Holocene paleoenvironmental records from Nikolay Lake, Lena River Delta, Arctic Russia

Andrei Andreev[a,*], Pavel Tarasov[b], Georg Schwamborn[a], Boris Ilyashuk[c],
Elena Ilyashuk[c], Anatoly Bobrov[d], Vladimir Klimanov[e],
Volker Rachold[a], Hans-Wolfgang Hubberten[a]

[a]*Alfred-Wegener-Institut für Polar-und Meeresforschung, Forschungsstelle Potsdam, Telegrafenberg A43, D-14473 Potsdam, Germany*
[b]*Department of Geography, Moscow State University, Vorobievy Gory, 119899 Moscow, Russia*
[c]*Institute of North Industrial Ecology Problems, Kola Science Center, Russian Academy of Sciences, Fersman St. 14, 184200 Apatity, Russia*
[d]*Department of Soil Sciences, Moscow State University, Vorobievy Gory, 119899 Moscow, Russia*
[e]*Institute of Geography, Russian Academy of Sciences, Staromonetny 29, 109017 Moscow, Russia*

Abstract

Radiocarbon-dated pollen, rhizopod, chironomid and total organic carbon (TOC) records from Nikolay Lake (73°20′ N, 124°12′ E) and a pollen record from a nearby peat sequence are used for a detailed environmental reconstruction of the Holocene in the Lena Delta area. Shrubby *Alnus fruticosa* and *Betula exilis* tundra existed during 10,300–4800 cal. yr BP and gradually disappeared after that time. Climate reconstructions based on the pollen and chironomid records suggest that the climate during ca. 10,300–9200 cal. yr BP was up to 2–3 °C warmer than the present day. Pollen-based reconstructions show that the climate was relatively warm during 9200–6000 cal. yr BP and rather unstable between ca. 5800–3700 cal. yr BP. Both the qualitative interpretation of pollen data and the results of quantitative reconstruction indicate that climate and vegetation became similar to modern-day conditions after ca. 3600 cal. yr BP. The chironomid-based temperature reconstruction suggests a relatively warm period between ca. 2300 and 1400 cal. yr BP, which corresponds to the slightly warmer climate conditions reconstructed from the pollen. Modern chironomid and rhizopod assemblages were established after ca. 1400 cal. yr BP.
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1. Introduction

Reconstructing the climate history of high Arctic regions is important for understanding present and past vegetation and climate changes in the Northern Hemisphere. The study of Arctic paleoenvironmental records enables qualitative and quantitative estimations of past climate changes and provides a basis for prediction of future changes in the region.

* Corresponding author. Fax: +49-331-2882137.
E-mail addresses: aandreev@awi-postdam.de (A. Andreev),
paveltarasov@hotmail.com (P. Tarasov),
gschwamborn@awi-postdam.de (G. Schwamborn),
ilyashuk@inep.ksc.ru (B. Ilyashuk), elena.ilyashuk@inep.ksc.ru
(E. Ilyashuk), Anatoly@bobrov.soils.msu.su (A. Bobrov),
paleo@glasnet.ru (V. Klimanov), hubbert@awi-postdam.de
(H.-W. Hubberten).

Fossil pollen records are a source of information about past changes of vegetation and can be used for quantitative reconstruction of climatic changes. The fossil remains of chironomids (non-biting midges, Diptera: Chironomidae), and rhizopods (testate amoebae, Protozoa: Testaceae) are also increasingly used. Chironomids spend much of their life cycle as aquatic larvae and many species are stenotopic. They respond rapidly to climatic fluctuations because of their short life cycles and the dispersal abilities of the winged adults. Temperature is usually the most important parameter explaining the geographic distribution and abundance of midges (Walker et al., 1991; Brooks and Birks, 2001). The chitinous head capsules, abundant and well preserved in lake sediments, are a valuable source of information for reconstructing paleoenvironmental change (Walker, 2001). Testate amoebae are a group of free-living protozoans with an organic shell (*testa*). Their well-defined ecological preferences and the relatively good preservation of fossil shells in lake sediments, peats and buried soils make them useful for the reconstruction of climate and environmental changes (Harnisch, 1927, 1948; Grospietsch, 1953; Schönborn, 1962; Meisterfeld, 1977; Tolonen, 1986).

Despite increased research of the Siberian Arctic over the last decades, the paleoenvironments of the Lena River Delta are still poorly understood. Andreev et al. (2002) examined late Quaternary pollen records from the Bykovsky Peninsula (Laptev Sea coast, location 3 on Fig. 1) east of the delta. The Bykovsky Peninsula Ice Complex deposits accumulated during the last 60,000 ^{14}C yr BP. Mostly open Poaceae and Cyperaceae associations with Asteraceae, *Artemisia*, Ranunculaceae, Caryophyllaceae and Cichoriaceae dominated in the area during the late Pleistocene. Unfortunately, the Holocene pollen data from the peninsula are discontinuous because Ice Complex sedimentation stopped ca. 14,000 cal. yr BP. The radiocarbon-dated pollen spectra indicate that shrubby (*Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Ericales) tundra covered the Bykovsky Peninsula between ca. 9100 and 5200 cal. yr BP. After that time, vegetation and climate became similar to modern (Andreev et al., 2002).

Changes in the diatom (Laing et al., 1999), pollen, stomate (Pisaric et al., 2001a) and midge (Porinchu and Cwynar, 2002) assemblages in a core from a forest–tundra lake south of the Lena River Delta (Fig. 1) location 4 reflect environmental changes since at least ca. 14,000 cal. yr BP. The records clearly show late glacial environmental changes, which can be interpreted as Allerød and Younger Dryas events. The data suggest that the treeline
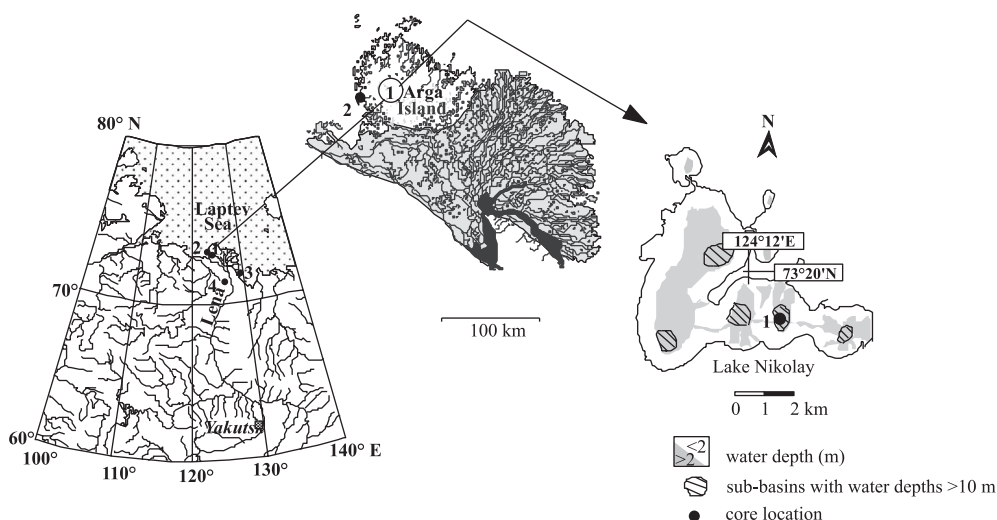

Fig. 1. Maps showing the location of coring sites in the Nikolay Lake (Lena River Delta) and other sites studied in the region. 1—Nikolay Lake core; 2—Barbarina Tumsa section; 3—Bykovsky Peninsula; 4—Dolgoe Lake core.

advanced across the region from ca. 9100 cal. yr BP and subsequently retreated southwards from ca. 4100 cal. yr BP.

This paper presents a multiproxy investigation of the Holocene climate, vegetation and lake ecosystem dynamics in the western part of the Lena Delta, where relatively little paleoecological work has been carried out to date. The reconstructions are based on the interpretation of pollen, rhizopod, chironomid and total organic carbon (TOC) records from the sediments of Nikolay Lake. The chronology is based on 13 AMS ages. Additionally, an AMS-dated pollen record from a nearby sandy peat sequence is also used for reconstruction of vegetation changes.

Quantitative climate reconstructions using the Nikolay Lake pollen record are performed with the information-statistical (IS) (Klimanov, 1976, 1984) and best modern analogues (BMA) methods (Guiot, 1990). Applying two different approaches provides a more robust reconstruction. Both methods have already been applied to fossil pollen records from northern Eurasia, including sites from the Russian Arctic (e.g., Frenzel et al., 1992; Cheddadi et al., 1997; Velichko et al., 1997; Andreev and Klimanov, 2000; Andreev et al., 2003, 2004). Furthermore, a quantitative reconstruction of mean July air temperature was performed using a chironomid-temperature inference model based on a modern calibration set from a subarctic region of northern Sweden (Larocque et al., 2001).

2. Study area

Nikolay Lake (73°20′ N, 124°12′ E) is the largest body of water in the Lena River Delta region and is situated in the northwestern part of Arga Island (Fig. 1). The island is one of the major geomorphologic elements of the Lena Delta and is characterised by numerous lakes with a submeridional orientation of the long axis typifying lake depressions (Grigoriev, 1993). Nikolay Lake consists of five subbasins and is about 8 km wide from east to west and about 6 km long from north to south. Approximately 70% of the lake basin has a water depth of less than 2 m. A maximum water depth of 30 m was recorded in one subbasin. Recent

studies suggest that the lake is of thermokarst origin (Schwamborn et al., 2002a).

