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THICK POLYGONAL PEATLANDS IN CONTINUOUS PERMAFROST ZONE OF WEST SIBERIA

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The study focuses on the structure of peatlands with large syngenetic ice wedges in the Yamal and Gydan Peninsulas (northern West Siberia). Thick polygonal peat plateaus formed in floodplains and laidas or in lacustrine-palustrine inliers within hypsometrically higher terraces. Peat accumulated at high rates and reached thicknesses of 4–5 m in 700–1000 years. The presence of Boreal (Holocene) tree macrofossils at the base of many peat sections confirms the tree line advance as far as the contemporary tundra during the Holocene optimum.

Ice wedge, stable isotope, peatland, radiocarbon, peat accumulation rate, northern West Siberia, Holocene

INTRODUCTION

Forests growing in a temperate climate of West Siberia, where swamps occupy more than 50 % of the territory, are especially favorable for accumulation of peat reaching a thickness of 8–10 m. North of the tree line, peat thickness is commonly presumed to reduce as vegetation becomes less abundant in colder conditions [*Liss et al., 2001*]. In the review of *Kremenetski et al.* [*2003*], 5–6 m thick peatlands are reported for areas south of the Polar Circle only.

However, large peatlands occur in northern West Siberia as well, with peat as thick as 5 m (2.2 to 2.5 m on average) in the North Sosva-Ob' interfluve and south of the Khudosei River valley in the Upper Taz-Yenisei interfluve [*Vasil'chuk and Trofimov, 1983*], or even 9.2 m in the Nadym area [*Kashperyuk and Trofimov, 1988*].

POLYGONAL PEATLANDS

We studied polygonal peatlands which fall beyond the common peatlands of the tundra subzone [*Liss et al., 2001*] because of greater thicknesses (>2 m) and up to 3–4 m ice wedges both in the south and north of the Yamal and Gydan peninsulas (Fig. 1).

Polygonal peatland in the Shchuchiya River valley in the southern Yamal Peninsula (Table 1, Fig. 2) was sampled from 5.0–5.5 m sections in outcrops and boreholes at 67°10′ N, 69°05′ E (Fig. 3). The peatland is located in the southern tundra subzone dominated by shrub birch, with alder thickets and patches of larch forests along the river.

Syngenetic wedge ice, more than 5 m high and up to 2 m wide on top, cuts through the entire peat section and penetrates into lacustrine silt and clay below. Preserved fragments of ice veins found beneath peat are also syngenetic, most likely of a Holocene age, according to stable isotope data.

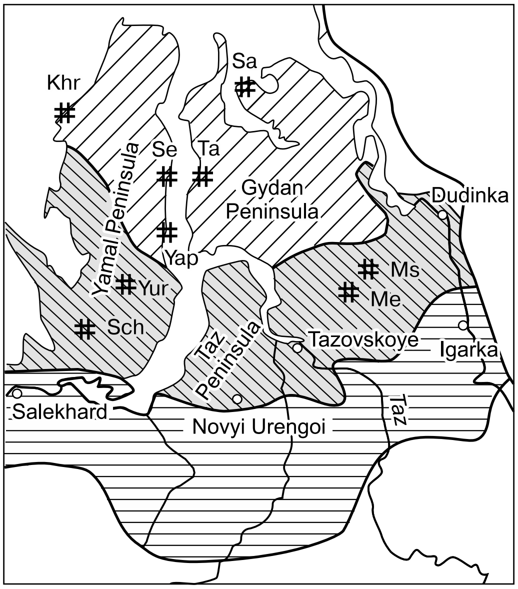

Fig. 1. Location map of polygonal peatlands, more than 4 m thick, in northern West Siberia.

1, *2* – continuous permafrost: mean annual ground temperatures below –5 °C (*1*) and from –3 to –5 °C (*2*); *3* – discontinuous and sporadic permafrost: mean annual ground temperatures from 0 to –3 °C; *4* – boundaries of permafrost zones; *5* – thick peatlands, with their names abbreviated as Khr = Kharasavei, Yur = Yuribei, Sch = Shchuchiya, Se = Seyakha, Sa = Salemlekabtambda mouth, Yap = Yaptiksale, Me = Messoyakha valley, Ms = west of Messoyakha Village, Ta = Tadibeyakha valley.

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Table 1. **Composition and cryostructures of polygonal peatlands**

