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NEW DATA ON PERMAFROST THICKNESS ON THE LENA–ALDAN INTERFLUVE

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For the first time, data on the ground temperature to a depth of 650 m in a borehole with a restored thermal regime have been obtained f for the Lena–Aldan interfluve. The results of geothermal measurements attest to an anomalous permafrost thickness for this territory (750–780 m). Changes in the ground temperature with depth reflect the nonstationary thermal regime of permafrost with a negative geothermal gradient to a depth of 200–300 m. The permafrost thickness is estimated, and possible reasons for its difference in relatively nearby areas are considered.

Keywords: *geothermal research, ground temperature, permafrost, Quaternary deposits, thermophysical properties, permafrost thickness.*

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INTRODUCTION

The surface of the Central Yakutian Lowland within the Lena–Aldan interfluve was finally shaped in the Quaternary period. This is a flat slightly dissected plain with absolute heights up to 240 m asl, often swampy, with a large number of lakes and with pronounced manifestation of various cryogenic processes. The plain relief of the Lena–Aldan interfluve is complicated by a series of terraces, thermokarst basins, heaving mounds, and polygonal formations. Quaternary deposits have different thicknesses (30–50 m) and composition (mainly quartz–feldspar sands, gray clays, sands with an insignificant content of pebbles) depending on the particular conditions. They compose the upper part of the slightly undulating structural denudation plain. Quaternary deposits are underlain by the Jurassic deposits, whose thickness in the borehole reaches 520 m. They are mainly represented by coarse and medium-grained quartz–feldspar sandstones with rare interlayers of fractured shale. At their base, there is a layer of conglomerates with carbonate cement and interlayers of coarse-grained sandstone of 20–30 m in thickness. The lower part of the sedimentary strata of the platform is represented by the Middle Cambrian deposits consisting of dense gray dolomite with interlayers of limestone of white to black color; their thickness recovered in the borehole is 190 m. These calcareous rocks contain numerous quartz veinlets.

According to the geological-structural zoning, the site is located on the closing flank of the Aldan Anteclise, which is complicated by the eastern flank of the blocky Yakutian Uplift and the Ust-Aldan Depression [*Geodynamic map..., 1992*].

The climate of the region is sharply continental with the mean annual air temperature of –8.5°C and the mean annual precipitation of 200–250 mm; about 80–85% of the annual precipitation falls the warm period (April–October) [*Kotlyakov, Lorius, 2000; Balobaev, Shepelev, 2001*]. According to geocryological zoning, the territory belongs to the zone of continuous permafrost with rock temperatures from –2.0 to –4.5°C [*Geocryological map..., 1997*]. The geocryological conditions of the Lena–Aldan interfluve were considered in a number of works [*Katasonov, Ivanov, 1973; Ivanov, 1984; Shepelev et al., 1984*]; however, data on the permafrost thickness in this region are very limited. The basis for assessing the depth of the base of the permafrost was geophysical research and the discovery of fresh aquifers in the course of drilling of geological and hydrogeological exploration and production boreholes. According to these data, the thickness of the permafrost zone was estimated at 240 m (village of Tuora-Kyuyol), 400 m (village of Telei-Diring), 561 m (village of Churapcha), and 530 m (village of Arylakh). Targeted geothermal studies of the territory were not conducted because of technical difficulties in the preparation and equipment of boreholes.

The purpose of our study was to clarify the depth of the permafrost base and to more fully characterize the natural conditions for the formation and temperature changes of rocks.

METHODS

Geothermal research. During drilling, the thermal field of the rocks is disturbed and then restored to its natural state. The temperature of frozen strata takes a particularly long time to recover. Even 4–5 months after the completion of drilling, the temperature curves for boreholes (thermograms) are characterized by the presence of non-gradient zones (Fig. 1).

