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GEOLOGICAL CRYOGENIC PROCESSES AND FORMATIONS

RECONSTRUCTION OF THE FORMATION HISTORY OF THE PEAT PLATEAU IN THE LOWER REACHES OF THE NADYM RIVER

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This study presents new data on the cryolithological structure of a ridge-shaped peat plateau typical for the north of Western Siberian, located in the lower reaches of the Nadym River. Two wells were drilled at the top of the ridge and in the inter-ridge depression, with subsequent core analysis. Grain-size distribution, shape and surface structure of sand quartz grains, botanical composition and radiocarbon age of organogenic deposits were determined. The study revealed the presence of a three-layer peat-sand-loam ridge structure. The lower loam layer with a ~60 % volumetric ice content was affected by frost heaving. Layers of pure ice are identified below this loam layer. The ridge was formed as a result of water migration with the complementary influence of ice injection; it is of the peat-mineral type. In the ridge formation history, we identified the stages of loam and sand deposit accumulation at the end of the Late Pleistocene; bogging occurred at the beginning of the Holocene (10.6–9.8 ka BP), while active frost heaving was during the Subboreal stage (5.5–5.0 ka BP). Currently, there is a decrease in the upper organic horizon thickness and some erosion. It is proposed to consider peat-mineral and mineral frost heave landforms (mounds and ridges) as a separate type of cryogenic landforms.

Key words: *frost mound, frozen ground, permafrost zone, Upper Quaternary deposits, Nadym region.*

INTRODUCTION

Heaving processes of various types of deposits are common within large peat massifs in the north of Western Siberia, as well as in other arctic regions of the Northern Hemisphere [*Evseev, 1976; Landscapes..., 1983*]. Migrational frost mounds (MFM), the formation of which is related to the migration of water from shallow-lying water-bearing horizons to the freezing front, are distinguished among various forms of cryogenic landscapes [*Popov, 1967*]. Use of this term stems from the need for genetic characterization when describing convergent landscape forms, as well as from the fact that the peat, mineral, and peat-mineral mounds stand out in deposit composition among MFM [*Evseev, 1976; Landscapes..., 1983*].

In the north of Western Siberia, MFM are seen predominantly in the southern tundra, forest-tundra, and in the northern taiga region of the irregular bedding of the contemporary and ancient permafrost thicknesses [*Shpolyanskaya, Evseev, 1972*]. The northern boundary of their distribution matches the northern boundary of the discontinuous development of permafrost (MFM are rarely seen north of the river mouth of the Nyda and Taz rivers), the southern boundary is the southern boundary of the distribution of sporadic permafrost [*Evseev, 1976*].

Frost mound research has a many-year history. The theoretical explanation of the heaving process, the description of the cryogenic structure, genesis and MFM morphology are given in various works of Russian scientists [*Popov, 1967; Shpolyanskaya, Evseev, 1972; Evseev, 1976; Berdnikov et al., 2019*]. Individual studies are dedicated to the results of annual monitoring of cryogenic heaving [*Moskalenko, Ponomareva, 2004; Ponomareva et al., 2012*]. The dynamic of the vegetation cover on large-mound peat bogs has been thoroughly analysed, as well as their typical identifying features, which persist in the identification of landscape peculiarities of the territory and the drafting of integral ecological maps [*Tyrtikov, 1979; Ponomareva, 2010*].

MFM of the peat-mineral type, which significantly differ from classic peat mounds in their structure and development dynamic, are particularly interesting. They form in areas of distribution of deposits of various genesis and composition (loams, clays and sometimes dusty loams) and can be morphologically expressed both as hills and ridges. An ice core (a local accumulation of segregated ice) is often absent here, and heaving horizons are covered by a thickness of sand deposits and a thin peat layer from the surface. A separate type of mineral MFM is also identified, the top peat layer of which has been removed by erosion and deflation [*Vasi'lchuk, 2008*]. In Western literature the term "lithopalsa" or "lithalsa" is usually used to signify mineral MFM [*Calmels et al., 2008; Wolfe et al., 2014*]. Peat-mineral and mineral MFM frequently signify genetically different landscape forms complicated by heaving (kames and moraine hills, eskers, etc.) in complex geomorphological conditions [*Wolfe et al., 2014*], which creates additional ambiguity for conducting field research in thematic cartography. There are almost no special studies of age, the history of development and peculiarities of the distribution of peat-mineral MFM, although these questions are considered key in regard to the conditions of the northern taiga of Western Siberia [*Vasil'chuk, 2008*].

The goal of the present work is the reconstruction of the formation history of a peat-mineral MFM (as a frost ridge) in the lower course of the Nadym River.

AREA AND OBJECT OF RESEARCH

The studied territory is located within the bogged and lakeside second above-floodplain terrace of the Kheygiyakha River (left tributary of the Nadym River, 15 km south of the river mouth) (Fig. 1). The absolute heights of the surface fluctuate within 20 to 36 m.

