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GEOPHYSICS

The First Ever Application of Electromagnetic Sounding for Mapping the Submarine Permafrost Table on the Laptev Sea Shelf

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Abstract—The inconsistency between the position of the submarine permafrost table in the East Arctic seas revealed by simulation and anomalies in the distribution of dissolved methane associated with ascending torchlike ejections of bubbling methane made it necessary to develop a representative geophysical express method, which allows the position of the submarine permafrost table to be determined. The method is based on sounding of the generated primary electromagnetic field in the near zone of the medium and measurement of the induced secondary EM field. The reliability of the method is confirmed by core drilling in the Laptev Sea.

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The investigation of regularities in the distribution and degradation of relict frozen sequences on the Arctic shelf of Russia (further, permafrost, or PF) is now one of the most topical tasks. This is primarily determined by the potential climatic role in destabilization of the underlying megapool of gas hydrates and their extensive ejections into the water column and atmosphere [1–3, 6, 7]. It is evident that the presence of a continuous, i.e., gas impermeable, permafrost screen provides for stability of the gas hydrate megapool; otherwise, methane is ejected into the water column and the atmosphere. The recently established inconsistency between the position of the permafrost table revealed by simulation [8, 9] and the position of anomalies in the distribution of dissolved methane [4, 5] associated with ascending torchlike ejections of bubbling methane [6, 7] made it necessary to organize an international scientific consortium, which includes marine biochemists, geophysicists, and permafrost experts, to develop a representative method for mapping the permafrost table. Permafrost degradation related to the sea transgression during the last ~15 kyr stimulates expansion of discharge areas of subpermafrost water on the Siberian Arctic shelf [9], in addition to extensive methane ejections, which increases engineering–geological risks during exploration and development of shelf gas and oil accumulations. This determines the practical significance of such investigations. Unlike on continents, where geophysical methods were developed for permafrost survey several decades ago [10], such investigations for the Arctic shelf are scarce. For example, it is impossible to outline the distribution of permafrost sequences using the data derived from single boreholes drilled on the Laptev Sea shelf. The available seismoacoustic data [11] provide no possibility to discriminate between thawed and frozen rocks as well.

This communication is dedicated to description of the instrumental approach using principles of time–domain electromagnetic sounding technology [12] in natural environments. The method used in this investigation is based on time–domain electromagnetic sounding by generation of the primary EM field in the medium and measurement of the induced secondary EM field, which depends on the electrical resistance of the latter. The depth of the electromagnetic field distribution is determined by its frequency. Thus, measuring the secondary EM field at different frequencies, we receive the chance to estimate the electrical resistance of rocks at different depths. It is of importance that the electrical resistance of permafrost sequences is several orders of magnitude higher as compared with that of thawed rocks. The presence of ice in frozen rocks, which is characterized in the pure state by resistance of 10^6 Ω m, provides the represen-

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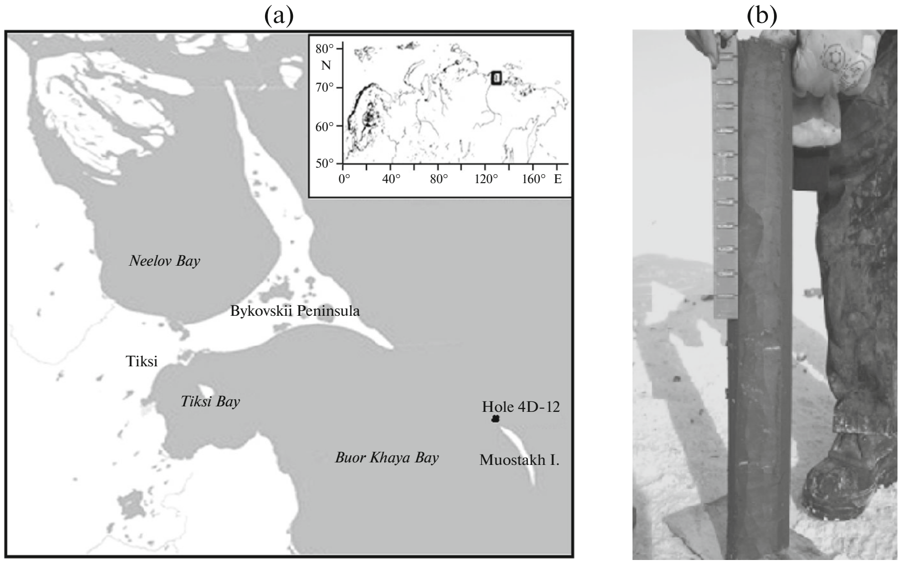

