# $^{14}C$ DATING OF PEAT AND $\delta^{18}O$-$\delta D$ IN GROUND ICE FROM NORTHWEST SIBERIA

Yurij K Vasil'chuk[1] • Högne Jungner[2] • Alla C Vasil'chuk[3]

**ABSTRACT.** We present new radiocarbon dates from a number of Holocene peat deposits along a north-south transect across the Yamal Peninsula. The samples were collected from frozen peat deposits with large ice wedges in: the northern tundra near Seyaha Settlement, in the Central Yamal Peninsula, the southern tundra in Shchuch'ya River valley at the Edem'yaha mouth, the southern part of the Yamal Peninsula, and the southern forest tundra near Labytnangi Town. $^{14}C$ dates of wood remains from the tundra in the Yamal Peninsula could be used to reconstruct a northern limit of forest during the Holocene Optimum. The wood layers at the bottom of the peat give evidence for immigration of trees further north beyond the present boundary. The first forest appearance in the Seyaha River valley area is dated about 9 ka BP according to the oldest peat date in the Seyaha cross section. This suggests that summer temperatures were higher than at present. Very fast accumulation of peat (around 5 m/ka: about 9–8 ka BP at Seyaha and about 7–6 ka BP at Shchuch'ya) also supports this observation.

In contrast, oxygen isotope composition of Holocene syngenetic ice wedges from the area ($\delta^{18}O$= –19.1 to –20.3‰ in the Seyaha cross-section and –17.3 to –20.3‰ in the Shchuch'ya River) show that winter temperatures were significantly lower than presently, i.e. the climate during the Holocene Optimum was slightly more continental. The frozen peat near Labytnangi has thawed during the last 20 years, indicating global warming.

## INTRODUCTION

It is generally assumed that peat grows very slowly in the tundra zone and evidence for slow peat accumulation in the northern areas is well-known. The average rate of peat accumulation in tundra is about 1 m per 1000 years or less. We have, however, found two sites far north of the Polar Circle where accumulation rate of peat is about 5 m during 1000 years. Dating results show that this fast accumulation of peat has taken place during the Holocene Optimum. In addition, dated tree remains found in the peat bogs point to the immigration of forest far north into the tundra during the Holocene Optimum. Taken together, these results indicate that during this period the climate was warmer and the permafrost was degraded throughout vast areas of tundra. However, we have also found numerous evidences of severe winter conditions during this time.

Syngenetically freezing peat (i.e. peat that freezes just after accumulation) is a well-preserved material containing unchanged complete palaeoclimatic and palaeobotanic information. Therefore, it is useful for radiocarbon dating.

## REGIONAL SETTING

The first study site is located near Seyaha settlement in Central Yamal, at the coast of Ob Bay about 500 km north of Salekhard in the northern part of Western Siberia (70°N, 72°E). The second study site is located in the Shchuch'ya River valley, near Edem'yaha Creek in southern Yamal Peninsula, about 200 km north of Salekhard (67°N, 69°E), and the third studied site is located near Labytnangi town, about 2 km west of Salekhard (66°30´N, 67°E), close to the modern northern boundary of forest tundra (Figure 1).

The first region is covered by typical tundra—the northern limit of forest tundra is about 450 km to the south. The second region is southern tundr, with the northern limit of forest tundra located about

[1]Faculties of Geology and Geography, Lomonosov's Moscow State University, 119899, Vorob'yovy Gory, Moscow, Russia. Corresponding author. Email: vasilch@orc.ru.

[2]Radiocarbon Dating Laboratory, Helsinki University, POB 64, FIN-00014 Helsinki, Finland

[3]Laboratory of Palaeogeography of Pleistocene, Faculty of Geography, Lomonosov's Moscow State University, 119899, Vorob'yovy Gory, Moscow, Russia


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25 km to the south. Climatically, the Seyaha region corresponds to the Arctic zone. The climate today is continental with a mean annual temperature of –9.8 °C, mean winter temperature –16.4 °C, mean January temperature –22.9 °C, mean summer temperature +5.6 °C, and mean July temperature +7.2 °C. The winter (with mean day temperatures below 0 °C) duration is 255 days and summer (with mean day temperatures above 0 °C) lasts for 110 days. Tundra vegetation dominates the area, with low shrubs such as dwarf birch and willow occurring in river valleys only.

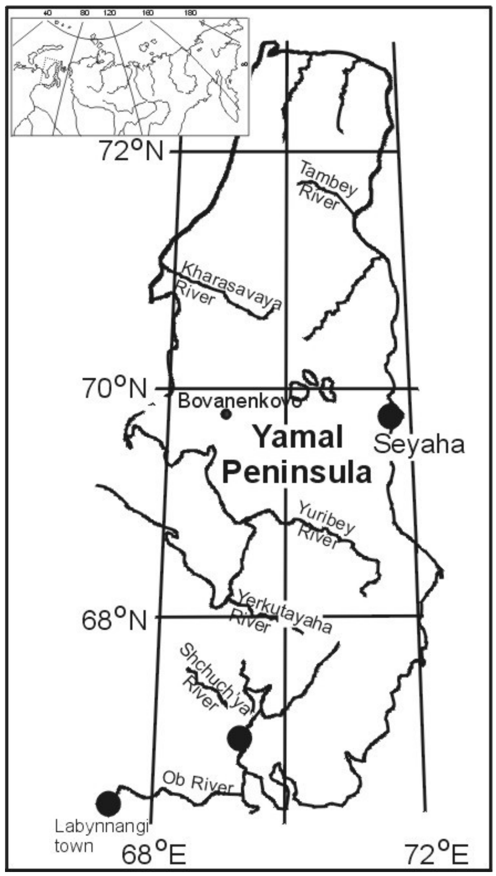


Figure 1 Location of studied cross-sections at Seyaha, Shchuch'ya and Labytnangi Holocene peat bogs and present northern limit of forest

The climate in the Shchuch'ya River valley region is also continental, with a mean annual temperature of –7.5 °C, mean winter temperature –16.1 °C, mean January temperature –24.0 °C, mean summer temperature +8.4 °C, and mean July temperature +13.2 °C. The winter duration is 236 days, and summer lasts for 129 days. The region is also dominated by tundra vegetation, but trees such as birch and larch grow in the valleys of large rivers.