The thickness of the peat in the peat bogs is 1.0–1.5 m on average (up to 5 m in depressions). Alluvial deposits present as fine-grained and medium-grained sands with rare inclusions of quartz gravel and quartz pebbles, as well as vegetation remains of various degrees of decomposition [*Braduchan et al., 2015*]. The sands are 4 to 10 m thick and are underlain by icy loams [*Geological survey..., 1954; Braduchan et al., 2015*]. There is clear oblique or lens-like stratification of the river mouth facies in the sands, which changes into horizontal stratification upon transition into the floodplain facies. The age of the sands was determined using the radiocarbon dating method and optically infrared stimulated luminescence (IR–OSL) in two sections: in the sand quarry near the river mouth of the Kheygiyakha River (dated using oblique stratification sands of the river mouth facies) and directly within the work area in one of the lakeshore outcrops (dated using vegetation remains). In the first case, an age of 24 ka BP was obtained; in the second, an age of 27 ka BP [*Sizov et al., 2020*], which corresponds to the beginning of the Sartan cryochrone (marine isotope stage 2 – MIS 2). The spore and pollen analyses indicate the existence of typical tundra and forest-tundra conditions during the formation period of the terrace [*Braduchan et al., 2015*].

The contemporary average annual air temperature is −5.6 °C. Data from years of observations reveal that the MFM temperature at a depth of 10 m has increased since the end of the 1970s: from −1.8 to −0.4 °C on large-mound peat bogs and from −1.0 to −0.2 °C on flat-mound peat bogs [*Moskalenko et al., 2012*]. The minimum temperature (−1.5...−2.0 °C) was recorded from 2009 to 2017 in the well drilled at the top of the peat-mineral mound.

The vegetation cover of the region belongs to the woodland subzone of the boreal zone [*Vegetation..., 1985*]. Larch and spruce-larch woodlands and open forests with *Larix sibirica* Ledeb. and *Picea obovata* Ledeb., which alternate with moss, lichen, and subshrub tundras, are typical for the flat interfluve zones of the region. Bogging of the territory is very high and reaches 70 % in the Nadym-Pursk interfluve.

The object of research is a small (approximately 300 m in length) peat-mineral frost ridge located near the inner margin of the second above-floodplain terrace of the Kheygiyakha River (Fig. 1) – the distance to the slope of the third above-floodplain terrace of lake-alluvial origin is less than 400 m. The ridge is complicated by thermoerosional scours and is washed away by lakes from the north, west and east. The studied object is located in the center of the area of heaving, where six ridges and 10 separate mounds of different heights can be distinguished. The length of some of the ridges attains 700 m, and the absolute height is 36.0 m. The ridges are divided by inter-ridge depressions with an amplitude of relative heights of over 10 m. The general direction of the ridges is northwest and west, often the ridges are divided by scour into local hills which form extended chains. Sparse forest vegetation consisting predominantly of cedar and larch is seen on the surface of individual ridges.

RESEARCH METHODS

Two wells were drilled using a drilling rig installed onto the chassis of a "Trekol" all-terrain vehicle: well 2 on the top of the ridge (absolute height: 34 m; coordinates: N 65°17′08.58″, E 72°50′39.75″) and well 3 in the inter-ridge depression (absolute height: 27 m; coordinates: N 65°17′01.02″, E 72°50′44.11″). Drilling took place from July 28, 2018 with a 10 cm-diameter core sample taken from peaty and loamy horizons. There was no core sample from sandy horizons. Samples were collected from deposits every 0.5–1.0 m for granulometry, morphoscopy, and morphometry of sand quartz grains. Well structure diagrams are presented in Fig. 2.

