**EARTH'S CRYOSPHERE**
SCIENTIFIC JOURNAL

*Earth`s Cryosphere*, 2019, vol. XXIII, No. 2, pp. 74–80 **http://earthcryosphere.ru/**

*METHODS OF CRYOSPHERIC RESEARCH*

DOI: 10.21782/EC2541-9994-2019-2(74-80)

# ELECTRICAL PROPERTIES OF PERMAFROST IN THE LAPTEV SEA COAST: EVIDENCE FROM RADIOWAVE MEASUREMENTS

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The electrical properties of permafrost in the Arctic coast near the Tiksi Bay have been studied by VLF to MF radio-frequency impedance soundings combined with VHF–UHF georadar surveys. The subsurface in the area shows heterogeneous geoelectrical patterns with variations according to lithology and particle size distribution. More heterogeneity is due to the presence of ice wedges and lenses of saline groundwater (cryopegs), as well as to flow of supra- and intra-permafrost waters. Joint interpretation of radio-frequency impedance and GPR data provide constraints on the shallow subsurface structure in the Arctic coast in the vicinity of Tiksi and on particular electrical properties of cryopegs. The properties of permafrost revealed by surveys at low and medium RF bands are included into the geoelectrical database for layered permafrost.

*Geoelectrical section, radio-frequency impedance sounding, ground-penetrating radar, cryopegs*

## INTRODUCTION

Permafrost in the eastern Arctic coast is as cold as −12 to −14 °C [*Gramberg et al., 2004*] but encloses lenses of unfrozen saline rocks (cryopegs) with unusual electrical properties [*Brouchkov, 1998; Sukhorukova, 2015*]. Radio-frequency (RF) soundings of permafrost can provide important information necessary for progressively increasing development of the Arctic coast and shelf. The reported RF impedance and GPR measurements have furnished new data on the electrical properties of permafrost and unfrozen rocks in the Laptev Sea coast in the vicinity of the Tiksi Bay.

Electromagnetic (EM) soundings at radiowave bands are broadly applied in geocryology for constraining depth-dependent resistivity variations, mapping of sporadic permafrost, detection of unfrozen rocks (taliks), etc. [*Melnikov, 1977; Arcone and Delaney, 1988; Bashkuev, 1996; Melchinov et al., 2006; Zykov, 2007; Tezkan and Saraev, 2008; Efremov, 2013; Makarov and Modin, 2013; Ageev and Ageev, 2017*]. However, special soundings of this kind have been very limited within the Arctic coast [*Bashkuev et al., 2006*]. Spatial permafrost monitoring near injector wells in oil fields of West Siberia included a large amount of multifrequency measurements in boreholes [*Cherepanov, 2017, 2018*]. Soundings of permafrost *in situ* revealed frequency dependence of electrical properties at 1 to 50 MHz and the Maxwell–Wagner effect [*Gubatenko, 1991*]. The frequency dependence of permafrost resistivity was studied in detail by *Frolov* [*2005*]. Earlier very low frequency (VLF) soundings at 30–300 Hz for petroleum exploration mainly focused on deep subsurface [*Zhamaletdinov, 2015*], while shallow subsurface geolectrical patterns and their correlation with geomorphology were neglected.

In the summer of 2015, a field team from the Institute of Material Sciences carried out combined radio-frequency EM surveys for assessment of present geocryological conditions on the Laptev coast near the Tiksi Bay.

## STUDY AREA

The study area is located at the junction of the eastern Siberian craton and the Laptev Sea plate [*Gramberg et al., 2004*]. The Laptev coast borders the North-Siberian Lowland with its shallow sediments composed of Quaternary sandstones and shales deposited in lacustrine-fluvial, marine, and glacial environments. The sediments store black and brown coal, oil, and gas. Geomorphologically it is a hilly plain with vast depressions and alluvial flats shaped up by Quaternary glaciaitons and transgressions. The lowlands are cut by a W–E system of moraine ridges with elevations of 150–250 m. The northern part of the area belongs to the zone of lichen and shrub tundra.