Depth, m	Peat and soil composition	Cryostructure	Ice content and cryogenic features
1	2	3	4
Polygonal peatland, Shchuchiya River, Southern Yamal, reported in 1977			
0–0.45	Dark brown peat	–	–
0.45–0.6	Light brown peat	Basal	Ice content 40–45 %
0.6–1.9	Dark brown peat, black when frozen, composed of hypnaceous moss, with sedge; abundant tree macrofossils	»	Ice content 40–45 %; ice lenses and crystals, 1–2 mm in diameter; ice content up to 55–60 % with ice inclusions, 10 cm in diameter; at a depth of 1.5 m
1.9–5.8	Black-brown peat; maximum thickness in polygon center, decreasing to 4.2–4.5 m toward ice wedges	»	Ice content 60 %, increasing to 70–90 % below 4.1 m; ice lens in 4.6–5.2 m interval; ice content 10–15 % in 5.2–5.7 m and 70–80 % below 5.7 m
5.8–6.5	Light gray dense clay, with minor sand; sand percentage increasing upward	Reticulate, cross-laminated, fine lenticular	Reticulate cell size 10 cm; nearly vertical ice lenses, 0.3–0.4 mm thick
Polygonal peatland, Shchuchiya River, Southern Yamal Peninsula, reported in 1997			
0.0–0.7	Dark brown peat with sedge stalks and leaves; horizontally layered	–	–
0.7–1.0	Black-brown peat with sedge stalks; fish scale at depth 0.75 m	Basal	Ice-rich
1.0–1.4	Black peat with sedge stalks, leaves, and larch cones	Massive	–
1.4–1.75	Light brown peat with willow branches	»	–
1.75–2.05	Black peat with branches and wood remnants	»	–
2.05–2.6	Black-brown peat	Basal, deformed reticulate	Ice-rich
2.6–4.5	Black-brown peat, ice-rich in middle part, with birch and larch branches	Deformed reticulate	–
4.5–6.5	Gray silt, with low peat content	Layered	Segregated ice, about 0.2–0.3 m, at 4.7 m depth; ice lens, 0.5 m wide and 1.5 m high, at 5.5 m depth
Polygonal peatland, shore of Ob' Gulf, Seyakha (Zelenaya) mouth, Central Yamal Peninsula			
0.0–0.1	Soil, silt with roots of modern plants	–	–
0.1–0.35	Gray fine silty sand	–	–
0.35–0.8	Brownish-black peat with shrub birch rootlets and leaves	–	–
0.8–2.15	Hypnaceous-sedge brown peat, with small branches	Massive	–
2.15–2.6	Hypnaceous-sedge brown peat, with tree remnants (stumps and roots); a birch stump with roots and a birch trunk, 0.4 m in diameter, at depth 2.5 m	Layered	Ice content to 50–60 %
2.6–3.1	Hypnaceous-sedge brown peat, with small rounded branches, wood debris, and nearly vertical birch trunks at depth 2.65 m	»	Ice content to 40–50 %
3.1–3.2	Black peat with wood	Basal	–
3.2–3.6	Viscous chocolate brown peat, with wood; a nearly vertical birch trunk at depth 3.6 m	»	–
3.6–4.5	Sedge brown peat; abundant tree remnants with stumps and roots; tree trunks with branches	Massive	–
Polygonal peatland, Yuribei valley, right side, 6 km north-north-east of Pederten-Penze mouth. Site 154-YuV			
0.0–0.95	Aeolian sand with turf	–	–
0.92–1.50	Dark brown, almost black peat, with abundant non-degraded wood remnants, shrub branches and roots	Massive	–
1.5–2.15	Dark brown peat with grayish hue, with minor amount of plant detritus	»	–
2.15–4.5	Poorly decayed yellowish-gray peat, darker and carbon-bearing in lower part	»	–

Continued tabl. 1

1	2	3	4
4.5–5.2	Drak-gray silt	Coss lenticular-layered	Ice content > 50 % at contact with peat cover
Polygonal peatland, Yuribei valley, right side, 9 km south-east of Lake Laeto. Site 160-YuV			
0.0–1.2	Poorly decayed dark brown peat	Massive	–
1.2–2.5	Black peat, decayed to medium degree	»	–
2.5–4.5	Poorly decayed black peat, with white birch trnks and branches	»	–
4.5–7.0	Dark gray, pale yellowish heavy-textured clay silt, with some sand in its lower part	Coarse lenticular	–
7.0–9.4	Light gray fine sand	Massive	–
Polygonal peatland, Yaptiksale village, Eastern Yamal Peninsula			
0.0–1.89	Grayish-yellow fine sand, with plane-parallel lamination, high iron content at base; black peat at depth 1.0–1.1 m	–	–
1.89–2.20	Reddish-brown peat	Basal	Ice inclusions, up to 1–3 cm in size
2.2–2.9	Gray peat, with abundant poorly decayed plant remnants	Massive	–
2.9–3.7	Brown peat with abundant poorly decayed plant remnants; thin layer of light color (sphagnum) peat at depth 2.7 m	»	–
3.7–5.0	Black peat with abundant (to 40 %) plant remnants; peat base as deep as 7.5 m	»	–
5.0–5.3	Light gray fine muddy sand	»	Ice-rich in 5.1–5.3 m interval
5.3–5.5	Transparent ice lenses	–	–
Polygonal peatland, Kharasavei, Western Yamal Peninsula			
0.0–4.6	Black peat, with light gray silt; locally with thin layers of fine light gray sand	Massive	–
4.6–5.1	Dark gray fine-debris clay silt, with enclosed pebble and gravel	Layered	–
5.1–5.8	Light gray sand	Massive	–
Polygonal peatland, Messoiakha valley, marine terrace II, 20 km downstream of Shchuchiya arm source. Site 11-KV			
0.0–0.2	Moss with peat	–	–
0.2–0.5	Poorly decayed dark brown peat	Basal	Ice-rich
0.5–1.4	Pure ice, sometimes, with minor organics	–	–
1.4–1.75	Dark brown peat	Basal	Ice-rich
1.75–2.2	Peaty gray and brown silt	Coarsely layered, fine lenticular	Ice-rich
2.2–3.0	Poorly decayed greenish-brown peat, with strong smell of hydogen sulfide; minor greenish silt	Massive	Ice-poor
3.0–4.8	Ice with minor peaty silt	–	–
4.8–7.0	Gray and greenish silt	Coarsely layered, fine lenticular	Ice-rich

The section begins with a 1.5-m layer of woody peat with birch trunks, up to 0.2–0.3 m in diameter, and with some amount of grass-hypnaceous peat. Tree macrofossils occur throughout the section, and a layer of pure woody peat, with trunks of larch trees and with fir and larch cones, is found at a shallow depth of 1.2–1.5 m. The presence of roots and near-root branches indicates the *in situ* peat origin and provides evidence that the trees grew in a peat-filled depression rather than being transported by a river. According to botanical analysis of plant detritus (by E.M. Volkova), peat is mainly grass-hypnaceous with tree remnants. Nearly pure buckbean (*Menyanthes*) peat at a depth of 3.2–3.4 m in the central part of the peatland is overlain by equisetum peat within the 2.6–2.8 m interval.