Fig. 1. Schematic map of the study area and location of the point of electromagnetic sounding and Hole 4D-12 (a); frozen core from the interval of 30–31 mbsf of the Hole 4D-12 section (light horizontal lenses are ice schlieren; the remainder of the hole section is characterized by massive cryogenic structures) (b).

tativeness of EM sounding for mapping boundaries between thawed and frozen rocks with variable ice saturation [10]. The uniqueness of this investigation consists in the fact that the first results of EM sounding in the Arctic region were tested by data on boreholes drilled simultaneously by the same scientific team.

Buor Khaya Bay of the Laptev Sea, which has been an object of our complex investigations for a long time beginning from the 1990s [14], was selected as the area for this study. Precisely this area is subjected beginning from spring of 2011 to core drilling aimed at revealing the position of the permafrost table for understanding the mechanism responsible for the formation of gas conduits, which determine ascending migration of methane [13]. Boreholes were drilled without drilling mud from the fast ice surface in March–April. In the first year (March–April of 2011), it was established that the depth of the permafrost table differs from its position assumed previously from the results of mathematical simulation of evolution and the present-day state of frozen rocks on the Laptev Sea shelf [8]. Moreover, it was shown that permafrost is missing at least up to 100 m in areas with a water depth of 12 m and the temperature in the upper 60-m-thick layer of sediments is approximately by 10°C higher as compared with that on land; in this connection, beginning from 2012 sites for drilling and EM sounding were selected within the isobath of 4 m (Fig. 1a), where the presence of permafrost was documented (Fig. 1b). Electromagnetic sounding carried out in the geometrical center of antenna loops was followed by drilling of borehole 4D-12 up to depth of 57 mbsf (Fig. 1b). The water depth at the drilling site was 2.5 m with fast ice being approximately 2 m thick. The hole recovered nonfrozen (thawed and cooled) surface sediments, while permafrost was first penetrated at a depth of 24.3 mbsf. The latter is represented by hard frozen sands with massive cryogenic structures. It should be noted that the intervals of 27–28 and 29–30 mbsf are composed of nonfrozen loams intercalating the sand sequence. Below, the section is represented by loams approximately 2 m thick with rare lenticular cryogenic structures (Fig. 1b), which are underlined up to the hole bottom by sands with massive cryogenic structures.

The geophysical measurements were carried out from the sea ice surface using an antenna consisting of the generating and measuring square loops and the instrumental Tsikl-7 complex [15]. At the first stage, the electromagnetic field was excited by a loop 25 × 25 m in size located on ice and its measurement was conducted by a loop 20 × 20 m in size located in alignment with the exciting loop for the study of the upper part of the geoelectric section, which made it possible to provide high resolution of the analyzed signal to depths of 100 m. The deep part of the geoelectric section was investigated using generating loops 400 × 400 m in size and a measuring loop 100 × 100 m in size located on ice in alignment with the exciting loop. With such sizes of the antenna, measurements of the electromagnetic field made it possible to obtain information of the electrical resistance of rocks up to a depth of approximately 1 km.