Permafrost thins down toward the shoreline and varies in thickness from 50 m in the Olenek Channel to 650 m near Tiksi community [*Gramberg et al., 2004*]. Rocks beneath large lakes and river channels remain unfrozen and form closed or open taliks. The above-floodplain terrace sections are remarkable by including an ice complex (Late Pleistocene layered sequence) consisting of ice-rich silt and clay silt. It is tens of meters thick and encloses lenses of outsize sand and peat, sporadic gravel and pebble, as well as thick ice wedges with their lower parts inserted up to 10 m into the sediments below. The ice complex lies upon sand and peat layers, locally reaching 7 m thick, and is overlain by lenses of modern lacustrine, aeolian, and floodplain deposits [*Gramberg et al., 2004*]. The seasonal thaw depth varies considerably as a function of moisture contents, vegetation, and relative elevation. In early September, the active layer thickness is 0.2–0.4 m in swampy peatlands, 0.5–0.7 m on drained and non-vegetated surfaces, and up to 1 m locally on terrace slopes; the average range is from 0.4 to 0.6 m [*Gramberg et al., 2004*].

Soils in northern Yakutia have a cryotic temperature regime. According to available data on the temperature pattern of tundra cryosols in the Bykovsky Peninsula near the Tiksi Bay [*Fedorov-Davydov et al., 2015*], the mean monthly ground temperature of the warmest month in the Arctic tundra is 1.5 °C. The annual sum of positive daily means is 75 °C at an average duration of the frost-free period of 61 days. Tundra loam cryosols receive 1300–2400 kcal/m$^2$ of incoming heat annually. The maximum thaw depth in the Arctic coast for 2001–2015 was in a range of 25–43 cm.

## METHODS

The surveys were performed by the combined radio-frequency (RF) impedance and ground penetrating radar (GPR) methods. The VLF–LF–MF data provided constraints on the surface impedance and depth-dependent resistivity at 43 stations. GPR data were collected along two profiles, 2.11 km of total length.

The knowledge of the surface impedance and resistivity structure of permafrost measured at VLF to MF frequencies can be used to check calculations for groundwave propagation in the high latitudes based on local electrical parameters.

The electromagnetic (radiophysical) problem for the Laptev coast in the vicinity of the Tiksi Bay was solved by analysis of amplitudes and phases of the EM field at stations of VLF to MF impedance soundings along the air-earth interface [*Bashkuev, 1996*]. The method implies direct measurements of impedance magnitude $|\delta|$ and phase $\varphi_\delta$ and is based on the skin effect. The normalized surface impedance is found from measured tangential components of the electric and magnetic fields ($E_\tau$ and $H_\tau$, respectively):

$$\delta = (E_\tau/H_\tau)\, Z_0,$$

$Z_0 = \sqrt{\mu_0/\varepsilon_0}$ is the characteristic impedance, where $\mu_0$ is the magnetic permeability ($4\pi\cdot10^{-7}$ H/m) and $\varepsilon_0$ is the dielectic permittivity ($8.854\cdot10^{-9}$ F/m); all parameters are meant in the free space.

The surveys were run using VLF to MF (25, 320, and 660 kHz) electromagnetic fields of radio stations, with an impedance meter. This is a selective microvoltmeter-phase meter that measures the frequency dependence of the amplitude and phase of the surface impedance, which are used to estimate electrical conductivity ($\sigma_i$), permittivity ($\varepsilon_i$), and thickness ($h_i$) of each *i*-th layer [*Bashkuev, 1996*]. We used an IPI-1000 portable impedance meter that ensures $|\delta|$ and phase $\varphi_\delta$ measurements to an accuracy of ±5 % and ±(1–2)°, respectively [*Bashkuev, 1996*]. The tangential component of the electric field $E_\tau$ was measured using a 20 m long symmetrical ungrounded receiver line applicable to both conductive and resistive sections. The magnetic tangential component $H_\tau$ was measured using a loop antenna with a tuner.

