

Holocene environmental history on the eastern slope of the Polar Ural Mountains, Russia

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The Holocene environmental history of the eastern slope of the Polar Ural Mountains has been reconstructed using pollen, spores, algae and other microfossils from the Chernaya Gorka palsa section (67°05'N, 65°21'E, 170 m a.s.l.). An initial oligotrophic lake was formed at the study site c. 9800–9500 ¹⁴C yr BP. Although tundra communities dominated the vegetation in the area, birch and larch trees might have grown at lower elevations. Dry and disturbed soil habitats also occurred around the lake. Algae (mostly *Pediastrum* and *Botryococcus*) started to expand in the lake as climate gradually improved after c. 9500 ¹⁴C yr BP. However, the role of mosses (mostly *Calliergon* and *Drepanocladus*) was most important for the infilling of the lake basin. Increased temperatures and subsequent improvement of hydrological conditions resulted in vegetation changes: stands of willows developed rapidly and the role of tree birch in the local vegetation increased. The lake was completely filled at c. 8600 ¹⁴C yr BP. Peat accumulation started with Bryales mosses and, later, *Sphagnum* became dominant. Stands of *Larix*, *Picea* and *Betula* became well developed during the Boreal climate optimum. Tree birch began to spread into the tundra. Different Bryales mosses formed peat c. 8000–6500 ¹⁴C yr BP. Cyperaceae later became the main peat-forming element. Dense spruce canopies with *Larix sibirica* and *Betula pubescens* surrounded the study site during the Atlantic period, pointing to the warmest climate during the Holocene. Summer temperatures might have been up to 3–4°C higher than today. However, a decline of spruce and an increase of birch around 6700–6300 ¹⁴C yr BP may reflect some climate deterioration. There are no dated deposits younger than 6000 ¹⁴C yr BP. It is assumed that Subboreal climate deterioration resulted in the development of permafrost and formation of the palsa at the site. The deposits, now protruding above the surrounding terrain, were eroded by wind, water and cryogenic processes.

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Our knowledge about palaeoenvironmental changes in the Eurasian Arctic, particularly in NE European Russia, has significantly increased over the past decade, with several pollen, diatom, macrofossil and insect records from the Polar Urals and adjacent regions published during the period (Andreev *et al.* 1998, 2001, 2005; Serebryanny *et al.* 1998; Koshkarova *et al.* 1999; Panova & Jankovska 2000; Oksanen *et al.* 2001; Välranta *et al.* 2001; Kultti *et al.* 2003; Panova *et al.* 2003; Paus *et al.* 2003; Sarmaja-Korjonen *et al.* 2003). Despite these studies, however, still little is known about the Holocene vegetation cover and climate changes at the NE rim of the Polar Urals (Fig. 1).

The climate fluctuations in the area have been studied dendrochronologically for many years (e.g. Shiyatov 1964, 1986; Vaganov *et al.* 1996), but reliable palaeoenvironmental reconstructions require high-resolution and well-dated sediment sequences containing palaeoclimatic proxy records, such as pollen and non-pollen palynomorphs. Nevertheless, high-resolution pollen, especially non-pollen palynomorph analysis of peat and/or lacustrine deposits, which could provide

long-term histories of vegetation and climate dynamics in the region, has not been done previously. A palsa profile, Chernaya Gorka in the Polar Ural Mountains, was chosen for the detailed palaeoecological study because of its proximity to the treeline limit and, therefore, its potential sensitivity to climate-driven changes in the past.

This article presents the results of pollen and non-pollen palynomorph analysis of the Chernaya Gorka palsa deposits and demonstrates new possibilities for the interpretation of palynological assemblages using non-pollen microfossils, e.g. algae, fungi, rhizopods, cladocera, rotatoria, and other often neglected biological remains which can successfully be used for the precise reconstruction of past environments. Such reconstructions are important for understanding regional and local environmental trends in the high Arctic regions. Moreover, they provide a basis for prediction of the future changes there, which is especially important for the Arctic areas of West Siberia, where anthropogenic influence strongly increased during recent decades.

