and No. 4 is the boundary of the water-ice phase transitions.

Figure 5 demonstrates the geoelectric section compiled according to the TDEM method results obtained on Site I along the line coinciding with the

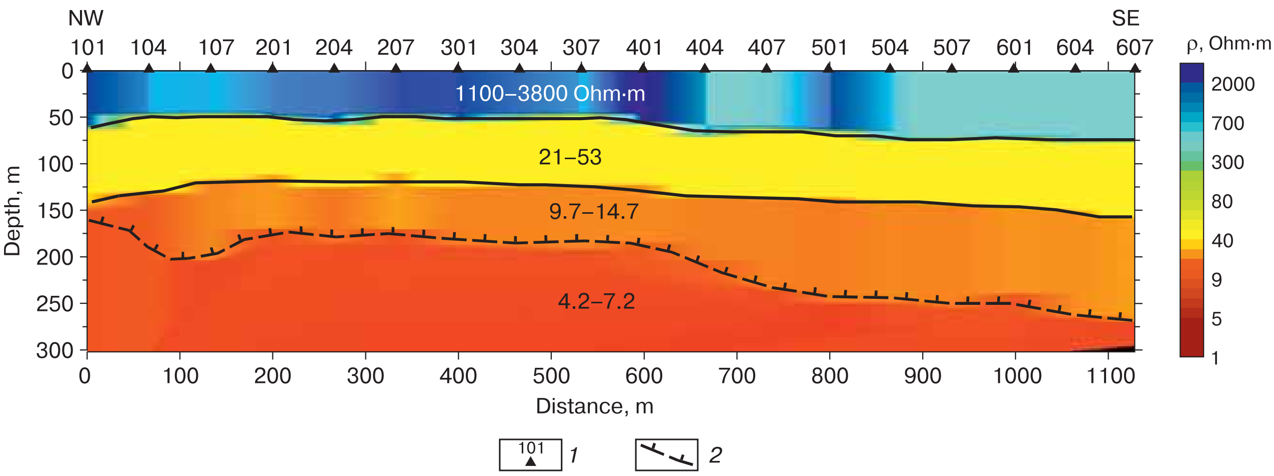

Fig. 5. Geoelectric section according to the near-field time-domain electromagnetic sounding:
1 – point of electromagnetic sounding; *2* – supposed boundary of the water–ice phase transitions.

profile line No. 3 in the ERT method. In the upper part of the section, up to the depth of 50–75 m, a highly-resistive layer (with the electrical resistivity varying from 1100 to 3800 Ohm·m) is distinguished. Those highly-resistive deposits are represented by frozen sand and loam with interlayers of massive ice.

At depths below than 50–75 m, a layer with reduced resistivity of 21–53 Ohm·m – probably due to an increase in the salinity of the section in the Upper Quaternary coastal-marine sediments of the Kazantsevo Formation – has been identified. Below the depth of 120–150 m, the resistivity of the sediments decreases up to 9.7–14.7 Ohm·m, which caused by an increase in the mineralization of porous water in Mid-Quaternary marine sediments of the Salekhard Formation. At the depth 160–260 m the upper border of the underlying layer with very low resistivity (4.2–7.2 Ohm·m) has been noted. It is assumed that the layer is the lower border of permafrost, which is consistent with other studies [*Trofimov, Baulin, 1984*]. Similar resistivity values of saline loam at the phase transition boundary have been mentioned in the papers [*Krylov, Bobrov, 1995; Zykov, 2007*].

The section in the Figure 5 illustrates horizontally-stratified structure of the medium with decrease of sediments resistivity by depth from several thousands to several Ohm·m. The upper part of the section is represented by high-resistive frozen medium with interlayers of massive ice. Reduced resistivity of underlying frozen ground is explained by their salinity. According to the near-field time-domain electromagnetic sounding, the bottom of permafrost is supposed to be at the depths of 200–300 m.

A feature of the section is the plunge of permafrost bottom along the profile to the southeast. Using the data of areal soundings, the map of the permafrost bottom depth has been compiled (Fig. 6). On the isthmus between the lakes, permafrost thickness reduced up to 150 m. That may be associated both with the warming effect of lake taliks, and with the influence of three-dimensional conductive heterogeneity on the result of one-dimensional inversion of the TDEM sounding data.

Geoelectric sections of the Site I (according to the ERT data) are presented in Fig. 7. The number of iterations of model selection for each profile was 5, while the standard deviation (SD), characterizing the selection error, varied from 4 % (profile 1) and 4.8 % (profile 2), to 9.3 % (profile 3) depending on quality of the input data.

An analysis of geoelectrical sections reveals that the layer of very high-resistive deposits is traced at depths of 10–90 m. That part of the medium consists of sand and loam with high contents of frozen porous

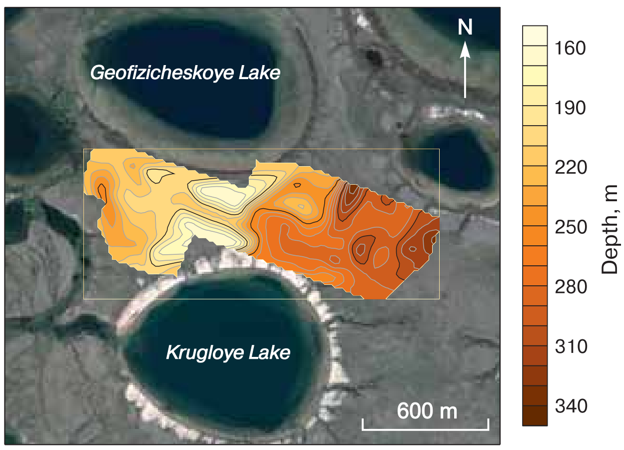

Fig. 6. Map of the permafrost base according to the near-field time-domain electromagnetic sounding data.