The collected data were inverted using the *Impedans* software [*Angarkhaeva, 2002*] to find the best fit (minimum rms error) of the impedance calculated for an *n*-layer earth to the measured values. The inversion was performed neglecting the frequency dependence of the electrical properties of permafrost in the 25–620 kHz range. The permittivity $\varepsilon_i$ for a three-layer model was assumed to be $\varepsilon_1 = 10$ for layer 1, $\varepsilon_2 = 7$ for layer 2, and $\varepsilon_3 = 10$ for layer 3 [*Melchinov et al., 2006; Efremov, 2013*]. The layer permittivities can be locked during the inversion because displacement current is much lower than conduction current at the working frequencies we used (25, 320, and 660 kHz).

GPR surveys were performed using an *Oko-2* radar with an AB-400 antenna unit, of 400 MHz central frequency [*Oko-2 Georadar, 2006*], which provides a penetration of 5 m and a 0.15 m depth resolution. During the surveys, the radar moved along profiles, 0.1 to 2 km in length, while the displayed signals (radargrams) showed the layered earth structure, as well as the location, depth, and size of metal or nonmetal objects [*GeoScan32, 2013*].

## RESULTS: SURFACE IMPEDANCE AND GPR DATA FROM PERMAFROST

Surface impedance was measured at very low (25 kHz), low (320 kHz) and medium (660 kHz) frequencies at 43 stations (Fig. 1) on the Tiksi Bay coast, along the roadways Neelov Bay – Tiksi airport – Tiksi, Tiksi – PGO (Polar Geophysical Observatory of the Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy), as well as along the coast to the Polarka station in the Sogo Bay. The collected radar images are shown in Figures 2 and 3.

In general, the values of impedance magnitude (scalar impedance $|\delta|$) and phase ($\varphi_\delta$) have large ranges indicating significant geoelectrical heterogeneity in the survey area. The surveys along the 2 km RF impedance profile 200 m from the shoreline in the vi-

