Study of the permafrost anisotropy using the controlled source radiomagnetotellurics and electrical resistivity tomography

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Summary

Results of the controlled source radiomagnetotellurics (CSRMT) with a horizontal electric dipole source and the electric resistivity tomography (ERT), obtained in a permafrost area in the Vorkuta region (Russia) are presented. The results of different inversion options compared: (1) isotropic 1D inversion of CSRMT data, (2) isotropic 2D inversion of separate CSRMT and ERT data, (3) joint anisotropic 1D inversion of CSRMT and ERT data. Based on results of the joint anisotropic inversion, a significant resistivity anisotropy of frozen Quaternary clayey sediments with the thickness up to 20 m in the upper parts of sections was revealed and the parameters (horizontal and vertical resistivity and anisotropy coefficient) were determined. In the resistivity sections obtained from the ERT data, the thickness of anisotropic layer is significantly overestimated. As a result, the earlier determined permafrost thickness in this area (more than 40 m) obtained from ERT data was clarified.

Introduction

In permafrost areas the alternation of micro- and macro-layers of sandy and clayey soils often meets, and they are characterized by the anisotropy of electric properties. Due to the different temperature dependence of the resistivity for coarse and fine-grained frozen soils, frozen media appear as anisotropic. Often, when water freezes, ice is released in the form of schlieren, forming lenticular cryogenic textures, which leads to an increase in the anisotropy. The most frequently anisotropic are finely dispersed frozen sediments (clays, loams). Accounting for anisotropy is important in interpreting data of DC and AC electric prospecting methods. Based on the use of anisotropy parameters, approaches have been developed to determine the ice content, an important parameter of frozen strata, which must be taken into account when carrying out the construction work in permafrost areas (Frolov, 1998).

The controlled source radiomagnetotelluric (CSRMT) sounding method has good prospects in the study of anisotropic media. We use a version of this method with a controlled source of electric type - a horizontal electric dipole (transmitter line) (Saraev et al., 2017). To determine the anisotropy parameters, CSRMT data are collected in the transition zone of the source, where the field has a mixed structure, including galvanic and induction modes. In the far-field zone, the field contains only the induction mode, and it is necessary to combine the CSRMT method with a DC method - vertical electrical sounding (VES) or electrical resistivity tomography (ERT). An approach to the joint anisotropic inversion of CSRMT and ERT data was considered in our article (Shlykov et al., 2021). In this extended abstract, we present the results of the CSRMT and ERT studies in the permafrost area near Vorkuta (Russia) and the results of the individual isotropic inversion of CSRMT and ERT data and their joint anisotropic inversion.

Studied area and measurement scheme

Quaternary glacial and alluvial sediments overlying Permian bedrocks (interbedded sandstones, siltstones, mudstones) compose the upper parts of sections at the studied area. The thickness of permafrost in this area, according to results of previous studies, was estimated in the range from 40 to 95 m (Manual, 2022).

Previously, ERT measurements were fulfilled in this area along four profiles 235 m long (Figure 1). The measured data presented in the article (Rossi et al., 2022), which are in an open repository, were used for the joint inversion with CSRMT data. CSRMT soundings were carried out with a step of 10 m along four ERT profiles. The source for the CSRMT method was a transmitter line 480 m long, located along the profiles. The measurements were performed on the source axis, in the area most sensitive to the vertical component of electric resistivity. The distances between the sounding stations and the nearest grounding of the transmitter line ranged from 95 to 340 m. In this case, the low-frequency parts of sounding curves corresponded to the transition zone, and the high-frequency part, to the far-field zone of the source.