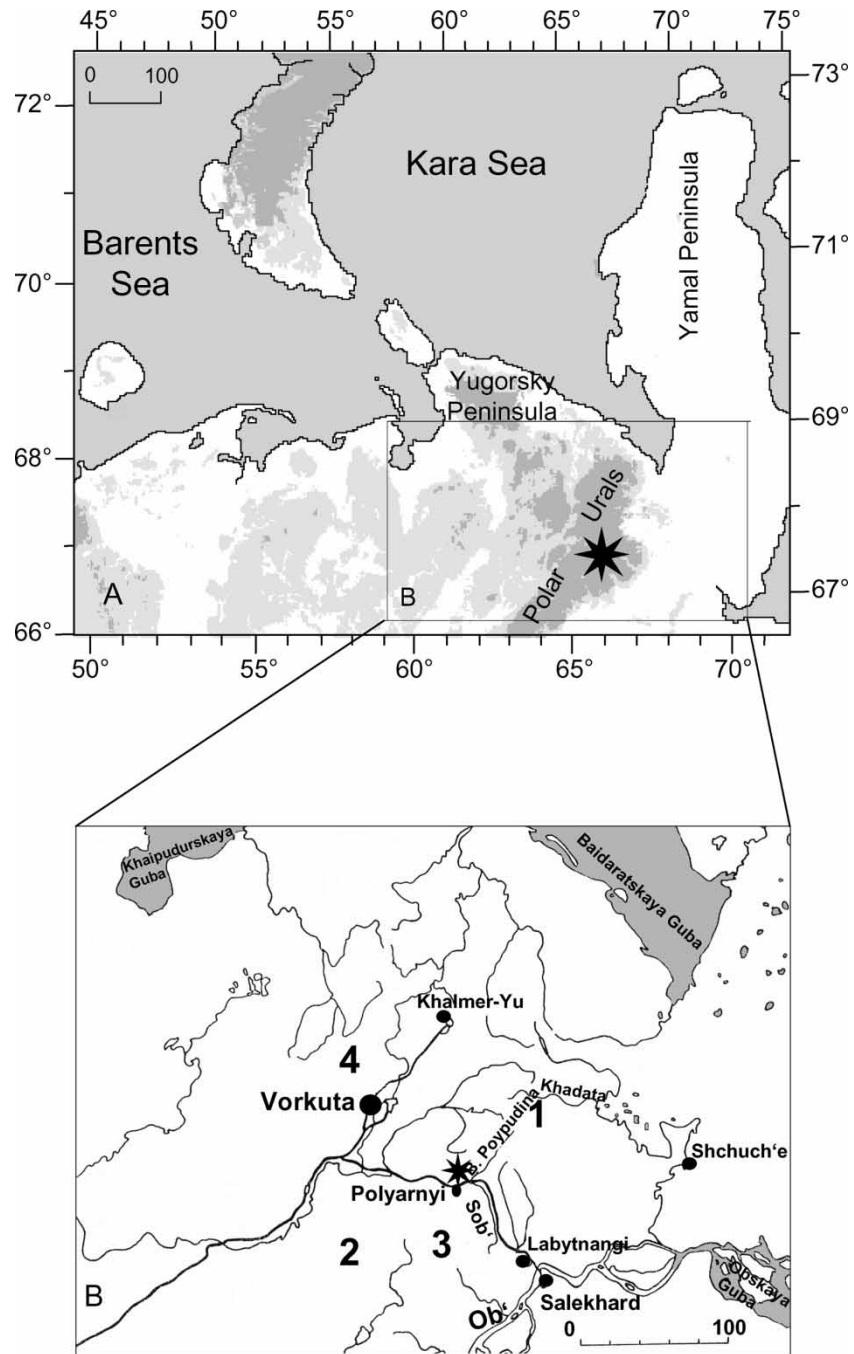


Fig. 1. A. Map showing the location of the Polar Urals Mountains and the studied Chernaya Gorka site. Light shading depicts elevations of 100–200 m a.s.l., while dark grey shading shows elevations >200 m a.s.l. B. Schematic map showing the location of studied palsa section (*) and other cited locations: 1 = Malaya Khadata Lake section (Surova 1967; Surova & Troitsky 1971; Surova *et al.* 1975); 2 = Bol'shaya Lagorta River section (Surova *et al.* 1975); 3 = Rai-Iz peat section (Koshkarova *et al.* 1999); 4 = Lake Lyadhej-To (Andreev *et al.* 2005).

Study area

The study area is located approximately 10 km east of the boundary between Europe and Asia in the Polar Ural Mountains. The study site, Chernaya Gorka, is located on the west bank of the Bol'shaya Poypudyna River, a tributary of the Sob' River, about 2 km north of the Polyarnyi settlement (67°05'N, 65°21'E, 170 m a.s.l.; Fig. 1). The site is a typical palsa, *c.* 20 m in diameter and more than 5 m high at the highest point.

The palsa is in a phase of degradation and traces of erosion by wind, water and cryoturbation are notable. The southern side is gradually being destroyed due to thawing within the frozen core, and a small lake (*c.* 20 × 15 m), roughly similar in size to the palsa, has been formed on the southern side. The study site is one of several solitary palsas on a wide, soggy area that is saturated by water flowing from an easterly mountain ridge. Most of these palsas are also in a state of degradation.

The surface on the top of the studied palsa is mostly devoid of vegetation, with only rare *Ledum palustre*, *Empetrum hermaphroditum*, *Arctostaphylos uva-ursi*, *Arctous alpina* and some other herbaceous species. The vegetation on the sides is denser and is formed primarily by *Ledum palustre*, *Rubus chamaemorus* and *Betula nana*, with an undergrowth of mosses and lichens. Distinct dominant taxa at the edge of the lake and along the outflow are *Salix lanata*, *S. lapponum* and *S. phyllicifolia*, with a herb layer of *Polemonium coeruleum*, *Polygonum bistorta*, *Trollius europaeus*, *Veratrum lobelianum*, *Carex* sp., and other species. *Sphagnum* prevails among the submerged vegetation advancing from the borders of the pool, and *Eriophorum russeolum* distinctly dominates the herbs.

Tundra vegetation occurs on the landscape surrounding the palsa, with the predominance of *Betula nana*, along with *Ledum palustre*, *Vaccinium vitis-idaea*, *V. uliginosum*, *Andromeda polifolia* and *Arctostaphylos uva-ursi*. A rich lichen (*Cetraria islandica*, *C. delisei*, *C. cucullata*, *C. nivalis*, *Cladonia alpestris*, *C. rangiferina*, *C. sylvatica*, *Alectoria* sp. div., *Thamnolia vermicularis* and *Dactylina arctica*) and moss (*Aulacomnium turgidum*, *Hylacomium splendens* and *Pogonatum* sp.) cover is noticeable.

Only sparse *Betula tortuosa* and rare *Larix sibirica* grow in the area surrounding the site. Denser stands of *L. sibirica* and *B. pubescens* with fewer *Picea obovata* were observed c. 1 km to the east at a lower elevation. Park spruce-larch and spruce-birch forests cover the eastern slopes of the Polar Ural Mountains, and are generally limited to areas below 150–160 m a.s.l. (Shiyatov 1964, 1996).

Climate characteristics from the nearby Sob' River valley (Shiyatov 1964; Kuvchinova 1968) can also be used for the Chernaya Gorka locality. Average January temperature is -22°C , while average temperature in July is $+12^{\circ}\text{C}$. Mean annual precipitation is approximately 600 mm. In such climatically extreme regions, the extent and depth of permafrost and the rate of summer thawing are of utmost importance for the vegetation, as well as the thickness of snow cover and its persistence into the growing period. Strong winds are also a limiting factor, since they cause the local accumulation of great snow masses and may suppress the height of the vegetation cover, or even completely destroy it, by means of the wind-driven frozen snow (i.e. the 'grinding effect').