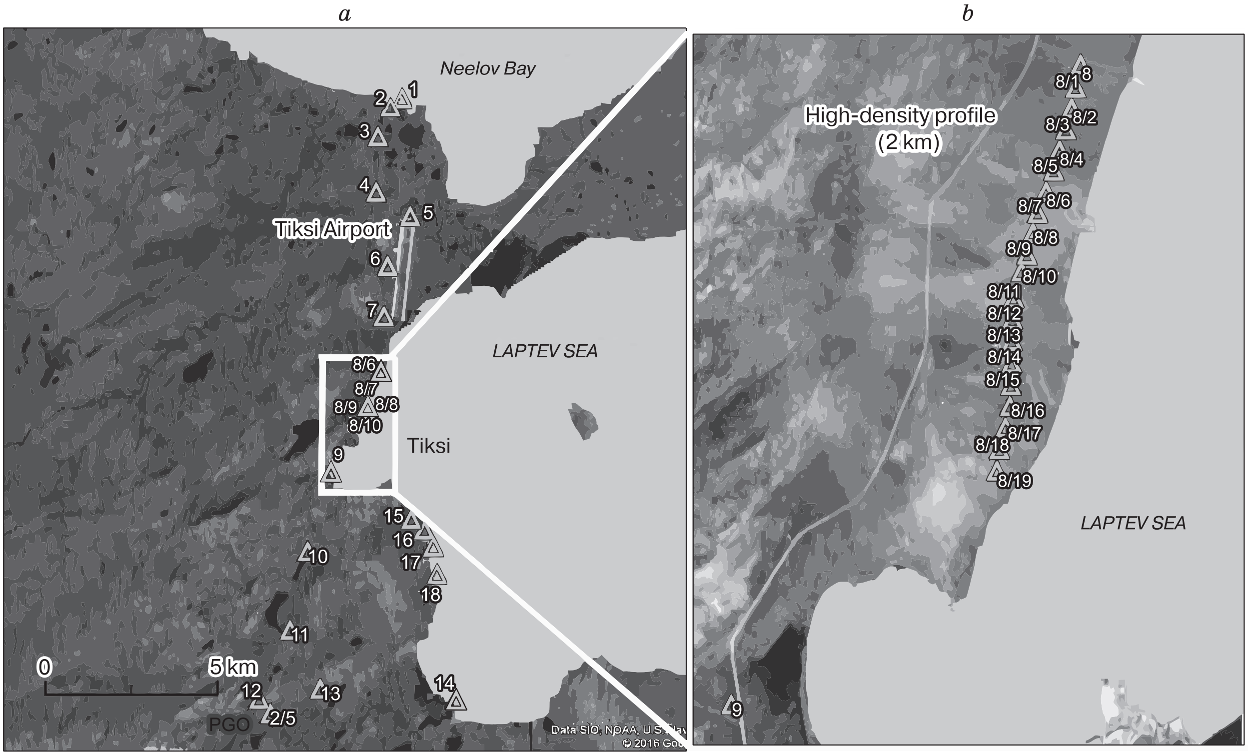


**Fig. 1. Location of radio-frequency impedance stations in the Laptev Sea coast near Tiksi Bay.**
*a*: all stations; *b*: stations along 2 km profile.

