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TEM surveys for search of taliks in areas of strong fast-decaying IP effects

N.O. Kozhevnikov [a,*], E.Yu. Antonov [a], A.K. Zakharkin [b], M.A. Korsakov [a]

[a] *A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

[b] *Siberian Research Institute of Geology, Geophysics, and Mineral Resources, Krasnyi pr. 67, Novosibirsk, 630091, Russia*

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Abstract

Lenses of water-saturated unfrozen rocks (taliks) in permafrost are important sources of freshwater in high-latitude regions. Taliks stand out against the host frozen rocks in much lower resistivity and thus are detectable by resistivity surveys. TEM soundings are especially efficient in this application as they can go without galvanic grounding, have small offsets, and are sensitive to buried conductors. Early-time TEM data in the Taz area of the Yamal-Nenets district bear strong effects of fast-decaying inductively induced polarization (IIP), which rules out the use of nonpolarizable earth assumption for their interpretation. The TEM responses are inverted by means of the TEM-IP software using the model of a polarizable earth with Cole–Cole complex frequency-dependent conductivity. The resulting earth model mainly includes three layers, with a 100 to 250 m thick highly resistive polarizable upper layer. The polarization parameters of the layer (chargeability, time constant and exponent) are typical of frozen sedimentary rocks, while the presence of a talik reduces notably the effective resistivity and chargeability. This feature can be used as a guide to taliks, as it was confirmed by TEM surveys and subsequent drilling.

Keywords: permafrost; talik; TEM surveys; fast-decaying induced polarization; inversion

Introduction

Lenses of water-saturated unfrozen rocks underneath rivers and lakes in permafrost (taliks) are often unique water reservoirs in high-latitude regions. Unfrozen rocks are well pronounced in data of DC resistivity surveys, which play the leading role in detection and characterization of taliks. Vertical electrical soundings are widely used in permafrost or structural research (Ogilvi, 1990) while DC profiling is workable if unfrozen rocks lie at relatively shallow depths. Measurements over frozen shallow ground may be problematic because a galvanic contact of electrodes with the earth is required.

TEM surveys are more efficient in this respect as they can go without grounding and have offsets smaller than the sounding depth. This way of resistivity imaging is advantageous over VES which requires offsets times greater than the depth of exploration (McNeill, 1980; Rabinovich, 1987). Since unfrozen rocks are usually better conductive than frozen ones (Stognii, 2003), another advantage of the TEM method important in permafrost applications is the sensitivity of TEM responses to conductors buried under resistive rocks (Artamonova et al., 2013; Matveev, 1974).

However, TEM data from permafrost areas are affected by fast-decaying inductively induced polarization (IIP) showing up as nonmonotonous voltage responses or even sign reversals at times between a few tens to a few hundreds of microseconds (Kozhevnikov et al., 1995; Krylov and Bobrov, 2002; Molchanov and Sidorov, 1985; Stognii, 2008). The polarization effects have to be taken into account to improve the quality of inversion and geological interpretation of TEM data from such areas.

There have been a number of publications concerning inversion of TEM responses of polarizable ground affected by fast-decaying IP (Krylov and Bobrov, 2002; Kozhevnikov and Antonov, 2006, 2008, 2012; Stognii, 2008), but the IIP issues relevant to detection of taliks have received little attention yet (Ageev and Ageev, 2013; Kozhevnikov et al., 2012). In this paper we report results of TEM surveys applied to search of taliks for water supply in high-latitude tundra.

Study area

The surveys were performed in the Taz area of the Yamal-Nenets district, within the Ob'–Taz artesian basin. The

* Corresponding author.
E-mail address: KozhevnikovNO@ipgg.sbras.ru (N.O. Kozhevnikov)

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basin consists of two groundwater layers that differ in structure and flow regime, as well as in chemistry and gas composition of waters. The better studied upper layer comprises three aquifers of different ages (Quaternary, Miocene, and Eocene–Oligocene ones) and locally reaches 300 m thick though ranging mainly between 50 to 250 m.

The Quaternary aquifer occurs throughout the area and is largely used for water supply. Being located in the permafrost zone, the aquifer is almost completely frozen, except for some restricted unfrozen zones beneath large rivers and lakes (Ivanov and Beshentsev, 2005).

The area lies in plain tundra with patches of swampy lowlands. Local geology is poorly known; there are no lithological or geophysical constraints available on the shallow subsurface to 150 m depth. The known near-surface lithology is composed of sand, clay, and clayey sand with different clay contents. No special geophysical water prospecting has ever been undertaken in the area.

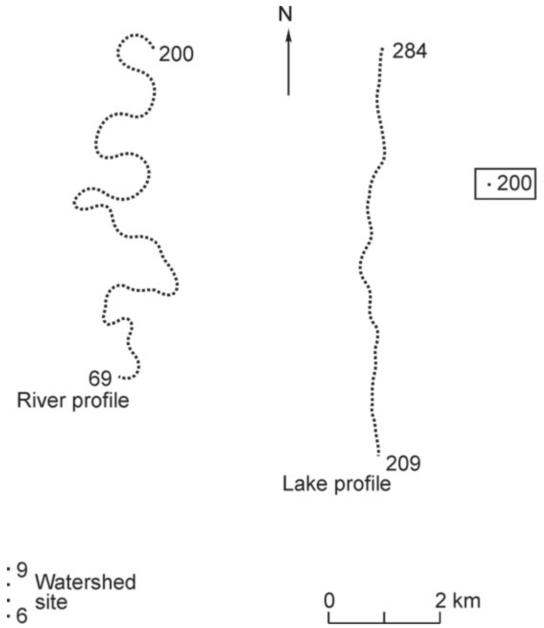

Fig. 1. Location map of TEM surveys. *1*, TEM stations and their numbers.