The first results of sounding revealed the presence of a high-resistance layer in the geoelectric section near the southeastern margin of the Lena River delta and Muostakh Island (Fig. 2a). The analysis of curves obtained by the time–domain electromagnetic sounding techique with the generating loop 25 × 25 m in size

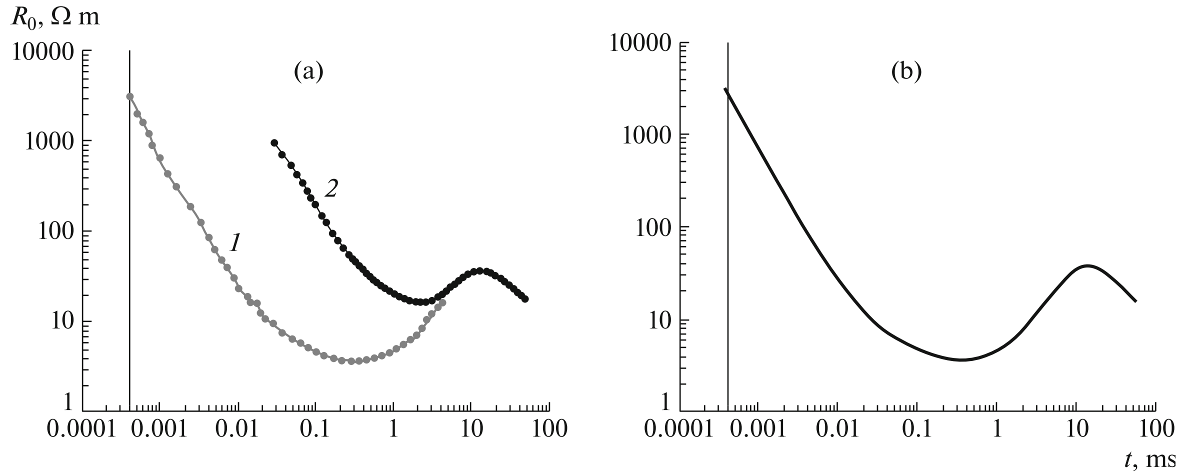

Fig. 2. Observed curves, time–domain electromagnetic sounding in the Muostakh Island area, Laptev Sea, antenna sizes: (*1*) 25 × 25 m, (*2*) 400 × 400 m (a); composite curve obtained by the time–domain electromagnetic sounding method in the Muostakh Island area (b).

indicates an increase in the apparent resistance with time (i.e., with depth) in the interval of 0.4–4.0 ms. The analysis of curves obtained by the time–domain electromagnetic sounding method with a generating loop 400 × 400 m in size reveals an increase in the apparent resistance with depth in the interval of 3–10 ms and its decrease in the interval of 20–50 ms (Fig. 2a). Figure 2b demonstrates the integral curve obtained by the time–domain electromagnetic sounding method in the Muostakh Island area. Its analysis allows the conclusion that electromagnetic sounding documented the high-resistance layer in the Muostakh Island area with an apparent resistance of >40 Ω m, which is 1–2 orders of magnitude higher as compared with that obtained for nonfrozen sequences. These data allow the electrical resistance of this layer and its depth to be estimated for its entire thickness from the top to the base.

The EM sounding was primarily aimed at assessing the reliability and accuracy of the obtained data. In this connection, two electromagnetic sounding procedures were performed near the northern extremity of Muostakh Island (Fig. 1) with generating loops 25 × 25 and 400 × 400 m in size (Fig. 2a). The measurements were conducted in the area of planned core drilling prior to the arrival of the drilling equipment. This made it possible to exclude the influence of the metallic equipment on the sounding results and obtain undistorted data on the position of the permafrost table. These measurements were followed by mathematical simulation of the geoelectric section using the data obtained by the time–domain electromagnetic sounding method. For mathematical simulation, the Faraday software (developed by P.Yu. Pushkarev, Moscow State University) was used. This program allows the electromagnetic field of the dipole to be calculated in the 1D medium. The technique of calculation of the dipole electromagnetic field at the surface of the horizontally bedded medium is described in detail by M.S. Zhdanov (1986). This model constructed for the point where hole 4D-12 was drilled after electromagnetic sounding is exemplified below.

