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Paleoenvironmental Changes in Northeastern Siberia during the Late Quaternary – Evidence from Pollen Records of the Bykovsky Peninsula

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Summary: New pollen and radiocarbon data from the Bykovsky Peninsula document the Late Pleistocene and Holocene environmental history of the Laptev Sea coast. More than 60 AMS-^{14}C and conventional ^{14}C dates indicate that the deposits accumulated during the last 60,000 radiocarbon yr BP. High concentration of green alga colonies (*Pediastrum* and *Botryococcus*) in the investigated sediment show that sedimentation was mostly in shallow water environments. Scarce grass and sedge communities dominated the vegetation 53-60 kyr BP. Climate was cold and dry. Open Poaceae and Cyperaceae associations with Asteraceae, Ranunculaceae, and Cichoriaceae, dominated in the area about 48-42.5 kyr BP. Steppic communities with *Artemisia* and shrubby tundra communities with *Salix* and *Betula* sect. *Nanae* were also present. Climate was dry, but relatively warm. Vegetation cover became denser about 42.5-33.5 kyr BP, reflecting more favorable climate conditions. Scarce Poaceae communities with some Caryophyllaceae, Asteraceae, Cichoriaceae, and *Selaginella rupestris* covered the Bykovsky Peninsula area during the Sartan (Late Weichselian) stage about 26-16 kyr BP. Disturbed, uncovered soils were very common in the area. Climate was extremely cold and dry. Poaceae and Cyperaceae associations with Caryophyllaceae, Asteraceae, Cichoriaceae dominated the vegetation in the late Sartan, ca 16-12.2 kyr BP. Climate was significantly warmer than in the early Sartan time. The Ice Complex sedimentation was interrupted about 12 kyr BP; most likely it was connected with the beginning of the Allerød warming. Shrubby (*Betula* sect. *Nanae, Alnus fruticosa, Salix,* Ericales) tundra was widely distributed on the Bykovsky Peninsula during the early-middle Holocene. Climate was most favorable between 8200 and 4500 yr BP. Vegetation became similar to modern after 4500 yr BP, suggesting a deterioration of climate.

Zusammenfassung: Neue Pollen- und Radiokarbondaten von der Bykowsky-Halbinsel dokumentieren die spätpleistozäne und holozäne Umweltgeschichte der Laptewseeküste. Mehr als 60 AMS-^{14}C- und konventionelle ^{14}C-Datierungen deuten darauf hin, dass die Ablagerungen während der letzten 60.000 ^{14}C-Jahre vor heute (v.h.) akkumuliert wurden. Hohe Konzentrationen an Grünalgenkolonien (*Pediastrum* und *Botryococcus)* in den untersuchten Sedimenten zeigen, dass sie meistens in flachem Wasser abgelagert wurden. Spärliche Gras- und Riedgras-Vergesellschaftungen dominierten die Vegetation um 53.000 bis 60.000 Jahre v.h.. Das Klima war kalt und trocken. Offene Poaceae- und Cyperaceae-Assoziationen mit Asteraceae, Ranuculaceae und Cychoriaceae überwogen im Gebiet um 48.000 bis 42.500 Jahre v.h.. Steppenvergesellschaftungen mit *Artemisia* und Strauchtundrenvergesellschaftungen mit *Salix* und *Betula* sect. *Nanae* traten ebenfalls auf. Das Klima war trocken aber relativ warm. Die Pflanzendecke wurde um 42.500 bis 33.400 Jahre v.h. dichter und widerspiegelt günstigere Klimabedingungen. Spärliche Poacea-Vergesellschaftungen mit etwas Caryophyllaceae, Asteraceae, Cichoriaceae und *Selaginella rupestris* bedeckten das Gebiet der Bykowsky-Halbinsel während des Sartan-Stadiums (Spätweichsel) um 26.000 bis 16.000 Jahre v.h.. Gestörte, unbewachsene Böden waren in diesem Gebiet weit verbreitet. Poacea- und Cyperaceae-Vergesellschaftungen mit Caryophyllaceae, Asteraceae, Cichoriaceae dominierten die Vegetation im späten Sartan um ca. 16.000 bis 12.000 Jahre v.h.. Das Klima war deutlich wärmer als im frühen Sartan. Die Eiskomplexbildung war um 12.000 Jahre v.h. unterbrochen, wahrscheinlich im Zusammenhang mit dem Beginn der Alleröd-Warmzeit. Eine Strauchtundra (*Betula* sect. *Nanae, Alnus fruticosa, Salix,* Ericales) war während des frühen bis mittleren Holozän auf der Bykowsky-Halbinsel weitverbreitet. Das Klima war zwischen 8.200 und 4.500 Jahren v.h. am günstigsten. Die Vegetation wurde nach 4.500 Jahre v.h. ähnlich der heutigen, was auf eine Klimaverschlechterung hinweist.

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INTRODUCTION

Despite increased research over the last decades, the paleoenvironment of Arctic Yakutia during the Late Pleistocene is still under discussion. Little is known about the environmental conditions during the sedimentation of ice-rich permafrost deposits (yedoma, Ice Complex). The deposits of up to 40 m thickness with large ice wedges are widely distributed in the Northern Yakutia (ROMANOVSKY 1993). Various hypotheses have been suggested to explain the origin and age of this formation, the most popular being the fluvial, eolian and polygenetic hypotheses.

Although a number of various studies were conducted on the Bykovsky Peninsula ice-rich deposits (TOMIRDIARO & CHERNEN'KIY 1987, SLAGODA 1993, SIEGERT et al. 1999) the genesis of the Ice Complex is still being debated. Palynological analysis is especially important for reconstruction of paleoenvironmental conditions during the formation of the sediments and may give a key information about its origin.

Palynological studies have already been done on ice-rich sections in the Northern Yakutia: GITERMAN 1976, 1977, LOZHKIN 1977, SHER et al. 1977, KAPLINA 1979, KAPLINA et al. 1978, 1980, KAPLINA & GITERMAN 1983, TOMIRDIARO 1980, RYBAKOVA & KOLESNIKOV 1983, RYBAKOVA & PIRUMOVA 1986, ALEKSEEV 1989, 1997, MAKEYEV et al. 1989, IGARASHI et al. 1995, ANDREEV et al. 2001b and others. Unfortunately, only a few of them are relatively well radiocarbon dated and at high-resolution, making difficult the correlation of the reconstructed environmental changes.

To improve our knowledge about the Late Quaternary environmental history of Northern Yakutia, the multidisciplinary research project „Paleoclimate signals in ice-rich permafrost“ was established within the German-Russian science cooperation „Laptev Sea System 2000“ in 1998. Within the scope of the project palynological studies of terrestrial permafrost sequences were carried out at a key stratigraphic section „Mamontovy Khayata“ on the Bykovsky Peninsula. The section lies northeast of the town Tiksi, Sakha Republic, Russia (Fig. 1). Here

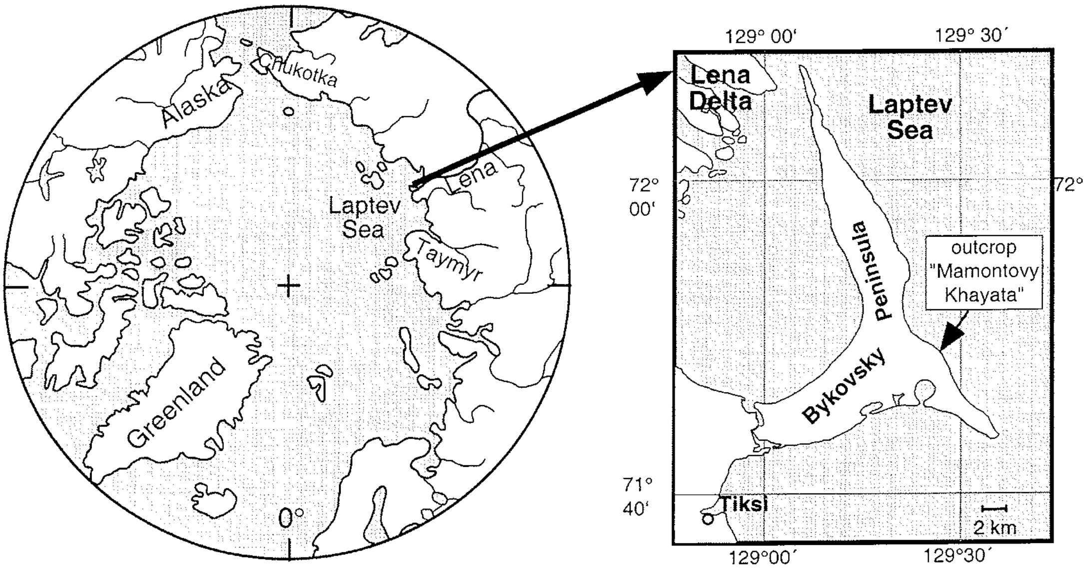

Fig. 1: Map of Arctic (A) and Tiksi region (B), showing the location of the Mamontovy Khayata site.