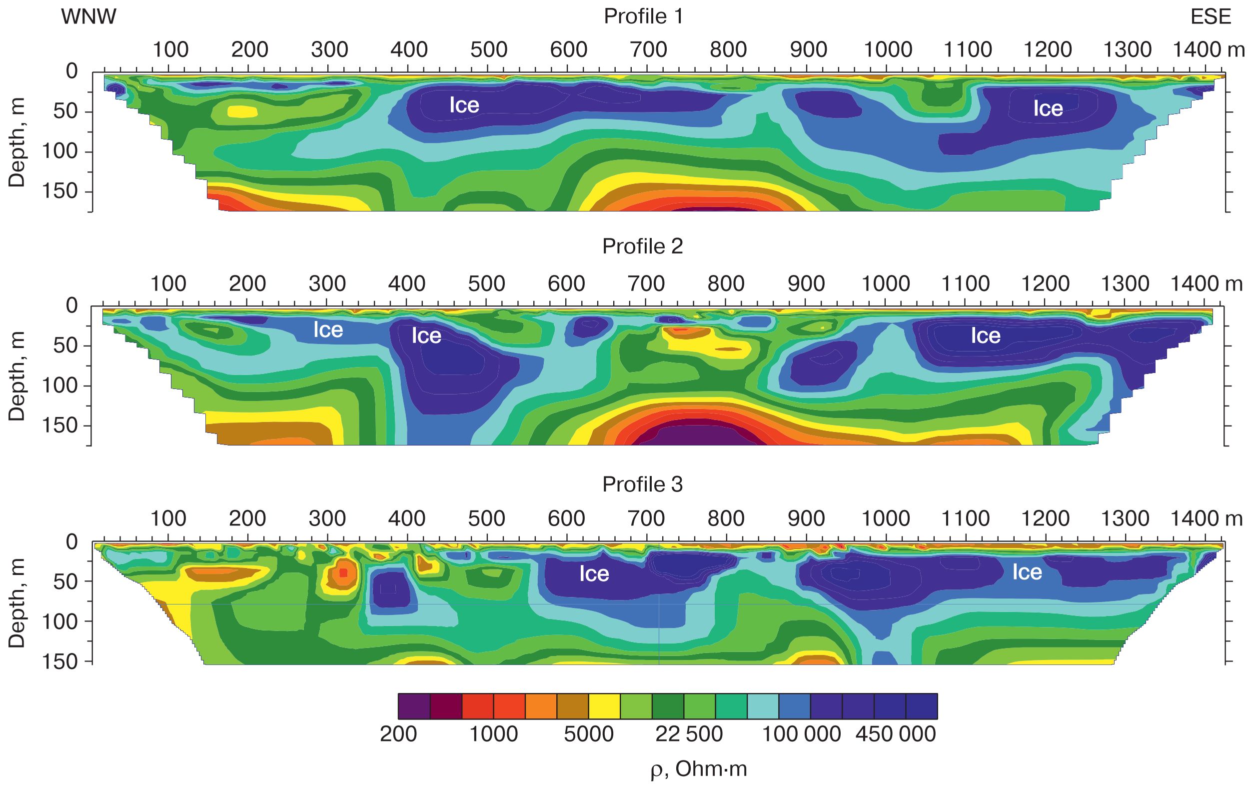

Fig. 7. Geoelectric sections according to the electrical resistivity tomography data.

low-mineralized water. It should be noted that the deposits resistivity, measured at quasi-direct current applying in the course of the electrical resistivity tomography, is significantly higher than the resistivity determined according to the near-field time-domain electromagnetic sounding data. So, for example, the upper part of the section has an electrical resistivity of hundreds of thousands Ohm·m and in some cases it exceeds a million Ohm·m. The deposits having resistivity of 10^5–10^6 Ohm·m are interpreted as massive ice.

The electrical resistivity of the frozen sediments is affected by their temperature, lithological composition, ice content and salinity. In addition, the distribution of resistivity in the geoelectric sections, constructed by two-dimensional inversion, depends on the influence of three-dimensional heterogeneities of the geological medium, situated aside from the profile. Therefore, during the interpretation of geoelectrical sections it is necessary to take into account the profile location with respect to such three-dimensional heterogeneities as lakes. At the same time, the nearness of the lakes also determines the geocryological conditions. For example, the north-western part of profile 3 in the interval of 100–500 m runs along the shore of Krugloye Lake (Fig. 3). Sediments of very high resistivity haven't been detected in that section of the profile (with the exception of the local anomaly at a depth of 380 m), which indicates the absence of massive ice. A reduced resistivity (up to 250–300 Ohm·m) has been observed along the intervals of 650–900 m on profile 1 (deeper than 25 m) and profile 2 (deeper than 100 m). Profile No. 2 in the intervals of 700–850 m runs 45 m aside from Krugloye Lake. We believe that abnormally low values of resistivity at depths on profiles 1 and 2 are due to the lateral influence of the Krugloye Lake talik, and the anomalies do not reflect the real geologic section.

Despite the fact that the two-dimensional geoelectrical model has been obtained up to a depth of 175 m as a result of inversion, and the standard deviation during solving the inverse problem was 4–9.3 %, one should be careful to trust the data obtained from depths over 60 meters. By means of the Res2Dinv program (version 3.55), using as an example the data of profile 1, the sensitivity of the blocks used in the inversion model has been estimated (Fig. 8). The value of normalized sensitivity (S_n) determines the amount of information about the resistivity of the model block, which is contained in the measured data, and varies from 0 to 1. The higher the value of normalized sensitivity, the more well-grounded is the model resistivity. Near-surface blocks usually have higher sensitivity than deeper ones, since the normalized sensitivity function takes on very high values near the electrodes [*Loke, 2009*].

As it is demonstrated in Fig. 8, the sensitivity of ERT method decreases sharply with depth if there is massive ice bedin a section. For example, in the pro-

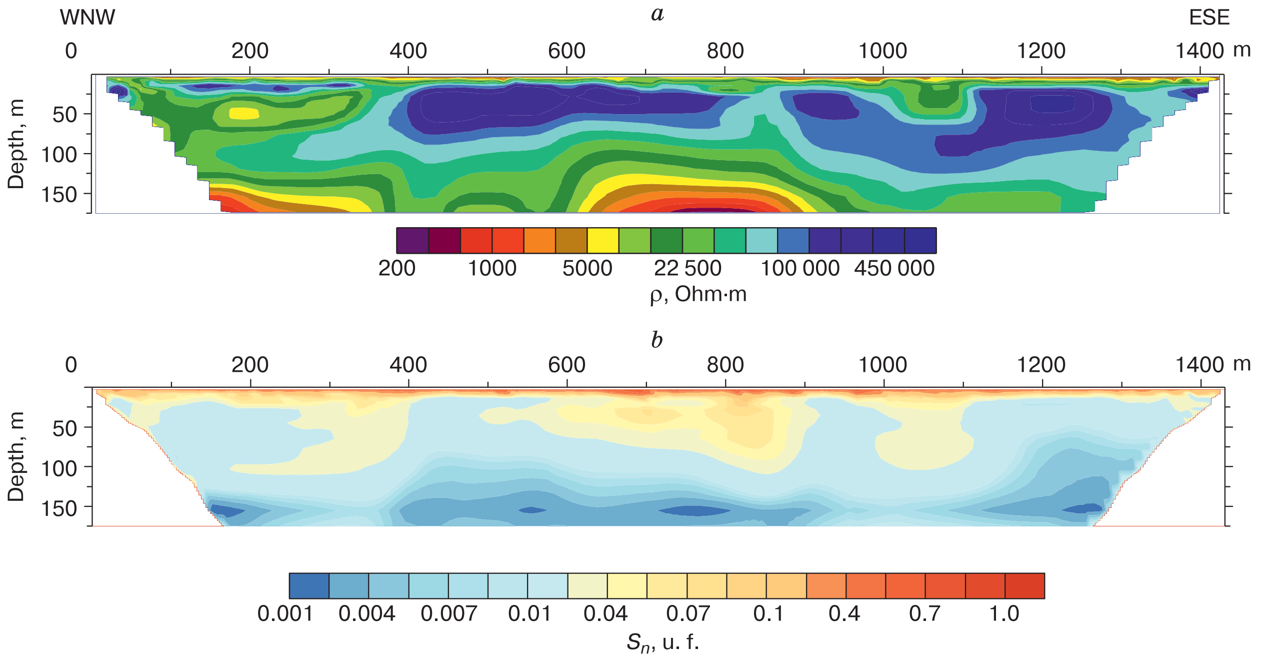

Fig. 8. Geoelectric section (*a*) and section of normalized sensitivity (S_n) of model blocks (*b*) along profile 1.

file intervals at the distances of 400–500 m and 1100–1300 m from the beginning of the profile, electrical current does not penetrate under objects of very high (more than 100 kOhm·m) resistivity, and the sensitivity of the method is limited to the first meters. The sensitivity increases to the depth of 50–75 m in areas where the resistivity of the medium decreases up to values of less than 100 kOhm·m.

