# Late Pleistocene and Holocene vegetation and climate on the northern Taymyr Peninsula, Arctic Russia

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BOREAS

Andreev, A. A., Tarasov, P. E., Siegert, C., Ebel, T., Klimanov, V. A., Melles, M., Bobrov, A. A., Dereviagin, A. Yu., Lubinski, D. J. & Hubberten H.-W. 2003 (September): Late Pleistocene and Holocene vegetation and climate on the northern Taymyr Peninsula, Arctic Russia. *Boreas*, Vol. 32, pp. 484–505. Oslo. ISSN 0300-9483.

Pollen data from a Levinson-Lessing Lake sediment core (74°28′N, 98°38′E) and Cape Sabler, Taymyr Lake permafrost sequences (74°33′N, 100°32′E) reveal substantial environmental changes on the northern Taymyr Peninsula during the last *c*. 32 000 $^{14}$C years. The continuous records confirm that a scarce steppe-like vegetation with Poaceae, *Artemisia* and Cyperaceae dominated *c*. 32 000–10 300 $^{14}$C yr BP, while tundra-like vegetation with *Oxyria*, Ranunculaceae and Caryophyllaceae grew in wetter areas. The coldest interval occurred *c*. 18 000 yr BP. Lateglacial pollen data show several warming events followed by a climate deterioration *c*. 10 500 $^{14}$C yr BP, which may correspond with the Younger Dryas. The Late Pleistocene/Holocene transition, *c*. 10 300–10 000 $^{14}$C yr BP, is characterized by a change from the herb-dominated vegetation to shrubby tundra with *Betula* sect. *Nanae* and *Salix*. *Alnus fruticosa* arrived locally *c*. 9000–8500 $^{14}$C yr BP and disappeared *c*. 4000–3500 $^{14}$C yr BP. Communities of *Betula* sect. *Nanae*, broadly distributed at *c*. 10 000–3500 $^{14}$C yr BP, almost disappeared when vegetation became similar to the modern herb tundra after 3500–3000 $^{14}$C yr BP. Quantitative climate reconstructions show Last Glacial Maximum summer temperature about 4°C below the present and Preboreal (*c*. 10 000 $^{14}$C yr BP) temperature 2–4°C above the present. Maximum summer temperature occurred between 10 000 and 5500 $^{14}$C yr BP; later summers were similar to present or slightly warmer.

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Recent field-based studies on the Taymyr Peninsula have documented restricted Late Weichselian glaciation in central Siberia (e.g. Möller *et al.* 1999; Alexanderson *et al.* 2001; Mangerud *et al.* 2002), thereby disproving the mostly theoretically based maximum glaciation scenario (e.g. Grosswald 1998; Grosswald & Hughes 2002). The environmental conditions associated with this minimal glacier cover, however, remain poorly understood. Better reconstruction of these environments requires longer and better-dated sediment sequences containing biological remains (i.e. pollen and macrofossils).

This article reconstructs vegetation and climate change on the northern Taymyr Peninsula based on new studies of long pollen sequences from Levinson-Lessing Lake and Cape Sabler, Taymyr Lake (Fig. 1). These sequences were discovered in the 1990s as part of the multidisciplinary German–Russian research Project ‘Taymyr’ (Melles *et al.* 1996). We build on prior Project ‘Taymyr’ pollen work for Levinson-Lessing Lake (Hahne & Melles 1999) and macrofossil work for Cape Sabler (Kienast *et al.* 2001) by generating additional pollen data, developing much better age models, performing quantitative environmental reconstruction, and revising the pollen-based interpretations. Moreover, we compare our new records with others assembled for Project ‘Taymyr’ (Hahne & Melles 1997; Kienel *et al.* 1999; Siegert *et al.* 1999; Andreev *et al.* 2002b; Andreev *et al.* in press) and with the published environmental records from adjacent areas of Taymyr (Belorusova & Ukraintseva 1980; Nikol’skaya 1980; Nikol’skaya *et al.* 1980; Andreeva & Kind 1982; Belorusova *et al.* 1987; Velichko *et al.* 1997; Andreev & Klimanov 2000). This comparison gives a detailed picture of environmental changes on the northern Taymyr Peninsula since *c*. 32 000 $^{14}$C yr BP.

## Study area

### *Levinson-Lessing Lake*

Levinson-Lessing Lake (74°28′N, 98°38′E; 47 m a.s.l.)

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DOI 10.1080/03009480310003388 

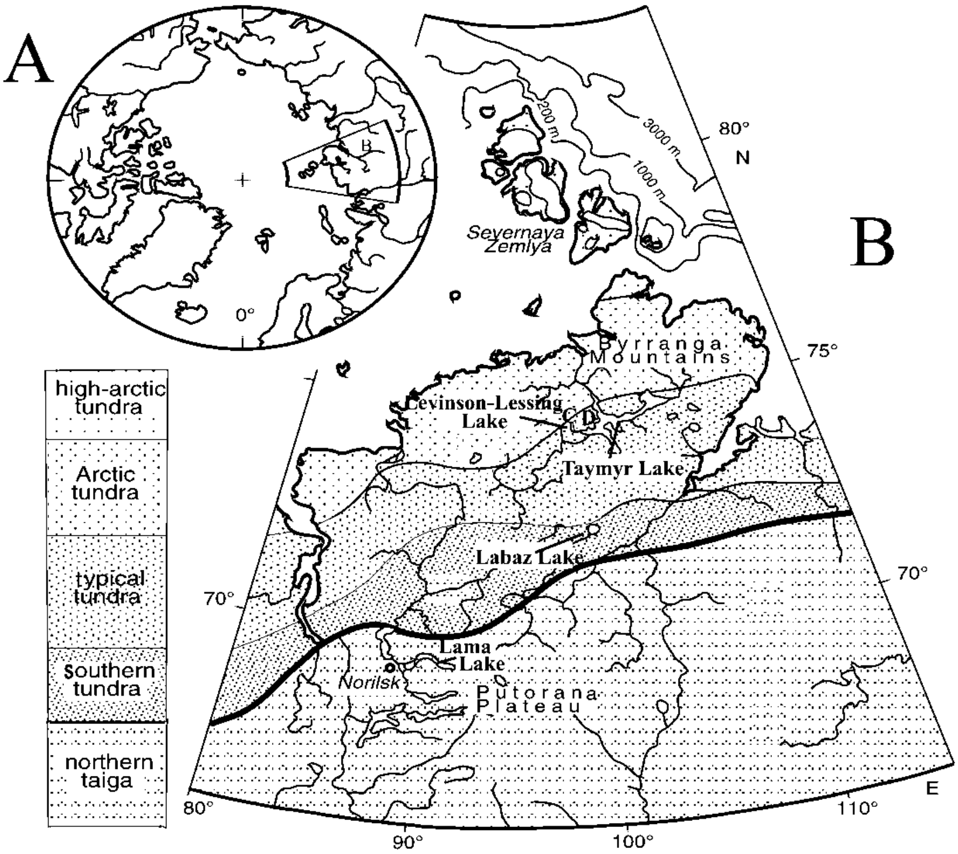


*Fig. 1.* A. Map of the Arctic. B. Map of Taymyr-Severnaya Zemlya region. C. Overview map of the Levinson-Lessing Lake area with coring site. Bathymetry in m. D. Overview map of the Cape Sabler area with sampled sites.

is the deepest lake (110 m) of the northern Taymyr Peninsula and lies within the limits of the Glavnyi Range, Byrranga Mountains (Fig. 1). The hills surrounding the lake reach altitudes up to 570 m a.s.l. The lake basin is 15 km long and 1–2 km wide, covering an area of *c*. 25 km$^2$. Inflow occurs via the Krasnaya River in the north and by numerous small streams on the relatively steep eastern and western slopes. Outflow is by the Protochnaya River in the south. The geomorphology of the lake area reflects its tectonic origin, reshaped by glacial erosion presumably during the early Weichselian (Anisimov & Pospelov 1999; Niessen *et al.* 1999). Bedrock is composed of terrigeneous Permian rocks (auleurolites) with intrusions of dolerites (Bolshiyanov & Anisimov 1995).

The continental Arctic climate in the lake basin includes long, severe winters and short summers. July temperature ($T_{VII}$) is only 5–7°C, while January temperature ($T_I$) is about $-33$ to $-35$°C. Mean annual temperature ($T_{yr}$) is about $-15$°C. Annual precipitation ($P_{yr}$) reaches 250 mm, with a maximum in summer (Atlas Arktiki 1985).

The lake basin lies within the zone of continuous permafrost, up to 500 m thick (Geokriologia SSSR 1989). Active layer thickness ranges from 20–30 cm in peatlands to 1 m in gravelly sediments without vegetation cover. Diverse types of gleysols dominate the lake surroundings, depending on the moisture regime (Anisimov & Pospelov 1999).

Levinson-Lessing Lake is situated at the border between the Subarctic and Arctic tundra zones. Vegetation varies from mountain desert with sparse lichen-herb cover to moss-forb tundra with discontinuous vegetation at high elevations, and dry sedge-forb tundra with dominant *Dryas octopetala*, *Salix polaris* and *Cassiope tetragona* (Anisimov & Pospelov 1999). In some places, vegetation is of steppe-like character with grasses dominating. The largest plant diversity occurs in the marginal meadows on the lowest Krasnaya River terrace. Willow shrubs (*Salix arctica, S. reptans, S. pulchra*) are sparsely distributed (Zhurbenko 1995).

### *Cape Sabler Peninsula*

The Cape Sabler Peninsula (74°33′N, 100°32′E) is located on the northwestern shore of Taymyr Lake, about 50 km east of Levinson-Lessing Lake (Fig. 1). A number of shallow lakes separate the peninsula from a low elevation portion of the Byrranga Mountains

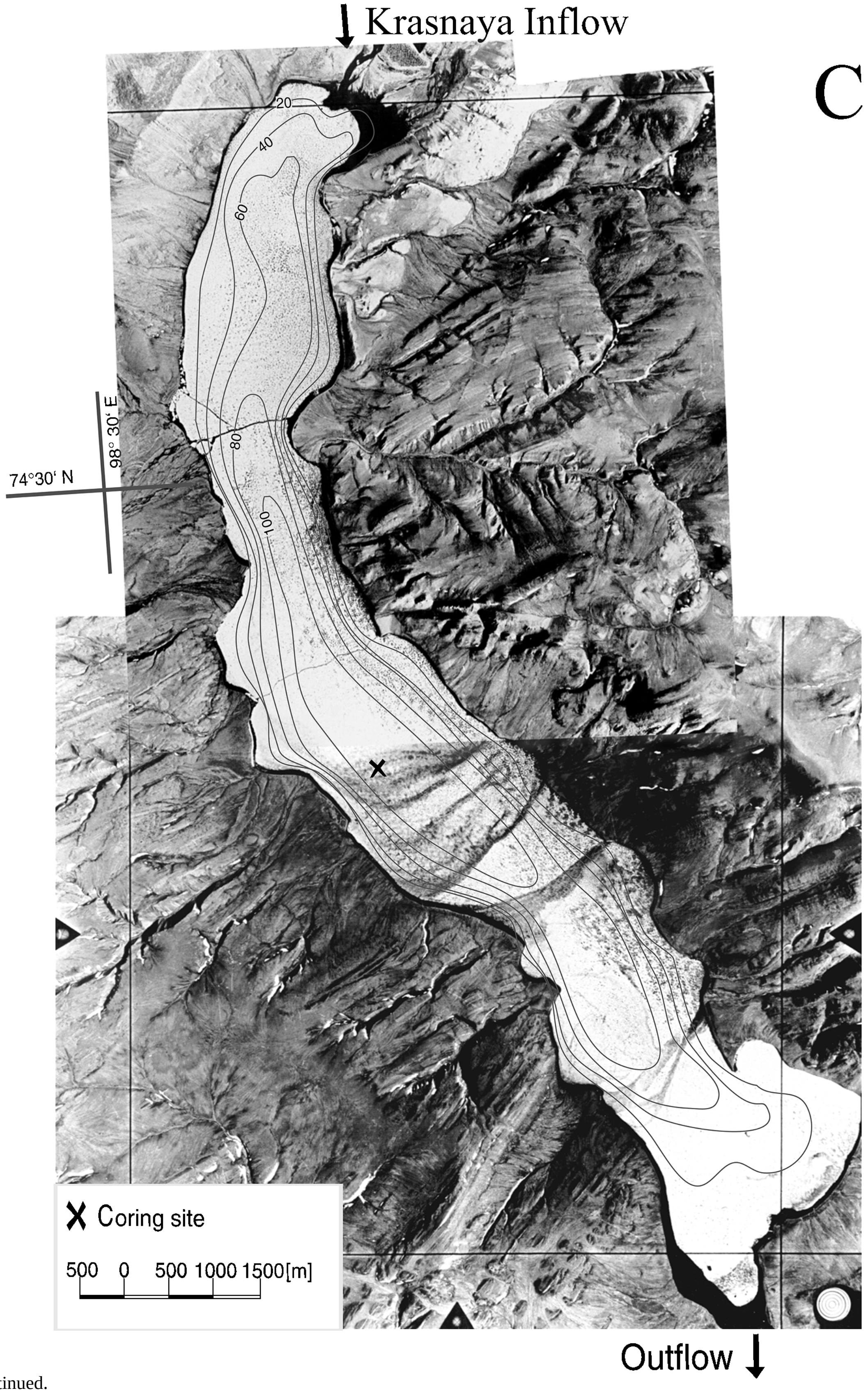


*Fig. 1.* Continued.

