Holocene vegetation history from the Salym-Yugan Mire Area, West Siberia

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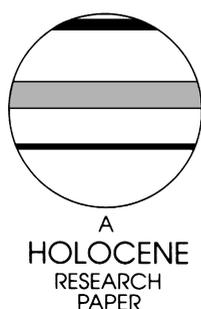
Abstract: The pollen stratigraphy of an ombrotrophic patterned ridge-hollow raised bog in the Salym-Yugan Mire Area in boreal West Siberia (60°10′N, 72°50′E) covers the entire Holocene period. Pollen data from three parallel peat cores suggest that, contrary to previous assumptions, *Betula* forests did not spread into tundra until the Boreal period (9000–10 000 cal. BP). After 9000 cal. BP, *Pinus sylvestris* and *Picea abies* forests displaced *Betula* forests in the area and dominated until 4100–4300 cal. BP, when *Picea* decreased considerably due to a climatic change and *Pinus sylvestris* became the most abundant tree species. Average pollen influx estimates during the wooded period, from about 9000 cal. BP onwards, were 5600–6350 grains cm^{-2} yr^{-1}, similar to pollen-trap estimates from boreal coniferous forests.

Key words: Paleoecology, palaeoclimate, vegetation history, boreal region, raised bog, mire, West Siberia, Holocene.

Introduction

West Siberia refers to the area between the Ural mountains and the Yenisey river, largely occupied by the Ob-Irtysh basin, lying 25–95 m above sea level. Mires of the West Siberian lowland cover 50–75% of the land (Romanova, 1967) and provide about 60% of all the peat deposits of the former Soviet Union and 40% of the global peat deposits (Walter, 1977). Knowledge of the vegetation history of this vast West Siberian area is important for a better understanding of climatic changes in the Northern Hemisphere during the Holocene. Present knowledge is based mostly on data collected from sites along the Ob and Irtysh rivers (Khotinskiy, 1984), and the palaeoclimatic reconstructions are based on only a few dated pollen diagrams (Velichko *et al*., 1997; Peteet *et al*., 1998; Khotinskiy, 1984; Blyakharchuk and Sulerzhitsky, 1999). Our aim is to reconstruct the Holocene vegetation history in the middle boreal vegetation belt from peat cores from the Salym-Yugan Mire.

Study area

The study area is situated in the Khanty-Mansi Autonomous District of the Tyumen Region (60°10′N, 72°50′E), in the central part of West Siberia, Russia (Figure 1). Salym-Yugan Mire is part of the Great Vasyugan Mire, which covers an area of 5.4 million hectares (Botch and Masing, 1983). The climate is continental, with mean January and July temperatures of –22°C and +16°C. The mean annual temperature is –3.2°C and the annual precipitation 400–500 mm (Russia's Weather Server, 1999). The study area is situated about 200 km south of the permafrost limit (Baulin and Danilova, 1984).

The study area is covered with wooded or open mires with islands of dry uplands. The wooded islands and dry soils on river banks comprise about 20% of the land area. The landscape is almost flat, and the absolute heights in the area range between 58 and 65 m a.s.l. Latin names of the tree species are according to Hämet-Ahti *et al*. (1998). The wooded mires are dominated mainly by Scots pine (*Pinus sylvestris* L.) with scattered Siberian pines (*Pinus cembra* L. ssp. *sibirica* (Du Tour) Krylov). The forests on dry uplands consist of pure young *Pinus sylvestris* stands. Birch (*Betula pubescens* Ehrh.) forests and a few large Siberian pines are found along riverbanks. Siberian fir (*Abies sibirica* Ledeb) larch (*Larix sibirica* Ledeb) and spruce (*Picea abies* L. Karst. ssp. *obovata* (Ledeb) Hulten) are completely absent on the dry uplands in the study area. However, *Picea abies* and *Abies sibirica* are relatively abundant about 10–20 km north of the study area, where dry uplands are more prevalent in the landscape. Paludification has been a strong process since the end of the last

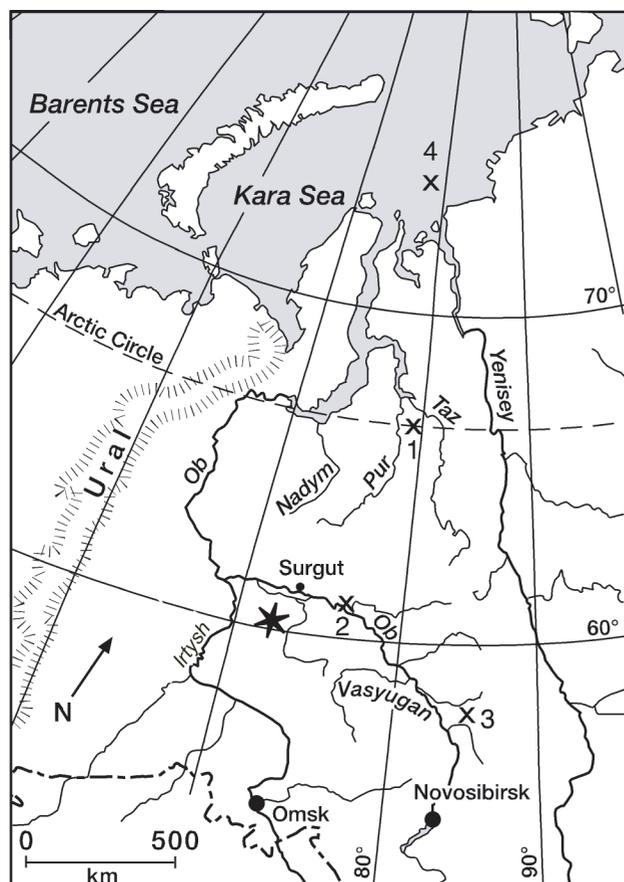*Author for correspondence (e-mail: aki.pitkanen@joensuu.fi)

Figure 1 Location of the study area (indicated with an asterisk). Sites referred to in text indicated by crosses (x). (1) Pur-Taz site. (2) Niznevartovsk site. (3) Bugristoye bog. (4) Sverdrup island.

Figure 2 Aerial view of the study site and the coring points (A, B and C). The point studied by Liss and Berezina (1981) is indicated by L. (Photograph provided by D.L. Varlyguin.)

glaciation (Walter, 1977). However, the mire has expanded slightly during recent millennia and was nearly to its present width 7000–8000 years ago (Turunen *et al*., 2001).

According to Grosswald (1980; 1998), the study area was covered during the last glaciation by an ice-dammed lake, which was formed by an ice sheet centred in the Kara Sea area. The latest studies (Mangerud *et al.,* 1999; Svendsen *et al.,* 1999) indicate that the maximum extent of the Eurasian ice sheet in the Kara Sea region during the Late Weichselian has been overestimated and that the great rivers of West Siberia had free outlets to the Kara Sea. However, the existence of ice-dammed lakes during earlier phases of Weichselian glaciation is possible.

