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ORIGINAL ARTICLE

Christian Bigler · Lena Barnekow · Markus L. Heinrichs · Roland I. Hall

Holocene environmental history of Lake Vuolep Njakajaure (Abisko National Park, northern Sweden) reconstructed using biological proxy indicators

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Abstract Holocene environmental and climatic changes are reconstructed using analyses of biological proxies in lake sediments from Vuolep Njakajaure, a lake located near the altitudinal treeline in northern Sweden (68°20′ N, 18°47′ E). We analysed biological proxy indicators from both aquatic and terrestrial ecosystems, including diatoms, pollen and chironomid head capsules, in order to reconstruct regional Holocene climate and the development of the lake and its catchment. During the early Holocene and after 2500 cal B.P., *Fragilaria* taxa dominated the diatom assemblages, whereas planktonic *Cyclotella* taxa prevailed during the major part of the Holocene (7800–2300 cal B.P.), indicating the importance of the pelagic habitat for diatom assemblage composition. The planktonic diatoms appeared at the same time as *Alnus* became established in the catchment, probably altering nutrient availability and catchment stability. The pollen record is dominated by mountain birch (*Betula pubescens* ssp. *tortuosa*) pollen throughout the Holocene, but high percentage abundances of Scots pine (*Pinus sylvestris*) pollen suggest the presence of a mixed pine-birch forest during the mid-Holocene (6800–2300 cal B.P.). Head capsules of Tanytarsini and *Psectrocladius* dominated the chironomid assemblage composition throughout the Holocene, in combination with *Corynocera ambigua* after 2300 cal B.P. A quantitative, diatom-based reconstruction of mean July air temperature indicated a relatively cold temperature during the early Holocene (9000–8000 cal B.P.) and after ca. 2300 cal B.P., whereas the mid-Holocene period is characterised by stable and warm temperatures. The overall patterns of Holocene climate and environmental conditions are similarly described by all biological proxy-indicators, suggesting relatively warm conditions during the mid-Holocene (ca. 7800–2300 cal B.P.), with a subsequent colder climate after 2300 cal B.P. However, the onset and magnitude of the inferred changes differ slightly among the proxies, illustrating different responses to lake development phases, land-uplift, and climate forcing (e.g., insolation patterns) during the Holocene in northern Sweden.

Keywords Diatoms · Pollen · Chironomids · Subarctic Sweden · Quantitative temperature reconstruction · Holocene

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C. Bigler (✉) · M. L. Heinrichs · R. I. Hall
Department of Ecology and Environmental Science and Climate Impacts Research Centre CIRC, Umeå University,
KBC plan 5,
SE-901 87 Umeå, Sweden
e-mail: christian.bigler@emg.umu.se

C. Bigler
NCCR Climate, Institute of Plant Sciences,
University of Bern,
Altenbergrain 21,
CH-3013 Bern, Switzerland

L. Barnekow
Department of Quaternary Geology,
Lund University,
Sölvegatan 12,
SE-223 62 Lund, Sweden
e-mail: lena.barnekow@geol.lu.se

Present address:
M. L. Heinrichs
Limnologische Station der TU München,
Hofmark 3,
82393 Iffeldorf, Germany
e-mail: markus.heinrichs@wzw.tum.de

R. I. Hall
Department of Biology, University of Waterloo,
200 University Avenue West,
N2L 3G1 Waterloo, Ontario, Canada
e-mail: rihall@sciborg.uwaterloo.ca

Introduction

In the light of exceptional climate conditions during the past decades, including warm summers and winters in Europe (Schär et al. 2004; Beniston 2005), the development of long-term records of environmental change and climate dynamics beyond the time-period covered by

instrumental and monitoring data is increasingly important in the assessment of natural climatic variability. Arctic, subarctic and alpine regions are particularly vulnerable to climate change, as the extent of snow cover and permafrost, and the duration of ice-cover on lakes, rivers and streams might be reduced (Magnuson et al. 2000), with serious implications for the environment and society (Hassol 2004). These regions have generally limited historical instrumental records. However, at the same time the human activity causing land-use changes, pollution, and/or eutrophication and leading to unnatural altered conditions is comparably low. Therefore, these regions have a great potential for palaeoecological investigations based on natural archives and proxies to reconstruct past climatic and environmental conditions (Smol et al. 2005).