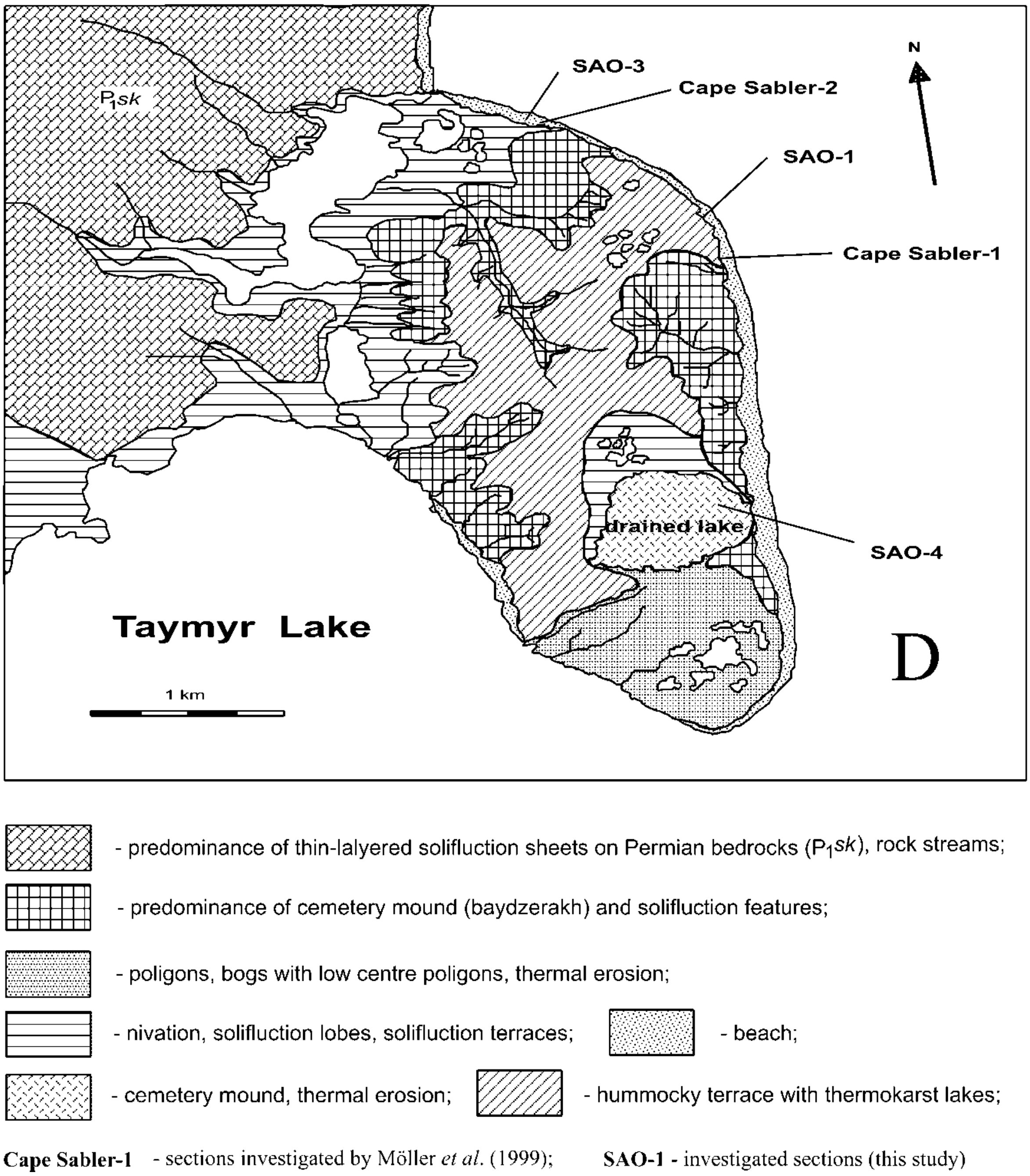


*Fig. 1.* Continued.

(Derevyagin *et al.* 1997). Permafrost features are widespread and include frost cracks, polygonal ground, ice wedges, thermokarst depressions, solifluction and nivation forms. The peninsula shoreline consists of silty cliffs up to 25 m high (Derevyagin *et al.* 1997; Möller *et al.* 1999).

The Cape Sabler Peninsula has similar climate, soil and permafrost characteristics as the Levinson-Lessing Lake area (Atlas Arktiki 1985). The Peninsula is situated within the northern belt of the Subarctic tundra. Herb-dwarf-shrub tundra dominates, with *Dryas punctata*, *Salix polaris*, *S. nummularia*, *Luzula nivalis* and *Carex ensifolia* and mosses like *Hylocomium alaskianum* and *Drepanocladus incinatus*. Sparse shrub communities of *Salix arctica*, *S. reptans*, *S. pulchra* and *Betula nana* are also present.

*Table 1.* AMS radiocarbon dates from Levinson-Lessing Lake PG1228 core. Dates from assumed contaminated layers are given in italics.

| NN | Core | Depth (cm) | Dated material | $^{14}C$ age | $\partial^{13}C$ | Lab. no. |
|---|---|---|---|---|---|---|
| 1 | 1228-3/1 | 0–2 | Humic acids | 6630 ± 40 | −21.9 | KIA3312 |
| 2 | 1228-3/1 | 105–111 | Non-identified macrofossils | 3740 ± 45 | −26.0 | AA40891 |
| 3 | 1228-3/2 | 149–156 | Non-identified macrofossils | 6640 ± 60 | −25.8 | AA40892 |
| 4 | 1228-4/1 | 198–200 | Humic acids | 8970 ± 40 | −27.5 | KIA3313 |
| 5 | 1228-4/1 | 199–205 | Non-identified macrofossils | 4970 ± 60 | −27.1 | AA40893 |
| 6 | 1228-4/1 | 245–251 | Non-identified macrofossils | 4635 ± 45 | −26.7 | AA40894 |
| 7 | 1228-4/2 | 299–306 | Non-identified macrofossils | 15 540 ± 110 | −25.0 | AA40895 |
| 8 | 1228-4/2 | 348–354 | Non-identified macrofossils | 6240 ± 50 | −26.3 | AA40896 |
| 9 | 1228-4/3 | 399–400 | Humic acids | 10 620 ± 50 | −25.5 | KIA3314 |
| 10 | 1228-4/3 | 400–406 | Non-identified macrofossils | 5210 ± 50 | −27.1 | AA40897 |
| 11 | 1228-4/3 | 448–454 | Non-identified macrofossils | 7970 ± 120 | −26.3 | AA40898 |
| 12 | 1228-4/3 | 467 | Aquatic moss remains | 5650 ± 90 | −23.1 | OxA-6526 |
| 13 | 1228-4/3 | 470 | Humic acids | 10480 ± 70 | −23.0 | KIA5289 |
| 14 | 1228-5/2 | 548–554 | Non-identified macrofossils | 10 065 ± 100 | −26.2 | AA40899 |
| 15 | 1228-5/2 | 599–600 | Humic acids | 11 930 ± 50 | −26.1 | KIA3315 |
| 16 | 1228-5/2 | 600–606 | Non-identified macrofossils | 11 450 ± 90 | −26.6 | AA40900 |
| 17 | 1228-5/3 | 648–654 | Non-identified macrofossils | 11 990 ± 170 | −27.0 | AA40901 |
| 18 | 1228-5/3 | 700–706 | Non-identified macrofossils | 13 700 ± 110 | −25.8 | AA40902 |
| 19 | 1228-6/1 | 748–756 | Non-identified macrofossils | 14 645 ± 95 | −26.4 | AA40903 |
| 20 | 1228-6/2 | 789–799 | Humic acids | 15 480 ± 80 | −26.4 | KIA3316 |
| 21 | 1228-6/2 | 799–803 | Non-identified macrofossils | 15 330 ± 130 | −25.5 | AA40904 |
| 22 | 1228-6/3 | 900–906 | Non-identified macrofossils | 16 800 ± 140 | −25.8 | AA40905 |
| 23 | 1228-6/3 | 904 | Humic acids | 19 640 ± 180 | −28.1 | KIA5290 |
| *24* | 1228-7/1 | *1000–1006* | *Non-identified macrofossils* | *11 090 ± 80* | −25.5 | *AA40906* |
| 25 | 1228-7/2 | 1095–1110 | Non-identified macrofossils | 20 170 ± 200 | −26.0 | AA40907 |
| 26 | 1228-7/2 | 1100 | Humic acids | 22 890 ± 260 | −28.3 | KIA5291 |
| 27 | 1228-7/3 | 1195–1210 | Non-identified macrofossils | 18 180 ± 170 | −25.6 | AA40908 |
| 28 | 1228-7/3 | 1199–1200 | Humic acids | 24 240 ± 170 | −24.7 | KIA3318 |
| 29 | 1228-8/2 | 1295–1310 | Non-identified macrofossils | 19 860 ± 190 | −25.6 | AA40909 |
| 30 | 1228-9/2 | 1595–1610 | Non-identified macrofossils | 21 020 ± 200 | −25.3 | AA40912 |
| 31 | 1228-8/3 | 1395–1410 | Non-identified macrofossils | 18 920 ± 140 | −25.9 | AA40910 |
| 32 | 1228-8/3 | 1399–1400 | Humic acids | 26 750 ± 210 | −23.7 | KIA3319 |
| *33* | 1228-9/1 | *1502–1506* | *Non-identified macrofossils* | *11 810 ± 90* | −26.3 | *AA40911* |
| 34 | 1228-9/2 | 1599–1600 | Humic acids | 27 980 ± 250 | −23.5 | KIA3320 |
| 35 | 1228-9/3 | 1700 | Humic acids | 28 150 ± 290 | −23.0 | KIA5292 |
| *36* | *1228-11/1* | *1707–1723* | *Plant remains* | *1890 ± 30* | −27.7 | *KIA 1401* |
| *37* | *1228-11/1* | *1723–1750* | *Plant remains* | *3720 ± 30* | −28.3 | *KIA 1402* |
| 38 | 1228-9/3 | 1741 | Humic acids | 29 350 ± 270 | −21.7 | KIA5293 |
| *39* | *1228-11/1* | *1748–1753* | *Non-identified macrofossils* | *6170 ± 55* | −26.1 | *AA40913* |
| *40* | *1228-11/2* | *1799–1800* | *Humic acids* | *11 640 ± 60* | −26.5 | *KIA3321* |
| *41* | *1228-11/2* | *1802–1806* | *Non-identified macrofossils* | *7640 ± 60* | −26.1 | *AA40914* |
| 42 | 1228-11/2 | 1820 | Humic acids | 26 590 ± 230 | −25.8 | KIA5294 |
| 43 | 1228-11/2 | 1845–1855 | Non-identified macrofossils | 24 800 ± 240 | −24.8 | AA40915 |
| 44 | 1228-11/3 | 1900 | Humic acids | 31 020 ± 360 | −21.7 | KIA5295 |
| 45 | 1228-11/3 | 1948–1953 | Non-identified macrofossils | 24 620 ± 250 | −25.1 | AA40916 |
| *46* | *1228-13/1* | *1995–2010* | *Non-identified macrofossils* | *11 360 ± 75* | −25.8 | *AA40917* |
| *47* | *1228-13/1* | *1999–2000* | *Humic acids* | *22 440 ± 100* | −26.1 | *KIA3322* |
| 48 | 1228-13/2 | 2100 | Humic acids | 32 270 ± 440 | −22.9 | KIA5296 |
| 49 | 1228-13/3 | 2198–2199 | Humic acids | 35 210 ± 590 | −22.5 | KIA3323 |

# Methods

## *Sampling, radiocarbon and pollen methods*

Piston core PG1228 (2210-cm-long) was collected from the central part of Levinson-Lessing Lake at 108 m water depth when ice cover was 2 m thick during the spring of 1995 (Fig. 1; Melles *et al.* 1994; Overduin *et al.* 1996). A gravity corer was used at the same site to recover the uppermost sediments (0–27 cm) with minimal disturbance of the water–sediment interface.

A pollen sampling interval of 10–20 cm was used for the upper 980 cm of the core, and 50 cm for most of the deposits below (except 20 cm for 1680–1820 cm and 10 cm for 1840–2000 cm depths). Sampling intervals for AMS $^{14}C$ dating of macrofossil remains (Table 1) were *c*. 50 cm for the upper 800 cm of the core and *c*. 100 cm in the deposits below (except *c*. 50 cm between the 1748 and 1855 cm depth). Additional $^{14}C$ dating was conducted on humic acids, extracted from 19 samples, using KOH for extraction and HCl for cleaning.