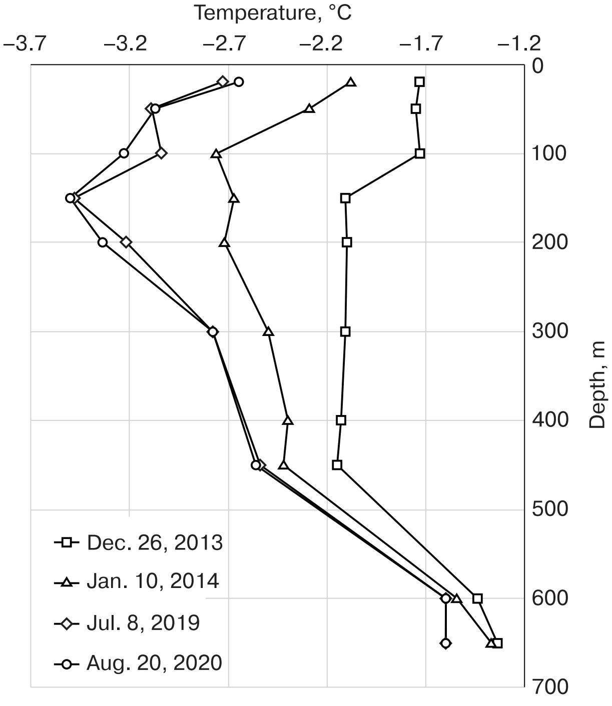

Fig. 1. Ground temperature distribution in borehole 2.

See Fig. 3 for location.

When determining the permafrost thickness, the method of temperature measurements in a borehole with restored temperature conditions was used. To do this, the borehole was equipped with a stationary geothermal installation with 10 sensors based on semiconductor thermistors and MASTECH MY65 multimeters recording the resistance of thermistors. A detailed description of the characteristics of thermistors, preparation of geothermal installations, and field research methods is given in [*Balobaev et al., 1985*].

The lower boundary of the permafrost was found from the data of temperature measurements in the borehole by extrapolating the measured temperature to the 0°C isotherm. For this purpose, structural features and geothermal parameters of the particular sections of the stratigraphic column were taken into account [*Zheleznyak, 1999*].

Thermophysical research. To determine the thermophysical properties of rocks, 17 samples were taken from the core of borehole 2. The thermophysical study was carried out at room temperature. Before the experiment, the samples were moistened in a desiccator. This created the conditions of the sub-permafrost stratum, where the rocks are, as a rule, in a state of complete water saturation. Since the samples had a significant density, their moisture content, even with excessive moisture, was negligible. Therefore, the thermophysical information obtained for positive-temperature rocks could also be applied to their negative-temperature counterparts.

Measurements of thermal conductivity and thermal diffusivity of the rocks were carried out using the Thermal Conductivity Scanning (TCS) setup (Fig. 2) with an error in determining the values of thermophysical properties of 3% (at a confidence level of 0.95). This setup implements the method of optical scanning of rock proposed by Yu.A. Popov [*Popov et al., 1983, 1999, 2012*]. During TCS operation, the sample under study is heated by a light spot that moves along the flat or cylindrical surface of the core sample at a constant speed.

The initial temperature and degree of heating of the sample are recorded by infrared (IR) radiation receivers. The field of view of each of them moves along the same sample surface at the same speed as