The peat near Labytnangi town is interesting because it simulates the Holocene Optimum thawing near the southern limit of the permafrost area. Thirty years ago, it was frozen (the ground temperature below –2 °C), but during the last 10–15 years the peat thawed very quickly due to global warming. In this area climate is also continental, with mean annual temperature of –7.0 °C, mean winter temperature –15.3 °C, mean January temperature –23.6 °C, mean summer temperature +8,9 °C, and mean July temperature +13.8 °C. The winter duration is 229 days, and summer duration is 136 days.

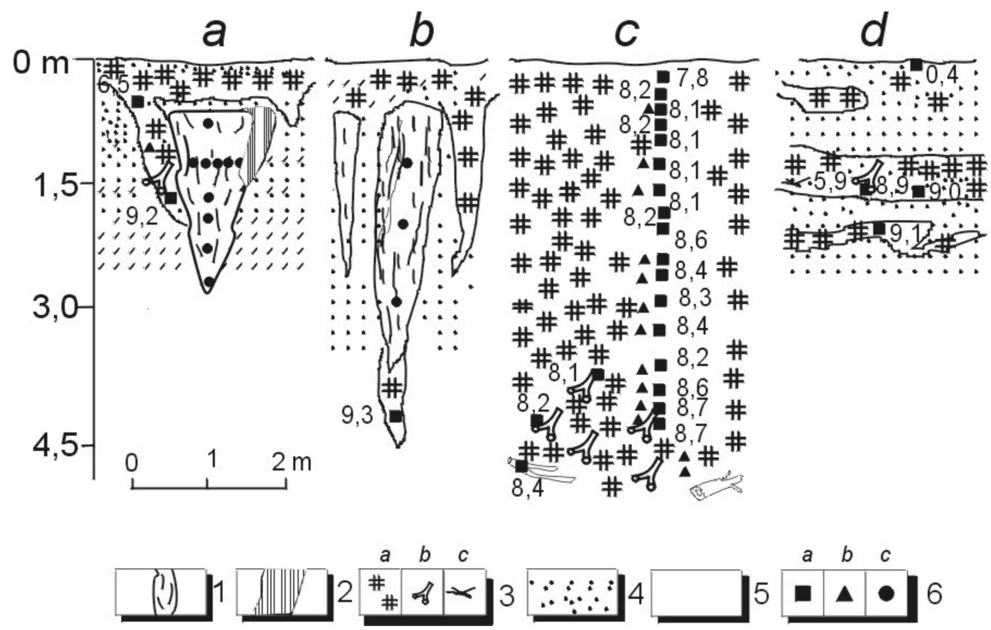

Figure 2 [14]C dates and sampling points of four fragments of Seyaha Holocene peat: (a) large syngenetic ice wedges in paragenesis with peat wedges; (b) narrow ice wedges in paragenesis with peat wedges; (c) thick peat; (d) peat margin: 1. striped ice of syngenetic ice wedges; 2. white ice of lateral border of ice wedge, 3. plant remains : peat(a), birch stumps, trunks, roots (b), larch needles (c), 4. sand; 5. sandy loam; 6. sampling points from: a) peat b) lens ice, c) ice-wedge ice. Note that not all dates of fragment (c) are shown.

### THE PEAT PROFILES

The peat near Seyaha settlement is an inset in a 22–24 m lagoon-marine terrace. It occurs as numerous peat lenses exposed in upper part of the terrace (Figure 2 above). The thickness of these lenses range from 3 to 5 m. Several layers containing numerous tree remains (such as trunks with crust, branches, twigs, and roots) can be found in the section. Sometimes, the trunks occur vertically in a living position. The structure of the central part (see Figure 2c) of the peat cross-section is (from top to bottom) as following:

Layer 1. From 0 to 0.1 m. soil layer, loam with roots of modern plants

Layer 2. From 0.1 to 0.35 m. dusty fine gray sand

Layer 3. From 0.35 to 0.8 m. brownish black peat with rootlets and leaves of dwarf birch

Layer 3. From 0.8 to 2.15 m. frozen brown moss-sedge peat with twigs

Layer 4. From 2.15 to 2.6 m. frozen brown moss-sedge peat with remains of trees, and stumps with roots. Stump of birch with roots and trunk of birch, diameter 0.9 m was found at the depth 2.5 m. The layer is characterized by high content of structure forming ice.

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Layer 5. From 2.6 to 3.1 m. frozen brown moss-sedge peat with small rounded twigs, fragments of wood, a trunk of birch occurred just vertically is found at the depth 2.65 m. The layer is characterized by high content of structure forming ice.

Layer 6. From 3.1 to 3.2 m. frozen black peat with wood

Layer 7. From 3.2 to 3.6 m. frozen chocolate viscous peat with wood, vertically occurred trunk at the depth 3.6 m.

Layer 8. From 3.6 to 4.5 m. frozen brown sedge peat with abundance of tree remains and stumps with roots.

Plant remains studied in the peat show evidence of the very fast freezing typical of syngenetic conditions, because many delicate plant fragments such as moss-capsules, moss-caps, and small rootlets are well preserved. The inundation regime often changed from biocenoses with *Drepanocladus, Equisetum, Carex caespitosa, C. limosa, C. acuta* and *Oxycoccus to Sphagnum sect acutifolia, Carex vesicaria, C. rotundata*.

Thick syngenetic ice wedges occur at the margin of the peat (see Figure 2 a, b) penetrating 3–4 m into the permafrost. There are peat wedges near the ice wedges. This, together with the considerable number of ice wedges, forms evidence for syngenetic origin of the ice wedges.

The peat in the Shchuch'ya River valley is an inset in the 7-m-high alluvial terrace (Figure 3). The site is located in the southern part of the Yamal Peninsula. Large syngenetic ice wedges cut throughout the peat, down to a lacustrine loam layer. Thick wood remains as roots, trunks of birch, trunks, cones, and needles of larch, and cones of spruce are found in the bottom layer. The thickness of peat formation ranges from 5–5.5 m. The structure of the peat cross-section is (from top to bottom) as follows:

Layer 1. From 0 to 0.7 m. dark brown sedge peat

Layer 2. From 0.7 to 1.0 m. frozen brownish black peat

Layer 3. From 1.0 to 1.4 m. frozen black sedge peat with leaves of dwarf birch and larch cones

Layer 3. From 1.4 to 1.75 m. frozen brown moss-sedge peat with twigs of ground willow

Layer 4. From 1.75 to 2.05 m. frozen brown moss-sedge peat with remains of trees and stumps with roots

Layer 5. From 2.05 to 2.6 m. frozen brownish black moss-sedge peat, the layer is characterized by high content of texture forming ice in the middle part. At the depth of 3 m an ice wedge 0.5 m wide at the top occurs, the ice of ice wedge is white, with elemental veins well-pronounced.