Methods

TEM surveys were carried out using a *TSIKL-7* instrument (Tsikl-Geo, Novosibirsk, Russia) (Sekachev et al., 2006) under the leadership of Zakharkin. The TEM sounding system consisted of a receiver coil with an effective area of 2500 m^2 (Zakharkin, 1998) and a 35 m × 35 m transmitter loop. With the current 7A the maximum sounding depth was about 300 m.

The prospecting surveys were preceded by test soundings at a watershed site (Fig. 1). First, several soundings (TEM 6–TEM 9) spaced at 250 m were run using a central-loop array with a 70 m × 70 m transmitter. The acquired TEM data were affected by fast-decaying IP showing up as a large interval (from ≈ 30 to ≈ 300 μs) of sign reversal (negative voltage). In the subsequent exploration survey an offset-loop system was used with a receiver coil laid 45 m far from the 35 m × 35 m transmitter loop. With the offset-loop configuration, the IIP effects became smaller at the account of induction ones. This resulted in narrowing of the time range over which the interpretation in terms of conductive nonpolarizable earth was invalid.

Soundings at every 100 m were along two profiles in river and lake environments (Fig. 1). The river profile (TEM 69–200) ran along the channel of a frozen river and the N–S lake profile (TEM 209–284) traversed three small peat lakes and a large 2800 m × 1600 m lake, all located east of the river line.

The repeated measurements showed the greatest errors (10–30% or more) at the earliest times (below 20–30 μs). Notable errors occurred also at 100–200 μs, in the narrow range of voltage reversal and very rapid change.

Potentialities of TEM surveys for detection of taliks: numerical experiments

The late-time parts of offset-loop responses are only weakly affected by fast-decaying IP and are thus suitable for inversion using *PODBOR* software (Mogilatov et al., 2007) to the resistivity patterns to depths within a few hundreds of meters in terms of a 1D model of conductive nonpolarizable layered earth. However, fast-decaying IP rules out the use of the nonpolarizable earth model for inversion of the early-time parts of TEM responses. The only way to solve the problem was to apply an inversion algorithm taking into account the polarization effects. Note that *PODBOR* software has been improved lately and its updated version can invert TEM data affected by fast-decaying IP.

Unlike their frozen counterparts, unfrozen unconsolidated sediments have low resistivity and exhibit no fast decaying induced polarization (Ageev, 2012; Kozhevnikov and Antonov, 2012; Kozhevnikov et al., 1995, 2012). Therefore, it is reasonable to assume that talik in permafrost should show up as a nonpolarized conductive layer among resistive polarizable rocks.

Before inversion of IIP-affected TEM data, we ran forward modeling based on a realistic resistivity model in order to find out whether the due regard for fast-decaying IP can improve geological interpretation of transient responses with implications for locations of taliks.

The synthetic data were generated and inverted using TEM-IP software (Antonov et al., 2010, 2014; Korsakov et al., 2013) designed for forward modeling and inversion of TEM responses in terms of a layered conductive polarizable earth. Fast decaying induced polarization is taken into account via the Cole–Cole complex frequency-dependent conductivity σ(ω)

$$\sigma^*(\omega) = \sigma_0 \frac{1 + (j\omega\tau)^c}{1 + (1-m)(j\omega\tau)^c}, \quad (1)$$

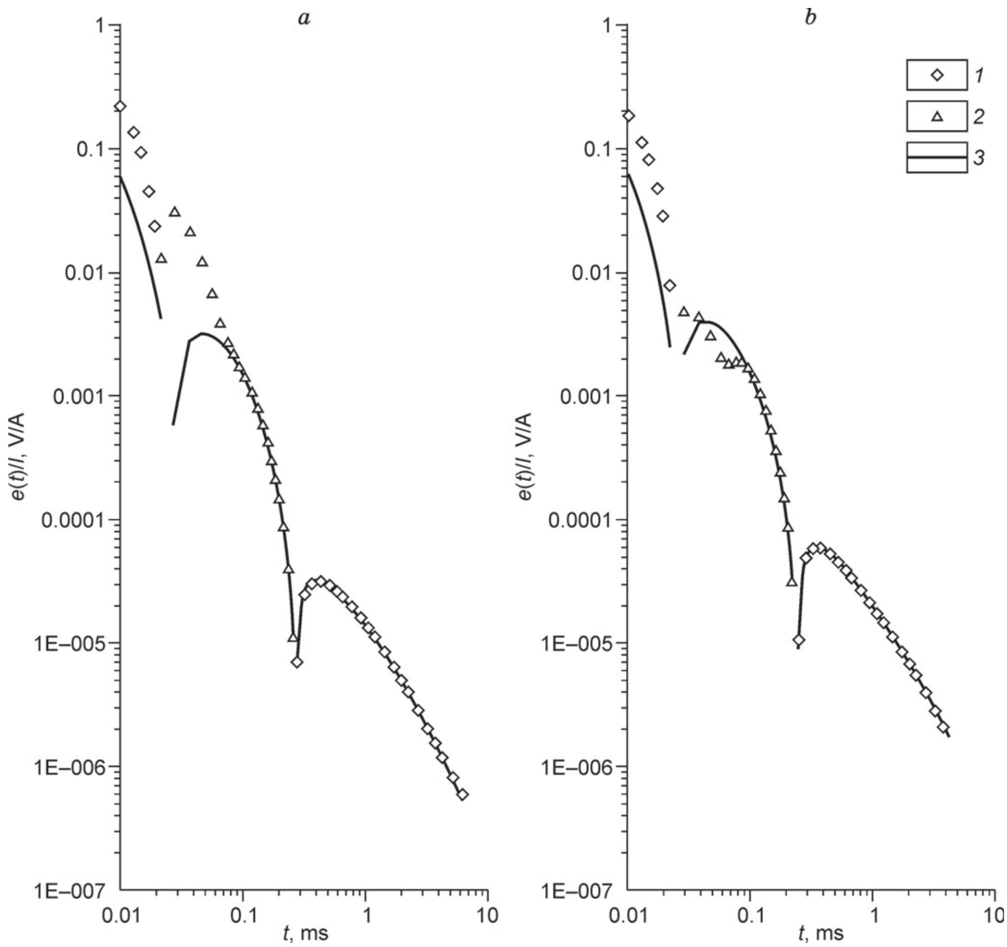

Fig. 2. Measured (*1*, *2*) and computed (*3*) TEM voltage responses at watershed site. *a*, TEM 6; *b*, TEM 8. *1*, *2*, positive and negative voltages, respectively. Configuration: induction receiver coil, 2500 m^2 effective area, at the center of a 71 m × 71 m transmitter loop. Inversion done in terms of 1D conductive and polarizable earth model.