The area is characterised by an Arctic climate with long, severe winters and short summers. Present day mean July (T_{VII}) and mean January (T_I) temperatures are around 5 and -30 °C, respectively. The mean annual temperature (T) varies between -13 and -15 °C. Annual precipitation (P) is about 200 mm with most falling in summer (Atlas Arktiki, 1985).

The study area is in the zone of continuous permafrost. The thickness of the permafrost reaches 500–600 m (Grigoriev et al., 1996), while the active layer is about 20–40 cm thick. Soils in the area are mainly tundra-gley and peaty-gley (histosols and inceptisols). The area belongs to the 'northern tundra zone' (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*.

3. Methods

Cores were collected from the central part of one of the lake subbasins (Fig. 1). Drilling of the lake sediments was performed from 2.2-m-thick ice in the spring of 1999 using a frozen-ground rotary coring kit (Schwamborn et al., 2002a). A 325-cm-long core (A1) was recovered from 14 m below the ice cover. In this core, only the upper 95 cm unit has been interpreted as being lake sediment; the lower 230 cm unit has been interpreted as having the same origin as the sediments in the bluffs around the lake (Schwamborn et al., 2002a,b). Subsamples taken at 5 cm intervals were used to analyse the organic carbon content (TOC) of this core. A gravity corer was used to collect additional short cores adjacent to the longer core, in order to have enough material for other analyses. Material from the longest gravity core of 83 cm (CN2), recovered a very short distance (less than 10 m) from core A1, was used for micropaleontological (pollen, rhizopod and chironomid), TOC and

Table 1
Radiocarbon dates from Lake Nikolay

Core	Sample depth (cm)	Lab. no	^{14}C yr BP	Cal. yr BP (95.4% probability)
CN2	1−3	KIA12527	506 ± 36	560 ± 60
CN2	9−11	AA40889	1547 ± 49	1430 ± 110
CN2	21−23	AA40890	2943 ± 45	3113 ± 180
CN2	41−43	KIA12528	4475 ± 38	5130 ± 170
CN2	57−59	KIA18396	8090 ± 70	9100 ± 95
CN2	77−79	KIA18397	8940 ± 90	10,110 ± 180
A1	10−15	KIA9113	2080 ± 30	2050 ± 100
A1	30−35	KIA9114	4335 ± 40	4931 ± 100
A1	55−60	AA40887	6975 ± 53	7800 ± 130
A1	65−70	AA40888	7777 ± 90	8680 ± 300
A1	90−95	KIA9115[a]	6330 ± 101	7210 ± 220
A1	90−95	KIA12529[a]	7090 ± 40	7880 ± 90
A1	95−100	KIA9116	12,480 ± 60	14,900 ± 700

Radiocarbon ages (^{14}C yr BP) are calibrated into calendar years (cal. yr BP) following Stuiver et al. (1998).
    [a] Ages assumed to be "too young".

$\delta^{13}C_{org.}$ analyses. Each subsample is 2 cm in length. Samples for radiocarbon dating were taken from both cores. Selected plant remains were AMS radiocarbon dated at the Leibniz Laboratory, Kiel and the AMS Laboratory of the Arizona University. A total of 13 samples were dated from cores A1 and CN2 (Table 1 and Fig. 2).

The sandy peat profile, Barbarina Tumsa (73°34′N, 123°21′E), is situated ca. 30 km from the lake (Fig. 1). Samples for pollen analyses were collected from the cleaned section in 10 cm intervals during field work in 2001. A total of four samples were dated from the profile (Table 2).

Total organic carbon (TOC) was analysed using a Metalyt-CS-1000-S (Eltra) in homogenised samples after removal of carbonate with 10% HCl at a temperature of 80 °C. The analyses were accurate to ± 5% for TOC contents > 1 wt.% (wt: weight) and ± 10% for TOC contents < 1 wt.%.

A stable carbon isotope profile was determined for the TOC contents from core A1. $\delta^{13}C_{org.}$ contents were measured using a FINNIGAN DELTA S mass

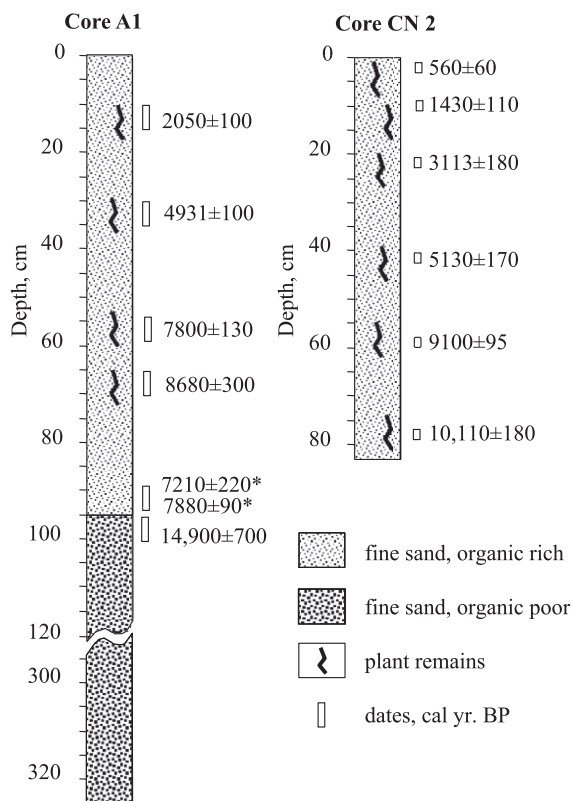Fig. 2. Lithology and cal. ages for cores A1 and CN2.

Table 2
Radiocarbon dates from Barbarina Tumsa section

Sample depth (cm)	Lab. no	^{14}C yr BP	Cal. yr BP (95.4% probability)
80−90	KIA18401	1795 ± 35	1805 ± 65
150−160	KIA18400	3180 ± 30	3460 ± 50
190−200	KIA18399	3800 ± 30	4280 ± 140
230−240	KIA18398	6280 ± 40	7290 ± 60

Radiocarbon ages (^{14}C yr BP) are calibrated into calendar years (cal. yr BP) following Stuiver et al. (1998).
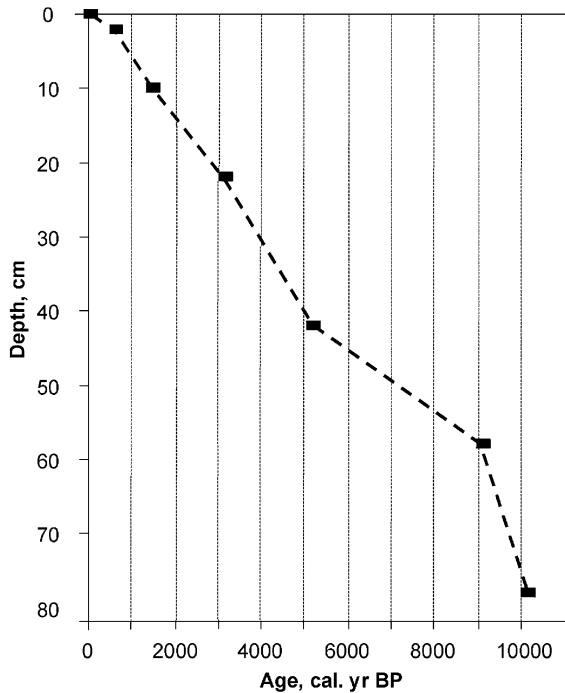
Fig. 3. Age/depth model.

spectrometer after removal of carbonate with 10% HCl in Ag-cups and combustion to CO_2 in a Heraeus elemental analyser (Fry et al., 1992). Accuracy of the methods was determined by parallel analysis of international standard reference material. The analyses were accurate to ± 0.2‰.

The core CN2 sediments were analysed for testate amoebae, pollen and chironomids. For rhizopod analyses, dry samples weighing 5 g were placed in 50 ml of water. Large organic and mineral particles were removed with a 500 μm sieve. A drop of suspension (0.05 ml) was placed on a slide and glycerol was added. On average, five subsamples per level were examined at ×200–400 magnification using a light microscope. The density of rhizopod shells was calculated according to the method used in soil studies (Geltzer et al., 1985).

For chironomid analysis, wet samples were sorted in a Bogorov counting tray under a dissecting microscope (×25 magnification). To better preserve fragile parts (especially mandible and labrum) of the chironomid head capsules, the sediments were not sieved or treated with KOH (Walker, 2001). Chironomid head

capsules were removed and mounted onto microscope slides in glycerol for taxonomic identification. Whole head capsules, and fragments containing more than half of the mentum, were counted as one head capsule. Split fragments of head capsules that included half the mentum were counted as one-half. Identifications were based on descriptions provided by Wiederholm (1983), as well as on several other publications (Pankratova, 1970; Hofmann, 1971; Sæther, 1975; Cranston, 1982; Sæther and Wang, 1996; Schnell, 1998; Makarchenko and Makarchenko, 1999). Generally, the total number of counted head capsules in each sample reached 100. The relationship between the profundal chironomid taxa and trophic conditions was reconstructed using the lake typology established by Sæther (1979). The Shannon–Weaver index (H') was used to calculate species diversity in the chironomid spectra, following Southwood (1971). All taxa, even rare species, were included in the analysis. To interpret the chironomid record in terms of T_{VII}, we used the estimated temperature optima ($T_{VII\text{-}opt}$) for chironomid taxa from Gaussian logit regression models based on a modern calibration set of 100 lakes located in a subarctic region of Sweden (Larocque et al., 2001).

