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ИЗВЕСТИЯ

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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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A. E. Melnikov[1, 2], N. N. Grib[1], Zhang Ze[3]

[1]Technical Institute (branch) of North-Eastern Federal University named after M.K. Ammosov Neryungri, Russia,
[2]Melnikov Permafrost Institute of the Siberian Branch of the Russian Academy of Sciences, Yakutsk, Russia,
[3]Main State Laboratory of Engineering Geocryology, North-West Institute of Eco-Environment and Resources, Chinese Academy of Sciences, PRC.
E-mail: MelnikowDron@mail.ru, grib@nfygu.ru, zhangze@lzb.ac.cn

LOCALIZATION OF THERMOKARST PROCESSES IN THE SWATHE OF A GAS TRUNKLINE USING GEOPHYSICAL METHODS

Abstract. This paper presents the results of a series of geophysical studies carried out at a natural gas pipeline site in South Yakutia. The research was aimed at delineating areas in which hazardous cryosolic processes and phenomena can occur. To this end, the research objectives included a determination of the boundaries of areas where permafrost is present, a determination of the capacity of the seasonally thawed (seasonally frozen) layers and talik areas, as well as the establishment of underground ice boundaries and presence of karst cavities in the ground. It is established that the main threat to the economic development of the territory is active permafrost degradation causing the formation of thermokarst depressions of various sizes with deep talik zones underneath. It is noteworthy that several cycles of this cryogenic process are simultaneously observed over a limited area (having a length of less than 2 km): from the emergence of a thermokarst depression to the formation of a submerged funnel with a depth of several metres. The localisation of such anomalies is very accurately interpreted using such geophysical methods as electron tomography and ground-penetrating radar (GPR).These methods are sufficiently valid for a real-time determination of the characteristics of hazardous cryogenic processes and phenomena in given geological engineering and geocryological situations. The results obtained from testing wells at the site under investigation are characterised by high convergence with those of the qualitative interpretation of geophysical sections.

The specific features of thermokarst phenomena described for an individual site of the Power of Siberia natural gas pipeline are characteristic for the entire route of this pipeline passing through the territory of South Yakutia.

Keywords: South Yakutia, cryogenic processes, gas pipeline, electron tomography, GPR sounding, drilling of wells, thermokarst.

Introduction. The paper presents the results of geophysical studies and drilling works carried out during the construction of the Power of Siberia gas trunkline, which are aimed at delineating the areas of the development of hazardous permafrost processes and phenomena. In particular, data are presented on the nature of developingthermokarstprocesses in a particular section of the structure. The features of thermokarst manifestation described below for the pipeline section are characteristic of almost the entire route of a linear installation passing through the territory of South and Central Yakutia [2, 7, 10, 15].

*General characteristics of the work area.*Geomorphologically, the territory comprises a mid-mountainous region composed mainly of Archean strata, overlapping horizontal Cambrian sediments interspersed with isolated intrusive massifs [3]. These form a monotonous table-step relief with small absolute elevations (up to 1000 m). The climate of the area under study is characterised as sharply continental, associated with the relatively high latitude of the territory under consideration and, consequently, a lower level of solar irradiance. The continental climate here manifests itself in low annual and winter temperatures, large seasonal and diurnal fluctuations and low precipitation [9, 11]. For this climate, a key characteristic is the long duration of the winter period, which typically lasts 7 to 7.5 months. On some days, the air temperature can fall to -50ºC almost everywhere. The long cold season contributes to the deep freezing of lakes and rivers along the line of the linear structure – often involving the complete freezing of the latter – and the formation of frost. The difference in average temperatures between seasons is more than 50ºC. Located in the zone of sub-open-air light forests and goletz deserts, the region is characterised by severe permafrost conditions [5, 8, 16]. Here exist both low-temperature perennially cryotic rocks (PCR) of continuous distribution as well as large massifs of thawed rock with individual islands of permafrost. The depth of the permafrost roof is in the range of 0.5–3.5 m and is determined by the value of its seasonal thaw. The PCR depth varies from 10 to 500 m. Its maximum values are characteristic of mountain elevations. The average annual temperature of rocks varies from 0 to -4.5ºC. On watersheds with absolute elevations of 1400–1500 m, the average annual temperature of rocks can reach -8ºC. The levelled, weakly-dissected relief with impededsurface water runoff conditions, as well as the widespread development of PCR, causes the widespread formation of wetlands, various thermokarst forms and pingos.