The population dynamics of buckbean (*Menyanthes trifoliata* L.) records the seasonal thaw depth of Shchuchiya peat. Its pollen percentage is the highest in the 1.5–1.8 m depth interval [*Vasil'chuk, 2007*] but the pollen grains are only sporadic slightly down and up the section. The 1.5–1.8 m interval was deposited when the summer thaw depth was large enough to permit the existence of buckbean within peat. *Me-*

Fig. 2. Polygonal peatland in the Shchuchiya valley.
Photograph by Yu. Vasil'chuk.

nyanthes disappeared from the peatland periphery only in the end of the deposition cycle: neither pollen nor plant remnants are found above 0.3–0.4 m.

High-resolution dating of the peatland (Table 2) showed the same ages on its margins and in the center. The basal woody layer accumulated from 7400–7100 yr BP to 6100 yr BP. The peat structure stability is confirmed by dates obtained previously at the *Aerogeologiya* R&D company: 7680 ± 110 yr (LU-1081) at the base and 6140 ± 80 yr (LU-1082) near the top [*Vasil'chuk, 1992*]. Note that a similar age of 7290 yr BP was reported for the lower peat layer in an outcrop not far from Lake Nyulsaveito in the upper reaches of the Khadyttayakha River in the southern Yamal Peninsula [*Panova et al., 2008*]. Peat in that area was deposited during the Holocene optimum, which lasted from 9500 to 4300 yr BP in Yamal, when forested tundra vegetation grew within the present tundra [*Vasil'chuk, 1982; Vasil'chuk et al., 2001*].

Thick syngenetic ice veins formed concurrently with the accumulation of woody and other peat layers, judging by an AMS ^{14}C age of 7150 ± 75 yr for a moss pedicle sampled from the axis of an ice vein (Hela-262) [*Vasil'chuk et al., 2000*]. Therefore, wedge ice formed almost all the time while peat was accumulating.

The patterns of stable water isotopes in the analyzed ice samples are generally within the contemporary variation ranges. Namely, $\delta^{18}O$ are −19.8 to −18.2 ‰ in two syngenetic ice veins from peat and −20.3 to −17.5 ‰ in a lower buried small ice vein, while a currently growing ice vein has $\delta^{18}O$ = = −18.2 ‰. The δD values are from −151.0 to −139.6 ‰ (about 12 ‰ difference) in the two veins above and −138.8 to −136.0 ‰ in the lower small vein, against −135.7 ‰ in the modern vein.

Polygonal peatland in the Seyakha (Zelenaya) River mouth is located near Seyakha village

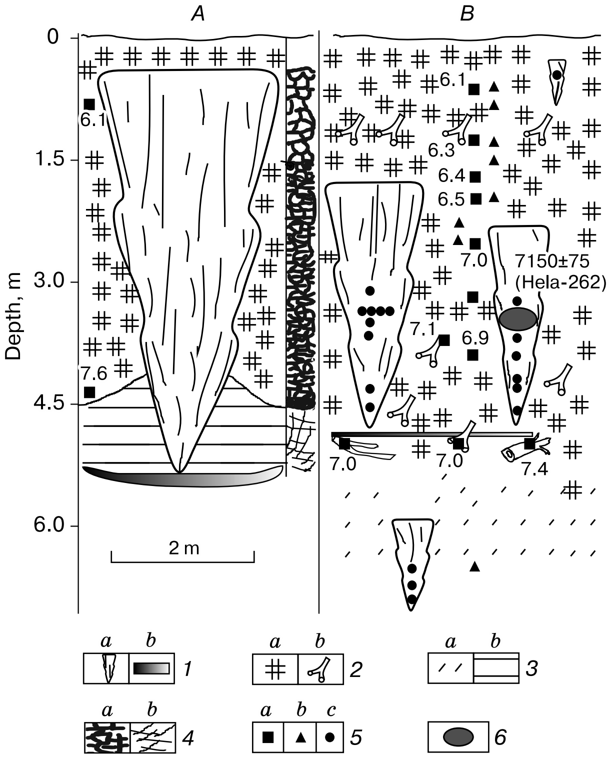

Fig. 3. Polygonal peatland in the Shchuchiya River valley.

A: large ice wedges in the middle of the section studied in 1977; *B*: small buried ice wedges in the peatland margins sampled in 1997. *1* – wedge ice (*a*), segregated ice (*b*); *2* – plant remnants: peat (*a*), birch trunks, branches, and roots (*b*); *3* – silt (*a*), clay (*b*); *4* – cryostructure: basal (*a*), fine lenticular-reticulate (*b*); *5* – sampling sites of organic material for radiocarbon dating (*a*) and isotope analysis of segregated (*b*) and wedge (*c*) ice; *6* – sampling site of moss pedicle for AMS dating and its ^{14}C age.

(70°10′00″ N, 72°30′30″ E) on the Ob' Gulf shore, in a typical tundra subzone (Fig. 4). Holocene peat forms an inlier in 22–24 m marine terrace III and consists of several deposits which crop out near the terrace top (Fig. 5; Table 1). The deposits are 3–5 m thick and 100 to 200 m wide (Fig. 4). Peat is mainly grass-hypnaceous, with predominant sedge, and locally contains *in situ* birch trunks with white bark, branches, and roots (Table 2). An up to 1.5 m thick layer rich in wood at the section base (Fig. 5, *B*) records the onset of peat deposition in wet lowlands. The oldest wood ages of 8700–8800 yr BP (Table 2) mark forest degradation as a consequence of swamping after deep thawing and thermokarst formation. A 4 m thick layer of peat had formed for 700–800 years from 8600 to 7800 yr BP, and the accumulation rate was thus as high as ~3 mm/yr, even counted with more than 40 % of ice and 2.5 m of pure peat. This rate is faster than that in Middle Vasyugan peatland [*Preis, 2015*].