Layer 6. From 2.6 to 4.5 m. frozen black peat with trunk of birch, stumps with roots and crust

Layer 7. From 4.5 to 7.0 m. frozen gray lacustrine sandy loam with ferrugination and peat spots

At the depth 6.75 – 6.85 m. lens segregated ice with bubbles occurs

At the depth 6.4 – 6.5 m. ice wedge occurs, rose Grey, 0.5 m wide at the top.

In the central and margin parts of the peat, large ice wedges occur at 4.3 to 5.5 m. The width of the ice wedge at the top is 2.0 m (Figure 3a). It has smoothed shoulders and contains a vertical peat layer within.

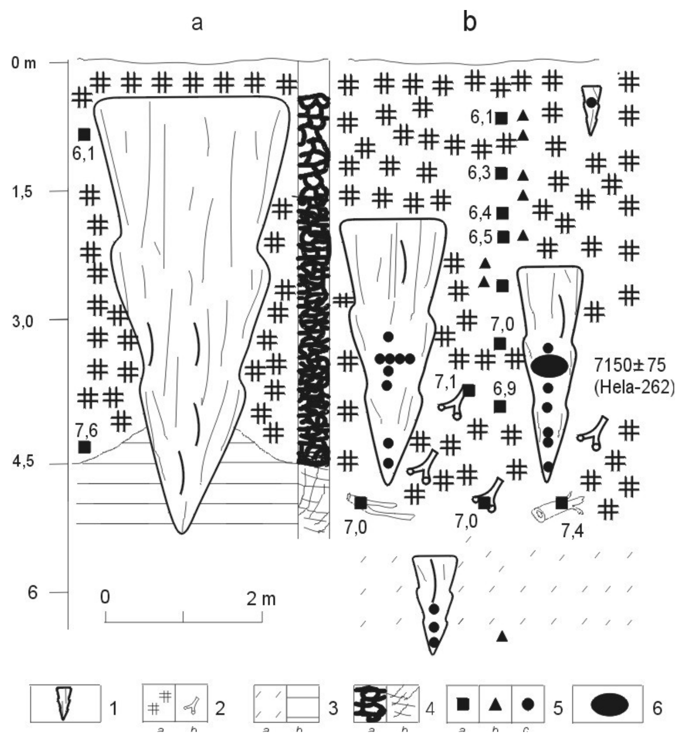


Figure 3 $^{14}$C dates and sampling points of two fragments of Shchuch'ya Holocene peat: a) large syngenetic ice wedges in paragenesis with peat wedges described in 1977; b) narrow ice wedges in paragenesis with peat wedges described in 1997; c) thick peat.
1. vertically striped ice of the syngenetic ice wedges; 2. plant remains: a) peat, b) stumps, stems, roots; 3. sandy loam; 4. sampling points from lens ice (a), ice wedge ice (b).

Plant remains studied in the peat exhibit the very fast freezing typical of syngenetic conditions, because small delicate plant fragments such as moss leaves and rootlets are well preserved. This peat is dominated by mosses. Remains of foliaceous trees, together with remains of *Equisetum sp., Eriophorum sp., Carex acuta, C.rostrata, C.chordorriza,* Carex caespitosa, and grasses, were also found at the depth of 6.75 m. In the middle part of the cross-section (at the depths 2.7–1.4 m) roots of coniferous trees and *Menyanthes trifoliata* remains were found together with *Equisetum sp., Carex caespitosa, C. nigra, C.acuta,* and *Eriophorum*. In the upper part, plant remains of foliacerous and coniferous trees were found. There were also many sedges remains of different species (*Carex limosa, C. chordorriza, C.lasiocarpa, C.rotundata).*

The peat near Labytnangi on the left Coast of the Ob River is located near the northern limit of forest tundra, at 110 m above the sea level. It is about 2 m thick and large syngenetic ice wedges cut through the peat down to the lacustrine loam layer. Wood remains (root trunks of birch, trunks, cones, and needles of larch, and cones of spruce) were found in the bottom layer. The structure of peat cross-section is (from top to bottom) as follows:

Layer 1. From 0.0 (3.0) to (3.3) 0.7 m. brown moss-sedge peat with modern roots

Layer 2. From 0.7 to (3.0) 1.1m. yellow moss sedge peat

Layer 3. From 1.1 to 2.6 m. brownish black peat with remains of trees, roots and leaves

Layer 4. From 2.6 to 3.0 m. gray brownish loam

The botanical composition of this peat is different from the ones mentioned above. The development of a high moor in permafrost condition is observed here. At the bottom of the peat we found the remains of *Bryales, Equisetum, Sphagnum sect. Cuspidata, Carex limosa, C.canescence, Vaccinium uligonosum, Menyanthes trifoliata*. Toward the top, remains typical of high moor plants such as *Ledum sp., Vaccinium sp., Andromeda polyfolia, Sphagnum squarrosum* occur.

## $^{14}$C SAMPLES AND DATES

### Seyaha Cross-Section

The dates from Seyaha cross-section are shown in Table 1. The sample of peat with small twigs in peaty vein (see Figure 2a) at the top of the section is dated to 9280 ± 140 BP (Hel-4031). This peaty vein is accompanied by a large Holocene syngenetic ice wedge (ice of rose-gray color). The similar peaty vein at the bottom of syngenetic ice wedge (see Figure 2b) formed during the first half of the Holocene Optimum and was dated to 9300 ± 100 BP (GIN-2472). Moreover, the peaty vein has been formed due to an increasing seasonal thawing caused by summer warming at the beginning of the Holocene Optimum. Relatively warm summers and severe winters led to the filling of the peaty wedge with organic material due to frost cracking in dried sites, but in places where Late Pleistocene ice-wedge ice were located close to the surface they thawed and produced small lakes, in which peat bogs formed. However, severe winters provided intensive aggradation of permafrost and ice-wedge growth even in shallow water lakes.

The lowermost peat (formed in wet relief depressions) contains a thick (up to 1.5 m in height), woody layer at the bottom (see Figure 2c). The oldest wood is dated to about 8.7–8.6 ka BP (see Table 1).