General characteristics of the area under study[17] (figure 1). The length of the study area was 1.8 km. Here the gas pipeline route crosses an extensive depressed hollow from north to south. Relative elevations within the entire area are notgreater than 5 m. On gentle slopes, surface sediments consist of sandy loams and light clay soils with a thickness of 2.5–3.2 m. On the northern slope, they are underlain by native sandstones, while the southern slope features perennially cryotic, slightly icy sandy loams and

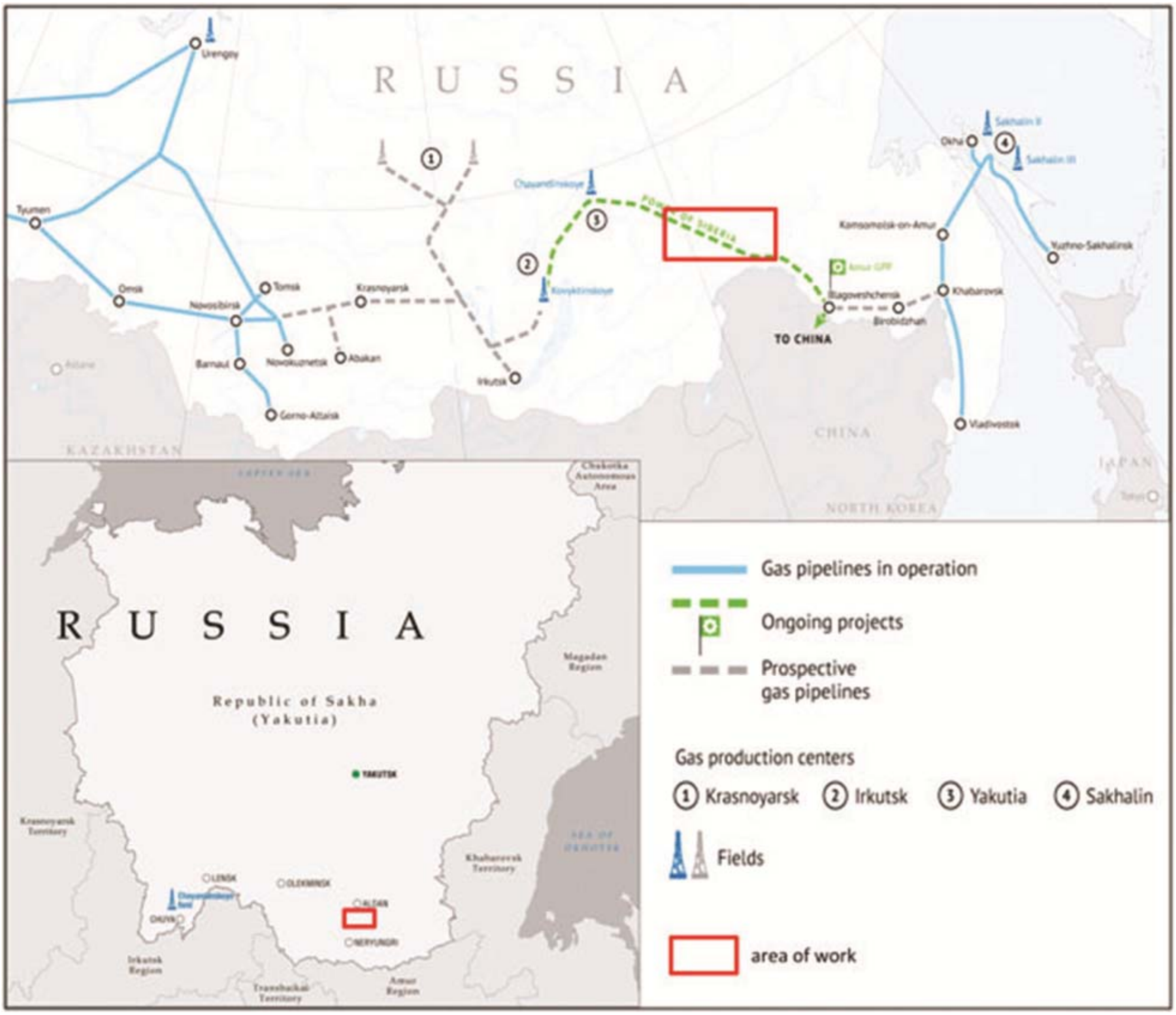


Figure 1 – Survey map of the area of study

soils having a thickness of more than 10 m. In the basin itself, the surface sediments are composed of highly decomposed peat with a thickness of 1.4–1.9 m, below lies the horizon of sandy loam and light loam, which can be traced in some places to a depth of 15 m. The lower part of the basin has a marshland character with a wide extension of degrading peatlands and numerous sinkholes having significant areal dimensions (figure 2).

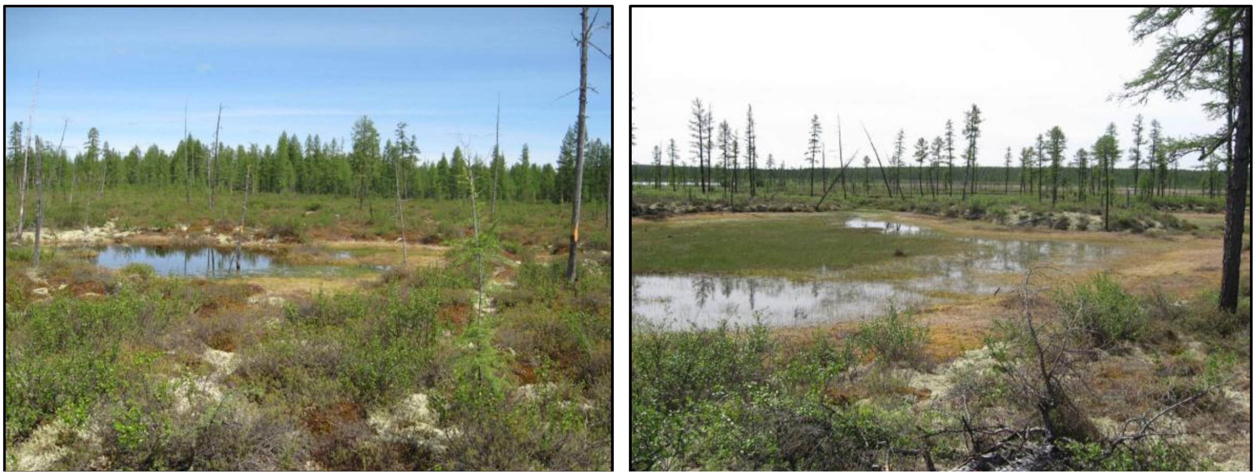


Figure 2 – Inundated thermokarst hollow on the surface of the peatland [17]

Working Methodology. The complex of geophysical studies included electro-tomography [1, 19] – the use of which in Russia is regulated by the Federal Agency for Construction, Housing and Communal Services [14] – and ground-penetrating radar (GPR) [6]. Geophysical methods were assigned the following main tasks: the establishment of boundaries in terms of sites with the presence and absence of PCRs; determination of the thickness of the seasonally thawed layer and talik zones; the establishment of boundaries for the development of underground ice and the presence of karst cavities in the massif.

To solve the tasks, based on the known geocryological, hydrological, technological and other conditions of the studied area, electrical exploration work was carried out using Scala-48 equipment (Electrometry Design Bureau, http://nemfis.ru) with Schlumberger installation. The depth of the study of the soil massif was 40 m. The minimum length of the geophysical profile is 235 m. For primary data processing, including filtering, compiling and exporting to IPI2Win, Res2dInv, Res3dInv formats for further construction of geophysical sections, the SibER Tools program was used.

GPR surveys were carried out using the “OKO-2” equipment with “Triton” antenna unit (LogisGeotech, http://www.geotech.ru). The depth of the soil massif subjected to GPR was 40 m. The assembly, processing and interpretation of obtained georadar data was carried out using the Geoscan32 program.

The works were carried out in three phases. The first comprised geophysical surveys with preliminary interpretation of the data obtained. At this stage, an assessment of the characteristics of the hazardous area was carried out and a determination of the possible locations of confirmatory boreholes was made. The locations of the geophysical profiles and boreholes are shown in figure 3. The second stage included the actual drilling of bores. At the third stage, a comparison of geophysical sections and drilling data was carried out.

