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ARCTIC PEATLANDS OF THE YAMAL-GYDAN PROVINCE OF WESTERN SIBERIA

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Based on the foregoing seminal research works, this paper focuses on peat formation processes proceeded under extreme climatic and permafrost conditions of the northern West Siberia. It has been shown that because of the extreme climatic and permafrost conditions, rather than despite of them, peatlands up to 7.5 m thick reinforced with large ice wedges currently occupy extensive areas in the tundra zone. Vertical growth of peatlands is found to be most intense (at a rate 1.5–4.4 mm/year) in a limited time period from 9 to 6 kyr BP, which suggests that lower horizons of peatlands up to 3.0–4.5 m thick accumulated in just 1500 years' time. The three reasons that determined the active vertical growth of peatlands have been identified and thoroughly discussed in this research: huge ice content, abundance of wood remains in peatlands, and intense frost heaving during the freezing of a newly formed peat layer. It has been shown that birch stands of high bonitet class grew in the tundra only locally, in the areas underlain by insulation-radiogenic taliks, which proves that in the Holocene, there was no northward shift to 400–500 km of the northern boundary of the forest tundra.

Peat, ice wedges, Arctic peatland, rate of vertical growth of peatlands, insulation-radiogenic talik

INTRODUCTION

Numerous evidence of radiocarbon-dated peat in both southern and northern provinces of Western Siberia indicate that the paludification and peatland-forming processes began to evolve most actively only in the Holocene [*Khotinsky, 1977; Neishtadt, 1985; Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The harshest climatic and geocryological (permafrost) conditions established themselves in the vast circumpolar area during the Pleistocene climatic minimum (20.0–18.0 kyr BP). In high-latitude regions, the mean annual temperatures of air (T_a) and deposits (T_d) dropped to –25...–20 °C, while the amount of precipitation was 20 % less than today. The permafrost zone with the perennially frozen strata (permafrost strata, PS) ranging between 500 and 1000 m in thickness, occupied 95–100 % of the area. In the Allerød interstadial (12.0–11.0 kyr BP) and the Older Dryas (11.0–10.3 kyr BP) (Fig. 1, *A*), the mean annual air temperatures both in summer and winter were by far lower than their contemporary values. The steppe and tundra groups dominated in the vegetation cover within a huge circumpolar area [*Velichko, 1973; Levina and Orlova, 1993; Zykin et al., 2001*].

The Pleistocene/Holocene transition dated 11,000–12,000 yrs BP was marked by a climate warming [*Kind, 1974; Khotinsky, 1977, 1989; Badu et al., 1986; Trofimov et al., 1986; Levina and Orlova, 1993; Sher, 1997; Volkova, 1999; Zykin et al., 2001*]. Whilst climate is known to have been nonuniform throughout the Holocene (Fig. 1, *A*). Analysis of the cryogenic process evolution trends allowed the author to divide the Holocene into two parts [*Fotiev, 2009*], with the first termed the "*degradation era*" marked by climate warming liable for permafrost thawing from the surface, which has caused the degradation of PS of Pleistocene age across a vast territory. The second part – the "*agradation era*" – featured by general climate cooling ensured the subsequent long-term refreezing of thawed sediment, and newly formed PS of Holocene age.

A 10–15 °C rise in T_a, with affiliated increase in the amount of rainwater and the snow cover depth compared to period of the Pleistocene climatic minimum, significantly reshaped the geothermal conditions of the upper horizons of PS. At the end of the *degradation era*, T_d increased throughout the entire permafrost zone (PZ), and so did the active layer (AL) thickness; while progression of the top-down thawing of permafrost resulted in lowering of the permafrost table formed in the Pleistocene. The thickness of permafrost strata thawed from the surface progressively decreased northwards, and in the area of Salekhard located at the latitude of the Arctic Circle it did not exceed 50 m. The northern boundary of the area of permafrost deposits subjected to top-down thawing reached approximately the 69–68th parallel[1] (Fig. 2) [*Baulin et al., 1967; Badu et al., 1986; Trofimov et al., 1986; Dubikov, 2002; Fotiev, 2009*].

[1] The presence of ice wedges in Pleistocene sediments served as a criterion for this boundary delineation in the Yamal-Gydan province. North of 69–68° N, polygons with ice wedges preserved in all types of deposits, as well as in all elements of the relief. Farther to the south of 69–68° N, ice wedges preserved only in peatlands, while those occurring below the deepened active layer base within the sand and sand-loam layers experienced melting.

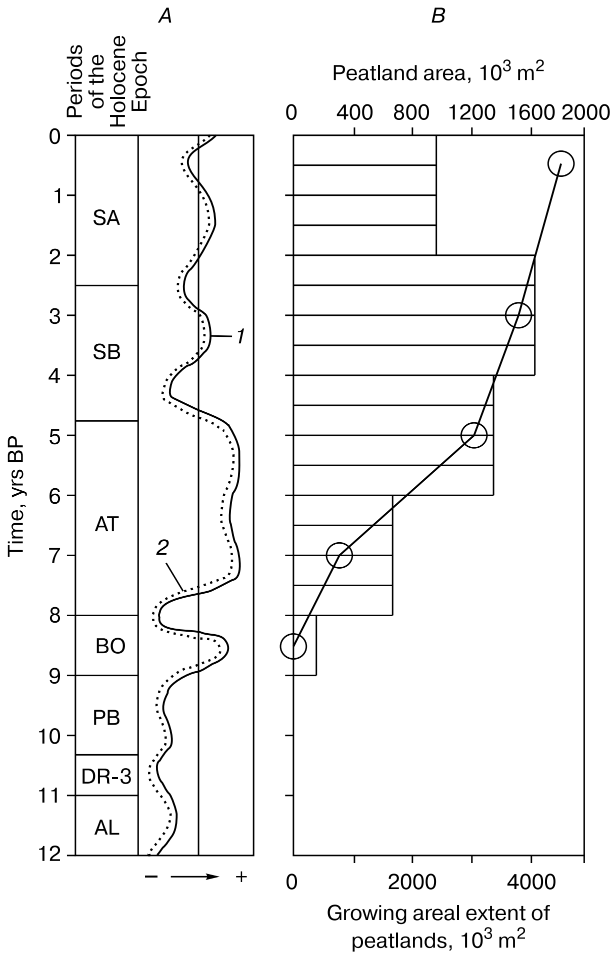


Fig. 1. Climate variability in the Holocene (*A*) [*Khotinsky, 1989*] and development of paludification process in Western Siberia (*B*) [*Neishtadt, 1985*]:

1 – air temperature; *2* – humidification.
Periods of the Holocene Epoch: AL – Alleroed, DR-3 – Older Dryas, PB – Pre-Boreal, BO – Boreal, AT – Atlantic, SB – Sub-Boreal, SA – Sub-Atlantic.