where $j = \sqrt{-1}$; ω is the angular frequency, in s^{-1}; σ_0 is the dc conductivity, in S/m; m is the chargeability, $(0 \le m \le 1)$; c is the exponent $(0 \le c \le 1)$; τ is the IP relaxation time constant, in s.

Inversion of TEM data consisted in search for the section parameters from the space of model data **M** that provided the minimum of the objective function (**P**):

$$\varphi(\mathbf{P}) = \left\{ \frac{1}{N-1} \sum_{i=1}^{N} \left[\frac{\varepsilon^{\mathrm{meas}}(t_i) - F_{\mathbf{P}}(t_i)}{\delta(t_i)\, \varepsilon^{\mathrm{meas}}(t_i)} \right]^2 \right\}^{1/2}, \qquad (2)$$

where t_i is the ith measurement time (time delay), N is the total number of measurement times; $\varepsilon^{\mathrm{meas}}(t_i)$, voltage measured at the t_i time delay; F_{P} is the forward operator; $\delta(t_i)$ is the relative measurement error at the t_i measurement time. The set of model parameters is $\mathbf{P} = (\sigma_j, h_j, m_j, \tau_j, c_j)\Big|_{j=1,M}$, where M is the total number of layers, σ_j is the conductivity, h_j is the thickness, m_j is the chargeability, τ_j is the relaxation time, and c_j is the exponent of the jth layer. Minimization of (2) was run by means of a modified method of Nelder and Mead (1965).

TEM-IP software includes several algorithms for forward modeling and individual or joint inversion of transient responses to a conductive polarizable horizontally layered earth; it also allows import/export and graphic visualization of data (Antonov et al., 2014; Korsakov et al., 2013).

The software is project-oriented, i.e., it allows integrating TEM data (line or areal) into a titled project for further structuring, fast access, and working with each object separately.

Forward calculations are made using the Unv_QQ module (Kozhevnikov and Antonov, 2007, 2008, 2009). The Fourier forward algorithm includes several resource-intensive cycles (up to 99.5% computing time) run in parallel to accelerate the computation proportionally to the number of processors in use.

First we estimated transient responses with a talik-free model, then incorporated a talik as a nonpolarizable conductive layer and repeated the computation. Finally, the talik effect was estimated by comparing the two responses.

The reference geoelectrical model was created using the watershed test results, for two main reasons: the site was apparently devoid of taliks (i) and the use of central-loop soundings especially sensitive to IIP effects was favorable for estimating reference model polarization parameters (ii).

Table 1. Parameters found by inversion of TEM responses measured at watershed site

Parameter	TEM 6	TEM 7	TEM 7	TEM 8	TEM 8	TEM 9	TEM 9	Average
ρ_1, Ohm·m	1600	470	1420	515	1690	765	1470	1100
m_1	0.71	0.45	0.73	0.46	0.74	0.49	0.65	0.60
τ_1, μs	177	103	190	91	188	101	148	140
c_1	1	1	1	1	1	1	1	1
h_1, m	170	132	155	129	140	145	147	145
ρ_2, Ohm·m	2.4	8.2	1.5	8.3	2	5.9	4.7	4.7
h_2, m	15.7	127	10.5	121	6.8	53.4	32.9	50
ρ_3, Ohm·m	15	25	14	24	8.8	12	9.8	16

Note. Configuration: receiver coil, 2500 m^2 effective area, at the center of a 71 m × 71 m transmitter loop.

Comparison of typical TEM responses measured in the field and found through inversion (Fig. 2) shows that the model responses match the measured ones quite poorly at early times below a few tens of microseconds but good or very good at later times.

The models obtained through inversion are presented in Table 1. Two versions of models for points TEM 7–9 both account well for the observations and thus illustrate the equivalence. The resistivity section consists of three layers, with a 10^3 Ohm·m polarizable upper layer having its polarization parameters ($m = 0.6$, $\tau = 150$ μs, $c = 1$) typical of frozen sediments (Kozhevnikov and Antonov, 2006, 2008, 2012; Stognii, 2010). The second layer, with a low resistivity of a few Ohm·m, a thickness about 50 m on average and a bulk conductance of ≈10 S, may consist of clay in which a large portion of pore water remains unfrozen at negative temperatures. The 15 Ohm·m bottom layer is probably composed of clay as well.

The three-layer model with these parameters (Fig. 3*a*) was used for reference to estimate the effects of a talik embedded in the top layer, which makes the model a five-layer one (Fig. 3*b*). The talik has the thickness h_2, relatively low resistivity (Fig. 3*b*, $\rho_2 = 200$ Ohm·m) and zero chargeability.

We checked how transient responses change depending on the resistivity of a 50 m thick talik with its top surface at the 50 m depth (Fig. 4). The talik resistivities $\rho_2 = 10$, 20, 50, 100, 200, 500, and 10^3 Ohm·m used for calculations corresponded to rocks of different porosities, salinities, and other properties. For comparison, the same figure shows responses corresponding to the reference model.