Among natural climate archives, lake sediments play an important role and contain not only information from the lake ecosystem itself (e.g. diatoms, chironomid larvae), but also from the surrounding landscape (e.g. pollen, spores, plant macrofossils). This makes it possible to study different organisms from ancient environments and their co-existence and responses to environmental change. Furthermore, the continuous accumulation of lake sediments allows the development of chronologies, an essential requirement when comparing different proxies and archives. This so-called "multi-proxy approach" is a powerful and widely accepted methodological approach, successfully applied at different locations and timescales (Ammann 2000; Birks et al. 2000; Oldfield and Berthier 2001).

The subarctic, mountainous landscape in northern Sweden offers an ideal setting for investigating past climate using the multi-proxy approach. Lakes are numerous, relatively easily accessible and located along broad climatic and ecological gradients. These include sites within coniferous forest dominated by *Pinus sylvestris*, mountain birch forest dominated by *Betula pubescens* ssp. *tortuosa* and alpine tundra situated above the tree-limit, formed by mountain birch at an elevation of 600–700 m a.s.l. The area is sensitive to climate change due to shifting influences of air masses with Atlantic or Arctic origin, leading to contrasting temperature and precipitation regimes (Shemesh et al. 2001; Hammarlund et al. 2002). For these reasons, many palaeoecological studies have been conducted in the region. Thus compared with other arctic and subarctic regions, the Abisko region probably offers the highest density of studies applying different methodological approaches to reconstruct past climate and environments. Karlén (1976, 1988) investigated tree relicts and glacial activity in sediments from proglacial lakes to reconstruct climatic conditions during the Holocene. Palaeoecological studies using pollen in peat profiles were initiated by Sonesson (1974), continued by Küttel (1984) and were later refined with a comprehensive investigation of pollen and plant macrofossil remains in lake sediments along an altitudinal transect by Berglund et al. (1996) and Barnekow (1999a, b). Pine trees were recovered and used for the reconstruction of past summer temperature from tree-rings (Briffa et al. 1988; Grudd et al. 2002). Furthermore, pieces of wood from different tree species were recovered near a small lake above the treeline and used to reconstruct past tree-line fluctuations (Kullman 1999). Sedimentological studies of proglacial lake sediments were conducted in the Kårsa Valley, a valley adjacent to the main Abisko Valley, to establish past changes in glacial activity of the Kårsa glacier and in-lake processes (Snowball 1996; Snowball and Sandgren 1996). Past precipitation patterns have been reconstructed using oxygen isotope analysis of lake sediments (Berglund et al. 1996; Hammarlund et al. 2002) and subfossil diatoms (Shemesh et al. 2001).

Since the establishment of a palaeoecological research unit within the Climate Impact Research Centre at Abisko in 1997, extensive efforts have been made to assemble calibration sets for aquatic biological proxy-indicators in northern Sweden, namely diatoms (Bigler et al. 2000; Rosén et al. 2000; Bigler and Hall 2002) and chironomids (Larocque et al. 2001). This has been done in order to provide a basis for quantitative reconstruction of past climatic and environmental variables based on these organisms. Diatoms (Bacillariophyceae) are well-established palaeoenvironmental indicators and, for example, are sensitive to acidification, eutrophication and climate related variables. A large number of taxa exist with different ecological requirements (Stoermer and Smol 1999). Head-capsules of chironomid larvae (non-biting midges) have been shown to be valuable temperature indicators (Walker et al. 1991) and have become one of the most important zoological proxy indicators in lake sediments (Battarbee 2000). The calibration effort in northern Sweden has improved our knowledge of modern distribution patterns of diatoms and chironomids in subarctic regions and has provided a set of quantitative reconstruction tools, in the form of transfer functions, for lake-water pH (diatoms), July air temperature (diatoms, chironomids), and ice-cover duration (diatoms). The temperature models were validated by comparing reconstructions based on biological proxy indicators with instrumental climate data, for both diatoms (Bigler and Hall

Fig. 1 Lake Vuolep Njakajaure within the Abisko National Park, the river Abiskojåkka (in the foreground) and its tributary Nissunjåkka (on the right) and the characteristic mountain formations including Lapporten ('The Gate to Lapland'). Photograph by Peter Rosén (June 2000)