Abb. 1: Karte der Arktis (A) und Region um Tiksi (B) mit dem Standort des Aufschlusses „Mamontovy Khayata".

we present new palynological data and their AMS and conventional radiocarbon ages for this key site. The pollen spectra of the Mamontovy Khayata section record trends and oscillations in vegetation and climate since about 60 radiocarbon kyr BP, and give new information about the sedimentation environment during their formation.

STUDY AREA

The Mamontovy Khayata site is centrally located on the Laptev Sea coast of the Bykovsky Peninsula between 71° 40' - 71° 80' N and 129°-129° 30' E (Fig. 1). Coastal and thermokarst erosion has created up to 40 m high coastal cliffs, trending NNW-SSE, and extending intermittently for about 2 km.

The Ice Complex deposits consist of ice-rich, silty sands. Based on the intensity of pedogenetic processes as well as on the content of plant remains three different levels within the Ice Complex unit can be distinguished (Fig. 2). The middle part is characterized by the presence of peat lenses and numerous peaty paleosols whereas the lower and the upper parts contain fewer peat inclusions and other plant fossils and are only slightly influenced by soil formation. The top of the Ice Complex is covered by a sandy horizon. The studied deposits contain large amounts of ground ice in the form of massive polygonal ice wedges and have segregated ice in the sediment. The observed thick-banded and lens-like reticulated cryostructure is typical for sediments formed in poorly drained landscapes with near-surface position of the permafrost table. The deposits, especially paleosols are disturbed by cryoturbation in a thickness of 0.5-1 m. The banded ice and sediment layers are bent upwards up to 2 m from the horizontal position on the contact with ice wedges. Thermokarst and thermal erosion during the Holocene partly denuded the Ice Complex. Middle-grained sands were deposited in such thermokarst depressions and thermoerosional valleys. They are covered by peat layers or peaty cryosols (Fig. 2).

The modern climate of the area is characterized by long (8 month), severe winters, and short, cold summers with about 9 °C for July temperatures, -32 to -34 °C for January temperatures, and about 200-300 mm for annual precipitation (Atlas Arktiki 1985). Soils in the area are mainly tundra-gley and peaty-gley (histosols and inceptisols) with an active-layer thickness of about 30-40 cm (Atlas Arktiki 1985). Permafrost has a thickness of 500-600 m (Grigoriev et al. 1996). This area belongs to the zone of northern tundra (Atlas Arktiki 1985). Moss-grass-low shrub tundra dominates the vegetation, with vascular plant species such as *Betula exilis*, *Dryas punctata*, *Salix pulchra*, *Cassiope tetragona*, *Oxyria digyna*, *Alopecurus alpinus*, *Poa arctica*, *Carex ensifolia*, *C. rotundifolia*, and *Eriophorum medium*, mosses such as *Aulacomnium turgidum*, *Hylocomium alaskanum*, *Drepanocladus iniciatus*, and *Calliergon sarmentosum*, and lichens such as *Alectoria ochroleuca*, *Cetraria cuculliata*, and *C. hiascus*

FIELD AND LABORATORY METHODS

Ice Complex deposits of the Mamontovy Khayata site were investigated during the 1998 through 2000 field seasons. Because of their cryogenic structure it was not possible to collect samples from one continuous section. Therefore samples were taken on single thermokarst mounds, in which hummocks remain after melting of surrounding ice wedges. Sections were described and sampled for pollen, radiocarbon and other analyses after cleaning the undisturbed perennially frozen ground. The detailed descriptions of the sampled sections are published already (Siegert et al. 1999, Sher et al. 2000).

Out of a total number of 102 samples analyzed for palynomorphs, 61 were radiocarbon dated (Tab. 1). Their ages span from more than 59 kyr BP to the modern time.

Several continuous subsequences are presented as pollen diagrams (Figs. 4 through 9). In addition we created a generalized pollen diagram (Fig. 3) using the radiocarbon ages of the samples in order to present all radiocarbon dated pollen samples from the Mamontovy Khayata deposits. Because of the disturbation of the deposits as well as the assumed bumpy paleore-

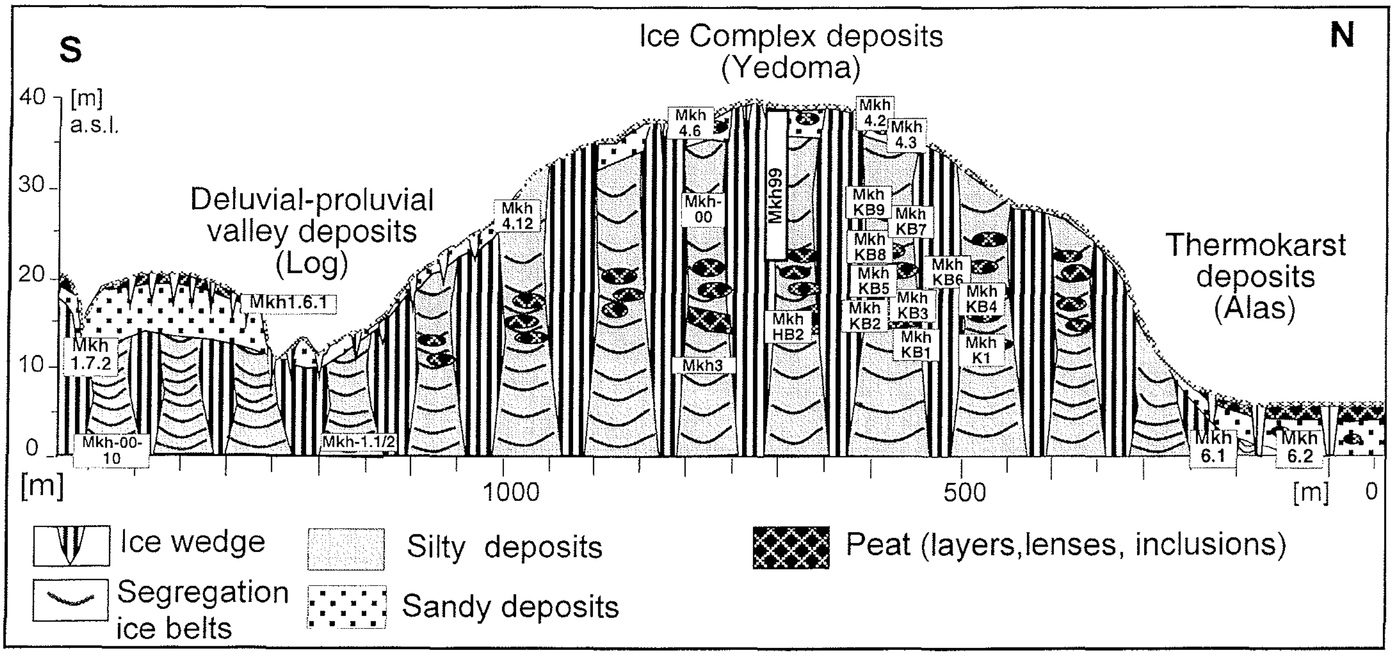

Fig. 2: Generalized section of Late Quaternary sediments of the Mamontovy Khayata outcrop with the positions of the sections investigated for pollen.

Abb. 2: Generalisierter Schnitt der spätquärtären Sedimente des Aufschlusses „Mamontovy Khayata" mit den Positionen der pollenanalytisch untersuchten Teilprofile.

lief of the former landscape (nets of large ice wedge polygons) there are some differences between the pollen sample diagram presented by altitudes and that as presented by ages. Nevertheless, it seems that our paleoenvironmental reconstructions are independent of the method of presentation of the pollen data; either method points to the same conclusions. In this case the age sequence seems to be more objective than the altitude sequence.

Pollen samples were prepared using standard techniques (FAEGRI et al. 1989). Modifications involved: multiple treatments of cold HF for samples (ca 1 cm^3) with high silica content, up to 7 days each, punctuated by rinses with concentrated HCl; followed by two minutes of acetolysis and glycerin mounts. For each sample, 200-300 terrestrial pollen grains were counted at 400 x magnification, and spores were tallied in addition. The relative frequency of pollen was calculated based on the tree and herbs pollen sum; the percentage of spores was based on the sum of pollen and spores; the percentage of redeposited taxa (Tertiary spores and Pinaceae) was based on the sum of pollen and redeposited taxa, and the percentage of algae was based on the sum of pollen and algae (BERGLUND & RALSKA-JASIEWICZOWA, 1986). The TILIA plotting program was used for graphing the pollen data (GRIMM 1991). Then the original diagrams were re-drawn with CorelDraw software. Pollen zonation was done by visual inspection.

RESULTS

Pollen zonation was made only in the generalized pollen diagram (GPD) (Fig. 3) and in the Mh-99 section (Fig. 4). No pollen zonation was made in the other investigated sequences (Figs. 5 through 9) as all samples belong to the same zones.