At a low resistivity of the talik (a few tens of Ohm·m), the responses differed markedly from the reference ones, especially at the times from a few tens to a few hundreds of microseconds (Fig. 4*b*). Namely, there was no voltage polarity reversal, which may serve as a diagnostic feature. As the talik became more resistive, the TEM responses approached ever more those without it.

Then we studied the effect of talik thickness (Fig. 5), assuming that $\rho_2 = 200$ Ohm·m and h_2 varies from 5 to 100 m. The depth to the talik top was $h_1 = 50$ m, as in the previous case. The talik thickness variations, especially, between 50 and 100 m, influenced the TEM responses only weakly. In

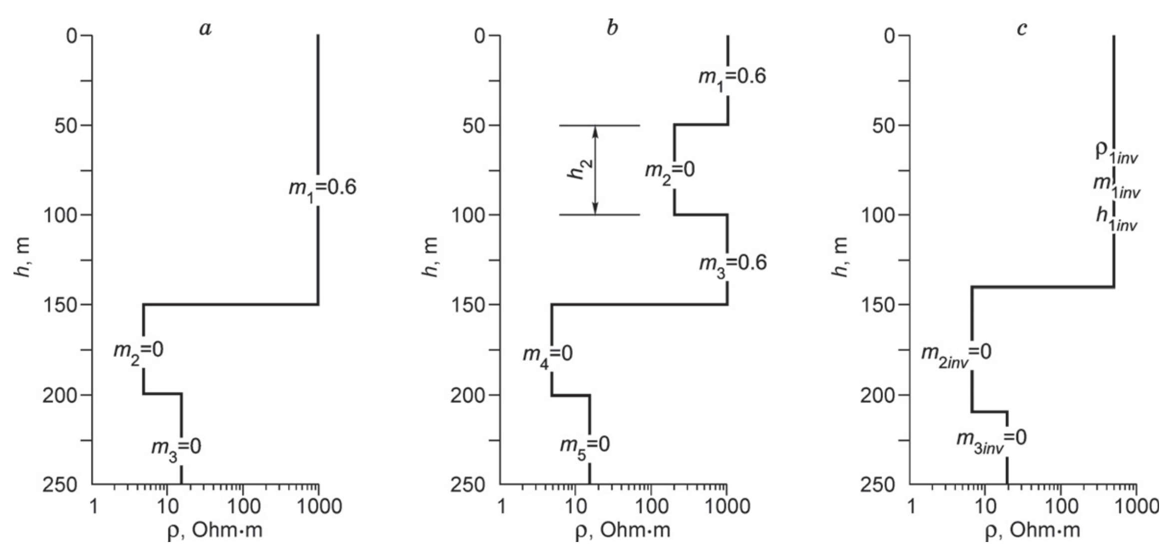

Fig. 3. Geoelectical models. *a*, Reference model (without talik), found by inversion of central-loop transient responses at the watershed site; *b*, model with a talik in upper polarizable layer; *c*, model obtained by inversion assuming a three-layer earth model, with a talik that influences the effective parameters of the upper layer.

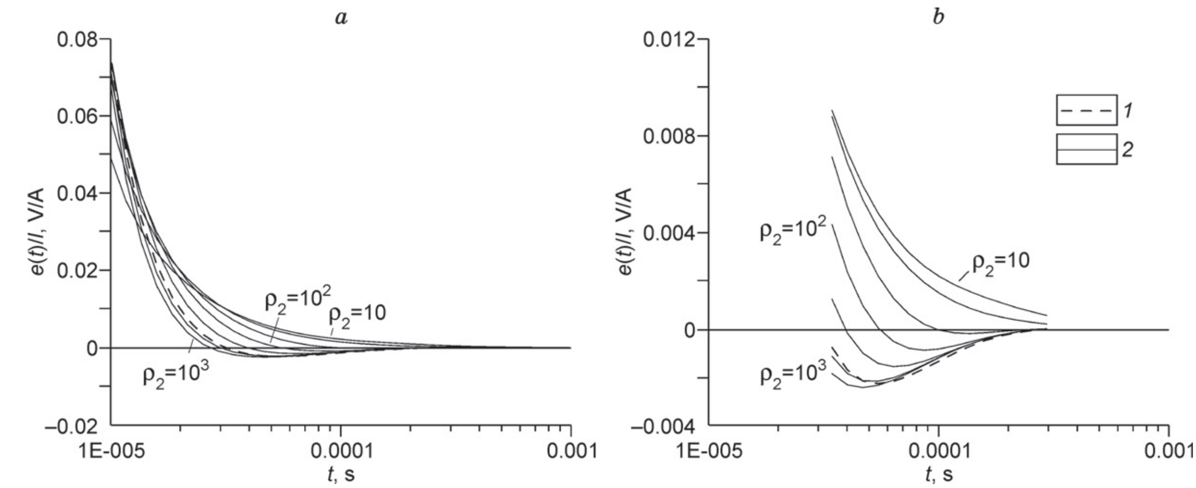

Fig. 4. Influence of talik resistivity on TEM voltage responses. *a*, Voltage responses, general view; *b*, exaggerated vertical scale in zone of strongest talik influence. *1*, reference model; *2*, talik: $h_2 = 50$ m, $\rho_2 = 10–10^3$ Ohm·m.