Results. The results of the qualitative interpretation of geophysical sections in the study area are shown in table 1. For the site, two well locations on profiles 29 and 34 are recommended (see figure 3). Geophysical anomalies corresponding to the probable presence of PCR are noted on these profiles. The main hazard for the construction is the presence of thermokarst structures. Geophysical anomalies, indicating the development of thermokarst processes, were recorded in all longitudinal profiles.

The differences in the dynamics of the development of this cryogenic process in a limited area are highly indicative in the constructed sections of profiles 29 and 34 (figures 4, 5). Thus, in contrast to the wave pattern of peat and underlying sands, a phase correlation region is distinguished on the GPR section

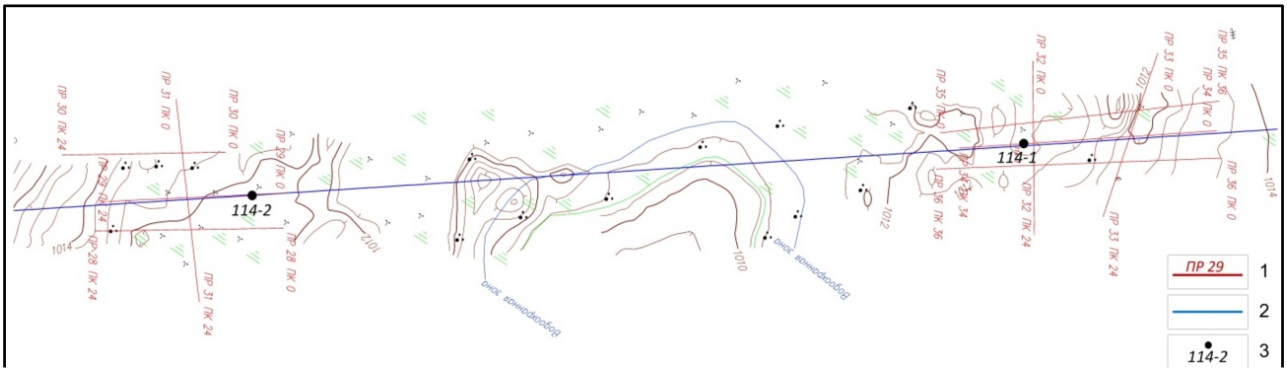


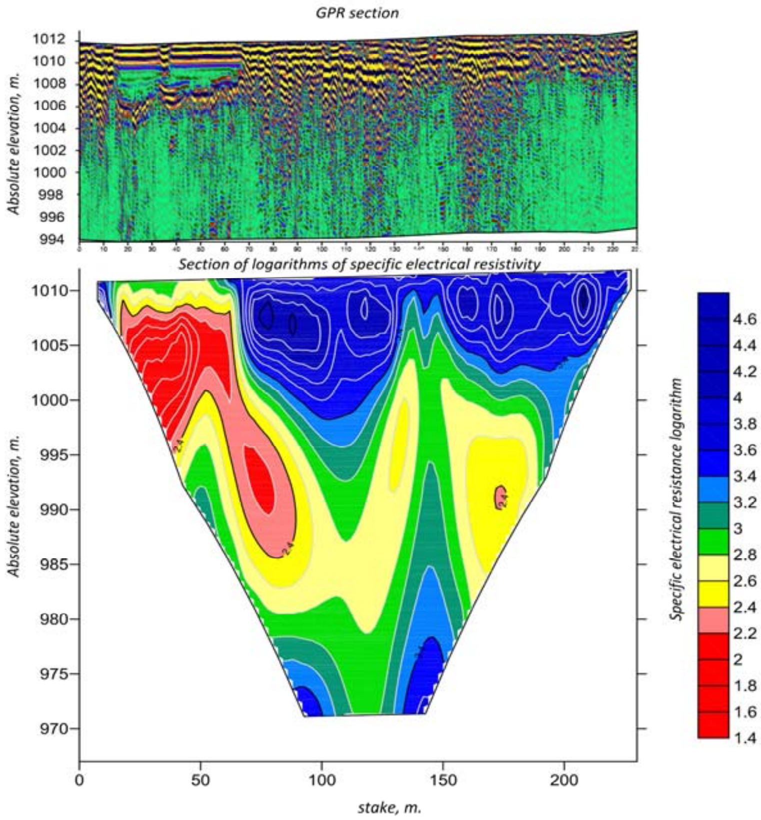
Figure 3 – Arrangement of geophysical profiles at the study site:
1 - geophysical profile; 2 - gas pipeline route; 3 - borehole and its number