According to the results of the TDEM method, in the section along profile 1, at the depth of 60–90 m, the roof of the low resistivity layer (about 30 Ohm·m) has been identified, as well at a depth of 140–220 m, the top of layer with resistivity on the order of 8 Ohm·m has been detected. Those layers have been inserted, as layers with fixed resistance, in the electrotomography data by profile 1. After that, the inverse problem has been solved. As a result, the section (shown in Fig. 9) has been compiled. After completing 5 iterations, standard deviation was 4 %, i.e. the insertion of two layers with fixed resistivity has not affected the model selection error. That confirms the weak sensitivity of the ERT method to changes in resistivity of soils lying deeper than 50–75 m. At the same time, the introduction of layers with fixed resistivity at certain depths lead to a change in the geoelectrical structure of the upper part of the section within the depth range of 0–90 m. For example, such structural features of the section as a thin layer of high resistivity has become more pronounced in the profile interval of 0–400 m, and the anomalies caused by massive ice have acquired an elongated shape.

Two-dimensional data of the ERT soundings have been combined into the three-dimensional data set. After completing that, the thickness and electrical

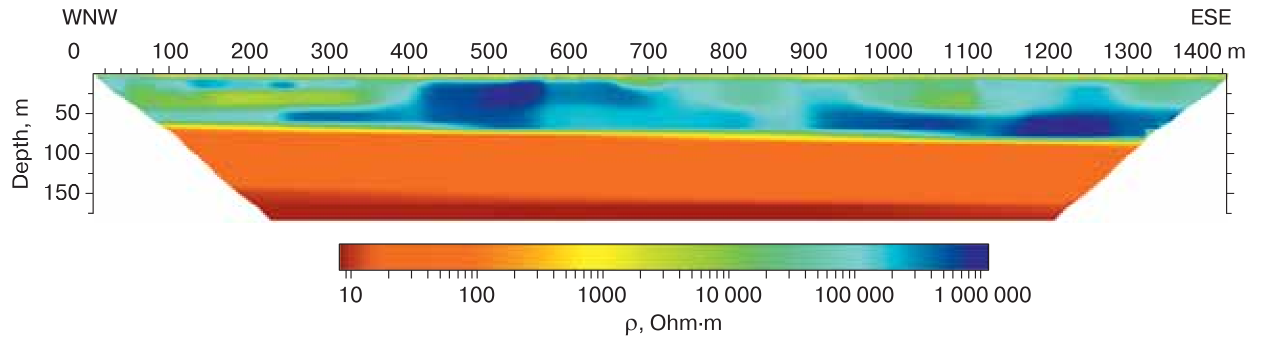

Fig. 9. Geoelectric section along profile 1, constructed as a result of two-dimensional inversion of electric tomography data with fixed layers, with a known position of the layer roof and electrical resistivity according to the TDEM data.

resistivity of the low-resistive layers selected according to the TDEM sounding data have been affixed in that data set, after which three-dimensional inversion has been carried out using Res3Dinv software.

Figure 10 displays a three-dimensional model of the resistivity distribution in the Site I according to the ERT data, on which an anomaly of high electric resistivity caused by massive ice is displayed by means of the isosurface corresponding to 100 kOhm·m. In the northwestern part of the site the anomaly decreases in size and wedges out as massive ice bed approaches Krugloye Lake. Influence of Krugloye Lake on the geoelectric model is also expressed in the wedging out of a high-resistive layer, located near the lake (Fig. 10). That may be due to both local lithologic heterogeneity, which can be seen on the satellite image at the shoreline of the lake near the profile, and the lateral effect of the lake on distribution of electrical current in the medium. A three-dimensional model of the resistivity distribution in the medium allows us to visualize the structure of the study site and to outline the wedging out of massive ice bed in the vicinity of Geofizicheskoye Lake.

As a result of the ERT sounding method at the Site I, the following has been established. The deposits of the upper part of the section up to the depth of 75 m have a very high resistivity, reaching hundreds of thousands of Ohm·m, and in some cases exceeding one million Ohm·m. High resistivity of the sediments can be explained by their lithological composition (sands and loams) and low mineralization of the frozen porous water. The highest resistivity values are characteristic for massive ice beds. Such a high level of electrical resistivity prevents the penetration of electrical current into the depths, as a result of which the sensitivity of the method is limited to a depth of 50–75 m. Under the layers with a resistivity of more than 100 kOhm·m, the sensitivity of the method is confined by the depth of the top of those layers.

The introduction of layers with a fixed resistivity and a depth, established according to the TDEM sounding data, into the two-dimensional ERT model does not lead to a change in selection error when solving the inverse problem. That confirms the insensitivity of the ERT method to properties of the sediments occurring deeper than 60 m.

In the three-dimensional model of the resistivity distribution in the medium, nearby the Krugloye and Geofizicheskoye lakes, the regular wedging-out of an abnormally-high-resistivity layer has been noted. That may be due either to thawing out of massive ice in the vicinity of the lakes, or to the lateral influence of three-dimensional conductive heterogeneity on the distribution of electrical current in the medium. In the Site II, situated between the Parisento and Krugloye lakes, profile 3 runs through the borehole 202. A geoelectrical section along the profile 3 is demonstrated in Fig. 11. The inversion of data has been performed with the fixation of resistivity and border of loam from the depth of 57 m, determined according to the drilling data (Fig. 2).

The level of electrical resistivity of the deposits, established by the ERT method, is in good agreement with the archival data of lateral logging sounding. Out of comparison of the geoelectrical section with the drilling data, it follows that the layers of anomalously high resistivity correspond to massive ice, as well as to the sediments with high ice content. However, in the

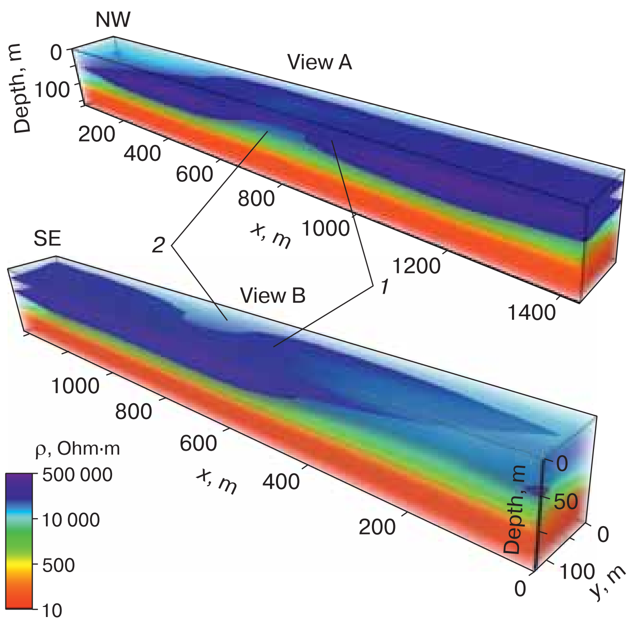

Fig. 10. Three-dimensional geoelectric model according to the electrotomography data:

1 – electrical-resistivity isosurface of 100 kOhm·m; *2* – wedging-out of high-resistive layer nearby Krugloye Lake. View of the geoelectric model from the southern (A) and northern (B) sides.