Table 2. **Radiocarbon dating of organic material from thick polygonal peatlands**

Depth, m	Dated material	^{14}C age, yr BP	Calendar AMS ^{14}C (calibrated in *OxCal 4.2 IntCal13*)	Laboratory sample number
1	2	3	4	5
Polygonal peatland, Shchuchiya River, Southern Yamal Peninsula, sampled in 1997				
0.8	Peat	6110 ± 110	5310–4785	Hel-4138
1.4	»	6300 ± 100	5476–5030	Hel-4139
1.8	»	6450 ± 100	5566–5224	Hel-4137
2.05	»	6570 ± 100	5665–5328	Hel-4136
2.8	»	7020 ± 100	6069–5717	Hel-4135
3.7	»	6960 ± 100	6016–5667	Hel-4133
3.7	Birch trunk	7140 ± 100	6227–5809	Hel-4134
3.7	Moss pedicle from wedge ice	7150 ± 75	6212–6891	Hela-262
5.5	Wood	7420 ± 110	6461–6066	Hel-4140
5.5	Birch trunk	7090 ± 110	6121–5742	Hel-4141
5.5	Same	7070 ± 120	6123–5726	Hel-4142
Polygonal peatland, Ob' Gulf shore, Seyakha (Zelenaya) mouth, Central Yamal Peninsula				
0.5	Black peat	7850 ± 150	7085–6431	Hel-3945
1.0	Brown peat	8220 ± 140	7555–6900	Hel-3946
1.2	Same	8180 ± 140	7529–6770	Hel-3947
1.4	»	8230 ± 140	7574–6983	Hel-4035
1.9	»	8110 ± 130	7456–6691	Hel-4036
1.9	»	8120 ± 120	7484–6746	Hel-4024
2.1	Brown peat with branches	8210 ± 130	7539–6907	Hel-4037
2.3	Same	8440 ± 130	7742–7136	Hel-4025
2.5	Brown peat with wood	8820 ± 140	8254–7600	Hel-4038
2.65	Same	8260 ± 140	7586–7022	Hel-4039
2.65	Birch trunk	8210 ± 160	7574–6771	Hel-4048
2.68	Brown peat with wood	8520 ± 130	7985–7283	Hel-4040
2.7	Same	8370 ± 120	7593–7128	Hel-4026
2.8	»	8240 ± 110	7538–7042	Hel-4049
3.0	Black peat with wood	8330 ± 130	7583–7084	Hel-4027
3.1	Same	8180 ± 140	7529–6770	Hel-4028
3.2	Chocolate brown peat	8320 ± 110	7568–7123	Hel-4029
3.4	Tree trunks (vertical)	8610 ± 130	8011–7452	Hel-4041
3.5	Chocolate brown peat	8490 ± 130	7846–7178	Hel-3948
3.6	Chocolate brown peat with wood	8350 ± 110	7584–7137	Hel-4051
3.6	Tree trunks (vertical)	8400 ± 140	7682–7071	Hel-4042
3.65	Brown peat	8260 ± 140	7586–7022	Hel-4030
3.9	Same	8600 ± 140	8011–7422	Hel-3949
4.0	Birch trunk	8740 ± 130	8218–7585	Hel-3944
4.0	Peat around birch trunk	8790 ± 170	8291–7553	Hel-4034
1.65	Brown peat near ice wedge	9280 ± 140	9120–8243	Hel-4031
1.2	Same	6560 ± 150	5751–5217	Hel-4068
Polygonal peatland, Yuribei valley, right side, 6 km north-north-east of Pederten-Penze mouth. Site 154-YuV				
2.8	Shrub birch	8830 ± 40	8203–7755	GIN-2478
4.3	Hypnaceous brown peat	9230 ± 50	8596–8302	GIN-2479
Polygonal peatland, Yuribei valley, right side, 9 km south-east of Lake Laeto. Site 160-YuV				
4.0	Brown peat	7460 ± 100	6474–6089	MGU-714
Polygonal peatland, Yaptiksale village, Eastern Yamal Peninsula				
1.0	Peat with sand	1580 ± 180	25–801 AD	GIN-2638
4.0	Birch wood	8700 ± 50	7937–7594	MGU-713
5.0	Peat	8960 ± 140	8467–7657	MGU-816

Continued tabl. 2

1	2	3	4	5
Polygonal peatland, Kharasavei, Western Yamal Peninsula (71°10′ N, 66°51′ E)				
4.6	Brown peat	9360 ± 120	9123–8300	GIN-2652
Polygonal peatland, Salemlekabtambda mouth, 2 km east of Matyui-Sale factory, Mamont Peninsula, northern Gydan Peninsula, marine terrace II				
0.1	Black peat	490 ± 100	1289–1635 AD	GIN-3582
0.2	Peat nest	6520 ± 60	5615–5363	GIN-3624
0.4	Peat spot	3230 ± 60	1658–1395	GIN-3620
0.5	Peaty silt	11070 ± 150	11255–10756	GIN-3581
0.6	Same	11080 ± 120	11190–10771	GIN-3625
1.2	Brown peat	9970 ± 120	10014–9250	GIN-3631
1.6	Same	9570 ± 50	9176–8775	GIN-3580
2.4	»	9920 ± 50	9654–9276	GIN-3623
3.3	Light brown peat	10230 ± 70	10427–9680	GIN-3590
3.5	Peat from lemming hole	8630 ± 60	7811–7546	GIN-3626
4.1	Brown peat	9940 ± 70	9755–9271	GIN-3583
Polygonal peatland, Taz region, west of Messoyakha [*Batuev et al., 2015*]				
0.1	Peat	3950 ± 70	2831–2206	LU-6950
1.4	»	5980 ± 80	5202–4687	LU-6951
2.9	»	6330 ± 90	5479–5064	LU-6952
4.2	»	3930 ± 80	2832–2147	LU-6953
5.4	»	5630 ± 50	4556–4351	LU-6954
5.5	»	7560 ± 90	6591–6240	LU-6955

Fig. 4. Polygonal peatland in the Seyakha (Zelenaya) River mouth.