A standard HF technique was used for pollen preparation (Berglund and Ralska-Jasiewiczowa, 1986). The relative frequency of arboreal and non-arboreal pollen taxa was calculated based on the sum of terrestrial pollen taxa. At least 200 pollen grains were counted in every sample. Calculation of spore percentages was based on a sum of pollen and spores. The relative abundances of reworked taxa (Tertiary spores and redeposited Quaternary pollen) were based on a sum of pollen and redeposited taxa, and the percentage of algae was based on a sum of pollen and algae (Berglund and Ralska-Jasiewiczowa, 1986). Tilia/TiliaGraph software (Grimm, 1991) was used for the calculation of chironomid, rhizopod, pollen and spore percentages, and for drawing diagrams (Figs. 5–8).

Two statistical approaches were used to reconstruct climate from the pollen record: the IS and standard BMA methods. Details of the IS method are described in Klimanov (1976, 1984). Reconstruction of past climate was based on the established relationships (transfer function) between percentages of tree and shrub taxa calculated for more than 800 surface pollen

spectra from the former USSR, and modern climate variables (T_{VII}, T_I, T and P) at the sampling sites derived from the Climatic Atlas of the USSR (Klimaticheskiy Atlas SSSR, 1960). The ratio between arboreal and nonarboreal pollen was also taken into account. The reliability and accuracy of the method, determined by testing with modern pollen spectra, (Klimanov, 1976, 1984) is very high (statistical error of ± 0.6 °C for T_{VII}, ± 1.0 °C for T_I and ± 25 mm for P). However, statistical errors in the pollen-based climate reconstructions of the Russian Arctic must be larger, due to the fact that the Arctic region was relatively poorly represented in the data set used for the method calibration.

The standard BMA method (Guiot, 1990) uses a chord distance to determine the similarity between each analysed pollen spectrum and each spectrum in the reference data set. PPPBase software (Guiot and Goeury, 1996) was used to perform all calculations and allowed us to choose the most suitable number of best analogues and to exclude "bad" analogues from the calculation. In the present study, the BMA approach was used with the modern pollen data set, which includes 1106 surface pollen spectra from northern Eurasia. These data mainly came from the compilation of Tarasov et al. (1998). However, for the present study, we compiled more than 200 additional spectra from the Russian Arctic (Bolikhovskaya and Bolikhovskii, 1994; Edwards et al., 2000; Lozhkin et al., 2001; Pisaric et al., 2001a; Solovieva, personal communication). A total of 77 arboreal and nonarboreal pollen taxa were included in the analysis. Modern climate variables at the pollen sampling sites were calculated from the updated version of the Leemans and Cramer (1991) climate database (Cramer, personal communication).
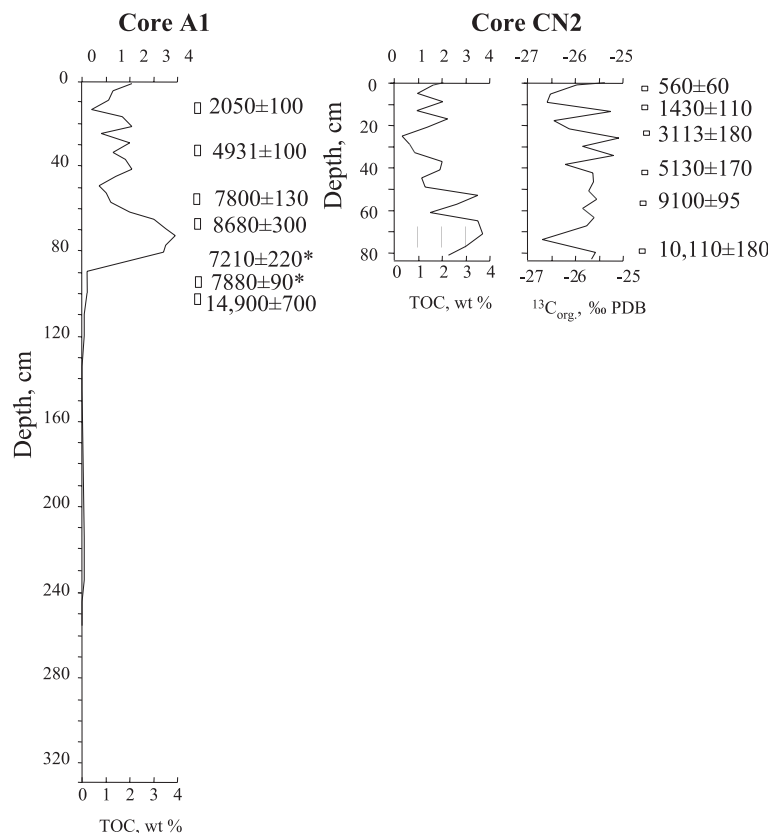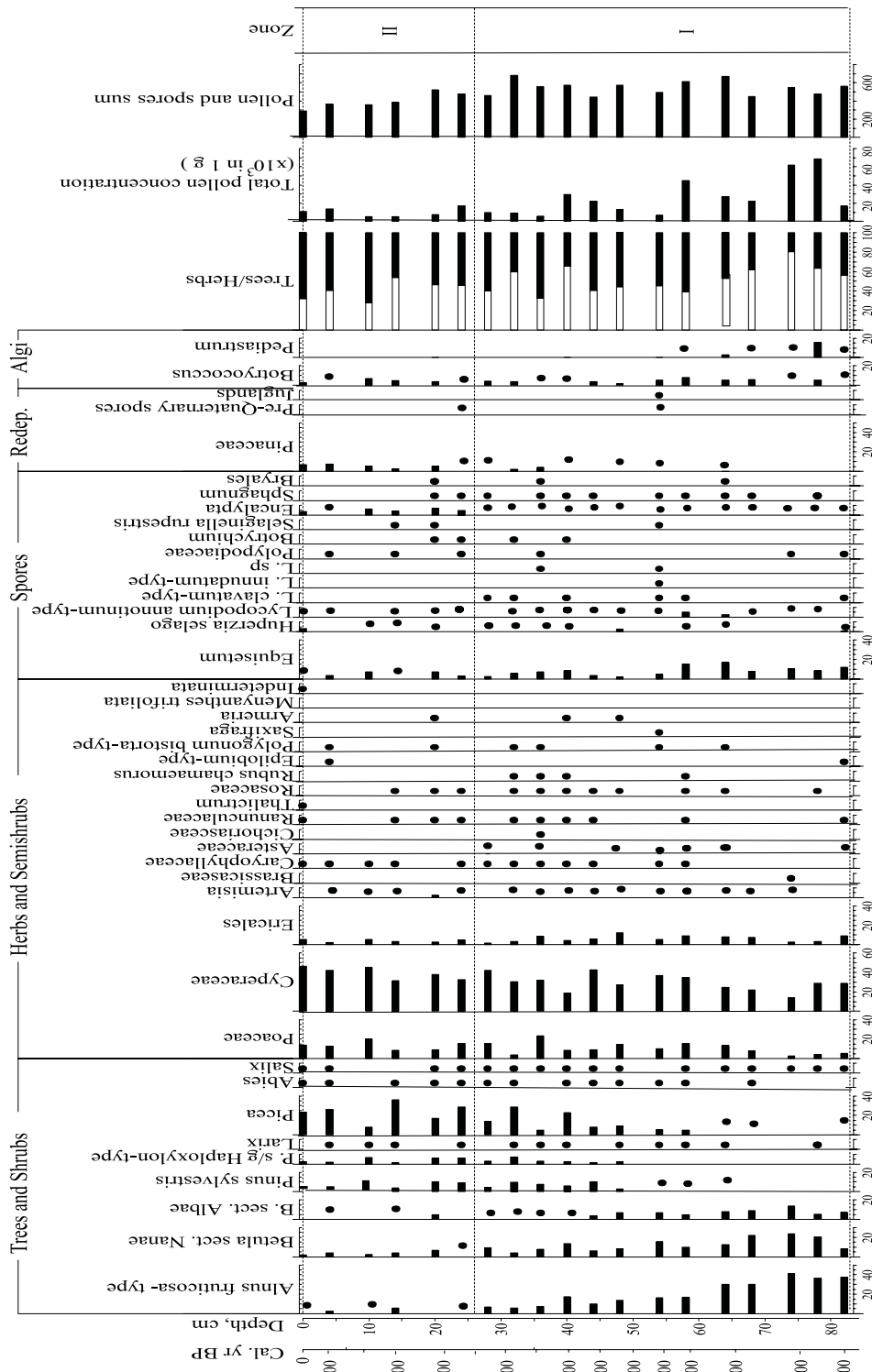

Fig. 4. Total organic carbon (TOC) and organic carbon isotopes from cores A1 and CN2.