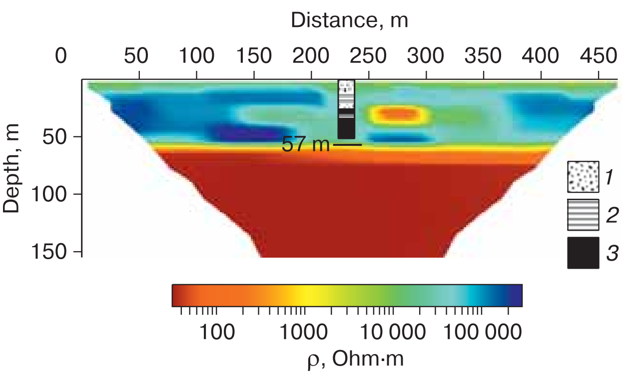

Fig. 11. Geoelectric section along profile 3 through borehole 202.

Two-dimensional inversion with fixed layers: *1* – sand; *2* – clay with ice inclusions; *3* – ice. Number of iterations – 5; standard deviation – 5.9 %.

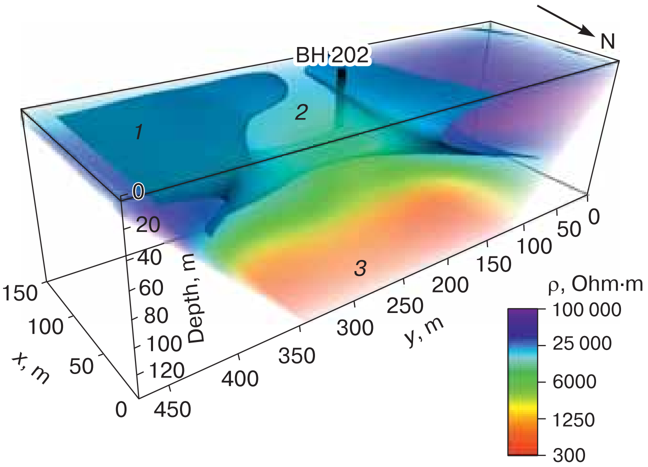

Fig. 12. Volumetric distribution of resistivity in Site II according to the results of three-dimensional inversion.

1 – electrical-resistivity isosurface of 20 kOhm·m, showing the distribution pattern of massive ice; *2* – area of low resistivity; *3* – low resistivity of the model associated with saline loams of marine origin. Number of iterations – 6; standard deviation – 8.3 %.

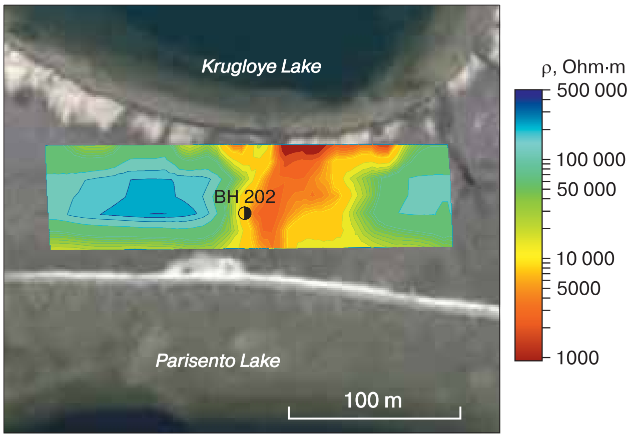

Fig. 13. Resistivity at depth of 30 m according to the results of three-dimensional inversion on a satellite image of the Site II.

central part of the profile, within the range of 250–300 m, at the depth of 25–40 m, a general tendency for decrease in the resistivity of deposits with a locally anomalous resistivity (less than 1000 Ohm·m) has been observed. The geoelectrical section in Fig. 11 demonstrates that massive ice has a heterogeneous structure.

In order to give a complete idea about massive ice distribution between the Krugloe and Parisento lakes, a three-dimensional inversion of the ERT areal data has been carried out. The inversion has been performed both with fixation of layers with a known resistivity and a roof depth, and without any *a priori* information. After completing of 6 iterations, fixation of layers at a depth leads to an increase in the selection error from 8.3 % (without fixing of parameters) up to 10.4 % (with fixed parameters). So the structure of the upper part of the section up to a depth of 75 m does not change significantly. Figure 12 shows the result of three-dimensional inversion without fixed parameters of the model.

The isosurface of the resistivity, corresponding to 20 kOhm·m, displays the distribution of the high-resistive sediments including massive ice. It is easy to see that high-resistive layers have a discontinuous distribution pattern. An area of reduced resistivity is identified in the central part of the section, which means the absence of massive ice beds. Starting from a depth of 80 m, the resistivity of the model decreases down the section to the first thousand Ohm·m, which we attribute to the influence of saline loams of marine origin. Although resistivity of frozen loams in that model is 100 times higher than that of other sediments at the same depth, determined according to the TDEM data within the Site I, the general trend to the increasing of electrical conductivity of deposits at depths of more than 60–70 m has been noted in both methods. A scheme of the resistivity distribution at the depth of 30 m is displayed at a satellite image of the Site II (Fig. 13). The pattern of resistivity distribution demonstrates that there is no massive ice between the lakes, and borehole 202 having drilled-in that ice, is located in the selvedge of the high resistivity anomaly. Spatially the low resistivity anomaly is associated with a linear lowered landform, disposed between the lakes. That may mean the existence of a paleochannel, i.e., it is possible that in the past the lakes were connected by a watercourse.

Cross-section of the three-dimensional model of resistivity along the boreholes line between Krugloye and Parisento lakes is shown in Fig. 14. As can be seen in Fig. 14, the part of the section containing massive ice stands out by the resistivity more than 100 kOhm·m. It should be noted that an icy clay layer within the depth interval of 20–30 m in no way stands out in the resistivity section. In a first approximation, the thickness of the high resistivity layer is consistent with thickness of the strata containing massive ice. However, the resistivity of the sediments underlying the ice bed is greatly overstated in comparison with the model obtained according to the TDEM sounding data in the Site I.

Thus, an analysis of the electrotomography data in the Site II has demonstrated that massive ice has a discontinuous distribution, as it was previously assumed according to the drilling results. A zone of low resistivity that does not contain massive ice has been revealed between the Krugloye and Parisento lakes. Obviously, that zone is associated with an old channel connecting the lakes in the past.

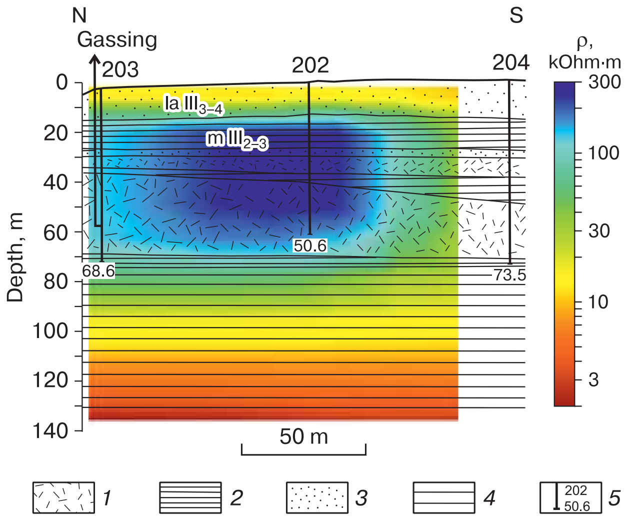

Fig. 14. Geoelectric section along the borehole line between the Krugloye and Parisento lakes according to three-dimensional inversion.