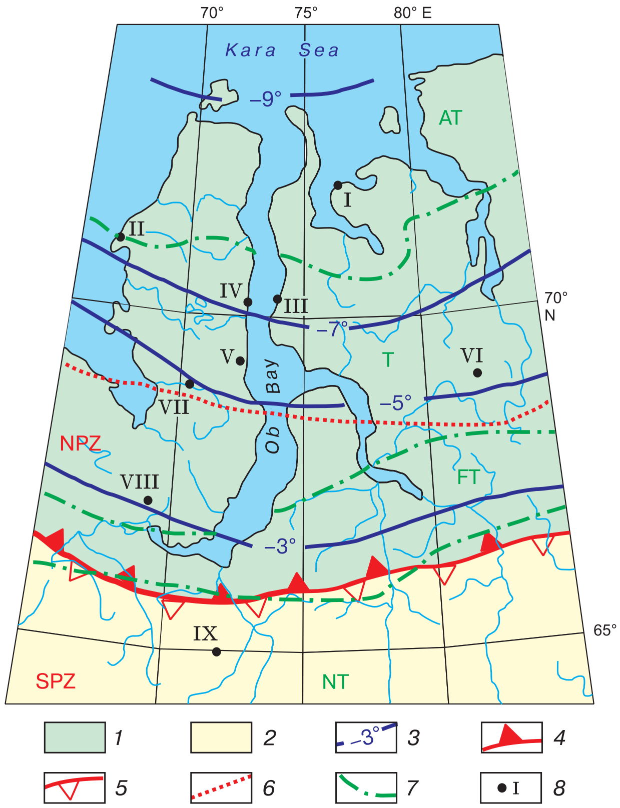


Fig. 2. Arctic peatlands of the Yamal-Gydan province:

1 – Northern Permafrost zone (NPZ); *2* – Southern Permafrost zone (SPZ); *3* – isotherms for rocks (°C); *4* – southern boundary of the Northern Permafrost zone; *5* – northern boundary of the Southern Permafrost zone; *6* – northern boundary of sands and sand-loams thawed from top down during the degradation era of the Holocene; *7* – boundaries of natural zones: AT – Arctic tundra, T – tundra, FT – forest-tundra, NT – northern taiga; *8* – Peatland number and its location.

According to the calculations by [*Baulin, 1985*], *climate cooling* which followed the degradation era, triggered the long-term freezing of deposits that experienced top-down thawing in the *degradation era* of the Holocene, prompting thereby formation of PS of the Holocene age. On the Yamal and Gydan peninsulas, thickness of PS of the Holocene age ubiquitously exceeded the thaw depth of deposits south of the 68–69th parallel, inasmuch as the Holocene and Pleistocene permafrost strata had merged, with their boundary dividing the area of the present-day PZ into two permafrost subzones, Northern and Southern. The boundary between the subzones in Western Siberia supposedly passes between 67 and 66° N (Fig. 2) [*Fotiev, 2009*].

Peat deposition along with the formation of the world's largest high-latitude peatland within the West Siberian lowlands commenced in the Boreal period – ca. 9.0 kyr BP – and proceeded throughout the Holocene (Fig. 1, *B*) [*Neishtadt, 1985*]. In its southern provinces, the extensive peatlands within wide river valleys and on flat watersheds reach 8.0–9.0 m in thickness. Bottom layers of peat, for example, in Boloto Gladkoe peatland (the Ob river valley in the vicinity of Novosibirsk city, 55° N) are dated 8,710 yrs, while those in Lukoshkin Yar peatland (the Irtysh river valley) – 9,980 yrs BP [*Zykin et al., 2001*]. In the northern provinces, the thickness of some peatlands reaches 4.0–6.0 m or, occasionally, more. The bottom layers of peat in such peatlands on marine terrace II along the northern coast of the Gydan peninsula (72° N) are dated 9,940 years BP [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. Accumulation of peat in both southern and northern provinces, therefore, began almost concurrently, despite the ca. 2000 km distance between them and the fact that they had formed under different climatic and permafrost conditions. The problems of timing of peatlands inception and the rate of their layered accumulation under varied climatic and permafrost conditions are still debatable. Specifying the sedimentary environments during the formation of peatlands under the severe climatic and geocryological conditions of the Yamal-Gydan province of Western Siberia presents therefore a significant interest.

PEATLANDS AND ICE WEDGES

History of study of peatlands and ice wedges[2] in the northern West Siberia spans a period of more than 45 years [*Baulin et al., 1967; Vasil'chuk and Trofimov, 1983; Badu et al., 1986; Trofimov et al., 1986; Bolikhovskii, 1987; Kashperyuk and Trofimov, 1988; Zykin et al., 2001; Blyakharchuk et al., 2012; Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. Nevertheless, given the varied climatic and permafrost conditions, interpretation of their depositional environments still remains controversial. The author relied on earlier research, specifically, by *Yu.K. Vasil'chuk and A.C. Vasil'chuk* [*2016*], to use it as source material for this study.

Peatland I: Mamont peninsula at the northern coast of the Gydan peninsula. Coordinates: 72° N, 76°23′ E (Fig. 3, I) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The *peatland* with peat thickness[3] measuring up to 5.0 m formed in the thermokarst depression on Marine Terrace II (2nd MT). Grass-hypnaceous peat with twigs of shrubs and herbaceous stems underlies the layer of peaty sand-loam with thickness up to 50 cm. There are no evidences of tree remains even in the bottom layer. *Ice wedges* (height: 4.0–6.0 m, width: up to 3.0 m) occur at a depth of 0.7 m. They extend through the peatland to approach the top of Late-Pleistocene sand layer. Troughs developed above the ice wedges divide the peatland surface into polygons.

Peatland II: Cape Kharasavey, western coast of the Yamal Peninsula. Coordinates: 71°11′ N, 66°52′ E (Fig. 3, II) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The 4.6 m-thick peat formed on a 8.0 m-high marine terrace (MT) I. Hypnaceous and sedge-hypnaceous peat with interlayers of sand-loam or sand underlies 0.5–0.7 m-thick layer of peaty sand-loam. Wood remains are present in the bottom peat horizon. *Ice wedges* reaching 5.0 m in height (rarely up to 7.0 m) and 1.5 m in width at the top, occur at a depth of 0.5–0.7 m (Fig. 3, II). The troughs above ice-wedges divide the peatland surface into polygons.

Peatland III: the Tadibe-Yakha river valley**,** western coast of central Gydan Peninsula. Coordinates: 70°22′ N, 74°07′ E (Fig. 3, III) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The *peatland* with peat thickness of 4.2 m occurs as inset on the above-floodplain terrace I, nearing the Ob Bay coast. The uppermost layers (0.0–3.0 m interval) of very ice-rich (up to 50–60 %) peat alternate with 10–20 cm thick interlayers of ice. The bottom horizon (3.0–4.2 m interval) of peat contains prolific wood remains. *Ice wedges* (height: 4.0 m, width at the top: 2.2 m) expand through the peat into alluvial sands. The troughs above ice wedges divide the peatland topography into polygons that measure up to 8 × 10 m in size.