of profile No. 34. A wave pattern of this type is typical for inundated objects that are bounded below by a layer with good reflective properties. The stages of thermokarst development are clearly expressed in the resistivity section. The thawing of the soil massif to the left of bore No. 114-1 on the profile has just begun (see figure 5); the funnel to the right represents a thermokarst in active drawdown phase. For profile 29, thermokarst is characterised by an even more intensive development, with a through talik having formed in the frozen layer.

Table 1 – Results of the qualitative interpretation of geophysical sections in the study area

Characteristics	Qualitative assessment								
	Profile								
	No. 28	No. 29	No. 30	No. 31	No. 32	No. 33	No. 34	No. 35	No. 36
Intervals located close to the surface of the PCR	100.0 – 230.0 m. A talik is established on the interval of 0 – 100.0 m.	67.0 – 230.0 m. A talik is established on the interval of 17.0 – 100.0 m.	45.0 – 75.0 m. Taliks are established at intervals of 10.0 – 45.0 m and 175.0 – 230.0 m.	0 – 230.0 m	0 – 230.0 m	0 – 230.0 m	50.0 – 340.0 m. A talik is established on the interval of 266 – 284 m.	0 – 80.0 m, 96.0 – 233.0 m. A talik is established on the interval of 80.0 – 96.0 m.	33.0 – 105.0 m, 159.0 – 264.0 m, 273.0 – 350.0 m. A talik is established on the interval of 264.0 – 273.0 m.
Depth of seasonally thawed layer	from 0.2 – 4.0 m	not expressed on geo-physical sections	not expressed on geo-physical sections	not expressed on geo-physical sections	not expressed on geo-physical sections	not expressed on geo-physical sections	0.5 – 1.0 m	0.5 – 1.0 m	0.5 – 1.0 m
Loose sediment thickness	6.0 – 12.0 m	6.0 – 12.0 m	3.0 – 9.0 m	3.0 – 9.0 m	4.0 – 9.0 m	4,0 – 20.0 m	4.0 – 9.0 m	4.0 – 10.0 m	4.0 – 10.0 m
Recorded depth of PCR roof	4.0 – 12.0 m	from 0 m	from 0 m	from 0 m	from 0 m	from 0 m	from 0.5 m	from 0.5 m	from 0.5 m
Probable bottom edge			at a depth of 11 m	from 3 to 15 m	from 16 to 25 m	from 40 to 45 m	from 10 to 25 m	from 10 to 25 m	from 10 to 25 m
Depth of talik zones	more than 40 m	more than 40 m	more than 40 m	not inter-sected	not inter-sected	not inter-sected	4.2 m	Lower limit of the talik deeper than 40 m	2.2 m
Interval of probable presence of ice formation	180.0 – 202.0 m	71.0 – 101.0 m 111.0 – 128.0 m 155.0 – 168.0 m	47.0 – 66.0 m	0 – 9.0 m	35.0 – 80.0 m 90.0 – 148.0 m 187.0 – 230.0 m.	67.0 – 96.0 m	122.0 – 266.0 m. 284.0 – 340.0 m.	40.0 – 70.0 m 108.0 – 156.0 m.	610.0 – 256.0 m. 285.0 – 328.0 m