1 – ice; *2* – clay with inclusions of ice; *3* – frozen sand; *4* – loam; *5* – borehole, its number and depth (m).

MODELING OF THERMAL AND ELECTRICAL FIELDS

A decrease in the electrical resistivity of the sediments occurring near the lakes is traced in the resistivity distribution plan (Fig. 13), as well as that is observed in the section along the borehole line (Fig. 14). Such an effect can be caused by the warming of frozen sediments due to contact with water. To assess the warming effect of the water bodies, a two-dimensional model of the temperature distribution in the medium has been constructed according to the thermometry logging data of the boreholes 202, 203, 204. Figure 15 displays that the warming effect of water bodies is clearly revealed, since the temperature in the boreholes located closer to the lake is higher (by 2–4 °C) than in a borehole located 100 meters from it. However, due to the limited number of boreholes, the temperature distribution model has turned out to be very approximate. An increase in the temperature of the frozen sediments, occurring near the lake, from –8 to –4 °C leads to a decrease in their resistivity. For instance, the resistivity of sands will decrease from 10^5 to 10^4 Ohm·m according to an approximate dependence from [*Bogolyubov et al., 1984*]. Figure 13 demonstrates that the resistivity of sediments near the lakes decreases by about an order of magnitude, which can be interpreted as the thermal effect on the electrical conductivity of the frozen stratum.

Since the temperature of the medium is an important factor determining the resistivity of frozen ground, it is necessary to represent the pattern of its distribution near the lakes. The Comsol Multiphysics v. 4.0 software package [*Multiphysics..., 1998*] has been used to calculate the temperature field model between the lakes and determine the configuration of the lake taliks. The program allows to set the geometry and properties of the medium model and the boundary conditions and, using the Heat Transfer module, to solve the heat transfer equation by means of the finite element method.

Based on the drilling data (Fig. 2), a horizontally layered model of the medium has been set: at depths of 0–12.5 m – a layer of sand, 13–26 m – a layer of clay, 27–37 m – a layer of sands with high ice content, 38–66 m – massive ice bed, 67–300 m – a layer of marine loam. There is a linear change in all physical properties into the intervals between the layers. Average values of thermal conductivity, specific heat ca-

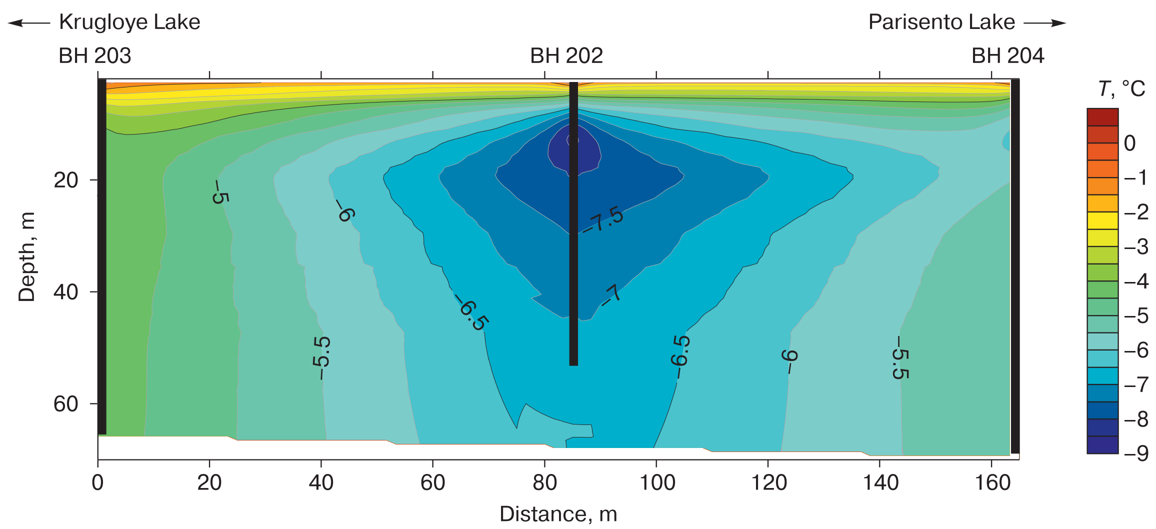

Fig. 15. Permafrost temperature in the section between the Krugloye and Parisento lakes according to thermometry at boreholes 202, 203, 204 in 1992–1993.

Table 1. **The values of physical parameters of medium**

Type of deposits	Thermal conductivity, W/(m·K)		Specific heat, J/(kg·K)		Density, kg/m^3		Freezing point, °C
	frozen state	thawed state	frozen state	thawed state	frozen state	thawed state	
Sand	1.80	1.65	1600	1200	1750	1750	–0.4
Clay	1.55	1.45	1200	1500	1500	1500	–0.6
Icy sediments (water-saturated)	2.0	1.10	1800	2900	1350	1400	–0.1
Ice (water)	2.25	0.65	2000	4212	917	1000	0
Loam (marine)	1.65	1.50	1225	1450	1500	1500	–1.8

pacity and density have been taken for each type of the sediments in two states: the frozen and thawed ones [*Gavriliev et al., 2013; Aleksyutina, Motenko, 2017*]. Those physical parameters are given in Table 1.

The shape of the lakes in the model has been assumed as cylindrical (i.e. with a flat bottom and vertical walls). That is justified by the fact that the radii of the lakes much exceed their depths. The radius and depth of the Parisento and Krugloye lakes are 2500 m and 35 m, 300 m and 25 m, respectively (Fig. 16). The heat flux at the modeling site has been chosen equal to 0.05 W/m^2, since that value is consistent with numerous studies on the heat flux in that region [*Kurchikov, 2001; Duchkov, Sokolova, 2014; Iskorkina et al., 2018*].

The day surface temperature has been assumed to be –10 °C, which corresponds to the mean annual air temperature in that area. As the initial conditions throughout the medium, a temperature plot has been taken, corresponding to the equilibrium state under given boundary conditions (heat flux at the lower boundary and surface temperature at the top layer). The temperatures of +1, +2, +3 °C have been at the bottom of the lakes at the initial time, on the circles with a radius of 300, 200 and 50 m, and 2500, 1500, 500 m for the Krugloye and Parisento lakes, respectively. That is justified by experimental data on temperatures at the bottom of the lakes. After that, the medium has been presented as a finite element grid, and the heat transfer equation has been solved. The formation of thermokarst lakes on the Yamal Peninsula occurred in the first half of the Holocene Climatic Optimum [*Slagoda et al., 2016*]. Due to the lack of information about exact time of formation of Parisento and Krugloye lakes, the time interval of 6000 years has been taken for the calculation. During that time interval, the heating of the under-the-lake medium has been simulated, while the phase transition has been taken into account.

The calculated temperature field of the section is displayed in Fig. 17. The layers lying deeper than 70 m are presented by marine saline loams, in which the mineralization of solutions increases by depth and can significantly exceed 1 g/L [*Badu, 2015; Trofimov, Krasilova, 2017*]. As a result, the authors suggest that the sediment transition from the frozen to cooled state occurs at a temperature of –1.8 °C [*Roman, 2007*]. That had been taken into account when determining the boundaries of the taliks.