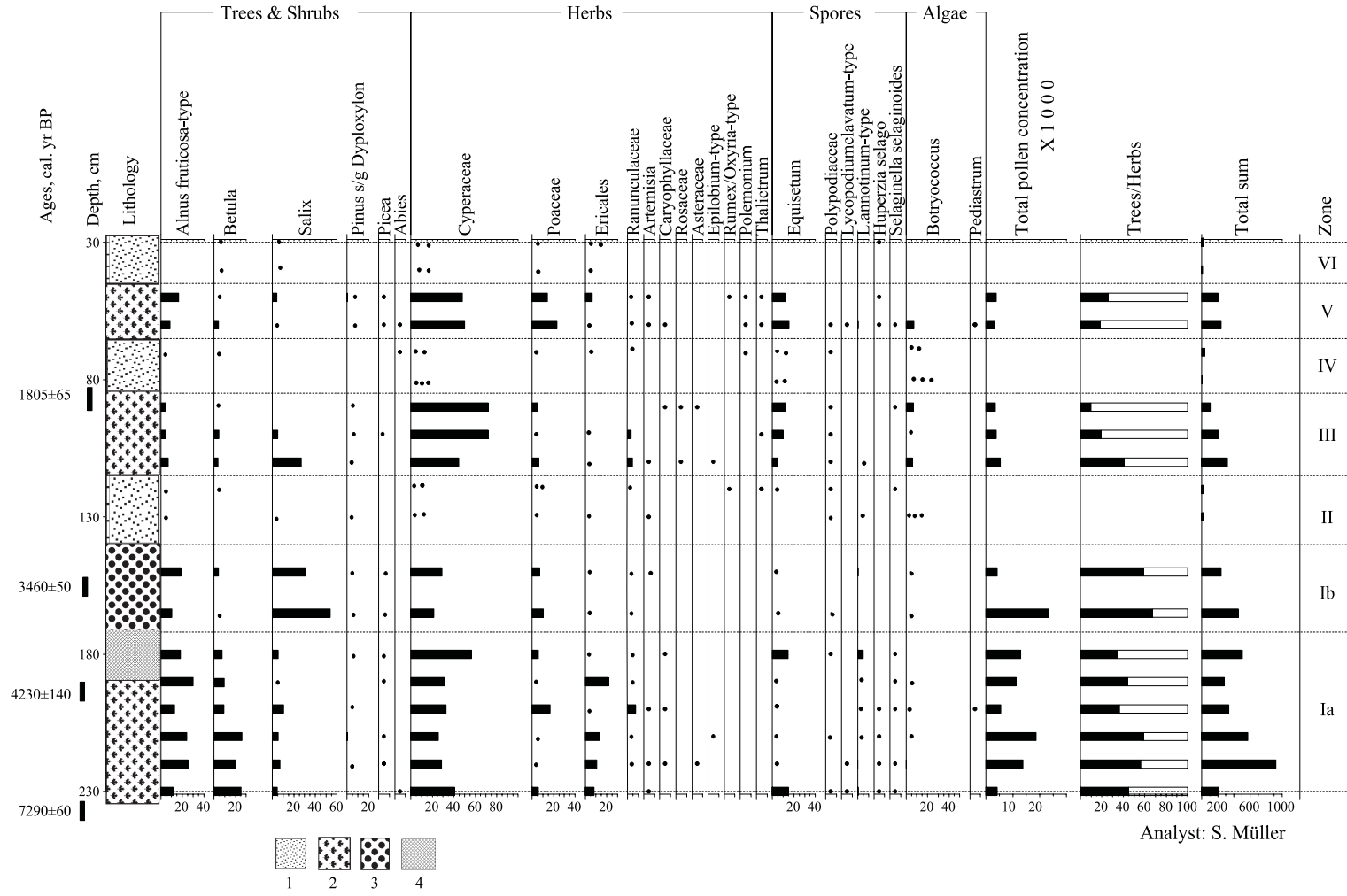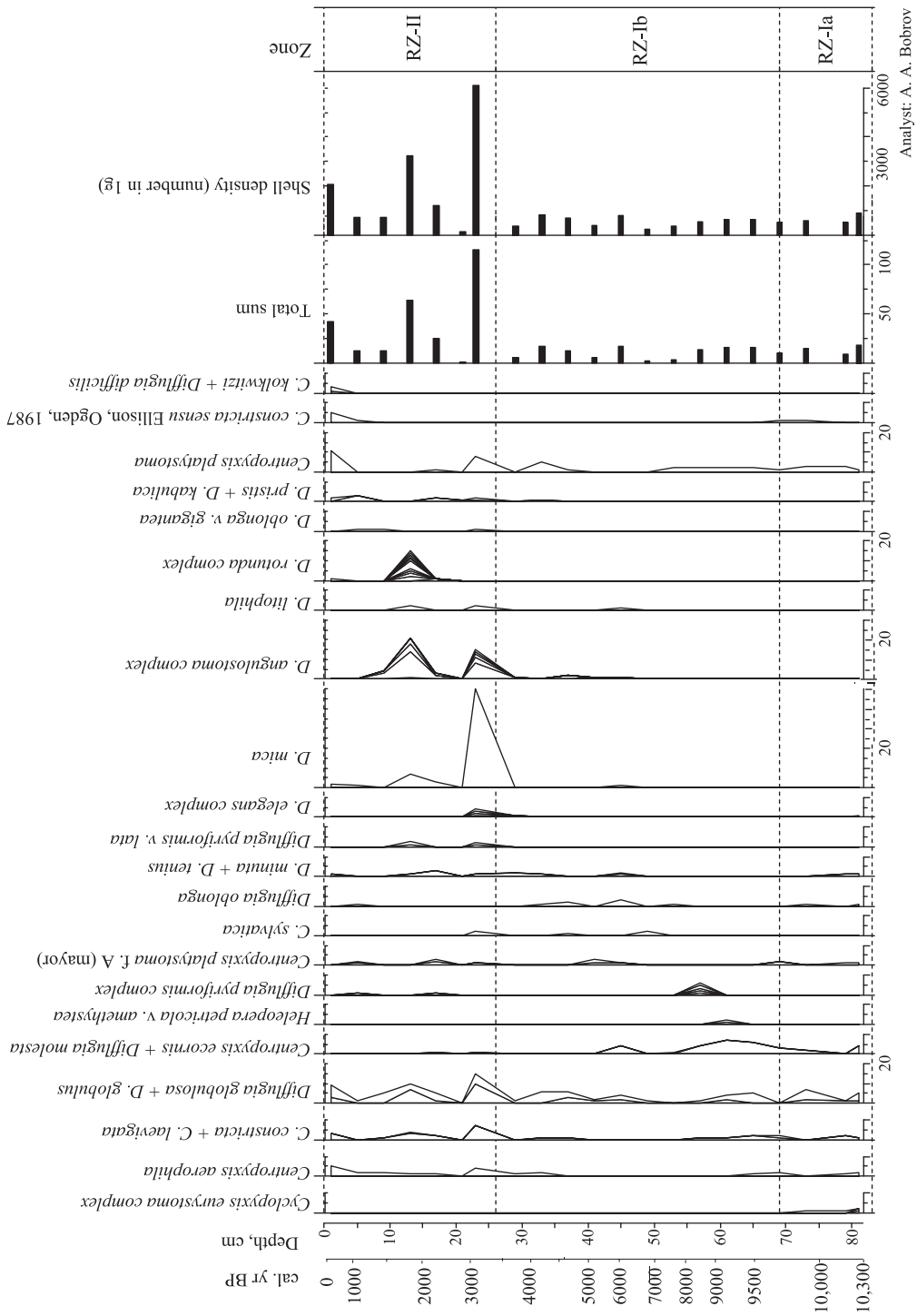Fig. 5. Pollen percentage and spore diagram of core CN2. ● —less than 1%.

Fig. 6. Pollen percentage and spore diagram of the Barbarina Tumsa section. ●—less than 1%; 1—sand; 2—sandy peat; 3—slightly decomposed peat; 4—sand with peat lenses.

Fig. 7. Rhizopod percentage diagram of core CN2.

Chironomids were used to reconstruct T_{VII} by weighted averaging partial least squares (WA–PLS) regression (ter Braak and Juggins, 1993) based on the Swedish calibration data set (Larocque et al., 2001). The T_{VII} range in the data set is 7.0–14.7 °C. The best prediction model was obtained using a two-component WA–PLS regression that yielded a root mean square error of prediction (RMSEP, based on jack-knifing) of 1.13 °C, a coefficient of determination (r^2) of 0.65 and a maximum bias of 2.1 °C between measured and predicted T_{VII} values (Larocque et al., 2001). The T_{VII} reconstructions from the fossil chironomid assemblages were performed using the program WA–PLS 1.51 (Juggins and ter Braak, unpublished). To stabilise variances among taxa, percentage data were transformed using the natural logarithm ($\ln[x+1]$) prior to reconstructions. Sample-specific prediction errors were estimated by Monte Carlo simulation (500 simulations; Birks, 1995). A locally weighted regression smoothing (LOESS; Cleveland et al., 1993) with a span of 0.25 was used to help highlight the major trend in the reconstructed values.

