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RESEARCH OF MOUNTAIN PERMAFROST OF THE SUBPOLAR URALS BASED ON STUDIES OF MORAINE PEATLANDS

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Permafrost conditions of the Subpolar Urals are characterized by the example of peat bogs of the lateral moraine in the vicinity of Narodnaya mountain area (Polar Urals, Russia). Changes in permafrost conditions due to warming, studied by georadar survey and radiocarbon dating. It was found that the depth of the seasonally thawed layer (STL) ranged from 10 to 140 cm at a permafrost surface temperature of 0 °C. The structure of the peat deposit was checked on a dry section of the swamp using a pit 40 cm deep.

Keywords: *Subpolar Urals, permafrost, GPR, cryogenic processes, peat, climate, radiocarbon studies*

Modern warming causes a significant change in landscape conditions in the Arctic, in particular, increase in STL is what causes the growth in peatlands. The stability of permafrost is of fundamental importance to socio-economic well-being and ecological services, involving broad impacts to hydrological cycling, global budgets of greenhouse gases and infrastructure safety [*McGuire et al., 2018*]. Degrading permafrost can alter ecosystems, damage infrastructure, and release enough carbon dioxide (CO_2) and methane (CH_4) to influence global climate. The permafrost carbon feedback is the amplification of surface warming due to CO_2 and CH_4 emissions from thawing permafrost. An analysis of available estimates permafrost carbon feedback strength and timing indicate 120 ± 85 Gt of carbon emissions from thawing permafrost by 2100. Climate change causes changes in the Arctic environment, primarily due to permafrost degradation, which is sensitive to changes in air temperature and precipitation, leading to a change in the activity of certain exogenous processes [*Kislov, et al., 2023*].

Modern climate changes and permafrost reaction. At present, intensive permafrost degradation is observed in the Subpolar Urals. An analysis of the annual percentage deviations from the long-term average for nearby stations in the European North of Russia shows that the rate of increase in the mean annual air temperature over the past 30 years has ranged from 0.08 to 0.16 °C/10 years. In the region under consideration, in the period 2003–2012, the average annual air temperature increased by 0.05 to 0.07 °C/year, and the duration of the warm period increased by 2 weeks. The amount of precipitation increased by 1–3 mm/year, which led to an increase in the maximum snow depth by 1.8 cm/year. Simultaneously with the change in air temperature in the studied region, there is an increase in the STL depth by up to 1.13 m over the period from the mid-1970s to 2018 [*Pastukhov et al., 2017; Streletskiy et al., 2021*]. Long-term observations of the state of permafrost have shown the growth rate of permafrost temperature from 0.01 to 0.06–0.07 °C/year. High velocities are characteristic of cold permafrost, while low velocities are characteristic of warm permafrost, which somewhat reduces the spatial variability of temperatures in cryogenic landscapes [*Vasiliev et al., 2020*]. The temperature of the rocks decreased within negative values. In modern conditions, along the western foothills of the Subpolar Urals, a high-temperature (from -0.5 to -1 ° C), thin up to 50 m, insular cryogenic stratum is widespread. At the same latitude, but in the eastern part, cryogenic conditions are more severe. It is dominated by a cryogenic stratum with temperatures from -1 to -2 °C, thin up to 100 m, insular in distribution. At heights from 600 m, a discontinuous cryogenic stratum dominates (from -1 to -2.5 ° C), up to 150 m thick. Above 800 m, permafrost conditions become even more severe. In the axial part of the ridges, where Holocene permafrost merged with

Neopleistocene strata, there is a low-temperature (from -3 to -11 °C), thick from 300 m, continuous cryogenic stratum, with an age of tens of thousands of years [*Fotiyev*, *2015*]. In order to determine if climatic conditions are reaching the above conditions, this study subsurface permafrost conditions in the Subpolar Urals using georadar surveys using radiocarbon dating data of selected peat cores to clarify changes in permafrost conditions and develop recommendations for the future.