Photograph by Yu. Vasil'chuk.

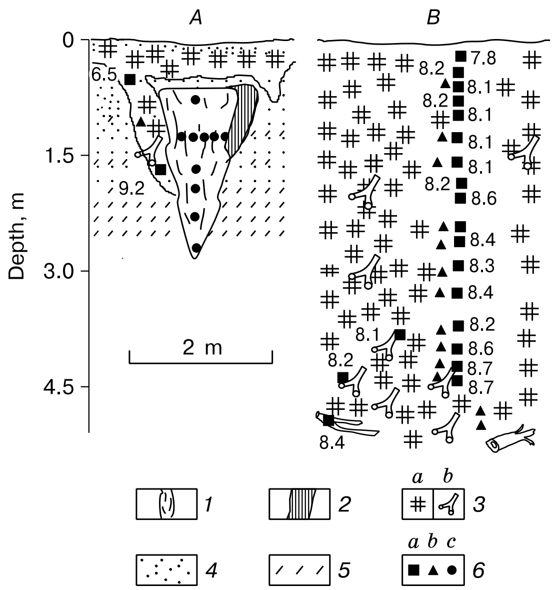

Fig. 5. Polygonal peatland in the Seyakha (Zelenaya) River mouth.

A: large ice wedges syngenetic with peat veins; *B*: thick peatland. *1* – wedge ice; *2* – sugar-white ice; *3* – plant remnants: peat (*a*), birch trunks, branches, and roots (*b*); *4* – sand; *5* – silt; *6* – sampling sites of organic material for radiocarbon dating; numerals show ^{14}C ages in kyr BP (*a*) and isotope analysis of segregated (*b*) and wedge (*c*) ice.

Syngenetic wedge ice in thermokarst depressions coexists with peat soil veins (Fig. 5, *A*). Both ice and peat veins have their heads at the same depth about 0.5–0.7 m below the surface and reach heights of 2.0–2.5 m and 2 m, respectively. The peat veins are composed of frozen poorly degraded sandy peat with small branches and bark of trees and with leaves of dryad, saxifrage, and shrub birch. Most likely they formed along frost cracks at the same time as the ice wedges, judging by their concordant attitude. Peat samples from the vein bottom and top have ages 9280 and 6560 yr BP, respectively, and thus fall within the Holocene optimum interval when wedge ice was forming as well. A 9300 yr BP age obtained for a soil vein outside the peatland within terrace III [*Vasil'chuk and Vasil'chuk, 1995*] suggests that the peat veins formed rapidly in the beginning of the Holocene optimum. At that time the seasonally thawed active layer became much drier while harsh winter conditions caused freezing of lacustrine and paludal deposits and produced wedge ice.

Segregated ice from frozen peatland has $\delta^{18}O$ higher than Holocene wedge ice (–14.6 to –12.1 ‰ against –20.3 to –19.1 ‰) and δD –146.1 to –135.2 ‰. This is a reasonable difference because $\delta^{18}O$ corresponds to those of the source paludal water for segregated ice and snow for wedge ice, while the snow $\delta^{18}O$ correlates with mean winter air temperatures [*Vasil'chuk, 1992, 2006*].

Good preservation of wood and bark, as well as successive depthward decrease of ice salinity (576 mg/L at a depth of 3.5 m, 452 mg/L at 2.9 m, 430 mg/L at 2.7 m, 189 mg/L at 2.6 m, and 18 mg/L at 0.6 m) evidence of syngenetic peat freezing. The lake-bog depression (or several small depressions) formed by thawing of abundant highly saline segregated ice in the upper part of lagoon-marine terrace III [*Vasil'chuk and Vasil'chuk, 1995*].

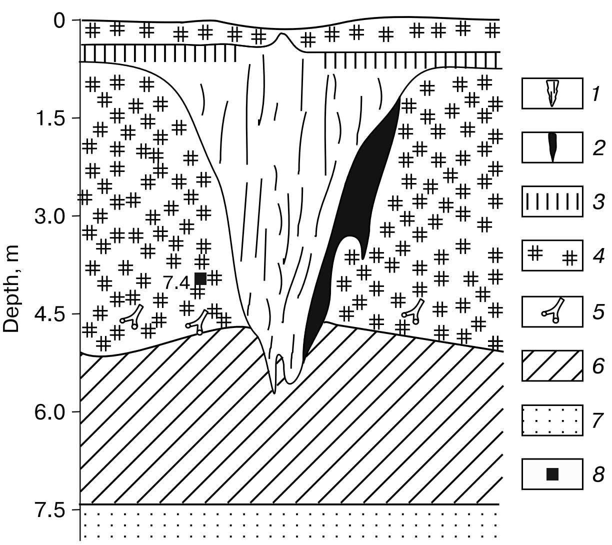

Fig. 6. Polygonal peatland in the Yuribei River valley (9 km southeast of Lake Laeto).

1–3 – ice: syngenetic vein (*1*), rim (*2*), segregated (*3*); *4* – peat; *5* – plant remnants; *6* – clay silt; *7* – sand; *8* – sampling site of organic material for radiocarbon dating and its ^{14}C age.