Profile No. 29



Profile No. 34

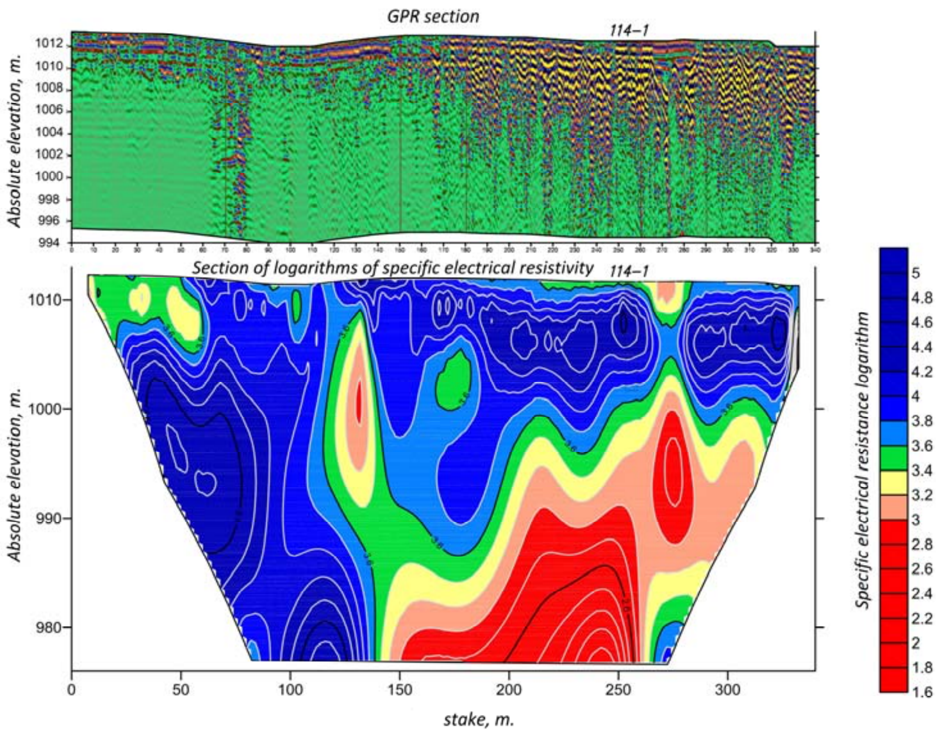


Figure 4 – GPR cut and section log of specific resistivity along geophysical profiles 29 and 34