Material and methods

Three peat cores were taken from the central plateau along a transect at 800 m intervals in September 1998 with a Russian side-cutting peat sampler 50×500 mm (Jowsey, 1966). Two peat cores (4.54 and 5 m long) with radiocarbon datings from several depths were chosen for pollen analyses (cores A and B). In addition, pollen samples were analysed from the basal peat of core C, which had the oldest radiocarbon age (Figure 2). Peat subsamples of 1 cm^3 were taken from the basal 10 cm at continuous 1 cm intervals, at 2 cm intervals between 10 and 20 cm from the base and at 10 cm intervals for the rest of the cores. The pollen samples were weighed and treated according to procedures described by Berglund and Ralska-Jasiewiczowa (1986), excluding sieving of samples. A minimum of 200 arboreal pollen grains were counted, but in a few samples poor in pollen the minimum number of tree pollen counted was 50 pollen grains. The relative pollen values of tre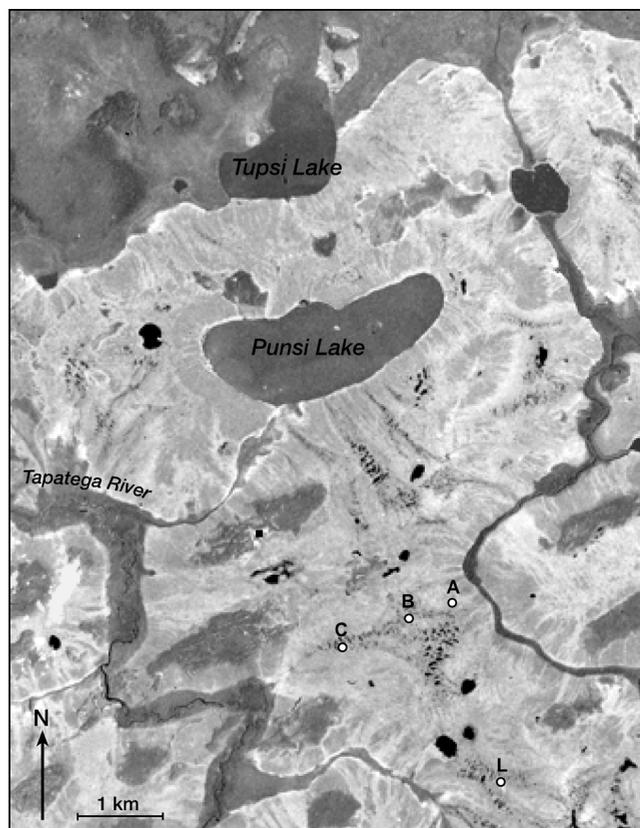es and herbs were based upon the total pollen sum including all identified pollen taxa and unidentified pollen (Varia). Spores were excluded from the total pollen sum. Spore values were based on the sum of spores (excluding *Sphagnum*) and total pollen. *Sphagnum* values were calculated from the sum of *Sphagnum* spores and total pollen. For absolute pollen values, the volume of pollen samples was based on the volume-mass samples of the peat cores (Turunen *et al*., 2001). Pollen influx values were calculated according to the formula $(C*L)/T$, in which C = average pollen concentration of samples (pollen grains cm^{-3}) between two radiocarbon datings, L = length (cm) of the sequence between datings, and T = time period (cal. BP yr) in the peat sequence.

The treeless vegetation phase is evident in the pollen assemblages. However, the long-distance transport of arboreal pollen (AP) and the weak pollen production of non-arboreal pollen (NAP) may obscure the interpretation of the data (Birks and Birks, 1980). Studies from tundra areas indicate that about 60–25% of the pollen consists of NAP taxa (including Cyperaceae and Poaceae as major taxa), reflecting a treeless vegetation (Aario, 1940; 1943; Ritchie, 1974; Ritchie and Lichti-Federovich, 1967; Lichti-Federovich and Ritchie, 1968). In forest tundra areas, which are open wooded landscapes, the proportion of NAP is lower (18–12%) (Ritchie, 1974; 1977; Lichti-Federovich and Ritchie, 1968). In this study, AP values less than 25% of the total pollen are interpreted to indicate treeless vegetation.

Peat samples taken for ^{14}C dating (Table 1) were analysed at the University of Helsinki Dating Laboratory. All results were corrected for isotopic fractionation based on the ^{13}C values given in Table 1. Radiocarbon ages were converted to calendar years using CALIB 3.0.3 (Stuiver and Reimer, 1993). Two additional datings (Table 1) from the marker level of an abrupt increase of pine and birch pollen in the study area were made by Liss and Berezina (1981).

The names of chronozones and their ages (converted to calibrated radiocarbon years) used in this paper follow Mangerud

Table 1 Peat radiocarbon datings from the studied points. Two additional datings (TA-933 and TA-934) are based on marker levels of abrupt increases in birch (1) and pine (2) pollen (Liss and Berezina, 1981). Peat constituents: C = *Carex*; Er = *Eriophorum*; Eq = *Equisetum*; L = wood; Mn = *Menyanthes*; N = shrub; S = *Sphagnum*; Sch = *Scheuchzeria*; H = degree of decomposition in von Post's (1922) 10-grade scale. Calendar date refers to the calibrated calendar years (Stuiver and Reimer, 1993)

Site	Sample depth (cm)	Peat material	$\delta^{13}C$	^{14}C date (yr BP)	Calibrated age (yr BP)
A	95–100	Sch-C-S, H3	–23.1	850 ± 80	780
	195–200	N-Er-S-C, H4	–25.9	3690 ± 120	4110
	295–300	N-Sch-S-C, H3	–24.9	5530 ± 140	6350
	410				9000 2)
	420				9910 1)
	490–495	Mn-Eq-C,H6	–28.5	9420 ± 110	10430
	495–500	Mn-Eq-C, H6	–28.6	8940 ± 130	10000
B	95–100	S-C, H6	–26.1	1760 ± 80	1740
	195–200	N-Er-C-S, H5	–26.7	3860 ± 100	4310
	245–250	Sch-C-S, H5	–27.2	5550 ± 100	6360
	295–300	S, H4	–26.6	6220 ± 130	7210
	345–350	Er-C-S, H4	–26.2	6980 ± 110	7805
	393				9000 2)
	413				9910 1)
	444–449	N-S-C, H4	–28.4	9640 ± 120	10945
	449–454	N-S-C, H4	–28.7	9250 ± 110	10330
C	310				9000 2)
	330				9910 1)
	330–335	N-C, H6	–27.8	10370 ± 130	12305
	335–340	N-C, H6	–27.7	9530 ± 100	10835

et al. (1974). The limits of chronozones *sensu* Mangerud *et al*. (1974) are not fully equivalent with those of biozones used in Russian literature (Khotinskiy, 1984).

Results and interpretation

The pollen stratigraphy of cores A and B is presented in Figures 3 and 4. The pollen diagram from the base of core C is shown in Figure 5. According to the main components and changes in pollen assemblages, the stratigraphy can be divided into 5 zones.

NAP zone
NAP taxa dominate between the base of peat and a major increase in *Betula* pollen (Figures 3 and 4). In core C, the *Betula* pollen increases 10 cm from the base of peat, suggesting a considerably lower peat-accumulation rate in the basal level compared with cores A and B (Figure 5). The increase in *Betula* pollen at another site is dated to 9910 cal. BP (Table 1).