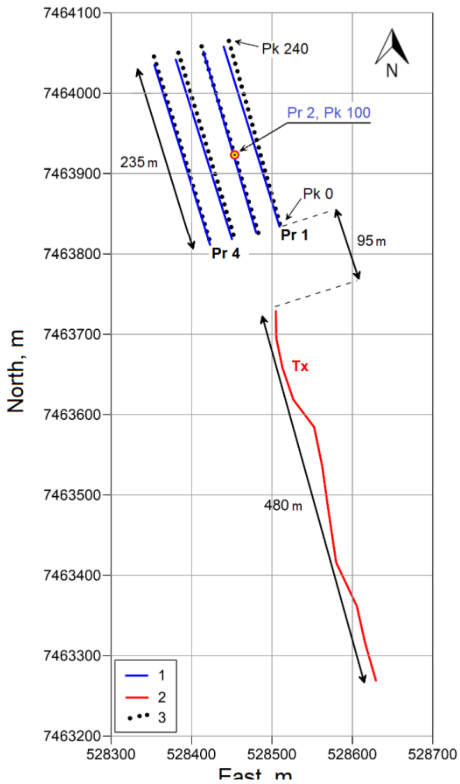

Figure 1 *Scheme of measurements. 1 – ERT profiles, 2 – CSRMT transmitter line, 3 – CSRMT stations. The yellow-red circle marks PK-100 on profile 2.*

The soundings by the CSRMT method were carried out using the GTS-1 transmitter and the RMT-5 recorder (Saraev et al., 2017). The horizontal component of the electric field along profiles (*Ex*) and the horizontal component of the magnetic field (*Hy*) perpendicular to *Ex* were measured, so the soundings were performed in the scalar version. At each sounding station, the field was excited successively at frequencies of 0.5, 5 and 50 kHz. Since the current shape of the GTS-1 transmitter is a rectangular meander, the measurements of the signals of fundamental frequencies and odd subharmonics made it possible to derive detailed sounding curves in the frequency range of 1-1000 kHz

Results

The sounding data were inverted in different ways: (1) isotropic 2D inversion of ERT data in the ZondRes2D program (http://zond-geo.com), (2) isotropic 1D inversion of the CSRMT data, accounting the transition zone, in the CS1D program (Shlykov, 2014), (3) isotropic 2D inversion of CSRMT data accounting the transition zone, in the MARE2DEM program (Key, 2016), (4) anisotropic joint 1D inversion of CSRMT data, accounting the transition zone, and ERT data in the CS1D program (Shlykov et al., 2021). A set of VES data for the 1D inversion was formed by extracting from the 2D set of ERT data (AMN setup) using MN measuring dipoles located close to the CSRMT stations.

An example of a result of the 1D anisotropic joint CSRMT and ERT inversion for PK-100 on the profile 2 (shown in Figure 1) is presented in Figure 2. The apparent resistivity (ρ_a) curve for the VES method is located above the corresponding CSRMT curve. This difference is a result of the influence of anisotropy in the third layer of the section. The anisotropy coefficient $\lambda = \sqrt{\rho_V/\rho_H}$ (ρ_V - vertical, ρ_H - horizontal resistivity) in this layer is estimated by the average value of 2.24 (Figure 2), that is, the vertical resistivity is five times higher than the horizontal one.

At frequencies below 10 kHz, the CSRMT curves go beyond the far-field zone, which manifests in an increase in the values of ρ_a and a decrease in the values of φ_Z. At high frequencies, the field in the CSRMT method corresponds to the far-field zone of the source and depends on the value of ρ_H. The VES field contains a galvanic mode and depends on the resistivity geometric mean $\rho_m = \sqrt{\rho_V \rho_H}$. Therefore, to study the anisotropy of the upper part of the section, it is necessary to combine the CSRMT and ERT methods.