Between the lakes, the isotherm of –1.8 °C runs at a depth of 220 m. Beyond the zone of influence of the lakes, the permafrost bottom lies at a depth of 240 m, which is consistent with the data of electromagnetic soundings, obtained by means the TDEM method. As can be seen out of the presented picture,

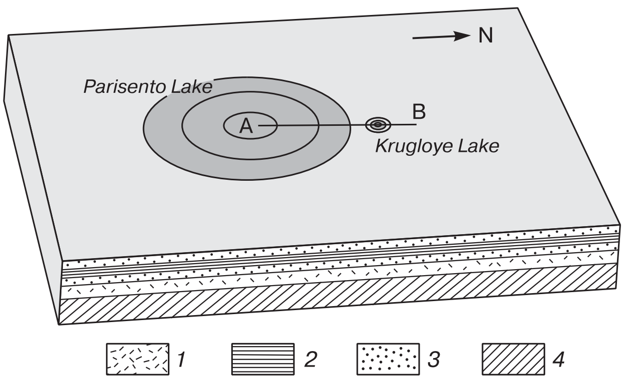

Fig. 16. The model scheme for calculating a thermal field.

1 – ice; *2* – clay with ice inclusions; *3* – frozen sand; *4* – marine loam; AB – line of cross-section.

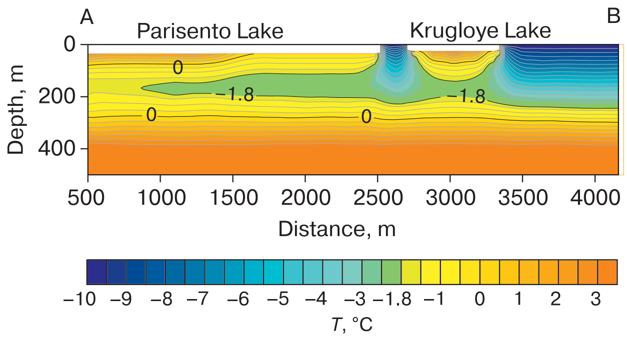

Fig. 17. Temperature distribution in a cross-section along the AB line (see Fig. 16) under the lakes according to numerical modeling results.

the taliks situated under the Krugloye and Parisento lakes are not connected. Calculations have shown that there is an open talik (presumably with a radius of 800 m) under Parisento Lake, closer to its central part. The calculated thickness of the talik situated under Krugloye Lake has been estimated as 140 m. In 1986, the VSEGINGEO employees carried out electrical-resistivity prospecting and seismic survey in the water area of Krugloye Lake. The electrical exploration methods included the vertical electric sounding of the lake bottom, using a three-electrode array, and the seismic prospecting was performed by the method of refracted waves. The research results have demonstrated that the thickness of the talik in the central part of the lake was about 140 m. Thus, the calculated value of the talik depth by the mathematical modeling of the thermal field does not contradict the results of geophysical studies of the past years [*Pugach et al., 1990*].

Based on the obtained results, it can be concluded that the lakes significantly (by 4–6 °C) change the temperature in the inter-lake space at the depths of 20–40 m, which is consistent with the data of borehole thermometry. Thus, the influence of lakes can be one of the main factors in the reduction of resistivity in geoelectric sections. However, a conductive three-dimensional heterogeneity in the form of a water body, located away from the profile, can also produce a similar effect on the results of the ERT data inversion.

To simulate the effect of three-dimensional conductive heterogeneity on water bodies, a simple two-layer medium with a boundary at a depth of 70 m has been set. The model included two lakes and taliks below them (Fig. 18). The talik configuration has been taken by the temperature modeling results. The resistivity of 100 kOhm·m has been established for frozen sediments in the upper part of the medium, that of 30 Ohm·m has been assumed for a frozen loamy base. The resistivity of water in the lakes has been taken

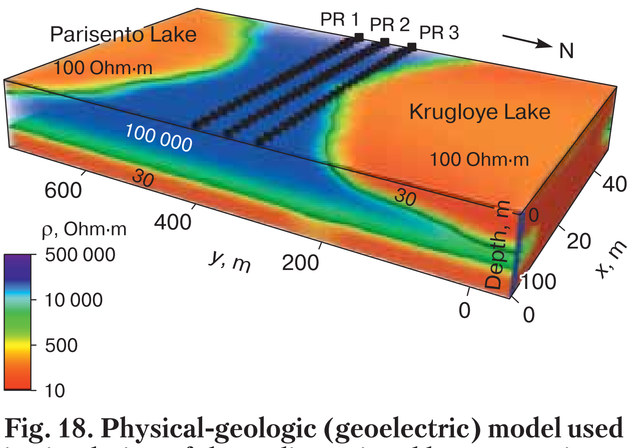

Fig. 18. Physical-geologic (geoelectric) model used in simulation of three-dimensional heterogeneity.

equal to 100 Ohm·m, that of thawed sediments has been assumed to be 30 Ohm·m. The order of the selected resistivity values are consistent with the data of geophysical surveys given above, as well as with the results of the application of vertical electric sounding in the water area of Krugloye Lake [*Pugach et al., 1990*]. The ZondRes3d program has been used to solve the direct problem in the medium, defined as a three-dimensional one [*Kaminsky, 2001–2010*].

For three profiles located at different distances from the lakes (Fig. 18), the apparent resistance values has been calculated for an array similar to that used in field measurements. After that, for each profile, the inverse two-dimensional problem was solved in the Res2dInv program. As a result, geoelectric sections have been obtained along three profiles located at distances of 5, 50, and 100 m away from the lake (Fig. 19).

False anomalies of reduced resistivity are most distinct in the profile located near the lake (exactly, 5 m away from it). As they move away from the lake, the anomalies of the reduced resistivity become less pronounced.

To quantify the effect of three-dimensional heterogeneity on the distribution of resistivity in a two-dimensional model, the relative deviation of the section resistivity (in comparison with a simple two-layer model without lakes) has been calculated (Fig. 20) using the formula:

$$\Delta\rho = \frac{\rho_{3D} - \rho_s}{\rho_{3D}} \cdot 100\,\%,$$

where $\Delta\rho$ is the relative deviation of the resistivity of the three-dimensional model with lakes as compared to the simple model, ρ_{3D} is the resistivity calculated according to the model containing three-dimensional heterogeneity, ρ_s is the resistivity calculated in the simple three-dimensional model without heterogeneities.

Figure 20 demonstrates the profile located 5 m away from the lake that shows the most severe distortion in the resistivity over the entire section by up to 100 %. That is due to the fact that the electrical current flows through a nearby highly-conductive medium represented by a lake and a talik under it.

At 50 m away from the lake the relative deviation of the resistivity up to a depth of 25 m is close to 0 %. Below a depth of 25 m, when the size of the AB current line is commensurate with the distance to the lake, the resistivity distortion reaches 70 %. The highest values of that for the section (80 %) are revealed at depths of 75–90 m, which are associated with the overlapping influence of two water bodies. Relative deviations on the profile located 100 m away from the water body are the lowest. Understatement of resistivity relative to the reference two-layer model by up to 60 % is manifested in the depth interval of 50–100 m.