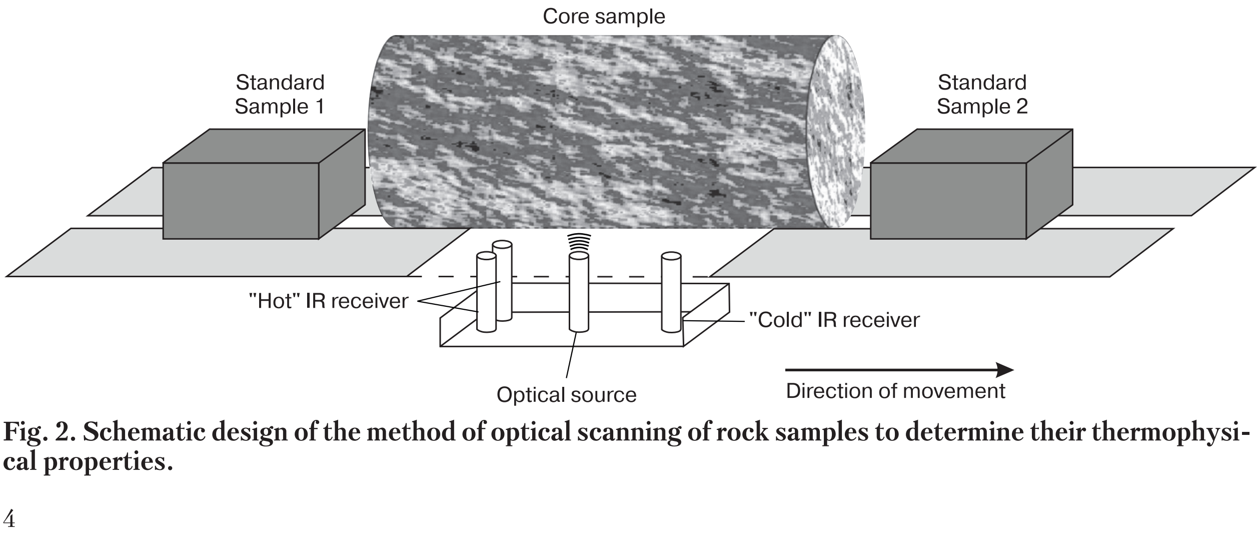

Fig. 2. Schematic design of the method of optical scanning of rock samples to determine their thermophysical properties.

the heating spot. The test sample is placed in the setup together with two reference samples with known values of thermal conductivity and thermal diffusivity. The thermophysical properties of a rock sample are determined based on a comparison of their heating levels with the heating level of reference samples.

Measurements were made on the cylindrical surface of the core (when scanning the samples along the core axis) and on the flat surface of the samples. In some cases, measurements on the cylindrical surface of the core and on its ends were combined.

When scanning samples with an optical radiation source and temperature sensors, a thermal conductivity profile is recorded. This makes it possible to determine both the average values of thermal conductivity for the entire sample and its local values in separate parts of the sample. Thus, it becomes possible to differentiate between the rocks with close thermal conductivity values but with different structural and textural characteristics.

RESULTS

In 2012 and 2013, the Yakutian survey expedition of Yakutskgeologiya JSC drilled hydrogeological boreholes to provide drinking water for the villages of Churapcha and Dyabyla (Ozhulun) (Fig. 3). Borehole 1 was located 100 m from the shore of the pond in the village of Churapcha, and borehole 2 was found 200 m from a thermokarst lake near the village of Dyabyla. The absolute heights of the borehole heads were 181 and 172 m asl, respectively. Thermokarst mounds were found near the lake at the Dyabyla site. The project assumed the drilling of the boreholes to a depth of 600 m. In borehole 1 (Fig. 4), Quaternary deposits to a depth of 12 m were represented by loam; deeper, to a depth of 45 m, by sand with inclusions of small and coarse gravels (up to 5% of the volume). Under the Quaternary deposits, to a depth of 566 m, poorly cemented frozen sandstones with siltstone interbeds of the Jurassic system were found. At the base of the exposed section of Jurassic deposits, gray sandstones and conglomerates were present. Below, limestones of the Cambrian system occurred.

At the depths of 561–569 m, within the layer of light-colored sandstones with lenses of conglomerates, water inflow into the borehole was recorded, as a result of which the groundwater level was established at a depth of 169.2 m. The borehole was drilled to a depth of 625 m; after drilling and logging operations were completed, geothermal measurements were carried out in the borehole. According to the obtained data, subzero temperatures of the rocks were noted down to a depth of 561 m, and their minimum values (–1.3°C) were at the depth interval of 300–325 m. A sharp change in the temperature gradient of rocks in the range of 561–569 m was due to the presence of an aquifer associated with the contact of sandstones of the Jurassic system and limestones of the Cambrian system. Judging by the drilling data, the contact zone of sandstones and limestones was