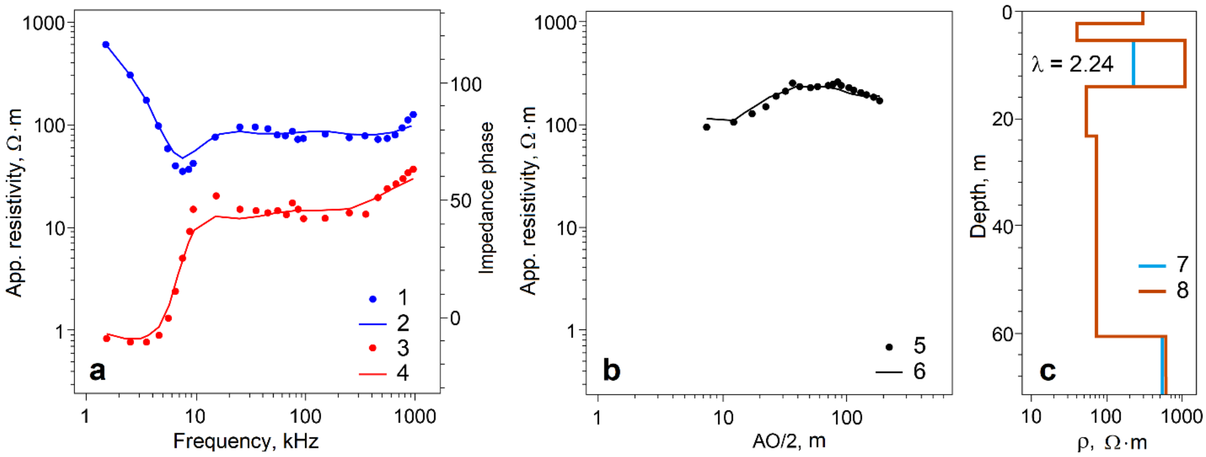

Figure 2 *Results of the joint 1D anisotropic inversion of ERT and CSRMT data for PK-100 in the profile 2. a) CSRMT curves: 1 - ρ_a field curve, 2 - ρ_a model curve, 3 - phase field curve, 4 - phase model curve; b) VES curves for the three-electrode AMN array: 5 – ρ_a field curve extracted from ERT data, 6 – ρ_a model curve; c) 1D anisotropic model: 7 – ρ_H, 8 – ρ_V.*

Geoelectric sections along the profile 2, derived from results of various inversions, are shown in Figure 3. The third anisotropic layer of the section is shown in yellow in Figure 3.3. At some stations, the value of λ reaches 4.7. The isotropic 2D inversion of ERT data significantly overestimates the thickness of the third high-resistive anisotropic layer (shown in red in Figure 3.4). Values of the thickness of the high-resistive layer (from 30 to 50 m) based on the results of previous studies using the ERT method (Rossi et al., 2022) are overestimated.

From drilling data in the vicinity of this area, it was determined that the identified anisotropic layer corresponds to frozen loams with layered and reticulated cryotexture (Rossi et al., 2022). According to results of the joint inversion of the CSRMT and ERT data, the top of the high-resistive anisotropic layer lies at a depth of 2 to 5.5 m, the bottom - from 8 to 20 m (Figures 3.2, 3.3).