The dates marking the beginning of the peat formation agree with a number of $^{14}$C dates for the wood material in the bottom layer dated to 8300–8600 BP. The dates older than 8700 BP are obtained from the bottom part of the peat. They date the stage of forest degradation resulting from active bog formation after intense thermokarst thawing. The completion of the peat accumulation is dated to about 7800 BP and occurred later than more than 4 m of peat that accumulated over 700–800 yr. This is an extremely rapid rate of peat accumulation. However, it should be noted that the peat is saturated with ice.

Regular occurrence in agreement with autochthonous accumulation pattern is observed at the depth of 1–2 m, where peat is dated to 8000–8200 BP. However, a date older than 8800 BP was obtained at 2.5-m depth. That peat is obviously re-deposited, since poorly rounded twigs and fragments of wood are abundant in that layer. Most probably, a combination of autochthonous and allochthonous peat accumulation took place here. At depths of 3–4 m the dates seem to be in agreement with an autochthonous pattern. The date 8260 ± 140 BP at the depth of 3.65 m is slightly young but its lower age limit 8400 fits the other dates.

Table 1 $^{14}C$ dates of organic material in the thick peat near Seyaha settlement (eastern Yamal Penninsula, northwest Siberia)

| Field nr | Material | Height (asl)/ depth (m) | Lab nr (Hel-) | $^{14}C$ age (BP) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|
| 363-YuV/147 | Black peat | +21.5 /0.5 | 3945 | 7850 ± 150 | –29.4 |
| 363-YuV/150 | Brown peat | +21.2/0.8 | 4061 | 7970 ± 120 | –26.2 |
| 363-YuV/151 | Brown peat | +21.0/1.0 | 4062 | 7760 ± 110 | –26.7 |
| 363-YuV/152 | Brown peat | +21.0/1.0 | 3946 | 8220 ± 140 | –28.3 |
| 363-YuV/154 | Brown peat | +20.8/1.2 | 3947 | 8180 ± 140 | –28.6 |
| 363-YuV/155 | Brown peat | +20.6/1.4 | 4035 | 8230 ± 140 | –26.5 |
| 363-YuV/156 | Brown peat | +20.5/1.5 | 4047 | 7940 ± 150 | –26.6 |
| 363-YuV/158 | Brown peat | +20.3/1.7 | 4063 | 8180 ± 130 | –27.9 |
| 363-YuV/161 | Brown peat | +20.1/1.9 | 4036 | 8110 ± 130 | –28.1 |
| 363-YuV/162 | Brown peat | +21.0/2.0 | 4024 | 8120 ± 120 | –28.8 |
| 363-YuV/163 | Brown peat with twigs | +19.9/2.1 | 4037 | 8210 ± 130 | –28.5 |
| 363-YuV/164 | Brown peat with twigs | +19.8/2.2 | 4064 | 8280 ± 120 | –28.2 |
| 363-YuV/165 | Brown peat with twigs | +19,7/2,3 | 4025 | 8440 ± 130 | –28,7 |
| 363-YuV/137 | Brown peat | +19.5/2.5 | 4060 | 8470 ± 120 | –29.4 |
| 363-YuV/166 | Brown peat, wood, twigs | +19.5/2.5 | 4038 | 8820 ± 140 | –28.5 |
| 363-YuV/168 | Brown peat with wood | +19.4/2.6 | 4065 | 8390 ± 120 | –27.5 |
| 363-YuV/169 | Brown peat with wood | +19.35/2.65 | 4039 | 8260 ± 140 | –29.0 |
| 363-YuV/171 | Birch | +19.35/2.65 | 4048 | 8210 ± 160 | –25.6 |
| 363-YuV/170 | Brown peat with wood | +19.32/2.68 | 4040 | 8520 ± 130 | –28.8 |
| 363-YuV/172 | Brown peat with wood | +19.3/2.7 | 4026 | 8370 ± 120 | –28.1 |
| 363-YuV/173 | Brown peat with wood | +19.2/2.8 | 4049 | 8240 ± 110 | –28.1 |
| 363-YuV/174 | Black peat with wood | +19.0/3.0 | 4027 | 8330 ± 130 | –28.8 |
| 363-YuV/175 | Black peat with wood | +18.9/3.1 | 4028 | 8180 ± 140 | –28.9 |
| 363-YuV/176 | Black peat with wood | +18.85/3.15 | 4050 | 8130 ± 120 | –26.1 |
| 363-YuV/177 | Chocolate peat | +18.8/3.2 | 4029 | 8320 ± 110 | –29.2 |
| 363-YuV/178 | Chocolate peat with wood | +18.6/3.4 | 4066 | 8290 ± 120 | –29.2 |
| 363-YuV/179 | Wood located vertically | +18.6/3.4 | 4041 | 8610 ± 130 | –28.3 |
| 363-YuV/180 | Chocolate peat | +18.5/3.5 | 3948 | 8490 ± 130 | –29.1 |
| 363-YuV/181 | Chocolate peat with wood | +18.4/3.6 | 4051 | 8350 ± 110 | –28.9 |
| 363-YuV/182 | Wood located vertically | +18.4/3.6 | 4042 | 8400 ± 140 | –28.7 |
| 363-YuV/184 | Wood | +18.35/3.65 | 4030 | 8260 ± 140 | –29.0 |
| 363-YuV/185 | Brown peat | +18.2/3.8 | 4067 | 8320 ± 150 | –27.3 |
| 363-YuV/186 | Brown peat | +18.1/3.9 | 3949 | 8600 ± 140 | –29.1 |
| 363-YuV/133 | Birch | +18.0/4.0 | 3944 | 8740 ± 130 | –27.8 |
| 363-YuV/134 | Peat around the birch | +18.0/4.0 | 4034 | 8790 ± 170 | –28.3 |

We have observed earlier the re-deposition of peat even in autochthonous regime. In autochthonous peat from the upper part of a 12–15 m terrace near the Salemlekabtambda River, the two dates that are older than 11,000 BP occur in the top layer of the peat above the date of 8630 BP (Vasil'chuk and Vasil'chuk 1995, see Figure 2c).

Allochthonous re-deposition of peat is obviously caused by a short-term elevation of water level in a peat bog and the state of the lake's regime. This process led to wash out and removal of older peat along the coast.