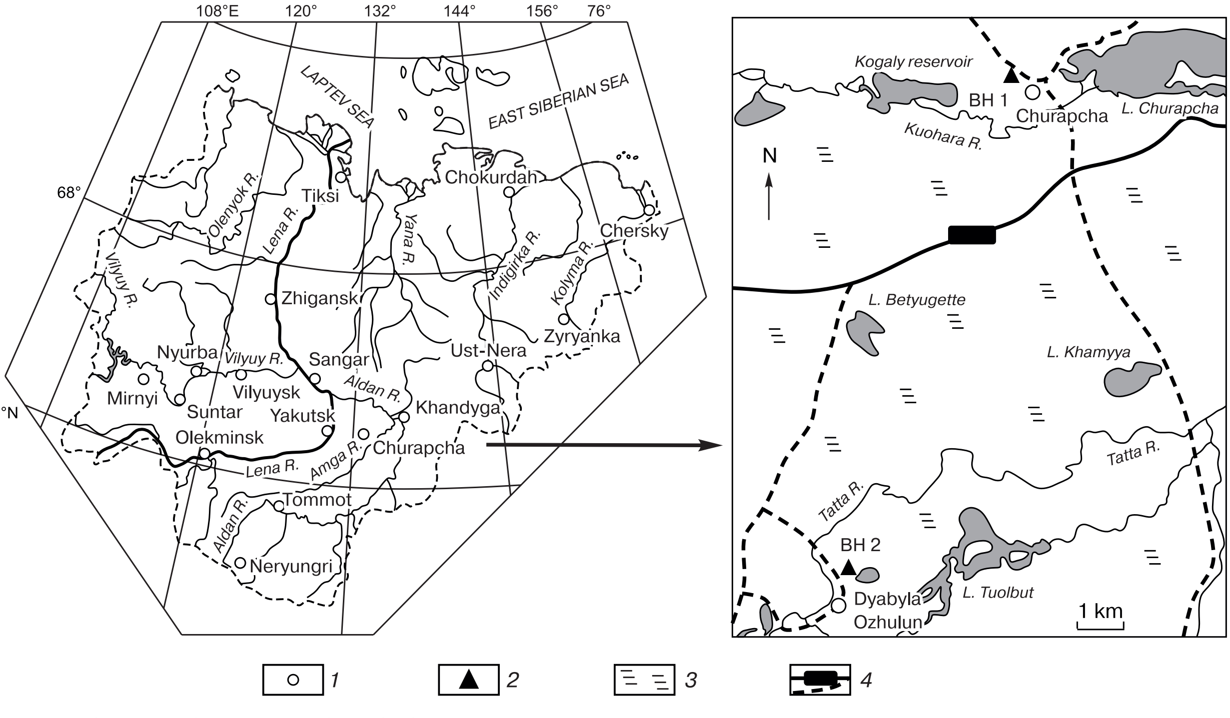

Fig. 3. Scheme of location of boreholes.

1 – settlements, *2* – borehole, *3* – thermokarst, *4* – roads.