Material and methods

The maximum thickness of the organic deposit within the palsa is 2.15 m. The thickest profile was sampled from an open pit dug to the southern side of this palsa on 1 August 1994. Palynological analyses were carried out at 5-cm intervals. Processing included KOH deflocculation and treatment with

HF followed by acetolysis and the mounting of pollen samples in glycerine. A minimum of 600 pollen grains were counted; spores and non-pollen palynomorphs were tallied in addition. Pollen percentages were calculated based on the total pollen sum. The percentage of spores was based on the sum of pollen and spores, the percentage of algae on the sum of pollen and algae, and the percentages of other identified palynomorphs on the sum of pollen and sums of other identified palynomorphs (separately for each group).

TILIA and TILIAGRAPH were used for graphing the pollen data (Grimm 1991). Pollen zonation was done by visual inspection of the pollen percentage diagram.

Four samples (Table 1) were radiocarbon-dated at the Radiocarbon Laboratory of the Institute of Physics, Silesian Technical University in Gliwice, Poland. All discussed dates are given in the radiocarbon years.

Results

Radiocarbon chronology

A piece of *Salix* wood, likely a root (V. Čulíková, pers. comm. 1996), from 205 cm depth is radiocarbon-dated to the end of the Preboreal period, at about 9200–9500 yr BP (Table 1). The lowermost limnic sediments of Chernaya Gorka (215–205 cm depth) contain relatively large amounts of *Artemisia* and *Chenopodiaceae*, indicating a rather dry and cold environment. Similar pollen spectra occur in the Holocene records of northern Eurasia (e.g. Surova et al. 1975; Khotinskiy 1984; Velichko et al. 1997; Andreev et al. 2002, 2003, 2004) and are dated to 9800–9500 ^{14}C yr BP. Taking into consideration the radiocarbon age of the *Salix* wood and pollen composition at the same depth, we therefore suggest that organic accumulation at the site began not earlier than 9800–9500 ^{14}C yr BP.

Limnic sedimentation continued until the beginning of the Boreal period. Although two radiocarbon ages (Table 1) from moss peat (180 cm) and *Sphagnum* peat (150 cm) are inverted, they are nearly identical, taking into consideration the statistical errors. We assume that peat accumulation started around 8800 ^{14}C yr BP. Similar ages of the basal peat layers: 8670 ± 100 yr BP (Tln-85) from the Malaya Khadata Lake section (Surova et al. 1975) and 8530 ± 40 yr BP (SOAN-3028) from the Rai-Iz peat section (Koshkarova et al. 1999) have been reported from adjacent areas.

An oligotrophic, *Sphagnum*-dominated peat bog developed during the Boreal and the beginning of the Atlantic periods. A shift to *Cyperaceae*-dominated peat was radiocarbon-dated to 6000 yr BP (15–20 cm depth), indicating the transition from moss peat accumulation to sedge peat during the middle Atlantic period. This likely occurred c. 6700 ^{14}C yr BP, as

Table 1. Radiocarbon ages (^{14}C yr BP) from the studied palsa section.

Laboratory no.	Depth, cm	Dated material	^{14}C ages, yr BP
Gd-9938	15–20	Cyperaceae peat	6020 \pm 200
Gd-10776	150	Slightly decomposed <i>Sphagnum</i> peat	8720 \pm 180
Gd-9947	180	Strongly decomposed moss peat	8620 \pm 270
Gd-9935	205	<i>Salix</i> wood (probably a root)	9230 \pm 280

inferred from the *Betula* sect. *Albae* pollen peak. Two radiocarbon dates from the Malaya Khadata peat section: 6745 \pm 70 (Tln-84) and 6315 \pm 70 (Tln-64) yr BP date a similar peak to approximately 6700–6300 ^{14}C yr BP (Surova *et al.* 1975). Unfortunately, the uppermost surface of the studied palsa has been destroyed by wind denudation and records much younger than 6000 ^{14}C yr BP are missing.

Pollen zones

The spectra in the pollen zone I (PZ-I, 215–205 cm; Fig. 2) are dominated by *Betula*, Cyperaceae and Poaceae pollen. Pollen of *Artemisia* and Chenopodiaceae are also characteristic. PZ-II (205–175 cm) is notable for an increase in *Salix* pollen contents (in the lower part of PZ-II) and *Betula* sect. *Albae* (in the upper part of PZ-II), while Poaceae and *Artemisia* are gradually decreased. High amounts of Bryales spores, rhizopods (*Assulina*, *Arcella*) and algae remains (*Pediastrum*, *Botryococcus*, *Tetraedron*, *Scenedesmus*) are also noticeable in the zone. PZ-III (175–80 cm) is characterized by decreases in Poaceae and *Salix* percentages and significant increases in Cyperaceae and *Thalictrum* percentages. *Thalictrum*, *Filipendula* and *Potentilla* appear exhibiting an increase similar to that for the fern spores. A *Sphagnum* peak also occurs in this zone. The upper part of the zone (starting from 110 cm) is characterized by a gradual increase in *Picea* pollen percentages. PZ-IV (80–0 cm) is notable for high amounts of *Picea* pollen in the spectra. An increase in *Betula* sect. *Albae* pollen is noticeable in the middle part of PZ-IV.

Abundance of some pollen types in surface samples

Larix

In the Labytnangi-Yamal Peninsula transect of surface pollen samples (unpublished), we found a very strong underrepresentation of *Larix* pollen compared to its occurrence in modern vegetation. Similar results have been obtained by Levkovskaya (1967) and Surova & Troitsky (1971). *Larix* pollen was encountered very

rarely, despite the fact that it is the only tree currently present in the area. In the forest-tundra zone north of the village of Obskaya, *Larix* pollen is rarely found even directly under living trees. These observations imply that even rare occurrences of *Larix* pollen in the pollen records indicate its local presence in the landscape.

Betula

B. sect. Albae-type (tree birch) pollen are produced by *B. pubescens* and *B. tortuosa*. Distinguishing between the pollen types (*B. sect. Nanae* and *B. sect. Albae*) is problematic in some cases; in this study, all problematic pollen grains have been assigned to *B. sect. Albae*-type. Surface pollen samples collected in different vegetation habitats show that pollen of *B. sect. Albae*-type always dominates over *B. sect. Nanae*-type (Jankovská unpublished). Thus, *B. sect. Nanae*-type is usually underrepresented in the spectra. It is likely that pollen of the low/dwarf shrub *B. nana* falls directly to the ground and is not spread as readily by wind as the taller *B. tortuosa* or *B. pubescens*.