The most abundant taxon is Cyperaceae, which increases in cores A and B from about 20% in the basal peat to 60–80% near the upper limit of the NAP zone. In core B, the ratio of Cyperaceae to other NAP taxa indicates that Cyperaceae pollen was twice as abundant in the NAP and AP-NAP zones compared to the zones above. Also, the values of other NAP taxa are higher in this zone, including *Salix*, *Artemisia*, Chenopodiaceae, Asteraceae, Cichoriaceae, Poaceae, Rosaceae, Caryophyllaceae and undefined herbs (Varia). They are most abundant in the basal 10 cm of cores A and B (Figures 3 and 4). The ratio of Poaceae to AP pollen indicates that there are on average 40 Poaceae pollen grains to 100 AP pollen in this zone (Figure 6). That is about 30 times higher in value than in zones above. The AP percentage of total pollen ranges between 10 and 48%, and the averages in cores A, B and C were 37%, 29% and 28%, respectively, suggesting

an open treeless landscape. If Cyperaceae is excluded from the pollen sum, the AP percentage value is 63–65%. *Pinus* pollen was almost absent in this zone except in core A, where a small amount of pine pollen was found in all samples. In core A, mineral particles were abundant in the bottom 30 cm of peat, but in cores B and C only in the 3 cm layer above the base. Mineral matter and relatively abundant *Pinus* pollen suggests a mixing of peat in core A that is not seen in cores B and C. The mixing may have been caused by cryogenic processes in permafrost soil (see Velichko and Nechyev, 1984). While the values of *Picea* and *Betula* were between 20 and 40%, relative AP values calculated versus NAP indicate significant long-distance transport of AP taxa (Figure 6). *Larix* pollen values up to 3.5% were found. The average *Larix* values in cores A and B were 0.7 and 0.9%, respectively (Figures 3, 4 and 5).

Ephedra pollen was present in a few samples in this zone, but was absent in higher peat layers. *Filipendula*, Rubiaceae, Apiaceae and Lamiaceae pollen were found in this zone, mostly in the lower samples. Values of *Equisetum* and Polypodiaceae spores were considerably higher than in the pollen zones above. However, in relation to NAP, *Equisetum* and Polypodiaceae in the NAP zone are equally abundant as in other zones, suggesting that the higher values are caused by the low representation of AP taxa. Bryales spores were not quantified but were very abundant in several samples. In higher zones, the Bryales spores were generally much less abundant.

AP-NAP zone
This zone is defined between the stratigraphic level at which AP percentages reach an average level of 90%. The lower limit is defined by an abrupt increase in *Betula* and *Pinus* pollen (Figures 3, 4 and 5). The amount of *Picea* pollen apparently begins its increase prior to *Betula* and *Pinus* pollen as indicated by the *Picea*/NAP pollen ratio (Figure 6). There is a decline in *Picea* pollen values between 413 and 393 cm in core B, and corresponding declines are also found in cores A and C (Figures 3, 4 and 5). The continuous presence of Ericaceae pollen begins in this zone at the level where *Betula* pollen increases. The relative abundance of NAP pollen and spores declines due to an increase in AP taxa (see Figure 6).

AP1 and AP2 zones
The AP1 zone in core A (380–310 cm) and core B (383–273 cm) is similar to the AP2 zone in both cores and differs only in the virtual absence of *Abies* pollen. *Abies* pollen is found continuously in core A at 310 cm and in core B at 273 cm. The establishment of the *Abies* pollen curve in core A occurred about 7500 cal. BP, as extrapolated from the radiocarbon age at the 300 cm level. The corresponding age estimate for the *Abies* curve in core B is 7700 cal. BP (Figures 3 and 4). The age of the lower limit of the AP1 zone is about 8700 cal. BP. The abundance of *Picea* pollen, with values up to 20%, is characteristic of this zone, indicating that *Picea* was abundant in the study area.

AP3 zone
Decreasing *Picea* pollen values begin at the 2 m level in cores A and B (4100–4300 cal. BP) and decline to less than 5%. At the same time, *Pinus sylvestris* and *P. cembra* pollen values increased and *Betula* pollen decreased. The decrease in *Betula* pollen values is probably caused by an increase in *Pinus* pollen, since the *Betula*/NAP ratio showed no decrease in *Betula* pollen (Figure 6).

In the AP3 zone the average AP percentage increased slightly in core B, from the previous 90.7% (NAP2 and NAP1 zones) to 94.3%. The difference is highly significant on Student's test (t = 4, df:28, significance level 0.01). The change may be due to a decrease in Cyperaceae pollen from an average 3.5% in the AP2 and AP1 zones, to 1.1% at the limit of the AP3 zone. Since the
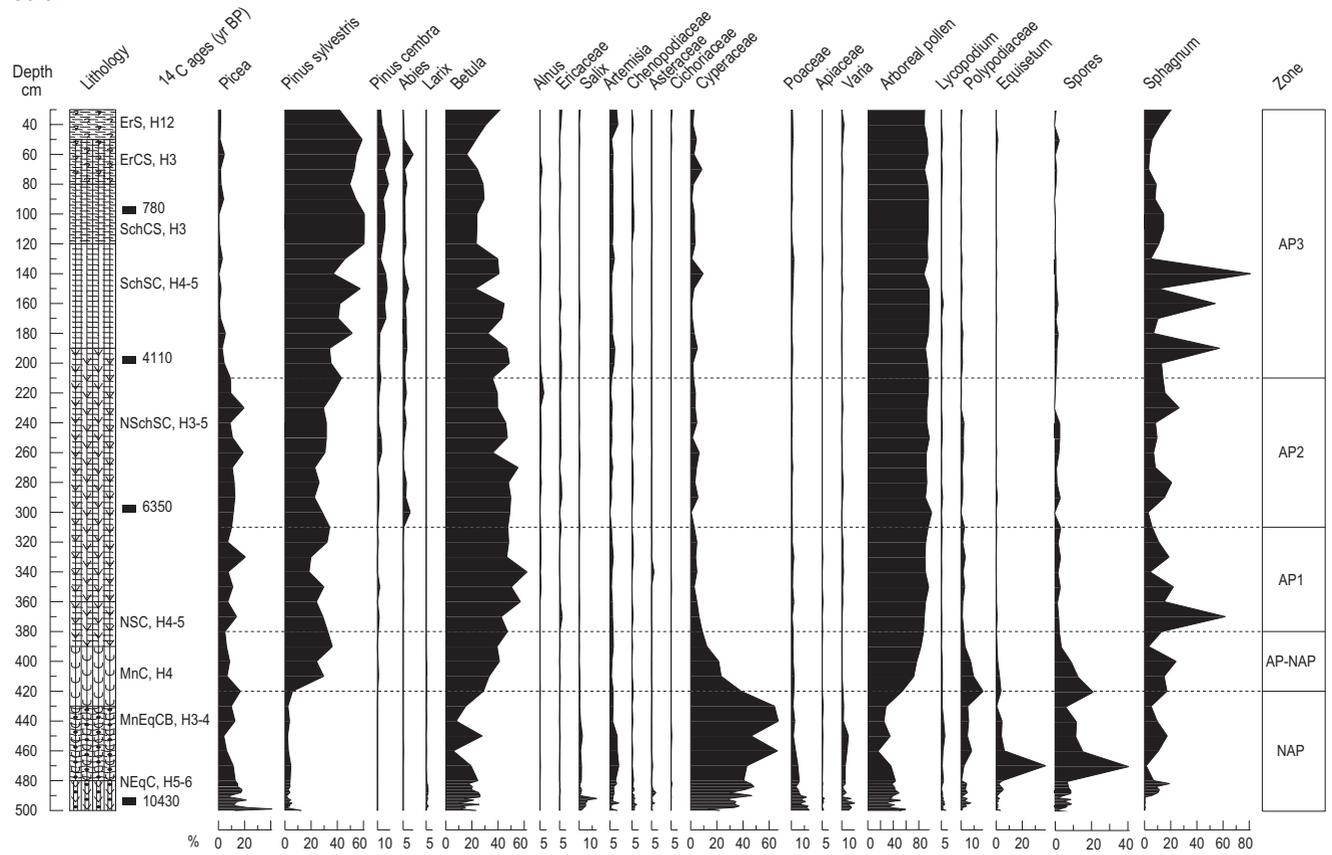
Core A