### Shchuch'ya Cross-Section

The study of Shchuch'ya cross-section began in 1977. Two $^{14}C$ dates were previously obtained (see Figure 3a): 6140 ± 80 BP (LU-1082) at the top and 7690 ± 110 BP (LU-1081) at the bottom (Vasil'chuk 1992:68). A number of new dates are reported here (see Figure 3b, Table 2). The beginning of peat formation at this locality took place at 7200–7100 BP according to the $^{14}C$ dates and the top layer, which is dated to about 6100 BP. Thus, about 5 m of peat accumulated in about 1000 years.

Table 2 $^{14}C$ dates of organic material in the thick peat of the Shchuch'ya River valley (southern Yamal Peninsula, northwest Siberia)

| Field nr | Material | Height (asl)/ depth (m) | Lab nr | $^{14}C$ age (BP) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|
| 364-YuV/67 | Black peat | +14.3/0.7 | Hel-4138 | 6110 ± 110 | –28.6 |
| 364-YuV/74 | Black peat | +13.6/1.4 | Hel-4139 | 6300 ± 100 | –28.5 |
| 364-YuV/60 | Black peat | +13.2/1.8 | Hel-4137 | 6450 ± 100 | –28.0 |
| 364-YuV/52 | Black peat | +13.0/2.0 | Hel-4136 | 6570 ± 100 | –28.0 |
| 364-YuV/48 | Black peat | +12.3/2.7 | Hel-4135 | 7020 ± 100 | –28.0 |
| 364-YuV/45 | Peat around a birch | +11.4/3.6 | Hel-4133 | 6960 ± 100 | –28.4 |
| 364-YuV/46 | Birch | +11.4/3.6 | Hel-4134 | 7140 ± 100 | –22.7 |
| 364-YuV/80 | Birch | +9.5/5.5 | Hel-4140 | 7420 ± 110 | –26.2 |
| 364-YuV/81 | Birch | +9.5/5.5 | Hel-4141 | 7090 ± 110 | –25.6 |
| 364-YuV/82 | Birch | +9.5/5.5 | Hel-4142 | 7070 ± 120 | –22.1 |
| *AMS data from ice-wedge* | | | | | |
| 364-YuV/168 | Moss | +11.4/3.6 | Hela-262 | 7150 ± 75 | –24.9 |

### The Peat Cross-section Near Labytnangi Town

Ten dates were obtained for this peat profile (Table 3). The thickness of this cross-section is smaller than at the other sites, because this peat grew almost on the boundary of autochthonous organic material formation. Two samples of wood from the bottom layer of the peat were dated to 4840 ± 110 (Hel-4340) and 4690 ± 100 (Hel-4339). Active peat growth ceased at 2300 BP.

Table 3 $^{14}C$ dates of organic material in the peat near Labytnangi town in northwest Siberia

| Field nr | Material | Depth (m) | Lab nr (Hel-) | $^{14}C$ age (BP) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|
| 367-YuV/10 | Peat | 0.2 | 4342 | 2310 ± 80 | –24.9 |
| 367-YuV/11 | Yellow peat | 0.3 | 4343 | 2770 ± 90 | –26.0 |
| 367-YuV/15 | Brown peat | 0.7 | 4344 | 4070 ± 70 | –28.8 |
| 367-YuV/20 | Brown peat | 1.3 | 4345 | 4920 ± 90 | –26.4 |
| 367-YuV/7 | Peat | 1.5 | 4341 | 4670 ± 110 | –27.1 |
| 367-YuV/21 | Brown peat | 1.5 | 4346 | 4410 ± 90 | –27.2 |
| 367-YuV/1 | Wood | 1.8 | 4338 | 4780 ± 120 | –26.4 |
| 367-YuV/2 | Wood | 2.0 | 4339 | 4690 ± 100 | –26.1 |
| 367 YuV/4 | Wood | 1.1 | 4340 | 4840 ± 110 | –26.0 |
| 367 YuV/35 | Peat | 0 | 4347 | Modern | –28.6 |

## STABLE ISOTOPE SAMPLES AND DATES

Stable oxygen isotope measurements on ice samples were performed by E Sonninen at the Mass-spectrometry Laboratory of the Dating Laboratory (Helsinki University), and several deuterium determinations were made by Dr J van der Plicht at the Center for Isotope Research at the University of Groningen and by Prof Dr M Geyh at the Joint Geoscientific Research Institute in Hannover.

Table 4 Oxygen isotope composition of syngenetic ice-wedge ice in the thick peat near Seyaha settlement, northwest Siberia[a]

| Field nr | Height (asl)/ depth (m) | $\delta^{18}O$ (‰)[b] | $\delta D$(‰) | $d_{excess}$ (‰) |
|---|---|---|---|---|
| *Segregated ice from the peat* | | | | |
| 363-YuV/151 | 21.2/0.8 | –12.1 | –101.3 | –4.5 |
| 363-YuV/148 | 21.4/0.6 | –12.5 | | |
| 363-YuV/154 | 20.8/1.2 | –12.5 | | |
| 363-YuV/156 | 20.5/1.5 | –12.93 | –107.7 | –4.3 |
| 363-YuV/159 | 20.2/1.8 | –13.8 | | |
| 363-YuV/163 | 19.9/2.1 | –14.14 | –112.7 | +0.42 |
| 363-YuV/166 | 19.5/2.5 | –14.18 | –112.0 | +1.44 |
| 363-YuV/172 | 19.3/2.7 | –14.6 | | |
| 363-YuV/173 | 19.1/2.9 | –14.27 | –111.2 | +2.96 |
| 363-YuV/178 | 18.7/3.3 | –14.01 | –109.4 | +2.68 |
| 363-YuV/181 | 18.4/3.6 | –13.9 | | |
| 363-YuV/183 | 18.4/3.6 | | –106.5 | |
| 363-YuV/186 | 18.1/3.9 | | –110.7 | |
| *Ice-wedge N 1 (Figure 2a)* | | | | |
| 363-YuV/193 | +21.0/1.0 | –19.3 | | |
| 363-YuV/194 | +20.7/1.3 | | –140.6 | |
| 363-YuV/196 | +20.7/1.3 | | –135.2 | |
| 363-YuV/192 | +20.7/1.3 | –19.5 | –143.4 | +12.6 |
| 363-YuV/198 | +20.7/1.3 | –19.5 | | |
| 363-YuV/197 | +20.7/1.3 | –19.7 | | |
| 363-YuV/196 | +20.7/1.3 | –17.9 | | |
| 363-YuV/195 | +20.7/1.3 | –17.9 | | |
| 363-YuV/191 | +20.3/1.7 | –19.7 | –146.1 | |
| 363-YuV/190 | +19.8/2.2 | –20.1 | | |
| 363-YuV/188 | +19.5/2.5 | –19.8 | | |
| 363-YuV/189 | +19.0/3.0 | –19.1 | –137.6 | +15.2 |
| *Ice-wedge N2 (Figure 2b)* | | | | |
| 283-YuV/5 | +20.5/1.5 | –19.9 | | |
| 283-YuV/4 | +20.0/2.0 | –19.4 | | |
| 283-YuV/2 | +19.0/3.0 | –20.3 | | |

[a] $\delta^{18}O$ analyses were been done at the Isotope Laboratory of Helsinki University (E Sonninen), $\delta^{18}O$ and $\delta D$ at the Center for Isotope Research, Groningen (J van der Plicht) and at Hannover Isotope Laboratory (M Geyh).