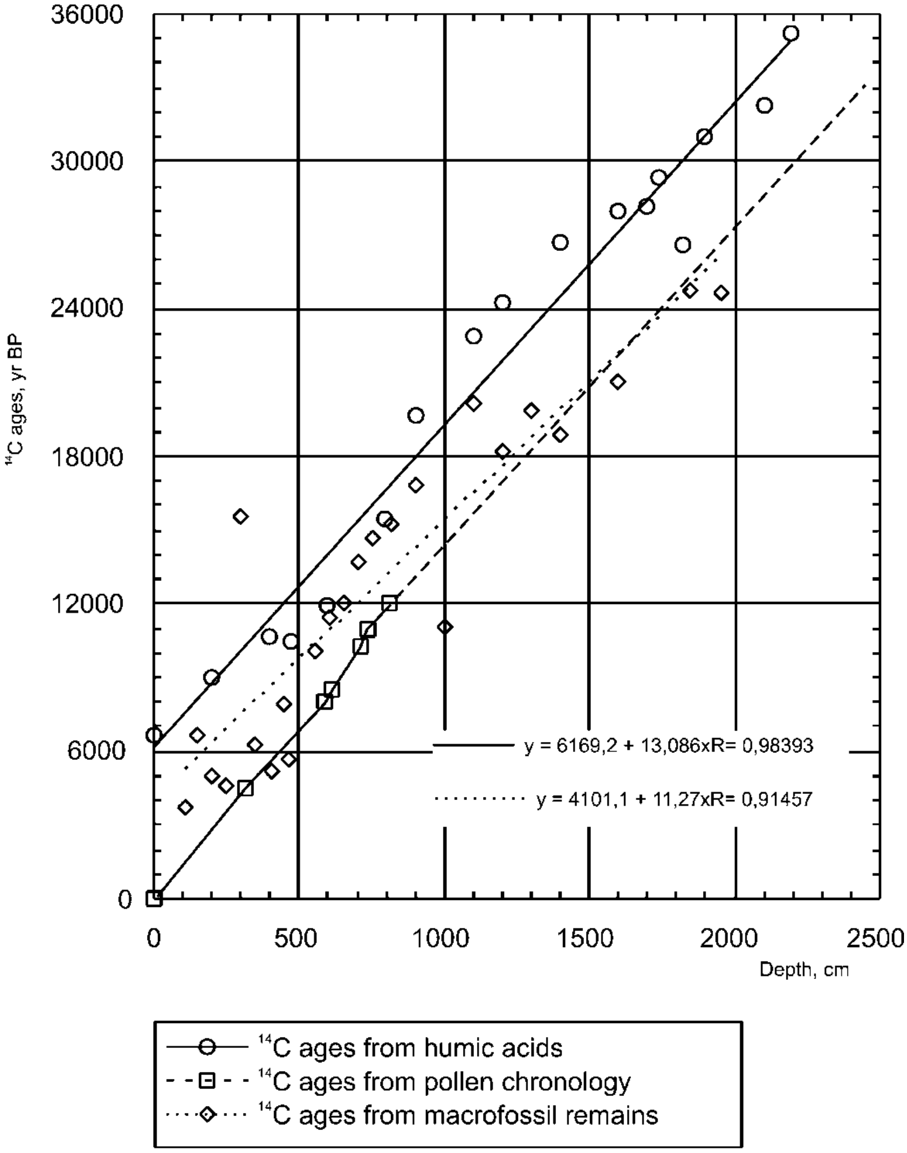


*Fig. 2.* Age/depth model for the core PG1228 from Levinson-Lessing Lake.

The AMS $^{14}C$ dating of the core was adjusted for an unanticipated problem associated with using the rope-supported coring device at 110 m water depth. Below 10 m sediment depth, the corer slowly started to open before the intended depth; this problem potentially allowed sediments from the upper third of each 3-m section (below 10 m sediment depth) to be displaced. Sediment below approximately 1 m in each 3-m section appears to lie at the correct depth. All potentially displaced $^{14}C$ samples (*italicized*, Table 1) were not considered for the age-depth model (Fig. 2). We have also excluded pollen data corresponding to the potentially displaced material from interpretation.

The 27-m sediment section from Cape Sabler, SAO-1 (Fig. 1; Derevyagin *et al.* 1997) was sampled in summer 1996 at 100-cm intervals for radiocarbon analyses (Table 2) and in 10–20 cm intervals for pollen and testate amoebae analysis. Unfortunately, it was not possible to sample two intervals, 1000–1140 cm and 1770–2100 cm, because of sediment disturbance. Additional pollen samples at 10–20 cm intervals were taken from a 270-cm-long section (SAO-3) and a 310-cm-long section (SAO-4) (Fig. 1). Four levels were sampled for radiocarbon dating from these short sections (Table 2).

Two methods were used to process the pollen samples. Most of the SAO samples started with a heavy-liquid separation (Berglund & Ralska-Jasiewiczowa 1986) followed by acetolysis and glycerin mounting (analyses by G. N. Shilova, Moscow State University). Additional samples from section SAO-1

*Table 2.* Conventional and AMS radiocarbon dates from Cape Sabler terrestrial profiles: SAO-1, SAO-3 and SAO-4. Dates not used for the reconstructions are given in italics.

| NN | Section | Depth (cm) | Dated material | $^{14}$C age | $\partial^{13}$C | Lab. no. |
|---|---|---|---|---|---|---|
| *1* | *SAO-1* | *70–80* | *Peat* | *2270 ± 80* | −26.0 | *AWI-96-1* |
| 2 | SAO-1 | 130 | Sedge peat | 1575 ± 20 | −25.8 | KIA5745 |
| 3 | SAO-1 | 160–170 | Sedge-moss peat | 2700 ± 25 | −27.1 | KIA5746 |
| 4 | SAO-1 | 260–270 | Plant remains | 6730 ± 30 | −26.7 | KIA5747 |
| 5 | SAO-1 | 300–350 | Peat | 10170 ± 130 | −25.0 | AWI-96-2 |
| 6 | SAO-1 | 500–600 | Peat with small twigs | 12310 ± 170 | −26.3 | AWI-96-3 |
| 7 | SAO-1 | 570 | Plant remains | 11855 ± 50 | −27.1 | KIA5748 |
| *8* | *SAO-1* | *1000–1050* | *Peat with small twigs* | *18220 ± 320* | | *AWI-96-4* |
| *9* | *SAO-1* | *1320* | *Moss peat* | *19020 ± 300* | | *AWI-96-5* |
| 10 | SAO-1 | 1320 | *Salix* leaves | 18065 ± 60 | −26.4 | KIA5749 |
| 12 | SAO-1 | 1500–1550 | Plant remains | 19520 ± 270 | −26.6 | AWI-96-6 |
| 13 | SAO-1 | 2100 | Peat | 26750 ± 650 | −27.0 | AWI-96-7 |
| *14* | *SAO-1* | *2100* | *Moss peat* | *30300 +180/−170* | −25.8 | *KIA5750* |
| *15* | *SAO-1* | *2180* | *Shrub twigs* | *29540 ± 790* | −26.4 | *AWI-96-8* |
| *16* | *SAO-1* | *2310* | *Alkaline residue of woody remains and roots* | *32060 +220/−210* | −25.5 | *KIA5751* |
| | | | *Humid acids, woody and non-identified plant remains* | *26720 ± 150* | | |
| 17 | SAO-1 | 2500 | Roots, non-identified aquatic plants remains | 29960 ± 790 | −25.5 | AWI-96-10 |
| 19 | SAO-1 | 2520 | Alkaline residue of woody and non-identified plant remains | 30760 +210/−200 | | KIA5752 |
| 20 | SAO-3 | 120 | Non-identified plant remains | 2060 ± 110 | | AWI-96-11 |
| 21 | SAO-3 | 140 | Non-identified plant remains | 2340 ± 70 | −27.0 | AWI-96-12 |
| 22 | SAO-3 | 265 | Non-identified plant remains | 4380 ± 90 | −23.4 | AWI-96-13 |
| 23 | SAO-4 | 70-80 | Peat with woody remains | 2820 ± 60 | −26.3 | AWI-96-14 |

and all samples from core PG1228 were processed using standard HF techniques (Hahne & Melles 1999).

Pollen percentages are based as follows: (1) arboreal and non-arboreal pollen taxa from the sum of terrestrial pollen taxa; (2) spores from the sum of pollen and spores; (3) redeposited taxa – Tertiary spores and redeposited pollen – from the sum of pollen and redeposited taxa; and (4) algae from the sum of pollen and algae (Berglund & Ralska-Jasiewiczowa l986). Calculations and plotting were performed with Tilia/TiliaGraph software (Grimm 1991).

Testate amoebae were extracted from sediments with a 500-μm sieve. A drop of the concentrate was placed on a slide, then glycerol was added. Normally, 5 subsamples were examined at 200–400 × magnification with a light microscope.

## *Climate reconstruction methods*

To quantitatively reconstruct climate from the pollen records, two statistical techniques were used: (1) the statistical-information (IS) method and (2) the best modern analogue (BMA) method. The IS method (Klimanov 1984; Velichko *et al.* 2002) determines the statistical relationship between recent pollen spectra and climate and then applies this relationship to fossil pollen records to reconstruct past environments. Specifically, it uses the total pollen/spore ratio as well as the relative abundance of the 14 most common arboreal taxa. Because the method is mostly based on statistical correlations between arboreal pollen and climate, reconstructions in treed areas and treed time intervals are more reliable than treeless areas (like the northern Taymyr) and treeless time (like the Late Weichselian). Despite these problems, the IS reconstruction for the Late Pleistocene on northern Taymyr Peninsula remains helpful; as it shows consistent climate trends.

The BMA method (Guiot 1990) was used to reconstruct climate changes from the PG1228 pollen record. The method uses chord distances to determine the similarity between each analysed pollen spectrum and each spectrum in the reference pollen data set of 1110 modern pollen samples collected in the former USSR and Mongolia territories (Tarasov *et al.* 1998, 2002). In this study, minimum and maximum values for each climate variable were reconstructed from the 10 best modern analogues determined for each fossil sample. Table 3 lists the 39 pollen taxa identified in the PG1228 record that have been used in the climate reconstructions. Modern climate values for each of the 1110 modern pollen sampling sites have been calculated from an updated version of the climate database of

*Table 3.* Pollen taxa identified in the Levinson-Lessing record and used in the climate reconstruction by the BMA method.

| Taxa name |
|---|
| *Alnus* undif., Apiaceae, Artemisia, Asteraceae undif., *Betula* undif., Boraginaceae, Brassicaceae, Caryophyllaceae, Chenopodiaceae, Cyperaceae, Dipsacaceae, *Dryas*, *Ephedra*, Ericales, Fabaceae, Gentianaceae, *Hippophae, Juniperus*, Lamiaceae, *Larix*, Liliaceae, Onagraceae, Papaveraceae, *Picea*, *Pinus* (Diploxylon), *Pinus* (Haploxylon), Plantaginaceae, Poaceae, Polygonaceae, *Populus*, Ranunculaceae, Rosaceae, *Rumex*, Rubiaceae, *Salix*, Saxifragaceae, Scrophulariaceae, *Thalictrum*, Valerianaceae |

Leemans & Cramer (1991) with precise topography (W. Cramer, pers. comm. 2001). PPBase software facilitated the calculations (Guiot & Goeury 1996; http://medias.obs-mip.fr/paleo_utils).

Because the BMA method takes into account arboreal as well as non-arboreal pollen it has better potential than the IS method for treeless areas such as northern Taymyr. Nevertheless, we did not apply the method either to the lower part of the Levinson-Lessing record or to the Cape Sabler pollen data because of low pollen concentration and potential sediment displacement discussed above.

How much can we trust quantitative climate reconstructions based on pollen data? This question is especially important for the Russian Arctic, a region where an appropriate database of the reference surface samples is still under construction. Past studies assessed the reliability of the climate reconstruction techniques for northern Eurasia by reconstructing present-day climate characteristics from modern pollen spectra. Reported errors in the IS method were $\pm$0.6 °C for $T_{yr}$ and $T_{VII}$; $\pm$1.0 °C for $T_I$; and $\pm$25 mm for $P_{yr}$ (Klimanov 1984). However, these results were obtained with the data sets in which the Arctic was poorly represented.

Recent tests demonstrate that the BMA method reconstructs modern climate variables in the Arctic with reasonably high accuracy (Tarasov *et al.* 2002; Andreev *et al.* in prep.). Correlation coefficients between reconstructed and calculated climate variables have suggested that $T_{VII}$ and annual sum of the day temperatures above 5°C (the so-called sum of growing-degree-days with temperatures above 5°C, GDD5) can be reconstructed with reasonably high confidence ($R = 0.80$ and 0.82, respectively). Among the other tested variables, P and runoff (difference between P and evaporation (E)) were reconstructed from the modern spectra with relatively high accuracy ($R = 0.68$ and 0.61, respectively).