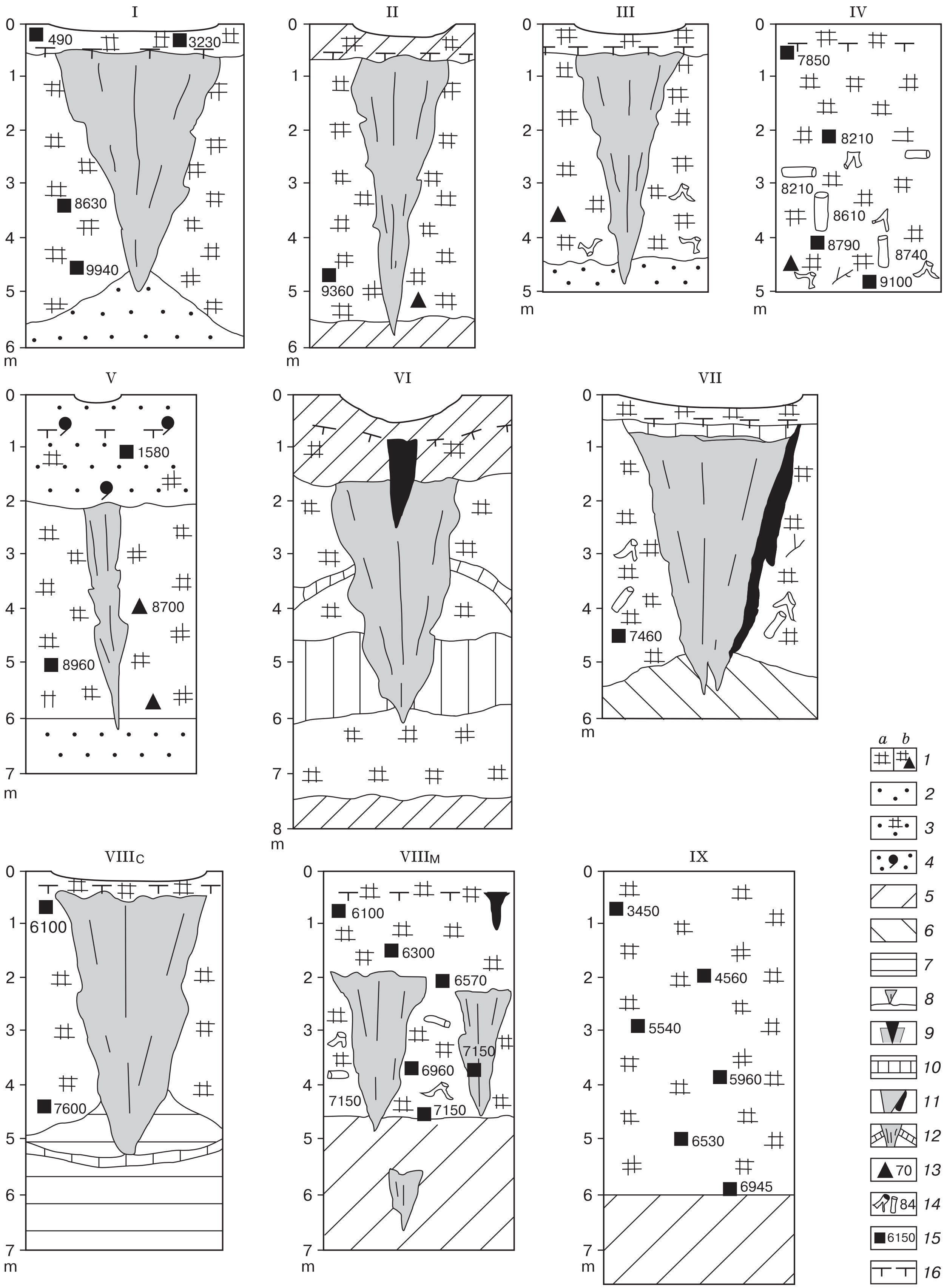
Peatland IV: the Ob Bay, eastern coast of the Yamal Peninsula, south of Se-Yakha village. Coordinates: 70°10′ N, 72°30′ E (Fig. 3, IV) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The *peatland* with a thickness exceeding 5.0 m formed as an inset in a 22–24 m high lagoon-marine terrace III (3rd LMT) within a thermokarst depression and is overlain by a thin (0.3 m) layer of sand-loam. The upper layers (0.30–2.15 m interval) of sedge-hypnaceous peat exhibit leaves and twigs of dwarf birch (Betula nana) alone, while the bottom horizon (2.15–4.5 m interval) of sedge-hypnaceous peat abounds with wood remains, thick trunks (up to 30–40 cm in dia), stumps with roots, and twigs of dwarf birch, and some birch trunks standing in a vertical position. Ice content of the peat mantle ranges between 40 and 60 %. At the base of the peatland, there is a thick (up to 1.5 m) layer of woody peat remarkably abounding in wood remains. In the adjacent outcrops, *ice wedges* (height: 2.5 m, width at the top: 1.2 m) underlie the AL base and merge into the peatland[4]. Troughs developed above the ice wedges divide the peatland surface into polygons.

Peatland V: the Ob Bay, eastern coast of the Yamal Peninsula, south of the Yaptik-Sale village. Coordinates: 69°23′ N, 72°31′ E (Fig. 3, V) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The *peatland* with a thickness varying between 5.0 m (in the middle) and 3.0 m (in marginal parts) formed on the lagoon-marine terrace

[2] Abbreviation "ПЖЛ" (commonly translated as IWP) is generally understood to mean polygonal wedge ice in the Russian literature on geocryology and characterizes ground ice filling of frost cracks. However, it tends to be interpreted equivocally due to the coincident acronym letters for the Russian words "polygonal" and "repeated", which allows to decipher the abbreviation by some geocryologists either as "repeated wedge ice" (polygonal systems of ice-wedges is formed basically by repeated frost cracking), accentuating the recurrent nature of ice formation within patterned ground or as "polygonal ice wedges" with an emphasis on the formation of ice wedges, by other researchers. In Russian literature, the fixed term "жильный лёд (vein ice)" corresponds to English "wedge ice". However, the term "wedge" which also suggests tapering off from top downward describes the occurrence type of such ice in the host sediment more adequately, than "vein". The latter is therefore not recommended by the author for expanding the Russian abbreviation. He proposes to use a Russian term "полигонально-клиновидный лед (ПКЛ)" – literally "polygonal wedge ice" (or ice wedge polygons, IWP), instead, which implies ice formation from surface water filling frost cracks, some of which freezes immediately on contact with the permafrost, while the rest of the water freezes during the following winter season.