4. Results and interpretation

4.1. Lithostratigraphy

The A1 core (325 cm) can be divided into two sedimentary units (Fig. 2) based on the field description and TOC measurements. The upper 95 cm consists of organic-rich fine sand, lake sediments with rare plant macrofossil fragments. The lower 230 cm consists of organic-poor fine sand deposited in nonlacustrine conditions (Schwamborn et al., 2002b). Grain size data suggest only a small influx of material from the lake catchment but a significant aeolian drifted fraction within the lake sediments (Schwamborn et al., 2002a). Core CN2 (83 cm) consists of organic-rich fine sand with rare plant macrofossil fragments and is similar to the upper unit of core A1 (Fig. 2).

The lower 240–190 cm of the Barbarina Tumsa section (Fig. 6) is sandy peat, overlaid by 20 cm of sand with peat lenses. From 170–140 cm is slightly decomposed peat. From 140–115 cm and 85–65 cm are sand with rare plant remains, overlaid by ca. 30 cm and ca. 20–25 cm of sandy peat, respectively. The uppermost 40–50 cm is sand.

4.2. Chronology

A total of 13 ages (six from CN2 and seven from A1) were obtained from the analysed cores (Table 1). The oldest date, 14,900 ± 700 cal. yr BP (Table 1) indicates the age of sand underlying the lacustrine sediments in Nikolay Lake. The sands forming the second fluvial terrace in the Lena River Delta are also IR–OSL dated between 14,500 and 10,900 yr BP (Schwamborn et al., 2002b).

The six AMS ages of handpicked plant fragments from core CN2 provide a reliable depth/time relation (Fig. 3), which has been used for the chronology. The four AMS ages of handpicked plant fragments from the upper 70 cm of core A1 provide a consistent depth/time relation similar to core CN2. However, two dates from 90–95 cm of core A1 show younger ages (7880 ± 90 and 7210 ± 220 cal. yr BP). These dates are assumed to be unreliable due to possible contamination of the sediments by younger organic material during the coring.

We assume that the lacustrine sedimentation started about 10,300 cal. yr BP. A rather high sedimentation rate (ca. 25 cm/1000 yr) in the first 1000 yr after lake formation was probably due to continuous shore abrasion during that time. The sedimentation rate decreased to ca. 4 cm/1000 yr between ca. 9000 and 5000 cal. yr BP. After 5000 cal. yr BP, the sedimentation rate reached ca. 7 cm/1000 yr.

All dates from the Barbarina Tumsa section (Table 2) are in good agreement and indicate that peat accumulation started about 7300 cal. yr BP. However, because peat accumulation in this section was repeatedly interrupted by sand accumulation, we are prevented from using this record for quantitative environmental reconstruction.

4.3. Organic carbon record

The total organic carbon (TOC) and isotope ($\delta^{13}C_{org.}$) records were obtained from bulk organic material from cores A1 and CN2. The upper 95 cm of core A1 (Fig. 4) consists of lake sediments with relatively high TOC content (3.9 wt.%) and the lower 230 cm consists of organic-poor nonlacustrine sediments (TOC < 0.3 wt.%). Relatively organic-rich sediments of core CN2 have a narrow range of
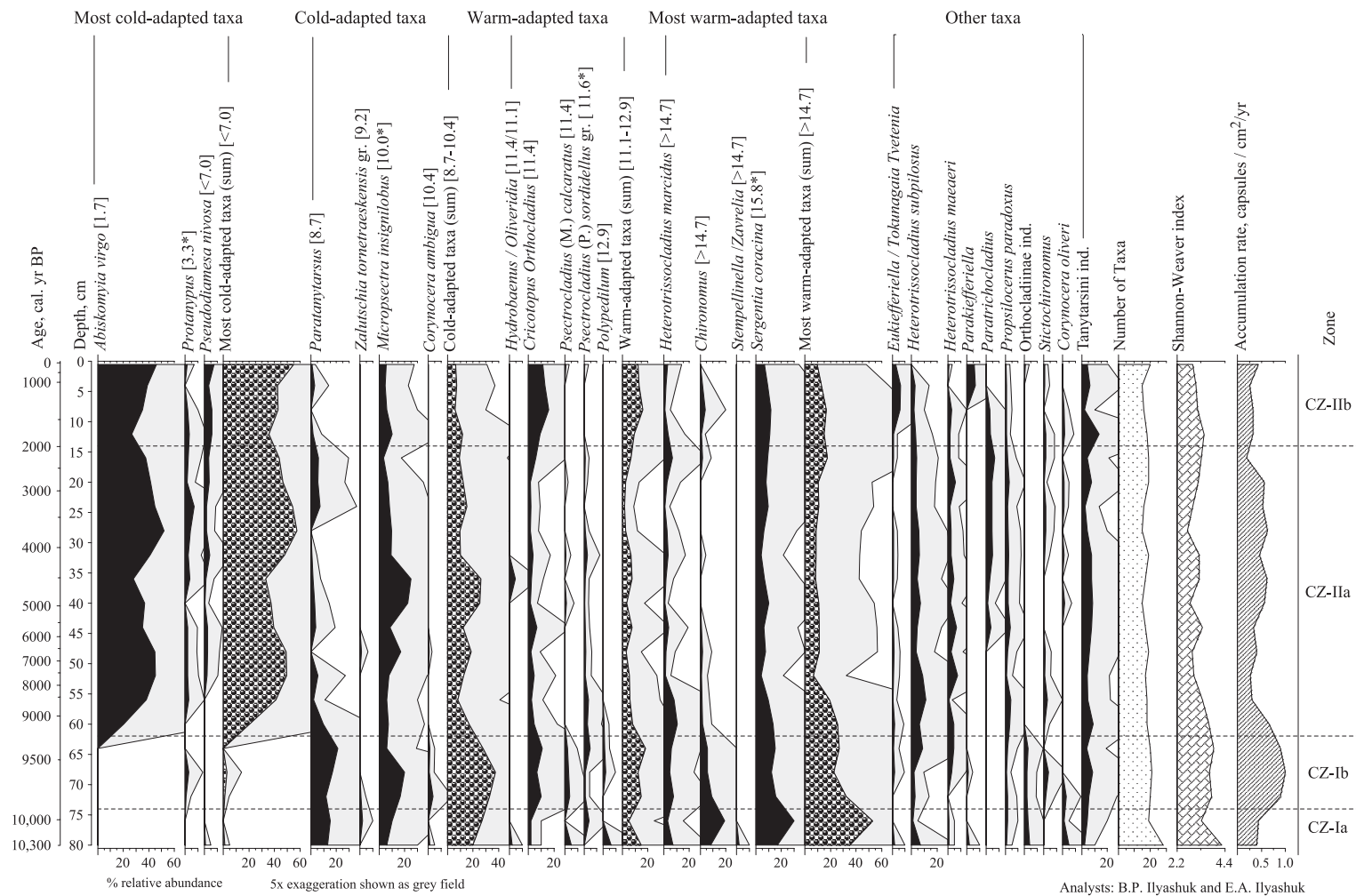
Fig. 8. Chironomid diagram of core CN2. Mean July air temperature optima ($T_{VII-opt}$) for taxa are indicated in square brackets. * – taxa having no significant relationship with T_{VII}, according to the models described by Larocque et al. (2001).

$\delta^{13}C_{org.}$ values, between $-25‰$ and $-27‰$ PDB (Fig. 4). This is similar to $\delta^{13}C_{org.}$ values from terrestrial plant material ($-26.6‰$ to $-24.3‰$ PDB) from the Arctic Siberia (Gundelwein, 1998). In contrast, fresh-water plankton generally has depleted $\delta^{13}C_{org.}$ values of $-30.0\pm 3‰$ PDB (Ariztegui and McKenzie, 1995). Modern $\delta^{13}C_{org.}$ values of autochthonous macrophytes (26.3‰ PDB) from Lake Nikolay fall between these two ranges.

A negative correlation between TOC concentrations and the $\delta^{13}C_{org.}$ values in the upper unit is seen in Fig. 4. A prominent maximum in TOC content at about 8500 cal. yr BP and a few minor TOC maxima towards the top of the section are paralleled by downward shifts in $\delta^{13}C_{org.}$. These findings imply that low $\delta^{13}C_{org.}$ values can be explained by an increasing contribution from plankton, and thus indicate rather high lake bioproductivity. The strong relationship between $\delta^{13}C_{org.}$ and TOC values points to a lacustrine rather than terrestrial source of the organic matter. The generally rather small range of carbon isotope values suggests that the lake environment was environmentally stable after the bioproductive maximum at about 8500 cal. yr BP.

4.4. Pollen

The sandy deposits underlying the lake sediments and recovered in the lower sedimentary unit of core A1 (95–325 cm) contain very few pollen grains. We identified mostly Poaceae and Cyperaceae pollen with single grains of *Artemisia* and a few other taxa. The extremely low pollen concentration and poor pollen preservation in these sediments make the calculation of pollen percentages impossible. Thus, these results cannot be presented in a pollen diagram. The relatively high content of green algae colonies (*Pediastrum* and *Botryococcus*) in the sample from 95–100 cm suggests a shallow unstable water body (e.g., small pond or marsh). The pollen assemblage of this sample is richer than in the lower part of this sand unit. We identified a few pollen of Cyperaceae, Poaceae and *Artemisia* as well as single grains of *Betula* sect. *Nanae*, *Salix*, and *Alnus fruticosa*.

