EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth's Cryosphere, 2021, vol. XXV, No. 6, pp. 23–33 http://earthcryosphere.ru/

GEOTHERMAL FIELDS AND THERMAL PROCESSES IN CRYOSPHERE

THERMAL REGIME OF CRYOLITHOZONE AT YTYMDZHA DEPRESSION, ALDAN SHIELD

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The results of geocryological studies in the Ytymdzha Depression of the Aldan Shield have been presented. From 1999 to 2001, several exploration boreholes were drilled in the central part of the depression, which made it possible for the first time to obtain information on the geotemperature field, the thermophysical properties of rocks and the thickness of the permafrost stratum. The long-term series of monitoring of the temperature regime of the active layer obtained for the bogged floodplain terrace, the river terrace, and the south-facing slope have been adduced. The temperature of rocks at a depth of 1 m varies from 4.8 to –11.7 °C, with average annual temperature ranging from –1.0 to –4.9 °C. The work has resulted in the sublongitudinal permafrost-geothermal section along the central part of the Ytymdzha Depression, within which the thickness of permafrost varies from 106 to 251 m.

Keywords: *ground temperature, geothermal gradient, permafrost thickness, Ytymdzha Depression.*

INTRODUCTION

The superposed, sublatitudinal depressions of the Aldan Shield (Chulman, Tokarikan, Guvilgra, Ytymdzha and Toko) composed by Mesozoic deposits are the main sources of coal for industrial development. Presently there is active field development within the Chulman Depression (Neryungri, Kabaktinsky and Denisovsky mining and processing plants) and within the Toko Depression (Elga mining and processing plant)). But, according to data from geological prospecting [*Chereposcky, 2004*], all Mesozoic-age depressions are promising for coal mining.

The coal-bearing regions of Southern Yakutia vary greatly in the extent of study of their permafrost conditions. Owing to coal field development and an abundance of factual material, the eastern part of the Chulman Depression and the western part of the Toko Depression are among the most studied regions of the modern cryolithozone distribution [*Belokrylov, Efimov, 1960; Kudryavtsev, 1975; Zheleznyak et al., 1996*].

At the same time, the Ytymdzha, Guvilgra, Toko depressions and a series of smaller structures have no clear characterization of permafrost conditions, they are mapped and described analogously to the Chulman Depression [*Ershov, 1989*]. The impact of surface air temperature inversion presents a deciding factor that determines the discontinuous distribution of permafrost within the Chulman Depression [*Belokrylov, Efimov, 1960*; *Alekseyev, Filosofov, 1970*], while a normal altitudinal zonation is more characteristic of the Toko Depression [*Zheleznyak et al., 1996*; *Zheleznyak, 2005*]. For almost the entire territory of Southern Yakutia (beyond regions of industrial field development) the type and depth of freezing, as well as the permafrost temperature regime, are not reliably determined owing to the absence of factual material.

On the example of the Ytymdzha Depression, specific features of permafrost conditions are considered in comparison with those of larger geological divisions similar in structure and developmental conditions. Data on the temperature regime of permafrost are presented for the first time. For the further expansion of the western Southern Yakutian coal mine surplus and the development of gold-placer deposits it is necessary to consider permafrost parameters. Specifically, in the Ytymdzha Depression, this is owing to the presence of large coal horizons which are potentially suitable for industrial development [*Zhelinsky et al., 1976; Cherepovsky, 2004*].

Permafrost conditions influence the conservation of gas content in coal basins and affect the emission of greenhouse gases [*Gresov et al., 2014*], which makes this research more relevant.

MATERIALS AND METHODS

The work is based on the results of field permafrost-geothermal research conducted from 2001 to 2019 by the staff of the Laboratory of Geothermal Energy of the Permafrost Institute SB RAS. The opportunity to complete the first geothermal measurements in the region arose owing to the geological prospecting works of OJSC Uzhyakutgeologiya

(1999–2001), which consisted of drilling exploratory boreholes 500 m deep in the central part of the Ytymdzha Depression.

During this work, the staff of "Uzhyakutgeologiya" tried to identify the depth of the permafrost base using indirect signs, such as the appearance of water in the borehole, loss of drilling fluid, drilling out of ice plugs, etc. The archive materials provide a brief description of permafrost conditions, according to which the permafrost thickness varies from 30 to 140 m. Beginning in 2001, researchers of the Permafrost Institute SB RAS conducted work to obtain thermometric borehole logging immediately after drilling. Later (2006, 2012, 2016), geothermic measurements were conducted in the boreholes returned to thermal equilibrium. As a result, geothermic measurements were conducted in six boreholes up to a maximum depth of 240 m. Thermistor installations, which were used to determine temperature, were manufactured and calibrated in the Laboratory of Geothermal Energy of the Permafrost Institute SB RAS, with observational error up to 0.05 °C [*Balobaev et al., 1985a*].

Overall, the depth of the permafrost base was identified in 12 boreholes within the Ytymdzha Depression using various methods (calculations, direct measurements, thermal logging analysis, etc.). Direct geothermal measurements were carried out within six boreholes after a long period of recovery of the thermal state of the rocks after drilling. In addition, data from geothermal research and permafrost distribution peculiarities of the nearby Guvigra, Tokarikan and Toko depressions were used to build the permafrost-geothermal section [*Zheleznyak, 2005*].

Calculating the parameters of deep freezing is impossible without information about the thermal physical properties of the rocks composing the section. A typical feature of Mesozoic Age depressions is the persistence of the stratigraphic composition of the deposits [*Zhelinskiy, 1980*]. Single measurements of the thermophysical properties of rocks (Durai and Kabakta formations) performed for the Ytymdzha Depression (6 samples) showed a high convergence of the results with samples from the Chulman and Toka depressions [*Gavriliev, 2013*]. Based on the similar genesis of the depressions, the thermal conductivity of rocks is considered to be the same as in the samples obtained in the Chulmakan and Elga areas [*Gavriliev, 2013*] and is shown in Table 1. The standard thermal conductivity of individual samples has increased values relating to the effective thermal conductivity of the entire strata. This is explained by the presence of cracks, heterogeneity of the section and a difference in structure and texture on stratigraphic boundaries. Effective thermal conductivity of the studied horizons is determined by the material composition, and the similarity in values with the Jurassic series of the Viluy sedimentary basin is established [*Semenov et al., 2018*]. Owing to the dominance of fine-grain sandstone we assume that the Durai Suite is characterized by a large value of effective thermal conductivity. The distribution of rocks of a different lithology (in percentages) was obtained based on deep drilling data (Table 1).