Salix

Numerous *Salix* pollen in the surface samples were found only under living willow stands. Little or no pollen was found at short distances from low creeping dwarf willows. This finding implies that a large abundance of *Salix* pollen indicates the dominance of willow in the local vegetation.

Alnus fruticosa (*A. viridis*)

This shrub spreads its pollen relatively easily. In the surface transect, *A. fruticosa* pollen was found several hundred metres distant from the plants. Single pollen grains in the pollen record therefore indicate the presence of this species in the wider surroundings, and abundant grains indicate its presence in close vicinity to the sampling site.

Pinus sylvestris and *P. sibirica*

Pollen grains of these trees are present in all surface samples from the northern taiga to the northern tundra. However, the nearest living trees are more than 100 km south of the most southern surface sample site. Long distance transport of *Pinus* pollen should thus be taken into account in the interpretation of all pollen diagrams. Very few *Pinus* trees and/or long-distance pollen transport are capable of creating the so-called pine-forest pollen spectrum in an open tundra landscape.

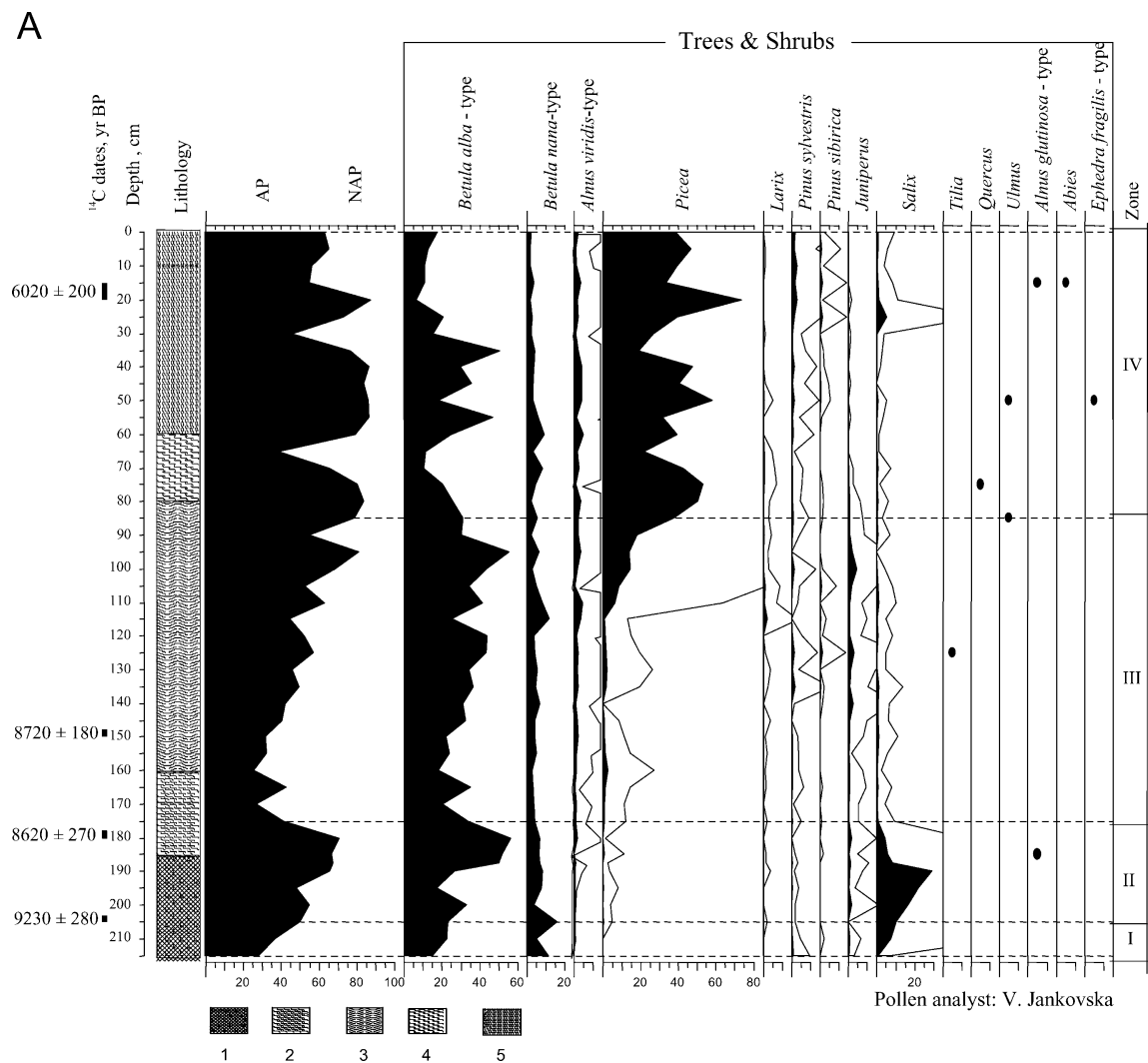


Fig. 2. Pollen, spore and non-pollen palynomorphs diagram of the Chernaya Gorka palsa section. Taxa are expressed as percentages (black), low percentages exaggerated 10 times as empty curves, minor taxa (less than 2%) as dots: 1 = lacustrine sediments; 2 = strongly decomposed green moss peat; 3 = *Sphagnum* dominated peat; 4 = slightly decomposed green moss peat; 5 = herb peat. A. Percentage diagram of AP/NAP, trees, and shrubs pollen. B. Percentage diagram of herb pollen. C. Percentage diagram of spores and palynomorphs.