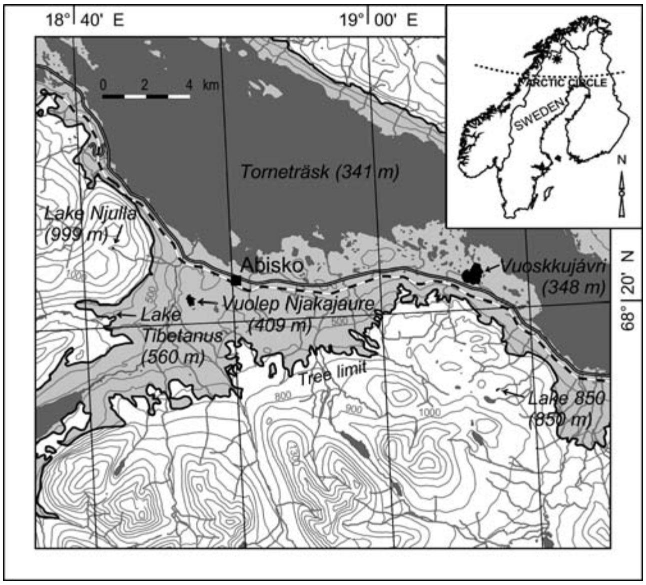

Fig. 2 Location of Vuolep Njakajaure, the route of the railway (built 1902; dashed line) and the road (built 1984). The locations of four additional lakes near Vuolep Njakajaure with multi-proxy palaeoenvironmental reconstructions are indicated

2003) and chironomids (Larocque and Hall 2003). In a next step, the models were applied to reconstruct quantitatively regional Holocene temperature and lake-water pH patterns based on sediment cores from lakes above the tree-line (Rosén et al. 2001; Bigler et al. 2003; Larocque and Bigler 2004; Larocque and Hall 2004), within the birch forest (Bigler et al. 2002; Larocque and Hall 2004) and within the mixed coniferous-birch forest (Heinrichs et al. 2005) in northern Sweden.

In this paper, we present the Holocene diatom stratigraphy from Lake Vuolep Njakajaure (henceforth referred to as Vuolep Njakajaure), a lake within the birch forest near Abisko (Figs. 1 and 2). We analyse the changes in diatom assemblage composition by means of Correspondence Analysis and provide a quantitative reconstruction of mean July air temperature by applying the regional diatom calibration set (Bigler and Hall 2002). In order to add to previous results based on multi-proxy approaches in the Abisko region, a main purpose of this study is also to compare diatom assemblage shifts with those of pollen (Barnekow 2000) and chironomids (Heinrichs et al. in press), assessing whether they are responding similarly to environmental changes. In contrast to other lakes investigated in the Abisko surroundings, Vuolep Njakajaure has partly calcareous bedrock in the catchment and the present-day lake-water pH is circumneutral. As a consequence of long-term natural acidification during the Holocene (Bigler et al. 2002, 2003), most other lakes show slightly acidic conditions (Bigler and Hall 2002). It has been shown that changes in lake-water pH may influence diatom-based temperature reconstructions (Bigler and Hall 2003). As the lake-water pH in Vuolep Njakajaure probably remained circumneutral during the entire Holocene, the diatom-based temperature reconstruction may be less affected by changes in lake-water pH than in other lakes.

Material and methods

Study site

Vuolep Njakajaure (68°20′ N, 18°47′ E) is situated in the Abisko Valley, south of Lake Torneträsk and within the Abisko National Park, northern Sweden, at an elevation of 409 m a.s.l. (Figs. 1 and 2). The lake has a maximum depth of 13.7 m, and is circumneutral (pH 7.5 in March 1997) (Barnekow et al. 1998).

In general, the vegetation in the Abisko Valley has a mosaic-like structure with patches of sparse mountain-birch forest (*Betula pubescens* ssp. *tortuosa*), with scattered and isolated stands of Scots pine (*Pinus sylvestris*) on favourable sites, and treeless heath and mire vegetation. The treeline is formed by mountain birch reaching up to 600–700 m a.s.l., while the upper limit of Scots pine reaches ca. 450 m a.s.l. (Barnekow 1999a, 2000). The Abisko Valley is in the rain shadow of the mountains to the west, and the measured annual precipitation is ca. 300 mm. The mean annual temperature is −0.8 °C, with January the coldest and July the warmest month, reaching −11.9 and 11.0 °C respectively (Fig. 3) (Alexandersson et al. 1991).

Fieldwork, sediment retrieval, depth-age model, and sample preparation

Overlapping sediment cores were collected in late winter 1991 from the deepest part of Vuolep Njakajaure (Barnekow et al. 1998) using a Russian coring device (Jowsey 1966). The collected cores were correlated using Saturated Isothermal Remanent Magnetisation (SIRM) analysis. In the lowest part (343–334 cm), the core consisted of grey, silty clay, followed by grey, laminated silty gyttja (334–333 cm). The main sequence of the Holocene core (333–33 cm) was described as dark-brown, laminated algal gyttja (with weak laminae between 65–33 cm). The uppermost part was non-laminated, brown,