To determine the thermal regime of the active layer in 2013, three observation points were equipped within the landscapes typical for the Ytymdzha Depression (bogged floodplain terrace, river terrace, south-facing slope). Logging stations HOBO U-22 and HOBO U-23 with TMC50-HD sensors, which are widely utilized to conduct geothermal monitoring, were used [*Konstantinov et al., 2011*]. The sensors were located in a thin plastic pipe and planted into soil pits. Vegetation was not removed and suffered minimum possible disruptions. A continuous series of observations was obtained in two of three points owing to disruption by wild animals, as well as challenges in reaching the object for annual maintenance.

In 2019, an automatic APIK-008 soil measuring complex was installed on the first river terrace. It is a portable weather station with broad possibilities for monitoring meteorological parameters, but in the present article only average air temperature values are provided.

Table 1. **Distribution of the main types of rocks (%) in the Ytymdzha Depression based on drilling and thermal conductivity data**

Series	Sandstones			Siltstones	Charcoal	Effective thermal conductivity, W/(m·°C)
	fine-grained	medium-grained	coarse-grained			
Kabakta	27	38	4	25	4	1.7–1.9
Duray	43	9	5	40	2.5	1.9–2.1
Area	Standard thermal conductivity*, W/(m·°C)					
Chulmakan	2.99 (12)			–	0.9–1.1	
Elga	2.57 (4)			2.57 (1)	–	

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* Ground thermal conductivity in the frozen condition according to R.I. Gavrilov. Parenthetical text shows the number of samples.

BRIEF DESCRIPTION OF THE ENVIRONMENT OF THE STUDIED AREA

The Ytymdzha Depression is located in the central part of the Aldan Shield (Fig. 1). The boundaries of the depression are determined by the boundary of Mesozoic and Archean rocks. From the south, the depression is bordered by the Gonam Range and the Koltan-Dzhur Range, with maximum altitudes of up to 1848 and 1831 m, respectively. From the north, the Ytymdzha Depression is limited by the area of distribution of Proterozoic rocks of the Aldan Highlands (Fig. 2). Flexure folds on gentle monocline stratum bedding serve as evidence of a block structure of the basement, which is typical for the whole series of Mesozoic depressions [*Imaev et al., 2000*]. Due to the block structure of the basement distribution, the structure and composition of the cover can change abruptly within a small area [*Zhelinskiy, 1980*].

The Ytymdzha Depression is a regional sublatitudinal depression, 130 × 30 km in size. The total thickness of the Mesozoic deposits reaches 1100 m, which is established by geophysical work and confirmed by drilling data [*Rukovich, 2018*]. The thickness of the Quaternary deposits is determined to be 5–15 m and decreases as the altitude decreases. Based on geological survey data with a scale of 1:200 000, Quaternary deposits are predominantly of alluvial, colluvial-solifluctional, lake and bog origin. In a geomorphological respect, the depression is characterized by an undulating topography with watersheds located 200–300 m on average above the valleys. In the central part of the depression, ground temperature monitoring up to the depth of zero annual amplitude was conducted in:

1. A bogged floodplain terrace (peat bog, *mari* (in Yakutia – bogs with rare larches)) with a depleted larch forest or its absence; the elevation range is 550–650 m (Fig. 3, *a*).
2. The erosional river terrace with a pine-larch forest and a *Ledum*-lichen cover with rare birches, alders; the elevation range is 600–700 m (Fig. 3, *b*).
3. The south-facing slope with diluvial grus-sandy loam deposits and vegetation of larch, alder with a forb-blueberry-*Ledum* cover; elevation range 700–1000 m (Fig. 3, *c*).

The water content of the loose deposits of the active layer was not determined and is provided according to monograph data [*Kudryavtsev, 1975, p. 86*].

Permafrost processes include solifluction, frost sorting, the formation of patterned ground, the formation of aufeis, rock glaciers and frost heaving.

According to the results of annual observations, the air temperature in the Ytymdzha Depression for the period from 01.08.2019 to 31.07.2020 was –7.0 °C, which is the average value in respect to the weather stations in the Chulman (–5.2 °C) and Toko (–8.5 °C) depressions (Table 2). This agrees with the prevailing westerlies that increase the severity of climatic conditions in the eastern direction. The temperature inver-