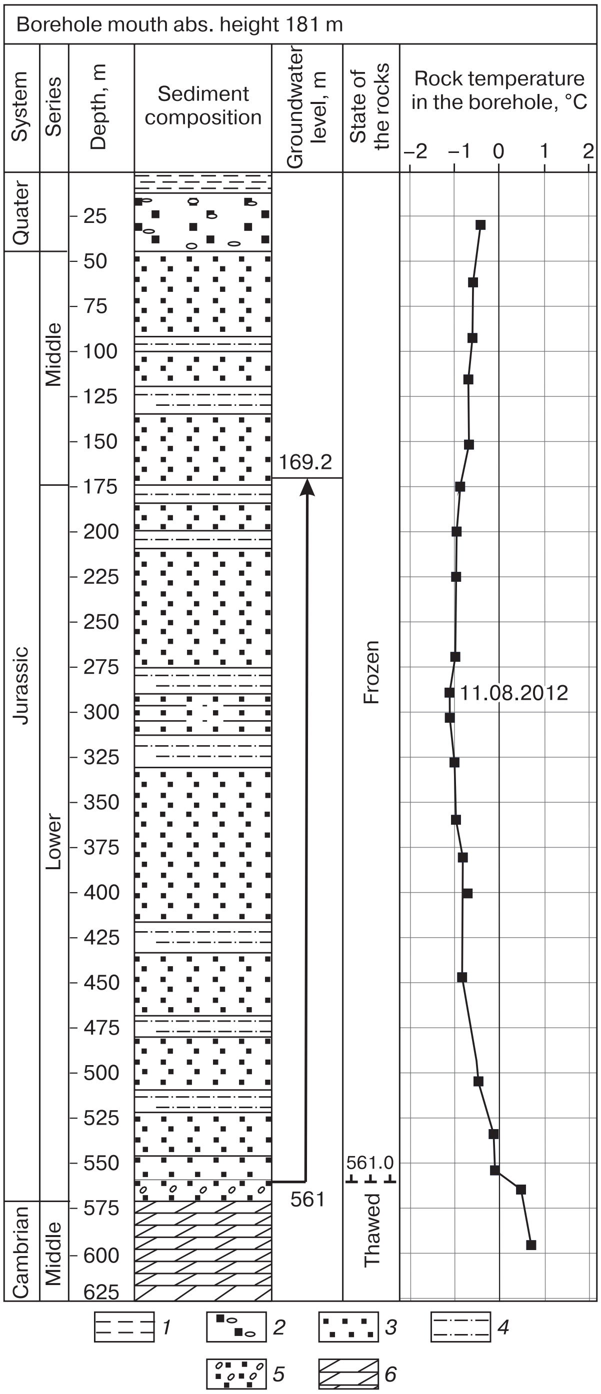

Fig. 4. Geological section and rock temperature distribution in borehole 1 (Churapcha).

1 – loam, *2* – coarse-grained sand with inclusions of fine and coarse gravels, *3* – sandstone, *4* – siltstone, *5* – conglomerate with sandstone interlayers, *6* – limestone.

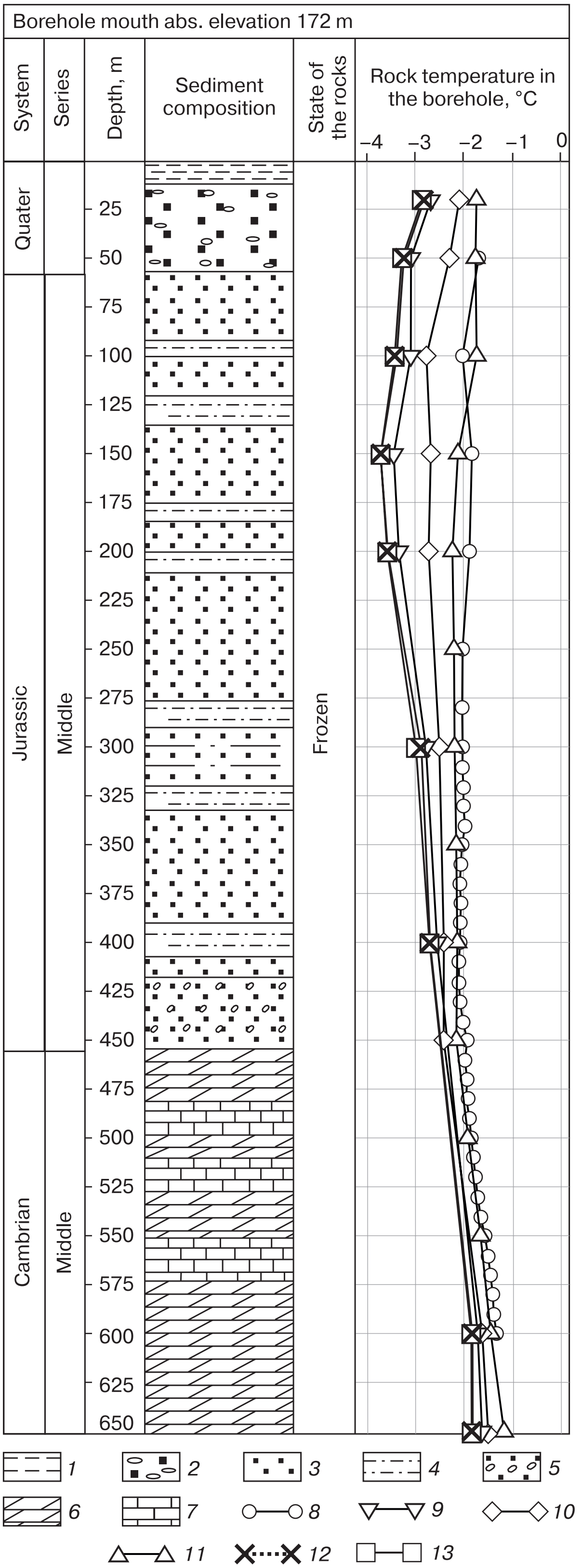

Fig. 5. Geological section and rock temperature distribution in borehole 2 (Dyabyla).

1 – loam, *2* – coarse-grained sand with inclusions of fine and coarse gravels, *3* – sandstone, *4* – siltstone, *5* – conglomerate with sandstone interlayers, *6* – limestone, *7* – dolomite. Dates of temperature measurements: *8* – December 13, 2013; *9* – December 26, 2013; *10* – January 10, 2014; *11* – February 7, 2015; *12* – June 20, 2018; *13* – August 20, 2020.

fractured, aquiferous, and its thickness was 7–8 m. Above this interval, the rocks were in the frozen state; below it, dense limestones that served as a water barrier were present.