[3] Here and further in the text the term "peat thickness" is used by the author to mean cumulative thickness of icy peat massif (Arctic peatland), comprising peat and woody fragments, texture-forming ice, interlayers of congelation ice, and ice wedges in its composition.

[4] The peat outcrop described in the text and shown in Fig. 3 is destitute of ice wedges.


I
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II
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6570
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IX
3450
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3
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7
8
9
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11
12
70 13
84 14
6150 15
16

Fig. 3. Ice wedges in Arctic peatlands of Western Siberia.

1 – peat: *a* – w/o wood fragments, *b* – with wood fragments; *2* – sand; *3* – peaty sand; *4* – saline sand; *5* – sand-loam; *6* – clay-loam; *7* – clay; *8* – ice wedge; *9* – modern growing ice wedge; *10* – interlayer of segregated ice; *11* – rimming ice; *12* – rings of segregated ice; *13–15* – sampling points for radiocarbon dating (^{14}C), kyr BP: *13* – wood, *14* – wood remains: roots, stumps, trunks and twigs of white-barked birch, *15* – peat; *16* – active layer base (permafrost table).
Compiled by S.M. Fotiev after [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*].
Arctic peatlands developed: I – on marine terrace II of the northern coast of Gydan peninsula; II – on marine terrace I of the western coast of Yamal peninsula, Cape Kharasavey area; III – on marine terrace I of the western coast of Gydan peninsula; IV – on marine terrace III of eastern coast of Yamal peninsula to the south of Seyakha village; V – on marine terrace I of eastern coast of Yamal peninsula to the south of Yaptik-Sale villagee; VI – on above-floodplain terrace I in the Messo-Yakha river valley; VII – on marine terrace III in the Yuribey river valley; VIII – on the floodplain in the Shchuch'ya river valley; IX – on the floodplain in the Kheigayakha river valley.

(7.0–9.0 m a.s.l.) and is subjacent to up to 2.0 m thick layer of saline peaty sand[5]. The upper horizon of grass-hypnaceous peat contains prolific plant residues, however, wood remains are totally missing. The bottom horizon (3.7 to 5.0 m interval) of sedge-gypnum peat is interspersed (up to 40 %) with wood remains. *Ice wedges* (height: 4.0 m, width at the top: 0.5 m) cut through the peat and merge into the underlying sands (Fig. 3, V). Troughs developed above the ice wedges divide the peatland surface into polygons.

Peatland VI: The Messo-Yakha river valley, southern part of the Gydan Peninsula. Coordinates: 69°10′ N, 82°11′ E (Fig. 3, VI) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. *Peatland* with peat thickness of 6.0 m formed on above-floodplain terrace I within the oxbow lake. It underlies a thick (up to 1.5 m) layer of sand-loam with thin interlayers of peat. The upper layers (1.5 to 4.8 m interval) of very ice-rich (up to 45–60 %) sedge-hypnaceous peat contain wood remains. The bottom horizon (6.0–7.5 m interval) of sphagnum and grassy peat, partitioned from the upper horizon by a thick (up to 1.5 m) interlayer of congelation ice, is wholly destitute of wood remains (Fig. 3, VI). *Ice wedges* (5.5 m in height, up to 2.0 m in width) occur at a depth of 1.5 m from the surface. They cut through the upper horizon of peat and pierce through the layer of congelation ice. Currently, a young ice wedge (height: 1.5 m, width at the top: 0.3 m) is evolving in the peatland below the AL base (Fig. 3, VI). Troughs above the ice wedges divide the peatland surface into polygonal network averaging 10 × 10 m in size.

Peatland VII: the Yuribey river valley, Central Yamal peninsula. Coordinates: 68°12′ N, 69°41′ E (Fig. 3, VII) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. *Peatland* with 5.5 m thick peat mantle formed on lagoon-marine terrace III within the thermokarst depression. It occurs from the surface downwards, and is underlain by lacustrine clay-loams (Fig. 3, VII). The uppermost layers (0.0–2.5 m interval) of grass-hypnaceous peat contain abundant fragments of shrub branches and bark. The bottom horizon (thickness: from 2.5 to 5.5 m) of sedge-hypnaceous and grassy peat contains fragments of trunks, branches and birch bark. *Ice wedges* 5.0 m in height, with the width at the top reaching 3.0 m, occur at a depth of 0.7–1.0 m and are separated from the base of AL by a 15 cm-thick layer of congelation ice. *Ice wedges* expand into the underlying clay loams through the peatland thickness (Fig. 3, VII). Troughs above the ice wedges divide the peatland surface into polygonal networks averaging 10.5 × 12.0 m in size.

Peatland VIII: the Shchuch'ya river valley, southern part of the Yamal Peninsula. Coordinates: 67°10′ N, 69°05′ E (Fig. 3, VIII) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The peatland with 5.5 m-thick peat mantle formed on the alluvial floodplain developed in the oxbow lake. Although the age of peat is found to be the same, the peat layers differ in thickness and peat composition, while ice wedges vary in size, and their occurrence conditions differ for the central and marginal parts of the peatland.

Central part of the Peatland (Fig. 3, $VIII_C$) is composed of grass-hypnaceous peat with sedge stalks and birch branches. However, neither trunks, roots nor large branches of birch have been documented even in the bottom horizon. The thickness of peat overlying the layer of clay-loams, is 5.8 m in the central part of polygons, which thins out to be only 4.2 m in the proximity to the ice wedges. Ice content of the peat is huge, ranging from 45 % at a depth of 0.4–0.6 m to 70–90 % at a depth of 4.0–5.0 m. *Ice wedges* (5.0 m in height, 2.0 m in width) are subjacent to the AL base and pierce through the peat mantle into the lacustrine clays. Troughs above ice wedges divide the peatland surface into polygons.

Marginal part of the Peatland (Fig. 3, $VIII_M$) is composed of grass-hypnaceous peat with woody residues. At the base of the peatland, there is a thick (up to 1.5 m) layer of woody peat with fragments of birch trunks 20–30 cm in diameter, roots and branches of birch and, rarely, larch. *Ice wedges* are featured by three levels of occurrence. The first comprises small ice wedge (which is 1.2 m high, 0.6 m wide at the top) occurring at a depth of 5.8 m in the layer of lacustrine sand-loam underlying the peatland. Ice wedges attributed to the second level (height: 2.5–3.0 m, width: at the top 0.9–

[5] Fairly high (up to 1.2 %) salinity of the sand indicate that the sand layer formed during one of consecutive marine transgressions.

1.3 m) occur in the lower portion of the peatland at a depth of 1.7–2.2 m from the surface. The third level is represented by a young, growing ice wedge currently sized 0.6 m (height) by 0.25 m (width), occurring at a depth of 0.4–0.6 m, directly beneath the AL base.

Peatland IX: the Kheiga-Yakha river valley (Nadym river basin). Coordinates: 65°19′ N, 72°00′ E (Fig. 3, IX)[6] [*Blyakharchuk et al., 2012*]. Peatland whose peat thickness is 6.0 m formed on the river floodplain in the oxbow lake. The peatland massif is underlain by lacustrine sand-loam.