In this study, the methods have been applied together only to the upper part of the PG1228 pollen record covering the last 17 000 years. We assumed that in this record the above-mentioned problems (e.g. low pollen concentration or non-arboreal pollen dominance) can be neglected, as their influence on the reconstructions is supposed to be minimized. However, the absolute climate values obtained from the pollen records dated before 20 000 yr BP for the northern Taymyr Peninsula are suspect and thus have not been plotted on any figure.

## Results

### *Levinson-Lessing Lake*

*Lithology and stratigraphy.* – Core PG1228 consists of two main sediment types (Ebel *et al.* 1999). Fine-grained laminae (*c.* 0.7 mm) constitute about 80% of the core and consist of couplets with silt-sized basal and clay-sized top layers. These regular laminae probably represent annual layers. The remaining 20% of the core is comprised of sandy layers, which occur irregularly throughout the sequence. The thickness of these layers varies between 2 mm and 20 cm; they are derived from collapses of delta front sediments and subsequent down-slope sediment transport to the lake centre (Ebel *et al.* 1999). The sediments throughout the core appear to be continuously deposited; there is no evidence of erosion or non-deposition.

*Chronology.* – In total, 49 samples from core PG1228 were AMS $^{14}C$ dated (Table 1; all ages are uncalibrated). Our age-depth model for this core is based on correlation with a regional pollen chronology for the upper 8 m of the core and macrofossil dates below 12 m. Corrected humic acid dates provide age constraint throughout the core, but particularly in the gap between 8 and 12 m.

Although the macrofossils picked throughout the core were expected to provide reliable dates, many are too old and only give maximum age constraints (Fig. 2). On average they deviate by *c.* 2500 yr from a $^{14}C$ constrained Holocene pollen chronology for adjacent areas on the Taymyr Peninsula (Belorusova & Ukraintseva 1980; Nikol'skaya 1980; Nikol'skaya *et al.* 1980; Andreeva & Kind 1982; Belorusova *et al.* 1987; Clayden *et al.* 1997; Velichko *et al.* 1997; Andreev & Klimanov 2000; Andreev *et al.* 2002b; Andreev *et al.* in press). This large discrepancy probably reflects a high content of reworked organic matter in the mostly unidentified macrofossil samples (including Permian coal fragments) and occasional visible sediment disturbance.

To help resolve the dating problems, a narrow fraction of humic acids was extracted from the bulk sediment at 19 levels throughout the core. The resulting humic acid ages (Table 2) are consistently 4000 to 6000 years older than the regional Holocene pollen chronology (Fig. 2). A similar offset is observed between humic acids and macrofossils in the lower half of the core. These lower macrofossil ages are, in turn, consistent with an extrapolation of the overall regional pollen chronology. Assuming a constant age offset for the humic acids, the basal age for the core is estimated at *c.* 33 000 $^{14}C$ yr BP (Fig. 2).

Sedimentation rates appear to have an approximately linear trend in the core. Nevertheless, all three age constraints (humic, pollen chronology and macrofossils) suggest at least one deviation from this linear trend some time between about 600 and 1200 cm sediment depth; thus, slower rates occurred for an unknown duration some time between *c.* 17 000 and *c.* 8,000 $^{14}C$ yr BP).

*Pollen.* – The pollen diagram for core PG1228 from Levinson-Lessing Lake was zoned by visual inspection

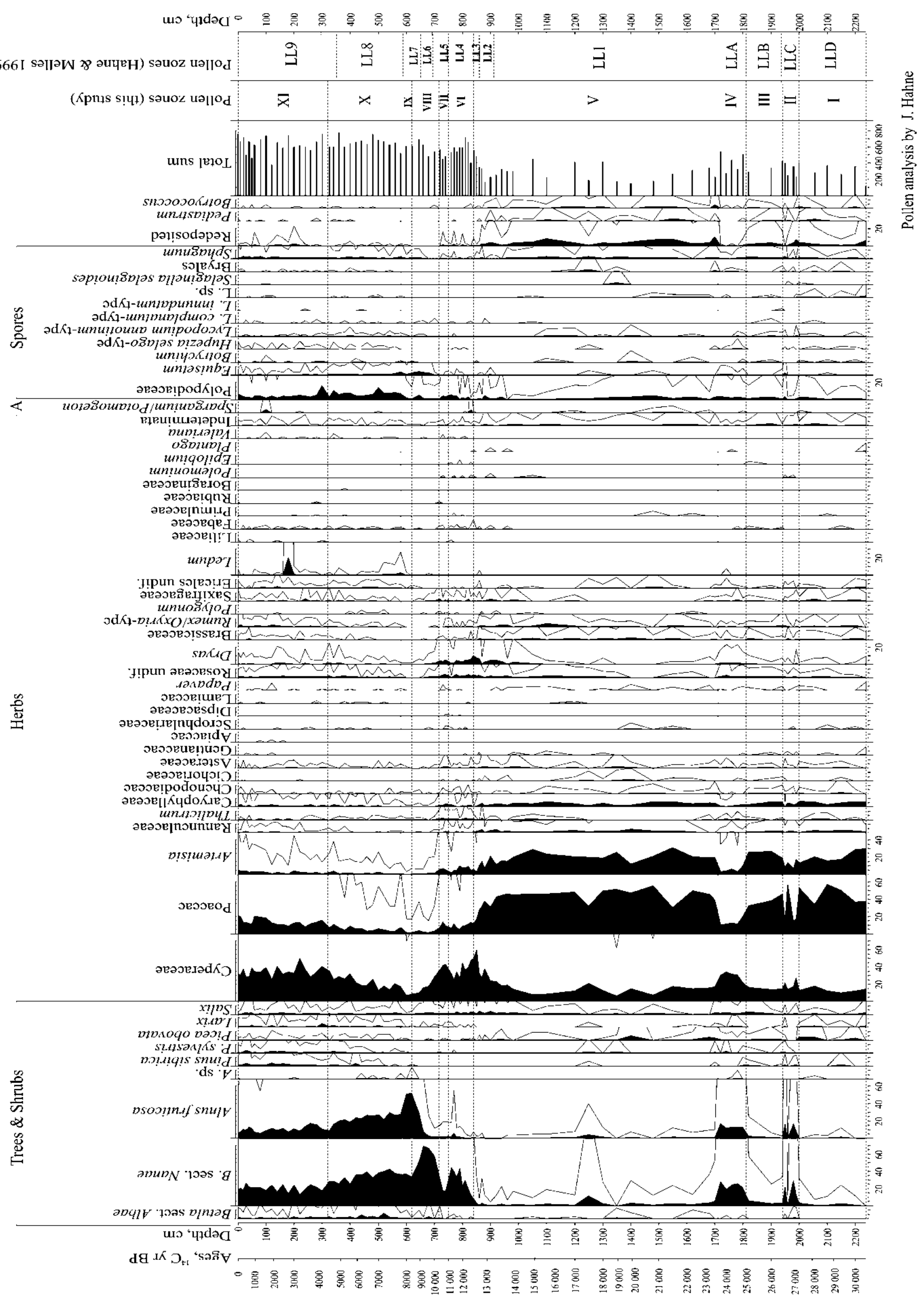


*Fig. 3.* Percentage pollen and spore diagram of the Levinson-Lessing Lake PG1228 core (72°22′6″N, 99°42′2″E).

(Fig. 3). The basal pollen zone I (PZ-I) is notable for its very low pollen concentration (up to 500 grains per $cm^3$). Its spectra are dominated by *Artemisia,* Poaceae, Cyperaceae and Caryophyllaceae. PZ-II (2200–1940 cm) is characterized by two peaks of *Betula* sect. *Nanae, Alnus fruticosa* and Cyperaceae pollen. PZ-II was excluded, however, from further interpretation because of potential sediment displacement. PZ-III (1940–1810 cm) is similar to PZ-I. The pollen spectra of PZ-IV (1810–1710 cm) are dominated by *Betula* sect. *Nanae, Alnus fruticosa* and Cyperaceae pollen. Pollen concentration is relatively high (up to 5000 grains per $cm^3$). PZ-IV was also excluded from further interpretation because of potential sediment displacement. The pollen content of PZ-V (1710–1280 cm) is similar to that of PZ-I and PZ-III. A lower sample at 1240 cm is characterized by high contents of *Betula* sect. *Nanae, Alnus fruticosa* and Cyperaceae pollen, while Poaceae and Caryophyllaceae contents are low. The upper part of PZ-V is characterized by a gradual decrease of *Artemisia* and Poaceae pollen percentages, while Cyperaceae and Rosaceae (mostly *Dryas*) increase. PZ-VI (850–750 cm) is notable for a dramatic increase in *Betula* sect. *Nanae* and Cyperaceae pollen contents, and a decrease in *Artemisia*, Caryophyllaceae and Poaceae. Pollen concentration increases significantly (up to 15 000 grains per $cm^3$) in this zone. PZ-VII (750–710 cm) is characterized by increasing Cyperaceae, Poaceae, Caryophyllaceae, *Artemisia* and other herbs, whereas *Betula* sect. *Nanae* decreases. Pollen concentrations are significantly lower in this zone than in PZ-VI (up to 5000 grains per $cm^3$). In PZ-VIII (710–660 cm) *Betula* sect. *Nanae* pollen percentages dramatically increase (up to 65%), whereas herbs decrease. Total pollen concentration is up to 20 000 grains per $cm^3$ in this zone. PZ-IX (660–595 cm) is notable for a dramatic increase (up to 52%) in *Alnus fruticosa* pollen content and a significant decrease in *Betula* sect. *Nanae* one. Pollen concentration is at its maximum (up to 48 000 grains per $cm^3$) in this zone. PZ-X (595–315 cm) is characterized by a gradual decrease of *Betula* sect. *Nanae* and *Alnus fruticosa* pollen contents, whereas Cyperaceae and Poaceae gradually increase. In this zone, pollen concentration is relatively high (up to 8000 grains per $cm^3$). The pollen spectra of PZ-XI (315–0 cm) are dominated by pollen of Cyperaceae, Poaceae, *Betula* sect. *Nanae*, and *Alnus fruticosa*. Pollen concentration is lower in this zone than in PZ-X.

### *Cape Sabler sections*

*Lithology.* – SAO1. The 27-m-high section of the lake terrace is of lacustrine sediments (Derevyagin *et al.* 1997). The predominating facies is laminated, or massive silt, mostly rich in plant detritus (moss remains, woody twigs, seeds and other plant remains). In the basal part of the section there is an interbedding of clay and fine sand beds. Thick (up to 1.2 m) peaty layers with high silt content characterize the sequence (Figs 4, 5). For detailed lithological, geomorphological and stratigraphical descriptions of the SAO1 section and the terrace, see Derevyagin *et al.* (1997) and Möller *et al.* (1999).

SAO3. The lower part of the section (310–120 cm) is composed of interbedded fine-grained grey sand and silt layers, including numerous peaty layers with plant remains (Fig. 6). At 120–100 cm depth, sand with moss and other plant remains is common. The upper 100 cm of the section consists of grey and yellow fine sand, rich in plant detritus and peat lenses.

SAO4. The lower part of the section (270–210 cm) is formed by a layer of fine-grained grey sand (Fig. 7). The upper layer, 210–105 cm, is composed of an interbedding of fine-grained grey sand, peaty layers and silt layers, including numerous plant remains. The 105–95 cm layer is a peat, overlaid by *c.* 10 cm of silt, rich in plant remains. The upper 85–70 cm layer is a non-decomposed peat layer overlain by sandy silt (70–45 cm) and well-decomposed peat (45–10 cm). The uppermost 10 cm is the modern soil.

*Chronology.* – In total, 18 AMS and conventional $^{14}C$ ages were obtained from the SAO1 sequence (Table 2). A reasonable age sequence, combined with an apparent lack of erosional events or hiatuses, suggests that the sediments were formed continuously during the last *c.* 30 000 radiocarbon years. A few age reversals reflect the reworked character of the dated material. We believe that the youngest dates are more reliable, as there is no evidence of possible contamination of the sediments by younger organic material. All $^{14}C$ dates assumed as reworked (*italicized*, Table 2) were not considered for the palaeoenvironmental reconstructions.

Three conventional $^{14}C$ ages were obtained from sequence SAO3, and only one age from SAO4 (Table 2). The dates indicate that SAO3 and SAO4 sections accumulated during the late Holocene.

*Pollen.* – There are two pollen diagrams for sequence SAO1 (Figs 4, 5), both zoned by visual inspection. Fig. 4 is based an analysis by J. Hahne, whereas Fig. 5 is based on an analysis by G. N. Shilova. The diagrams supplement each other, as Hahne's analysis mostly covers the Holocene, whereas Shilova's the Pleistocene part of the section. In the overlap, both diagrams reflect similar trends, but differ in the number and amount of identified palynomorphs. The differences may be due partly to the different techniques used for pollen treatment, but may also reflect different palynological training.