The pollen diagram for core CN2 (Fig. 5) was zoned visually. Pollen zone I (PZ-I, 83–26 cm) is

notable for its rather high (up to 70,000 grains/cm^3) pollen concentration, pointing to high pollen production by plant communities in the area and probably rather dense vegetation cover. The pollen spectra are dominated by pollen of *Alnus fruticosa*, *Betula* sect. *Nanae*, Poaceae and Cyperaceae, suggesting that shrubby tundra vegetation dominated the area around the lake.

There is a gradual decrease in total pollen concentration and percentages of *Alnus fruticosa*, *Betula* sect. *Nanae* and *Betula* sect. *Albae* pollen in the upper part of PZ-I. An increase of *Picea*, *Pinus* s/g *Haploxylon*-type, and *P. sylvestris* pollen reflects the increasing significance of long-distance transport. The pollen spectra mirror changes in the local vegetation and a lower productivity of the plant communities.

PZ-II (26–0 cm) has relatively high percentages of *Picea* and *Pinus* and relatively low (up to 12,000 grains per cm^3) pollen concentration. Cyperaceae–Poaceae dominates the pollen spectra and indicates that herb tundra dominated the area around the lake. Relatively high amounts of reworked Pinaceae pollen and *Encalypta* (moss growing on disturbed soils) spores may reflect rather scarce vegetation cover, as well as soil disturbances.

The pollen diagram of the Barbarina Tumsa section was also zoned by visual inspection (Fig. 6). PZ-Ia (240–175 cm) has a relatively high (up to 20,000 grains per cm^3) pollen concentration, pointing to a relatively high pollen production of plant communities around the site. The pollen spectra are dominated by pollen of *Alnus fruticosa*, *Betula*, *Salix*, Ericales, Poaceae and Cyperaceae, suggesting that shrubby tundra vegetation dominated the area. PZ-Ib (175–140 cm) shows an increase in the percentage of *Salix* pollen, while that of *Betula* and Ericales is significantly decreased.

PZ-II (140–115 cm) is a sandy layer with only a few, poorly preserved pollen grains, making counting difficult. PZ-III (115–85 cm) has relatively high percentages of *Salix* and Cyperaceae pollen and *Equisetum* spores. Pollen concentration is relatively low. PZ-IV (85–65 cm) is similar to PZ-II. PZ-V (65–45 cm) has a relatively low pollen concentration with Cyperaceae, Poaceae pollen and *Equisetum* spores dominating. PZ-VI (the upper 45 cm) is identical to PZ-II and PZ-IV.

4.5. Rhizopods

Generally, the sediments contain few rhizopod shells. Those that were identified belong to 57 species, varieties and forms of testate amoebae (Appendix A). The rhizopods were grouped into assemblage zones (Fig. 7). Only two species, *Centropyxis constricta* and *Centropyxis aerophyla*, are eurybiotic; all others are hydrobiotic. Oligotrophic *Centropyxis* and *Difflugia* species dominate all the samples, reflecting the oligotrophic character of the lake environment. Changes in shell density and species diversity may indicate changes in shell preservation conditions, and/or in environmental conditions. Assuming that there were no changes in the sediment lithology, abrupt changes in rhizopod abundance and species diversity are likely to indicate environmental changes in the lake basin.

Rhizopod zone I (RZ-I, 83−26 cm) is characterised by a very low shell density. We subdivided the zone into RZ-Ia (83−69 cm), characterised by the presence of *Cyclopyxis*, *Arcella* and *Centropyxis ecornis* v. *megastoma*, and RZ-Ib (69−26 cm), characterised by a relatively high content of *C. ecornis*, *Centropyxis sylvatica*, and *Difflugia* species. Relatively high species diversity in the lower part (83−57 cm) of RZ-I may point to an environment favourable for the rhizopods. A significant decrease in shell density and low species diversity in the sediments between 57−45 cm may reflect climate deterioration.

RZ-II (26−0 cm) has a relatively high shell density and may indicate a more favourable environment for the rhizopod communities. An abrupt decrease in shell density and species diversity in the sediments between 23−17 cm may reflect climate deterioration, whereas an increase above 13 cm may reflect climate amelioration.

4.6. Chironomids

Chironomids are absent in the sandy unit underlying the lacustrine sediment. Single remains of *Abiskomyia* and *Micropsectra* were only found at 95−100 cm in core A1, suggesting the existence of shallow water in the lake depression. This suggestion is consistent with the pollen data from the same sample.

A total of 2533 chironomid head capsules were found in core CN2. The capsules belong to 37 taxa from five subfamilies: Orthocladiinae, Diamesinae, Prodiamesinae, Tanypodinae, Chironominae (tribes Chironomini and Tanytarsini). Ceratopogonidae remains are absent from all samples.

Chironomid diagram is zoned by visual inspection (Fig. 8). Chironomid zone I (CZ-I, 81−62 cm) has extremely low (0−3%) numbers of strongly cold-adapted taxa with $T_{VII-opt} < 7$ °C and the highest abundance of strongly warm-adapted taxa with $T_{VII-opt} > 14.7$ °C. In this zone, *Abiskomyia*, which has a very low $T_{VII-opt}$ of 1.7 °C (Larocque et al., 2001), is absent. Chironomini make up 26−52% of the specimens in all layers, while Orthocladiinae are relatively rare (18−42%). Species richness (19−28 taxa) and assemblage diversity ($H' = 3.31−4.26$) are high. We subdivided the zone into two subzones. CZ-Ia (81−74 cm) is characterised by a predominance of *Chironomus* and *Sergentia coracina* and strongly warm-adapted taxa (35−53%), while CZ-Ib (74−62 cm) is characterised by a predominance of *Paratanytarsus* and *Micropsectra insignilobus* and taxa with a lower $T_{VII-opt}$ (8.7−10.4 °C; 35−46%). The highest accumulation rate of chironomid head capsules is in the CZ-Ib subzone.

CZ-II (62−0 cm) has a high abundance of strongly cold-adapted taxa (>30%, with the exception of the bottom layer where these taxa make up 20%). *A. virgo* dominates in all chironomid assemblages of this zone. Strongly warm-adapted taxa make up 7−26%. *Sergentia coracina*, which has a wide thermal range and $T_{VII-opt} = 15.8$ °C (Larocque et al., 2001), is present at low values (4−13%) in all layers. CZ-II is characterised by fluctuations in the relative abundance of *A. virgo*. Decreases (at 45−35 and 13−11 cm depth) are in phase with increases in the relative abundance of *Paratanytarsus*, *Micropsectra insignilobus* and *Cricotopus*/*Orthocladius*, which have a higher $T_{VII-opt}$ (8.7−11.4 °C). We subdivided the zone into two subzones. CZ-IIa (62−14 cm) has a relatively low abundance of *Cricotopus*/*Orthocladius*, while CZ-IIb (14−0 cm) has a relatively high abundance of *Cricotopus*/ *Orthocladius* and *Eukiefferiella*/*Tokunagaia*/*Tvetenia*. The accumulation rate of chironomid head capsules is relatively high throughout CZ-IIa and relatively low in CZ-IIb.

According to Sæther's (1975) lake typology, chironomid assemblages from core CN2 point to oligotrophic conditions during the lacustrine sedimentation (Fig. 9a). However, assemblages from 77–55 cm indicate moderately oligotrophic conditions, while assemblages from 53–0 cm and from the bottom of the core indicate ultraoligotrophic conditions.

4.7. Quantitative climate reconstructions

4.7.1. Pollen-based reconstructions

In the application of the BMA method to the surface pollen spectra, the option of eight modern analogues with logarithmic transformation of taxa percentages gave the best correlation between actual and pollen-reconstructed climate for spectra from the Russian Arctic (Tarasov et al., 2002). This approach was used for the Nikolay Lake pollen record. Tarasov et al. (2002) suggested that modern values of T_{VII} and the annual sum of day temper-

atures above a 5 °C base (sum of growing-degree-days with temperatures above 5 °C; GDD5) could be derived from Arctic surface pollen spectra with reasonably high confidence ($R = 0.80$ and 0.82, respectively). However, pollen spectra from the Russian Arctic do not show a clear response to changes in T_I and the moisture index, important bioclimatic variables in the forested regions (Prentice et al., 1992). P and runoff (difference between P and evaporation (E) calculated as in Cheddadi et al., 1997) were also reconstructed from the modern spectra with relatively high correlations ($R = 0.68$ and 0.61, respectively).