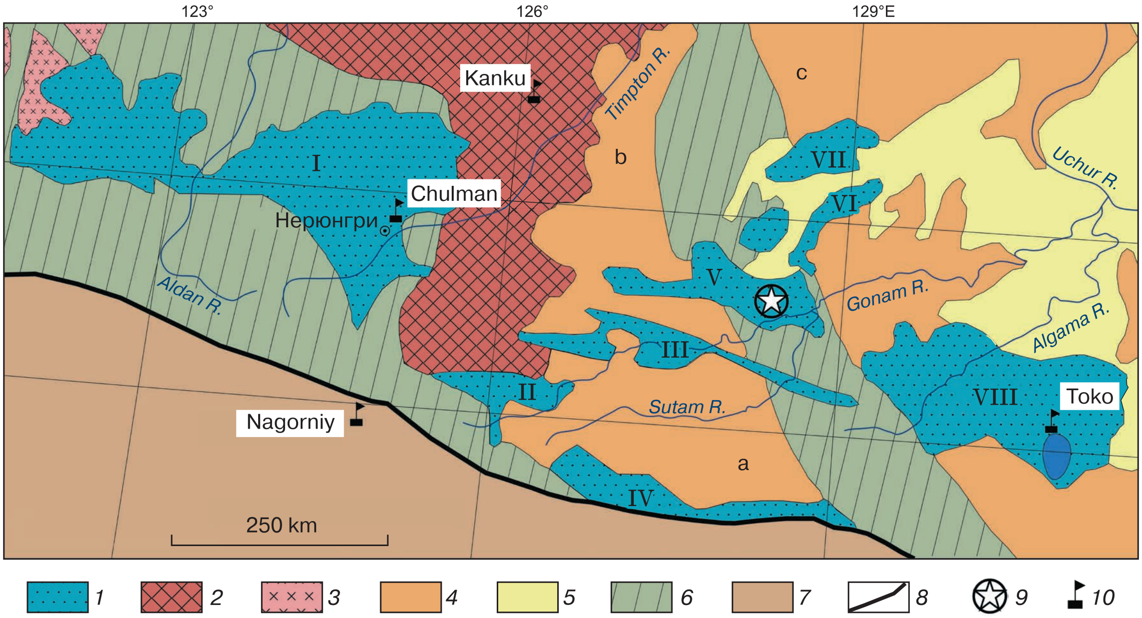

Fig. 1. Geological structures of the central part of the Aldan Shield.

1 – superimposed depressions with Mesozoic rocks (I – Chulman, II – Tokarikan, III – Guviglra and Atugey-Nuyam, IV – Sutam, V – Ytymdzha, VI – Gynam-Cemdzhyn, VII – Kuranakh-Gynym, VIII – Toko); 2–5 – superterraines: 2 – Nimnyr, granulite-orthogneiss (V–Є); 3 – West-Aldan, granite-greenstone (V–Є); 4 – Sutam (a), Seym (b), Uchur (c), granulite-paragneiss (V–Є); 5 – Vendian–Cambrian platform cover; 6 – tectonic mélange zones; 7 – Stanovoy belt; 8 – Stanovoy fault; 9 – study area; 10 – weather stations.

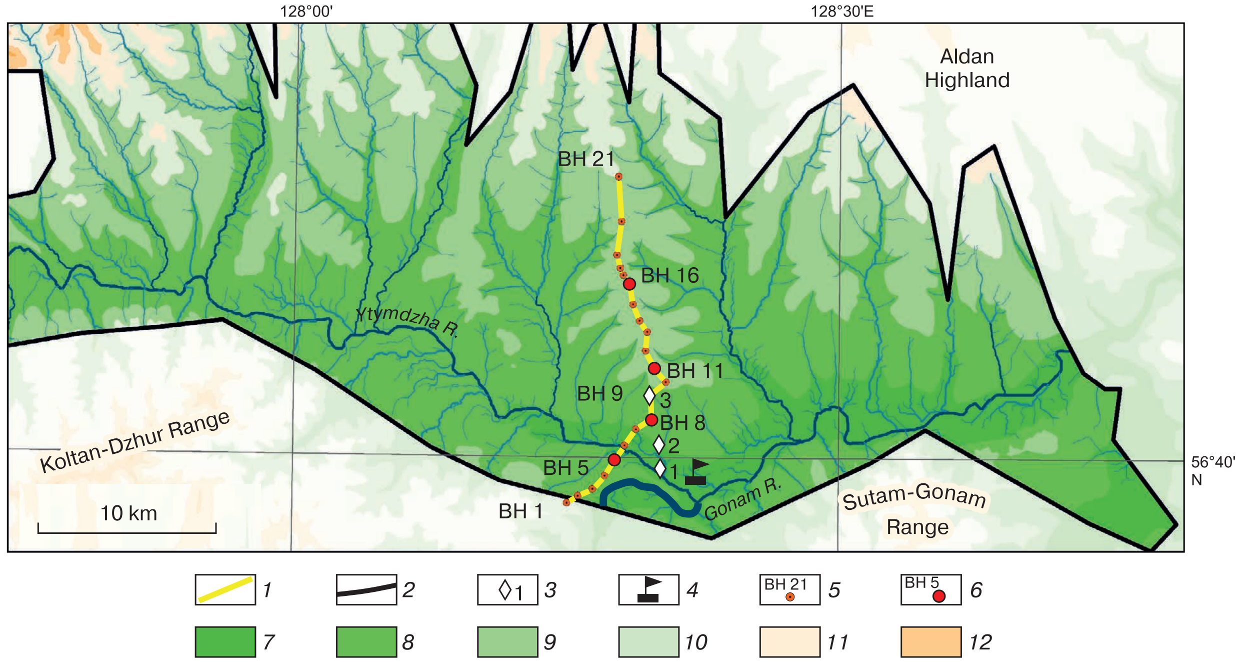

Fig. 2. Study area in the eastern part of the Ytymdzha Depression.

1 – drilling profile; 2 – Ytymdzha Depression boundary; 3 – areas of geothermal monitoring and their numbers; 4 – APIK location; 5 – deep boreholes; 6 – boreholes with geothermal measurements; 7–12 – surface elevation, m: 7 – less than 600; 8 – 600–800; 9 – 800–1000; 10 – 1000–2000; 11 – 1200–1400; 12 – 1400–1600.

Fig. 3. Areas of temperature monitoring:

a – floodplain terrace; b – river terrace; c – south-facing slope, borehole 9. Photo by R.G. Sysolyatin.

Table 2. **Main climate parameters at weather stations in the region for the period 01.08.2019–31.07.2020**

Weather station	Elevation, m	Air temperature, °C				Sum of winter temperatures*, °C·month
		average	maximum	minimum	Amplitude	
Ytymdzha (APIK-008)	568	–7.0	35.0	–49.0	84.0	–134.3
Chulman	858	–5.2	32.7	–41.4	74.1	–110.4
Toko	825	–8.5	32.3	–50.6	82.9	–137.0
Nagorniy	842	–5.4	32.0	–38.0	70.0	–110.0
Kanku	1218	–7.3	30.1	–40.9	71.0	–129.7

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* October–April.

sion observed in the Chulman Depression [*Alekseyev, Filosofov, 1970*] can occur as in Ytymdzha Depression with similar topography as in the eastern part of the Toko Depression. The weather stations Toko and APIK-008, located in local topographic lows of the Ytymdzha Depression, are characterized by minimum mean annual temperatures and maximum annual air temperature amplitudes.