The pollen analysis of J. Hahne (Fig. 4) shows a lower limit for PZ-I at a depth of 2520 cm. The upper limit of PZ-I at about 600-cm depth is less clear because of sparse samples. PZ-I is characterized by very low pollen concentrations and the presence of large amounts of reworked palynomorphs. The pollen spectra are

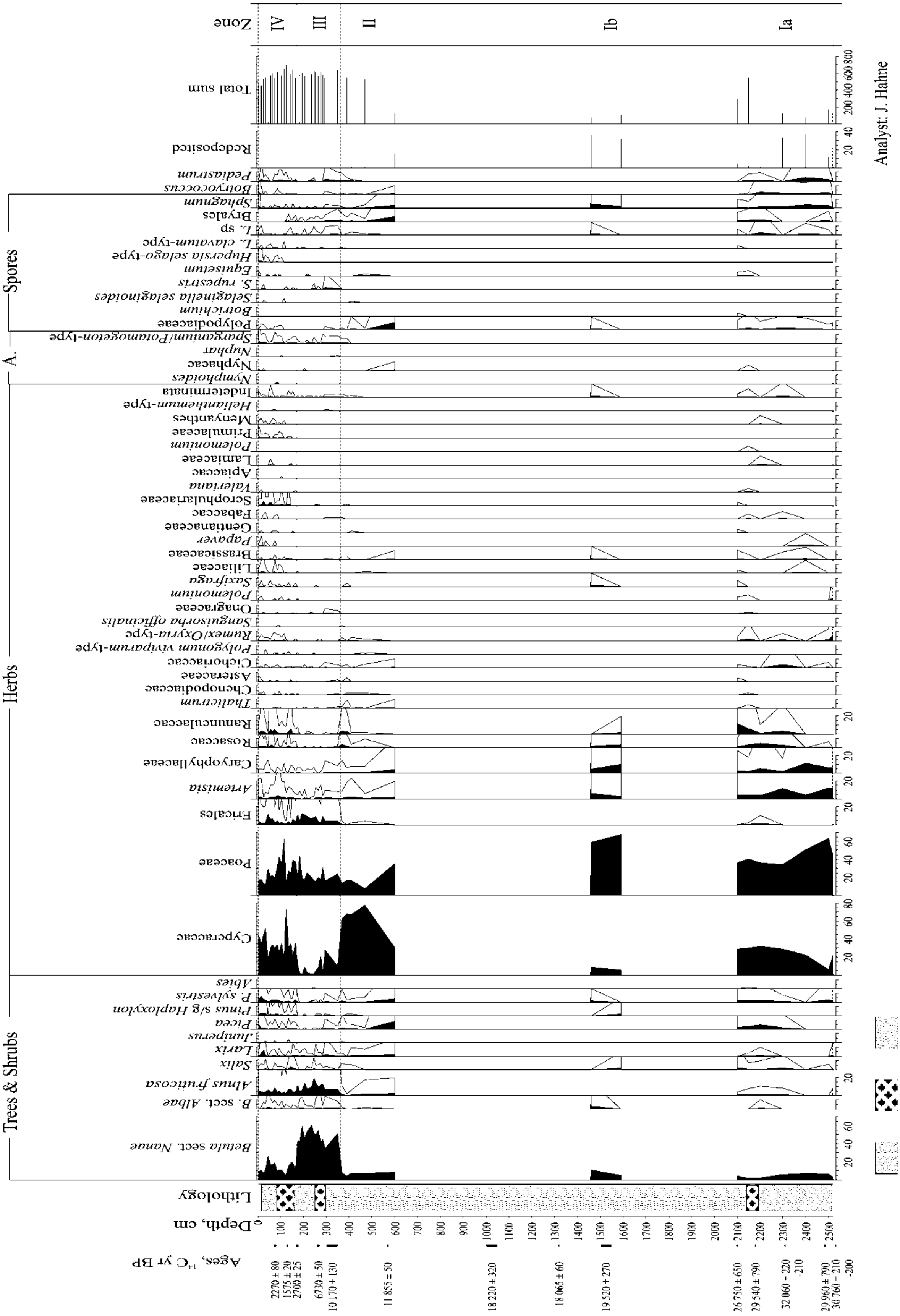


*Fig. 4.* Percentage pollen and spore diagram from SAO1 (HF method). 1. Silt with plant remains. 2. Silty peat. 3. Silt.

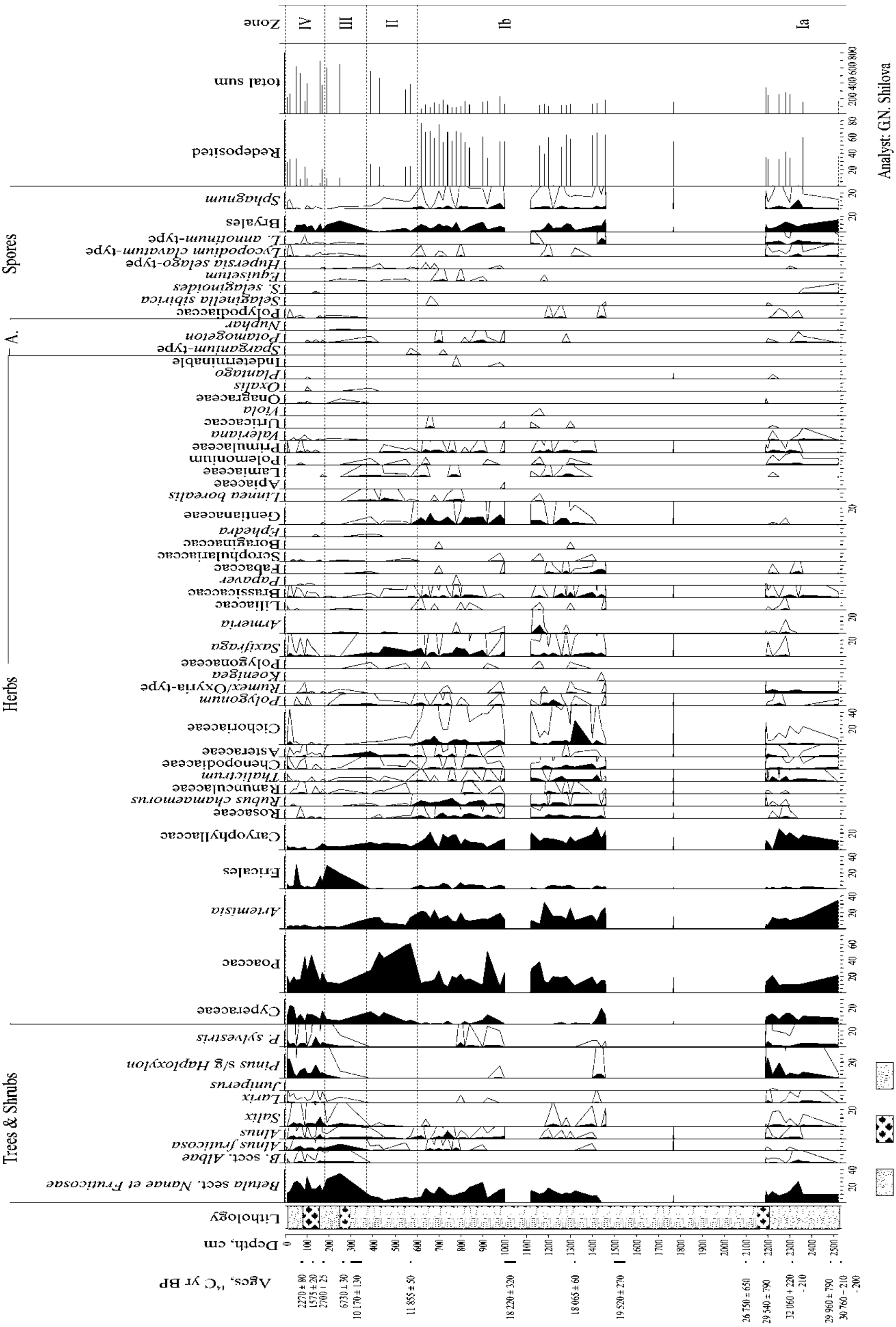


*Fig. 5.* Percentage pollen and spore diagram from SAO1 (heavy-liquid separation method). 1. Silt with plant remains. 2. Silty peat. 3. Silt.

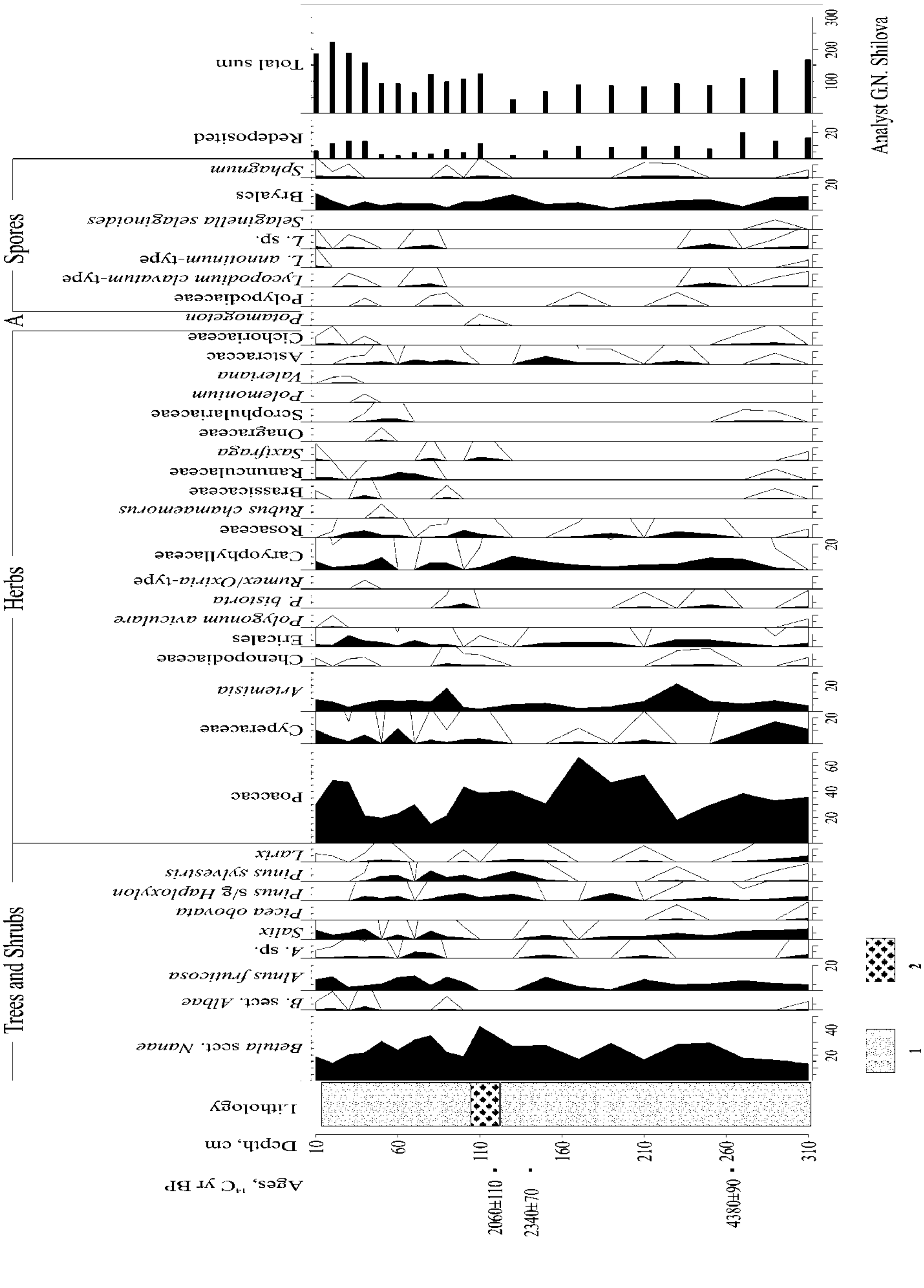


*Fig. 6.* Percentage pollen and spore diagram from SAO3. 1. Interbedding of fine-grained grey sand and silt layers, including numerous peaty layers with plant remains. 2. Sand with numerous moss and other plant remains.