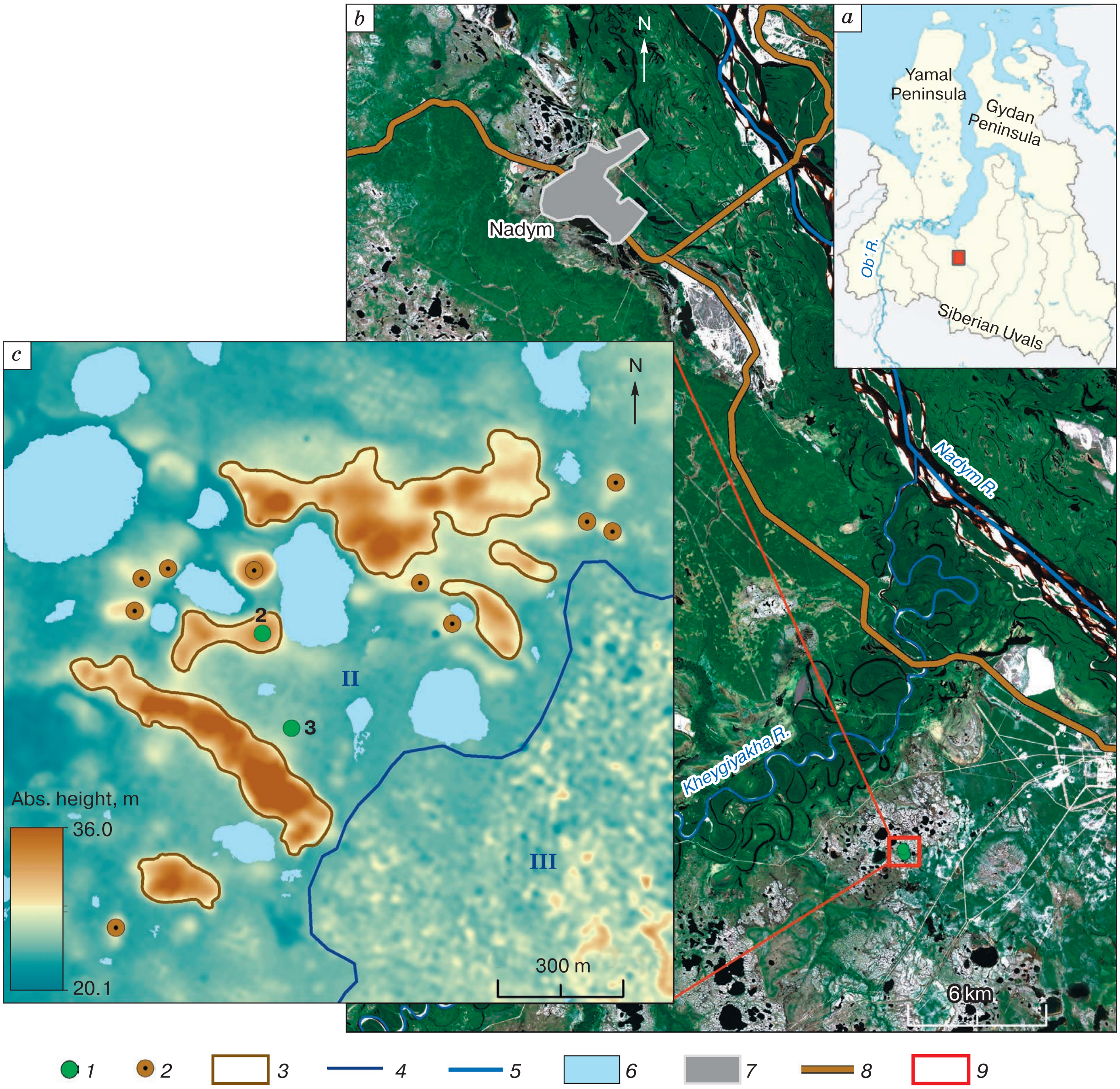

Fig. 1. Overview map of the work area:

a – key map of the north of Western Siberia (work area indicated using red rectangle); *b* – Sentinel-2A satellite image (resolution: 10 m, date the photo was taken: June 18, 2016); *c* – ArcticDEM digital model of landscape (resolution: 2 m). *1* – wells; *2* – migrational frost mounds; *3* – migrational frost ridges; *4* – boundary between the II and III above-floodplain terraces of lake-alluvial origin [*Braduchan et al., 2015*]; *5* – rivers; *6* – lakes; *7* – Nadym Town boundaries; *8* – roadways; *9* – work territory boundary.

The granulometric composition of sand samples weighing 500 g was determined using the dry method according to the traditional sieving method (sieve analysis) on the Analysette 3 PRO vibratory sieve shaker (Fritsch, Germany) in the range from 0 to 2000 μm, fractions were then weighed on laboratory scales with a resolution of 0.1 g. Fractions <125 μm were divided using the Analysette A22 laser particle sizer (Fritsch, Germany), after which the mass percents of each fraction were calculated in Excel 2013 (Microsoft, USA). The granulometric composition of loamy samples was determined directly using the Analysette A22 laser particle sizer (Fritsch, Germany) (the required size of the sample was calculated automatically in the device). The Friedman-Sanders classification was used to describe results [*Friedman, Sanders, 1978*].

Analysis of quartz grains from medium-grained and coarse sand was carried out under a binocular microscope using a method created in the RAS Geo-

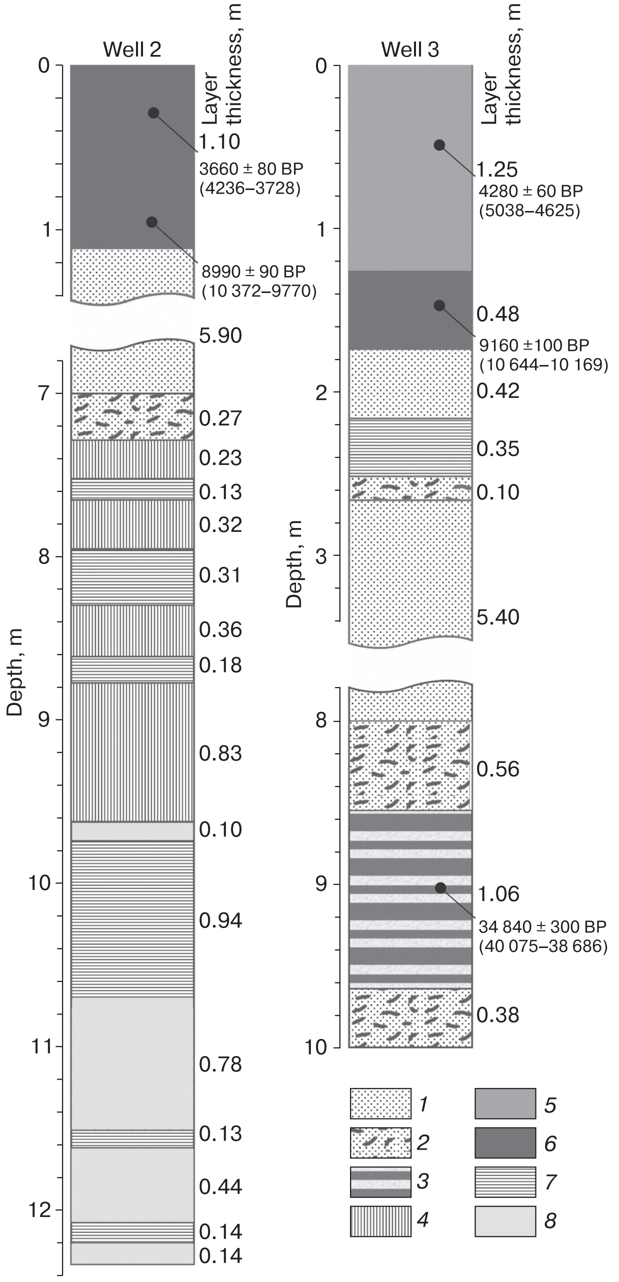

Fig. 2. Structure of deposits in wells 2 and 3 based on results of drilling.