Values of GDD5 in our reference data set vary from 114–3800 °C day, T_{VII} from 4.7–28.6 °C, P from 180–710 mm and $P - E$ from 17–270 mm. Modern climate values at the Lake Nikolay site, derived from the modern climate database (Cramer, personal communication), are 250 mm (P), 66 mm ($P - E$), 223 °C day (GDD5) and 8.7 °C (T_{VII}). The T_{VII} from the database is slightly higher than
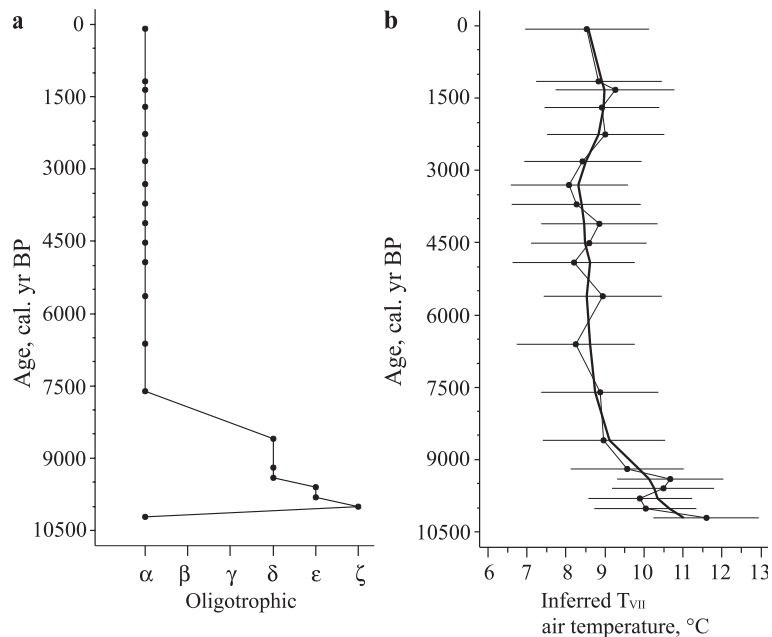

Fig. 9. (a) Trophic conditions in Nikolay Lake reconstructed from fossil chironomid assemblages. (b) Chironomid-inferred mean July air temperatures. The non smoothed temperature data (thin line), a LOESS smoother with a span of 0.25 (thick line) and the sample-specific prediction errors derived by Monte Carlo simulation (500 simulations) are shown.
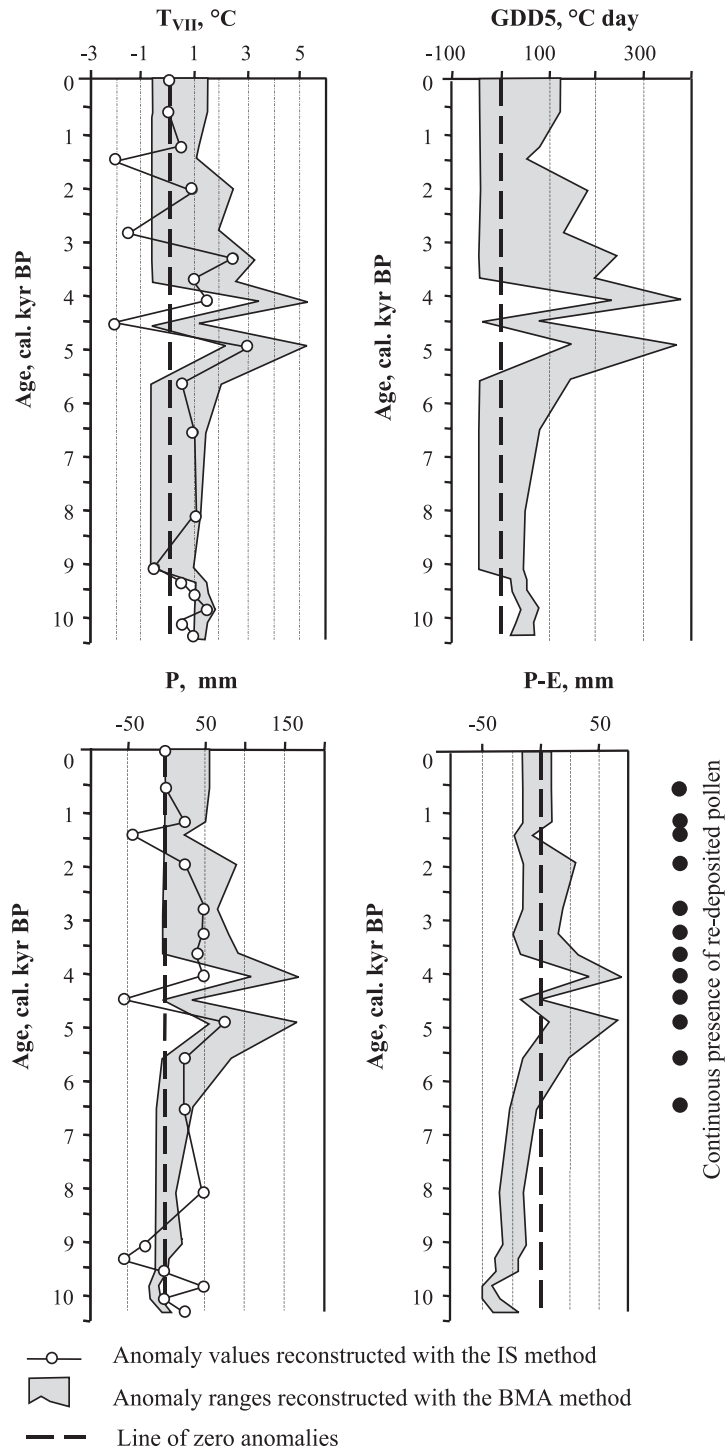
Fig. 10. Climate derived from the core CN2 pollen record by IS (Klimanov, 1984) and BMA (Guiot, 1990) methods. Anomalies are calculated as the difference between reconstructed and modern climate values from the Lake Nikolay area.

that from the Atlas Arktiki (1985). We assume that this difference should not affect our climate reconstruction because only one source was used for the reconstruction of climate variables from modern and fossil pollen spectra. Fig. 10 shows anomalies between reconstructed and modern values from the database.

Both IS and BMA methods produce comparable results in reconstruction of thermal and hydrological changes during the last 10,300 cal. yr (Fig. 10). Negative anomalies of T_{VII} and P reconstructed by the IS method are sometimes greater than that suggested by the BMA method. However, the differences are relatively small compared to the statistical errors of the IS reconstructions.

The reconstructions suggest that climate was relatively warm, (T_{VII} up to 2 °C higher than the present day) and dry ($P - E$ from 15–50 mm lower than the present day) during ca. 10,300–9200 cal. yr BP. Both reconstructions suggest a decrease in summer temperatures at about 9100 cal. yr BP. After a period of relative stability (ca. 9000–5800 cal. yr BP), climate conditions became very unstable between 5800 and 3700 cal. yr BP. A rise in summer temperatures at ca. 5000 cal. yr BP was followed by a significant decrease in temperatures at ca. 4500 cal. yr BP. Another increase in the summer temperatures is dated to ca. 4100 cal. yr BP. Hydrological parameters show similar patterns of change, with increases in precipitation and runoff at ca. 5000 and 4100 cal. yr BP, and a decrease at ca. 4500 cal. yr BP. Climate became quite stable and similar to modern-day conditions after ca. 3600 cal. yr BP. During this period, temperature and runoff values do not show significant differences from modern values. However, reconstruction by the BMA method suggests that P was similar to, or slightly higher, than today.

The presence of reworked Pinaceae pollen in the record (redeposited pollen and spores are not included in the statistical analyses) might be an indicator of unstable conditions in the lake basin associated with climate changes. Reworked pollen grains are absent from the lower part of the record but are continuously present from 54 cm (Fig. 4). This corresponds well to the period after ca. 6500 cal. yr BP when precipitation and runoff started to rise, causing an influx of ancient pollen

from the reworked shore material to the lake sediments.

4.7.2. Quantitative T_{VII} reconstructions based on the chironomid record

The T_{VII} reconstructions based on the modern calibration set from a subarctic region of northern Sweden (Larocque et al., 2001) are shown in Fig. 9b. Of the 37 chironomid taxa present in the Nikolay Lake fossil assemblages, 22 appear in the modern calibration data. The 15 fossil taxa not present in the calibration set comprise 7.6–21.6% of the fossil assemblages. However, the results obtained are interesting and comparable with pollen-based T_{VII} reconstructions.

The chironomid-based reconstructions suggest that the highest T_{VII} (9.9–11.6 °C) were during ca. 10,300–9200 cal. yr BP. T_{VII} decreased gradually to 8.2 °C from ca. 9000–6500 cal. yr BP. Later, during ca. 6500–3300 cal. yr BP, T_{VII} were very unstable. Two short-term warm oscillations with relatively high T_{VII} (up to 8.9 °C) occurred at ca. 5600 and from 4500–4100 cal. yr BP. At ca. 3300–2300 cal. yr BP, T_{VII} were about 9.0 °C. Thereafter, from ca. 2300–1400 cal. yr BP, they were also relatively high T_{VII} (8.9–9.3 °C). The reconstructions suggest that a cooling begun after ca. 1400 cal. yr BP, when T_{VII} decreased to 8.5 °C (the uppermost chironomid assemblage). This chironomid-based reconstruction of T_{VII} is very close to the modern value (8.7 °C) derived from the climate database used for the surface pollen calibration.