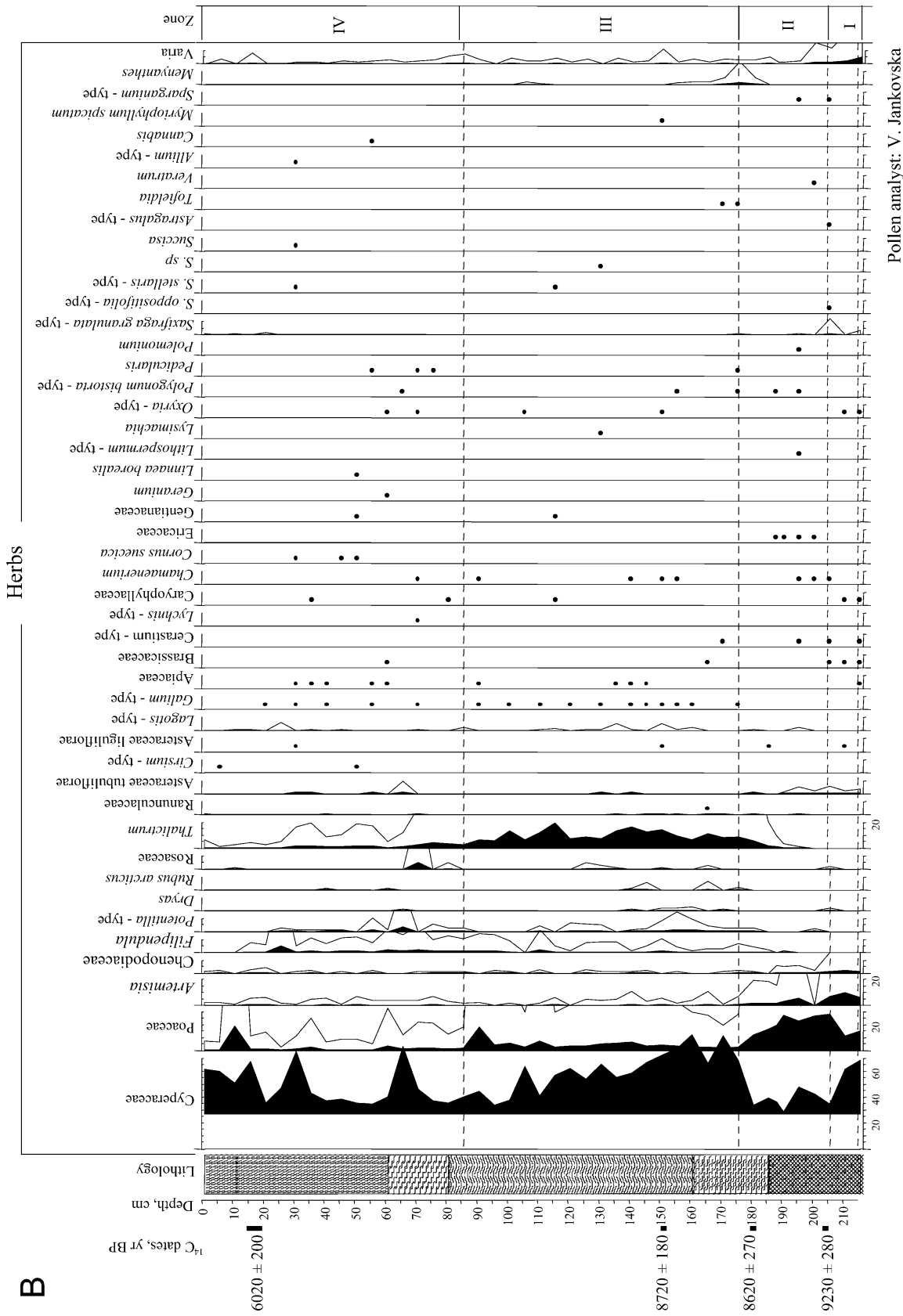


Fig. 2 (Continued)