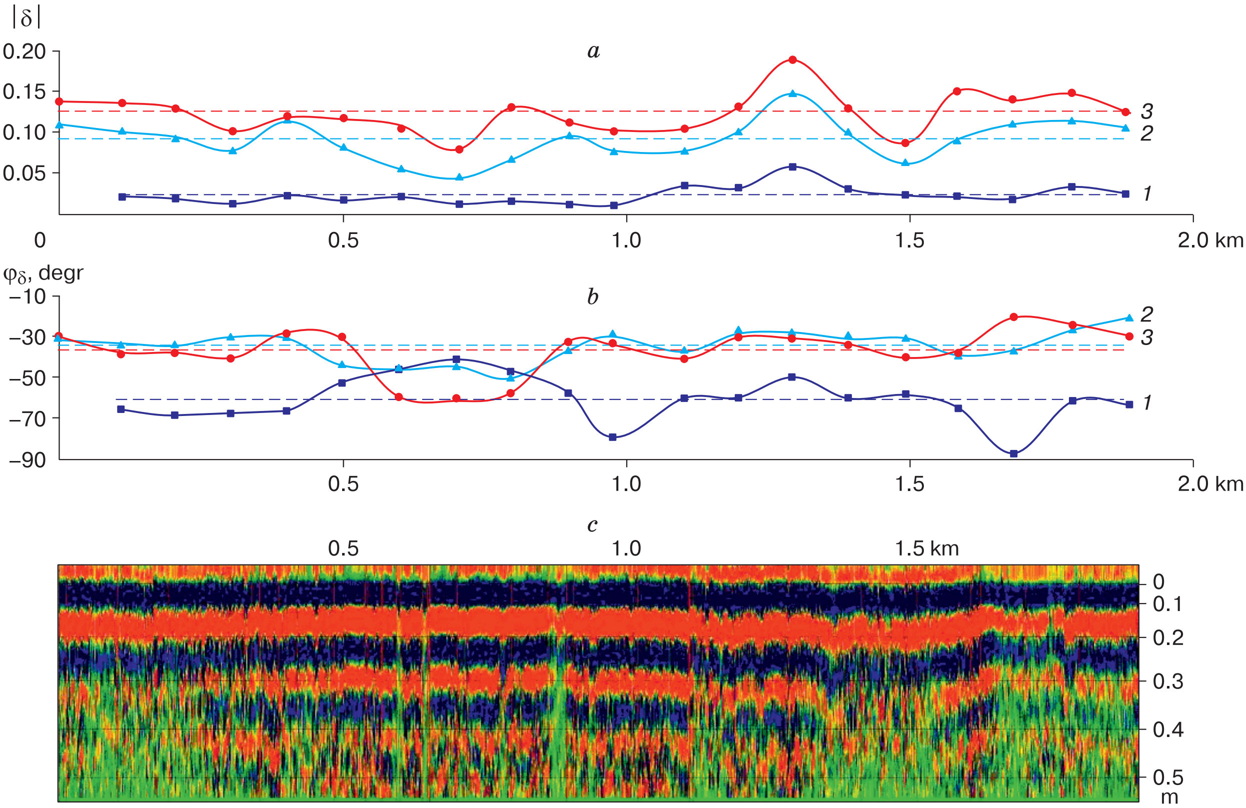


**Fig. 2. Scalar impedance |δ| (*a*) and phase $\varphi_\delta$ (*b*) measured at 25, 320 and 660 kHz (lines *1*–*3*, respectively) and radargram (*c*) along 2 km profile near the Tiksi Bay coast.**

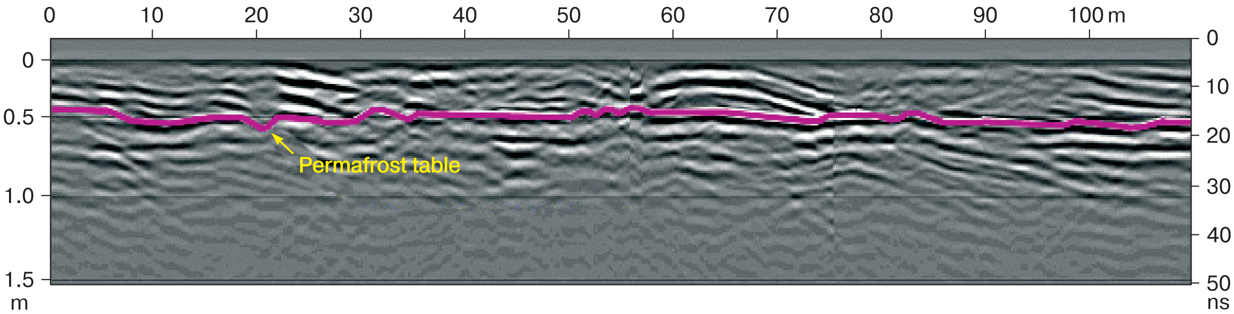


**Fig. 3. Radargram of 110-m profile within Polar Geophysical Observatory.**

cinity of Tiksi (20 stations) were combined with *Oko-2* GPR surveys.

The $|\delta|$ and $\varphi_\delta$ measurements at different frequencies (Fig. 2) gave average values of $|\delta| = 0.024$, $\varphi_\delta = -61°$ at 25 kHz, $|\delta| = 0.092$, $\varphi_\delta = -35°$ at 320 kHz, and $|\delta| = 0.124$, $\varphi_\delta = -37°$ at 660 kHz. According to the radar data, there is a 0.2–0.24 m thick moistened layer with a permittivity of $\varepsilon = 25$. The earth in the middle part of the profile between 0.3 and 1.7 km is less conductive, judging by lower attenuation of the signal in the unfrozen active layer and by the presence of prominent multiples. Resistivity in this profile part may be lower because of better drainage due to a sloping surface and streams. The active layer is 45–50 cm thick within the 110-m long GPR profile in the territory of the Polar Geophysical Observatory located 5 km far from the shoreline (Fig. 3).

## DISCUSSION

The surveys revealed sediments and bedrocks in the permafrost section. The RF impedance data were inverted by means of Tikhonov's regularization [*Bashkuev, 1996*]. Figure 4 shows example inversion results for frequency-dependent impedance at two sedimentary (stations 5 and 3: panels *a* and *b* of Fig. 4, respectively) and bedrock (stations 13 and 14: panels *c* and *d* of Fig. 4, respectively) sites; the obtained parameter values are listed in Table 1.