ACTIVE LAYER TEMPERATURE

The temperature regime of the active layer was studied on the bogged floodplain terrace, the drained river terrace and the south-facing slope at a depth of 1 m (Fig. 4). The minimum values of the mean annual ground temperature were obtained at the floodplain terrace and vary from –1.2 °C (2015) to –4.9 °C (2017). During the observation period the ground temperature at a depth of 1 m did not exceed –0.1 °C, falling as low as –14 °C (February 2015). The thermal inertia at sites with water content exceeding 60 % is quite high, minimum temperatures are noted in February–March, maximum temperatures in December.

Compared to highly moist areas, more drained landscapes differ significantly in temperature regime. Average annual temperature from –1.0 °C (2015) to –2.7 °C (2017) and maximum values of active layer temperature up to 4.8 °C (August 2015) make terraces with pine-larch forest and an abundance of brush the warmest areas.

The temperature in the active layer on the south-facing slope was measured with an interruption from January 2015 to June 2016, and in May 2019 the measuring equipment was destroyed by a forest fire. The ground did not warm to temperatures higher than +1.3 °C (01.09.2014) in the observation area, and sometimes it cooled to –11.7 °C (March 2018). The mean annual ground temperature values varied from –3.0 °C (2014) to –3.9 °C (2018).

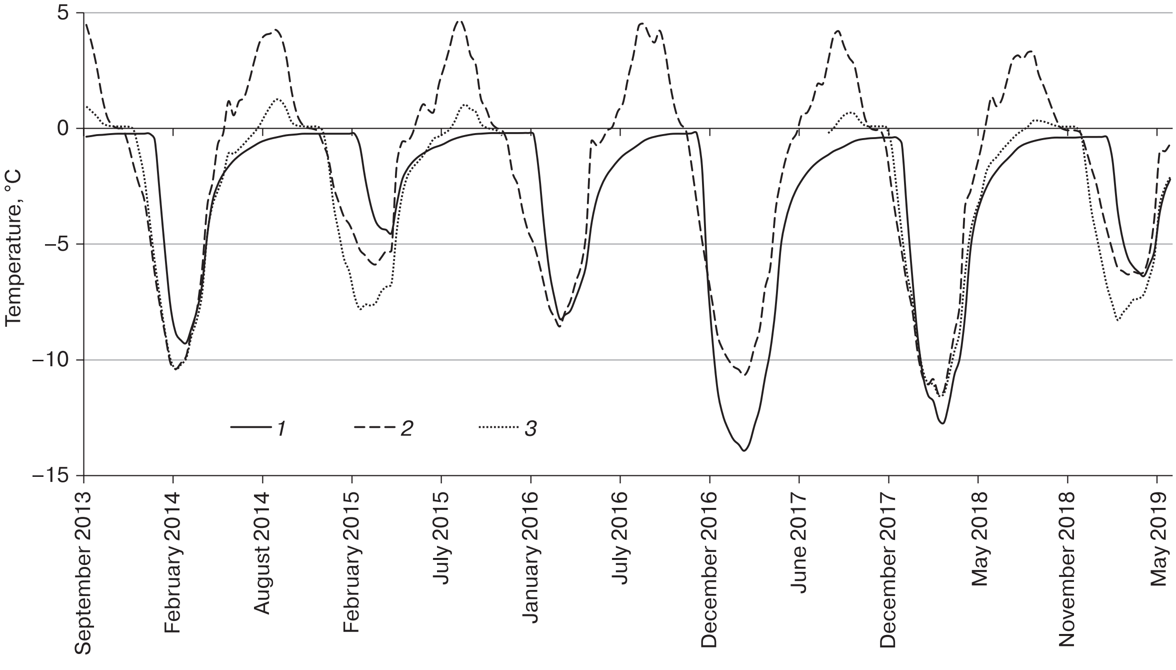

Fig. 4. Variation of ten-day ground temperature at depth 1 m.

1 – floodplain terrace; 2 – river terrace; 3 – south-facing slope.

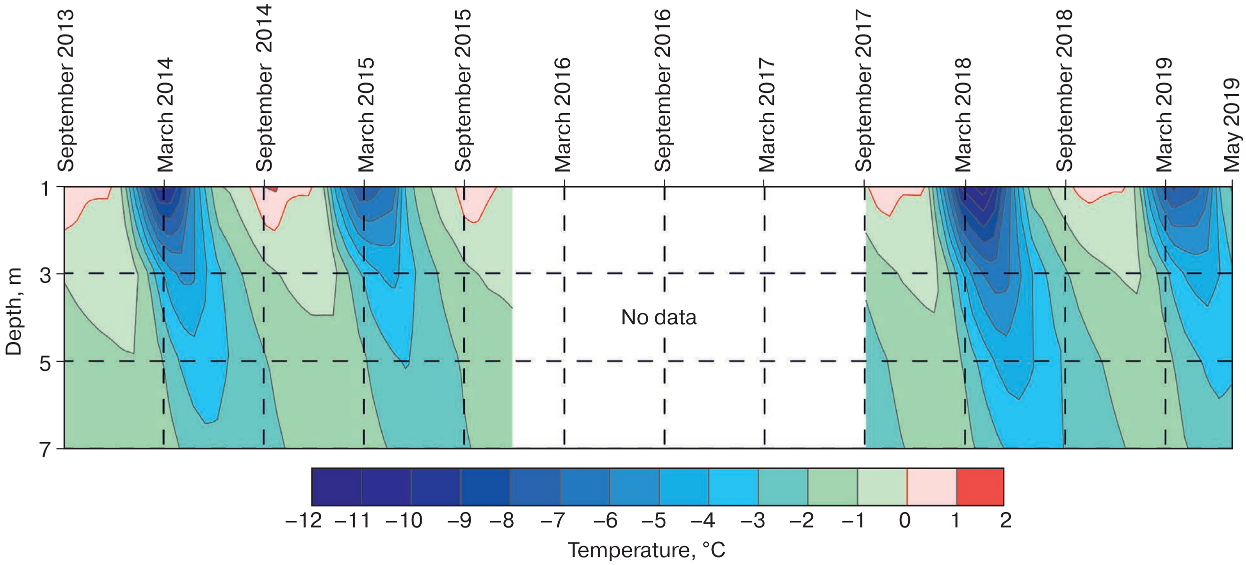

Fig. 5. Rock temperature variation in the layer of annual temperature fluctuations in borehole 9.