In 2013, 9.5 km south of borehole 1, on the outskirts of Dyabyla, hydrogeological borehole 2 was drilled with a design depth of up to 600 m (Fig. 5). Quaternary sediments were represented by loams in the upper 12 m; below, to a depth of 58.8 m, there were gray sands with inclusions of coarse and fine gravels. The underlying Jurassic deposits with a total thickness of 394.2 m were represented by gray fine- and medium-grained quartz-feldspar sandstones with siltstone interlayers. The lower part of Jurassic deposits (from a depth of 412.5 m) was represented by conglomerates with gravels of metamorphic and igneous rocks cemented by calcareous sandstones, with interlayers of medium- and coarse-grained silicified sandstone. Below 453 m, rocks of the Cambrian system – limestones and ferruginous limestones with interlayers of marls and dolomitic limestones – were found. Core samples were taken from typical layers characterizing the strata along the section, and the thermophysical properties of the rocks were determined from them (Table 1).

In the course of drilling borehole 2, water inflows were not recorded. Geothermal measurements carried out immediately after the end of drilling and then after one week showed subzero temperatures along the entire borehole; at the bottom (600 m), the rock temperature was −1.3°C. Further drilling of the borehole continued to a depth of 650 m; however, no water inflow was observed. At the end of drilling, geothermal measurements established a subzero temperature of −1.2°C at the bottom of the borehole.

At the time of the initial geothermal measurements, the temperatures of the rocks along the borehole had not recovered. It was decided to equip the borehole with a stationary geothermal unit to a depth of 650 m. In the period from 2013 to 2020, repeated temperature measurements were taken in the borehole every year. So, after a year and a half, the temperature regime in the borehole changed significantly; in recent years, the temperature of the rocks at the same depth intervals has been constant, which indicates the restoration of the thermal regime.

Temperature curve for borehole 2 has a pronounced non-stationary regime associated with climate warming and the influence of a talik under a nearby lake. The minimum rock temperatures (−3.6°C) are observed at a depth of 150 m; down to this depth, the geothermal gradient has a negative value (−0.6°C/100 m). Below, there is an area with a positive temperature gradient from 0.45 to 0.90°C/100 m, which varies depending on the thermal conductivity of the rocks. Based on six geothermal measurements (2013–2020) and using the method of two and three thermograms [*Kutasov, 1976*], the depth of the zero isotherm (permafrost thickness) was estimated at 750–780 m. An anomalously large permafrost thickness was established for this location in the study area.

Table 1. **Thermophysical properties of rocks in borehole 2**

Depth, m	Rock	λ, W/(m·K)	$a \cdot 10^{-6}$, m^2/s	c_γ, kJ/(m^3·K)
466	Limestone gray	1.88	1.2	1567
486	Limestone light gray	2.05	0.93	2204
500	Dolomite limestone, light gray, massive	2.14	1.4	1529
506	Light gray limestone, drain (micro-granular)	2.28	1.2	1900
522	Limestone with marl, almond-tone texture	2.25	1.01	2228
534	Limestone ferruginate	1.87	1.14	1640
559	Limestone marl, dark gray, microgranular	2.81	1.18	2381
570	Marl dark gray	1.43	0.66	2167
597	Limestone brown with inclusions of gray crushed limestone	2.07	1.19	1739
598	Limestone ferruginous, grayish brown, microgranular	2.21	1.09	2028
605	Limestone ferruginous, brown	2.16	1.15	1878
615	Limestone wavy banded, light gray	2.11	1.6	1319
630	Limestone ferruginous, brown, spotted	2.27	1.33	1707
633	Limestone ferruginous, wavy-banded	2.23	1.23	1813
640	Limestone wavy-banded, brownish gray, microgranular	2.31	1.21	1909
644	Limestone with wavy ferruginous areas, microgranular	2.02	1.3	1554
650	Limestone, interlayering of brown and light gray, microcrystalline	2.34	1.09	2147

Note: λ – thermal conductivity; *a* – thermal diffusivity; c_γ – volumetric heat capacity.