The most typical layered resistivity structure of summer tundra is $\rho_1 < \rho_2 > \rho_3$: $\rho_1$ from 67 to 260 Ohm·m and thickness from 0.7 to 2.1 m in layer 1; $\rho_2$ from 1040 to 5300 Ohm·m and thickness from 11 to 84 m in layer 2; $\rho_3$ from 100 to 580 Ohm·m in layer 3; bedrocks (stations 13, 14) have resistivities in a range of 560 to 5300 Ohm·m. Undeformed bedrocks with low porosity and few cracks are highly resistive (4800 to 5300 Ohm·m), with a $\rho_2/\rho_1$ ratio from 3.6 to 9.5.

Conditions in permafrost are locally favorable for high groundwater salinity and formation of brine lenses called cryopegs [*Brouchkov, 1998; Sukhorukova, 2015*]. Saline water in cryopegs remains liquid at rather cold negative temperatures. We studied a large conductive cryopeg zone by VLF to MF impedance soundings and obtained very low values of scalar impedance $|\delta|$ and phases of $\varphi_\delta < -60°$. The impedance was the lowest ($|\delta|_{min} = 0.004$–$0.027$) in cryopegs at the Polar Geophysical Observatory (Fig. 5; Table 2). For instance, the parameters of layers 1, 2, and 3 at station 1 are, respectively: $h_1 = 1.1$ m, $\rho_1 = 52$ Ohm·m; $h_2 = 12$ m, $\rho_2 = 9$ Ohm·m; $\rho_3 = 3$ Ohm·m.

In addition to the electrical parameters of the layered earth, important information can come from statistical values of scalar impedance and phase. The phase shift corresponds to inductive reactance at all stations and varies from −87 to −7°. At higher frequencies, the impedance magnitude increases while the phase shift becomes less inductive: the percentages of phase shifts corresponding to high inductance ($\varphi_\delta < -45°$) are 90 % at 25 kHz but only 25 % at 660 kHz. The scalar impedance values are high and the phase angles correspond to inductance in the tundra zone of the Neelov Bay but the respective values are lower in hilly areas, where the phase angles show low inductance and the scalar impedance is commensurate with that of tundra.

## CONCLUSIONS

Combined broadband radiowave surveys by two methods revealed lateral and depth-dependent variations in the electrical properties of sedimentary and bedrock permafrost in the Laptev coast around the Tiksi Bay. The geoelectrical sections are highly heterogeneous due to variations in lithology and particle sizes of rocks, to the presence of ice wedges and cryopegs, as well as to flow of supra- and intra-permafrost groundwaters. The surveys revealed cryopeg zones in the vicinity of the Tiksi Bay and provided constraints on their electrical properties.

The reported VLF–LF–MF (radio-frequency impedance) and UHF (georadar) data and results of their inversion have provided generalized constraints on the permafrost structure to a depth of 100 m. The complete depth coverage was achieved by combinati-