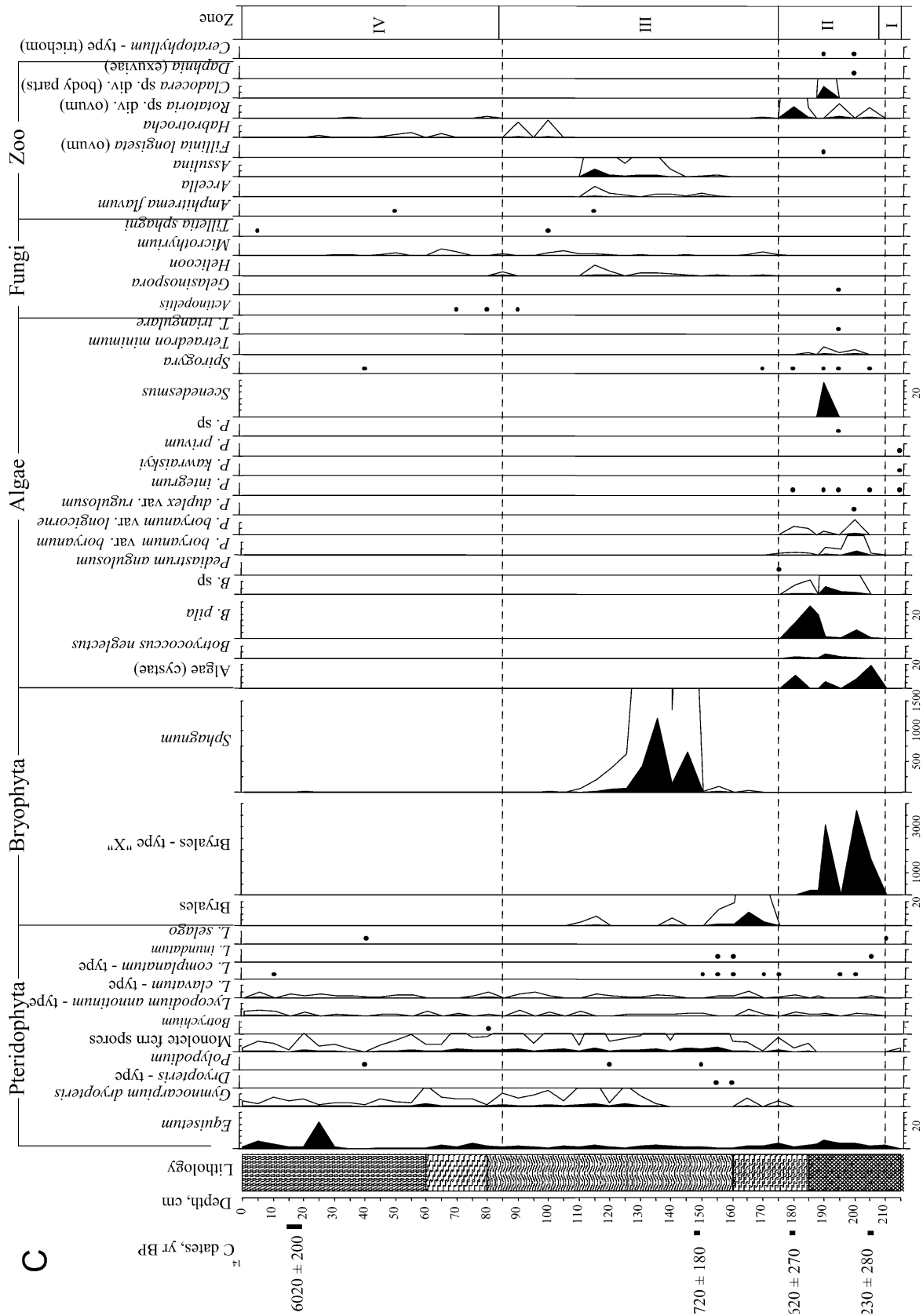


Fig. 2 (Continued)

Palaeoecological reconstruction and discussion

An initial stage, PZ-I, c. 9800–9500 ¹⁴C yr BP

Increased temperatures towards the end of the Late-glacial period drove the thawing of glaciers, snow patches and permafrost. The thaw-generated meltwater accumulated during the summer on the deep, impermeable permafrost in places lacking an outlet. At the Chernaya Gorka site, the initial water body was probably formed 9800–9500 ¹⁴C yr BP. In its initial phase, it was most likely completely devoid of aquatic vegetation, but *Sparganium* (cf. *angustifolium*) appeared and it is likely that *Eriophorum* (*E. russeolum* or *E. scheuchzerii*) began to penetrate from the rims of the lake. The only microfossils encountered are sporadic colonial green algae (*Pediastrum kawraiskyi*, *P. integrum* and *P. privum*). Although rare, they unambiguously indicate the existence of very cold oligotrophic water. For example, *P. integrum* was found in several surface pollen samples from different locations in the subarctic zone (moist tundra habitats) and *P. kawraiskyi* in samples from very shallow water habitats, e.g. at Kharasavei on the northern Yamal Peninsula within the zone of northern tundra. Thus, we assume that the initial water body was a small, shallow lake with very cold oligotrophic water.

Rather high amounts of *Salix* pollen suggest that the lake was surrounded by a rim of willows. However, the dominant vegetation of the wider surroundings probably consisted of tundra communities: dwarf-shrub tundra (*Betula nana*, dwarf *Salix* species, Ericaceae) and shrub tundra (taller *Salix* species, *Betula tortuosa*) with an undergrowth of lichens and mosses. Species from *Astragalus*, *Allium*, *Cardamine*, *Cerastium*, *Chamaenerium*, *Dryas*, *Oxyria*, *Saxifraga*, *Veratrum*, *Polygonum*, *Polemonium*, *Equisetum* and, in greater numbers, Caryophyllaceae, Cyperaceae, Asteraceae grew in the area. Grasses were also very common. Relatively large amounts of *Artemisia* and Chenopodiaceae indicate habitats with dry microenvironments and/or disturbed soils.

Considering the marked underrepresentation of certain pollen types in the assemblage, even the extremely low *Larix* values allow us to assume the occurrence of some larch trees not too far away from the study area. Tree birch and larch forests probably grew in close vicinity to the site. The negligible pollen values of *Picea*, *Pinus sylvestris* and *P. sibirica* are ascribed to long-distance transport. Macrofossil remains of *Picea obovata* dated to 9370 ± 40 ¹⁴C yr BP (SOAN-3105) have been found at the Rai-Iz site (Koshkarova *et al.* 1999), suggesting that spruce might have been growing in the Polar Urals region by 9400 ¹⁴C yr BP, at least in the southern parts. The northern limits of the pine species were even farther to the south in the past than today.

Late Preboreal/early Boreal, PZ-II, c. 9500–8600 ¹⁴C yr BP

The original small lake was for the greater part filled in during the late Preboreal/early Boreal, starting c. 9500 ¹⁴C yr BP. Algae started to expand in the lake as climate gradually improved. *Pediastrum integrum*, *P. boryanum* var. *longicorne* and *Botryococcus pila* are primary indicators, growing mainly in small, cold, oligotrophic lakes (Jankovská & Komárek 2000; Komárek & Jankovská 2001). These taxa are followed by *Pediastrum boryanum* var. *boryanum*, *P. duplex* var. *rugulosum*, *Tetraedron minimum* (sporadically *T. triangulare*), *Scenedesmus* and *Spirogyra*. The present habitat of *Botryococcus neglectus* is a natural mesotrophic environment. The presence of an aquatic environment is also supported by eggs of rotatoria (cf. *Fillinia longiseta*, *Rotatoria* sp. div.), exuviae of *Daphnia* and different parts of cladocera.

For the infilling of the lake, the role of mosses (*Calliergon*, *Drepanocladus* and others) was most important. Towards the end of the Preboreal and in the Boreal, *Menyanthes trifoliata*, *Comarum palustre* and Cyperaceae also contributed to the infilling. The occurrence of *Menyanthes* confirms that temperatures were higher than present (Surova *et al.* 1975).

Increased temperatures and subsequent improvement of hydrological conditions (thawing of glaciers and permafrost) resulted in vegetation changes. A gradual decrease of *Artemisia* and Chenopodiaceae pollen percentages indicates that the dry and disturbed habitats disappeared in the area surrounding the lake. A dramatic increase in *Salix* pollen percentage could be related to locally moister conditions. Stands of willows (most likely *Salix lanata*, *S. glauca*, *S. lapponum*, and possibly *S. phyllicifolia*) developed. Cyperaceae and Poaceae grew in the vicinity of the lake. The increasing role of the tree birch in the local vegetation is also characteristic of this period. *Alnus fruticosa* and *Picea* probably were not present in the area, but they began to spread in the surrounding regions (Surova *et al.* 1975; Koshkarova *et al.* 1999).