Figure 3 Relative pollen diagram of selected taxa from core A. Peat constituents: C = *Carex*; Er = *Eriophorum*; Eq = *Equisetum*; L = wood; Mn = *Menyanthes*; N = shrub; S = *Sphagnum*; Sch = *Scheuchzeria*; B = *Bryales*; H = degree of decomposition in von Post's (1922) 10-grade scale.
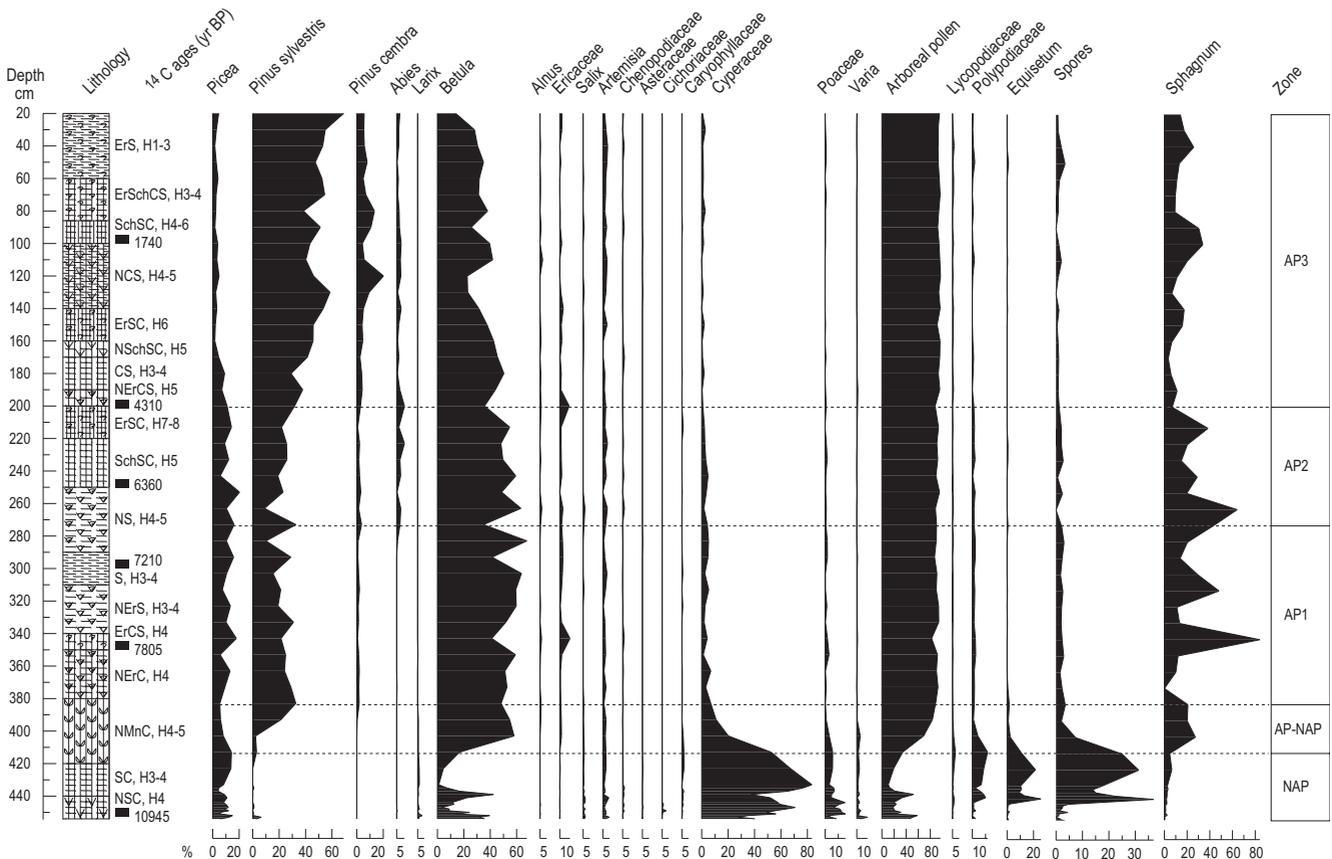
Core B

Figure 4 Relative pollen diagram of selected taxa from core B. See Figure 3 for explanation of peat type symbols.
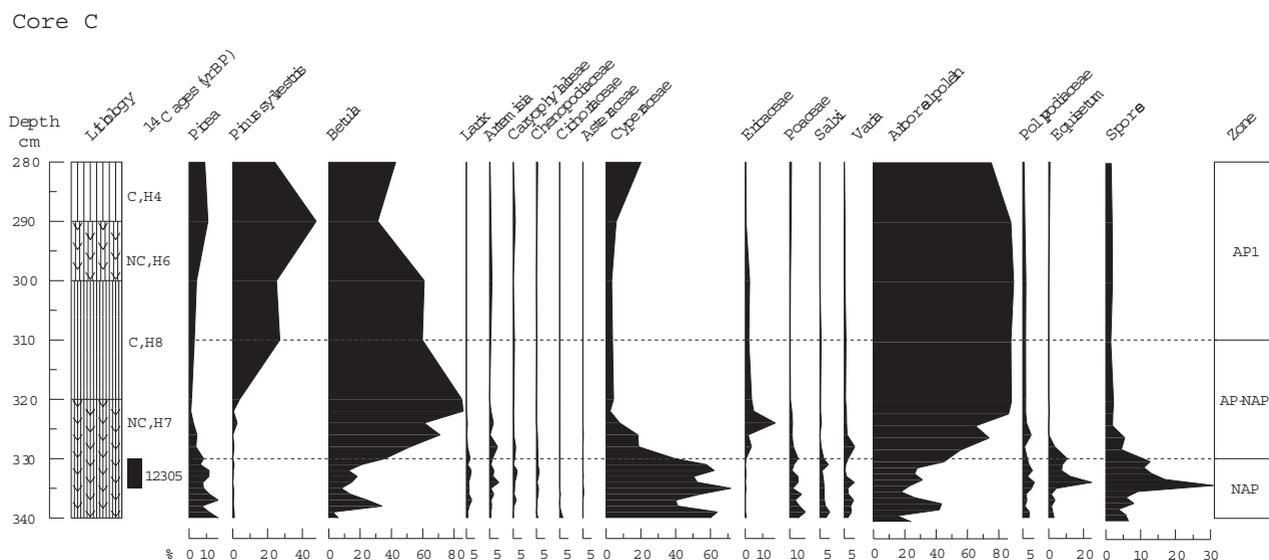
Figure 5 Relative pollen diagram of selected taxa from core C (280 cm to bottom). See Figure 3 for explanation of peat type symbols.
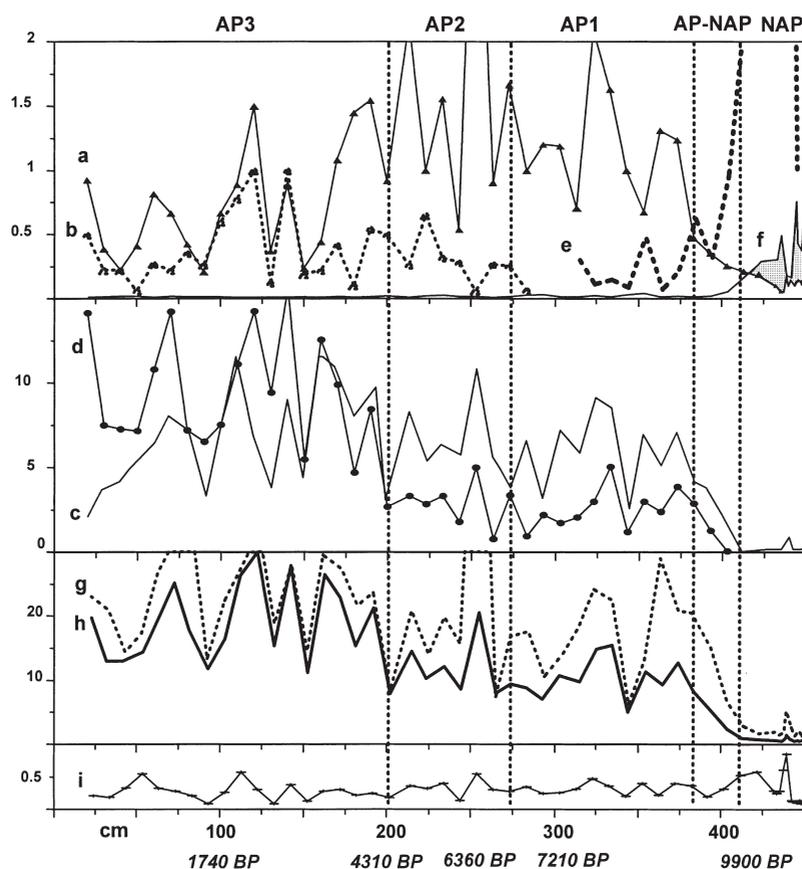