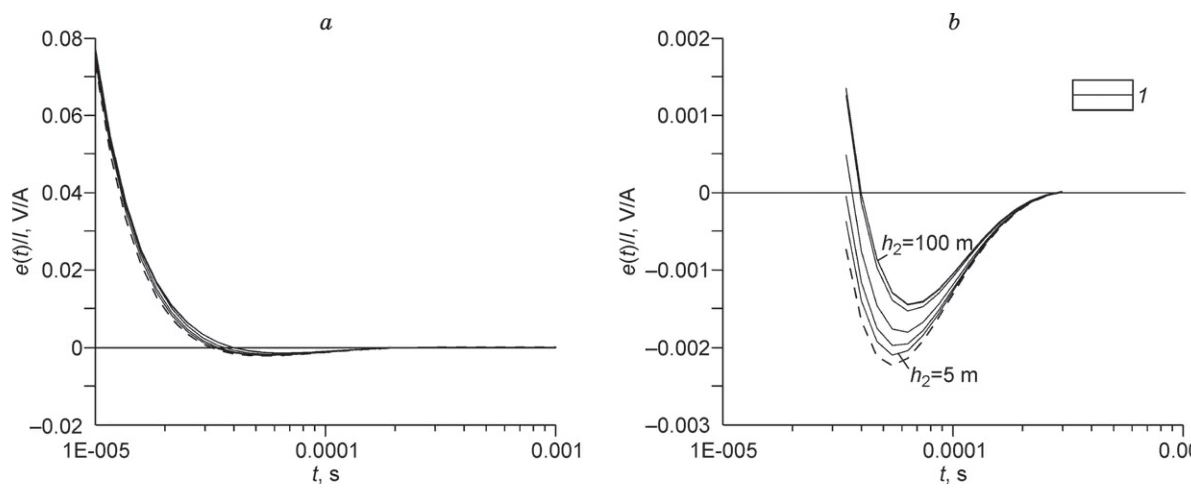

Fig. 5. Influence of talik thickness on TEM voltage responses. *a*, Voltage responses, general view; *b*, exaggerated vertical scale in zone of strongest talik influence. *1*, talik: $h_2 = 5–100$ m, $\rho_2 = 200$ Ohm·m. Other symbols same as in Fig. 4.

the zone of minimum, however, the difference of the transients from those in the reference model (Fig. 5*b*) should be resolvable by advanced TEM systems.

In order to see which parameters can be found through inversion of TEM data and check its quality, we undertook a numerical experiment as in (Kozhevnikov and Antonov, 2007, 2008, 2009, 2010), trying to simulate the "reality" as faithfully as possible. One of us (author #1) prepared a set of starting geoelectrical models, computed the respective TEM responses and added noise to them; the other (author #2) inverted the synthetic responses in terms of a horizontally layered conductive polarizable model. The talik thicknesses h_2 were: 0, 5, 10, 20, 50, 75, and 100 m. Obviously, at $h_2 = 0$, in the absence of talik, the model consisted of three layers and corresponded to the reference one of Fig. 3*a*. The models with a talik of $h_2 = 5$, 10, 20, 50 and 75 m included five layers (Fig. 3*b*), and that with $h_2 = 100$ m had four layers. The models with the zero and largest thicknesses ($h_2 = 0$ and $h_2 = 100$ m) can be considered as specific degenerate cases of the five-layer model.

Thus, the model consisted of a 150 m thick frozen polarizable upper layer with the embedded talik in it; the layer parameters were: $\rho_1 = \rho_3 = 10^3$ Ohm·m, $m_1 = m_3 = 0.6$, $\tau_1 = \tau_3 = 150$ μs, $c_1 = c_3 = 1$. Down the section there followed a nonpolarizable layer with $h_4 = 50$ m and $\rho_4 = 5$ Ohm·m and a nonpolarizable base of $\rho_5 = 15$ Ohm·m. The talik had a resistivity $\rho_2 = 200$ Ohm·m and a chargeability $m_2 = 0$.

The experiment included three steps.

1. Inversion of synthetic TEM data in terms of a three-layer reference model with a polarizable upper layer. This layer is equivalent to three upper layers of the five-layer model at $h_2 =$ 5, 10, 20, 50 and 75 m and to two upper layers of the four-layer model at $h_2 = 100$ m.

2. Inversion using a starting model with a nonpolarizable talik embedded into the upper polarizable layer (*a priori* information communicated to author #2).

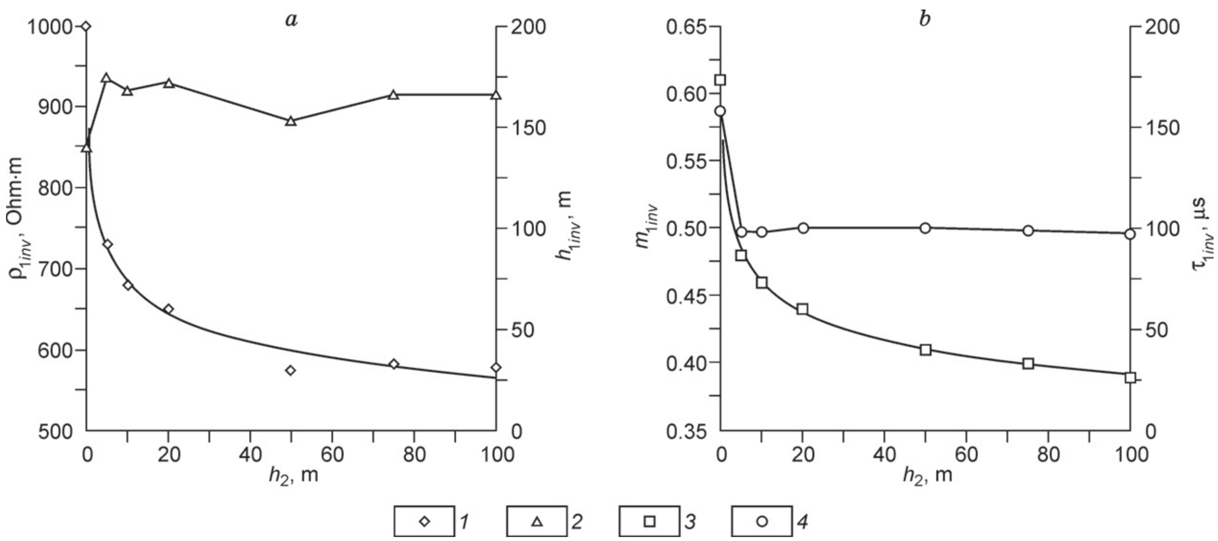

Fig. 6. Variations of ρ_{1inv} (*1*), h_{1inv} (*2*), m_{1inv} (*3*), and τ_{1inv} (*4*) of upper equivalent layer in the three-layer model as a function of talik thickness h_2.