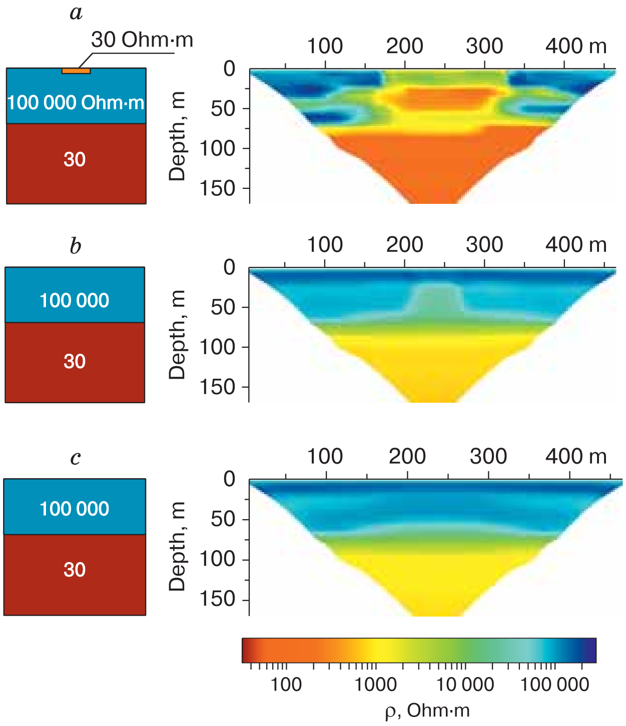

Fig. 19. Effect of three-dimensional heterogeneity caused by water bodies on the distribution of resistivity according to the results of two-dimensional inversion.

Distance of profiles from the lake: *a* – 5 m; *b* – 50 m; *c* – 100 m.

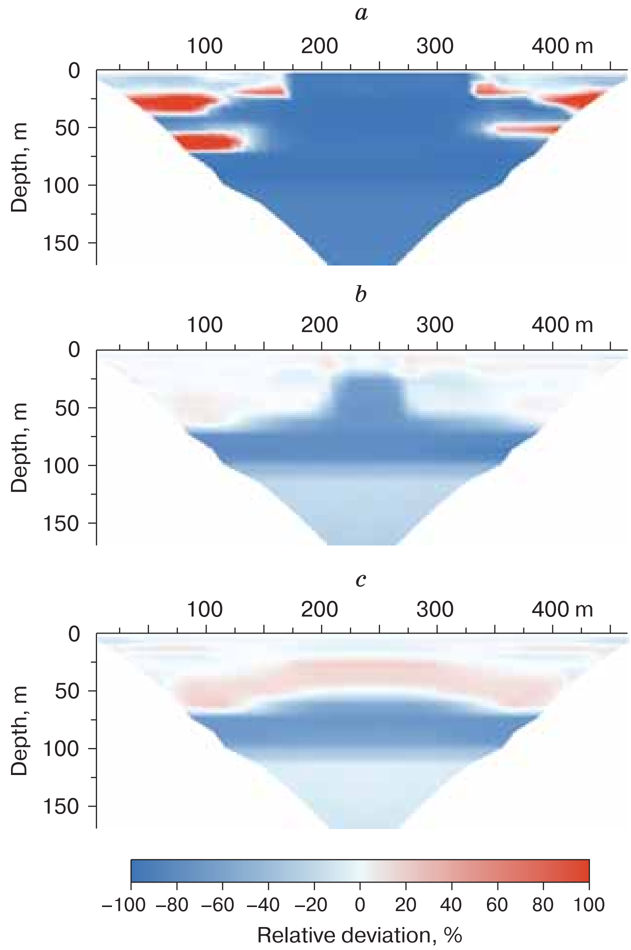

Fig. 20. Relative deviation of resistivity as compared with a simple model without heterogeneities.

Distance of profiles from the lake: *a* – 5 m; *b* – 50 m; *c* – 100 m.

Thus, the results of numerical mathematical modeling have demonstrated that the presence of three-dimensional conductive heterogeneities in the form of lakes away from the sounding profile leads to an understatement of the model resistivity which begins to appear at depths equal to half the distance to the conductive heterogeneity. At 5 m away from the coast the relative decrease in the resistivity of the two-dimensional model reaches 100 %. At a distance from the coast the effect of conductive heterogeneity begins to appear at the pseudo-depth of the section, equal to half the distance to the lake.

Along with the influence of three-dimensional heterogeneity on the inversion results, a certain contribution to the final model of resistivity is made by the area of warmed permafrost near the lake. The only way to obtain a realistic geoelectric model that reflects the geocryological structure of a section near a water body is to locate sounding profiles across the coastline.

CONCLUSIONS

A horizontally layered structure of the medium has been established, according to the TDEM data. The upper part of the section up to the depths of 50–75 m is represented by high-resistive frozen sediments with the inclusion of massive ice. The decrease in resistivity down the section is associated with marine saline loams. The thickness of permafrost is 210–300 m, according to the TDEM data.

According to the ERT data, the sediments of the upper part of the section up to the depths of 50–75 m have a very high resistivity, reaching hundreds of thousands Ohm·m and in some cases exceeding one million Ohm·m. High resistivity of the sediments is due to their lithologic composition (sands) and low salinity of the porous and massive ice. The highest resistivity values are characteristic of massive ice beds. Such a high electrical resistance prevents the penetration of electrical current into the depth as a result of which the sensitivity of the method is limited to the depth of 50–75 m. Under the layers having resistivity of more than 100 kOhm·m, the sensitivity of the method is limited by the depth of the roof of those layers.

When solving the inverse problem of electrotomography, the introduction of deep layers with a known resistivity in the geoelectric model practically does not affect the selection error but makes the structure of the upper section more realistic, emphasizing the horizontally layered pattern of the high resistivity anomalies caused by massive ice.

According to the data of on-site studies by the ERT method, it has been found that the massive ice bed between the Krugloye and Parisento lakes is not of continuous distribution as it seemed earlier according to the drilling data. An anomaly of the low resistivity of deposits has been revealed, presumably related to the old channel connecting those lakes in the past.

Such geological heterogeneities as a lake and a lake talik cause anomalies of low resistivity in the electrical tomography sections. Moreover, the anomalies are associated both with the influence of a three-dimensional conductive heterogeneity located away from the profile, and with an increase in the temperature of permafrost near the lake.

Calculation of the thermal field has demonstrated that there is a closed talik under Krugloye Lake up to a depth of 140 m, and an open talik has formed under Parisento Lake. Those taliks, despite the relatively small distance between the lakes, are not connected. The permafrost temperature rises by 4–6 °C between the lakes, what also affects its electrical resistivity.

Modeling of the three-dimensional heterogeneity effect on the electric field has revealed that when solving the two-dimensional inverse problem for the profiles located near water bodies, a false anomaly of reduced resistivity (reaching 100 %) arises in geoelectric sections. Such high values are typical for the profiles located in the immediate vicinity of the lakes. The farther the profile is located from the lake, the less is that influence. Moreover, a decrease in resistivity begins to appear at the depth equal to half the distance to the lake. Thus, a decrease in the resistivity is associated both with an inhomogeneous temperature field and with the influence of three-dimensional heterogeneity, which is currently not possible to separate.

The authors thank V.A. Dubrovin for the provided geocryological information, as well as they thank the Information and Computing Center of Novosibirsk State University for the possibility of using computing resources.

That work has been supported by the FNI project No. 0331-2019-0007 "Geoelectrics in geological environment research: technologies, field experiment, and numerical models".