Radiocarbon ages of autochthonous peat and wood remnants record *in situ* peat deposition between 8350 and 7830 yr BP. The climate during rapid wedge ice growth, including during the Holocene optimum, differed from the present conditions by colder winters, with 2–4 °C lower mean winter temperatures (inferred from $\delta^{18}O$ and δD of ice), but 2–3 °C warmer summers (indicated by abundant tree vegetation).

Yuribei polygonal peatlands in central Yamal crop out within the remnant Kazantsevo plain along the Yuribei River. The peat section 6 km north-northeast of the Pederten-Penze River, at 68°10′50″ N, 66°51′50″ E is 4.3 m thick (Table 1) and its base has an age of 9230 yr.

Another peatland (Table 1) is located downstream, on the Yuribei River right side, 9 km southeast of Lake Laeto (68°12′ N, 69°41′ E), in lagoon-marine terrace III. Botanical analysis shows mainly fen grass-hypnaceous peat composition, sedge-hypnaceous and fen grass from the base to the depth 1.85 m. The peat base was dated at 7460 yr. The peatland has a patterned surface with 10.5 × 12.0 m polygons delineated by 0.3 to 1.5 m wide and <0.6 m deep troughs. The section includes a 1.5 m wide and ~4 m high wedge of distincly columnar ice (Fig. 6), with a ~15 cm thick horizontal layer on top.

Yaptiksale polygonal peatland in eastern Yamal was studied in the 7–9 m high escarpment of lagoon-marine terrace I at 69°23′08″ N, 72°31′33″ E. Peat is mainly of fen hypnaceous type, varying in thickness from 3 m in the margin to 5 m in the center (Fig. 7), and is composed of fen sphagnum in a layer at a depth of 2.7 m. Peat lies under 2 m of saline (1.2 % dissolved salts) layered sand with allochthonous peat dated at 1580 yr (Table 2). The peatland encloses a narrow (0.5 m) wedge of opaque ice, more than 4 m high. Peat at the base of the section has an age of 8960 yr, while wood of well preserved white-bark birch is 8700 yr old.

Polygonal peatland near Kharasavei Village is exposed in marine terrace I that rises 8 m asl on the Kara shore, 0.5 km north of the Kharasevei Cape (71°10′50″ N, 66°51′50″ E). It is up to 4.6 m thick hypnaceous and sedge-hypnaceous fen peat cut by ice wedges, from a depth of 0.5–0.7 m, which reach 7 m high and 1.5 m wide on top. Ice is brownish, with a sugar-like texture and a weakly pronounced columnar structure. Peat at the section base has an age of 9360 yr and contains wood.

Polygonal peatland in the Salemlekabtambda River mouth was studied near the Matiyisale factory at 72°00′06″ N, 76°23′31″ E (Fig. 1), in the northern Gydan Peninsula (Fig. 8). Holocene peat occupies a

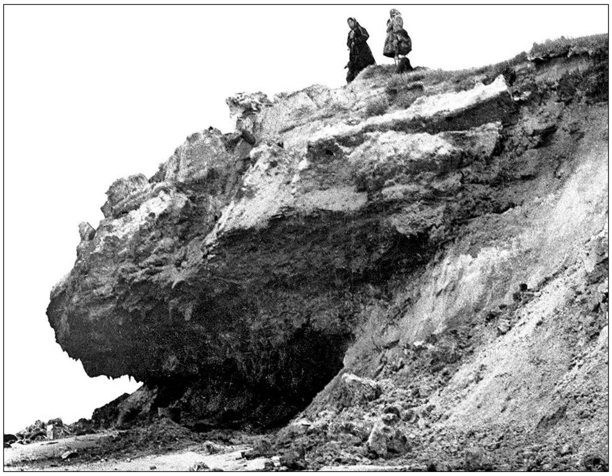

Fig. 7. Polygonal peatland near Yaptiksale village (Yamal Peninsula).

Photograph by Yu. Vasil'chuk.

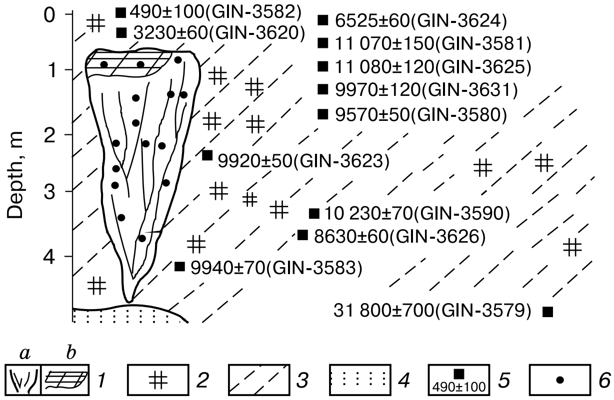

Fig. 8. Polygonal peatland in the Salemlekabtambda River mouth (Gydan Peninsula).

1 – columnar syngenetic wedge ice (*a*) and cave ice on top of ice wedges (*b*); *2* – peat; *3* – silt; *4* – sand; *5* – sampling sites of organic material for radiocarbon dating and its ^{14}C ages; *6* – sampling sites for isotope analysis of wedge ice.

depression in marine terrace II. The peatland has a prominent patterned surface with ice wedges reaching 4.5–6.0 m high and 3 m wide on top. The host sediments are deformed along contacts with ice; the peat base is 1.0–1.5 m shallower at the ice contact than in the polygon center, which confirms a syngenetic origin of ice. A sample from the boundary between Holocene peat and the ice complex below gave an age as old as 31,800 yr BP, which suggests possible allochthonous origin of some peat. The onset of peat deposition was timed according to the minimum date of 9940 yr BP at a depth of 4.4 m, but its end is difficult to constrain because older organic components produce inverse age patterns (Table 2). The age obtained for reliably autochthonous peat of plant remnants from a lemming hole at a depth of 3.5 m is 8630 yr BP represents only the middle section (Fig. 8).