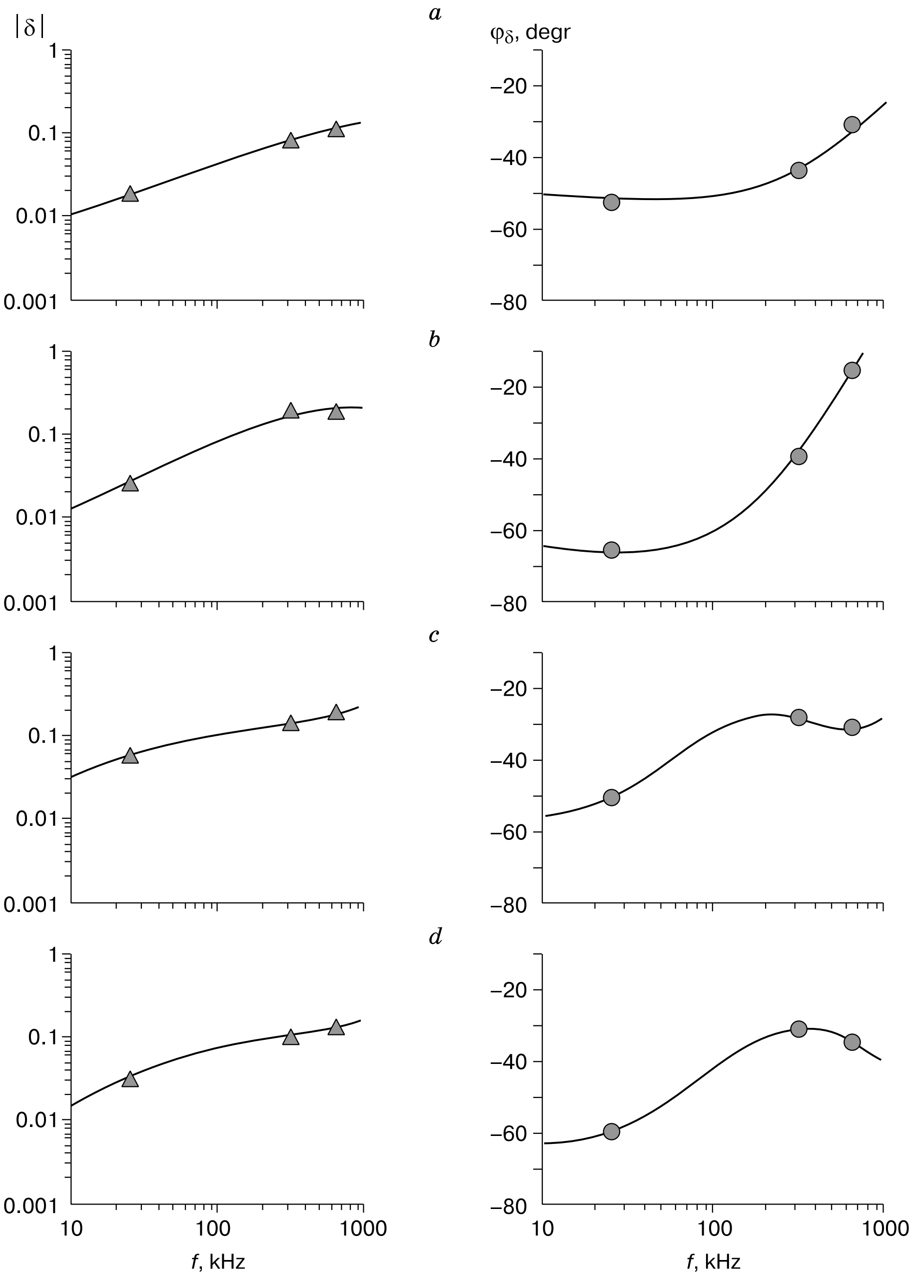


**Fig. 4. Interpreted radio-frequency impedance data from vicinities of Tiksi community, Arctic coast, in sedimentary (*a*, *b*) and basement (*c*, *d*) rocks: station 5, profile from Tiksi airport, 10.07.2015 (*a*); station 3, outer marker, 07.07.2015 (*b*); station 13, profile from Tiksi airport, 10.07.2015 (*c*); station 14, profile from Tiksi airport, 10.07.2015 (*d*).**

Table 1. **Resistivity ($\rho_i$) and thickness ($h_i$) of layers according to radio-frequency impedance data from sediments and bedrocks**

| Station | $\rho_i$, Ohm·m | | | $h_i$, m | | |
|---|---|---|---|---|---|---|
| | $\rho_1$ | $\rho_2$ | $\rho_3$ | $h_1$ | $h_2$ | $h_3$ |
| 5, profile from Tiksi airport | 67 | 1040 | 170 | 0.73 | 11 | ∞ |
| 3, outer marker | 260 | 5100 | 100 | 2.1 | 31 | ∞ |
| 13, profile from Tiksi airport | 1350 | 4860 | 580 | 24 | 84 | ∞ |
| 14, profile from Tiksi airport | 560 | 5300 | 100 | 17 | 32 | ∞ |