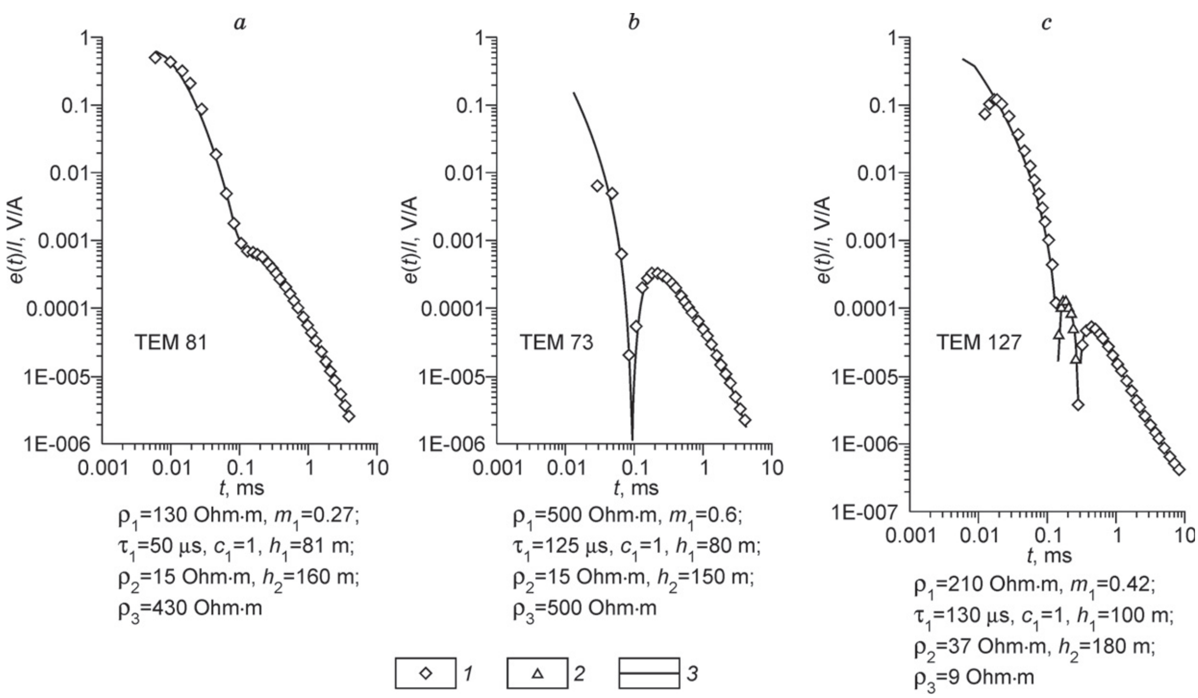

Fig. 7. TEM voltage responses measured with an offset-loop configuration and results of their inversion in terms of a three-layer model with a polarizable upper layer. *a–c*, See text for explanation. *1–3* are same as in Fig. 2.

3. Inversion using a starting model with known resistivity of permafrost enclosing the talik ($\rho_1 = \rho_3 = 10^3$ Ohm·m) and total thickness of three upper layers $h_{123} = h_1 + h_2 + h_3 =$ 150 m (additional *a priori* information communicated to author #2).

According to inversion results for the five-layer model (steps 2 and 3), the effect of the talik on TEM responses is too weak to constrain reliably its parameters as a separate layer. Nevertheless, incorporating a talik into a three-layer model (step 1) causes significant changes to effective or equivalent parameters $\rho_{1\mathrm{inv}}$, h_{1inv}, m_{1inv}, and τ_{1inv} of the top layer (Fig. 3*c*), which actually comprises three sublayers (Fig. 3*b*). The inversion-derived ρ_{1inv}, h_{1inv}, m_{1inv}, and τ_{1inv} of the upper layer plotted against the talik thickness h_2 (Fig. 6) show regular decrease in ρ_{1inv} and m_{1inv} with increasing h_2. These changes can indicate the presence of a talik, and its thickness can be estimated if *a priori* information on the near-surface structure is available.

The sensitivity of ρ_{1inv} and m_{1inv} to the talik thickness is the highest at h_2 from zero to a few tens of meters (Fig. 6)