Figure 6 Ratio of *Picea*/NAP (a), *Abies*/NAP (b), *Betula*/NAP (c) *Pinus*/NAP (d), *Picea*/spores (*Equisetum*, Polypodiaceae and Lycopodiaceae) (e), Poaceae/AP (f), AP/NAP (Cyperaceae excluded) (g), AP/NAP (h) and NAP/spores (excluding *Sphagnum*) (i). The average *Picea*/NAP value between 1740 cal. BP and present was 0.6 (s.e. ±0.1, s.d. 0.4), between 4310 and 9000 cal. BP 1.4 (s.e. ±0.2, s.d. 0.8), prior to 9000 cal. BP 0.14 (s.e. ±0.02, s.d. 0.08). Although values after 1740 cal. BP probably indicate transport of spruce pollen from sources at least several kilometres from the site, *Picea*/NAP values prior to 9000 cal. BP are considerably lower, suggesting the absence of spruce in the landscape. Increasing values of *Picea*/NAP ratio from 450 to 383 cm without any fluctuations suggest that spruce was possibly approching the study area during the Boreal period. The data are from core B.

Cyperaceae/NAP ratio indicates that Cyperaceae pollen decreased to half from the previous level in relation to other NAP taxa, the decrease in Cyperaceae percentage values indicates an actual decline in its abundance. However, in core A there is no corresponding change in the average AP and Cyperaceae percentages at the AP3 zone limit. The absence of this change in core A indicates that the change in core B must be local.

Pollen concentration and influx

The pollen concentration values are highly variable between samples (Figure 7). During the wooded phase (after 9000 cal. BP) pollen concentrations ranged between 13410 and 908510 grains/cm^3. In the NAP zone, the concentrations were between 4660 and 760550 grains/cm^3. Pollen influx estimates are shown in Figure 8. The average influx values from the present to 9000
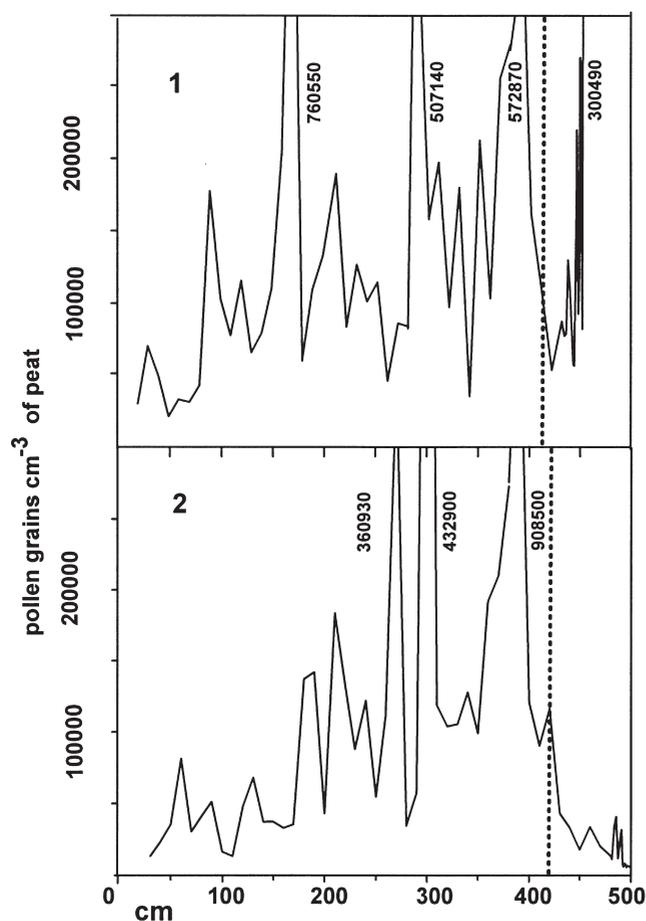
Figure 7 Pollen concentration curves of cores A (2) and B (1). Abrupt increase in *Betula* pollen (about 9900 cal. BP, the upper limit of the NAP zone) is indicated with a dotted line.
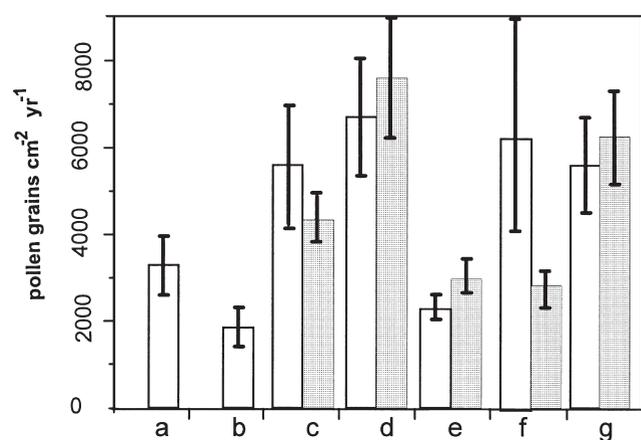

Figure 8 Average pollen influx values calculated from cores A and B. Estimates calculated from core B are indicated in the grey columns. The estimates are calculated for the following time periods. (a) Present to 780 cal. BP. (b) 780–4110 cal. BP. (c) 4110–6350 cal. BP. (d) 6350–9000 cal. BP. (e) 9000–9910 cal. BP. (f) prior to 9900 cal. BP. (g) Present to 9000 cal. BP.

cal. BP in cores A and B were 5600 grains cm^{-2} yr^{-1} and 6350 grains cm^{-2} yr^{-1}, respectively. The average influx estimate for NAP taxa between the present and 9000 cal. BP is only about 500 grains cm^{-2} yr^{-1}.