Pollen zone I (PZ-I) of the GPD includes 4 samples, radiocarbon dated earlier than 52.9 yr BP. This zone is notable for large amounts of reworked indeterminate Pinaceae. Poaceae and Cyperaceae pollen dominated in the pollen spectra. In addition, a relatively high content of *Pediastrum* colonies was observed in this zone. PZ-II of the GPD (48-33.5 kyr BP) is characterized by dominance of Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, *Artemisia*, *Saxifraga*, and presence of *Salix*, *Betula* sect. *Nanae* pollen, *Selaginella rupestris* spores. A high concentration of green alga colonies (*Pediastrum* and *Botryococcus*) is also typical for this zone. PZ-III of the GPD includes only two samples, radiocarbon dated to 28,470 and 28,110 yr BP. It is marked for a clear increase in *Selaginella rupestris* and *Equisetum* spore contents, while Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, and Ranunculaceae dominated the spectra. PZ-IV of the GPD (25.6-16 kyr BP) is characterized by a dramatic increase in reworked indeterminate Pinaceae, an increase in Poaceae, Cichoriaceae pollen and *Selaginella rupestris* spore percentages, while Cyperaceae and *Artemisia* pollen percentages decreased significantly. High concentration of green alga colonies (*Pediastrum* and *Botryococcus*) is also typical for this zone. PZ-V of the GPD (15-12.2 kyr BP) is noticeable by an increase of Cyperaceae and Ericales pollen contents. A large number of *Encalypta* spores is also noticeable in this zone. PZ-VI of the GPD (8200 yr BP to modern) is characterized by a dramatic increase in tree and shrub pollen (*Betula* sect. *Albae*, *B.* sect. *Nanae*, *Alnus fruticosa*, *Salix*) as well as Ericales pollen in the lower part of the zone. A relatively large number of *Encalypta* spores is also noticeable in this subzone. Decrease of *Betula* sect. *Albae*, *B.* sect. *Nanae* and *Alnus fruticosa* pollen contents occur in the upper subzone, while the role of long distance transported pollen of *Picea* and *Pinus* increases in the spectra.

	Sample ID	Material	Altitude a.s.l. (m)	Age	Lab. Number
1	MKh-1.2-1	peat, woody remains	2.70	58,400 +4960 /-3040	KIA 6730
2	MKh00-10-1	plant remains	0.20	57,180 +5330 /-3180	KIA 12509
3	MKh00-10-5	plant remains	1.70	54,930 +4280 /-2780	KIA 12510
4	MKh-1.1-2	plant remains	3.40	52,870 +3600 /-2480	KIA 6729
5	MKh-6.1-2	woody remains	1.30	>52,900	KIA 6731
6	MB-6.3-1	plant remains	1.50	47,400 +2730 /-2030	KIA-6737
7	MKh-KB1-2	woody remains	13.00	48,140 +2090 /-1650	KIA 6703
8	MKh-KB1-4	woody remains.	13.75	44,580 +1290 /-1110	KIA 6704
9	MKh-K1-5	moss remains	10.50	45,300 +1200 /-1050	KIA 8160
10	Mhh-K1-12	woody remains	13.00	47,900 +1630 /-1360	KIA 6702
11	MKh-K1-16	plant remains	13.35	42,630 +980 /-870	KIA 6701
12	MKh-3	peat	10.00	45,090 +2770 /-2060	KIA 6727
13	MKh-KB2-2	moss remains	14.80	44,280 +1320 /-1130	KIA 6705
14	MKh-HB2-2	peat	15.05	41,740 +1130 /-990	KIA 6726
15	MKh-HB2-4	peat	15.25	>43,080	KI-4427.013
16*	MKh-HB2-8	peat	15.55	41,390 +2470 /-1890	KI-4427.029
	MKh-HB2-8	peat	15.55	>39,500	KI-4427.023
	MKh-HB2-8	peat	15.55	36,350 +2340 /-1810	KI-4447.02
17	MKh-HB2-10	peat	15.75	>38,610	KI-4427.033
18	MKh-KB3-1	peat, woody remains	15.00	39,320 +600 /-560	KIA 6706
19	MKh-KB5-2	woody remains.	17.20	37,760 +490 /-460	KIA 6709
20	MKh-KB5-2	peat, plant remains	17.20	37,010 +530 /-500	KIA 6710
21	MKh-KB4-4	plant remains	16.00	35,860 +610 /-570	KIA 6707
22	MKh-KB4-6	woody remains	17.20	36,800 +480 /-450	KIA 6708
23	MKh-KB6-3	peat and plant remains	18.40	36,020 +450 /-420	KIA 6711
24	CM-1.2-1	plant remains	24.00	35,050 +340 /-330	KIA 8164
25	MKh-KB8-3	woody remains	18.50	35,050 +390 /-370	KIA 6714
26	MKh-KB8-4	woody and plant remains	17.50	34,800 +340 /-330	KIA 6715
27	MKh-KB7-3	woody remains	20.70	33,450 +260 /-250	KIA 6712
28	MKh-KB7-5	woody remains	22.30	33,580 +240 /-230	KIA 6713
29	MKh-KB9-3	woody remains	22.25	28,470 ±160	KIA 6716
30	MKh-4.12-2	peat	24.10	24,460 +250 /-260	KIA 6721
31	MKh-4.12-3	peat	26.00	4,455 ±35	KIA 8161
32	MKh99-20	plant remains	23.30	28,110 +230 /-220	KIA 10361
33	MKh99-18	plant remains	24.70	25,570 +170 /-160	KIA 10360
34	MKh99-16	plant remains	26.20	24,470 +160 /-150	KIA 10359
35	MKh99-14	plant remains	27.50	23,800 ±170	KIA 10358
36	MKh99-12	plant remains, twigs	28.80	22,060 ±150	KIA 10357
37	MKh99-10	twigs	30.20	20,600 +210 /-200	KIA 9197
38	MKh99-23	twigs	31.00	19,340 ±110	KIA 9196
39	MKh99-9	plant remains, twigs	32.60	17,350 ±130	KIA 10356
40	MKh99-8	twigs	33.30	17,160 ±90	KIA 9195
41	MKh99-6	plant remains	34.10	14,730 ±100	KIA 10355
42	MKh99-5	plant remains	35.30	13,920 ±100	KIA 9194
43	MKh99-4	plant remains	36.40	12,790 ±60	KIA 10354
44	MKh99-3	peat	37.00	7790 ±50	KIA 10353
45	MKh99-1	woody remains	37.60	7520 ±50	KIA 10352
46	MKh00-1	plant remains	37.60	18,490 ±150	KIA 12508
47*	MKh-4.3-4	peat	36.40	12,160 ±185	KI-4429.01
	MKh-4.3-4	peat	36.40	12,150 ±70	KI-4429.013
	MKh-4.3-4	woody remains	36.40	12,355 ±50	KIA 6719
48	MKh-4.2-3	woody remains	34.10	12,525 ±50	KIA 6718
49	MKh-4.6-1	peat and woody remains	37.00	8230 ±50	KIA 6720
50	MKh-4.6-2	peat	36.65	7310 ±65	KI-4856
51	MKh-6.1-6	peat	1.40	2910 ±30	KIA 6733
52	Mkh-6.2-6	peat	2.10	2885 ±30	KIA 6736
53	MKh-6.2-8	peat	2.25	2980 ±35	KI-4426.013
54	MKh-6.2-12	peat	2.52	2740 ±35	KI-4426.023
55	MKh-6.2-17	peat	2.78	3020 ±70	KI-4426.033
56	MKh-1.7.2-5	woody remains and peat	10.50	1400 ±60	KIA 6724
57	MKh-1.6.1-2	peat	17.20	1080 ±35	KIA 6722
58	MKh-1.6.1-3	peat	17.35	1105 ±35	KIA 6723
59*	MKh-1.6.1-4	peat	17.45	1220 ±60	KI-4428.01
	MKh-1.6.1-4	peat	17.45	1930 ±60	KI-4428.013
60	MKh-1.6.1-7	peat	17.75	1240 ±60	KI-4428.023
61	MKh-1.6.1-3	peat	18.05	1360 ±35	KI-4428.033

Tab. 1: Radiocarbon dated pollen spectra from Bykowsky Peninsula: Mamontovy Khayata (Mkh), Mamontovy Bysagasa (MB), and Cape Mammoth (CM); * sample age used in pollen diagram, when there is more than one age determination (SCHIRRMEISTER et al. 2002).

Tab. 1: Radiokarbon-datierte Pollenspektren der Bykowsky Halbinsel: Mamontovy Khayata (Mkh), Mamontovy Bysagasa (MB) und Kap Mammoth (CM); * im Pollendiagramm benutztes Alter, falls mehrere Datierungen vorliegen (SCHIRRMEISTER et al. 2002).