Thus, in the borehole near the village of Dyabyla, carbonate strata of the Cambrian system are found at a depth of more than 450 m; in the village Churapcha, they occur at a depth of more than 575 m. Thus, a gentle slope of the Cambrian strata from the Yakutian Uplift of the Aldan Anteclise towards the Lower Aldan Depression is traced.

Based on the results of determination of the thermophysical properties of rocks along the section and reference data, it was established that they differ insignificantly in the junction zone of the Cambrian carbonate and Jurassic silicate deposits. Consequent-

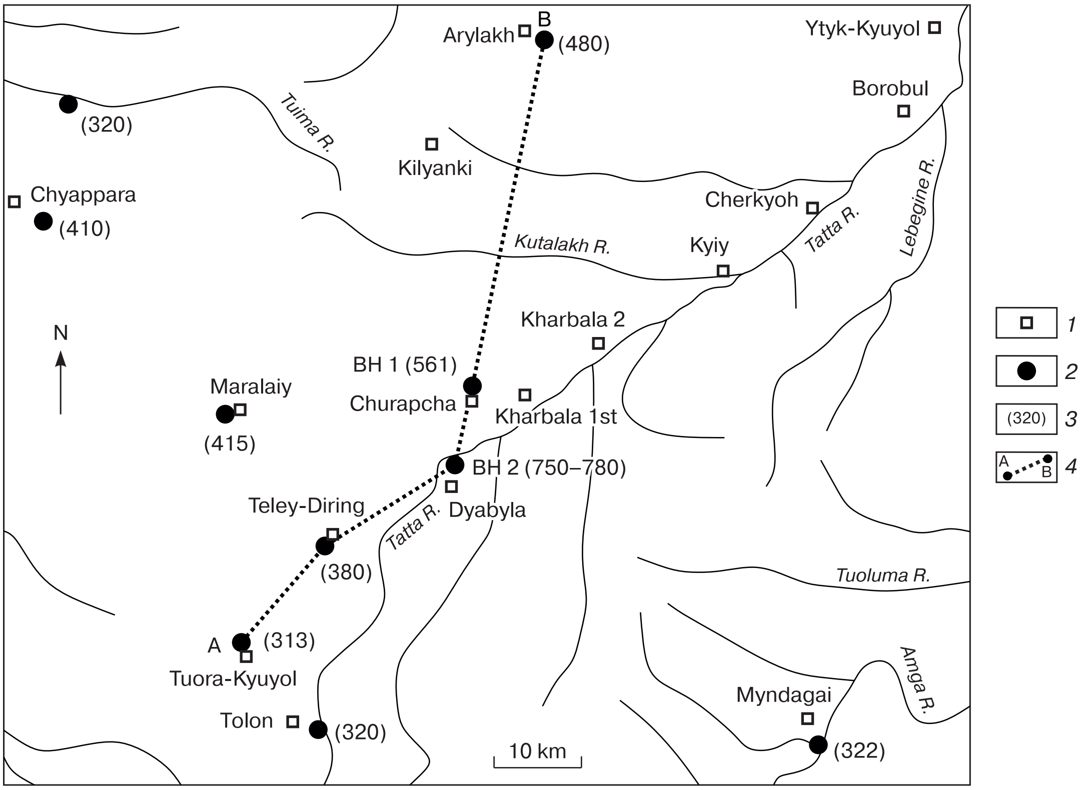

Fig. 6. Scheme of location of boreholes with data on the depth of the base of the frozen strata.

1 – settlements, *2* – hydrogeological boreholes, in which the base of the frozen strata was determined, *3* – depth of the base of frozen strata, *4* – line of geocryological section A–B (see Fig. 7).

ly, a change in the temperature gradient of rocks can only be due to the presence of cracks, as well as the existence of aquifers or ice-saturated horizons [*Geological map..., 2000*].