Discussion

Age of the basal peat and absolute pollen values

The NAP zone covers the Preboreal (about 10 000–11 000 cal. BP) period and the zone's upper limit is in the early Boreal period (about 10 000–9500 cal. BP). The basal peat datings in cores A and B are only slightly different from the dating for the stratigraphic upper level of the NAP zone from another site (Table 1). Because there is 40–80 cm peat between the upper level of the NAP zone and the base of peat in cores A and B, the radiocarbon ages for the basal peat of cores A and B may be too young. Peat radiocarbon ages that are too young are fairly common and are caused by the downward transport of younger carbon by roots or water flow (Tolonen *et al.*, 1992). Since the pollen stratigraphy of the basal peat in all cores suggests corresponding ages, possibly the basal peat in cores A and B are as old as the base of core C. The basal peat layers of core C date back to Lateglacial times, to the Younger Dryas period (about 11 000–13 000 cal. BP). The relatively abundant NAP taxa in the NAP zones of cores A, B and C correlate well with pollen assemblages between 8600 and 10 600 radiocarbon years BP at a site near Niznevartovsk, about 200 km northeast of our study site (Khotinskiy, 1984). Pollen influx estimates based on radiocarbon datings are 6300 grains cm^{-2} yr^{-1} for the core A and 3900 grains cm^{-2} yr^{-1} for the core B NAP zone. One could assume that cores A and B are of the same age as suggested by the pollen stratigraphy. If the pollen influx estimate for core A is calculated according to the radiocarbon age of the base of core B, the pollen influx estimate for the NAP zone of core A is about 3000 grains cm^{-2} yr^{-1}. The age of the basal peat in cores A, B and C may also be considerably older than radiocarbon ages suggest. High NAP percentage values and AP/NAP ratio (Figures 3, 4, 5 and 6) indicate open treeless vegetation, with most of the NAP consisting of dominating elements of open tundra pollen assemblages (Cyperaceae, *Salix* and Poaceae) (Gajewski, 1995; Gajewski *et al.*, 2000; Prentice *et al.*, 1996). Pollen trap studies indicate very low total pollen influx (less than 500 grains cm^{-2} yr^{-1}) under open tundra conditions (Hicks, 1986). Therefore, the high pollen concentration values in the NAP zone would suggest a much higher age for the basal peat than suggested by the radiocarbon ages. However, peat initiation data from other sites of West Siberia suggest that peat accumulation started not earlier than 9000–10 600 radiocarbon years BP in this region (Peteet *et al.*, 1998).

Absolute pollen values are not determined in Siberian mires. The maximum pollen concentration values reported by Jasinski *et al.* (1998) at a site in the Lena river valley (open larch forest tundra) are at the same magnitude as values from our study site, and the minimum values (3400–12 000 grains cm^{-3}) are of same magnitude as the minimum values in the NAP zone.

Interpretation of tree pollen percentage values

The AP values ranging 20–60% in cores A, B and C in the NAP zone (Figures 3, 4 and 5) correspond to values found at tundra areas (Aario, 1940; 1943; Ritchie, 1974; Ritchie and Lichti-Federovich, 1967; Lichti-Federovich and Ritchie, 1968) and thus indicate treeless vegetation. In treeless regions, relative AP values can be high due to long-distance transport of tree pollen and to poor pollen production of local NAP taxa. For example, in Arctic Sverdrup Island, 100 km north of the coast of the Kara Sea, the highest *Picea* values are about 20% and highest tree *Betula* values 20–30% of total pollen in peat samples (Andreev *et al.*, 1997). At Somerset Island, Canada (about 1000 km north from the forest limit), long-distance pollen comprises 20–40% of total pollen (*Picea* 5–25% and *Betula* 5–20%) in surface lake-sediment samples (Gajewski, 1995). The most important local taxon in Somerset Island is Cyperaceae, which comprises 10–60% of pollen in surface-sediment samples. Poaceae and *Oxyria digyna* pol-

len are also important local taxa in surface-sediment samples, comprising 5–40% of pollen. At Banks Island (western Arctic Canada), about 600 km from the northern timber limit, there is up to 50% long-distance pollen (*Alnus* 0–20%, *Picea* <5–30% and *Pinus* 0–10%) in lake-sediment cores covering the Holocene period. In Banks Island pollen, shrub birches (5–40%), Cyperaceae (10–60%) and Poaceae (5–60%) are the most important local taxa (Gajewski *et al.,* 2000). The lake-sediment pollen values are similar to pollen trap values from tundra areas (Ritchie and Lichti-Federovich, 1967). However, one could suspect that low AP values in our data are result of high deposition of *in situ* Cyperaceae pollen, because remains of sedges are important, or even a major constituent of the peat matrix in the NAP zones of cores A, B and C. The lake-sediment data quoted above indicate that very high Cyperaceae percentage values are common at tundra sites. In eastern Finland, Cyperaceae percentage values up to 90% dating back prior to 10 000 cal. BP were reported from lake sediments (Bondestam *et al.,* 1994). Thus, the high Cyperaceae percentages in the NAP zone are necessarily not of *in situ* origin or due to the mire environment. Furthermore, the AP/NAP ratio calculated without Cyperaceae, and the Poaceae/AP ratio (Figure 6), clearly indicate that AP is scarce in relation to dry-land NAP taxa prior to 9900 cal. BP.

AP percentage values in the NAP zone of cores A, B and C are similar to those found at Banks Island and Somerset Island (Gajewski, 1995; Gajewski *et al.,* 2000), suggesting that the distance to the tree-line may have been very great. The very low values of *Betula*/NAP ratio (Figure 6) prior to 9900 cal. BP suggest that the peaks in *Betula* values as high as 40% are also due to long-distance transport (Figure 6), although a considerable proportion of *Betula* pollen in the NAP zone may originate from local shrub birches (*Betula nana*). In Sverdrup Island (Andreev *et al.,* 1997), situated 300–400 km north from the present pine limit, there is about 20% *Pinus* pollen in the surface soil, but in samples dating back to 9770–11640 radiocarbon yr BP *Pinus* pollen is almost absent. Therefore the virtual absence of *Pinus* pollen and low *Betula*/NAP values suggest that those species may have been present at a very long distance from our study site prior to 9900 cal. BP. Macrofossil data from 400 km north of our study site indicates that tree birches were present there about 10 000 cal. BP (Peteet *et al.,* 1998). At a site 1000 km south, *Pinus* pollen was virtually absent prior to 8100 cal. BP (Kremenetski *et al.,* 1997). As well, at Bugristoye bog, 600 km southeast of our study site, *Pinus* pollen values were low prior to 9500 cal. BP (Blyakharchuk and Sulerzhitsky, 1999). The data above suggest that *Pinus sylvestris* and *P. cembra* forests were absent in large parts of West Siberia during the Preboreal and early Boreal period and were only beginning to expand across the area.

Despite the high *Picea* pollen percentages (10–20% in most samples) in cores A, B and C, the low values of the *Picea*/NAP ratio suggest long-distance transport of *Picea* pollen at least prior to 9900 cal. BP (Figure 6). Also, the ratio of spores (excluding *Sphagnum*) to *Picea* pollen suggests long-distance transport of spruce pollen (Figure 6). Since the spores (excluding *Sphagnum*)/NAP ratio suggests that the influx of spores has remained at a low, relatively constant level during the Holocene, the spores/*Picea* ratio may reliably indicate low influx of *Picea* pollen in the NAP zone. *Picea*/NAP ratio values of the same magnitude as prior to 9900 cal. BP (Figure 6) can be calculated from pollen data several tens of kilometres north of the *Picea* limit in northern Finland (Hyvärinen, 1975), but also from pollen data from Somerset Island (Gajewski, 1995), hundreds of kilometres north of the spruce forests.

Larix pollen percentages are not proportionate to its real abundance, and even very low values may indicate its presence (Clayden *et al.,* 1997). Clayden *et al.* (1997) estimated a *Larix* pollen influx of 100–600 grains cm^{-2} yr^{-1} at a larch forest tundra site in Taimyr peninsula during the past 6000 years. The data of Clayden *et al.* (1997) suggest a *Larix*/NAP ratio between 0.2 and 0.8. At our study site, the values of *Larix*/NAP ratio (mean = 0.017, SD = 0.019) in the NAP zone were 10 times lower than the lowest *Larix*/NAP values estimated from the data of Clayden *et al.* (1997), suggesting long-distance transport of *Larix* pollen to our study site. However, only macrofossil studies can prove with certainty whether larch trees were present in the study area.