[b] $\delta^{18}O$ values in three modern ice wedges from the same area: –18.7, –18.3 and –16.6‰.

The $\delta^{18}O$ values obtained for samples from ice lenses in the frozen peat at Seyaha varied from –14.6 to –12.5‰ (Table 4, previous page). These values are higher (isotopically heavier) than values obtained for Holocene ice-wedges ($\delta^{18}O$ about –17 to –19‰) in this area. This reflects the influence of stable isotope fractionation due to intense evaporation in warm summers during the Holocene Optimum.As shown by Chatwin (1983), even under autochthonous conditions, wash out and break of peat accumulation could occur. The change in type of peat accumulation led to changes in peat composition and influenced oxygen isotope composition. Minimum oxygen isotope values correspond with break of peat accumulation, probable during drainage of bog massive (as described by

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Chatwin, this is fixed foresting of the bog). The drainage of the bog led to its temporary freezing. The forest peat formed on a subaerial frozen surface.

During the field investigation in the Shchuch'ya River valley we assumed that ice wedges, which were located in the underlying lacustrine silt, are relicts from a Late Pleistocene ice-wedge system. The $\delta^{18}O$ values (–20.3‰) show that this assumption may be correct, because $\delta^{18}O$ values for Late Pleistocene ice-wedges near Seyaha were found to be –20 to –20.5 ‰. The structure of the ice in the wedge ice of the lacustrine silt slightly differs from that in the upper ice layers.

The $\delta^{18}O$ value for a sample from structure forming ice in the thick peat in the Shchuch'ya River valley, near Edem'yaha Creek mouth was –14.7‰, i.e. close to the values found for structure-forming ice in the peat near Seyaha settlement. These values differ clearly from $\delta^{18}O$ values for ice wedges.

The $\delta^{18}O$ values obtained for Shchuch'ya syngenetic ice wedges are low in comparison with the values for structure-forming ice in all areas studied. For two upper ice wedges we obtained $\delta^{18}O$ values from –19.8 to –18.2‰, and corresponding $\delta D$ from –151 to –139.6‰. For ice wedges from the underlying lacustrine sandy loam $\delta^{18}O$ values varies between –20.3 and –17.5‰. When these values are compared with values for modern ice wedges in north part of the Yamal Peninsula ($\delta^{18}O$ –16 to –19‰, $\delta D$ = –135.7‰) we conclude that the winters in cold periods of the Holocene Optimum were colder than at present by 1.5–2 °C.

The deuterium excesses of modern (+9.9‰) and Holocene ice wedges (+4.7 to +8.0‰) are close to each other and to the value in precipitation (+10‰). This indicates that the water forming the ice wedges originates from precipitation. The similar isotope composition of ice-wedges at Seyaha and Shchuch'ya cross-sections, even if they are three degrees of latitude apart, is not surprising, because on the Yamal Peninsula isotherms of modern winter and January temperatures are sub-meridional. Evidently, this was the situation on the Yamal Peninsula during the Holocene Optimum. Thus, our results demonstrate a coincidence of isotherm distribution in Holocene and at present.

## DISCUSSION

Based on the investigations of the cross-sections of the Yamal Peninsula presented here three main problems can be discussed. The first is the determination of the timescale and extension of forest advancement in the tundra zone. The second is connected with the accumulation of peat in the tundra area. The third deals with the formation of syngenetic ice-wedges during the Holocene Optimum and, consequently, the prevailing climatic conditions.

### Forest Migration

Evidence for forest advancement far north on the Yamal Peninsula tundra was obtained prior to this investigation. A few rare findings of tree remains in some peats in the valleys of the Yuribey River, the Seyaha River, and the Yer'yaha River are known. The northernmost wood findings from the first valley terrace of the Puhuchayaha River are dated to 8.2 and 6.7 ka BP (No 22 and No 33 in Table 6). However, these findings can be taken as allochthonous and the possibility that they are driftwood deposited in the river valley at high sea level cannot be excluded. In contrast, the wooden layer in Seyaha is undoubtedly autochthonous. It is located at more than 20 m above the level of the Ob Bay and the Seyaha River, and contains different kinds of remains such as roots, branches, trunks with bark and remains of leaves and needles. This indicates that the most likely vegetation was that of open woodland. In depressions protected from wind small woods could exist. The first forest appearance in the Seyaha River valley can be dated to about 9000 BP, according to the oldest date in Seyaha valley (No 6 in Table 6).

Table 5 Oxygen isotope composition of syngenetic ice-wedge ice in the thick peat of the Shchuch'ya River valley, near the Edem'yaha Creek mouth (south of the Yamal Peninsula); $\delta^{18}O$ analyses have been done at Isotope Laboratory of Helsinki University (E Sonninen). $\delta^{18}O$ and $\delta D$ in Hannover Isotope Laboratory (M Geyh)