The depth of the active layer of the floodplain terrace does not exceed 1 m, which agrees with the calculation data. For the south-facing slope seasonal thawing can reach depths of 2.1–2.2 m under kriging interpolation (Fig. 5), which exceeds the values shown in the work [*Kudryavtsev, 1975, p. 86*]. On the river terrace, at a depth of 1 m, positive temperature is noted from June to mid-November. On the south-facing slope it is positive for no more than two months per year. On the floodplain terrace the active layer does not exceed 1 m.

A steady tendency toward active layer temperature changes is not observed. From 2014 to 2018, a decrease in temperature was noted at a depth of 1 m from −10.3 to −14.7 °C on the floodplain and river terraces, respectively. But the ground temperature in the winter period of 2019 differs by one of the highest values during the entire observation period. An analysis of the processes determining the temperature regime in the active layer requires a more detailed study of all affecting factors, which is not possible in our case owing to the absence even of snow cover data. The latter is highlighted as the main factor which determines the ground temperature regime in Siberia [*Sherstyukov, 2008*].

TEMPERATURE OF DEEP PERMAFROST HORIZONS

During geothermal measurements we were able to determine ground temperature up to depths of 95, 35 and 240 m in boreholes 5, 8 and 16, respectively (Table 3). The ground temperature regime is quasi-stationary, but below a depth of 40 m boreholes 5 and 16 show a stationary temperature distribution (Fig. 6). The geothermal gradient is negative in the zone up to 20–40 m depths and positive below, with average values from 1.0 to 1.8 °C/100 m. According to archive data, thermal logging measurements were taken in boreholes 7 and 13, and a geothermal gradient was identified. But all these measurements were taken in the unfrozen (subpermafrost) zone, 100–150 m below the calculated permafrost base. The gradient value was used when calculating the thickness of the permafrost (see below). For boreholes in which logging was not performed, an average geothermal gradient value of 1.6 °C/100 m was used.

On the flattened watershed (borehole 16), the minimum values of ground temperatures (−1.5 °C) are seen at 35–40 m deep, i.e. lower than the depth of zero annual amplitude indicated in [*Kudryavtsev, 1975, p. 75*]. Below, up to the permafrost base at a depth of 190 m, the temperature is rising with an average gradient of 1.0 °C/100 m. In unfrozen ground the geothermal gradient rises to 1.4 °C/100 m, and at a depth of 240 m the temperature reaches +0.7 °C. The average density of the heat flux in the frozen zone was 0.020 W/m^2, 0.028 W/m^2 in the unfrozen (subpermafrost) zone, the overall value was 0.022 W/m^2 for the 200 m (Table 4). The thermal conductivity in each specific depth range was estimated by the composition and homogeneity of the rocks.

Within the steep north-facing slope, borehole 5, owing to its proximity to a cliff, is impacted by side freezing, so at a depth of 40 m the ground temperature falls to −3.1 °C. To a maximum measured depth of 95 m, in direct proximity to a large coal horizon, it increases with a gradient of 1.8 °C/100 m and reaches −2.1 °C.

In the middle part of the south-facing slope (borehole 8) the minimum temperature (−2.1 °C) is seen at depths of 30 and 35 m.

Table 3. **Borehole (BH) location, temperature parameters and calculated permafrost thickness**

BH	Elevation, m	Topographic feature	Slope aspect	Slope, grad.	Temperature* at depth. 40 m, °C	Temperature gradient, °C/100 m		Effective thermal conductivity, W/(m·°C)	Permafrost thickness*, m	Heat flux, W/m^2	Permafrost thickness, m		
						average	by borehole logging				by equation (1)	by BH logging gradient	By gradient *
5	670	Slope	North	25	**−3.1**	**1.8**	1.6	1.8	251	0.021	308	234	221
6	580	Floodplain	None	0	−1.9	1.45	1.6	1.8	173	0.023	189	159	171
7	590	Terrace	»	0	−1.8	1.45	**1.1**	1.8	183	0.023	181	204	164
8	720	Slope	South	25	**−2.1****	1.45	**1.83**	1.8	187	0.021	221	155	185
9	750	»	»	10	−2.0	1.45	**1.26**	1.8	192	0.023	199	199	178
10	815	»	»	15	−1.7	1.45	**1.98**	1.8	154	0.022	178	126	157
11	840	Watershed	»	15	−1.1	1.45	**3.26**	1.8	106	0.022	129	74	116
12	870		»	10	−1.2	1.45	**1.29**	1.8	130	0.023	135	133	123
13	930	»	»	15	−1.3	1.45	**1.45**	1.8	135	0.022	145	130	130
14	950	»	»	5	−1.4	1.45	1.6	1.8	138	0.023	150	128	137
15	900	»	North	10	−1.5	1.45	1.6	2.8	145	0.023	159	134	143
16	880	»	»	15	**−1.5**	**1.1**	1.6	2.0	**190**	0.022	175	134	176

Notes. Bold text highlights measured (actual) values.

* Measured or calculated indicator.

** Temperature from depth 35 m.

We were able to measure the temperature in boreholes 7, 9 and 11 only in the layer of annual ground temperature fluctuations, and at the beginning of August 2006, at the deepest point possible for measuring, it was −1.2, −2.0 and −0.9 °C, respectively (Fig. 7). According to the temperature graphs obtained in deep boreholes (5, 8 and 16), minimum temperature values are attributed to depths of 35–40 m. The difference in temperatures between depths 10 and 35–40 m can range from 0.1 to 0.5 °C, which in addition to the topographic features can also be explained by the reaction to changes in the climate conditions in the region [*Zavadskij, 2013*]. This difference was taken into consideration when calculating ground temperatures at a depth of 40 m to draw a permafrost-geothermal section and is reflected in Fig. 8 and in Table 3.