Treeless vegetation prior to about 9900 cal. BP in large regions of West Siberia?

Contrary to our results, Russian literature (Blyakharchuk and Sulerzhitsky, 1999) suggests that middle West Siberia was covered with *Picea-Larix-Betula* forest tundra, and in the southern forest zone there were open *Betula* and *Picea-Betula* forests during the Preboreal period. Also, *Betula* forest-steppe vegetation is assumed to have been an important part of the present middle taiga area. According to earlier Russian vegetation estimates (Grichuk, 1984), trees were present during the last glacial maximum (LGM) about 16 000–20 000 radiocarbon yr BP in the middle Ob river region, forming a complex of tundra, steppe and forest vegetation. The mean summer temperatures during the LGM may have been similar to present, and the coldest average winter temperatures were 5°C lower than today (Velichko and Nechyev, 1984). However, more recent climate estimates (Tarasov *et al.,* 1999) suggest tundra or cool steppe vegetation and summer temperatures lower than present in West Siberia during the LGM.

The contradiction between recent data and the earlier view regarding vegetation history during the Preboreal period in West Siberia may result from interpretation of the pollen data. In Russian studies, pollen-data interpretations are based only on pollen percentages of individual taxa, and AP/NAP ratios are not used. The coexisting AP and NAP taxa during the early Holocene are interpreted as representing boreal forest, steppe and tundra elements, and the relatively high AP percentage values are believed to indicate the presence of trees in the region (Neustadt, 1957; Khotinskiy, 1984; Kremenetski *et al.,* 1997; Velichko *et al.,* 1997; Khotinskiy and Klimanov, 1997).

The NAP zone in Figures 3, 4 and 5 shows the same main features as a pollen diagrams from Surgut (120 km north of our study site) (Neustadt, 1974) and a site near Niznevartovsk (Khotinskiy, 1984; Neustadt and Selikson, 1985), about 200 km northeast of our study site. Khotinskiy (1984) believed that the *Picea* and *Betula* pollen values from the Niznevartovsk site indicate the presence of forests during the Preboreal period, although the high NAP percentages of Poaceae, Cyperaceae and *Artemisia* suggest treeless vegetation. A highly humified layer 20 cm thick containing tree stems (dated to 12 500 cal. BP) in a basal peat deposit below a thick layer of loam was used as evidence of forests at the Niznevartovsk site (Neustadt and Selikson, 1985). However, the wood was possibly carried to the spot by flooding over long distances, since the site was situated at the shore of the Ob river. However, in the Pur-Taz region (about 400 km north from our study site), the macrofossil data (Peteet *et al.,* 1998) indicate that *Larix-Betula pubescens* forests were present from at least 10 300 cal. BP onwards. The relatively low NAP values in the Pur-Taz region, in most samples less than 20% (Peteet *et al.,* 1998), correspond with values from forest-tundra sites (Hicks, 1986). At our study site, the NAP values were considerably higher prior to 9900 cal. BP, ranging from 52 to 90%.

Blyakharchuk and Sulerzhitsky (1999) suggested that open *Larix, Larix-Picea* and *Betula* steppe forests were present around the Bugristoye bog prior to 9200 cal. BP, about 700 km to southeast of our study site. The Bugristoye bog data agrees with data from our study site, since NAP (including Cyperaceae) was

so abundant at the site, possibly indicating instead completely treeless vegetation.

Preboreal climate
Based on the statistical interpretation of pollen assemblages (Klimanov, 1984), the average summer temperatures in West Siberia are estimated to be 2–3°C lower than present during the Preboreal period (Velichko *et al*., 1997). Despite the fact that the pollen data from our study site indicates treeless vegetation, *Larix* wood dated to Lateglacial times is found north of the present tree-line (Velichko *et al*., 1997; Peteet *et al*., 1998). Wood macrofossil data collected by MacDonald *et al.* (2000) indicate presence of spruce and birch trees beyond the present northern tree-line about 10 000 cal. BP and beginning of forest development there at that time. The date corresponds well with the beginning of increase in arboreal pollen in our data (Figures 3, 4, 5 and 6).

The presence of forests north of our study site at least 10 300 cal. BP (Peteet *et al*., 1998) indicates that a cool climate has not been the main cause of treeless vegetation in the study area. Estimates by Velichko *et al*. (1997) suggest that precipitation was near to present values in West Siberia during the Preboreal period, but pollen data from our study site suggest a drier climate. Abundance of Poaceae along with Asteraceae, Cichoriaceae, *Filipendula*, Rubiaceae, Caryophyllaceae and *Ephedra* found in the basal peat layers may indicate cool steppe conditions (Tarasov *et al.,* 1999) but *Artemisia* and Chenopodiaceae, also typical of steppe pollen assemblages, were not particularly abundant. However, the abundance of Cyperaceae, *Salix* and *Betula* (possibly partly *B. nana*) pollen in the NAP zone suggests tundra vegetation. The shrinking continental ice sheet in Scandinavia possibly caused a stable anticyclone in northern Europe that reduced the invasion of moist air masses from the Atlantic Ocean to Siberia (Khotinskiy, 1984). There is evidence of low annual precipitation in Fennoscandia (Digerfeldt, 1988; Donner *et al*., 1978; Huttunen *et al*., 1978) and the Russian Plain (Chepalyga, 1984) during the early Holocene.

Establishment of forests after 9900 cal. BP
The last remnants of the Scandinavian ice sheet disappeared about 9500 cal. BP (Eronen and Zetterberg, 1996), after which the influence of moist air masses from the Atlantic Ocean may have considerably increased in continental Eurasia. The increase in precipitation along the Russian Plain is reflected in the rising of the Caspian Sea about 8800 cal. BP (Chepalyga, 1984). At our study site, several charcoal layers were found within the peat and were dated between 8000 and 9000 cal. BP (Turunen *et al.,* 2001), suggesting climatic fluctuations including drought, at the limit of the Boreal and Atlantic periods.

In a vegetation zone map (Khotinskiy, 1984) for a period of about 9000–10 000 cal. BP our study site belongs to the *Betula* forest zone about 500 km north of the steppe area limit and near the southern limit of the *Pinus cembra-Picea* zone. Despite a sudden increase in *Betula* pollen at our site, the low *Betula*/NAP ratio value 9900 cal. BP indicates that tree pollen was not abundant but was still transported from distant sources during the early Boreal period. Also, the *Pinus*/NAP ratio indicates a timelag between the sharp increase of pollen and the actual establishment of trees in the region (Figure 6). This pattern suggests that, during the Boreal period (about 9000–10 000 cal. BP), trees were just becoming established in the region and that *Betula* forests may not have actually existed until the late Boreal period. Our data also contrast with the proximity of the *Pinus cembra-Picea* zone (about 100 km north from our site) reconstructed by Khotinskiy (1984). The near absence of *Pinus* pollen (Figures 4 and 5) suggests that both *P. sylvestris* and *P. cembra* forests must have been a long distance from our study site.

The decline in *Picea* pollen in the AP-NAP zone, most evident in core C (Figure 5), indicates that *Picea* was not present around 9900 cal. BP, but became established slightly later (Figure 6). The sharp increase in *Picea* pollen (Figure 6) correlates well with *Picea* macrofossil and pollen data for 9300 cal. BP from the Pur-Taz site (Peteet *et al*., 1998). The increase in tree pollen between 9900 and 9000 cal. BP is also contemporary with the development of forests beyond the present tree-line due to climatic warming that started around 9500 cal. BP (MacDonald *et al.,* 2000).