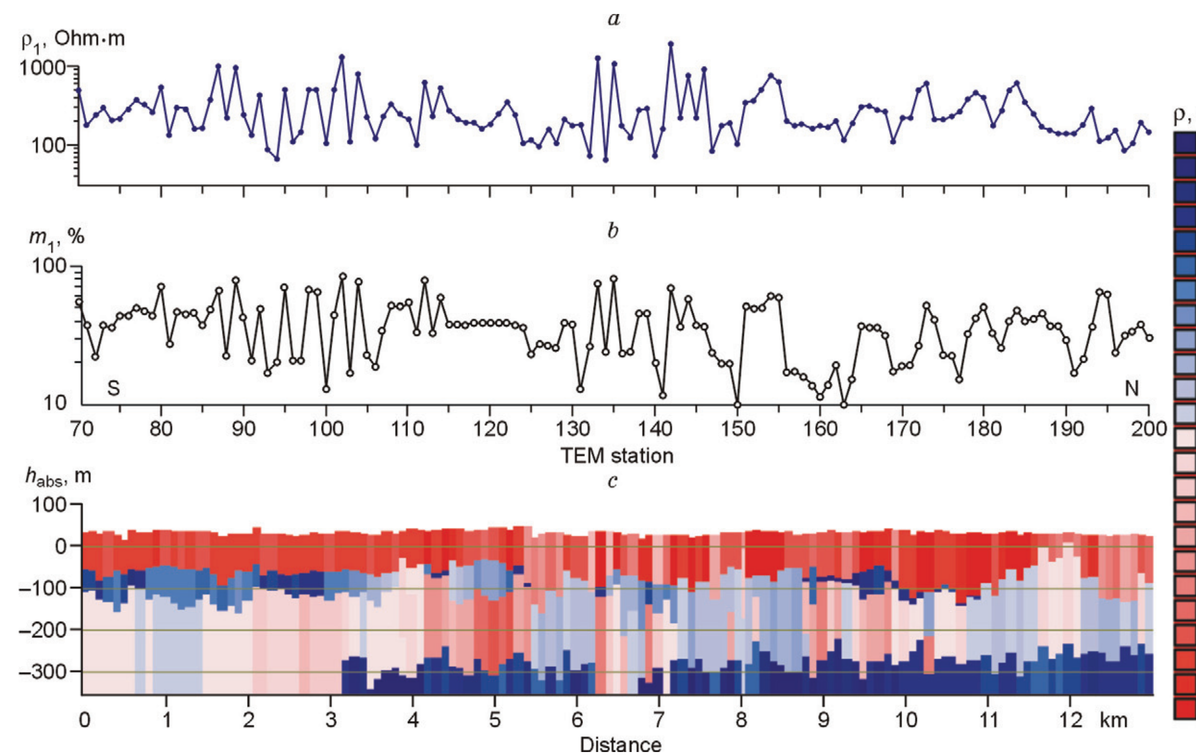

Fig. 8. Upper layer of resistivity ρ_1 (*a*) and chargeability m_1 (*b*), and resistivity section (*c*) along the river profile.

and decreases on further talik thickening (the h_2-dependence curves become less steep). Note that the talik in our case has quite a high resistivity (200 Ohm·m) chosen in order to test the TEM method in rather unfavorable conditions. It is reasonable to expect that ρ_{1inv} will change more strongly if the talik is more conductive (smaller ρ_2) and/or thicker.

In the absence of talik ($h_2 = 0$), the five-layer model degenerates into a three-layer one (Fig. 3) and the parameters of the resistive upper layer found through inversion (m_{1inv}, and τ_{1inv}) almost coincide with the true values (Fig. 6). This is consistent with our previous results for a two-layer polarizable earth (Kozhevnikov and Antonov, 2010) where we demonstrated a high quality of inversion to layer parameters when the upper layer was polarizable.

As the talik becomes thicker, the chargeability of the upper layer m_{1inv} in the equivalent three-layer model decreases (see above) but the time constant τ_{1inv} is either $\tau_{1inv} = 150$ μs without taliks or remains about 100 μs in the presence of a talik, whichever be its thickness. It is unclear why the time constant behaves in this way; we only note that this is a manifestation of equivalence in its estimates.

The thickness of the upper layer h_{1inv} found through inversion of synthetic TEM responses in terms of a three-layer model, irrespective of the talik thickness h_2, differs from the total thickness h_{123} for no more than 15% (10% on average). This is manifestation of H-equivalence: it is the thickness of a resistive layer lying over a conductive layer that controls the TEM response, which is almost independent of the upper layer resistivity if it is much higher than that of the conductive lower layer (Matveev, 1974).

Thus, the numerical experiments demonstrate that inversion of TEM data affected by fast-decaying IP provides the near-surface geoelectrical parameters, which can be used to indicate the presence/absence of taliks and to estimate the total thickness of the upper resistive part of the near-surface.

The above results were obtained for central-loop soundings, whereas the effect of fast-decaying IP will apparently be weaker in the case of the offset-loop configuration used in profile surveys. Furthermore, the actual efficiency of TEM surveys for detection of taliks will obviously depend on geological noise associated with lateral variations in near-surface parameters (resistivity, chargeability and others), but the amount of measurements at the watershed site was insufficient to estimate this noise affecting early-time TEM responses. However, the inference we draw from the numerical experiments that TEM data with significant IIP effects have implications for the search of taliks generally agrees with the results obtained from inversion of offset-loop TEM profile data.

TEM surveys along river and lake profiles: field results

Typical offset-loop transient responses and their inversion using a three-layer earth model with a polarizable upper layer (Fig. 7) show fast-decaying IP effects of different magnitudes from "weak" (Fig. 7*a*) to "strong" (Fig. 7*b*), up to monotony break and double sign reversal (Fig. 7*c*).