1 – sand, *2* – sand with vegetation detritus, *3* – interlayering of vegetation detritus and sand, *4* – icy loam, *5* – transitional peat, *6* – lowland peat, *7* – loam, *8* – ice.

graphy Institute [*Velichko, Timireva, 1995*]. Analysis of the microstructure of grain surface was carried out on the JSM-6510LV scanning electronic microscope (SEM) (JEOL, Japan) using secondary electrons (SEI – secondary electron image) in the Analytical Center for multi-elemental and isotope research SB RAS (Novosibirsk). Grain roundness was determined using L.B. Rukhin's template [*1969*] and A.V. Khabakov's five-grade scale [*1946*], where 0 is angular and IV is perfectly rounded. The roundness coefficient and degree of matting were determined for each sample [*Velichko, Timireva, 1995*]. Grain matting was determined visually from glossy to dull. Study of grain surface microrelief structure was carried out using published diagnostic features of grains of various genesis and deposition conditions [*Krinsley, Doornkamp, 2011*].

Botanical analysis of the peat and the degree of its decomposition were carried out by the microscopic method (with up to 5 % accuracy) in the Mire Ecosystems Laboratory of the Biology Institute of the RAS Karelian Research Center (Petrozavodsk) by N.V. Stoykina using the atlas of plant remains in peat [*Katz et al., 1977*] and by way of comparison with herbarium samples of plants. Peat typification based on botanical composition was completed using [*Tyuremnov, 1976*].

The liquid scintillation count method was applied for determining the absolute age of the peat and vegetation remains. The analysis was completed by the Radiocarbon Laboratory of the Institute of Environmental Geochemistry of the NAS of Ukraine (Kiev). The obtained radiocarbon dates were recalculated into calendar years through calibration using the publicly accessible program OxCal 4.3 [*Bronk, Lee, 2013*] based on the IntCal13 calibration curve.

RESEARCH RESULTS

1. Granulometric composition and morphoscopy of sand quartz grains. The results of granulometric composition analysis demonstrate a clear differentiation of sand and clay layers distinguished during describing (Fig. 3).

Fine and medium-grained sand fractions dominate in the composition of sand horizons (well 2: 1.1–7.27 m, well 3: 2.6–8.0 m). A fine and medium dust fraction with particle size 0.016–0.002 mm dominates in the clay deposits (well 2: 7.27–10.7 m). Horizons with predominantly large dust are seen in the top part and at a depth of 8.0 m in well 3. Thus, the base of the heaving ridge is composed of a dusty core which is not seen in the inter-ridge depression.

Morphoscopy results (Fig. 4) demonstrated that the roundness coefficient (*Q*) of quartz grains at a depth of 7 m in the sand horizon in well 2 was 80 %, degree of matting (Cm) was 50 %. The main element of grain surface morphology in well 2 is small pits (Fig. 5, *a*–*d*), and individual V-shaped grooves (Fig. 5, *b*, *c*) and sickle-shaped hollows are frequently seen. These elements indicate subaqueous grain processing. The presence of small pits in some grains (Fig. 5, *b*–*d*), most often developed in protruding parts of the grain, indicates the influence of aeolian processes.