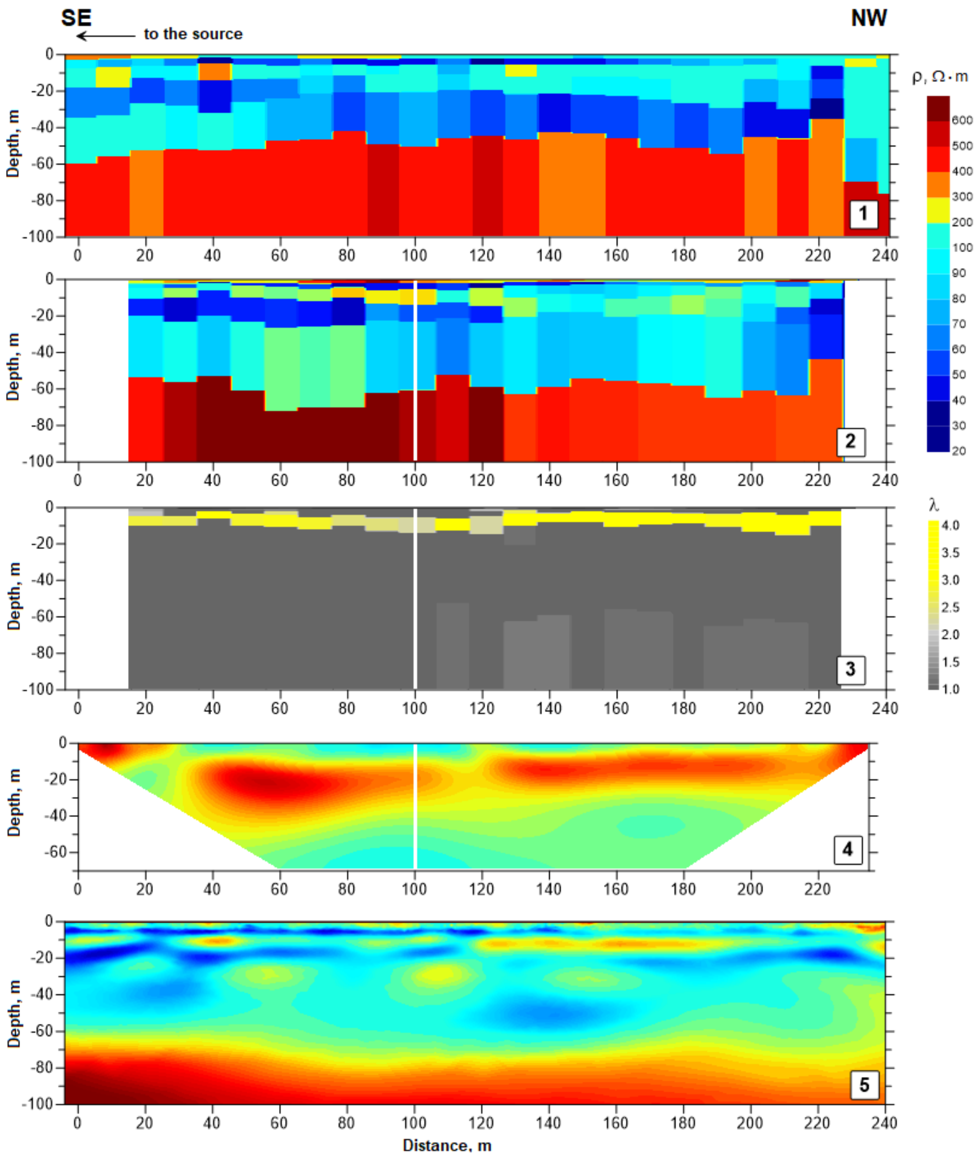

Figure 3 *Geoelectric sections along the profile 2. 1 – 1D isotropic inversion of CSRMT data, considering the transition zone. 2 –* ρ_H *based on the results of joint 1D anisotropic inversion of CSRMT and ERT data, 3 –* λ *based on the results of joint 1D anisotropic inversion of CSRMT and ERT data, 4 – 2D isotropic inversion of ERT data, 5 – 2D isotropic inversion of CSRMT data, considering the transition zone. The vertical white line marks PK-100, for which the sounding curves and the 1D anisotropic models are shown in Figure 2.*

In the lower part of the section, according to the CSRMT data, a high-resistive base was revealed at a depth of 60-70 m, according to the results of both isotropic and anisotropic inversions (Figures 3.2, 3.5).

This layer did not appear in the ERT data, because this method has small depth of investigations in this case. The position of the top of high-resistive base according to results of the 1D isotropic inversion of CSRMT data (Figure 3.1) differs from results of the 1D joint anisotropic inversion of CSRMT and ERT data (Figure 3.2) and the 2D isotropic inversion of CSRMT data (Fig. 3.5). The 1D isotropic inversion of the CSRMT data, due to S-equivalence, underestimates the depth to the high resistive base. Accounting the galvanic mode in the joint inversion of CSRMT and ERT data reduces this effect. According to the 2D isotropic inversion of CSRMT data, the depth to the high-resistive base corresponds to the result of the joint inversion of CSRMT and ERT data.

Conclusions

Based on results of the studies performed, it was shown that the combined use of the CSRMT and ERT methods made it possible to determine the anisotropy parameters (vertical and horizontal resistivity, and anisotropy coefficient) of frozen clayey Quaternary sediments in the upper part of the section, in the depth interval from 2 to 20 m. The anisotropy coefficient varies from 2 to 4. According to the ERT data estimates of the thickness of anisotropic layer, made without considering the influence of anisotropy, are overestimated. The underlying conductive rocks at depths of more than 20 m are probably in the thawed state. Therefore, the results of the studies performed make it possible to clarify the earlier estimates of the permafrost thickness in this area (more than 40 m) obtained from ERT data. According to the CSRMT data the high-resistive base at depths of 60–70 m was identified.

Acknowledgements

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