Study area. The site is geographically located between the upper reaches of the Khulga and Shchugor rivers in the basin of the river Balbanya, near the Zhelannoye rock crystal deposit (Barkova mountain area, Subpolar Urals, 65°12'03" N, 60°16'40" E). The territory belongs to the zone of continuous permafrost [*Abaturova et al., 2022*]. Permafrost is developed on almost all relief elements. Near Lake Bolshoye Balbanty (water-line mark 644 m a.s.l.), and up to altitudes of 700 m, the permafrost thickness is about 120 m at grounds temperatures from 0 to -0.5°C. In the middle part of the slopes, the temperature regime of the upper permafrost horizons is characterized by an average annual temperature of -2 to -3°C and slightly higher temperatures in the valleys of small streams flowing into the river Balbanya. At altitudes of about 800 m, the thickness of the permafrost is about 220 m, and the temperature is -2°C; at altitudes of about 900 m permafrost has a thickness of about 400 m and a temperature of -3°C. On the plateau-like peak of the Barkov Mountain, apparently due to the accumulation of snow in winter, the thickness of the permafrost decreases to 300 m. The thickness of the STL depends on the mineral substrate. In loamy-gravelly soils, it varies from 0.5 to 1.2 m; in sandy soils - from 0.8 to 2 m; in coarse soils - from 1.7 to 4 m; in rocks - from 3 to 3.5 m. During sub-zero temperatures, the STL completely freezes. Cryogenic processes are associated with seasonal thawing and freezing - solifluction, frost heaving of soils with soil sorting, frosty weathering of grounds.

GPR Research Methodology. The experience of using GPR to study the permafrost zone as a multiphase system is reduced to the identification of the permafrost, as well as the detection of heterogeneities within the STL and the upper part of the permafrost. The possibility of mapping such boundaries was shown earlier in the articles of Russian authors [*Kaverin et al., 2020; Kopylov et al., 2022; Sokolov et al., 2021; Tregubov et al., 2020*]. Foreign experience in the use of georadar for the study of permafrost is described in the researches [*Campbell et al., 2021; Kim et al., 2021*]. The contrast of the dielectric properties of the medium, due to the phase transition, water ice, in the subvertical direction ensures the appearance of reflected waves on georadarograms, according to the position of the in-phase axes of which the boundary between frozen and thawed rocks is mapped. The interpretation of GPR profiles was carried out using the RADAN 6.5 georadar data processing complex [*Geophysical…, 2007*]. In the course of field research, a SIR-3000 georadar with a 5103 high-frequency antenna (400 MHz, GSSI, USA) was used. In total, 26 georadar sections were obtained in the studied area. Four of them have a length of 105 to 152 m and are analyzed in this article.

Method for determining the age of peat. According to field observations in the studied area, it can be seen that after warming, thawing of underground ice and the end of relative stabilization of the earth's surface, soil formation and accumulation of peatlands begin on it. Peatlands, as a rule, grow on flattened (due to the accumulation of finely dispersed material) relief areas with sufficient moisture. In some cases, it is also seen that the swamp is formed when the dammed lake is overgrown. Peat for studying the rate of peat accumulation was taken from a bog of this type. To determine the age of peat, the studied sample was divided into horizons. Each peat horizon was cleaned of roots, stones and sand, washed through a fine sieve. The resulting mass was successively treated with hydrochloric acid to remove the mineral carbonate part, and then with alkali, washed and dried. From the pretreated samples, coal was obtained in a stainless steel reactor at 600°C. Next, at a temperature of 600–700°C, the reaction of coal with metallic lithium was carried out in a reactor under vacuum to form lithium carbide (Li_2C_2). The decomposition of lithium carbide with water in vacuum gave acetylene (C_2H_2), which was absorbed by the vanadium aluminosilicate catalyst to form benzene [*Arslanov et al., 1993*]. Synthesis of benzene samples was carried out in triplicate for each determined horizon. ^{14}C

activity in benzene was measured on a Quantulus 1220 scintillation spectrometer (PerkinElmer Inc., USA). To calculate the radiocarbon age of peat, the following relationship was used:

$$t = \frac{5568}{ln2} \cdot \frac{\ln {}^{14}C_0}{{}^{14}C}$$

where 5568 - is the half-life of ^{14}C, years; ^{14}C and $^{14}C_0$ are the measured and initial radiocarbon activities in the total carbon of the dated samples. The calibration (calendar) age of peat was determined using the OxCal 4.4.4 program using the IntCal 20 calibration curve.

Results and discussion. GPR studies. Profile 027, 100 m long, passed through the swamp between points 088 and 089 from north to south (Figure 1).