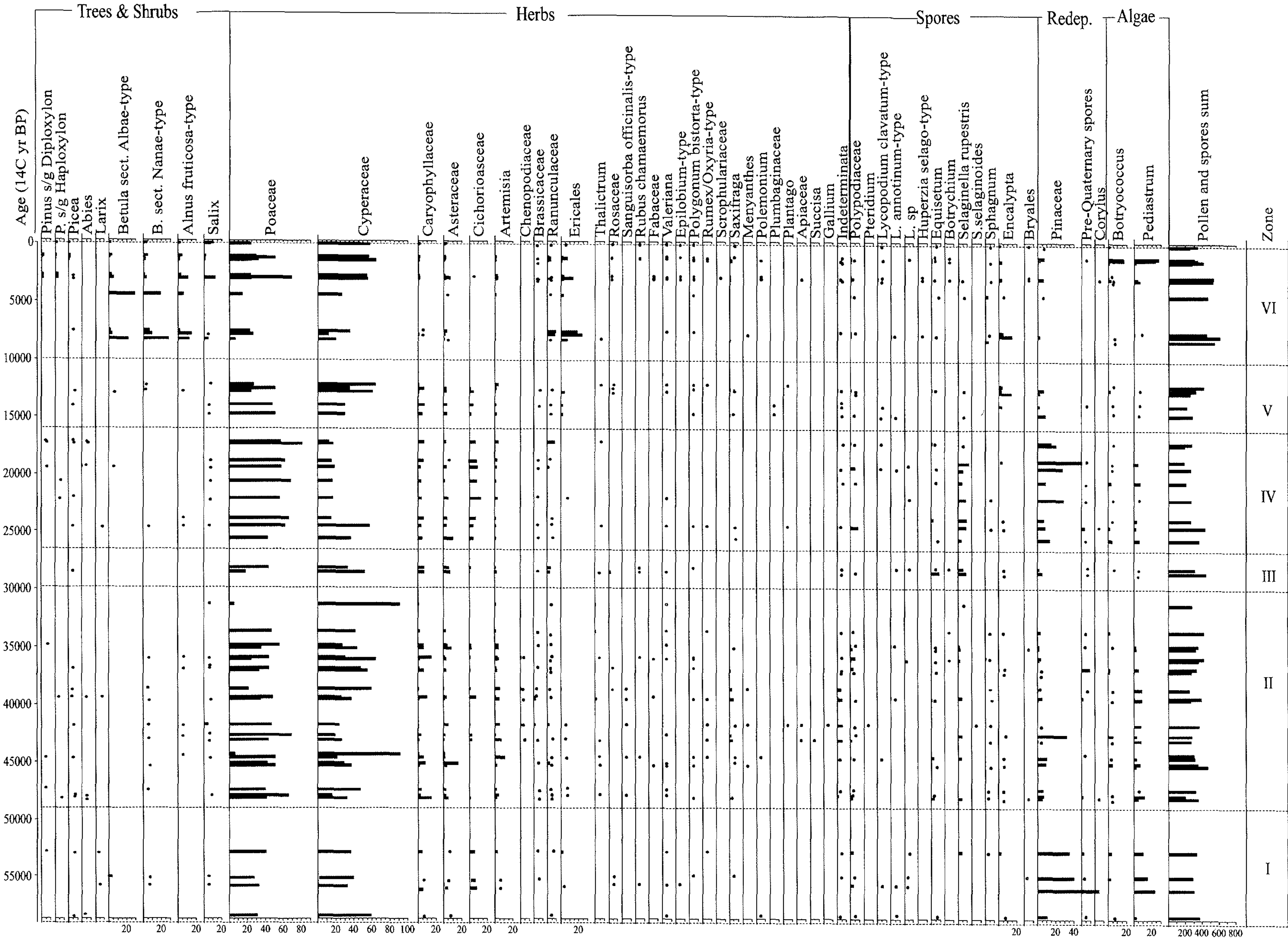

Fig. 3: Generalized percentage pollen and spore diagram of the Mamontovy Khayata sequences. • presence of pollen taxa with values less than 1 %.
Abb. 3: Generalisiertes Pollen- und Sporendiagramm der „Mamontovy Khayata"-Folge. • Pollen-Taxa mit Werten unter 1 %.

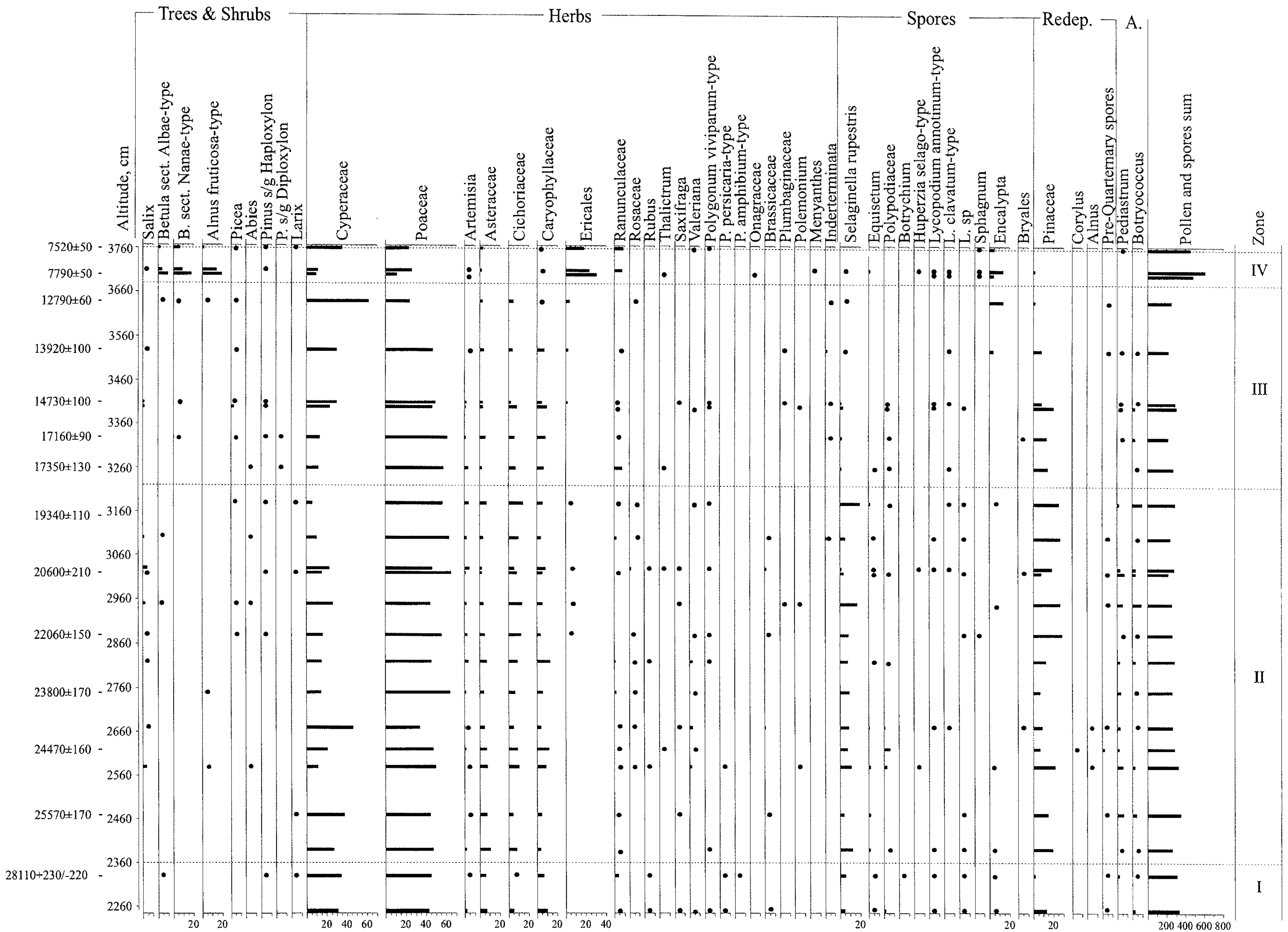

Fig. 4: Percentage pollen and spore diagram of the Mkh99 site. • presence of pollen taxa with values less than 1 %. **Abb. 4:** Pollen- und Sporendiagramm des Subprofils Mkh99. • Pollen-Taxa mit Werten unter 1 %.

The pollen diagram of the Mkh99 section was also zoned by visual inspection (Fig. 4). PZ-I of the Mkh99 includes only two samples (the upper one is radiocarbon dated to 28,110 +230/-220 yr BP). It is notable for a significantly low content of reworked indeterminate Pinaceae, Cichoriaceae pollen, and *Selaginella rupestris* spores, while Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, and Ranunculaceae dominated the spectra. Relatively low concentration of green alga colonies (*Pediastrum* and *Botryococcus*) is also notable in this zone. PZ II of the Mkh99 (ca 25.6-17.5 kyr BP) is characterized by a significant increase in reworked indeterminate Pinaceae pollen, an increase in Poaceae and Cichoriaceae pollen and *Selaginella rupestris* spore percentages. A relatively high concentration of green alga colonies (*Pediastrum* and *Botryococcus*) is also notable in this zone. In PZ III of the Mkh99 (ca 17.5-12.8 kyr BP) the concentration of *Selaginella rupestris* spore and green alga colonies decrease. A large number of *Encalypta* spores is also noticeable for the upper part of this zone. PZ VI of the Mkh99 (ca 8000-7500 yr BP) is characterized by a dramatic increase in tree and shrub pollen (*Betula* sect. *Albae*, *B.* sect. *Nanae*, *Alnus fruticosa*) as well as Ericales pollen. A relatively large number of *Encalypta* spores is also noticeable in this zone. The upper sample is characterized by a decrease of *Betula* sect. *Albae*, *B.* sect. *Nanae,* and *Alnus fruticosa* pollen contents.