References

Aleksyutina, D.M., Motenko, R.G., 2017. The composition, structure and properties of frozen and thawed rocks on the Baydaratskaya Bay coast, Kara Sea. Earth's Cryosphere XXI (1), 11–22.

Anisimova, N.P., Kritsuk, L.N., 1983. Using of cryochemical data for studying of subsurface ice genesis. In: Problems of Geocryology. Nauka, Moscow, pp. 230–239 (in Russian).

Antonov, E.Y., Kozhevnikov, N.O., Korsakov, M.A., 2014. Software for inversion of TEM data affected by fast-decaying induced polarization. Russian Geology and Geophysics 55 (8), 1019–1027.

Badu, Yu.B., 2015. Ice content of cryogenic strata (permafrost interval) gas-bearing structures, Northern Yamal. Earth's Cryosphere XIX (3), 9–18.

Badu, Yu.B., Trofimov, V.T., 1974. Main trends of permafrost cryogenic structure in Yamal Peninsula. In: Problems of Cryolithology. Moscow University Press, Moscow, 24 pp. (in Russian).

Baulin, V.V., 1985. Permafrost Soils of Petroleum-bearing Areas of USSR. Nedra, Moscow, 176 pp. (in Russian).

Bogolyubov, A.N., Bogolyubova, N.P., Lisitsyn, V.V., Kurandin, N.P., 1984. Recommendations for geophysical exploration while engineering site investigations for construction (electrical survey). Stroyizdat, Moscow, 104 pp. (in Russian).

Duchkov, A.D., Sokolova, L.S., 2014. Heat flow in Siberia. In: AllRussian Conference "Geophysical methods of investigation of the Earth crust". IPGG SB RAS, Novosibirsk, pp. 211–216.

Everest, J., Bradwell, T., 2003. Buried glacier ice in southern Iceland and its wider significance. Geomorphology 52 (3–4), 347–358.

Fague, A.N., Surodina, I.V., Yeltsov, I.N., 2016. Electrical resistivity tomography investigation of talik zones beneath thermokarst lakes (based on field measurements and 3D computer modeling). In: Interexpo Geo-Siberia Conference, vol. II (2), pp. 250–254 (in Russian).

Gavriliev, R.I., Zheleznyak, M.N., Zhizhin, V.I., et al., 2013. Thermophysical properties of the main rock types in the Elkon Mountain massif. Kriosfera Zemli (Earth's Cryosphere), XVII (3), 76–82.

Hauck, C., Mühll, D.V., 2003. Inversion and interpretation of two-dimensional geoelectrical measurements for detecting permafrost in mountainous regions. Permafrost and Periglacial Processes XIV (4), 305–318.

Hauck, C., Mühll, D.V., Maurer, H., 2003. Using DC resistivity tomography to detect and characterize mountain permafrost. Geophysical Prospecting LI (4), 273–284.

Iskorkina, A.A., Prokhorova, P.N., Stotsky, V.V., et al., 2018. Reconstructions of geothermal mode of the petromaternal Kiterbutsk suite of the Arctic region in Western Siberia taking into account the influence of paleoclimate. In: Proceedings of Tomsk Polytechnic University. Engineering of Georesources 329 (2), 49–64.

Kaminsky, A.E., 2001–2010. Program for 3-dimensional data interpretation of resistivity method and induced polarization method (ground, borehole and off shore variants) ZondRes3D. 2001–2010, Zond Geophysical software, 75 pp. – URL: http://zond-geo.ru (last visited: 10.02.2018).

Kozhevnikov, N.O., Antonov, E.Y., Zakharkin, A.K., et al., 2014. TEM surveys for search of taliks in areas of strong fast-decaying IP effects. Russian Geology and Geophysics 55 (12), 1452–1460.

Kritsuk, L.N., Polyakov, V.A.,1989. Isotopic research of natural water and ice in West Siberia. Engineering Geology, No. 4, 76–94.

Krylov, S.S., Bobrov, N.Y., 1995. Electromagnetic methods for exploration within permafrost. In: Geophysical Investigations of Cryolithozone / The Russian Academy of Sciences. Research Board of the Earth's Cryology. Moscow, No. 1, 208 pp. (in Russian).

Kurchikov, A.R., 2001. The geothermal regime of hydrocarbon pools in West Siberia. Geology and Geophysics 42 (11–12), 1846–1853.

Loke, M.H., 2009. Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys, RES2DINV Manual, 2009. – URL: http://www.abem.se/fi les/ res/2dnotes.pdf (last visited: 22.12.2015).

McClymont, A.F., Hayashi, M., Bentley, L.R., et al., 2013. Geophysical imaging and thermal modeling of subsurface morphology and thaw evolution of discontinuous permafrost. J. Geophys. Res.: Earth Surface 118 (3), 1826–1837.

Multiphysics, 1998. Introduction to COMSOL Multiphysics®. In: COMSOL Multiphysics, Burlington, MA, vol. 9, 2018 pp.

Olenchenko, V.V., Kozhevnikov, N.O., Antonov, E.Yu., et al., 2011. Distribution of permafrost in Chuiskaya basin (Gorny Altai) according to transient electromagnetic soundings data. Kriosfera Zemli (Earth's Cryosphere), XV (1), 15–22.

Pugach, V.B., Skvortsov, A.G., Timofeev, V.M., Tsarev, A.M., 1990. Resarch of sub-lake taliks in the transpolar region of the West Siberia using geophysical methods. In: Methods for Engineering Geocryological Survey: Collection of scientifi c papers / E.S. Melnikov (Ed.). VSEGINGEO, Moscow, pp. 139–143 (in Russian).

Roman, L.T., 2007. The influence of salinity on the strength and deformability of permafrost soils. Problems of construction on the salty permafrost soils. Epoha, Moscow, 224 pp. (in Russian).

Slagoda, E.A., Narushko, M.V., Preis, Y.I., et al., 2016. Reconstruction of thermokarst in the Late Pleistocene-Holocene from geocryological and botanical data (area of lake Sokhonto, Central Yamal). Earth's Cryosphere XX (4), 53–61.

Trofimov, V.T., Badu, Yu.B., Vasilchuk, Yu.K., et al., 1986. Exogeodynamics of Western Siberian Plate (spatiotemporal trends). Moscow University Press, Moscow, 245 pp. (in Russian).

Trofimov, V.T., Baulin, V.V. (Eds.), 1984. Map of the thickness and structure of permafrost in West Siberian plate. GlavTyumengeologiya; MGU; PNIIIS, Moscow, 1 sh.

Trofimov, V.T., Krasilova, N.S., 2017. Patterns of changes in the degree and spatial distribution of the soil salinity in the permafrost soil strata of the Arctic coast of Russia. In: Engineering-Geological Problems of Modernity and Methods for Their Solution. Geomarketing, Moscow, pp. 8–16 (in Russian).

You, Y., Yu, Q., Pan, X., et al., 2013. Application of electrical resistivity tomography in investigating depth of permafrost base and permafrost structure in Tibetan Plateau. Cold Regions Science and Technology 87, 19–26.

Zykov, Y.D., 2007. Geophysical Methods for Investigation of Cryolithozone. Moscow University Press, Moscow, 272 pp. (in Russian).

Received November 8, 2018
Revised version received November 19, 2019
Accepted November 29, 2019