DISCUSSION OF RESULTS

The result of the research is a sublongitudinal permafrost-geothermal profile through the central part of the Ytymdzha Depression (Fig. 8). To calculate the average depth of the permafrost base (Table 3) we used:

– the temperature gradient, obtained during thermal logging in boreholes;

– the average gradient obtained using direct measurements in the permafrost (boreholes 5, 16);

– the expression reflecting the stationary distribution of ground temperature in permafrost:

$$Z = T\frac{\lambda}{q} + 40, \qquad (1)$$

where Z is the calculated thickness of the permafrost, m; T is the temperature at a depth of 40 m, °C; λ is the effective ground thermal conductivity, W/(m·°C); q is the density of the inner heat flux, W/m^2 [*Carlsaw, Jaeger, 1964*].

The density of the heat flux for each borehole was determined using the formula

$$q = q_0 \cos\alpha, \qquad (2)$$

where q_0 is the starting value of the in-ground heat flux for the area, W/(m·°C); α is the surface slope angle.

Expression (2) reflects the impact of the relief on the heat flux density in the given area [*Balobaev, Levchenko, 1978*]. The starting value of the heat flux in the Ytymdzha Depression was not determined owing to the absence of deep geothermal boreholes. The measurement of the heat flux in the Chulman and Toko depressions allowed us to establish increased values of the in-ground heat flux relative to the rest of the Aldan Shield [*Zheleznyak, 2005*]. To calculate the thickness of the permafrost in the Ytymdzha Depression, we used the initial intensity of the in-ground heat flux q_0 at borehole 16 equal to 0.023 W/m^2 (Table 4).

Effective thermal conductivity of the strata was determined using material composition of rocks, percentages of rocks in suites and in the section. Thick coal horizons, which can decrease the thermal conductivity of the entire thickness owing to their own low thermal conductivity, have the biggest impact.

All calculated values of the permafrost thickness in borehole locations were used as reference points

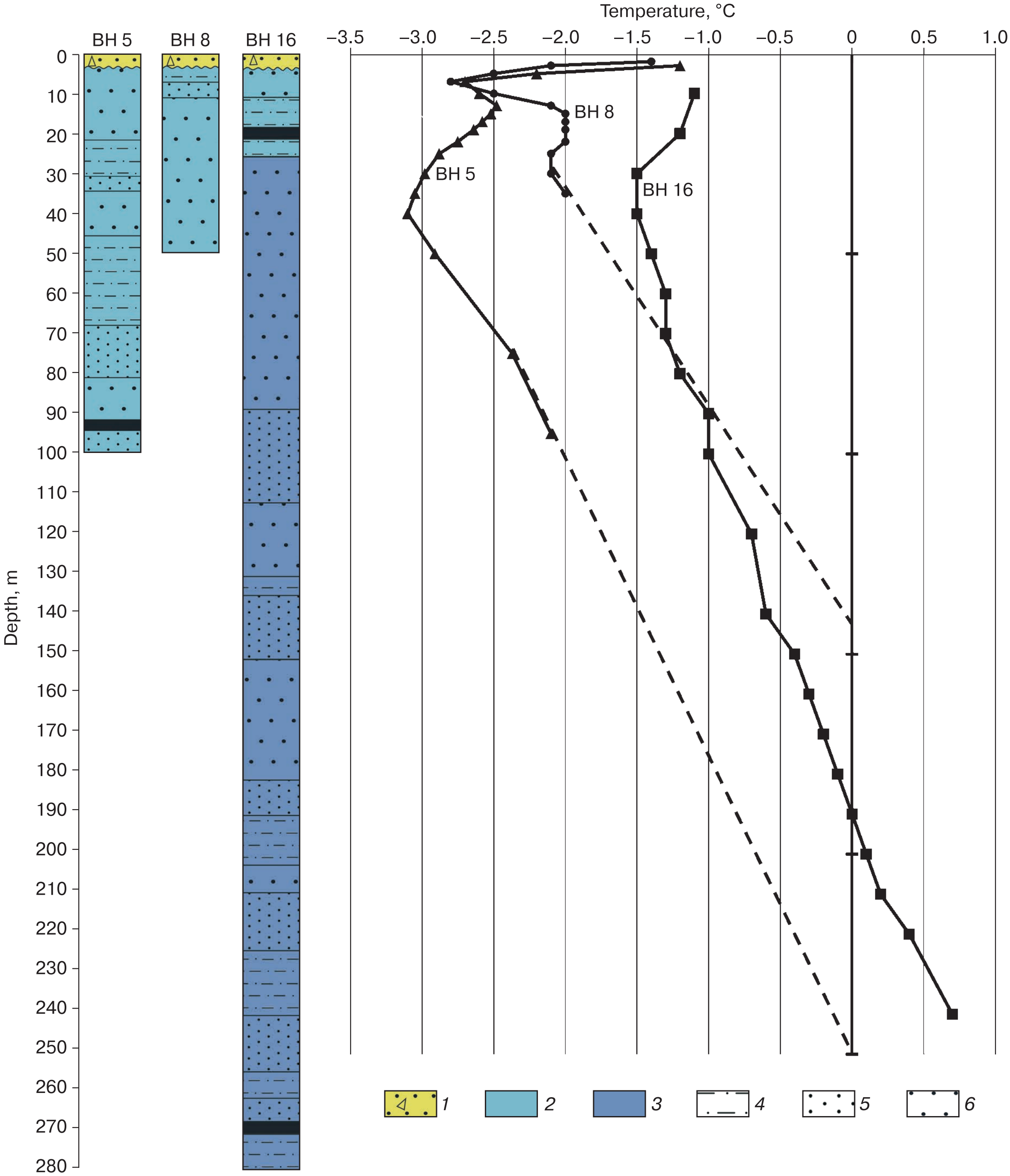

Fig. 6. Rock temperature variation in deep boreholes.