The upper horizons of peat are characterized by abundant pollen of Siberian cedar and pine-tree, as well as sphagnum moss spores, while the bottom horizon exhibits abundance of pollen of cinquefoil, sedge and birch-tree, as well as spores of green mosses and sphagnum. The peat is destitute of wood remains. The peat is frozen, however no IWPs have thus far been observed in the peatland. In the era of active peat deposition, their presence is evidenced by a poorly preserved polygonal network on the peatland surface.

CONDITIONS FOR ARCTIC PEATLANDS FORMATION

Excessive moisture content, flatness of the territory and weak erosional incision of the interfluves have largely contributed to the paludification of the territory, followed by peat formation both in southern and northern parts of Western Siberia. However, the environments liable for paludification and peat formation processes differed remarkably in the northern part due to a number of factors.

The entire area of the Yamal-Gydan province is subsumed into the Northern permafrost zone (Fig. 2), which technically implies: 1) extremely severe climatic and permafrost conditions at the end of the Sartan period (MIS-2), when T_a (air temperature) and T_d (temperature of deposits) dropped to −25...−20 °C; 2) a remarkable climate warming (by 10–15 °C) during the *degradation era* of the Holocene manifested itself across a vast area, through the negative temperatures range and thereby precluding permafrost melting from the surface downward; 3) severe modern climatic conditions (T_a variation: from −7 to −12 °C) and permafrost conditions (T_d varies from −3 to −10 °C, whilst the PS developed within 95–100 % of the area); and 4) being primordially confined to the tundra zone, which is generally characterized by scant vegetation dominated by grass-moss-lichen and shrubs. Despite the severity of climatic and permafrost conditions, and probably owing to them, peatlands with peat mantle thickness up to 7.0 m and more, occupy large areas in northern West Siberia[7]. Ice content varying from high and very high levels represents the most striking characteristic feature of the composition of peatlands formed under the harsh climatic and permafrost conditions. Ice fraction within the "body" of such peatlands is either commensurable with, or (which is more often) considerably exceeds the volume of biogenic material. In its essence, this is a peaty ice massif. As such, the peaty ice massif of this kind should be called (recommended) "Arctic peatland" rather than using the generally accepted term "peatland".

When studying Arctic peatlands, reinforced with thick ice wedges, there naturally arises a question of when the ice wedges formed – simultaneously with peat (syngenetically) or to follow the formation of peat (epigenetically)? The answer to this question still remains a subject of dispute.

It has been proven true to date by many researchers that in the north of Western Siberia, alluvial, slope and peat bog sediments of the Holocene age were freezing syngenetically. The thickness of the syngenetic deposits horizon did not exceed 15.0 m [*Baulin et al., 1967; Romanovsky, 1977; Vasil'chuk and Trofimov, 1983; Badu et al., 1986*; *Trofimov et al., 1986; Bolikhovskii, 1987; Kashperyuk and Trofimov, 1988; Dubikov, 2002; Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016, and others*]. L.N. Kritsuk holds a different point of view suggesting that "processes of peat deposition and formation of ice veins is never syngeneic in principle" [*Kritsuk, 2010, p. 289*].

As is known, syngeneic formation of ice wedge polygons (IWPs) and the host sediments is accompanied by: 1) changing conditions of sedimentation occurring in isolated polygonal troughs bounded on each side by ice wedges; 2) variability of cryogenic texture of the freezing sediments; 3) changes in the structure of ice wedges; 4) a specific relationship between ice wedges and segregation ice schlieren in the host sediments; and 5) deformation of the host sediments. The features of ice wedges formed thereby and their host sediments provide strong evidence of syngenesis [*Romanovskii, 1977*]. As many as 16 signatures of syngeneic growth of ice wedge polygons were discussed in detail in [*Romanovskii, 1977*].

Yu.K. Vasil'chuk has no doubts about syngenetic formation of peat and ice wedges in peatlands of the Yamal and Gydan peninsulas, either. He believes the raised shoulders at the peat-ice wedge side contacts with "welded" ice schlieren thereupon offer the most illustrative evidence of syngenesis. The enhanced climate continentality during the "Holocene Optimum" (9.5–4.3 kyr BP) is to be interpreted as a critical factor ensur-

[6] The peatland is located 150 km south of the Ob Bay, within the Southern permafrost subzone, which suggests: 1) T_a ranging from −6 to −7 °C, precipitation averaging 487 mm/year, 2) sporadic discontinuous permafrost, confined to peatlands and underlying up to 50 % of the area; T_d varying from +1.0 to – 2.0 °C; totally missing ice wedges [*Blyakharchuk et al., 2012*].

[7] According to A.P. Tyrtikov, active peat formation is possible only "where the permafrost is not continuous. In the areas of continuous permafrost, hummoky peatlands do not develop, while their presence here attests to the existence of sporadic permafrost in the past" [*Tyrtikov, 1979, p. 100*].

ing paragenesis of peat accumulation and formation of ice wedges, according to Yu.K. Vasil'chuk. Nearly identical radiocarbon dates (7,000 and 7,150 yrs BP) determined for peat and a moss stem from the ice-wedge axial part also indicate to the concurrent formation of peat layers and ice wedges (Fig. 3, Peatland $\mathrm{VIII_M}$) [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. The radiocarbon dates (7,165 yrs BP) of peat fragment sampled directly from the ice wedge body at a depth of 1.85 m in the peatland within the Marre-Salé area [*Forman et al., 2002*] also attest to the syngenetic formation of ice wedges and peat.

The author assumes the concurrent (syngeneic) formation of peat and wedges of ice in the Yamal-Gydan province to be perfectly natural. In peatlands, given identical climatic conditions, frost cracks are known to develop earlier, while cracking occurs more intensively [*Romanovskii, 1977*]. Frost cracks in peatlands form already at T_d = –2 °C, whereas in syngenetically freezing sand-loams and clay-loams – only at T_d = –6 °C [*Baulin et al., 1967*]. It is therefore not surprising that perennial freezing of the newly formed layers of peat and frost cracking thereof began already in the first phase of peat accumulation and recurrently repeated during the entire period of active growth of peatlands. The peat mantle thickness and height of ice wedges measuring equally (Fig. 3) also speaks for their connate formation.

Climate warming with the onset in the Subboreal period accompanied by an increase in the amount of precipitation, had prompted the growth of both T_d and AL thickness, and activation of the paludification and peat formation processes, with oases of forest vegetation emerging in the tundra zone.