Profile No. 29

Profile No. 34

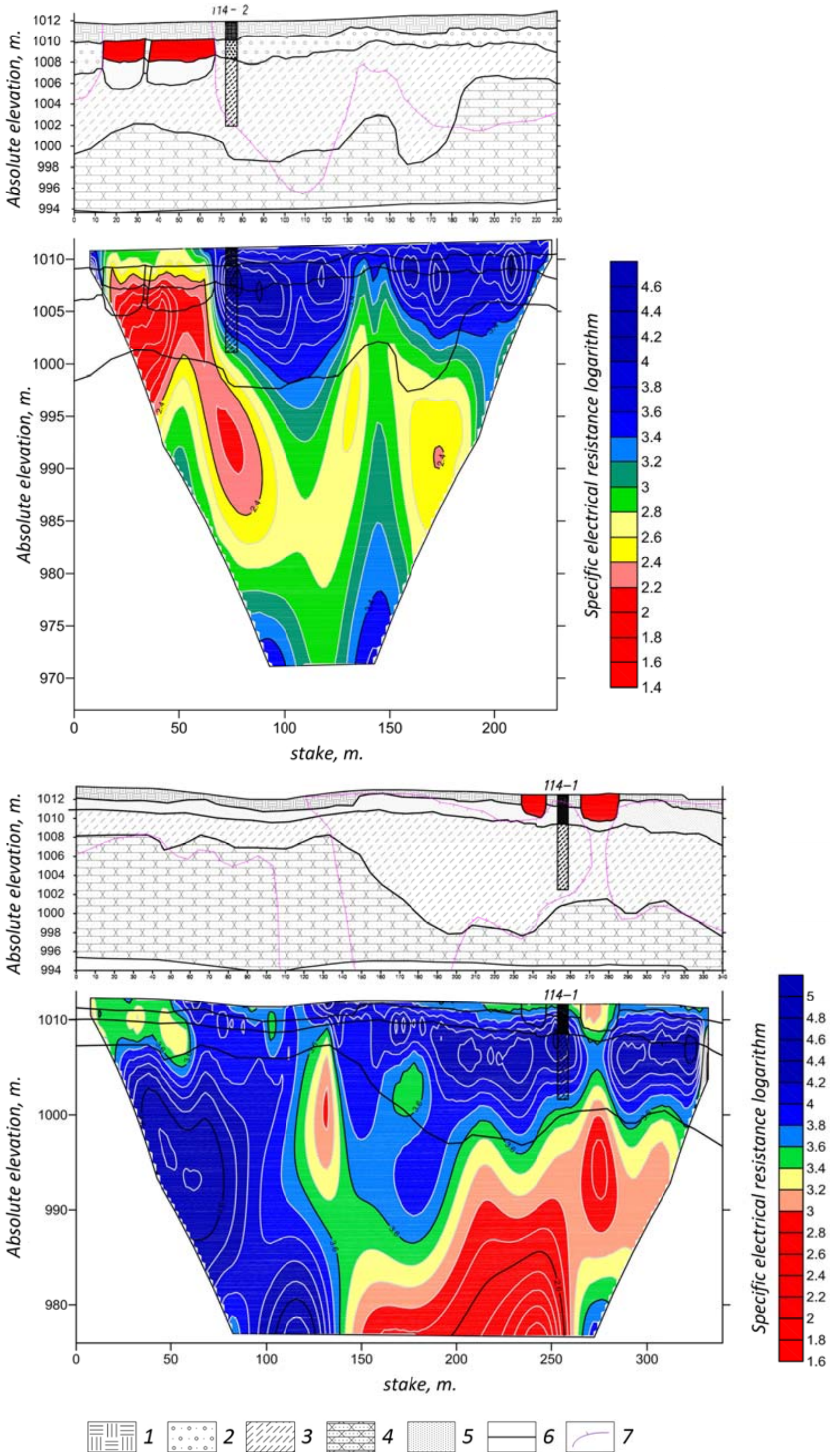


Figure 5. Results of the interpretation of complex geophysical data for profiles 29 and 34:
1 – peat; 2 – gravel sand; 3 – sandy loam; 4 – sandstones; 5 – fine sand; 6 – geological boundaries;
7 – boundaries of frozen rocks, runoffs – in the direction of permafrost

No less hazardous are the intervals of frozen rocks, separated by complex geophysical features. The soils of the section are subject to ice formation. Given that the frozen stratum is composed of sand, sandy loam and loam (table 2), a high degree of probability of liquefaction of soils due to thawing under technogenic impact can be assumed.

Table 2 – Data from boreholes No. 114-1 and No. 114-2 [18]

Borehole number 114-1			
Layer thickness, m	Depth of layer, m	Absolute elevation of the sole of the layer, m	Names of rocks and their characteristics
0.10	0.10	1011.71	Topsoil layer, frozen
1.10	1.20	1010.61	Brown peat, poorly decomposed, with organic residues; hard-frozen, cryogenic massif texture; water-saturated when thawed. From a depth of 0.4 m with an admixture of up to 30-50% of fine sand and pebbles 3-5%.
1.90	3.10	1008.71	The sand is fine, grey, hard-frozen; cryogenic massif texture, water-saturated when thawed.
6.90	10.0	1001.81	Sandy loam is grey, hard-frozen; plastic when thawing; massive cryogenic texture, less frequently lenticular; thickness of ice inclusions – 0.5-1.0 cm.
Borehole number 114-2			
0.10	0.10	1012.34	Topsoil layer, frozen
1.70	1.80	1010.64	Brown peat, poorly decomposed, with organic residues; hard-frozen, cryogenic massif texture; less frequently – lenticular; the thickness of ice inclusions is 0.5-1.0 cm, shot point line = 0.2 –unit fraction when water-saturated during thawing.
1.80	3.60	1008.84	The sand is gravelly, light grey, hard-frozen; cryogenic crusted texture, shot point line = 0.1 unit fraction when water-saturated due to thawing.
6.40	10.0	1002.44	Sandy loam is grey, hard-frozen; plastic when thawing; massive cryogenic texture, less frequently lens-shaped; thickness of ice inclusions – 0.5-1.0 cm.

Conclusion. The complex of geophysical studies, including electro-tomography and GPR sounding, has proven its effectiveness in localising thermokarst structures and processes in South Yakutia in the zone of influence of a linear structure.

The geophysical methods applied are sufficiently valid for a real-time determination of the characteristics of hazardous cryogenic processes and phenomena in given geological engineering and geo-cryological situations. The considered set of methods can be recommended for solving problems of identifying potentially hazardous cryogenic processes during the construction of linear structures.