1 – Quaternary deposits; 2 – Kabakta series (J_3kb); 3 – Duray series (J_2dr); 4 – siltstones; 5 – fine-grained sandstone; 6 – medium-grained sandstone. The dashed line corresponds to the gradient temperature increase.

when establishing the permafrost base (Table 3). The permafrost base shown in Fig. 8 is found at minimum depth at the sites of boreholes 9–11. The given area belongs to the south-facing slope and has a thick coal horizon. Such an impact of coal layers on the ground temperature regime has been noted before [*Balobaev et al., 1985b; Gresov et al., 2014; Gao et al., 2017*]. The maximum permafrost thickness is seen in borehole 5, where the steep slope increases the surface area which is involved in heat exchange with the atmosphere, and the north-facing slope decreases the incoming solar radiation.

Table 4. **Temperature and thermophysical rock parameters of borehole 16**

Depth range, m	Rock temperature difference, °C	Gradient*, °C/m	Ground thermal conductivity, W/(m·°C)	Heat flux**, W/m^2
40–50	0.10	0.010	2	0.020
50–60	0.10	0.010	2	0.020
60–70	0.00	0.000	2	0.000
70–80	0.10	0.010	2	0.020
80–90	0.20	0.020	2	0.040
90–100	0.00	0.000	2.1	0.000
100–120	0.30	0.015	2.1	0.032
120–140	0.10	0.005	2	0.010
140–150	0.20	0.020	2	0.040
150–160	0.10	0.010	1.9	0.019
160–170	0.10	0.010	2	0.020
170–180	0.10	0.010	2.2	0.022
180–190	0.10	0.010	2	0.020
190–200	0.10	0.010	2	0.020
200–210	0.10	0.010	2	0.020
210–220	0.20	0.020	2	0.040
220–240	0.30	0.015	2	0.030

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* Average value 0.011.

** Average value: 0.02 in permafrost, 0.028 in unfrozen ground, 0.022 in general.

The depth of the permafrost base in the central part of the Ytymdzha Depression provided in archive materials differs from the results obtained by the authors 50–100 m toward the increasing permafrost thickness. This is particularly prominent in borehole 16, where we were able to perform instrumental measurements up to the permafrost base. Here the difference is up to 100 m. According to measurement results, borehole 5 also shows a discrepancy in the current depth of the permafrost base, but the exact difference was not established. Compared to the Chulman and Toko depressions, the studied area has no thawed zones (aside from possible river taliks of the Ytymdzha and Gonam rivers) (Fig. 9). On flat watersheds and south- and west-facing slopes, there are thawed zones in the Chulman Depression [*Belokrylov, Efimov, 1960; Kudryavtsev, 1975*], while a decrease in permafrost thickness is seen in the Ytymdzha Depression under the same landforms. There is no significant difference in permafrost thickness (like in the Toko Depression [*Zheleznyak, 2005*], owing to the undulating terrain of the Ytymdzha Depression not contributing to the change in permafrost base depth.

A temperature inversion of surface air [*Alekseyev, Filosofov, 1970*] which creates a special kind of freezing, presented in the Chulman Depression [*Belokrylov, Efimov, 1960*], is not observed. However, the increase of the permafrost thickness in depressed areas (boreholes 6, 7) indicates a possible effect from the concentration of cold air masses in valleys.

In accordance with the relief, landscape conditions and the measured ground temperature in deep boreholes and the active layer, permafrost distribution in the Ytymdzha Depression is continuous (Fig. 8). Taliks in the Ytymdzha Depression can exist under the riverbeds of the Ytymdzha and Gonam rivers. Islands of *Chosenia* – a regional indicator of thawed ground [*Tyrtikov, 1969*] – are also attributed to them. Icing fields attributed to main rivers' tributaries can locally form zones of discontinuous freezing. A small amount of icing in such a tectonically active

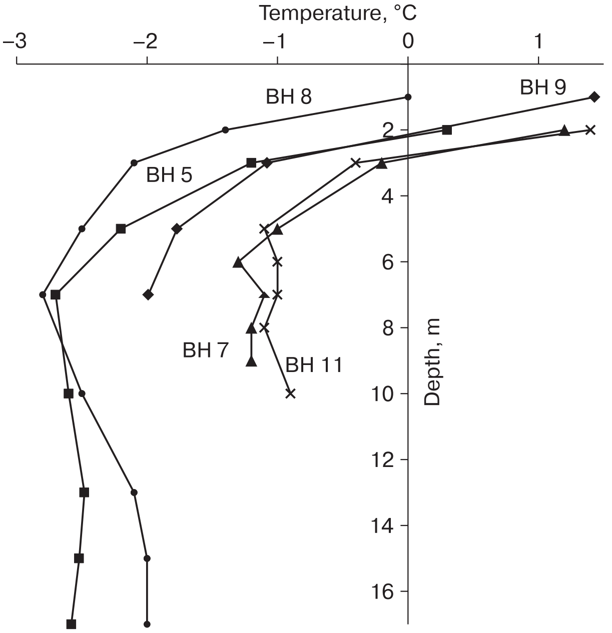

Fig. 7. Ground temperature in the layer of annual temperature fluctuations on 10.08.2006.