DISCUSSION

The oldest radiocarbon ages from the Bykovsky Peninsula are 58,400 +4960/-3040, 57,180 +5330/-3180, 54,930 +4280/-2780, 52,870 +3600/-2480, and >52,900 yr BP. The sample dated to >52,900 yr BP was collected from the section of most likely reworked sediments and was not used for paleoenvironmental reconstruction.

Large amounts of reworked indeterminate Pinaceae characterized the samples of PZ I of the GPD (Fig. 3) and the pollen spectra of MkhOO-10 (Fig. 5). The large number of reworked Pre-Quaternary Pinaceae pollen indicates intense denudation of the Pre-Quaternary deposits, which are widespread in the Primorsky range near Tiksi. This is in a good agreement with the supposed fluvial character of the lowest Ice Complex deposits (SIEGERT et al. 2001). The high contents of reworked material probably also indicate a scarce vegetation cover around the site as well as an active erosion in the denudation area. Relatively high content of green alga colonies (*Pediastrum* and *Botryococcus*), typical inhabitants of shallow fresh water pools suggests an aquatic environment during sedimentation. Scarce grass and sedge communities poor in other taxa, dominated the vegetation ca 60-53 kyr BP. Climate was cold and dry.

The dominance of Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, *Artemisia*, and *Saxifraga* in PZ II (48-33.5 kyr BP) of the GPD (Fig. 3) and the pollen spectra

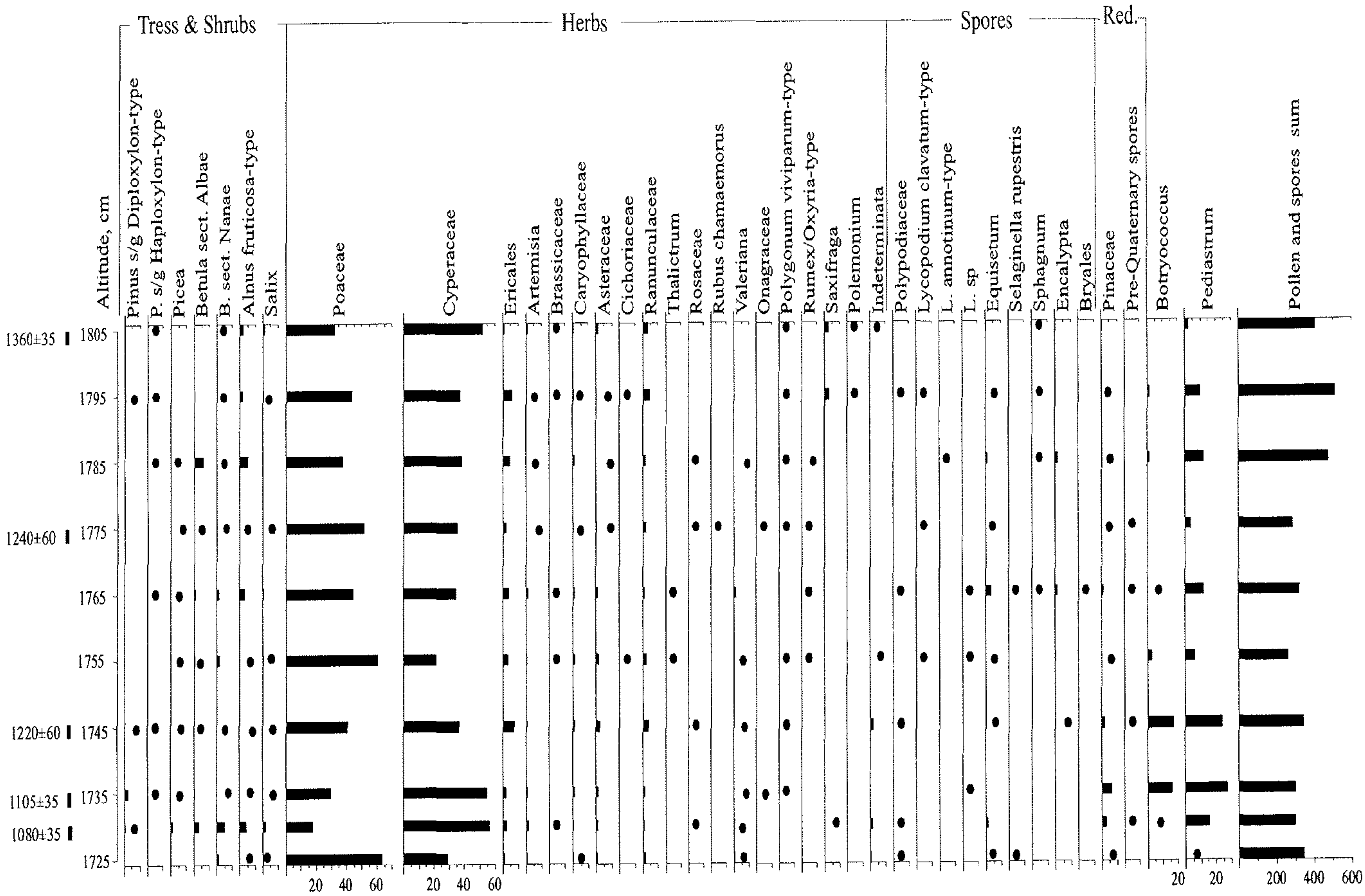

Fig. 5: Percentage pollen and spore diagram of the MkhOO-10 section. • presence of pollen taxa with values less than 1 %.

Abb. 5: Pollen- und Sporendiagramm des Subprofils MkhOO-10. • Pollen-Taxa mit Werten unter 1 %.

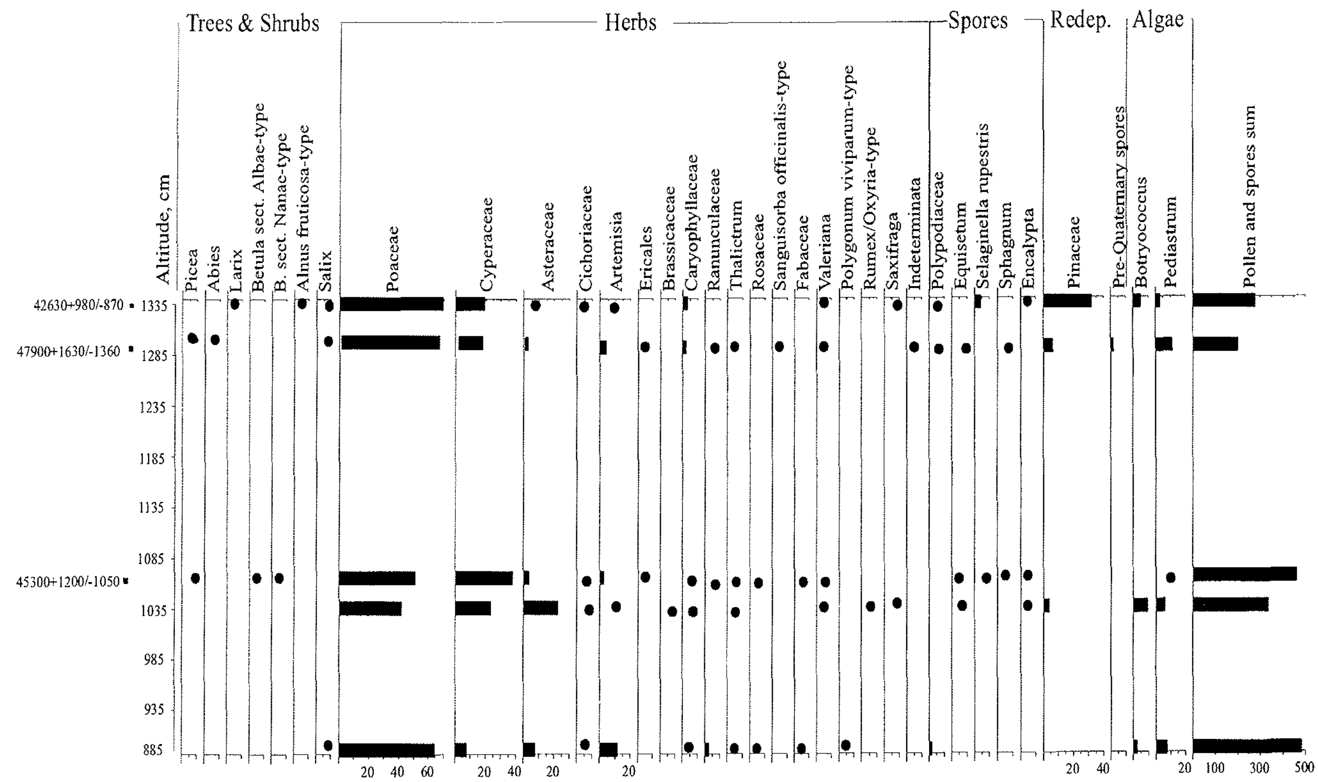

Fig. 6: Percentage pollen and spore diagram of the MkhK1 section. • presence of pollen taxa with values less than 1 %.

Abb. 6: Pollen- und Sporendiagramm des Subprofils Mkh K1. • Pollen-Taxa mit Werten unter 1 %.