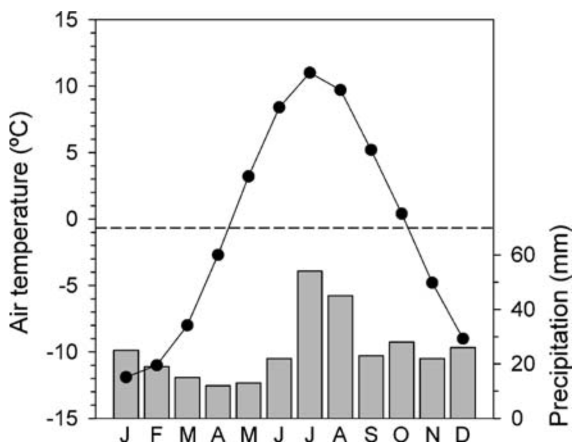

Fig. 3 Reference Normals (averages from 1961–1990) of monthly mean air temperature (*solid dots*), mean annual temperature (*dashed line*) and precipitation (*vertical shaded bars*) at Abisko (Abisko Scientific Research Station) (Alexandersson et al. 1991)

fine-detritus gyttja (33–0 cm) (Barnekow 2000). After core correlation, the sediment core was sampled (1-cm slices, 8-cm intervals) and analysed for pollen (Barnekow 2000), chironomids and diatoms.

The chronology is based on varve counting and AMS radiocarbon dates using plant macrofossils (Fig. 4). Because of the lack of identifiable laminations in the uppermost part of the sediment sequence (65–0 cm), the floating varve chronology was constrained by 17 calibrated radiocarbon dates, indicating that the uppermost 65 cm corresponds to 725 years (Barnekow et al. 1998). We assume a linear sedimentation rate for the uppermost sediment sequence (65–0 cm). Additional details of the chronology development, such as varve counting procedures, type of plant macrofossils used for dating and calibration procedure are presented elsewhere (Barnekow et al. 1998).

Diatom samples were prepared and mounted using standard techniques according to Håkansson (1984). At least 400 diatom valves were counted in each sample using phase contrast optics at 1000× magnification. The diatom taxonomy was kept consistent with the regional calibration set (Bigler and Hall 2002), which largely followed Krammer and Lange-Bertalot (1986–1991).

Pollen samples were treated according to method A, as described by Berglund and Ralska-Jasiewiczowa (1986). At least 800 pollen grains were counted at each level at 400× and 1000× magnification. Identification followed Faegri and Iversen (1989) and comparisons were made with a reference collection at the Department of Quaternary Geology, Lund University. *Betula pubescens* ssp. *tortuosa* and *Betula nana* were distinguished according to locally collected reference samples and by comparing pore depth and grain size (Birks 1968; Mäkelä 1996).

Chironomid head capsules were extracted and analysed following a widely accepted protocol (Walker 2001).

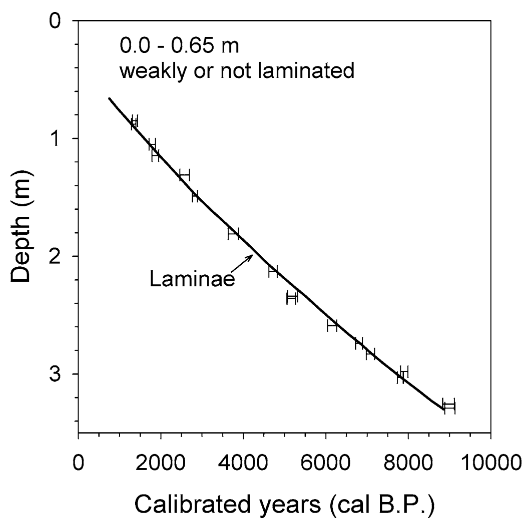

Fig. 4 Depth-age relationship of the Vuolep Njakajaure sediment record. The counted laminae (*solid line*) and AMS dated macrofossil samples with single standard deviation. The indistinctly and non-laminated uppermost part (65–0 cm) corresponds to an estimated 725 yrs period

Sediment samples of known volumes were deflocculated using warm 5% KOH. The samples were sieved onto a 95 µm Nitex®-mesh to remove unwanted debris, and rinsed with 5% HCl to dissolve any possible carbonates and neutralise residual KOH. The remains were sorted using a Bogorov counting tray under 10–25× magnification. Identifications were made at 400–1000× magnification using keys by Walker (1988), Wiederholm (1983) and Oliver and Roussel (1983).