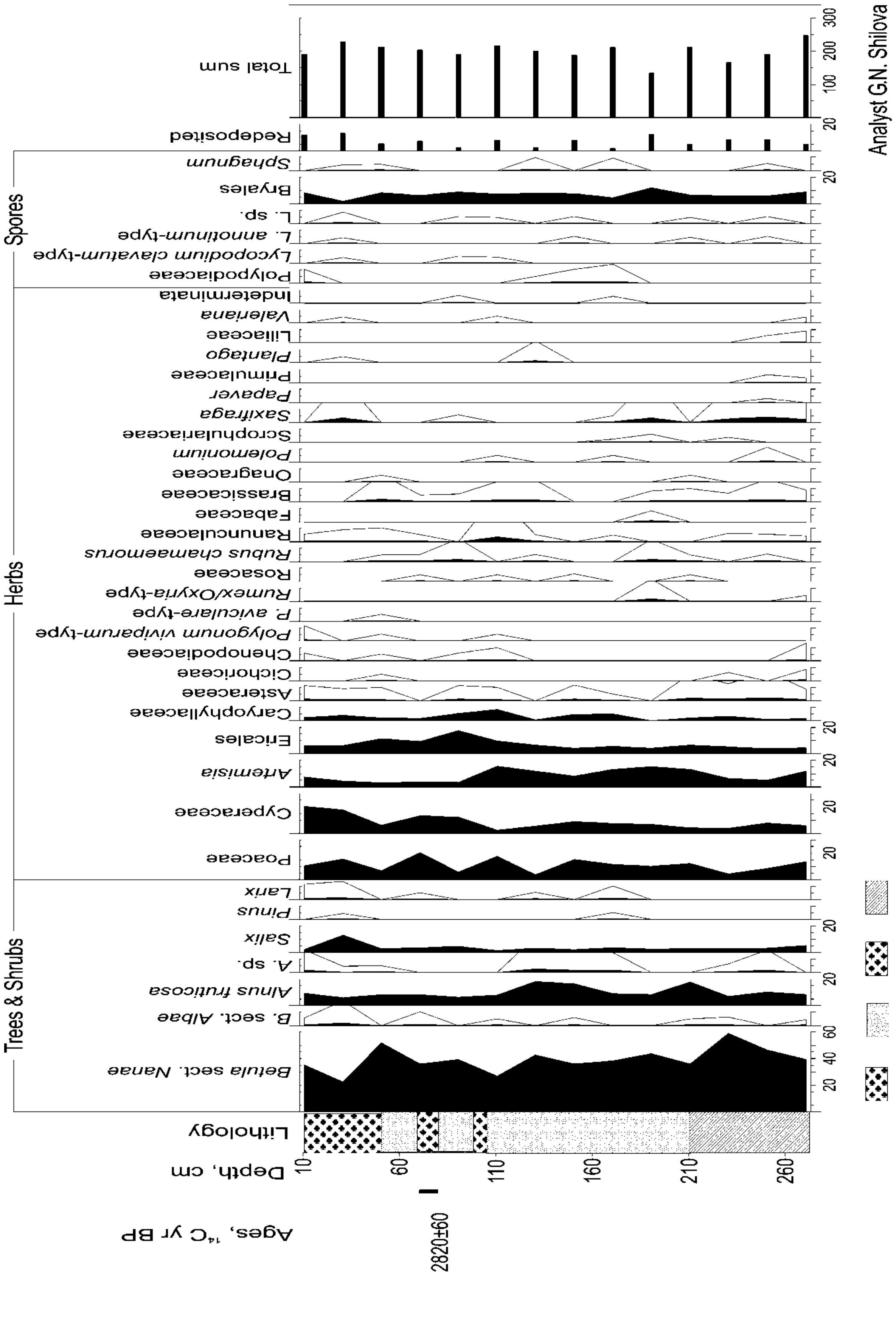


*Fig. 7.* Percentage pollen and spore diagram from SAO4. 1. Well-decomposed peat. 2. Silt. 3. Non-decomposed peat. 4. Interbedding of silt, sand and peat.

*Table 4.* List of testate amoebae species from SAO1 sequences.

| N | Species |
|---|---|
| 1 | *Arcella arenaria* v. *compressa* Chardez |
| 2 | *A. megastoma* Penard cf. |
| 3 | *Centropyxis aerophila* Deflandre |
| 4 | *C. aerophila* v. *sphagnicola* Deflandre |
| 5 | *C. aerophila* v. *minuta* Chardez |
| 6 | *C. cassis* (Wallich) Deflandre |
| 7 | *C. constricta* (Ehrenberg) Penard |
| 8 | *C. constricta* f. *minima* Decloitre |
| 9 | *C. gibbosa* Rampi |
| 10 | *C. orbicularis* Deflandre |
| 11 | *C. plagiostoma* Bonnet, Thomas (typica) |
| 12 | *C. plagiostoma* (major) |
| 13 | *C. plagiostoma* (minor) |
| 14 | *C. platystoma* (Penard) Deflandre |
| 15 | *C. sylvatica* (Deflandre) Thomas |
| 16 | *C. sylvatica v. microstoma* Bonnet |
| 17 | *C. sylvatica v. minor* Bonnet, Thomas |
| 18 | *Cyclopyxis eurystoma* (Deflandre) |
| 19 | *C. eurystoma* v. *parvula* Bonnet, Thomas |
| 20 | *C. kahli* Deflandre |
| 21 | *Geopyxella sylvicola* Bonnet, Thomas cf. |
| 22 | *Plagiopyxis callida* Penard |
| 23 | *P. declivis* Thomas |
| 24 | *Heleopera petricola* Leidy |
| 25 | *Nebela bigibbosa* Penard |
| 26 | *N. penardiana* Deflandre |
| 27 | *N. tincta* (Leidy) |
| 28 | *Schoenbornia humicola* Decloitre |
| 29 | *Phryganella acropodia* (Hertwig & Lesser) |
| 30 | *Assulina muscorum* Greeff |
| 31 | *Euglypha ciliata* f. *glabra* Wailes |
| 32 | *E. compressa* f. *glabra* Wailes |
| 33 | *E. laevis* (Ehrenberg) |
| 34 | *E.* sp. |
| 35 | *Trinema lineare* Penard |

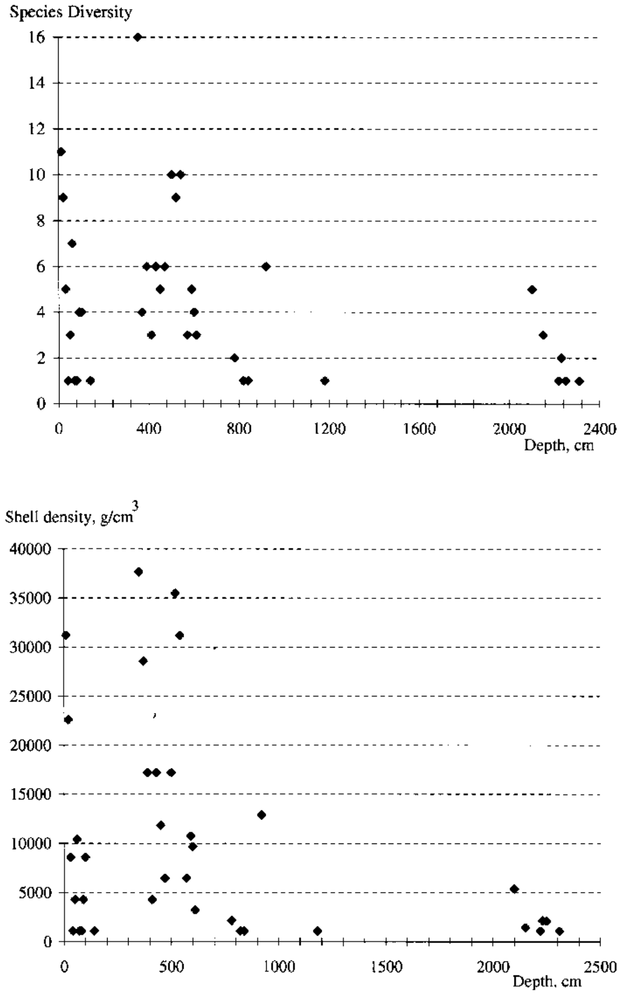


*Fig. 8.* Rhizopod diversity and density in SAO1 sediments.

dominated by Poaceae, Cyperaceae, *Artemisia*, Caryophyllaceae, Rosaceae and Ranunculaceae pollen. *Betula* sect. *Nanae* pollen occur as well. Two subzones are distinguished: PZ-Ib (1470–1590 cm) differs from PZ-Ia (2520–2110 cm) by distinctly lower Cyperaceae pollen contents, PZ-II (600–350 cm) is notable for a distinct Cyperaceae increase. PZ-III (350–180 cm) is characterized by an increase of *Betula* sect. *Nanae, Alnus fruticosa* and Ericales pollen contents, and a decrease in Cyperaceae. The pollen spectra of PZ-IV (180–0 cm) are dominated by Poaceae and Cyperaceae, although pollen of *Betula* sect. *Nanae* and *Alnus fruticosa* are numerous.

The analysis of G. N. Shilova (Fig. 5) shows that PZ-1 pollen spectra (2520–600 cm) are dominated by *Artemisia*, Poaceae, Cyperaceae, *Betula* sect. *Nanae* and Caryophyllaceae pollen. PZ-I is further characterized by low pollen concentrations and large amounts of reworked palynomorphs. Two subzones can be distinguished as well: PZ-Ia (2520 – *c.* 2200 cm), containing high amounts of tree pollen (most likely reworked), and PZ-Ib (*c.* 2200–600 cm), containing high amounts of herb pollen (Rosaceae, *Rubus chamaemorus, Saxifraga*, Cichoriaceae, Gentianaceae). PZ-II (600–310 cm) is notable for an increase in Poaceae, Cyperaceae and *Saxifraga* pollen contents, whereas pollen content of other herbs and *Betula* sect. *Nanae* significantly decrease. PZ-III (310–180 cm) is characterized by a high content of *Betula* sect. *Nanae, Alnus fruticosa* and Ericales pollen, and low contents of Cyperaceae and Poaceae. The pollen spectra of PZ-IV (180–0 cm) are dominated by Poaceae, *Betula* sect. *Nanae* and Cyperaceae pollen. Pollen content of *Pinus* is also fairly high.

The two remaining pollen records from Cape Sabler (SAO3 and SAO4) span only the second half of the Holocene and show similar trends; both form only one pollen zone each (Figs 6, 7). Minor differences in the type and amount of identified palynomorphs in these sections probably reflect local environments.

*Rhizopods (testate amoebae).* – In total, 106 samples were examined from the Holocene and Late Pleistocene sediments of the SAO1 section for rhizopods (testate

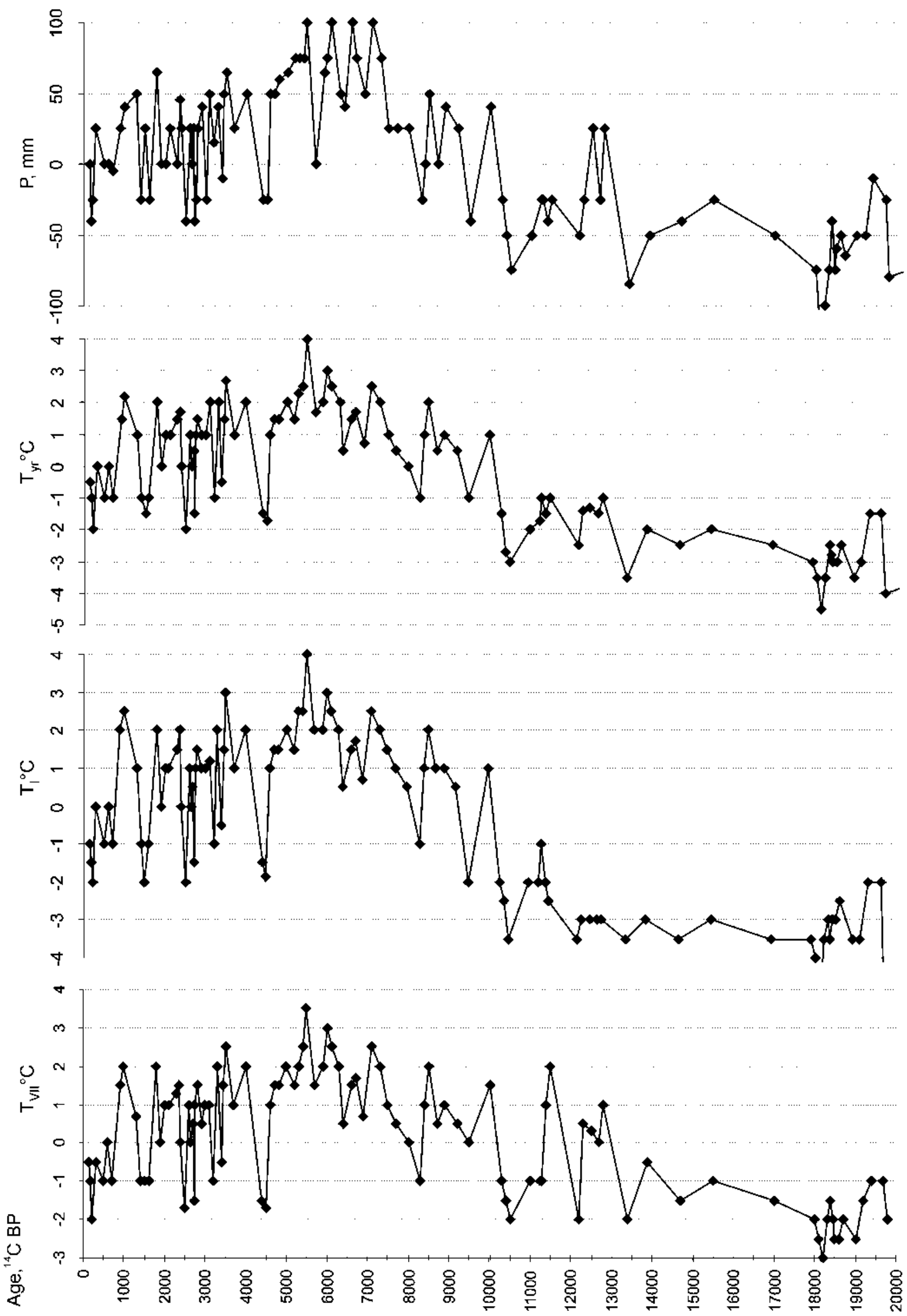


*Fig. 9.* The averaged climate anomalies, reconstructed by the information-statistical method (IS), using all studied pollen spectra (except the contaminated ones from core PG1228).