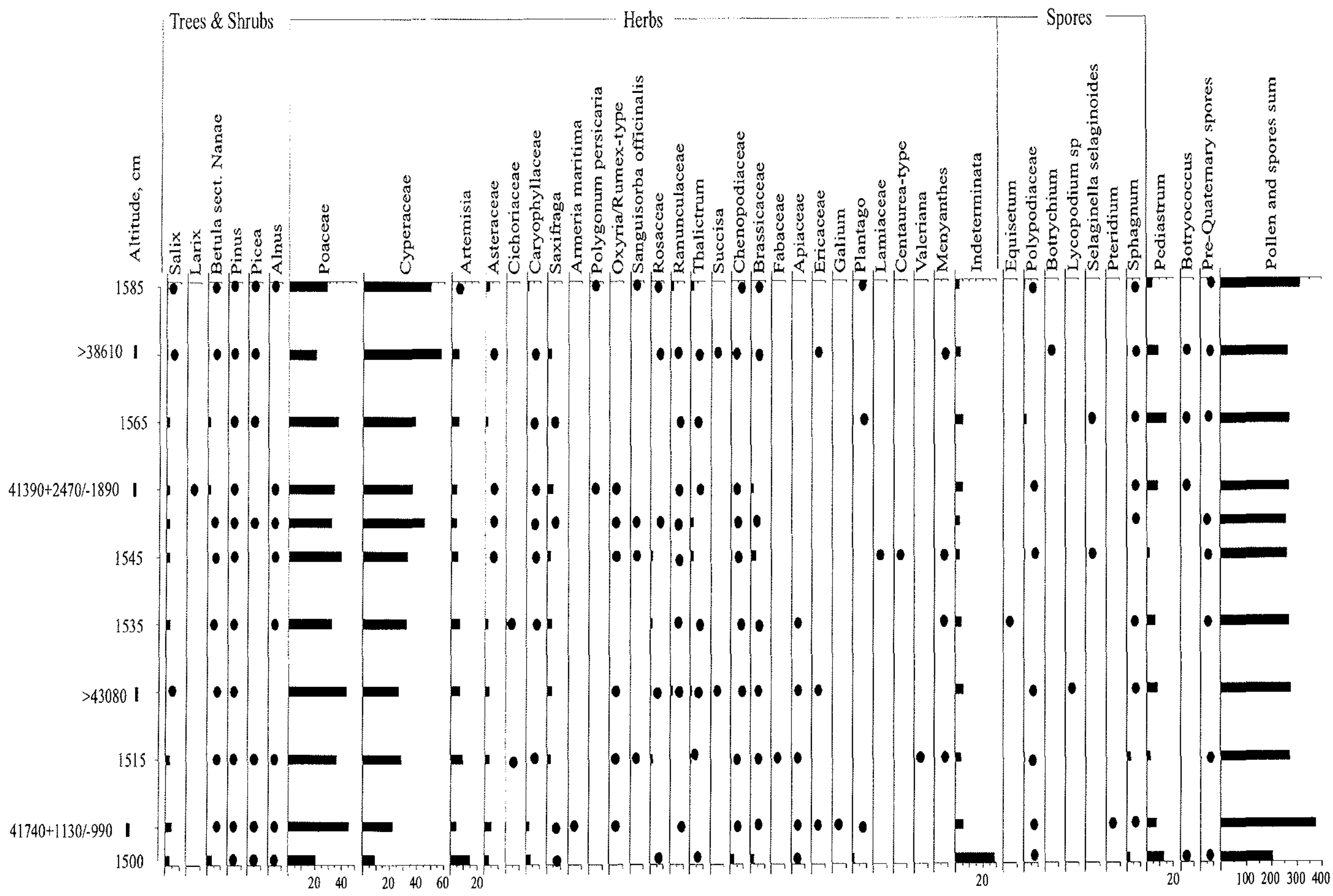

Fig. 7: Percentage pollen and spore diagram of the MkhHB-2 section. • presence of pollen taxa with values less than 1 %.

Abb. 7: Pollen- und Sporendiagramm des Subprofils Mkh HB2. • Pollen-Taxa mit Werten unter 1 %.

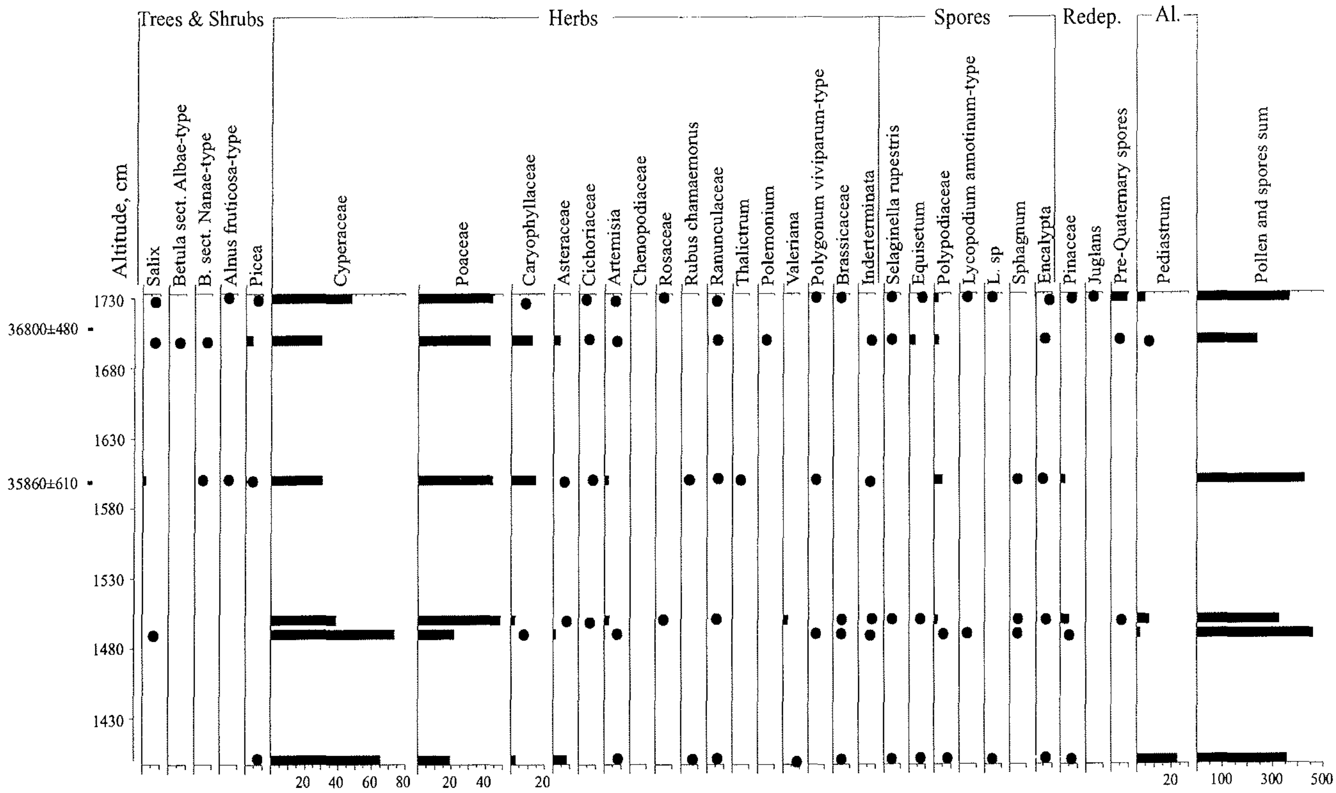

Fig. 8: Percentage pollen and spore diagram of the MkhK4 section. • presence of pollen taxa with values less than 1 %.

Abb. 8: Pollen- und Sporendiagramm des Subprofils Mkh K4. • Pollen-Taxa mit Werten unter 1 %.

of Mkh-K1 (Fig. 6), Mkh-HB2 (Fig. 7), and Mkh-KB4 (Fig. 8) sections suggests open, treeless vegetation. A relatively high content of *Artemisia* pollen (up to 15 %) reflects the presence of steppe-like vegetation. In addition, the presence of shrub taxa pollen (*Salix*, *Betula* sect. *Nanae*, and *Alnus fruticosa*) that shrub tundra communities were probably present in the vegetation as well. *Selaginella rupestris* spores, indicators of a very dry environment are also common in the spectra. A relatively high concentration of redeposited Pinaceae pollen in the samples, dated to 48-42.5 kyr BP is probably evidence of rather scarce vegetation cover in this time and of intense erosion of Pre-Quaternary (Paleogene) deposits in the surrounding area. Pollen spectra of two samples from the nearby situated Mamontovy Bysagasa and Cape Mammoth sites, radiocarbon dated to 47,400 +2730/-2030 and 35,050 +340/ -330 correspondingly, are very similar to the Mamontovy Khayata spectra.