An analysis of the morphology of the roof of the rocks underlying the Late Pliocene–Quaternary deposits of the Lena–Aldan interfluve [*Kamaletdinov, 1982*] made it possible to establish that modern neo-

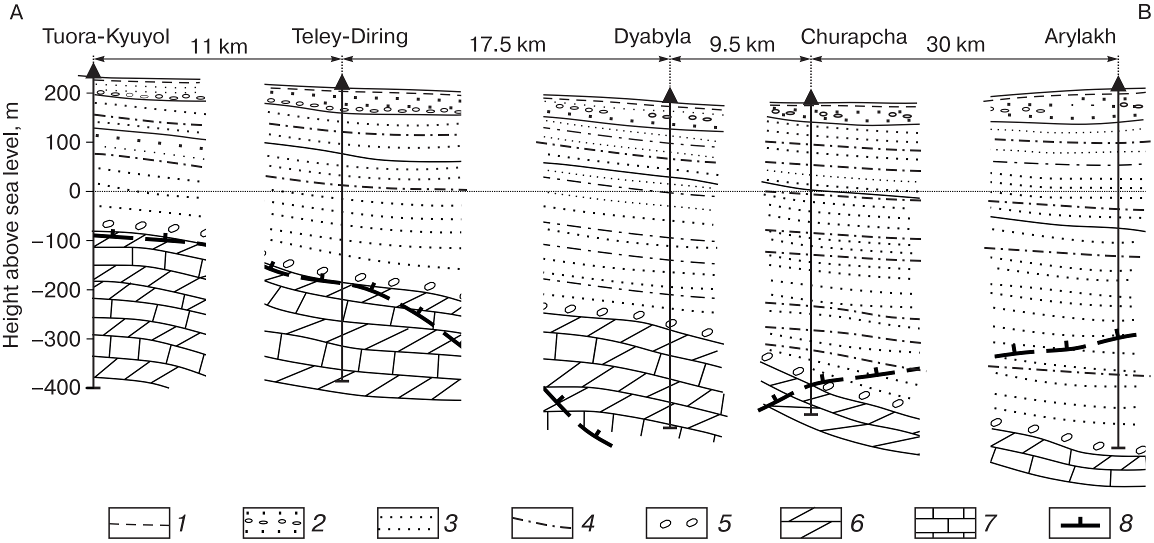

Fig. 7. Schematic geocryological section along profile A–B (see Fig. 6).

1 – loam, *2* – fine- and medium-grained sand with inclusions of fine and coarse gravels, *3* – coarse-grained sandstone, *4* – siltstone, *5* – conglomerate, *6* – limestone, *7* – dolomite, *8* – bottom of the rock mass with subzero temperatures.

tectonic movements and erosional processes had little effect on the vertical amplitudes of geological structures, which is manifested in the structure of the Quaternary strata and in the modern topography of the territory. The influence of changes in the base of erosion during the development of permafrost on the relief was insignificant. Therefore, in the opinion of the authors, the relief of the territory could not strongly affect the freezing depth. Nevertheless, the difference in the depth of the permafrost base in the boreholes is considerable, though the boreholes are found at a relatively small distance from one another. It is difficult to explain such a difference in temperature and thickness of the permafrost by geomorphological or lithological reasons. In this regard, the authors compared and analyzed the position of the permafrost base and the boundaries of sediments of different compositions of different ages (Figs. 6, 7).

According to the authors, the position of the permafrost base is specified by the presence and circulation of groundwater in fractured rocks formed in the course of changes in tectonic and paleogeographic situation rather than by changes in the composition of sediments at the boundary of the Jurassic and Cambrian systems. The formation of the zone of cryogenic disintegration of rocks had a significant influence on the hydrogeothermal conditions, the parameters and depths of which in this area of the Siberian Craton sedimentary section depend on the geological structure of the sedimentary strata and the depth of the crystalline basement during the freezing period.

CONCLUSIONS

1. First geothermal data have been obtained to a depth of 650 m for the Central Yakutia region, within the eastern flank of the Yakutian Uplift at the junction of the Ust-Aldan Depression and the Aldan Anteclise. Temperature distribution in the rocks attest to the nonstationary state of the frozen strata with a negative geothermal gradient to a depth of 150 m.

2. Permafrost thickness in the area of the village of Churapcha, as estimated from geothermal measurements, reaches 750–780 m, which is an anomalously high value for the studied region.

3. From the analysis of geological and geothermal data, it follows that the depth of the permafrost base is controlled by the groundwater circulation in the fractured rocks formed in the course of tectonic and paleogeographic events with a significant influence of cryogenic disintegration rather than by changes in the composition of the rocks at the boundary between the Jurassic and Cambrian deposits.

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