Middle Boreal/early Atlantic, PZ-III, c. 8600–8000 ¹⁴C yr BP

It is difficult to date the upper boundary of this interval. However, it is known that the early Atlantic sediments in the Polar Ural Mountains are characterized by the dramatic increase of *Picea* pollen percentages (Surova *et al.* 1975). Such an increase in the palsa peat section from the vicinity of the Malaya Khadata Lake was radiocarbon-dated to 7960 ± 100 (TIn-86) yr BP. Another ¹⁴C age, 7790 ± 80 (TIn-40) yr BP, from a section in the upper part of the Bol'shaya Lagorta River valley dates the sediments to slightly above the *Picea* peak. Thus, we may assume that the *Picea* pollen

increase at the studied palsa started not much earlier than 8000 ^{14}C yr ago.

The Bryales spores present at the beginning of this period, c. 8600 ^{14}C yr ago, are of a different type from those in the preceding limnic phase, indicating that mosses which formed peat are different from the mosses that dominated during the limnic stage. Later *Sphagnum* mosses became the basic peat-forming element. Peat consisting mainly of *Sphagnum* was formed up to the late Boreal/early Atlantic, approximately 8000 ^{14}C yr BP. The rhizopods (*Arcella*, *Assulina* and *Amphitrema flavum*) as well as fungi remains (*Helicoon* and *Microthyrium*) are typical of *Sphagnum*-dominated peat tundra. As observed on Spitsbergen by V. Jankovská (unpublished), remains of *Tilletia sphagni* (fungi parasailing on *Sphagnum*) indicate the local occurrence of *Sphagnum* even though its spores were not found. Remains of *Habrotricha* (rotatoria) are another important indicator of an oligotrophic *Sphagnum*-dominated wetland.

Climate amelioration enabled the spread of more cold-sensitive vegetation. Stands of *Larix*, *Picea*, and *Betula* of forest-tundra and northern-taiga character developed during the Boreal. Tree birch began to spread in the tundra. Light conditions favourable for the spread of *Juniperus* and *Alnus fruticosa* still persisted. Favourable hydrologic soil conditions enabled the spread of *Filipendula*, *Thalictrum*, *Polygonum bistorta*, Cyperaceae and probably *Lagotis* cf. *uralensis*. Primordial natural moist meadows were formed. Enhanced moisture availability also led to the spreading of fern. A regular occurrence of *Gymnocarpium dryopteris* (identified by J. van Leeuwen and S. Peglar, University of Bern) should be noted. *Menyanthes trifoliata* and *Comarum palustre* grew in wetlands, where *Sphagnum* was common. These vegetation changes occurred in the Polar Ural Mountains during the Boreal climate optimum and are similar in character to those in other parts of northern Eurasia (e.g. Khotinskiy 1984; Velichko et al. 1997; Andreev et al. 2002, 2004, 2005).

Early/middle Atlantic, PZ-IV, c. 8000–5800 ^{14}C yr BP

At the beginning of the interval, various Bryales mosses formed peat. Beginning in the middle Atlantic, Cyperaceae became the main peat-forming element. Dense canopies of spruce stands with *Larix sibirica* and *Betula pubescens* surrounded the study site. This scenario correlates well with other palaeoecological data from the Polar Urals (Surova & Troitsky 1971; Surova et al. 1975; Koshkarova et al. 1999) and from other arctic and subarctic areas of northern Eurasia (e.g. Velichko et al. 1997; MacDonald et al. 2000; Andreev et al. 2002, 2004).

The forests in the lower valleys of the Polar Urals were similar to the northern taiga type, and in lower altitudes, possibly to the middle taiga type. Forests

attained higher altitudes and latitudes than today. Surova & Troitsky (1971) comparing the Polar Ural forests during the Atlantic period to the present-day forests on the northern Ural Mountains conclude that summer temperatures were 3–4°C higher than today in northern regions of the Ural Mountains, and glaciers fully melted and disappeared. Similar climate parameters based on pollen and chironomid records were reconstructed for the northwestern rim of the Polar Ural Mountains (Andreev et al. 2005).

Spruce act to suppress the less competitive larch at lower altitudes and latitudes. The occurrence of *Larix* is limited primarily by light conditions, and therefore prevails over spruce only at higher altitudes and latitudes where spruce is less dominant. The decrease of *Larix* pollen at Chernaya Gorka during the later part of the Middle Holocene points to a decline in the proportion of larch in the surrounding spruce forests. The decline of *Juniperus* pollen indicates that juniper was also light-limited in the shady spruce forests. A distinct northward shift of all woody species distributions took place during the Atlantic period. This is supported by isolated pollen grains of *Ulmus* and *Quercus*, as well as by increased *Pinus* pollen values. Neither *Ulmus* nor *Quercus* grew at the study site at that time, and we assume that both *Pinus sibirica* and *P. sylvestris* pollen were transported from a long distance, as well as *Abies sibirica*. The taiga character of the forests in the Polar Ural Mountains during the Atlantic period is also supported by herb pollen such as *Linnaea borealis*, *Cornus suecica* and increased fern spores. Conspicuous is the abundance of *Gymnocarpium dryopteris* and various *Lycopodium* species. The *Cannabis* pollen came from long-distance transport and may be used as additional evidence of the northward shift of species distribution limits.

Surova et al. (1975) point to a cooling in the Polar Ural Mountains in the middle Atlantic period, inferred from a decline in spruce pollen and an increase in birch pollens. Two radiocarbon dates from the Malaya Khadata site: 6745 ± 70 (Tln-84) and 6315 ± 70 (Tln-64) yr BP date this interval to roughly 6700–6300 ^{14}C yr BP, which correlates well with palaeodata from arctic and subarctic areas of northern Eurasia (e.g. Velichko et al. 1997; Andreev & Klimanov 2000; Andreev et al. 2002, 2004 and references therein). The peaks of birch pollen in PZ-IV most likely have a similar age. A radiocarbon date of 6020 ± 200 ^{14}C yr BP from the overlying peat layer confirms such a conclusion.