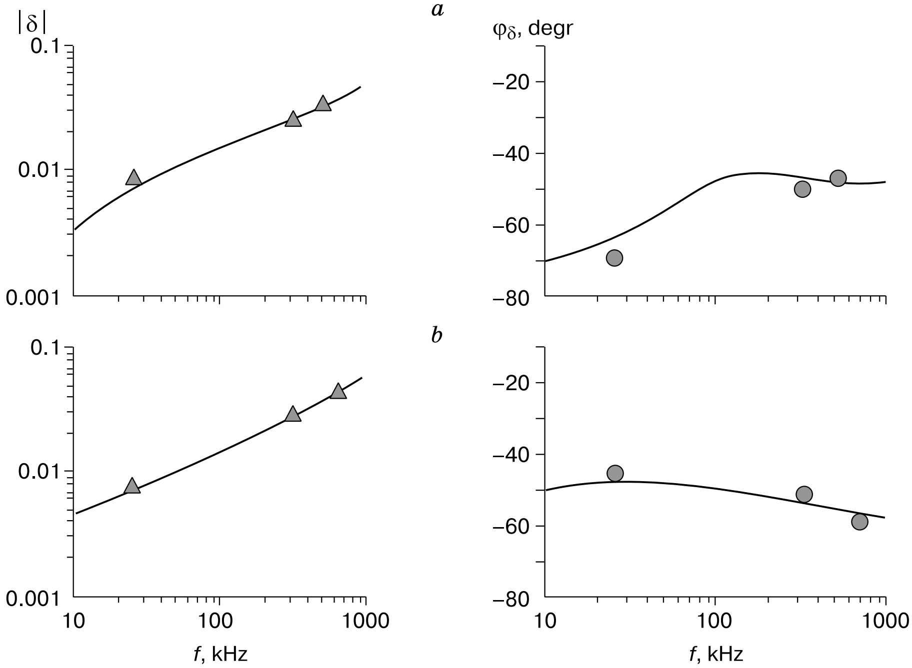


**Fig. 5. Interpreted radio-frequency impedance data from a cryopeg zone.**

*a*: station 2/5; *b*: station 12, within Polar Geophysical Observatory.

Table 2. **Resistivity ($\rho_i$) and thickness ($h_i$) of layers according to radio-frequency impedance data from cryopegs**

| Station number | $\rho_i$, Ohm·m | | | $h_i$, m | | |
|---|---|---|---|---|---|---|
| | $\rho_1$ | $\rho_2$ | $\rho_3$ | $h_1$ | $h_2$ | $h_3$ |
| 2/5 | 98 | 32 | 1.3 | 0.37 | 12 | ∞ |
| 12 | 515 | 30 | 8.6 | 1.0 | 29 | ∞ |

on of pulsed GPR measurements [*Vladov and Starovoitov, 2004; Semeikin et al., 2005*] at 50–1700 MHz that cover shallow depths of 0.1–30 m with long-period impedance soundings at 0.01–1.0 MHz penetrating to depths of 100–200 m. Nondestructive introscopy at VLF–LF–MF and UHF bands has 3–5 times greater performance than vertical electric soundings.

The methods of RF impedance and GPR measurements of permafrost and the obtained results can be used for engineering-geological surveys in northern Russia. The collected LF and MF data have made part of the database on electrical properties of layered permafrost [*Bashkuev, 1996; Bashkuev et al., 2006; Melchinov et al., 2006; Efremov, 2013*]. This knowledge is indispensable for development of the Arctic coast in the area of the Tiksi port, the sea gates of the Sakha Republic (Yakutia).

*The study was carried out as part of Project* Radiowave Propagation in Heterogeneous Impedance Channels *supported by the government of the Russian Federation.*

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*Received October 21, 2017*
*Revised version received October 29, 2018*
*Accepted November 16, 2018*