| Field nr | Height, (asl)/ depth (m) | $\delta^{18}O$ (‰) | $\delta D$ (‰) | $d_{excess}$ (‰) |
|---|---|---|---|---|
| Ice wedge N1(Figure 3) | | | | |
| 364-YuV/79 | +11.4/3.6 | –19.00 | –144.9 | +7.1 |
| 364-YuV/39 | +11.0/4.0 | –17.39 | –139.5 | –0.48 |
| 364-YuV/36 | +11.1/3.9 | –18.8 | | |
| 364-YuV/33 | +11.0/4.0 | –19.3 | | |
| 364-YuV/35 | +11.0/4.0 | –18.45 | –140.9 | +6.7 |
| 364-YuV/19 | +10.5/4.5 | –19.7 | | |
| Ice wedge No 2 (Figure 3) | | | | |
| 364-YuV/100 | +11.6/3.4 | –19.3 | | |
| 364-YuV/95 | +11.5/3.5 | –19.8 | | |
| 364-YuV/97 | +11.5/3.5 | –18.28 | –141.5 | +4.74 |
| 364-YuV/168 | +11.5/3.5 | | –146.7 | |
| 364-YuV/169 | +11.5/3.5 | | –148.8 | |
| 364-YuV/167 | +11.4/3.6 | –19.5 | | |
| 364-YuV/92 | +11.3/3.7 | –19.04 | –144.3 | +8.2 |
| 364-YuV/88 | +10.7/4.3 | –19.5 | | |
| 364-YuV/86 | +10.5/4.5 | –19.7 | | |
| Ice wedge of the lower stage (Figure 3) | | | | |
| 364-YuV/40 | +8.5/6.5 | –20.3 | | |
| 364-YuV/42 | +8.4/6.7 | –18.46 | –138.2 | +8.8 |
| 364-YuV/43 | +8.3/6.8 | –17.46 | –135.9 | +3.68 |
| Modern ice wedge | | | | |
| 364-YuV/176 | +14.4/0.6 | | –135.8 | +9.9 |
| Segregated ice from sandy loam | | | | |
| 364-YuV/44 | +8.3/6.8 | –16.21 | –124.1 | +5.58 |
| Segregated ice from peat | | | | |
| 364-YuV/67 | +14.2/0.8 | –13.42 | –104.0 | +3.36 |
| 364-YuV/69 | +14.0/1.0 | –13.36 | –106.2 | +0.68 |
| 364-YuV/74 | +13.6/1.4 | –14.22 | –108.3 | +5.46 |
| 364-YuV/76 | +13.5/1.5 | –14.11 | –110.4 | +2.48 |
| 364-YuV/52 | +13.0/2.0 | –13.18 | –103.8 | +1.64 |
| 364-YuV/50 | +12.6/2.4 | –10.80 | –98.1 | –11.5 |
| 364-YuV/49 | +12.4/2.6 | –12.88 | –124.1 | +0.24 |

According to the analysis of about 200 $^{14}C$ dates of wood, the time frame for the Holocene Optimum can be set at about 9.0–4.5 ka BP. This period is characterized by forest advancement in the present tundra zone. The oldest time limit of the Holocene Optimum is defined by dates from birch remains in interior areas of Central Yamal to be about 9.1–9.2 ka BP, and dates of about 8.9 ka BP from birch, pondweed (*Potamogeton sp*), and violet *(Viola sp.)* on the Gydan Peninsula. The younger time limit is fixed by the youngest dates from larch remains to about 4.9 ka BP in Upper Yuribey of the Yamal Peninsula, and by a birch sample from the Gydan Peninsula dated to 4.6 ka BP.

Table 6 $^{14}$C dates for wood samples from different sites on the Yamal Peninsula in northwestern Siberia[a]

| Nr (Figure 4b) | $^{14}$C date (BP) | Lab code | Material dated | Site |
|---|---|---|---|---|
| 1. | 9650 ± 40 | LU-781 | Wood | Tanlovayaha River |
| 2. | 9400 ± 160 | LG-30 | Birch leave | Yabroyaha River |
| 3. | 9280 ± 70 | GIN-2442 | Wood | Seyaha River |
| 4. | 9190 ± 80 | LU-1086 | Wood | Nyabyyaha River |
| 5. | 8940 ± 130 | Hel-4058 | Wood | Seyaha Settlement |
| 6. | 8770 ± 230 | LU-1088 | Wood | Tanlovayaha River |
| 7. | 8740 ± 130 | Hel-3944 | Birch | Seyaha Settlement |
| 8. | 8700 ± 500 | MGU-713 | Birch | Yaptiksale Settl. |
| 9. | 8680 ± 120 | LU-1087 | Wood | Baydaratskaya Bay |
| 10. | 8610 ± 130 | Hel-4041 | Wood | Seyaha Settlement |
| 11. | 8600 ± 150 | Hel-4054 | Birch | Seyaha Settlement |
| 12. | 8500 ± 150 | Hel-4052 | Birch | Seyaha Settlement |
| 13. | 8400 ± 140 | Hel-4042 | Wood | Seyaha Settlement |
| 14. | 8390 ± 120 | Hel-4065 | Wood | Seyaha Settlement |
| 15. | 8310 ± 130 | Hel-4053 | Ramules | Seyaha Settlement |
| 16. | 8280 ± 120 | Hel-4064 | Wood | Seyaha Settlement |
| 17. | 8260 ± 140 | Hel-4030 | Wood | Seyaha Settlement |
| 18. | 8250 ± 80 | LU-1139 | Wood | Puhuchayaha River |
| 19. | 8210 ± 160 | Hel-4048 | Birch | Seyaha Settlement |
| 20. | 8180 ± 230 | IPAE-79 | Larch | Khadytayaha River |
| 21. | 8180 ± 40<br>8400 ± 240 | B-6031<br>IPAE-77 | Root | Khadytayaha River |
| 22. | 8179 ± 231 | IPAE-72 | Larch | Khadytayaha River |
| 23. | 8130 ± 120 | Hel-4050 | Wood | Seyaha Settlement |
| 24. | 8040 ± 120 | Hel-4055 | Birch | Seyaha Settlement |
| 25. | 7820 ± 200 | IPAE-74 | Root | Khadytayaha River |
| 26. | 7800 ± 170 | IPAE-73 | Root | Khadytayaha River |
| 27. | 7690 ± 110 | LU-1081 | Wood | Shchuch'ya River |
| 28. | 7460 ± 100 | MGU-714 | Birch | Yuribey River |
| 29. | 7420 ± 110 | Hel-4140 | Birch | Shchuch'ya River |
| 30. | 7140 ± 100 | Hel-4134 | Birch | Shchuch'ya River |
| 31. | 7090 ± 110 | Hel-4141 | Birch | Shchuch'ya River |
| 32. | 7070 ± 120 | Hel-4142 | Birch | Shchuch'ya River |
| 33. | 7020 ± 100 | MGU-712 | Birch | Yuribey River |
| 34. | 6580 ± 60 | LU-1138 | Wood | Puhuchayaha River |
| 35. | 6550 ± 170 | IPAE-75 | Stem | Khadytayaha River |
| 36. | 6140 ± 140 | LU-1082 | Wood | Shchuch'ya River |
| 37. | 5990 ± 80 | Hela-200 | Needles of larch | Seyaha Settlement |
| 38. | 5550 ± 150 | BashGI-63 | Wood | Yuribey River |
| 39. | 5190 ± 60 | LU-1027 | Wood | Shchuch'ya River |
| 40. | 4900 ± 250 | BashGI-67 | Larch | Yuribey River |
| 41. | 4840 ± 110 | Hel-4340 | Wood | Labytnangi town |
| 42. | 4780 ± 120 | Hel-4338 | Wood | Labytnangi town |
| 43. | 4690 ± 100 | Hel-4339 | Wood | Labytnangi town |