The highest values of *Picea* pollen in the peat sediments, dated to c. 6200–5800 ^{14}C yr BP, suggest the maximum distribution of spruce in the region and the warmest climate at the study site during the Holocene. The pollen records and radiocarbon ages (6280 ± 70 (Tln-83)) and 5680 ± 120 (Tln-56)) from the Malaya Khadata site reflect a similar environment (Surova et al. 1975).

Deposits much younger than 6000 yr BP are absent at Chernaya Gorka, probably because of erosion of the palsa. According to Surova *et al.* (1975), degradation of the spruce forest in the Polar Ural Mountains took place during the Subboreal as a result of climate deterioration. The forest stands retreated farther from the valleys of the Polar Ural Mountains and tundra communities spread once again. The increased proportion of *Pinus* pollen can be interpreted as being due to long-distance transport from enhanced atmospheric circulation and/or movement of pine trees to the north. They assume a cooling of the climate and an increase of precipitation (particularly snow). The thicker snow cover resulted in the degradation of forests and in the resumed formation of mountain glaciers in the Polar Urals Mountains (Surova *et al.* 1975). A similar vegetation development is reconstructed from the preliminary pollen analysis of Chernyi Ruchey brook and Utinoye Lake (V. Jankovská, unpublished).

Local palsa development

According to Surova *et al.* (1975), the freezing of peat bogs in the Polar Ural Mountains started prior to 2500 ¹⁴C yr BP. The formation of permafrost in conditions of heavy water logging resulted in the upheaval of peat bogs and the formation of cryogenic structures of the palsa type. Subsequently, peat formation on the palsa stopped and the section elevated above the terrain became exposed to wind erosion, leading to degradation of the palsa. The conditions responsible for the development of vegetation and the extent and form of the palsa towards the end of the Atlantic can only be speculated upon because of missing late Holocene deposits. A feasible assumption is that peat growth continued during the Subboreal when the climate turned colder, but also that increasingly more of the peat became frozen. Eventually, the core remained frozen even during the summer, protected from thawing by the insulating outer peat layers. The growing ice then pushed the lake and peat deposits upwards, and a classic palsa was formed.

The gradual decline and disappearance of spruce forests in the valleys of the Polar Ural Mountains during the Subboreal period under conditions of cooling opened up the landscape, the palsa hence becoming exposed to the devastating effects of the deteriorating climate. The uppermost surface and slopes of the palsa became rather distant from the ground-water level, and peat formation stopped. Surficial peat layers gradually dried out during the summer, cracks were formed and mineralization took place. The sediment on top of the palsa protruding above the snow was exposed to wind erosion in winter. In addition, the originally frozen core of the palsa started thawing on the south side during summer. Thus, the south-exposed slope of the palsa thawed and a pool was formed. The eroding palsa gradually collapsed into this pool. At present, sub-

merged vegetation in the pool (mostly *Sphagnum* and *Eriophorum russeolum*) forms new peat deposits. The peat deposits of the original palsa are disintegrated and have been redeposited (collapsing in whole blocks, washing out by rain, blowing off by wind) in the present lake environment, mixed with pollen produced by recent vegetation.

Conclusions

An initial oligotrophic lake, formed *c.* 9800–9500 ¹⁴C yr BP, was surrounded by a rim of willows, but tundra communities dominated the vegetation in the area. Dry microenvironments and disturbed soil habitats supported *Artemisia* and *Chenopodiaceae*. Tree birch and larch might have grown in low elevations close to the lake.

The original lake basin started to fill in *c.* 9500 ¹⁴C yr BP. Algae (mostly *Pediastrum* and *Botryococcus*) started to expand in the lake coincident with climate amelioration. However, mosses (mostly *Calliergon* and *Drepanocladus*) were most important for the lake infilling, which finished *c.* 8600 ¹⁴C yr BP. When the lake almost completely disappeared, *Menyanthes trifoliata*, *Comarum palustre* and *Cyperaceae* also contributed to the infilling. Climate amelioration also resulted in vegetation changes around the lake as willow stands strongly developed and the role of tree birch increased.

Peat accumulation started *c.* 8600 ¹⁴C yr BP with Bryales mosses; later *Sphagnum* became dominant. Peat mainly consisting of *Sphagnum* was formed up to *c.* 8000 ¹⁴C yr BP. The continuously rising temperatures enabled the spread of more climatically and hydrologically demanding vegetation. Tree birch began to spread in the tundra. Stands of *Larix*, *Picea* and *Betula* became well developed during the Boreal climate optimum.

Various Bryales mosses formed peat *c.* 8000–6500 ¹⁴C yr BP; later *Cyperaceae* became the main peat-forming element. Dense canopies of spruce stands with *Larix sibirica* and *Betula pubescens* surrounded the study site during the Atlantic period. Summer temperatures may have been up to 3–4°C higher than today. A decline in spruce and an increase in birch at *c.* 6700–6300 ¹⁴C yr BP point to some cooling at that time.

Deposits dated younger than 6000 ¹⁴C yr BP are absent at Chernaya Gorka, probably because of wind erosion. Climate probably became colder during the Subboreal period, supporting the development of permafrost that resulted in the upheaval of the lake and peat sediments. When the palsa formed, peat accumulation stopped at the site. The deposits, protruding above the surrounding terrain, were subjected to erosion by wind, water and cryogenic action.

Such reconstructions are important for understanding regional and local environmental trends in the high

Arctic regions. Moreover, they provide a basis for prediction of the future changes there, which is especially important for the Arctic areas of West Siberia, where anthropogenic influence has strongly increased during recent decades.

Pollen and non-pollen microfossils have been successfully used in this study for the precise reconstruction of local palaeoenvironments demonstrating new possibilities for the interpretation of palynological assemblages. It is especially important for understanding regional and local environmental trends in swampy regions of West Siberia, where paludification processes are common.

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