The sudden increase in tree pollen at our study site beginning with *Betula* pollen is simultaneous at the Niznevartovsk site (Khotinskiy, 1984; Neustadt and Selikson, 1985) and at Bugristoye bog (Blyakharchuk and Sulerzhitsky, 1999), indicating that large areas of West Siberia were covered with *Betula* after 9900 cal. BP. At the Niznevartovsk site (Khotinskiy, 1984; Neustadt and Selikson, 1985) the increase in *Betula* pollen is dated at 9500–9100 cal. BP. The younger date is also the level at which *Pinus* pollen starts to increase. Considering the long-distance transport of *Betula* and *Pinus* pollen, the increase of both taxa in data from Niznevartovsk may be contemporary with the changes at our study site. The values of NAP taxa and spores (especially Polypodiaceae) were also high prior to 9100 cal. BP at the Niznevartovsk site (Khotinskiy, 1984; Neustadt and Selikson, 1985), suggesting a small influx of arboreal pollen.

A significant indicator of climatic change may be the increase in Ericaceae pollen in 9900 cal. BP at our study site, found also in other pollen diagrams based on peat samples (Neustadt and Selikson, 1985; Liss and Berezina, 1981; Blyakharchuk and Sulerzhitsky, 1999). Ericaceae pollen indicates sufficient precipitation for forest vegetation (Prentice *et al*., 1996).

Forests between 9000 and 4100 cal. BP
Corrected pollen values (Donner, 1972) and the AP/NAP ratio indicate that *Betula* forests of the late Boreal period changed to coniferous (*Pinus* and *Picea*) forests during the early Atlantic period (Figure 6). The use of corrected pollen values for data interpretation must be analysed critically, because different landscapes and climatic conditions affect pollen production. Thus, the estimates given here must be taken as magnitudes of abundance. Corrected relative pollen values suggest that *Picea* was the dominant tree species in forests, with an average proportion of about 40%. Our study site is situated in a relatively open mire, and therefore the pollen values may represent a large region. *Picea* forests were one of the key elements of the West Siberian taiga zone during the Atlantic period between 7800 and 3800 cal. BP (Velichko *et al*., 1997; Khotinskiy, 1984). *Pinus sylvestris* was almost as abundant as *Picea* according to corrected pollen values (Donner, 1972), but in the data from Niznevartovsk and Surgut (Neustadt, 1974; Khotinskiy, 1984; Neustadt and Selikson, 1985) over half of the *Pinus* pollen was identified as *P. cembra*. However, Liss and Berezina (1981) found only minor amounts of *P. cembra* pollen during the Atlantic period. Also, Blyakharchuk and Sulerzhitsky (1999) did not find *P. cembra* pollen to be dominant during the early Atlantic period; however, their data suggests an increase in *P. cembra* from 6000 cal. BP onwards. According to the vegetation zone map of Khotinskiy (1984), our study area belongs to the dark coniferous middle taiga zone in the *P. cembra-Picea* taiga subdivision between 5300 and 7000 cal. BP. Contrary to vegetation estimates by Khotinskiy (1984), our pollen data indicate the presence of *Pinus sylvestris-Picea* forests, in which *P. cembra* was only a minor part.

A continuous *Alnus* pollen curve with sporadic *Abies* pollen starts about at the level where total AP values are around 90% (in core A at 350 cm and in core B at 383 cm). At Bugristoye bog (Blyakharchuk and Sulerzhitsky, 1999), a continuous *Abies* curve starts between 8000 and 9000 cal. BP and is highest about 6000–7000 cal. BP. At our study site, a continuous *Abies* pollen curve starts later, about 6500 cal. BP, and values of about 5%

may be high enough to indicate its establishment in the region. A sharp decrease of *Abies* around 6000 cal. BP, followed by a considerable increase in *Pinus cembra* with no change in *Pinus sylvestris* abundance, is reported by Blyakharchuk and Sulerzhitsky (1999). However, at our study site, there was no evidence of a decline in *Abies* pollen, and no increase in *Pinus cembra* pollen.

From about 6500 cal. BP onwards, *Corylus, Tilia* and *Ulmus* pollen were found both at our study site and at Bugristoye bog (Blyakharchuk and Sulerzhitsky, 1999). At 5000–7000 cal. BP there was a climatic optimum in the Northern Hemisphere, including Siberia. The mean January temperatures were estimated to be about 5°C warmer than today, but mean July temperatures were similar to present in West Siberia. Estimated precipitation values were not different from present (Velichko *et al.*, 1997; Monserud *et al.*, 1998).

Forests 4100 cal. BP to present

There is evidence of a climatic change in Fennoscandia (Digerfeldt, 1988; Korhola, 1995; Hyvärinen and Alhonen, 1994; Reinikainen and Hyvärinen, 1997) about 4300 cal. BP, coinciding with a rapid decrease of *Picea* pollen after 4100–4300 cal. BP at our study site. In Siberia, the northern tree-line retreated near to its present limit between 4000 and 3000 cal. BP (MacDonald *et al.,* 2000). Decline of *Picea* pollen values to less than 5% indicate that spruce probably disappeared from the peatland islands and may have decreased considerably in large areas. Early Subboreal cooling occurred at 5300–4600 cal. BP and was followed by a warmer period at 4600–3400 cal. BP (Khotinskiy, 1984). There is no notion in Russian literature of a rapid decline of *Picea* pollen around 4000 cal. BP in West Siberia, although in an undated diagram from Surgut (Neustadt, 1974) a decline in *Picea* pollen correlates with the decline at our study area. Khotinskiy (1984) only remarks that *Picea* and *Abies* forests declined, but *Pinus cembra* and *Betula* forests became more important during the Subboreal and Subatlantic periods. Blyakharchuk and Sulerzhitsky (1999) found evidence of the beginning of palsa formations about 4900 cal. BP at Bugristoye bog, indicating a shift to a cooler climate, but no sharp decrease of *Picea*. However, in Bugristoye bog (Blyakharchuk and Sulerzhitsky, 1999) and at the Niznevartovsk site (Khotinskiy, 1984; Neustadt and Selikson, 1985) *Picea* pollen indicates a decrease in spruce between 5000 cal. BP and present. The data from our study site suggests only a slight increase in *Pinus cembra*, but rather a rapid increase of *Pinus sylvestris* after 4100 cal. BP (Figures 3, 4 and 6). The increase in *Pinus* may depict conditions during a subboreal warm period (Velichko *et al.*, 1997). In Bugristoye bog (Blyakharchuk and Sulerzhitsky, 1999) *P. cembra*, which began to increase around 5500 cal. BP, has been as abundant as *P. sylvestris* during the last 5000 years. A slight increase in *Betula* pollen and a corresponding decrease in *Pinus* pollen in core B at 110–120 cm may have been caused by climatic deterioration at 2800 cal. BP (van Geel and Renssen, 1998).

Conclusions

Climatic reconstructions from the Holocene period in West Siberia are based only on a few studies (Khotinskiy, 1984; Velichko *et al.*, 1997; Monserud *et al.*, 1998; Blyakharchuk and Sulerzhitsky, 1999), although this vast area is important for understanding climatic changes in the Northern Hemisphere. Contrary to previous studies, our data suggests that large areas of the middle Ob river region were treeless with tundra type vegetation prior to the Boreal period. Discrepancies between present data and the established view of the vegetation history of West Siberia suggest that knowledge of the vegetation history of the area is deficient. More detailed palaeovegetation studies are needed for better and more reliable climate reconstructions.

Acknowledgements

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