Inception of peatlands in the Yamal-Gydan province was taking place on high-elevation marine terraces in the Pre-Boreal period. The most ancient peatlands up to 5.0 m thick formed on the northern coast of the Gydan Peninsula on the 2[nd] MT surface [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. Bottom layers of peat in Peatland I began to accumulate 9,940 yrs BP at a rate of 0.7 mm/year (Fig. 4, Table 1). That much old dates were obtained for the bottom layers of Peatland II formed on the western coast of the Yamal Peninsula within the 1[st] MT at the Kharasavey river mouth (9,365 BP) and in central part of the Gydan Peninsula (9,600–9,230 yrs BP) [*Trofimov et al., 1986*]. Bottom layers of Peatland II containing wood remains formed at a rate of 1.4 mm/year (Table 1). However, most of the Arctic peatlands (No. IV, V, VI and $\mathrm{VIII_C}$) began to form only in the Boreal period (Fig. 4, Table 1). The thickness of bottom layers was increasing at a rate of 2.3–4.4 mm/year. Importantly, the thickness of Arctic peatlands increased in the Boreal Climatic Optimum era whose climate was warmer than today and characterized by higher mois-

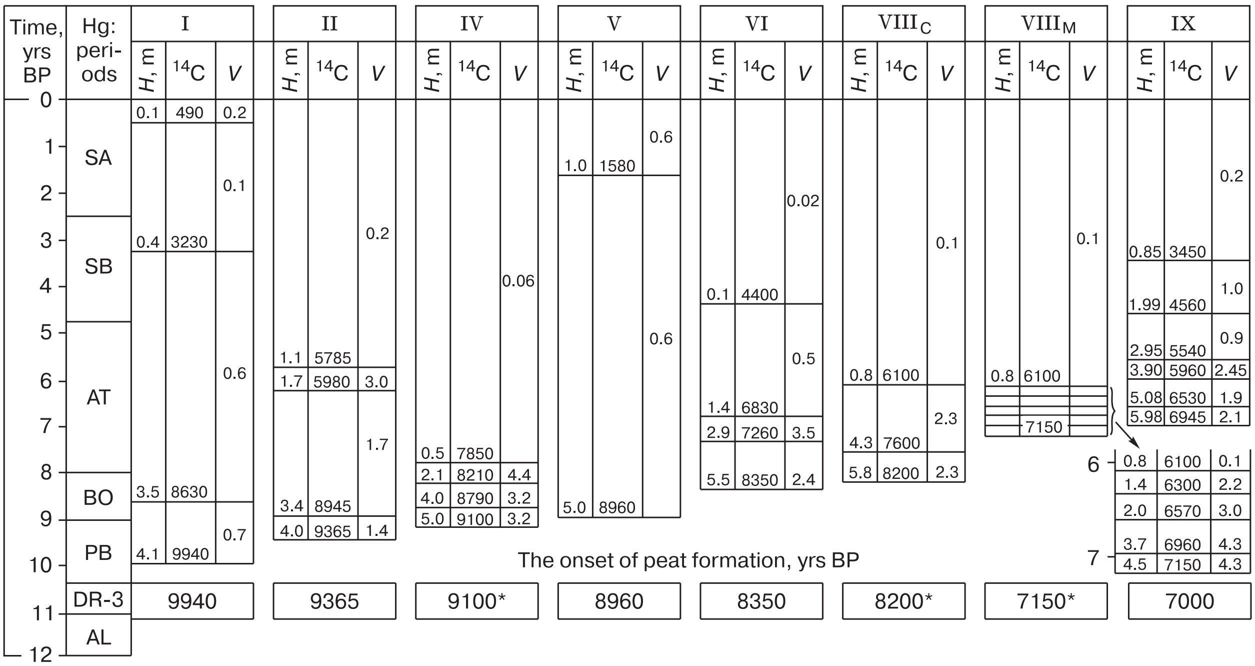

Fig. 4. Time and rate of deposition of individual layers of peatland.

Legend: I–IX – numbering of peatland sites (their location is shown in Fig. 1); T.S. – time scale, kyr PB; Hg – Holocene (periods of the Holocene: SA – Sub-Atlantic, SB – Sub-Boreal, AT – Atlantic, BO – Boreal, PB – Pre-Boreal, DR-3 – Older Dryas, AL – Alleroed); *H* – peat sampling depth (point) for radiocarbon dating, m; ^{14}C – radiocarbon dates, yrs BP; *V* – rate of accumulation of peatland layer, occurring within the sampling depth interval (for radiocarbon dating), mm/year.
Source of data on radiocarbon dated peat samples: Peatland sites I, IV, V, $\mathrm{VIII_C}$, $\mathrm{VIII_M}$ [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]; Peatland site II [*Forman et al., 2012*]; Peatland site VI [*Batuev et al., 2015*].
9100*, 8200*, 7150* – approximate timing of the onset of peat formation calculated for the bottom layer.

Table 1. **Time of the onset of peat accumulation and deposition rate estimated for individual layers of the peatland**

Peatland		Period of peat accumulation, BP			Peat accumulation			Source of data
No.	Peat thickness, m	Onset	End	Duration	Sampling points depth, m	^{14}C-date, BP	Rate**, mm/yr	
I	4.4	9940	0.0	9940	0.1	490	0.2	[*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]
					0.4	3230	0.1	
					3.5	8630	0.6	
					4.4	9940	0.7	
II	4.0	9365	0.0	9365	1.1	5785	0.2	[*Forman et al., 2002*]
					1.7	5980	3.0	
					3.4	8945	1.7	
					4.0	9365	1.4	
IV	5.0	9100*	7850	1250	0.5	7850	0.06	[*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]
					2.1	8210	4.4	
					4.0	8790	3.2	
					5.0	9100*	3.2	
VI	5.0	8350	4400	3950	0.1	4400	0.02	[*Batuev et al., 2015*]
					1.4	6830	0.5	
					2.9	7260	3.5	
					5.5	8350	2.4	
VII	4.5	7460	–	–	4.0	7460	–	[*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]
$VIII_C$	5.8	8200*	0.0	8200	0.8	6100	0.1	*Idem*
					4.3	7600	2.3	
					5.8	8200*	2.3	
$VIII_M$	4.8	7150*	0.0	7150	0.8	6100	0.1	*Idem*
					1.4	6300	3.0	
					2.0	6570	2.2	
					3.7	6960	4.3	
					4.5	7150*	4.3	
IX	6.0	7000	0.0	7000	0.85	3450	0.2	[*Blyakharchuk et al., 2012*]
					1.99	4560	1.0	
					2.95	5540	0.9	
					3.99	5960	2.45	
					5.08	6530	1.9	
					5.98	6945	2.1	

Note. The data calculated for: 7150*, 8200*, 9100* are approximate timing of the onset of peat accumulation, estimated from the growth rate defined for the bottom layer.