amoebae). None were found in 70 samples, including both Pleistocene and Holocene levels. Five samples contained only singular shells. In the 36 cases where rhizopods were present, 35 species, varieties and forms were found (Table 4). The number of species in these samples varied between 1 and 16 (Fig. 8). Generally, the species diversity is higher in the Holocene than in the Pleistocene sediments. No sphagnophilic species were found in the Pleistocene sediments. The species diversity is at its maximum (up to 16 species and infraspecific taxa) in the late Holocene samples (Fig. 8); the dominant complex consists of *Centropyxis constricta* f. *minor, C. aerophila, C. sylvatica* v. *minor* and *C. eurystoma* v. *parvula.*

## Climate reconstruction

*Information-statistical (IS) reconstruction based on Levinson-Lessing Lake and Cape Sabler pollen*

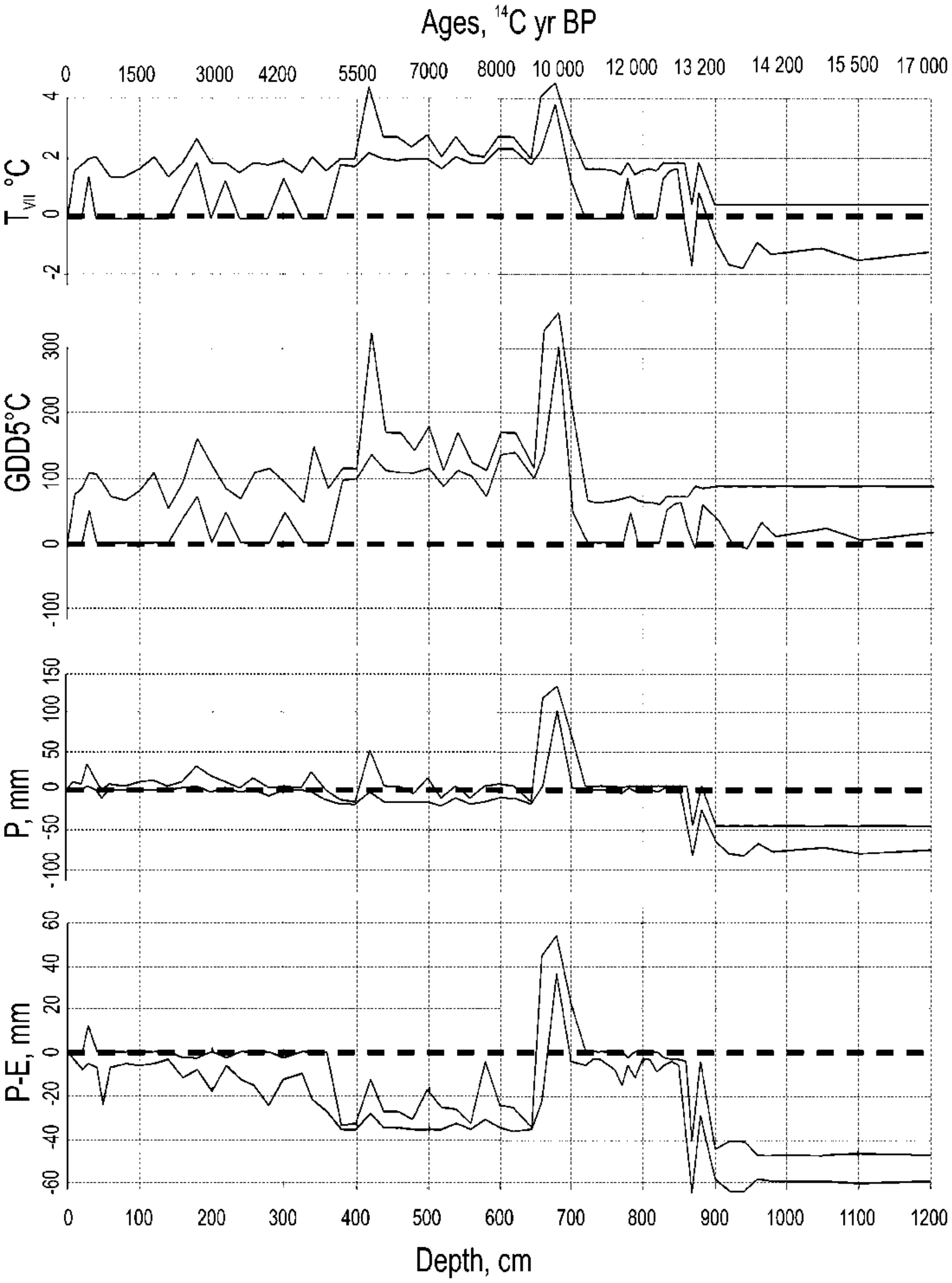


*Fig. 10.* Climate reconstruction from Levinson-Lessing Lake pollen record with the best modern analogue method (BMA). Two lines delimit a range between minimum and maximum values from the set of 10 modern analogues for each fossil spectrum.

*records c. 30 000 to c. 20 000 $^{14}$C yr BP.* – Temperatures at *c.* 30 000 $^{14}$C yr BP were below modern values, probably by about 2–5°C depending on the season (winter T more depressed). Precipitation was also lower, probably by about 50–100 mm. A subsequent climate amelioration may have occurred *c.* 27 000 yr $^{14}$C BP with T and P slightly above the present. Shortly after, cold, dry conditions returned, similar to those *c.* 30 000 $^{14}$C yr BP, and persisted until at least *c.* 20 000 $^{14}$C yr BP.

*About 20 000 $^{14}$C yr BP to the present.* – An extremely cold and dry climate is reconstructed for the Sartan stadial (equivalent to Late Weichselian), with T about 3–6°C below the present (seasonally dependent) and P up to 100 mm lower than today (Fig. 9). A warming event at the end of the Sartan stadial (equivalent to Bølling?) probably had $T_{VII}$ and P slightly higher than today, but $T_{yr}$ as much as 3°C lower. Later, during the Allerød (?), T and P were probably even higher (Fig. 9). A subsequent cooling (Younger Dryas?) reached values about 2–3.5°C below the present, with 75 mm less P. The first Holocene warming is associated with the early Preboreal, *c*. 10 000 $^{14}$C yr BP. Warm intervals with T and P higher than present have been reconstructed also for *c*. 9000, 8500, 8000–5500, 4000, 3500, 2300–2000 and 1000 $^{14}$C yr BP (Fig. 9).

### *BMA reconstruction based on Levinson-Lessing Lake pollen record*

*About 17 000 to* c. *13 000 $^{14}$C yr BP.* – Both $T_{VII}$ and GDD5 curves show similar pattern of temperature trends (Fig. 10). $T_{VII}$ was near or below present, while P was much lower, about 50–75 mm below the present. Runoff was also much lower.

*About 13 000 to* c. *10 000 $^{14}$C yr BP.* – $T_{VII}$ varied considerably but was mostly near the present or up to 2°C warmer. P was similar to the present, as was runoff.

*About 10 000 to* c. *5500 $^{14}$C yr BP.* – T was at its maximum, with July values 2 to 4.5°C higher than the present. GDD5 was 100 to 300°C higher than the present. P was similar to the present except for maximum values (50–130 mm higher than the present) near the beginning of this interval, when runoff also reached its maximum. The high T and similar P were probably the cause of the reduced runoff in much of this interval. The highest T occurred at the beginning and end of this interval.

*About 5000 $^{14}$C yr BP to the present.* – T dropped, with $T_{VII}$ fluctuating between 0 and 2°C above the present during the last 5000 $^{14}$C yr BP. P was similar to the present, although runoff may have been slightly lower.

## Discussion: palaeoenvironmental reconstructions

The pollen data from Levinson-Lessing Lake and Cape Sabler are the first long-term and high-resolution records from northern Central Siberia. Prior pollen work on Levinson-Lessing Lake (Hahne & Melles 1999) was based on the single $^{14}$C date and correlation with the pollen chronology published by Khotinskiy (1984). Although our pollen zonation is similar to that of Hahne & Melles (1999), there are significant differences in the environmental and chronological interpretation. Moreover, in the sections below, we compare our record with radiocarbon-dated environmental records from adjacent areas of Taymyr (Belorusova & Ukraintseva 1980; Nikol’skaya 1980; Nikol’skaya *et al.* 1980; Andreeva & Kind 1982; Belorusova *et al.* 1987; Velichko *et al.* 1997; Andreev & Klimanov 2000; Andreev *et al.* 2002b; Andreev *et al.* in press).

### *Late Karginsky interval (*c. *32 000–22 000 $^{14}$C yr BP)*

The oldest pollen samples from our study areas are dated to *c*. 30 000 $^{14}$C yr BP (Figs 3–5), similar to dates previously obtained on northern Taymyr Peninsula (Isaeva 1982; Möller *et al.* 1999). This places the older portions of our records within the Late Karginsky interstadial, which lasted until *c*. 25 000 $^{14}$C yr BP (Andreeva & Kind 1982). Sediment lithostratigraphies show no glacier ice at Levinson-Lessing Lake or Cape Sabler during the Late Karginsky. Pollen spectra instead suggest an overall dominance of open, steppe-like and tundra-like herb communities, with some short wetter period(s). Most of the spectra associated with this rather severe environment are characterized by low pollen concentrations and high amounts of reworked palynomorphs (Figs 3–5). The dominant taxa are Poaceae, Cyperaceae, *Artemisia*, Caryophyllaceae, Rosaceae and Ranunculaceae. Although pollen of *Betula* sect. *Nanae* are sometimes present, shrubs were mostly rare. The extraordinary high values of reworked pollen and spores (like ancient Pinaceae, *Juglans* and *Corylus*) for the heavy liquid separation of SAO1 PZ-Ia (Fig. 5) is probably misleading given much lower values for the HF separation (Fig. 4). This difference suggests that HF separation is more appropriate for the sediments containing reworked palynomorphs.

Our pollen-based reconstruction of a mostly severe Late Karginsky environment is supported by other proxies for northern Taymyr Peninsula. Eurobiotic rhizopods are present in the SAO1 sediments, suggesting a cold and dry environment. Moreover, macrofossil remains of typical steppe (*Ephedra, Kobresia, Leontopodium*) and tundra taxa (*Papaver, Dryas, Luzula*) from the Cape Sabler area have been used to reconstruct extremely severe cryoarid conditions for the Late Karginsky (Kienast *et al.* 2001).

A severe Late Karginsky environment has also been reconstructed based on pollen records from coastal areas of the Laptev Sea (Andreev *et al.* 2002a), East-Siberian Sea (Andreev *et al.* 2001) and western Yamal (Andreev unpublished). Hence, the harsh Late Karginsky environmental conditions around the Levinson-Lessing and Taymyr Lakes also occurred in a broad region of the high Eurasian North; these conditions probably reflect short distances to glaciated areas and to the Arctic Ocean.

Unlike the northern Taymyr and other northern areas during the Late Karginsky interstadial, the southern Taymyr probably experienced much less severe conditions. In the south, northern taiga or forest-tundra vegetation was present (Andreeva & Kind 1982; Andreev *et al.* 2002b). Because this southern area is presently treeless, the climate was warmer than the present.

Although environmental conditions on northern Taymyr during the Late Karginsky interstadial were most often severe, the IS-based climate reconstructions suggest some climate amelioration *c*. 27 000 yr $^{14}$C BP. This reconstruction is supported by a higher density of testacean shells in the Cape Sabler records, and especially by finds of rhizopods typical of wetter habitats (*Arcella megastroma* cf. and *Plagiopyxis callida*). Although a bud of *Populus tremula* (26 750 $\pm$ 650 yr BP) from the Cape Sabler area (SAO1) has been used to suggest that $T_{VII}$ was up to 6°C higher than today (Kienast *et al.* 2001), this bud may have been reworked. The Cape Sabler pollen records (Figs 4, 5) show that *Populus tremula* was probably unable to grow in this area during the Karginsky time. Moreover, it probably did not grow in southern Taymyr either (Andreeva & Kind 1982; Andreev *et al.* 2002b). The Cape Sabler sediments also contain significant amounts of well-preserved and obviously reworked tree and shrub pollen (including exotic taxa such as *Juglans*, *Corylus*, *Carpinus*). Therefore, even if climate ameliorated during a portion of Late Karginsky time, it is unlikely that the local climate was significantly warmer than today.