The $\delta^{18}O$ values of the largest ice wedge are in the range from –20.1 to –16.2 ‰, i.e., the difference is about 3–4 ‰ which corresponds to 3–4 °C changes in mean winter temperatures. The coexistence of oxygen isotope compositions more enriched and depleted than the present $\delta^{18}O$ within the same ice wedge is evidence that the winters during the Holocene optimum were either 1–2 °C warmer (seasonal means) or 2–3 °C colder than now.

Polygonal peatland in the lower reaches of the Tadibeyakha River was sampled at 70°22′21″ N, 74°07′32″ E on the left side of the Tadibeyaka River mouth, near the Ob' Gulf shore, in the central Gydan Peninsula. Peat is 4.2 m thick and forms 7 × 9 m and 8 × 10 m polygons cut by 3.5–4.0 m high ice wedges.

Polygonal peatlands in the Messoyakha River valley are abundant in the southern Gydan Peninsula. One such peatland occurs on the left-side Mes-

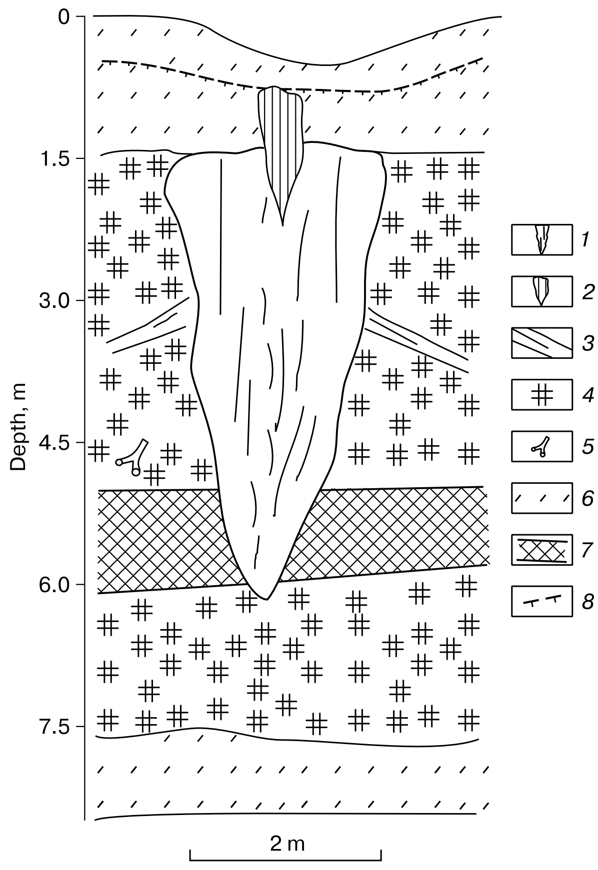

Fig. 9. Polygonal peatland in the Messoyakha River valley (20 km downstream of the Nedayakha inlet).

1–3 – ice: syngenetic wedge ice (*1*), young growing ice vein (*2*), segregated ice bands (*3*); *4* – peat; *5* – plant remnants; *6* – silt; *7* – intrusive-segregated ice; *8* – permafrost table.

soyakha terrace I, 20 km downsteam of the Nadayakha River mouth (a left tributary of the Messoyakha River), at 69°10′14″ N, 82°11′23″ E (point 9-KV). Peat forms ~10 ×10 m polygons and is locally as thick as 7 m. The section begins with buckbean and grass fen peat at a depth of 6–7 m followed by sphagnum fen peat in the 6–4 m interval. Ice wedges are more than 5.2 m high and about 2 m wide on top (Fig. 9). According to pollen spectra analyzed simultaneously in ice and peat [*Vasil'chuk, 2007*], ice formation began in the early Boreal, in a climate more continental than the present conditions. Another polygonal peatland, with more than 5 m thick peat and 3.8–4.0 m high ice wedges (Table 1), is located in marine terrace I on the Messoyakha left side, 20 km downstream of the Shchuchiya arm.

PEAT ACCUMULATION RATE

Almost all peatlands we studied occur within river valleys, this being evidence of drainage control over peat deposition. The peatlands along the Messoyakha River, near Kharasavei Village, and near Yaptiksale Village are located in terrace I and thus were deposited in a floodplain-laida environment. They are buried under 1.0–1.5 m of fine sand, possibly as a result of flooding, because hypsometically higher peat lacks any sand cover.

Other peatlands (Seyakha, Yuribei, and Messoyakha [*Batuev et al., 2015*]) were deposited in depressions at hypsometrically higher levels, within terraces II and III and upon the Kazantsevo surface. This peat has no sand cover and its thickness corresponds to the depth of thermokarst depressions in older sediments. High ice contents can produce domes, as in the case of Seyakha peat. All studied peatlands are composed of fen peat, often of sedge-hypnaceous type.

Polygonal peatlands, more than 5 m thick, are known from tundra settings in different regions: alas complexes of northern Yakutia [*Kaplina, 2009*], terrace I of the Lena estuary, the Bulkuskaya arm [*Bolshiyanov et al., 2015*], the Olenek mouth [*Makarov, 2009*], the Indigirka River right side, the Berelekh River [*Kaplina and Lozhkin, 1979*], northwestern Canada [*Zoltai et al., 1988*], etc.