The mathematical simulation consisted in the assignment of the three-layer horizontally bedded medium model (Fig. 3) and calculation of the electromagnetic field, which is induced by the generating loop (dipole) at the medium surface and measured by the receiving loop. Subsequently, the software made it possible to calculate the curve of the apparent resistance at the medium surface in accordance with [12]. Further, the calculated and observed curves derived from the time–domain electromagnetic sounding technology are compared with each other. If these curves demonstrate inconsistency, their consistency is achieved by changing the geoelectric model of the medium, i.e., changing the electrical resistance and thickness of layers (Fig. 3). When the consistency between the calculated and observed curves is achieved with an accuracy of 5%, changes in the geoelectric model are stopped and simulation is considered to have been successfully accomplished. The last geoelectric model, which provides the consistency between the calculated and observed curves, is considered as the final one (Fig. 3).

Figure 3 presents the model of the geoelectric section near Muostakh Island. According to observations and mathematical simulation, the top of the high-resistance layer is located at a depth of 25 mbsf (Fig. 3). The electrical resistance of the high-resistance layer amounts to 300 Ω m. For obtaining true values of the electrical resistance of frozen rocks recovered by drilling, we carried out its measurements using samples from Hole 4D-12 characterized by their natural states and salinity. In the middle, more ice-saturated part of the frozen rock section in the depth interval of 31.5–40.0 mbsf, the electrical resistance of sands is

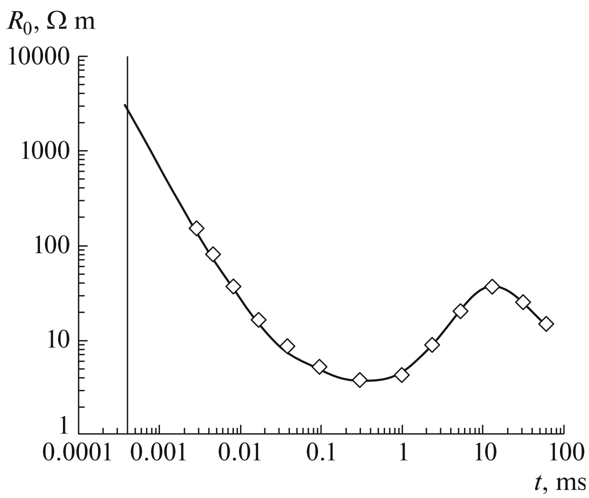

Fig. 3. Results of simulation of the geoelectric section at the drilling site of Hole 4D-12. The line corresponds to the observed curve of time–domain electromagnetic sounding; points are results of simulation. Geoelectric model: $R_0 = 3.8$ Ω m, $H = 25$ m (layer 1), $R_0 = 300$ Ω m, $H = 600$ m (layer 2), $R_0 = 1.5$ Ω m (layer 3).

estimated to be 500 Ω m and that for sands in the interval of 40–55 mbsf is equal to 300 Ω m. The measurements of this parameter in core samples from holes allow its true values to be assigned to layers in the geoelectric model while processing the results of electromagnetic sounding. Inasmuch as the field of the electromagnetic dipole at the surface of the horizontally bedded medium depends on both the electrical resistance of layers and their thicknesses [12], the electrical resistance measured in the drill core may be used for determining the thickness of layers with different values of this parameters up to depths of the permafrost table.