[a]After Vasil'chuk (1992) and Vasil'chuk and Vasil'chuk (1995) with addition from Hantemirov and Shiyatov (1999) and results from this paper

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### The Rate of Peat Accumulation

The mean rate of peat accumulation in tundra is usually on the order of 1 m per thousand years. The process of peat growth is not uniform. Periods of active growth alternate with periods of standstill. Even though the peat profiles at Seyaha and Shchuch'ya are dated with a great number of samples, periods with different growth rates cannot be distinguished. The important message is, however, the high mean growth rate observed, which gives information about the warm summer climate in the Holocene Optimum.

### Holocene Climatic Optimum

The isotope and $^{14}C$ data obtained indicate that the climate of the Holocene Optimum in the northwestern Siberia was highly continental. During the Holocene Optimum summers were warmer by 1–3 °C and winters were colder by 2–3 °C. This led to frost cracking and ice wedge formation in mineral alluvial, marine, and organic sediments. These results contradict the previous opinions claiming that both summer and winter temperatures were higher during the Holocene Optimum.

The ratio of winter and summer temperatures resulted in shrinking (as compared to Late Pleistocene) of permafrost zone area in western Siberia. Ground temperatures between 65–66°N were close to 0 °C, and at 66 °N, as a rule, colder than –5 °C.

More than 100 $^{14}C$ dates obtained from the peats with large ice wedges provide evidence for fast peat accumulation (Tables 1,2,3, and 6). AMS dating of a moss fragment from the ice-wedge body at the Shchuch'ya cross-section points to the formation of ice wedges being as old as 7000 BP (Figure 3) during the extreme phase of the Holocene Optimum. The Holocene Optimum in the Western Siberia appeared as relatively warm summers, with the advance of larch and birch up to 71–72°N, displacement of the discontinuous permafrost, and simultaneous formation of syngenetic ice wedges close to discontinuous permafrost zone. It was the time of considerable changes in the structure of permafrost zone of western Siberia when discontinuous permafrost zone narrowed. However, the continuous permafrost zone was stable and similar to the present one. Data obtained indicate intense ice wedge growth in peaty sediments right up to 67°N in the northwestern Siberia, and at the same time very fast accumulation of peat.

Winter temperature distribution was similar to the present ones in the Yamal and the Gydan Peninsulas (Figure 4). Isotherms were sub-meridian, January temperatures in axial parts of the Yamal Peninsula in the south and north were approximately equal and at about –26...–28 °C (at present they are –24...–25 °C). In eastern Gydan Peninsula they were down to –28... –30 °C (at present they are –28... –29 °C).

## CONCLUSIONS

The new $^{14}C$ dates from peat profiles at Seyaha, Shchuch'ya and Labytnangi indicate that: 1) the vegetation patterns within the tundra regions in the Early Holocene differed considerably from the present, in this period forest migrated far to the north in the Yamal Peninsula, 2) summer warming caused foresting of tundra, 3) simultaneously, the winters were colder and the climate was more continental than at present, 4) rapid peat accumulation (4–5 m per 1000 years) occurred during this period, and, 5) simultaneously with the peat accumulation in summer, freezing and formation of syngenetic ice-wedges took place in winter.

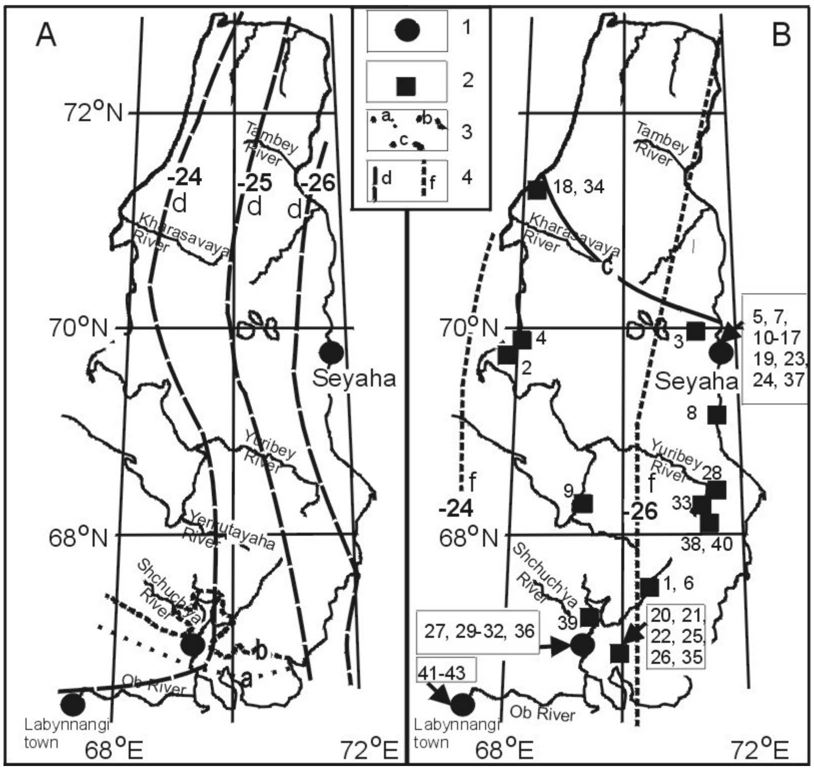


Figure 4 The forest immigration in Yamal tundra during the Holocene Optimum (B) reconstructed by $^{14}C$ dated wood (site numbers refer to Table 6) compared with northern limit of forest (taiga) at present (A). 1. Location of peat sites with wood remains, studied in detail in this paper; 2. Location of sites with wood remains; 3. Northern limit of present forest (a), present separate trees in river valleys (b) and the Holocene Optimum forest (c); 4. Modern (d) and the Holocene Optimum (f) mean January surface air temperature, isotherms for –24, –25, and –26 are indicated.

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