### *Interval* c. *26 000–20 000 $^{14}$C yr BP*

Pollen spectra for the *c*. 26 000–20 000 $^{14}$C yr BP interval, limited to Levinson-Lessing core PG1228, show conditions similar to the Late Karginsky: open steppe-like vegetation (Poaceae and *Artemisia* dominate) with some tundra-like communities (*Betula* sect. *Nanae*, *Salix*, Caryophyllaceae and other herb taxa). This result is based on PZ-III and PZ-V of PG1228. Two other pollen zones that seem to fall within this age interval, PZ-II and PZ-IV, were excluded because of potential displacement during coring (see above). The generally severe climate conditions for the interval *c*. 26 000–20 000 $^{14}$C yr BP on the northern Taymyr Peninsula were similar to those reconstructed for the Laptev Sea region from pollen records (Andreev *et al.* 2002a).

### *Sartan interval (*c. *20 000–10 000 $^{14}$C yr BP)*

Steppe-like vegetation dominated the northern Taymyr Peninsula during the Sartan (Late Weichselian Stadial, *c*. 22 000–10 000 $^{14}$C yr BP), although tundra-like communities with *Betula* sect. *Nanae*, *Salix* and Cyperaceae were also widespread. Pollen spectra in Levinson-Lessing core PG1228 contain large amounts of Poaceae, *Artemisia*, Caryophyllaceae, Ranunculaceae, Cichoriaceae and other herb taxa (upper part of PZ-V and PZ-Ib; Figs 4, 5). Macrofossil remains in Cape Sabler profile SAO1, $^{14}$C dated to 18 065 $\pm$ 60 yr BP, also show dominant steppe xerophytes and tundra cryophytes (Kienast *et al.* 2001). Moreover, very few rhizopod shells are found in the Sartan sediments (Fig. 8), which is also typical for Sartan sediments from the Laptev Sea region (Bobrov *et al.* in prep.). Thus, pollen, macrofossils and rhizopod shells all suggest an extremely cold climate during the Sartan interval. This is reflected in the IS and BMA reconstructions, which show the coldest climate during the Sartan (Figs 9, 10). Reconstructions of the LGM climate in northern Eurasia suggest that $T_I$ in Siberia were 7 to 15°C colder than the present and $T_{VII}$ 1 to 7°C colder, while $P$ was 100 to 300 mm lower than the present (Tarasov *et al.* 1999).

We suspect a warming at the end of the Sartan Stadial (Bølling?) as shown by a gradual decrease of *Artemisia* and Poaceae and increasing Cyperaceae and Rosaceae (mostly *Dryas*) pollen percentages in the upper part of Levinson-Lessing core PG1228 PZ-V (Fig. 3).

In contrast to the unclear warming signal (Bølling?), there is a distinct warming in the next youngest pollen zone in core PG1228 (PZ-VI), which can probably be correlated to the Allerød interstadial. Its age in PG1228 is constrained by correlation with pollen records from the adjacent areas (Velichko *et al.* 1997, 2002; Andreev *et al.* 2002b; Andreev *et al.* in press). Its age in the Cape Sabler SAO1 section is constrained by radiocarbon dates of 11 855 $\pm$ 50 and 10 170 $\pm$ 130 yr BP. The warming in core PG1228 is demonstrated by a dramatic increase of *Betula* sect. *Nanae*, *Salix* and pollen concentration, and significant decrease of *Artemisia*, Poaceae and other herb taxa pollen contents (Fig. 3). This same warming is expressed in SAO1 PZ-II in Fig. 5 with increases in Poaceae and Cyperaceae and decreases of *Artemisia*, Caryophyllaceae, Cichoriaceae, Gentianaceae, Rosaceae and other herbs. The high values of Cyperaceae pollen and low values of *Artemisia*, Caryophyllaceae, Rosaceae, Ranunculaceae and other herbs in the PZ-II in Fig. 4 can also be interpreted as a response of local vegetation to a wetter and slightly warmer climate. The occurrence of eurobiotic Testacea shells throughout the SAO1 sediments and the presence of soil and sphagnophilic species also signal a warm climate. Finally, both climate reconstruction methods suggest that $T_{VII}$ was up to 2°C higher than today (Figs 9, 10). Similar results are obtained from pollen records in the adjacent areas (Velichko *et al.* 1997, 2002; Andreev *et al.* 2002b; Andreev *et al.* in press).

A cooling of approximately Younger Dryas age is expressed in both core PG1228 and in section SAO-1. Pollen Zone-VII of PG1228 shows an increase of Cyperaceae, Poaceae, Caryophyllaceae, *Artemisia* and other herb taxa pollen content and decreasing *Betula* sect. *Nanae* contents and pollen concentration. Similar increases of *Artemisia*, Asteraceae, Rosaceae, Ranunculaceae and some other herb taxa occur in SAO PZ-II (Fig. 4) and in the upper part of SAO PZ-II (Fig. 5). Overall, these pollen spectra show that steppe communities became more dominant than during the prior warm period (Allerød?). Similar changes occurred in records from adjacent areas of Taymyr (Nikol'skaya 1980; Nikol'skaya *et al.* 1980; Velichko *et al.* 1997, 2002; Andreev & Klimanov 2000; Andreev *et al.* 2002b).

### *Holocene (*c. *10 000–0 $^{14}$C yr BP)*

Numerous and substantial environmental changes occurred at the Late Glacial/Preboreal transition on the northern Taymyr Peninsula. In core PG1228 PZ-VIII, *Betula* pollen percentages and total pollen concentration increased sharply while herb values decreased (Fig. 3). Similarly, SAO1 pollen records (PZ-III in Fig. 4) show increases of *Betula* sect. *Nanae* and Ericales pollen percentages, radiocarbon-dated to *c*. 10 200 yr BP. Dwarf birches, locally in mosaics with Ericales communities, dominated the vegetation in the area. Rhizopod species diversity increased and its spectra include some sphagnophilic, coarse-humus rhizopods (species from *Heleopera*, *Nebela* and *Triennia* genera) and calceophilic *Centropyxis plagiostoma* (Fig. 8). These changes suggest a much warmer and wetter environment than before *c*. 10 000 $^{14}$C yr BP. Our climate reconstructions have quantified this environment, showing that the early Preboreal warming *c*. 10 000 $^{14}$C yr BP resulted in $T_{VII}$ 3–4°C higher than the present and P about 100 mm higher (Figs 9, 10). A climate change of similar magnitude is recorded at a number of Northern Eurasian locations (e.g. Velichko *et al.* 1997, 2002; Andreev & Klimanov 2000; Andreev *et al.* 2002b).

The early Holocene was a period of higher-than-present temperatures on northern Taymyr Peninsula. Alder arrived locally about 8800–8500 $^{14}$C yr BP as shown by the dramatic increases in *Alnus fruticosa* pollen content (up to 52%) and total pollen concentration (up to 48 000 grains per cm$^3$) in PZ-IX of core PG1228 (Fig. 3) and a slight increase in *Alnus* pollen content at the bottom of PZ-III in section SAO1 (Figs 4, 5). Macrofossil remains of *Alnus fruticosa*, dated to $9300 \pm 100$, $8850 \pm 50$ and $8220 \pm 120$ $^{14}$C yr BP, have also been found north of its present distribution, close to the investigated sites (Nikol'skaya *et al.* 1980; Kremenetski *et al.* 1998). Vegetation cover was probably similar to the modern southern (shrub) tundra, where *Betula nana, Salix* and *Alnus fruticosa* dominate. The early Holocene *Alnus fruticosa* was probably restricted to well-protected habitats, as it is in the modern southern tundra zone. Generally, the northern limit of *Larix* forests with *Alnus fruticosa* was further north than today on the Taymyr Peninsula about 8600–8400 $^{14}$C years ago (Andreev *et al.* 2002b). At that time, during the so-called Boreal thermal optimum, the Arctic Ocean had a weaker influence on the Taymyr environment than today because of a lower sea level and, thus, a longer distance to the coast (Velichko *et al.* 1997; Andreev *et al.* 2002b). Summer insolation, another important factor, was still much higher than modern.

*Betula* sect. *Nanae* and *Alnus fruticosa* pollen content gradually decreases between *c*. 9000 and 5000 $^{14}$C yr BP in PZ-X of PG1228 (Fig. 3) reflecting their reduction in the local vegetation. Although decreasing, the percentages were still quite high and show that these shrubs remained either within or very close to the study sites. Coinciding with these decreases are gradual increases in Cyperaceae, Poaceae and Polypodiaceae. These changes most likely reflect rising sea level, declining summer insolation and onset of cooler, more maritime climate during the Atlantic period (Wolf *et al.* 2000). Thus, the shrubby tundra dominated by *Betula* sect. *Nanae*, and probably with *Alnus fruticosa* as co-dominant in some places, was gradually replaced with herb-tundra communities (mostly with Cyperaceae and Poaceae) between *c*. 8000 and 4500 $^{14}$C yr BP. Both climate reconstruction methods suggest a climate warmer than today during the Atlantic period (Figs 9, 10).

Holocene climate conditions appear to have deteriorated strongly after *c*. 4500 $^{14}$C yr BP to values similar to the present, where they remained for much of the late Holocene. Rhizopods became absent or had low species diversity and density (Fig. 8). There were also substantial decreases in total pollen concentration, *Betula* sect. *Nanae* and *Alnus fruticosa* pollen contents (PZ-XI, Fig. 3; PZ-IV, Figs 4, 5). Although reduced, these pollen taxa remained common in all late Holocene spectra (Figs 3–7). We believe that they mostly represent long-distance pollen, especially *Alnus*. A long-distance origin of arboreal pollen is also indicated by the increase of *Pinus, Picea* and *Larix* percentages. The present northern distributional limit of these taxa is a few hundred kilometres to the south. There are no *Betula* or *Alnus* shrubs in the Levinson-Lessing Lake area today despite modern pollen spectra with up to 20% of *Betula* sect. *Nanae* and up to 10% of *Alnus fruticosa* pollen (uppermost part of core PG1228). Thus, shrubless herb tundra has generally dominated the region since *c*. 4500 yr BP. In well-protected local sites, however, dwarf *Betula* sect. *Nanae* might even have dominated the vegetation. Its local presence about 2800 $^{14}$C yr BP is confirmed by macrofossil finds in profile SAO4 (Kienast *et al.* 2001).

Climate reconstructions (especially by the IS method) show a middle Holocene climate deterioration followed by conditions similar to the present (Figs 9, 10). Brief warming events interrupted the similar-to-present conditions of the late Holocene (warm events *c*. 4000, 3500, 2300–2000 and 1000 yr BP). Similarly dated climate fluctuations are recorded in many Northern Eurasian paleoenvironmental records (e.g. Velichko *et al.* 1997; Andreev & Klimanov 2000; Andreev *et al.* 2001, 2002b.)

## Conclusions

The first high-resolution, continuous pollen records for the northern Taymyr Peninsula reveal substantial vegetation and climate changes over the past 30 000 $^{14}$C yr BP, a period without any glacier cover. The oldest part of the record, corresponding to the Late

Karginsky and the Sartan intervals, shows a steppe-like vegetation with Poaceae, *Artemisia* and Cyperaceae dominating. Tundra-like communities with *Betula nana, Dryas* and *Salix* were probably present in moister sites. The coldest climate occurred within the Sartan period at *c*. 18 000 $^{14}$C yr BP. Subsequent Lateglacial climate fluctuations probably correspond to interstadial warmings and the Younger Dryas cooling. The Lateglacial/Preboreal transition, *c*. 10 300–10 000 $^{14}$C yr BP, is characterized by rapid warming and a change to shrubby tundra. Dwarf *Betula* and *Salix*. *Alnus fruticosa* arrived locally *c*. 9000–8500 $^{14}$C yr BP; the early Holocene also included *Betula* sect. *Nanae* communities. These taxa occurred when temperature and precipitation were higher than present. Shrubby tundra probably existed until cooler conditions arrived during the early Subboreal period, *c*. 4000–3500 $^{14}$C yr BP. The local vegetation developed into modern herb tundra at the end of the Subboreal period, *c*. 3000–2500 $^{14}$C yr BP. Brief warming events interrupted the similar-to-present conditions of the late Holocene (*c*. 4000, 3500, 2300–2000 and 1000 yr BP.)

*Acknowledgements.* – We thank the participants of the 'Taymyr 1995' and 'Taymyr/Severnaya Zemlya 1996' expeditions for their generous help in collecting samples. This research was made possible through the 'Taymyr' project of the German Ministry of Education and Research (Grant no. 03PL014A,B) and the project 'Natural climate variations from 10 000 years to the present day (KIHZ)' of the Helmholtz Association of National Research Centers (HGF). Pavel Tarasov was also supported by the Russian Foundation for Fundamental Investigations (RFFI grant nos. 00-05-22000 and 01-05-64471). We thank J. Hahne and G. N. Shilova for counting pollen and C. Zich for collecting material for AMS dating from core 1228.

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