The question concerning the possibility of mapping the permafrost base requires additional investigations, since there are no reasons to correlate the base of the high-resistance layer with that of the permafrost: the electrical resistance of the high-resistance layer may be controlled by gas hydrates, gases, bedrock, or a combination of these factors. Nevertheless, this investigation demonstrates for the first time the possibility of electromagnetic sounding application for mapping the permafrost table. The comparison of results of anticipatory measurements by the time–domain electromagnetic sounding method and Hole 4D-12 drilling demonstrate good consistency between the depth estimates obtained for the permafrost table: 25.0 and 24.3 mbsf, respectively. Thus, the electromagnetic investigations on the Laptev Sea shelf in the Buor Khaya Bay area revealed development of the high-resistance layer. The comparison between the occurrence depth of the top of this high-resistance layer and drilling results shows that its existence associates, at least in the upper part of the section, with permafrost and the position of the permafrost table is determined with high accuracy. This allows the time–domain electromagnetic sounding method to be used for mapping the top of relict frozen sequences on the Arctic shelf.

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REFERENCES

1. N. E. Shakhova, V. I. Sergienko, and I. P. Semiletov, Herald Russ. Acad. Sci. **79** (3), 237–246 (2009).
2. N. E. Shakhova, D. Yu. Nikol'sky, and I. P. Semiletov, Dokl. Earth Sci. A **429** (9), 1518–1521 (2009).
3. D. Nicolsky and N. Shakhova, Environ. Res. Lett. **5**, 015006 (2010). doi 10.1088/1748-9326/5/1/015006
4. N. Shakhova, I. Semiletov, A. Salyuk, V. Joussupov, D. Kosmach, and O. Gustafsson, Science **327**, 1246–1250 (2010).
5. N. Shakhova, I. Semiletov, I. Leifer, P. Rekant, A. Salyuk, and D. Kosmach, J. Geophys. Res. **115**, C08007 (2010). doi 10.1029/2009JC005602
6. N. Shakhova, I. Semiletov, I. Leifer, V. Sergienko., A. Salyuk, D. Kosmach, D. Chernikh, C. Stubbs, D. Nicolsky, V. Tumskoy, and O. Gustafsson, Nat. Geosci. **7** (1), 64–70 (2014). doi 10.1038/NGEO2007
7. N. Shakhova, I. Semiletov, V. Sergienko, L. Lobkovsky, V. Yusupov, A. Salyuk, A. Salomatin, D. Chernykh, D. Kosmach, G. Panteleev, D. Nicolsky, V. Samarkin, S. Joye, A. Charkin, O. Dudarev, A. Meluzov, and O. Gustafsson, Philos. Trans. R. Soc. A **373**, 20140451 (2015). doi 10.1098/rsta.2014.0451
8. N. N. Romanovskii, A. V. Gavrilov, T. P. Pustovoit, et al., Kriosfera Zemli **1** (3), 9–18 (1997).
9. N. N. Romanovskii, H.-W. Hubberten, A. V. Gavrilov, A. A. Eliseeva, and G. S. Tipenko, Geo-Mar. Lett. **25**, 167–182 (2005).
10. V. K. Khmelevskoi, *Electrical Exploration* (Moscow State Univ., Moscow, 1984) [in Russian].
11. A. G. Skvortsov, M. R. Sadurtdinov, and A. M. Tsarev, Kriosfera Zemli **18** (2), 83–90 (2014).
12. M. S. Zhdanov, *Electrical Exploration* (Nedra, Moscow, 1986) [in Russian].
13. I. P. Semiletov, N. E. Shakhova, V. I. Sergienko, I. I. Pipko, and O. Dudarev, Environ. Res. Lett. **7**, 015201 (2012). doi 10.1088/1748-9326/7/1/015201
14. I. P. Semiletov, I. I. Pipko, N. Ya. Pivovarov, V. V. Popov, S. A. Zimov, Yu. V. Voropaev, and S. P. Daviodov, Atmos. Environ. **30**, 1657–1671 (1996).
15. A. K. Zakharkin, *Methodological Recommendations on Electrical Exploration by Probing Field Steady-Stating in Nearest Zone With the Help of "Cycle" Equipment* (Siberian Sci. Res. Inst. Geol., Geophys., Miner. Raw. Materials, Novosibirsk, 1981) [in Russian].

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