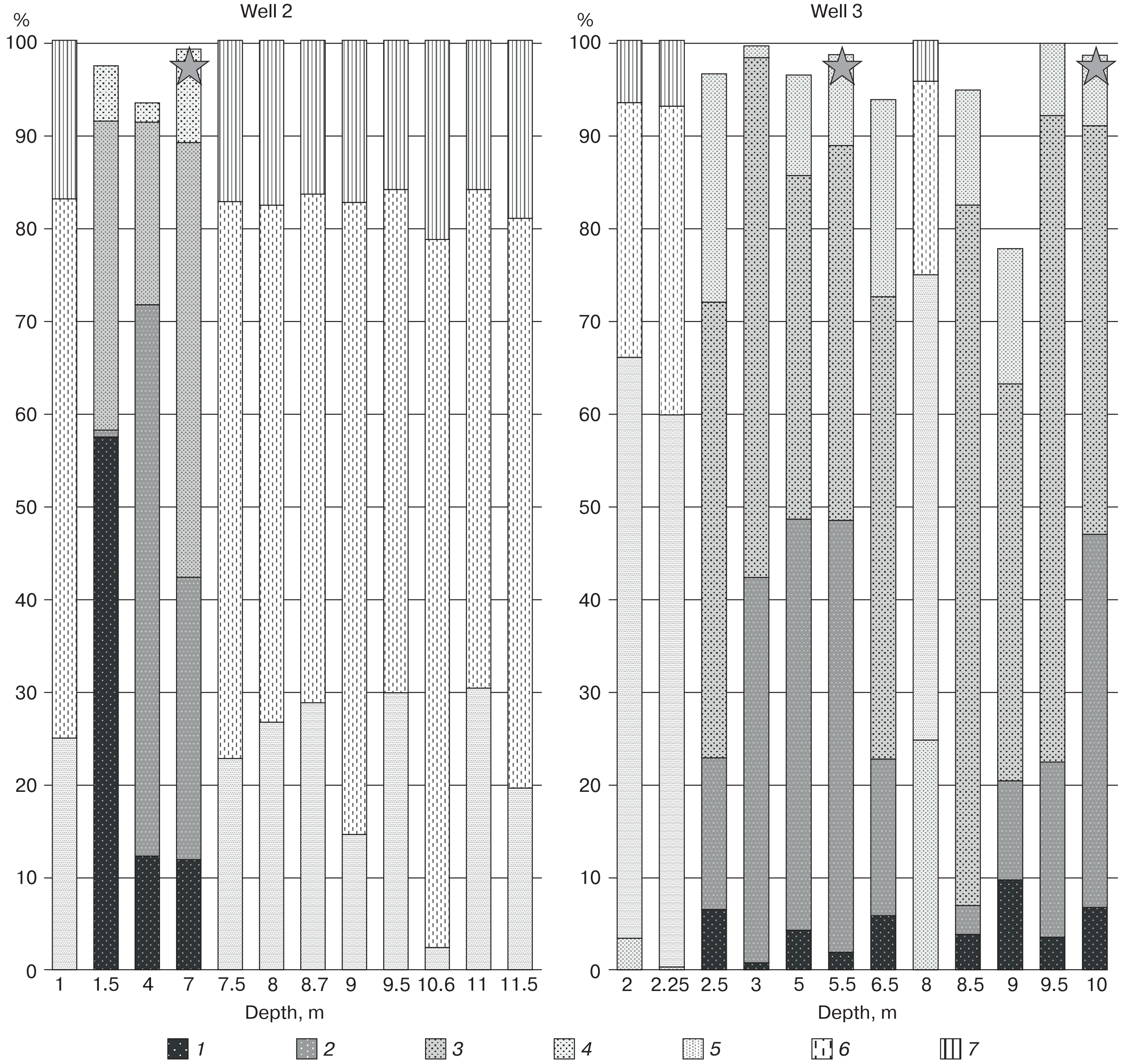

Fig. 3. Granulometric composition of deposits exposed by wells 2 and 3.

Stars mark sand quartz grain morphoscopy and morphometry samples. *1* – coarse sand, 0.5–1.0 mm; *2* – medium-grained sand, 0.25–0.50 mm; *3* – fine-grained sand, 0.125–0.250 mm; *4* – very fine-grained sand, 0.125–0.063 mm; *5* – large dust, 0.063–0.016 mm; *6* – medium and fine dust, 0.016–0.002 mm; *7* – clay, <0.002 mm.

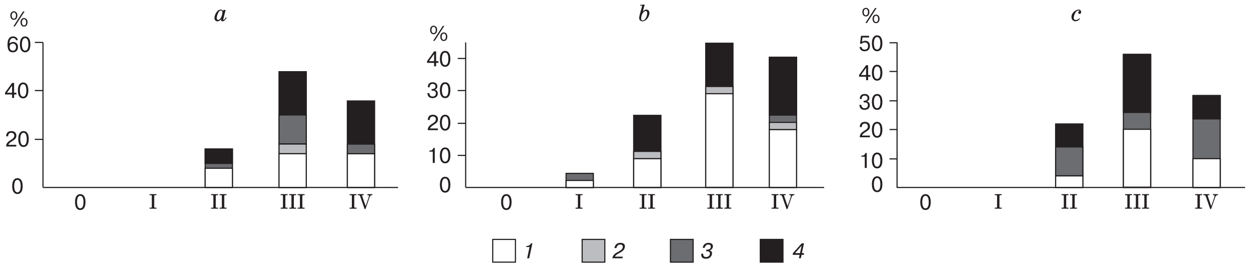

Fig. 4. Distribution based on grain roundness and matting of sand quartz grains from well samples.

a – well 2, depth 7 m; *b* – well 3, depth 5.5 m; *c* – well 3, depth 10 m. *1* – glossy surface, *2* – quarter-matted surface, *3* – half-matted surface, *4* – matted surface. 0, I, II, III, IV – roundness grades according to A.V. Khabakov's scale [*1946*].

The roundness coefficient in well 3 (sand sample from 5.5-m depth) is 77 %, the degree of matting is 41.5 %. Most grains have a well-defined small-pit surface (Fig. 5, *e*, *f*, *i*) which formed as a result of active water transport. Crescent-shaped depressions can also be seen in some grains (Fig. 5, *g*, *h*), which also indicates subaqueous processing, but in a calmer environment. Sometimes, small pits are seen (Fig. 5, *g*, *h*), which indicates transport in subaerial conditions.

The roundness coefficient (Q) in the sand sample from well 3 (10-m depth) is 77.5 %, the degree of matting (Cm) is 51 %. Regardless of surface matting, the predominance of well-developed small pits of the surface (Fig. 5, *j*, *k*) is typical for grains, being an indicator of fairly active river transport. Individual cres-