** The rate of vertical growth of peatland in the interval between points of peat sampling for radiocarbon dating.

ture content (Fig. 1, *A*) [*Orlova, 1990; Levina and Orlova, 1993; Zykin et al., 2001*]. The active growth of Arctic peatlands continued in the first half of the Atlantic period when climate was warmer than during the Boreal Period and was also characterized by excessive moisture content[8]. It was found that specifically in the first half of the Atlantic period accumulation of Arctic peatlands proceeded at a rate between 4.4 mm/year (Peatland IV) and 3.5 mm/year (Peatland VI). This period was also marked by the onset of peat formation in the marginal part of Peatland $VIII_M$ whose bottom layers deposited at a rate of 4.3 mm/year (Fig. 4, Table 1).

In the south of Western Siberia, the beginning of peat accumulation is dated only to the Boreal Period (Fig. 2, *B*) [*Neishtadt, 1985*]. Peat accumulation in Boloto Gladkoe peatland (southern part of the Southern permafrost zone) began 8,710 yrs BP, and ended 480 yrs BP. "Radicarbon dating has shown that peat accumulation was a long-time process lasting throughout almost the entire Holocene" [*Zykin et al., 2001*]. It follows that the peatland with peat thickness ranging between 8.0 and 9.0 m has formed in a time span of 8,230 yrs at a rate averaging 1.0 mm/year. While Peatland IX in the Kheyga-Yakha river valley (Fig. 3), located in the northern

[8] Relying on result of the spore-pollen diagram analysis for Peatland IX, *T.A. Blyakharchuk et al.* [*2012*] identified in the Holocene three periods of enhanced climate humidification: Boreal (9,000–8,500 yrs BP), Atlantic (6,500–6,000 yrs BP) and Subboreal (4,200–2,000 yrs BP).

part of the Southern permafrost zone, began to form only 7,000 yrs BP[9]. "According to radiocarbon dates, peat accumulation commenced in the period spanning from 7 to 3.4 kyr BP and, taking into account the accompanying frost heave processes, proceeded fairly intensely, at a rate of 1.5 mm/year, whereas after 3.4 kyr BP, up to the present day, the rate of peat accumulation has dramatically decelerated, averaging 0.2 mm/year" [*Blyakharchuk et al., 2012, p. 79*]. The maximum peat formation rate (2.5 mm/year) was reported only for the epoch of Atlantic climatic maximum (6,500–6,000 yrs BP) (Fig. 4, Table 1). Beginning from the second half of the Atlantic period till the present day, i.e. over the past 6,000 years accumulation rate in all of the Arctic peatlands in the Yamal-Gydan province has dropped to 0.5–1.1 mm/year and less (Fig. 4, Table 1).

The revealed huge (2.3–4.4 mm/year) rates of increase in thickness of Arctic peatlands in the tundra zone has called for substantiation of causes of this unintuitive phenomenon, totally uncharacteristic even of the southernmost provinces of Western Siberia. There have been found at least three reasons for this.The first consists in a significant volume content of ice in the peatland, the second is the abundance of wood remains whose content in the bottom layer of Peatland VI, for example, reaches 40 % [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*], while the third is the active heave processes inherent in ice formation within the freezing layer of peat, which prompted an increase in peat thickness within the Peatland area. Ice of Arctic peatlands is represented by three types: 1 – texture-forming ice, 2 – interlayers of congelation ice and 3 – wedge ice (Fig. 5).

Texture-forming ice results from ice formation during the syngenetic freezing of wetted peat. Depending on moisture content, ice content of the frozen peat varies from 10–20 to 40–60 %, while in the bottom layers of Peatland $VIII_C$ it approaches 70–90 % [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*].

Congelation ice in the form of subhorizontal interlayers develops either in the lower part (Peatland VI) or in the upper part above the ice wedge "head" (Peatland VII), while in Peatland III interlayers of ice alternate with peat interlayers (Fig. 3).

Wedge ice. Ice wedges usually form as water freezes in wedge-shaped cracks emerging in the freezing peatlands at the result of systematic, multiple processes of seasonal frost cracking.

Ice wedges from 2.0 to 5.0 m, locally up to 7.0 m in height, with their width at the top varying from 0.5 to 3.0 m (Fig. 3), dissect the peatlands into polyhedral prisms, while troughs (depressions) above the ice wedges divide the surface of the peatland into polygons from 3.0 to 10.0 m in size (Fig. 5)[10].

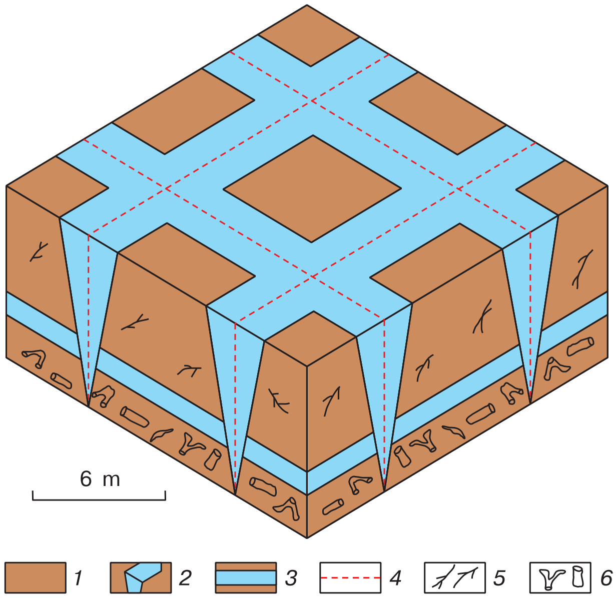

Fig. 5. Composition of Arctic peatland:

1 – peat (ice content: 50 %); *2* – ice wedge; *3* – interlayer of segregated ice; *4* – frost cracks; *5* – plant remains: leaves and twigs of shrubs; *6* – wood remains: wood fragments, roots, stumps, trunks and twigs of white-barked birch (more rarely, of larch).

The dates of peat layers in the uppermost part of the wedge body (7,600 years BP) and at the level of the ice wedge "head" (6,100 years BP) (Fig. 3, Peatland $VIII_C$) allowed us to roughly estimate the time of ice wedge formation. The appearance and growth of ice wedges in the peatland within the Shchuch'ya river floodplain is thus inferred to have taken place in the first half of the Atlantic period during a timespan of 1,500 years.

The abundance of wood remains in the bottom layers of peatlands and high (up to 50 %) content of pollen of woody vegetation in ice wedges and in the host peatlands testify to the presence of trees in the tundra zone during their formation [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*]. Radiocarbon dates of birch trunks[11] bear evidence of a short period lasting less than 2,000 years (from 8,750 to 7,000 years BP) of the optimal climatic and permafrost conditions ensuring active growth of white-barked birch whose trunk was

[9] That much belated onset of peat formation is accounted for by the peatland location on the river floodplain terrace. It has been established that accumulation of floodplain facies of the alluvium from above-floodplain terrace I and floodplain in the river valleys of Western Siberia, depending on the distance from the river mouth, ended in the interval from 8,670 to 5,880 yrs BP [*Volkov, 1984*].

[10] In the peatland block (Fig. 5), the ballpark estimates of peat amount to only 25 % of the total volume.