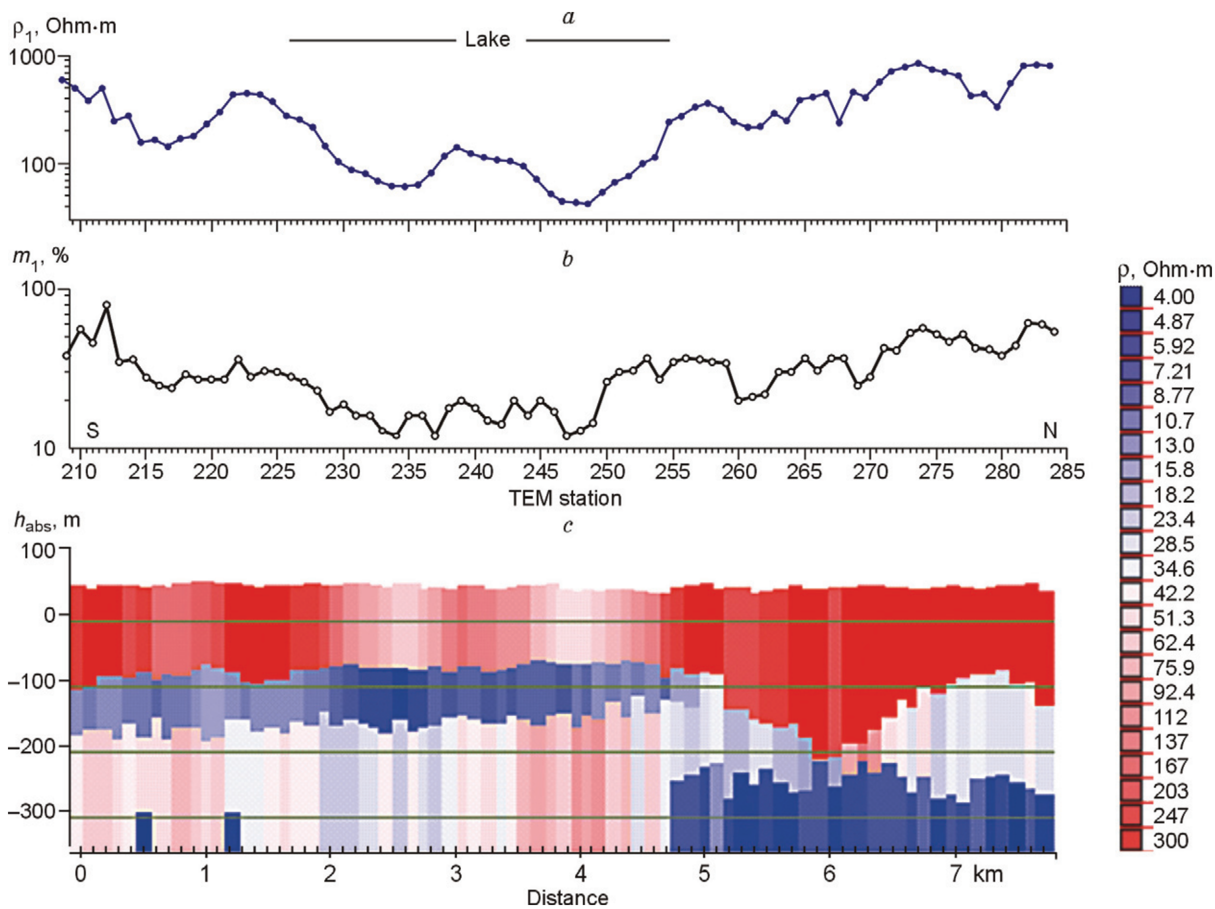

Fig. 9. Upper layer resistivity ρ_1 (*a*) and chargeability m_1 (*b*), and resistivity section (*c*) along the lake profile.

In accordance with the numerical experiment results, data from the river and lake profiles were inverted in terms of a three-layer model with a polarizable upper layer.

The upper layer resistivity ρ_1 and chargeability m_1 along the river profile as well as the resistivity section are shown in Fig. 8 (the image is straightened for clarity). Both ρ_1 and m_1 show uneven variations looking random and lack any regular features to be used as talik indicators. The bottom of the resistive ($\rho_1 > 100$ Ohm·m) upper layer lies between the depths of 50 m and 100 m below the surface (see the resistivity section in Fig. 8*c*) and is almost flat.

The inversion results for the lake profile (Fig. 9) show smaller local lateral variability in ρ_1 and m_1 than those of the river profile. On the regional scale however, regular changes of the parameters are evident within an interval of about 2 km, in the form of two resistivity minimums (40–200 Ohm·m) and a smooth chargeability low. Both resistivity and chargeability anomalies correspond to the large lake. This prompts the presence of a talik, to a large probability.

Two test boreholes and an exploratory hole which were drilled within the TEM anomalies upon completion of TEM surveys, did tap a talik composed of wet sand, of a surface area commensurate with the lake size (2.7 km × 1.7 km) and a thickness of ≈16 m.

The resistivity section (Fig. 9*c*) reveals some geological features not seen in the ρ_1 and m_1 plots. Namely, the thickness of the resistive layer increases significantly between stations 260 and 275 and conductive rocks (5 Ohm·m) occur at a depth about 300 m in the northern profile flank. It is difficult to interpret these features in terms of geology at the time being, but we mention them because they mean that TEM surveys may have other applications in the area except the search for taliks (e.g., 3D geological mapping).

The time constant τ_1 and the exponent c_1 are important diagnostic parameters in studies of polarizable earth. Along both profiles, τ_1 falls into the range from a few tens to a few hundreds of microseconds (about 100 μs on average) and $c_1 \approx 1$, which are the values common to fast-decaying induced polarization in frozen sediments (Kozhevnikov and Antonov, 2012). However, the presence of a talik causes no influence on the τ_1. Thus, among the Cole–Cole parameters, they are near-surface resistivity and chargeability that may be useful for detection of taliks.

Note in conclusion that the surveys along the river and lake profiles were performed using an offset-loop array with a fixed offset (45 m). Meanwhile, joint inversion of TEM responses measured by two arrays of different sizes reduces equivalence in estimates of both polarization parameters and resistivity (Kozhevnikov and Antonov, 2009). Thus multioffset (e.g., with two offsets) TEM soundings may be more informative for exploration of taliks.

Conclusions

TEM responses from the Taz Peninsula of the Yamal-Nenets Autonomous District exhibit strong effects of fast-decaying inductively induced polarization, which makes the nonpolarizable earth model inapplicable to infer the near-surface geoelectrical parameters from the TEM data.

The problem can be resolved by means of TEM data inversion using a model of a polarizable earth with a Cole–Cole complex frequency-dependent conductivity.

The geoelectrical model in the area consists mostly of three layers, with a highly resistive and polarizable 100 m to 250 m thick upper layer. The presence of a talik in it reduces the effective resistivity and chargeability of this layer, which may serve as a diagnostic feature for taliks detection. This inference was drawn from numerical experiments based on test TEM soundings and corroborated by field TEM surveys along the lake profile and subsequent drilling.

Constructive criticism by E.V. Pavlov was helpful to formulate more clearly some of our postulates.

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