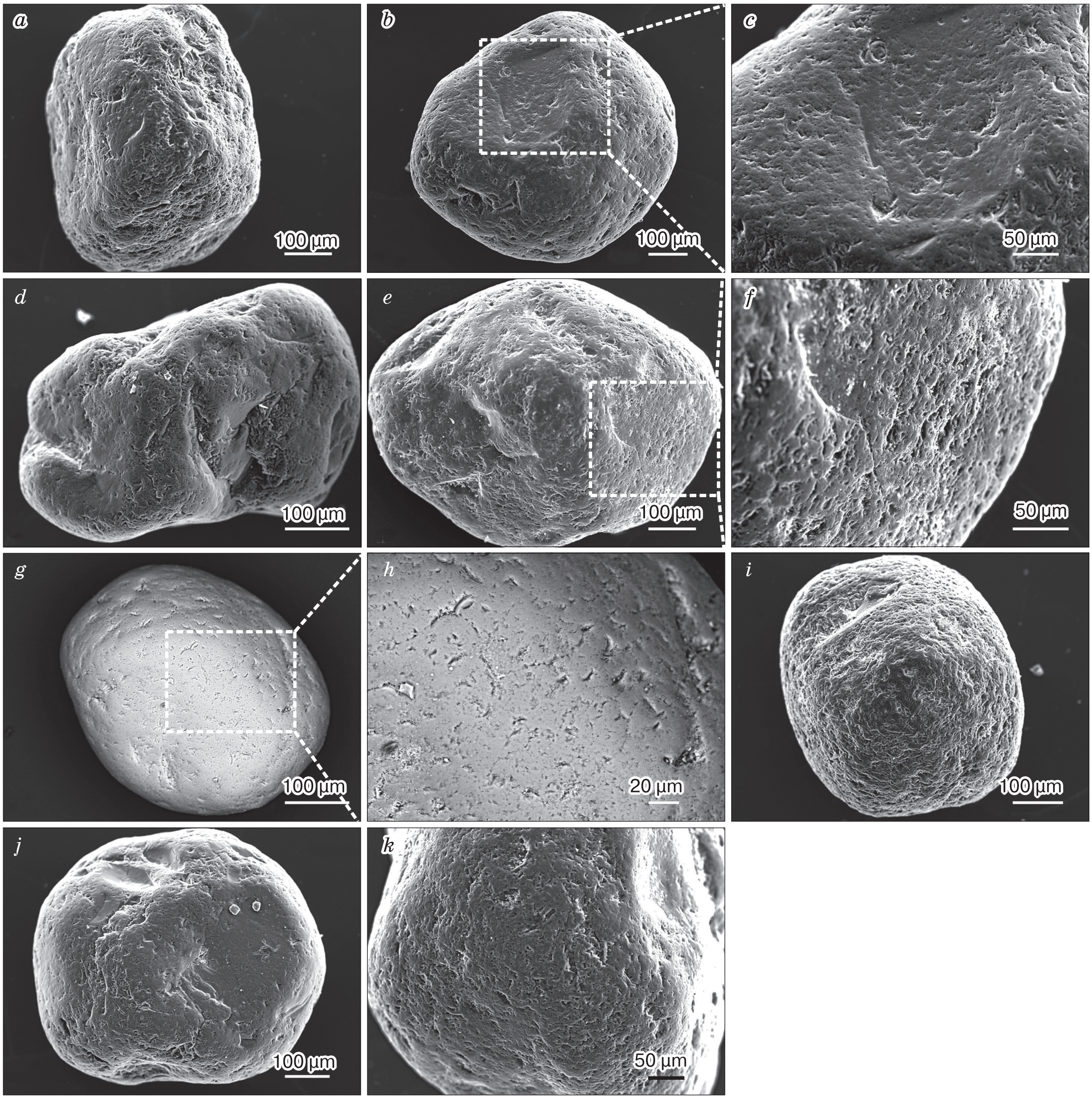

Fig. 5. SEI photographs of sand quartz grains.

a–*d* – well 2, sampling depth 7 m (*a* – half-matted grain with a small-pit surface; *b*, *c* – glossy grain with a small-pit surface and individual V-shaped grooves, micro pits are seen on protruding areas of the grain; *d* – half-matted grain with small-pit and micro-pit surfaces); *e*–*i* – well 3, sampling depth 5.5 m (*e*, *f* – glossy grain with a small-pit surface; *g*, *h* – glossy grain with sickle-shaped hollows and micro pits; *i* – glossy grain with a small-pit surface); *j*, *k* – well 3, sampling depth 10 m (*j* – half-matted grain with a small-pit surface; *k* – glossy grain with a small-pit surface).

cent-shaped hollows, usually forming in calmer aqueous environments, can be seen on some grains. Both features indicate water transport with varying flow rate: small-pit surfaces form during transport in an intense river flow, and crescent-shaped depressions form in calmer aqueous conditions.

It can be assumed that the formation of deposits in well 2 (depth 7 m) and in well 3 (depth 5.5 m) occurred owing to alluvial processes and insignificant aeolian processing. Despite similarities in indicators of degree of matting in grains from well 2, the absence of small pits typical for aeolian transport has allowed us to conclude that the formation of the deposits in well 3 (depth 10 m) had occurred under conditions of water flow.

2. Botanical composition of peat. Samples from well 2 were obtained from depths of 0.05 m (recent sample), 0.05–0.10 m and from the base of the peat bog from a depth of 1.0–1.1 m. Samples for well 3 were obtained from depths of 0.45–0.50 m and from the base of the peat bog from depths of 1.60–1.73 m. One sample was obtained from buried interlayers of vegetation detritus from well 3 from a depth of 8.8–8.9 m.

The botanical composition of the surface peat (well 2, depth 0–0.05 m) corresponds to contemporary vegetation: subshrub-moss-lichen groups of hilly peat bogs (Fig. 6). Peat from well 2 from a depth of 0.05–0.10 m is lowland, wood-bog, strongly decomposed (degree of decomposition is 45–50 %), and formed under taiga conditions of a lowland swamp forested by birches and willows. Peat from well 2 from a depth of 1.0–1.1 m is lowland, strongly decomposed, degree of decomposition is 45–50 %, belongs to the forest subtype (birch), formed under plant communities common in low (flood) banks of water objects (lakes, river floodplains). Peat from well 3 from a depth of 0.45–0.50 m is transitional, *Eriophorum-Sphagnum*, medium decomposed (approximately 35 %), formed under a *Gramineae-Eriophorum-Sphagnum* transitional swamp. Peat from well 3 from a depth of 1.65–1.73 m is marsh, quagmire, strongly decomposed, degree of decomposition is over 50 %. Peat of the given type could have formed under *Gramineae-Cyperaceae* swamps. Vegetation detritus from well 3 from a depth of 8.8–8.9 m is strongly decomposed (degree of decomposition is 35–40 %), formed under conditions of a mineral-peat *Gramineae-Hypnales* swamp.