Thick peat in the northern Yamal and Gydan shores began to accumulate in pre-Boreal time about 9500–9200 yr ago (Table 2), when larch appeared in the Nadym-Pur interfluve [*Blakharchuk, 2010*]. Peat accumulation rate in tundra and forested tundra of that time was 1.4–1.6 mm/yr but decelerated to 0.4 mm/yr in the Subboreal [*Vasiliev, 2000*]. Peat accumulation in the taiga zone (interfluve of the Ob' and Vasyugan rivers, 59°23′ N, 76°54′ E) was at rates of 2.4 mm/yr in pre-Boreal time and 0.86 mm/yr in the Boreal [*Inisheva et al., 2013*]. Peat in the Canadian tundra was deposited at a mean rate of 0.08–0.20 mm/yr [*Zoltai et al., 1988*]. Salemlekabtambda peat, 6 m thick, accumulated for about 2000 years during the 9600 to 7500–7000 yr BP time span, at ~3 mm/yr. It has been eroded and partly redeposited, and the upper bound of the deposition interval remains poorly constrained. Peat deposition may have completed 8630 yr ago, according to the age of plant remnants from the lemming hole, or possibly continued for some time later on.

Kharasavei peat began to deposit about the same time. If it was deposited at the same rate as Salemlekabtambda peat (0.76 mm/yr on average), it could reach a 4.6-m thickness at ~7000–6000 yr BP, given its high ice content. Seyakha peat accumulation lasted from 8200 to ~7000 yr BP. The available peat ages suggest that the 4-m peat layer grew for 800 years. Peat was deposited at a rate of 0.7 mm/yr in the 3.8–4.0 m depth interval and almost ten times faster (6.9 mm/yr) in the 3.80–3.65 m interval. The highest accumulation rate (20 mm/yr) is inferred for the interval between 3.10 and 3.65 m, where wood remnants are especially abundant and ice contents are relatively high (Table 1); the deposition slowed down to 5.4 mm/yr in the 1.9–3.1 m interval and on to 1.4 mm/yr within 0.5–1.9 m. These variations may record either the proper peat growth or transition to permafrost.

Messoyakha peat, 5.5-thick, was deposited from 6500 to 2200 yr BP, at rates from 0.05 mm/yr at the section base to 0.6 mm/yr in the middle, and 0.3 mm/yr in the upper part [*Batuev et al., 2015*]. Similar accumulation rates are known from thick polygonal peatlands worldwide. For instance, Kytalyk peat at the Berelekh River was deposited at a rate of 0.4–0.6 mm/yr [*Teltewskoi et al., 2016*], and Kukjuk peat with wedge ice in the Mackenzie mouth, on the Tuktoyaktuk Peninsula, was deposited since 7200 yr BP, at a mean rate of 0.7 mm/yr [*Vardy, 1997*].

Tree remnants occur at all sites, as far as the Kharasavei latitude (71°10′ N), in peat deposited in the place of lakes and bogs, both on terrace I (Yaptiksale, Shchuchiye, Kharasavei, and other peatlands) and on higher terraces (Seyakha, Yuribei, Messoyakha, Salemlekabtambda, Tadibeyakha, and other rivers). The wood layer in Seyakha peat is obviously autochthonous. It occurs more than 20 m above the Ob' Gulf water level and consists of diverse components, from roots and trunks with branches to bark and larch needles. It was apparently a scarcely growing forest or high-productivity coppices in river valleys sheltered form wind and in lake basins. The obtained ages of white-bark birch remnants are 8200–7500 yr BP for Seyakha peat; 7900–7500 yr BP for Yaptiksale peat; and 6400–5700 yr BP for Shchuchiya peat. Small birch grooves in thermokarst depressions were likely a common landscape element during the Holocene optimum.

The state of peat depends on water contents in its surface layer, its freezing or thawing, and composition. Dry, wet, and frozen peat differs markedly in thermal conductivity. Thermal conductivity of air-dry peat is very low, due to the presence of abundant air-filled pores: from 0.012 to 0.069 W/(m·K) in sphagnum peat depending on the degree of decay [*Roman, 1987*]. Thermal conductivity of wet and frozen water-saturated peat is 6.5–8 and 33 times that of dry peat, respectively [*Vardy, 1997*]. The peat cover provides cooling of the ground below at the account of high heat insulation in summer and tens of times lower insulation in winter. That is, peat works as a "thermosyphon", a seasonal cooling device. It strongly cools down in winter and keeps the ground cool in summer, judging by large areas occupied by polygonal peatlands, both in northern West Siberia and northern Canada.

The review of peatlands with ice wedges in different areas of northern West Siberia shows that the Holocene optimum was the time when the largest ice wedges began forming or older ones continued growing. Wedge ice of the respective ages, more than 5 m high and 3 m wide on top, occurs in the Shchuchiya and Yuribei river valleys and in the Kharasavei mouth.

Calculations according to the relationship between the stable isotope composition of wedge ice and mean winter air temperatures show that winters in some periods of the climate optimum were on average 1.5–2.0 °C colder than now [*Vasil'chuk, 1992*], but this did not affect active peat growth in summer. Thus, increasingly continental climate was favorable for the formation of thick peat in tundra. This idea is consistent with the finds of *Menyanthes trifoliata* macrofossils in peat and its pollen in both peat and wedge ice indicating that biocenoses with *Menyanthes trifoliata* proliferated in settings of cold winters and warm summers.

CONCLUSIONS

1. Polygonal peatlands in the Yamal and Gydan tundra are 4–5 m thick and occur either in floodplains and laidas or in hypsometrically higher lake-bog depressions.

2. Peat accumulated at high rates up to 5 mm/yr or faster and reached 4–5 m thick for 700–1000 years.

3. The large thickness of peat is due to fast accumulation rates, rapid freezing and high contents of segregated and wedge ice, as well as to the presence of a wood layer at the base and tree macrofossils along the whole section.

4. Stable isotope patterns in ice and the presence of wood at the peat base as far as 71° N record a strongly continental climate during the rapid formation of peat and wedge ice in the polygonal peatlands of northern West Siberia.

5. At that time, winters were 2–4 °C colder (seasonal means) but summers were 2–3 °C warmer than now; the warmer summers are indicated by active tree growth.

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