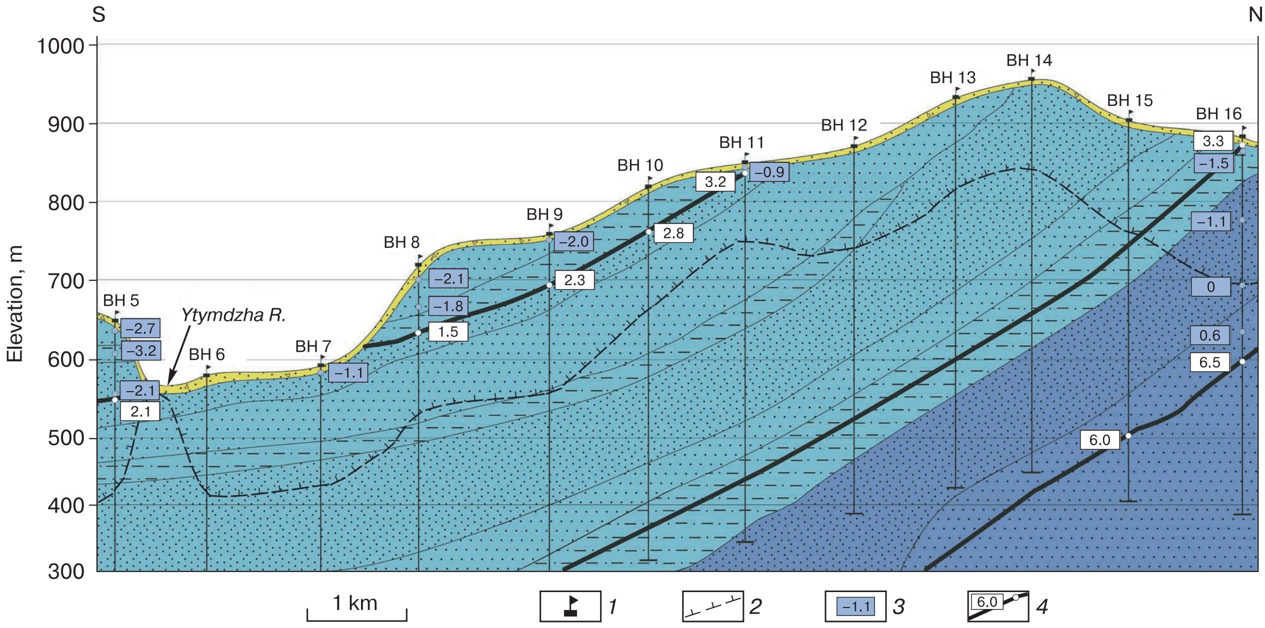

Fig. 8. Sublongitudinal permafrost-geological profile through the central part of the Ytymdzha Depression.

1 – location and number of deep boreholes; 2 – permafrost base according to the results of direct measurements and calculations; 3 – the ground temperature in the borehole, °C; 4 – large coal horizon and its thickness, m. For other symbols see Fig. 6.

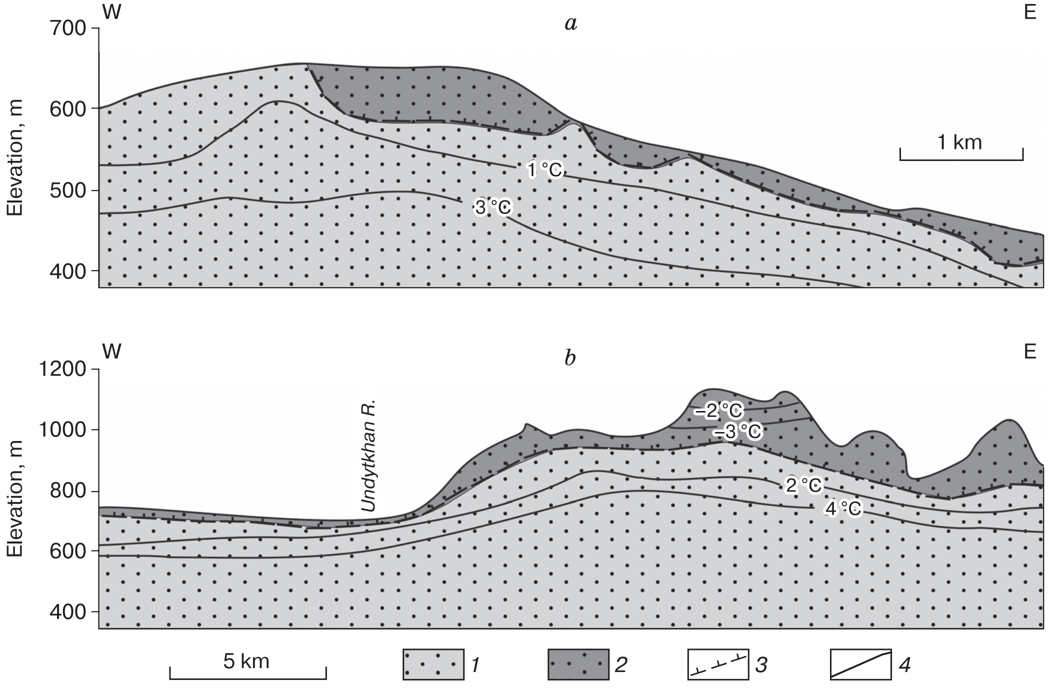

Fig. 9. Permafrost-geothermal sections on the areas of the Chulman (*a*) and Toko (*b*) depressions [Zheleznyak, 2005].

a – Ungra site; b – Elga site; 1 – unfrozen ground; 2 – frozen ground; 3 – permafrost base; 4 – isotherms.

structure indicates backfilling of the majority of cracks, through which underground water unloading can occur [*Fotiev, 1965*].

CONCLUSION

1. Floodplain terraces are characterized by the smallest thickness of the active layer, and within river

terraces (and, possibly, flat watersheds) the ground temperature is maximal.

2. The mean annual ground temperature at a depth of 1 m varies from –1.0 to –4.9 °C. Bogged river terraces are characterized by minimum values, while within river terraces the values are maximal with an average ground temperature rise of up to 4.0 °C per year.

3. Minimum ground temperature below the depth of zero annual amplitude varies from –1.5 to –3.1 °C. The measured geothermal gradient in permafrost equals 1.45 °C/100 m on average. According to a single measurement, the heat flux density in permafrost is 0.02 W/m^2, while in the unfrozen (subpermafrost) zone it increases to 0.028 W/m^2.

4. Based on the performed drilling and geothermal permafrost research, it was determined that the Ytymdzha Depression area has the most severe permafrost conditions among the Mesozoic depressions of the Aldan Shield. Permafrost has a continuous distribution, and its thickness varies from 106 to 251 m, according to calculations.

5. The relief and thermophysical properties of the ground affect the permafrost thickness. In the central part of the Ytymdzha Depression, the minimum depth of freezing is typical for south-facing slopes with a linked large coal horizon.

Acknowledgments. *The authors are grateful to Sergei Ivanovich Serikov for his valuable advice and assistance during the fieldwork.*

The work was carried out within the framework of the budget project AAAA-A20-120111690010-2 "Geothermal field and permafrost strata of the North-East of Russia. Peculiarities of Formation and Dynamics".

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Received February 28, 2021
Revised June 15, 2021,
Accepted September 7, 2021

Translated by M.A. Korkka