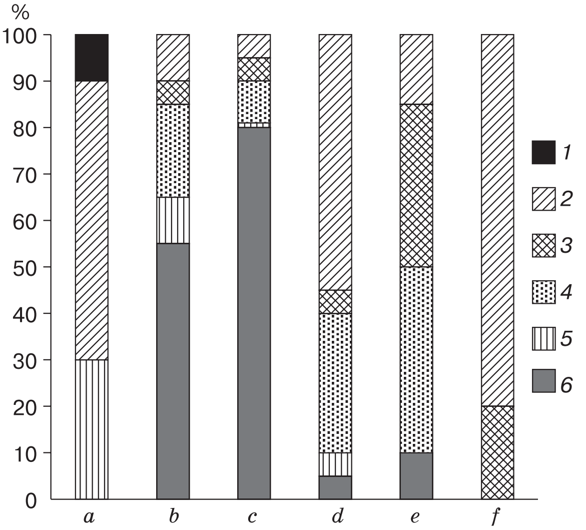

Fig. 6. Relationship between main botanical groups of plants in peat samples.

a – well 2, depth 0–0.05 m; *b* – well 2, depth 0.05–0.10 m; *c* – well 2, depth 1.0–1.1 m; *d* – well 3, depth 0.45–0.50 m; *e* – well 3, depth 1.65–1.73 m; *f* – well 3, depth 8.8–8.9 m. *1* – lichens, *2* – mosses, *3* – grasses, *4* – sedges and Cyperaceae, *5* – subshrubs, *6* – woody plants.

3. Absolute dating. Radiocarbon dating was completed from five samples of buried peat collected from the same depths as samples for botanical composition analysis, excluding the recent peat sample (well 2: 0.05–0.10 m and 1.00–1.10 m; well 3: 0.45–0.50 m, 1.65–1.73 m, and 8.80–8.90 m). The results reveal a Middle Holocene formation time frame of the top part of the peat bog in well 2 and the middle part of the peat bog in well 3, an Early Holocene formation time frame of the base of the peat bog in wells 2

Table 1. **Radiocarbon dating results of peat samples obtained from wells 2 and 3**

No.	Sample collection depth, m	Dating laboratory number	^{14}C age, years	Calibrated age (2σ, 95.4 %)	Calibrated age (1σ, 68.2 %)
				calibrated y.a.	
			Well 2		
1	0.05–0.10	Ki-19584	3,660 ± 80	3,982 ± 254	3,996 ± 115
2	1.0–1.1	Ki-19596	8,990 ± 90	10,071 ± 301	10,085 ± 139
			Well 3		
3	0.45–0.50	Ki-19598	4,280 ± 60	4,832 ± 207	4,845 ± 98
4	1.65–1.73	Ki-19613	9,160 ± 100	10,407 ± 238	10,358 ± 117
5	8.8–8.9	Ki-19626	34,840 ± 300	39,381 ± 695	39,372 ± 358

Note: σ – standard deviation.

and 3, a Kargin formation time frame of the vegetation detritus in well 3 at a depth of 8.8–8.9 m (Table 1).

DISCUSSION OF THE RESULTS

The characteristic feature of migrational mounds and heaving ridges to form groups has been described in both Russian and Western literature. Thus, a typical area where mounds and ridges are concentrated has been studied by V.P. Evseev [*1976*] in the area of the Pangoda River (tributary of the Pravaya Khetta River). Mounds of various heights stretch in a narrow line along a small stream for 1.5–2.0 km. The mounds are of various types (peat and peat-mineral) and heights (from 3–5 to 10–12 m), with asymmetric slopes and a base diameter of 30–100 m. It is noted that some mounds merge into each other through saddles, creating an illusion of a ridge, which is particularly typical for marginal mounds. According to V.P. Evseev [*1976*], such groups of mounds are linked to inner margins of alluvial terraces and peripheral areas of lake-swamp basins on the border of changing rock composition and freezing conditions.

Another peculiarity of large peat-mineral MFM is a multi-layer structure. In the top part there is usually strongly decomposed peat up to 1.5–2.0 m thick. Below lie sands or loamy sands 3.0–3.5 m thick. The bottom loamy part of the section can reach up to 10–13 m (from 50 to 90 % of the thickness of the drilled deposits) [*Evseev, 1976*]. Loams (predominantly of marine or lacustrine genesis) undergo heaving, the majority of migrational ice accumulation occurs here in the form of ice interlayers, and in some cases by way of the formation of an ice core.

According to Yu.K. Vasil'chuk [*2008*], questions related to intermediate forms between frost mounds of the palsa type and buglunnyakhs (pingo) remain unanswered. According to his data, the ice lens within the mound core could be the criterion for separating palsas and lithopalsas from pingos. However, cases have been described in areas of classical distribution of palsas (in the lower course of Ob' near the village Azovy) when ice lenses over 1 m thick lying in frost mound sections have been classified as the migrational type [*Vasil'chuk, 2008*].