5. Discussion and conclusions

Recent studies of the late Quaternary sedimentation history of the Lena Delta (Schwamborn et al., 2002a,b) suggest that sand deposits below the lacustrine sediments in Nikolay Lake are of the same origin as sands forming the second fluvial terrace in the Lena Delta. The ^{14}C and IR–OSL dates obtained from the terrace sediments on Arga Island (Schwamborn et al., 2002b) suggest that the formation of the second terrace started ca. 14,500 cal. yr BP. The 6430 ± 120 ^{14}C yr BP date obtained from the outcrop of the second terrace southeast of Arga Island (Schwamborn et al., 2002b) suggests

that terrace formation continued until the middle Holocene.

Biological remains are very rare in the late glacial sediments of core A1. The extremely low pollen concentration and poor pollen preservation are consistent with the highly energetic periglacial channel network and high accumulation rates suggested for the late glacial time in the Lena River Delta (Schwamborn et al., 2002b). However, the sample dated to 14,900 cal. yr BP (core A1) contains chironomids, spores of *Pediastrum* and *Botryococcus*, and rare pollen, indicating a shallow-water environment and sedge-grass–dwarf shrub tundra vegetation near the site. The presence of pollen and spores indicates that climate amelioration occurred during the interval corresponding to the Bölling or Allerød warming. Similar pollen spectra dated ca. 14,900 cal. yr BP are reported from the areas east (Andreev et al., 2002) and south (Pisaric et al., 2001a) of Nikolay Lake.

The lacustrine sedimentation in the lake basin is likely to have started around 10,300 cal. yr BP, according to the oldest date $10,110 \pm 180$ cal. yr BP obtained from the base of the lacustrine unit in core CN2. The pollen spectra dated to ca. 10,300–8000 cal. yr BP reflect that shrub tundra with shrub alder (*Alnus fruticosa*) and dwarf birch (*Betula nana*) grew around the lake at that time. The rather high pollen concentration reflects the high productivity of plant communities, which is in agreement with the relatively high TOC content of the lake sediments (Fig. 4). The chironomid record (Fig. 8) also demonstrates a high level of species richness and diversity, suggesting that the productivity of the lake ecosystem and trophic conditions in the lake peaked at this time (Fig. 9a). The relatively high abundance of strongly warm-adapted chironomid taxa, specifically *Chironomus*, and the extremely low occurrence of strongly cold-adapted taxa indicate that the climate from ca. 10,300–9500 cal. yr BP was warmer than today. The rather high species diversity reflected in the rhizopod data also suggests that this interval was the warmest during the last 10,300 cal. years (Fig. 7).

Climate reconstructions (Figs. 9b, 10) imply that temperatures during ca. 10,300–9200 cal. yr BP were up to 2–3 °C warmer than the present day. Other pollen and plant macrofossil data from the area (MacDonald et al., 2000; Pisaric et al., 2001b; Andreev et al., 2002) also imply that the warmest Holocene climate occurred during that time.

The changes in the chironomid assemblages (Fig. 8), specifically the appearance and subsequent predominance of *Abiskomyia*, one of the best indicators of cold climate (Walker and MacDonald, 1995; Larocque et al., 2001), with its modern distribution limited to lakes north of the treeline in the lower Lena River region (Porinchu and Cwynar, 2000), reflect cooling. Such deterioration in the local climate was probably connected to a rise of sea level in the Laptev Sea region (Bauch et al., 2001), declining summer insolation and the onset of colder, more maritime summer conditions. According to the chironomid record from Nikolay Lake, this may have started after ca. 9200 cal. yr BP. Similar changes are also reflected in the chironomid record from Dolgoe Lake, where the deposition of cool-water chironomid head capsules increases dramatically at that time (Porinchu and Cwynar, 2002).

Since ca. 6000 cal. yr BP, the proportion of *Alnus fruticosa* and *Betula nana* in the local vegetation decreased and these taxa probably disappeared from the area around the lake after ca. 5000 cal. yr BP. The 7300 cal. yr old pollen record from the nearby Barbarina Tumsa peat section (Fig. 6) reflects similar trends. *Alnus* and *Betula* shrubs disappeared from the vegetation around Barbarina Tumsa ca. 200–300 yr later than the lake site. This might be due to the fact that Barbarina Tumsa is closer to the Lena River and the vegetation might therefore be better protected from the severe winter winds. In general, the Arga Island pollen records are in good agreement with pollen data from the Bykovsky Peninsula, where *A. fruticosa* pollen also declined about this time (Andreev et al., 2002). The youngest *Larix* remains found above the modern treeline (Tit–Ary Island area, south of Arga Island) are also dated to ca. 5000 cal. yr BP (MacDonald et al., 2000).

The predominance of *Abiskomyia* in the chironomid assemblages (Fig. 8) and the presence of another cold stenothermic taxon, *Pseudodiamesa*, (Brooks and Birks, 2001; Larocque et al., 2001) suggest colder conditions in the area during the last 9000 cal. yr. However, the chironomid-based temperature reconstruction points to two short, warm

oscillations ca. 5600 and 4500–4100 cal. yr BP, consistent with pollen-based climate reconstructions (Fig. 10). This reconstruction suggests that climate conditions between ca. 5500–4000 cal. yr BP became very unstable, with a rise in summer temperatures at ca. 5500–4000 cal. yr BP and a sharp decrease in temperature ca. 4500 cal. yr BP. The chironomid-based reconstructions also suggest unstable conditions between ca. 6500–3300 cal. yr BP, with a significant decrease in T_{VII} occurring at ca. 5000 cal. yr BP. It is important to note that the chironomid-based reconstructions suggest that the significant climatic changes occurred earlier than the pollen-based reconstructions indicate. This might be due to the short life cycles of chironomids and their ability to respond more rapidly than terrestrial vegetation to climatic changes (e.g., Smol et al., 1991; Battarbee, 2000).

The pollen spectra indicate that herb tundra dominated the area around the lake after 4000 cal. yr BP. The significant amount of *Picea* and *Pinus* pollen, transported over long distances, suggests a decrease in pollen productivity of the local plant communities and/or sparse vegetation cover. Relatively high amounts of redeposited Pinaceae pollen and spores of *Encalypta* (moss growing on disturbed soils) may also indicate sparse vegetation cover and increased erosion during that time. The Barbarina Tumsa pollen record shows very high amounts of *Salix* pollen in the sediments radiocarbon dated between ca. 3500–2000 cal. yr BP, which may reflect the presence of dense *Salix* shrubs around the site due to thicker snow cover in the river valley during winter.

Pollen-based reconstructions of hydrological parameters from the Nikolay Lake sediments show a drastic increase in precipitation and runoff at 5500 and 4200 cal. yr BP and a decrease at 4500 cal. yr BP. The climate became relatively stable and similar to modern-day conditions after ca. 4000 cal. yr BP. Temperature and runoff are not significantly different from modern values, if the confidence intervals of the reconstructions are taken into account.

The chironomid record suggests that a relatively warm period may have occurred between ca. 2300–1400 cal. yr BP, consistent with the slightly warmer climate reconstructed from the pollen (Fig. 10). The modern chironomid assemblage was established at

ca. 1400 cal. yr BP, with a rise in the relative abundance of *Abiskomyia* and *Cricotopus/Orthocladius* species. This is also seen in the chironomid data from Dolgoye Lake, situated in the south near Tit–Ary Island, where the modern chironomid assemblage was established at ca. 1400 cal. yr BP (Porinchu and Cwynar, 2002).

Although the Nikolay pollen record does not indicate significant changes in temperature during the last 1500 years, changes in the chironomid assemblages and chironomid-based reconstruction suggest some cooling. Conversely, environmental conditions were favourable for rhizopods (or for preservation of their remains) during that interval, as indicated by the high density of rhizopod shells.

The continuous radiocarbon-dated multiproxy records from Nikolay Lake have enabled the reconstruction of environments during the last 10,300 cal. years in the western part of the Lena River Delta. Our results suggest that the local climate around the lake was warmer than the present day between 10,300–9200 cal. yr BP and was similar to the present after 3600 cal. yr BP. Biological proxies suggest that the period from 5800–3700 cal. yr BP was characterised by unstable climate conditions. However, this needs to be verified by further investigations.

Appendix A. List of testate amoebae in the Holocene deposits of Nikolay Lake

Taxa with similar ecological preferences were grouped into the following ecological complexes:

Cyclopyxis eurystoma complex	*C. eurystoma*, *Arcella vulgaris*, *C. ecornis* v. *megastoma*;
Difflugia pyriformis complex	*D. pyriformis*, *Pontigulasia compressa*, *P. elisa*; *Phryganella acropodoa* v. *australica*, *Centropyxis gibbosa*;
Centropyxis platystoma	Two forms: *major* and *minor*;
Difflugia elegans complex	*D. elegans*, *Difflugia ampla* c.f., *Centropyxis aerophila* v. *sphagnicola*, *Centropyxis* sp.;
Difflugia angulostoma complex	*D. angulostoma*, *Difflugia brevicola*, *Difflugia decloitrei*, *Difflugia labiosa*, *Difflugia litophila*, *Difflugia mammilaris*, *Centropyxis aculeata*;
Difflugia rotunda complex	*D. rotunda*, *Difflugia globularis*, *C. platystoma* v. *armata*, *C. ecornis* sensu Ogden, Hedley, 1980, *Difflugia* sp.

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