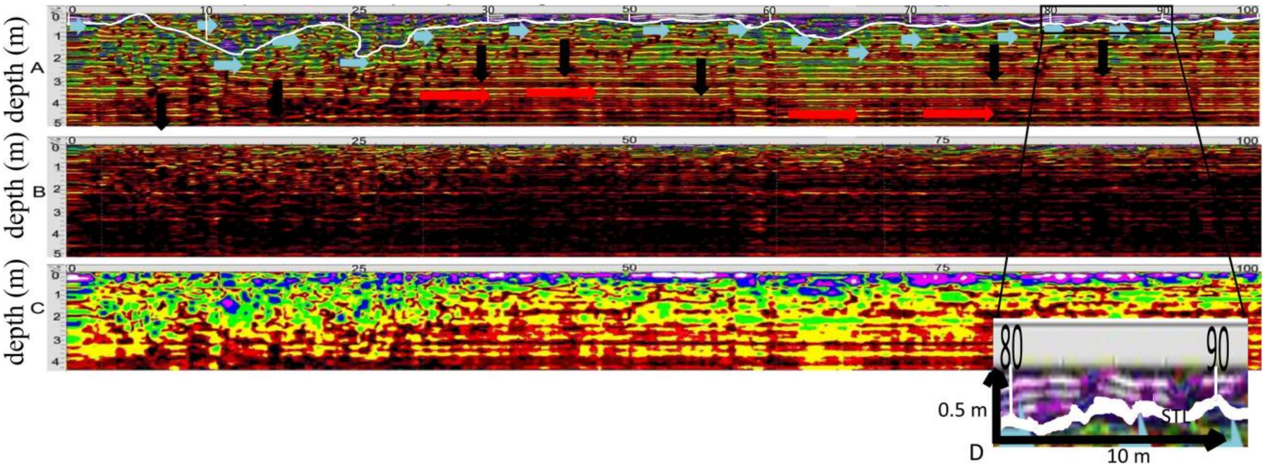

Fig. 1. Georadar profile 027. A – GPR, B – interpretation by deconvolution, C – interpretation by Hilbert transform; D – separate black box indicates the discovered patterns for STL and its display on a georadargram. Blue arrow and white line – STL boundary; red arrow – linear boundaries of deposit's adjoining; black arrow – tree structures. In Figure 1A vertical white lines show the depth of STL actually measured with a metal probe.

Approximately in the interval of 60–80 m from the surface, there is a hollow (apparently, the remains of a dammed lake) with a diameter of about 15–20 m. Here, the thickness of the STL reaches 1–1.2 m, which is confirmed by parallel sounding with a metal thermal probe. Throughout the profile in the region of 30–55 m, the thickness of the STL varied from 0.2 to 2 m. However, from a continuous strip, the character of humidification zones passes into subvertical disparate channels. Apparently, in this part of the swamp, a pattern is formed similar to that observed in the moraine language. The depth of the STL, estimated from the probe, ranged from 10 to 140 cm. In the section opened by the pit it is seen that the peat bog is underlain by frozen clay-loam. In the peatland itself, several boundaries of peat and gley accumulation are visible in the layers directly above the underlying loam, indicating a repeated change in the conditions of peat accumulation at the beginning of warming or the movement of rocks as a result of solifluction flows from nearby slopes. Thus, the raised bog is characterized by the presence of confluent permafrost.

Radiocarbon dating of a peat bog. The peat section was sampled within a raised bog located in a swampy area between a lateral moraine and a mountain slope about 2 km southwest of the Barkov mountain area.

According to the formation conditions, this swamp is similar to the one on which GPR profiling was performed, discussed above. Two cores 50 cm high were extracted to the permafrost. The core was divided into the following horizons 7–14, 14–20, 20–25, 25–30, 30–35, 35–40, 40–45, and 45–50 cm (Figure 2) and was used for radiocarbon dating. The beginning of peat formation refers to the time 2224±210 years (calibration (calendar) age, cal. year's ± sigma). That is, the average growth rate of a peatland is about 2.2 cm/100 years. The age curve shows an increase in the rate of peat accumulation in the period about 1000 years ago; while later and earlier the accumulation rate turned out to be lower and was approximately equal to 1.2 cm/100 years. In general, the low rate of peat accumulation is characteristic of the climatic conditions of the Subpolar Urals. For example, radiocarbon dating of frozen forest-tundra peatlands in the European North-East of Russia showed a growth rate of about 1.14 cm/100 years [*Vasilevich, 2018*].