Table 2. **Comparison of descriptions of migrational peat-mineral frost mound and frost ridge on the second above-floodplain terrace of the Kheygiyakha River**

Heaving shape	Relative height, m	Thickness, m			Ice volume*, %
		peat	sand	loam	
Frost mound***	6.7	0.5	6.7	2.8	35
Frost ridge****	7.5	1.1	5.9	3.7	up to 60**

* Owing to ice volume from ice injections (loams).

** In the ice ground layer.

*** Using [*Berdnikov et al., 2019*] results.

**** Present work.

Modern paleogeographic insights indicate that permafrost and MFM had formed in climate conditions that were apparently harsher than contemporary ones. Results of studies which used the palynological, isotopic and radiocarbon methods have revealed that intense bogging in the northern taiga subzone of Western Siberia had begun not earlier than 10 ka, almost at the very beginning of the Holocene, and had ended (for the largest MFM in the northern taiga subzone) with the cooling in the beginning of the Subboreal period (approximately 5.5–5.0 ka) [*Evseev, 1976; Vasil'chuk, 2008; Ponomareva et al., 2012*].

The studied migrational heaving ridge is located in an area typical for palsa distribution. In the section of well 2 at depths of 7.27–10.70 m lies ground ice: there are large grains and ice lenses with loamy material between them. The cryogenic texture in ice ground horizons is thick schlieren (schlieren up to 3 cm). The cryogenic texture in loamy horizons is thin schlieren (schlieren up to 0.5 cm). Ice volume in swelled loams is ~60 %. Below the depth of 10.7 m, up to the well bottomhole (12.35 m), the ice which composes the ice core of the heaving ridge is found. The ice is pure, is broken by chaotic fractures, and is interrupted by thin (not more than 0.15 m) loam interlayers. The significant thickness of ice lenses (0.78 and 0.44 m) may indicate an injectional mechanism of their formation. However, even the presence of pure ice lenses cannot unequivocally exclude a segregational migrational nature [*Vasil'chuk, 2008*] because an intense migrational ice accumulation in ice ground horizons of swelled loam has been identified. It can be said that the studied ridge has a predominantly migrational genesis with a complementary influence of ice injections.

The studied heaving ridge is analogous in structure to a well-studied, large MFM [*Berdnikov et al., 2019*] located 2.35 km northeast of well 2 (Table 2). One difference which can be noted is the presence of pure ice lenses in well 2, while well 1-2009 has only a schlieren cryostructure typical for migrational ice discharge [*Berdnikov et al., 2019*].

The reconstruction of the development of the studied heaving ridge allows us to preliminarily identify the following stages:

– formation of loamy, presumably lacustrine deposits of the Yermakov period (MIS 4), which are observed in the bottom part of well 2;

– the scour of the lacustrine deposits by the meandering stream bed of the Kheygiyakha River and the formation of floodplain deposits presented in the bottom part of well 3 (the beginning of the second half of the Kargin interstadial – MIS 3; 40–38 ka BP);

– the formation of the sand deposits of the second above-floodplain terrace of the Kheygiyakha River (the top part of wells 2 and 3) in streambed and, partly, subaerial conditions in the beginning of the Sartan cryochrone (MIS 2; 27–24 ka BP);

– a hiatus in the Sartan cryochrone (MIS 2; 24.0–11.7 ka BP) induced by cooling and by weakening of surface runoff, the appearance of frost fissures and cryoturbations;

– bogging of the terrace in the beginning of the Holocene (MIS 1), confirmed by the peat dates in wells 2 and 3 (10.6–9.8 ka BP). The formation of swamps on river terraces took place in northern taiga conditions;

– the beginning of heaving and the formation of mounds and ridges was apparently due to cooling in the Subboreal period (5.5–5.0 ka BP). Heaving could have occurred in colder climate conditions than contemporary ones.

The results of a series of works [*Ponomareva et al., 2012; Zykina et al., 2017*] allow us to make deductions about repeatedly changing climate conditions in the studied area during the late Holocene (from 2.0 ka BP – to contemporary time). Cryogenic processes (ice accumulation and heaving) activated during periods of cooling, peat formation processes intensified during periods of warming. Today, the top organic layer on large mounds and ridges is gradually becoming thinner, the depth of seasonal thawing is increasing, drainage conditions are improving, erosion processes are activating, i.e. there is a transition from the peat-mineral to the mineral type [*Berdnikov et al., 2019*].

CONCLUSION

The results of the research allow us to come to the conclusion that the studied heaving ridge has a predominantly migrational genesis (with a complementary influence of ice injections) and belongs to the peat-mineral type. The ridge is characterized by a three-layer peaty-sandy-loamy structure. The bottom loamy horizon, the ice volume of which is ~60 %, is affected by heaving. The sand horizon had formed at the end of the Kargin (MIS 3) and beginning of the Sartan (MIS 2) periods (40–24 ka BP). Bogging of the area occurred at the beginning of the Holocene (MIS 1; 10.6–9.8 ka BP). The beginning of active heaving and the formation of mounds and ridges in the studied area was apparently related to cooling in the Subboreal period of the Holocene (5.5–5.0 ka BP). Heaving processes had taken place during colder climate conditions than contemporary ones. Today, the top organic layer of the heaving ridge is gradually becoming thinner. It should be noted that during detailed studies of large-mound peat bogs in Western Siberia it is reasonable to consider peat-mineral and mineral forms of heaving (mounds and ridges) as a separate type of cryogenic landform.

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