High concentration of *Pediastrum* colony remains and permanent presence of *Botryococcus* indicates that the sedimentation was in shallow water bodies. Remains of hydrophilic rhizopods *(Difflugia globulosa, Arcella arenaria, Centropyxis platystoma, C. cassis, C. orbicularis* etc.) and ostracods (*Candona muelleri jacutica, C. rawsoni, C. levanderi, Limnocythere falcata, Eucypris dulcifons* and others*)* in many samples support this conclusion. It is important to note that *Botryococcus* colonies were also very abundant in all pollen spectra from the Oyagoskiy Yar section sediments, radiocarbon dated from >41,770 to 22,940 ±390 yr BP (IGARASHI et al. 1995).

Pollen spectra from the lower, undated part of the Bykovsky Yar diagram (below the radiocarbon date 33,040 ±810 yr BP (LU-1330), presented by TOMIRDIARO 1980), probably correspond to the 48-33.5 kyr BP zone of the generalized diagram. Although both diagrams show similar trends, it is difficult to compare them because of lack of radiocarbon dates in the Bykovsky Yar diagram, different sampling intervals, different pollen preparation techniques, and very different stile of presentation of pollen data. The main difference between two diagrams is huge amounts of so-called Bryales (spores of green mosses) in the Bykovsky Yar diagram. The presence of numerous small cysts of some algae (?) were noted in many samples from the Ice Complex of the Mamontovy Khayata site as well, but such cysts of unclear origin cannot be identified as Bryales. If so-called Bryales were removed from the Bykovsky Yar diagram, the diagram would be rather similar to ours.

Therefore, the pollen spectra show that open tundra-like Poaceae and Cyperaceae associations with some other herbs like Asteraceae, Ranunculaceae, and Cichoriaceae, dominated in the area about 48-42.5 kyr BP. Steppe-like communities with *Artemisia* and shrubby tundra communities with *Salix* and *Betula* sect. *Nanae* also were present in the vegetation cover. Later, 42.5-33.5 kyr BP, vegetation cover had probably become denser. The increase of pollen taxon diversity, reflecting high species diversity in the vegetation cover, is also evidence of a rather favorable climate. The wide-spread presence of som forest-zone rhizopods (e.g. *Cyclopyxix puteus* and *C. kahli* are distributed now only in forest and forest-steppe zones of Northern Eurasia) are also indicators of warmer summers. Climate was dry, but relatively warm, especially 42.5-33.5 kyr BP. Numerous remains of grazing mammals (KUZNETSOVA 2000) are also an oblique evidence of rather favorable climate condition and dense vegetation cover during this interval; the productivity of the plant communities should have been high enough to feed these grazing mammals.

This relatively warm interval seems to correspond well with the Karga (Middle Weichselian) interstade ca 48-33 kyr ago shown at other locations in northern Siberia (ISAEVA 1984, KAPLINA & LOZHKIN 1984, LOZHKIN 1987, ANDREEV et al. submitted). The colder interval, 48-42.5 kyr BP, does probably corresponds to the relatively cold interval during this interstade (LOZHKIN 1987, ANDERSON & LOZHKIN 2001). The warmer interval 42.5-33.5 kyr BP corresponds well to the optimum of the middle Karga interstadial (Malokhetskii warm interval) (KIND 1974, KAPLINA et al. 1978, ISAEVA 1984, LOZHKIN 1987 ANDERSON & LOZHKIN 2001).

There are only two radiocarbon dated samples (28,470 ±160 and 28,110 +230/-220 yr BP) for the 33.5-26 kyr BP interval (zone III of Fig. 3 and zone I of Fig. 4). Poaceae and Cyperaceae with Caryophyllaceae, Asteraceae, and Ranunculaceae dominated the pollen spectra, while the content of *Artemisia* pollen decreases. Peaks of *Selaginella rupestris* (indicator of dry uncovered soils) and *Equisetum* (mainly pioneer species on uncovered, disturbed soils) spores are notable in the spectra. The pollen spectra suggest that open Poaceae and Cyperaceae associations with some other herbs like Caryophyllaceae, Asteraceae, and Ranunculaceae dominated the area. Climate was dry and relatively cold. This period may be connected with a climate deterioration (Konoshelskii cool interval) that has been noted about 33-30 kyr BP in the adjacent regions (KAPLINA & GITERMAN 1983, ISAEVA 1984, LOZHKIN 1987, ANDERSON & LOZHKIN 2001, ANDREEV et al. submitted). This is also the time of the Zhigansk glacial advance in the Verkhoyansk Mountains (KIND et al. 1971).

A pollen spectrum from the peat layer of the Bykovsky Yar diagram (TOMIRDIARO 1980) radiocarbon dated to 28,500 ±1690 yr BP (LU-1329) contents high amounts of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix* pollen. Such spectra indicate that local wetland vegetation may have occurred in some well-protected places. Although the radiocarbon age of the dated sample is close to our radiocarbon dates, it is difficult to compare our pollen records with the spectrum from the peat layer of Bykovsky Yar. They reflect different environments and their actual ages may also be very different.

Pollen spectra from zone IV (25.6-16 kyr BP) of the GPD (Fig. 3) and from pollen zone II (ca 26-19 kyr BP) of the Mkh99 diagram (Fig. 4) contain many reworked indeterminate Pinaceae pollen grains, that may reflect a low pollen productivity of the local plant communities and/or a scarce vegetation cover. It can be assumed that scarce steppe-like Poaceae communities with some Caryophyllaceae, Asteraceae, Cichoriaceae covered the Bykovsky Peninsula. Indirect evidence of a very cold climate and scarce vegetation cover during this interval is a decrease in the remains of grazing mammals (KUZNETSOVA 2000). An increase of Cichoriaceae and *Selaginella rupestris* percentages proves that disturbed, uncovered soils were also common in the area. A relatively high content of *Pediastrum* and *Botryococcus* colonies indicates sedimentation in aquatic environment.

Pollen spectra from the Bykovsky Yar diagram (TOMIRDIARO 1980), radiocarbon dated to 21,630 ±240 (LU-1328) and 22,070 ±410 (LU-1263) yr BP and other radiocarbon dated pollen spectra from the north Yakutian Ice Complex deposits (KAPLINA & GITERMAN 1983, LOZHKIN 1987, IGARASHI et al. 1995, ANDERSON & LOZHKIN 2001) also suggest similar paleoenvironmental conditions. This cold interval corresponds to the Sartan (Late Weichselian) stage, observed in many Siberian regions (ANDERSON & LOZHKIN 2001).

Pollen spectra from the zone V (15-12 kyr BP) of the GPD (Fig. 3) and zone III (17.5-12.8 kyr BP) of the Mkh99 diagram (Fig. 4) are characterized by gradual decrease of reworked Pinaceae pollen, *Selaginella rupestris* spores and green alga colonies contents, and a slight increase of Cyperaceae and Ericales pollen contents. These changes suggest a denser vegetation cover than during the Last Glacial Maximum, although the large number of *Encalypta* spores in the upper part of the zones indicates the presence of disturbed soils in the area. A slight increase of Ericales and Cyperaceae presence in the vegetation probably reflects some amelioration of climate during this time. According to the pollen spectra, maximal warming was at about 12 kyr BP. This warming may correlate with the Allerød.

The Ice Complex sedimentation probably was interrupted about 12 kyr PB; most likely it was connected with the beginning of the Allerød warming. Unfortunately, there are no samples from the Mamontovy Khayata section dated between 12 and 8.2 kyr BP. This suggests a gap in the sedimentation or, more probably, broadly distributed processes of denudation and thermal erosion during the Younger Dryas and early Holocene.

Pollen spectra from the lower part of zone VI (8.2-4.5 kyr BP) of the GPD (Fig. 3) and the zone IV (8-7.5 kyr BP) of the Mkh-99 diagram (Fig. 4) are characterized by a dramatic increase of *Betula* sect. *Albae*, *B.* sect. *Nanae*, *Alnus fruticosa*, *Salix*, and Ericales pollen contents. Such changes suggest that a shrubby tundra or less likely an open birch forest was widely distributed in the Bykovsky Peninsula area during the early-middle Holocene. Birch tree remains from the Keliniar River area, radiocarbon dated to 8520 ±40 yr BP and from the Chekurovka area – 5610 ±200 yr BP (KREMENETSKI et al. 1998), as well as *Larix* remains from the Tiksi area, dated to 7744 ±35 yr BP and numerous *Larix* remains from the low Lena River region, dated between 7840 ±90 and 4200 ±70 yr BP (MACDONALD et al. 2000, PISARIC et al. 2001), all suggesting a northward movement of treeline in this region, are in agreement with our pollen records. The highest tree pollen percentages in the spectra, radiocarbon dated between 8230 ±50 and 4455 ±35 yr BP, reflect that climate conditions were most favorable during that time interval. The data are in good agreement with other pollen records from the region (ANDREEV et al. 2001a, PISARIC et al. 2001, SCHWAMBORN et al. 2001). Similar paleoenvironmental trends are mirroring in regional diatom records (LAING et al. 1999). A relatively high amount of *Encalypta* spores in our records reflects the presence of disturbed soils caused by solifluction and thermal erosion processes in the area about 8.2-7.8 kyr BP.