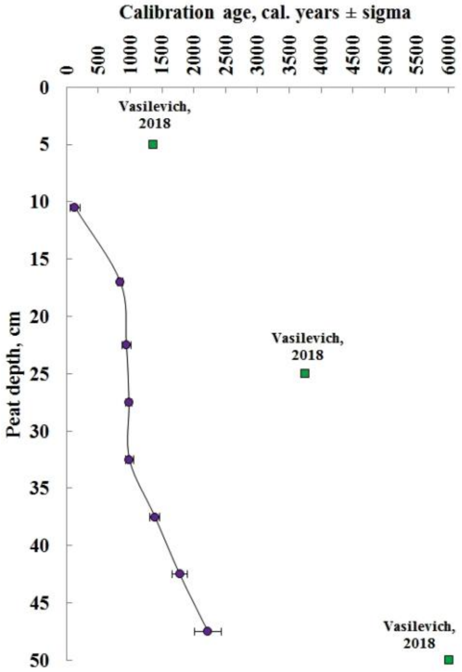

Fig. 2. Results of radiocarbon dating of the core compared with data [*Vasilevich, 2018*].

Conclusion. The influence of climate warming on the permafrost landscape of the Subpolar Urals in the area of Narodnaya mountain area has been studied. From marks about 644 m a.s.l. at the lake Big Balbanty and up to heights of 700 m permafrost thickness is about 120 m at a temperature of 0 to -0.5°C. At altitudes of about 800 m, the permafrost thickness reaches 220 m at a temperature of -2°C; at altitudes of about 900 m permafrost has a thickness of about 400 m and a temperature of -3°C. A similar structure, most likely, should have a permafrost section in the adjacent areas. According to georadar data, the STL in the bog is practically absent in areas with dry moss and increases to 0.8–1 m in areas where hollows are located on the surface of the bog. In the bog junction zone in the lateral moraine, in the driest areas, the continuous development of the STL is interrupted and individual watered channels appear on the radarogram, penetrating to a depth of 1.5–2 m. The depth of thawing in this swamp was also determined by measuring the depth of the STL and the temperature of the rocks using a thermometer and a metal probe 1.5 m long along a 100 m profile with a step of 10 m. It was found that the depth of the STL ranged from 10 to 140 cm at a permafrost surface temperature of 0 °C.

The structure of the peat deposit was checked on a dry section of the swamp using a pit 40 cm deep. It was found that the peat bog is underlain by frozen clay-loam. In the peatland itself, several boundaries of peat and gley accumulation are visible in the layers directly above the underlying loam, which indicates a repeated change in the conditions of peat accumulation at the beginning of warming or the movement of rocks as a result of solifluction flows from nearby slopes. In a bog adjacent to a bog studied by GPR, a 50 cm high peat monolith was sampled for radiocarbon dating at intervals of 5 cm years. The age curve shows a rapid growth of the peatland in the period about 1000 years ago, while later and earlier the accumulation rate turned out to be lower and amounted to about 1.2 cm/100 years. In general, the low rate of peat accumulation is characteristic of the climatic conditions of the Subpolar Urals and adjacent territories. Thus, it was found for the first time that for the region of Narodnaya mountain area (subpolar Urals) at altitudes of about 700 m, a steady accumulation of peat due to climate warming began no earlier than 2.2 thousand years ago.

Taking into account the above, it can be assumed that for the start of large-scale degradation of permafrost in the Subpolar Urals at altitudes above 700 m, the air temperature should reach the values characteristic of the Holocene optimum, which is approximately 1.5–3 °C higher than the current long-term average values.

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ИССЛЕДОВАНИЕ ГОРНОЙ МЕРЗЛОТЫ ПРИПОЛЯРНОГО УРАЛА НА ОСНОВЕ ИЗУЧЕНИЯ МОРЕННЫХ ТОРФЯНИКОВ

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Условия вечной мерзлоты Приполярного Урала охарактеризованы на примере торфяников боковой морены в районе горы Народной (Полярный Урал, Россия). Изменения условий вечной мерзлоты вследствие потепления, изучены с помощью георадарной съемки и радиоуглеродного датирования. Установлено, что глубина сезонно-талого слоя (СТС) составляет от 10 до 140 см при температуре поверхности вечной мерзлоты 0°С. Структуру торфяной залежи изучили на сухом участке болота в шурфе глубиной 40 см.

Ключевые слова: *Приполярный Урал, вечная мерзлота, георадар, криогенные процессы, торф, климат, радиоуглеродные исследования*