[11] The oldest dating of birch trunk (8,750–8,700 yrs BP) was obtained from Peatland sites IV, V, VI [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*], and for wood remains – at the mouth of the Kharasavey river (8,780 yrs BP) [*Forman et al., 2002*]. The dates of birch trunk (7,000 yrs BP) were youngest in the marginal part of Peatland $VIII_M$ [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*].

30–40 cm in diameter. The duration of the Boreal and first half of the Atlantic period account for the so called "Holocene vegetation apex". Thus far, neither trunks, stumps nor roots of birch have been observed within any of the studied Peatlands whose age is younger than 7,000 years.

The question of whether there was an extensive (500–600 km) expansion of woody vegetation into the Yamal-Gydan tundra zone as a result of a significant duration of climate warming episode in the first half of the Holocene has no unambiguous answer. Relying on the results of radiocarbon dating, Yu.K. Vasil'chuk, for example, made an inference about the northern taiga boundary in the Lower Holocene (9.5–4.3 kyr BP) to have advanced as far as Cape Kharasavey (71° N) and shifted even slightly more to the north [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*].

However, the abundance of wood, even birch trunks reported at peatlands and only in their marginal parts (Peatland $VIII_M$) is more likely to be an indication of local rather than zonal factors[12], which prompted the growth of white-barked birch of high bonitet class under fairly severe climatic and permafrost conditions of the Yamal-Gydan tundra, even during *degradation era* of the Holocene Epoch.

In the author's opinion, the strictly limited timeframe (8,750–7,000 yrs BP) for the period of active growth of trees attests to the interplay of heat and moisture being specific during the vegetation period, which reappeared neither in the second half of the Atlantic period, nor later. Birch stands of high bonitet class of trees on the surface of river/marine terraces existed only locally, along the leeward sides of depressions. Such areas should be considered as geothermal oases with elevated T_d against the backdrop of severe geothermal conditions characteristic of the surfaces of flat terraces destitute of trees[13]. Geotemperature oases with forest vegetation "transpired" and existed on sites within closed isolation and radiogenic taliks, with the depth ranging from 1.0 to 3.0 m, rarely more[14]. These have proven to be extremely susceptible, thermally, responding to slightest variation in the snowdrift height and to the amount of solar radiation incident on the surface.

Frost heave process has played an instrumental role in the formation of Arctic peatlands. Admittedly, the intensity of heaving is largely controlled by the conditions of the formation of segregated ice. Ice segregation proceeds the most intensely when the newly formed, highly moistened peat in the central part of polygons freezes from below. That was probably why the peatland thickness at the center of polygons measures 1.0–1.5 m more than on their periphery, in proximity to ice wedges. Being nonuniform in nature, frost heave creates dome-like forms on the subhorizontal surface of peatland [*Vasil'chuk Yu.K. and Vasil'chuk A.C., 2016*].

Despite the fact that active peat formation ended about 6,000 yrs BP and that the upper horizons of peat accumulated at a rate of 0.1 mm/year, the ice-wedge heads occur lower than the present-day position of the AL base (Fig. 3), which attests to a stable climate severity during the *degradation era* of the Holocene. The specific climatic conditions of this epoch precluded top-down thaw of permafrost peat layers reinforced with ice wedges. Ice wedges did not thaw from the surface even in the southernmost part of the Yamal peninsula (67° N) (the Shchuch'ya river valley, Peatland $VIII_C$), while the upper horizons of perennially frozen sands and sand-loams that host peat, thawed to a depth of 15–20 m (Fig. 3, Peatland $VIII_C$). It's only in the marginal part of this Peatland, probably as a result of the influence of local forcings, that ice-wedge heads occur in the frozen peat at a depth of 1.7–2.2 m (Fig. 3, Peatland $VIII_M$).

CONCLUSIONS

The paper has revealed specific climatic and permafrost conditions that enabled syngenesis of peat and ice wedges in the northern province of Western Siberia.

- It has been shown that the existing climatic and geocryological (permafrost) conditions in the first half of the Holocene (*degradation era*) provided for simultaneous formation of both peat and ice within peatlands.
- The established herewith limited time-frame (the Boreal period and the first half of the Atlantic period of the Holocene, 9,000–6,000 yrs BP) accounted for the era of active vertical growth of peatlands at a rate between 1.5 and 4.4 mm/year. As such, the specific combination of warmth and moisture proved unable to be recommenced in the second half of the Atlantic period, nor later. This resulted in sharply decelerated (to 0.5–0.1 mm/year) rate of the vertical growth rate of peatlands.
- The identified herewith three causes (settings) that determined the possibility of formation of lower horizons of peatland with thickness varying between 3.0 and 4.5 m at a vertical growth rate of 4.4 mm/year consist in: 1) the huge content in the peatlands of texture-forming, congelation and wedge ice, whose volumes are

[12] It appeared that despite climate warming being certainly an important zonal rather than determining factor, the second "vegetation apex" was not recorded at the second half of the Atlantic period (the Holocene Climate Optimum) [*Orlova, 1990; Levina and Orlova, 1993; Zykin et al., 2001*].

[13] At the present time, for example, T_d is 4–6 °C higher in depressions within the Cape Kharasavey area overgrown with high and dense shrubs, under appreciably thick snow drifts, compared with T_d in bare, snowless elevations whose surface is covered with moss-lichen [*Trofimov et al., 1989*].

[14] Isolation-radiogenic taliks are geothermal anomalies whose inception is attributed to the heat of incident solar radiation, that develop on leeward sides of lake basins with snowpatches up to 1.0–3.0 m in height, accumulated as a result of snowdrift transport. As such, steep sides of depressions, normal to wind direction provide the most favorable conditions for the formation of snow drifts [*Fotiev, 1991*].

commensurable, and more often considerably exceed the volume of peat; 2) the abundance of wood remains (up to 40 % of total volume) in the bottom layers of the studied peatlands; 3) the intense frost heave processes within the newly formed peat layer during its freezing.

• The duration of the epoch of optimal climatic and permafrost conditions providing for the growth of white-barked birch stands with a trunk 20–30 cm in diameter is found to be short-lived (from 8,700 to 7,500 yrs BP). In peatlands whose age is less than 7,000 years, no fragments of wood, or roots, stumps, trunks of tress have been encountered.

• It has been shown that in the first half of the Holocene, despite a significant (10–15 °C) temperature rise and an increase in air humidity (compared to Sartan period), there was no significant advance (shift) of the northern boundary of the forest-tundra on the territory of the present-day tundra. Birch stands of high bonitet class of trees tended to colonize not the entire surface of river or marine terrace. Rather, they appeared only on local sites within the bounds of isolation-radiogenic taliks.

• A peatland formed under the severe climatic and permafrost conditions whose ice content tends to be in excess (sometimes significantly) of peat content, is proposed to be termed **Arctic peatland**.

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