Pollen spectra from the upper part of zone VI (4500 yr BP - modern) of the GPD (Fig. 3) and the Mkh-1.6.1 (ca 1360-1100

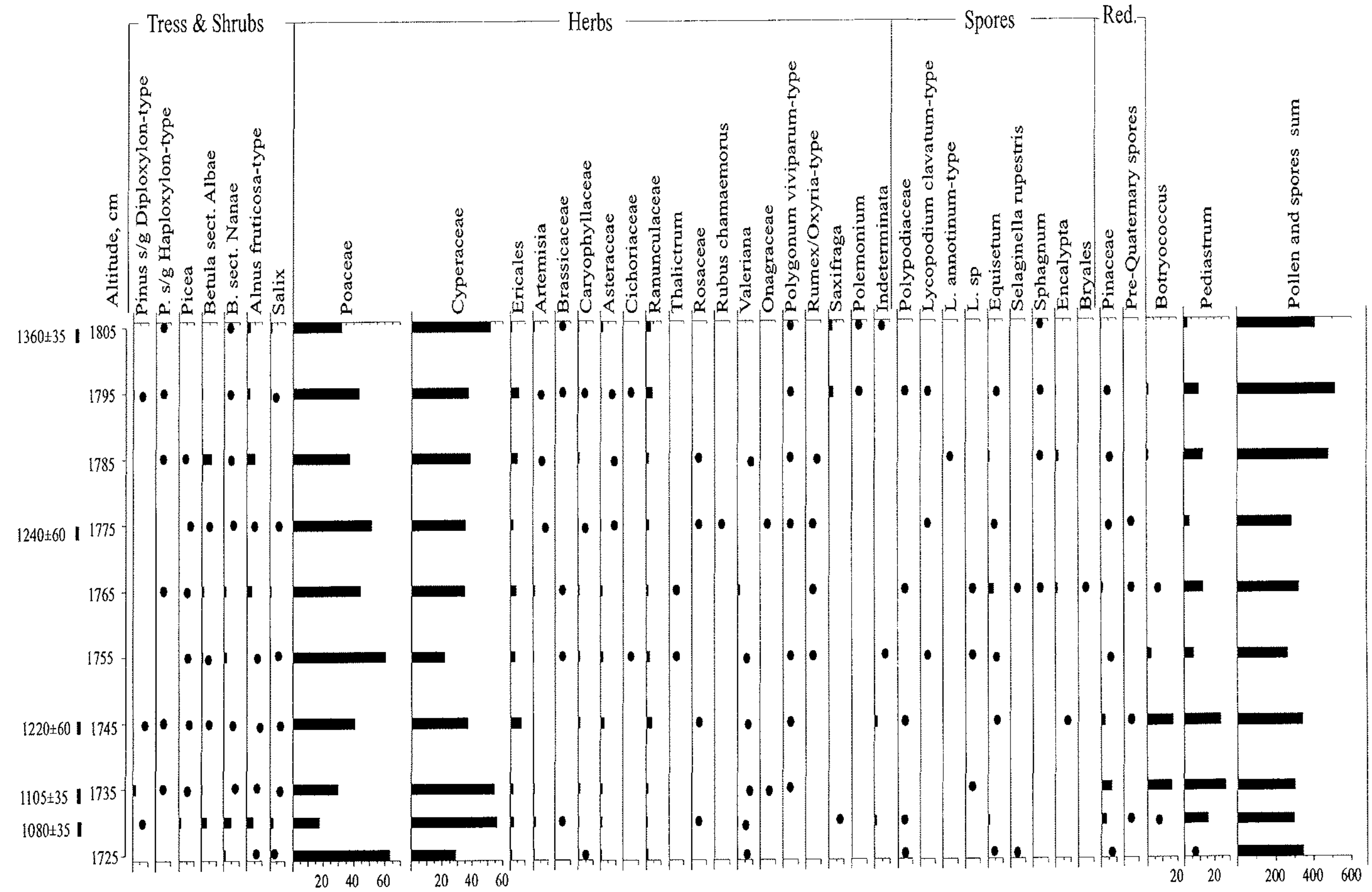

Fig. 9: Percentage pollen and spore of the Mkh1.6.1 section. • presence of pollen taxa with values less than 1 %.

Abb. 9: Pollen- und Sporendiagramm des Subprofils Mkh 1.6.1. • Pollen-Taxa mit Werten unter 1 %.

yr BP) diagram (Fig. 9) are characterized by decrease of *Betula* sect. *Albae*, *B.* sect. *Nanae,* and *Alnus fruticosa* pollen contents, while the role of long distance transported pollen of *Picea* and *Pinus* increase in the spectra. Vegetation became similar to the modern one at the beginning of the Subboreal period, after 4500 yr BP. These data are in the good agreement with other pollen records from the area (ANDREEV et al. 2001a, PISARIC et al. 2001, SCHWAMBORN et al. 2001). Such changes reflect a deterioration of climate about that time.

CONCLUSIONS

The presented results and discussions lead to the following general conclusions:

Apart from the Late Pleistocene/Holocene transition, there are no extreme changes in the vegetation cover of the studied area. Open tundra and steppe-like vegetation dominate over the entire interval of about 60 kyr. We did, however, divide this interval into eight distinct periods, which differ from one another by the density and diversity of the vegetation, the pollen productivity, and the presence of shrubs and disturbed soils (Tab. 2). These environmental fluctuations are in agreement with the conclusions from other paleoenvironmental archives like fossil seeds (KIENAST 2000), the history of the insect fauna (KUZMINA 2000) and the mammoth fauna (KUZNETSOVA 2000) as well as geochemical, mineralogical and sedimentological results (SIEGERT et al. 2002) and stable isotope analysis of ground ice (MEYER et al. 2001).

In many periods climate was colder and drier than today, but in some periods it was relatively warm. In general, the climate of Northeast Siberia was more continental than today because of the greater distance from the Arctic Ocean during the Late Pleistocene sea level sinking. Comparable paleoenvironmental tendencies are reconstructed by other authors in neighboring regions like Taymyr (ISAEVA 1984, ANDREEV et al. 2002), Yana-Indigirka, and Indigirka-Kolyma Lowlands (KAPLINA 1979, KAPLINA & GITERMAN 1983, LOZHKIN 1987, ANDERSON & LOZHKIN 2001). The repeated occurrence of shallow water indicators like green algae and ostracods reflect the local accumulation conditions of the studied Ice Complex deposits.

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Age ^{14}C yr BP	Characteristics of pollen spectra	Local environment	climate condition
60,000 - 53,000	- dominance of Poaceae and Cyperaceae pollen - high content of redeposited Pinaceae pollen - algae colonies (*Pediastrum* and *Botryococcus*)	- open treeless vegetation - scarce vegetation cover - shallow water environment	cold and dry
48,000 - 42,500	- dominance of Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, *Artemisia,* and *Saxifraga* - *Salix*, *Betula* sect. *Nanae*, and *Alnus fruticosa* pollen - *Selaginella rupestris* spores - relatively high content of redeposited Pinaceae pollen - algae colonies (*Pediastrum* and *Botryococcus*)	- tundra and steppe-like vegetation - shrubby tundra vegetation - very dry, uncovered soil - rather scarce vegetation cover - shallow water environment	dry, but warmer than during previous period
42,500 - 33,000	- low content of redeposited Pinaceae pollen - increase of pollen taxa diversity, - algae colonies (*Pediastrum* and *Botryococcus*)	- denser vegetation cover - higher plant taxa diversity - shallow water environment	dry and relatively warm
28,000 - 28,500	- Poaceae and Cyperaceae pollen with some Caryophyllaceae, Asteraceae, and Ranunculaceae - *Selaginella rupestris* - *Equisetum*	- open tundra and steppe-like vegetation - very dry, uncovered soil - uncovered disturbed soil	dry and cold
26,000 - 16,000	- high content of redeposited Pinaceae pollen, decreased Cyperaceae-pollen content - *Cichoriaceae* + *Selaginella rupestris* - *Encalypta* - algae colonies (*Pediastrum* and *Botryococcus*)	- scarce herb communities or/and their low pollen productivity - dry, uncovered soil - uncovered, disturbed soil - shallow water environment	extremely dry and cold
15,000 - 12,000	-decrease of reworked Pinaceae pollen, *Selaginella rupestris* spores and green algae colonies contents, slight increase of Cyperaceae and Ericales pollen contents - *Encalypta* - algae colonies (*Pediastrum* and *Botryococcus*)	- scarce herb communities or/and their low pollen productivity - uncovered, disturbed soil - shallow water environment	amelioration of climate
8,200 - 4,500	- dramatical increase of *Betula* sect. *Albae*, *B.* sect. *Nanae*, *Alnus fruticosa*, *Salix*, and Ericales pollen contents - *Encalypta*	- shrubby tundra and probably open birch forest (forest-tundra) - uncovered, disturbed soil	warmest and wettest climate conditions
4,500 - 0	- decrease of *Betula* sect. *Albae*, *B.* sect. *Nanae*, and *Alnus fruticosa* pollen content	- low shrub tundra	modern climate

Tab. 2: Vegetation and climate reconstruction for the last 60 kyr on the Bykovsky Peninsula.

Tab. 2: Vegetations- und Klimarekonstruktion der Bykowsky Halbinsel während der letzten 60.000 Jahre.

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