А. Е. Мельников[1, 2], Н. Н. Гриб[1], Чжан Цзе[3]

М. К. Аммосов атындағы СШФУ (филиалы) техникалық институты, Нерюнгри, Ресей,
[2]ФМҒҚМ «П.И. Мельников атындағы Тоңтану институты» РҒА СБ, Якутск, Ресей,
[3]Инженерлік геокрологияның негізгі мемлекеттік зертханасы,
Солтүстік-Батыс Экология және Табиғи ресурстар институты, Қытай ғылым академиясы, ҚХР

ТЕРМОКАРСТ ҮДЕРСІСТЕРДІҢ МАГИСТРАЛДЫ ГАЗ ҚҰБЫРЫНЫҢ АЛҚАБЫНДА ГЕОФИЗИКАЛЫҚ ӘДІСТЕРІМЕН ОҚШАУЛАУ

А. Е. Мельников[1, 2], Н. Н. Гриб[1], Чжан Цзе[3]

[1]Технический институт (филиала) «СВФУ им. М. К. Аммосова», Нерюнгри, Россия,
[2]ФГБУН «Институт мерзлотоведения им. П. И. Мельникова» СО РАН, Якутск, Россия,
[3]Главная Государственная Лаборатория Инженерной Геокриологии,
Северо-Западный Институт Экологии и Природных Ресурсов, Китайская Академия Наук, КНР

ЛОКАЛИЗАЦИЯ ТЕРМОКАРСТОВЫХ ПРОЦЕССОВ ГЕОФИЗИЧЕСКИМИ МЕТОДАМИ В ПОЛОСЕ МАГИСТРАЛЬНОГО ГАЗОПРОВОДА

Аннотация. В работе отражены результаты геофизических исследований, проведенные на отдельном участке магистрального газопровода в Южной Якутии. Изыскания были направлены на оконтуривание площадей развития опасных мерзлотных процессов и явлений: определение границ участков в плане с наличием и отсутствием многолетнемерзлых пород; определение мощности сезонно-талого (сезонно-мёрзлого) слоя и таликовых зон; установление границ развития подземных льдов и наличия карстовых полостей в массиве грунтов. Установлено, что основную опасность при хозяйственном освоении территории представляют активно деградирующие в настоящее время массивы многолетнемерзлых пород, обуславливающие образование термокарстовых просадок разных размеров и глубоких таликовых зон под ними. Примечательно, что на ограниченной площади (протяженностью менее 2 км) одновременно наблюдаются несколько циклов развития данного криогенного процесса – от «зарождения» термокарстового проседания до формирования обводнённой воронки с глубиной в несколько метров. Локализация таких аномалий весьма точно интерпретируется комплексом геофизических исследований, включающего в себя электротомографию и георадиолокационное зондирование. Информативность использованных методов в большинстве случаев достаточна для оперативного определения характеристик опасных криогенных процессов и явлений в данной инженерно-геологической и геокриологической обстановках. Данные результатов бурения заверочных скважин на исследуемой территории характеризуются высокой сходимостью с результаты качественной интерпретации геофизических разрезов.

Описанные в работе для участка трубопровода «Сила Сибири» особенности проявления термокарста характерны практически для всей трассы линейного объекта, проходящего по территории Южной Якутии.

Ключевые слова: Южная Якутия; криогенные процессы; газопровод; электротомография; георадиолокационное зондирование; бурение скважин; термокарст.

Information about authors:

Melnikov Andrey E., Cand. Sci. (Geology and Mineralogy), Head of the Research Department of the Technical Institute (branch) of the North-Eastern Federal University named after M.K. Ammosov, Neryungri, Russia; Researcher, Laboratory of Geothermal Cryolithozone of the Permafrost Institute named after P.I. Melnikov, SB RAS, Yakutsk, Russia. MelnikowDron@mail.ru; https://orcid.org/0000-0002-7910-9441

Grib Nikolai N., Dr. Sci. (Engineering), Prof., Department of Mining at the Technical Institute (branch) of the North-Eastern Federal University named after M.K. Ammosov Neryungri, Russia; grib@nfygu.ru; https://orcid.org/0000-0002-3818-9473

Ze Zhang, Cand. Sci. (Geology and Mineralogy), Research Fellow, State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Science, PR China; zhangze@lzb.ac.cn; https://orcid.org/0000-0001-7330-031X

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