Numerical analysis

Zonation of the diatom stratigraphy of Vuolep Njakajaure was performed using optimal partitioning and the sum-of-squares criteria (Birks and Gordon 1985) within the program ZONE (Lotter and Juggins 1991). The number of significant zones was assessed by comparison with the broken-stick model (Bennett 1996) and only statistically significant zones are presented. As the zonation of the pollen and chironomid stratigraphies was based on different methods in the original publications (Barnekow 2000; Heinrichs et al. in press), we recalculated zones for these records using the same methods as those used for the diatom data to ensure comparable zonation schemes for the three records.

To calculate the compositional turnover in the records, biostratigraphical data were analysed by Detrended Correspondence Analysis (DCA) using the program CANOCO (version 4.0) (ter Braak and Smilauer 1998). For this analysis, the data were square-root transformed to stabilise their variances and rare taxa were downweighted.

The quantitative reconstruction of mean July air temperatures using diatoms is based on a regional calibration set including surface sediments and environmental data from 100 lakes. We used Weighted Average Partial Least Squares (WA-PLS) regression and calibration (ter Braak and Juggins 1993) and the developed transfer function yielded a coefficient of determination (r^2) of 0.75 and a root-mean-squared-error of prediction (RMSEP) of 0.96 °C. Detailed information for the calibration set lakes and model development are given in Bigler and Hall (2002). From the Vuolep Njakajaure sediment core, we included all taxa available in at least three samples with >1% in one sample in the quantitative temperature reconstruction. All of them were represented in the calibration set.

Results

Diatom stratigraphy

The 43 samples analysed for diatoms in the Holocene sediment sequence were generally rich in well-preserved diatoms, except for the two oldest samples that did not contain any diatoms and were therefore excluded from numerical analyses. In total, 140 taxa were identified in the remaining 41 samples and the diatom stratigraphy was divided into six stratigraphical zones based on the numerical zonation (Fig. 5). Small *Fragilaria* taxa were dominant

during the early Holocene and since ca. 2800 cal B.P. (calibrated years before present), whereas the major part of the Holocene was dominated by planktonic *Cyclotella* taxa. In the following section, we briefly describe the most important characteristics of the diatom stratigraphy (Fig. 5).

The first zone (339–303 cm; >7800 cal B.P.) is dominated by small *Fragilaria* taxa (e.g., *F. brevistriata*, *F. construens* var. *venter*), a feature that is common in lake sediments of newly deglaciated terrain (Smol 1983). *Fragilaria* taxa may adapt quickly to changing environmental conditions (Lotter et al. 1999) and prosper in relatively high alkalinity conditions (Battarbee 1986; Bigler and Hall 2002). At the same time, a high relative abundance of *Mastogloia smithii* var. *lacustris* was recorded, a species preferring high conductivity and calcareous-rich conditions in littoral habitats (Krammer and Lange-Bertalot 1986–1991). Furthermore, *Amphora libyca*, *Brachysira zellensis* and *Navicula diluviana* reach their highest relative abundances in the first zone, all having ecological preferences that are similar to the other dominant taxa.

In the second zone (303–231 cm; 7800–5400 cal B.P.), planktonic *Cyclotella* taxa such as *C. comta*, *C. distinguenda* and *C. bodanica* var. *lemanica* dominate, whereas *Fragilaria* taxa and *Mastogloia smithii* var. *lacustris* decrease. The appearance of planktonic taxa could be a result of an intensification of thermal stratification of the water column, leading to an increasing abundance of diatoms in the epilimnion. The third zone (231–150 cm; 5400–2900 cal B.P.) is in general similar to the second zone, but with some shifts in relative abundance of the *Cyclotella* taxa. Specifically, *C. distinguenda* shows higher relative abundances and *C. bodanica* var. *lemanica* and *C. comta* decline in this zone. At the same time, *Cyclotella comensis* is recorded continuously, but at relatively low percentage (Fig. 5).

The fourth zone (150–142 cm; 2900–2700 cal B.P.) consists of one sample only, and more than 50% of the diatom sum is *Cyclotella comensis*. In the subsequent fifth zone (142–62 cm; 2,700–700 cal B.P.), the *Cyclotella* taxa show a decreasing trend, which is compensated for by an increasing abundance of mostly *Fragilaria* taxa (Fig. 5). This trend persists well into the sixth zone (62–0 cm; <700 cal B.P.). In addition, *Cyclotella comta* is replaced by *Cyclotella schumannii*, which accounts for about 20% of the assemblages in the last zone.

Vegetation history

Using the optimal partitioning approach, three significant pollen zones were identified (Fig. 6). In the original vegetation description, five zones were established using a stratigraphically constrained cluster analysis (CONISS,

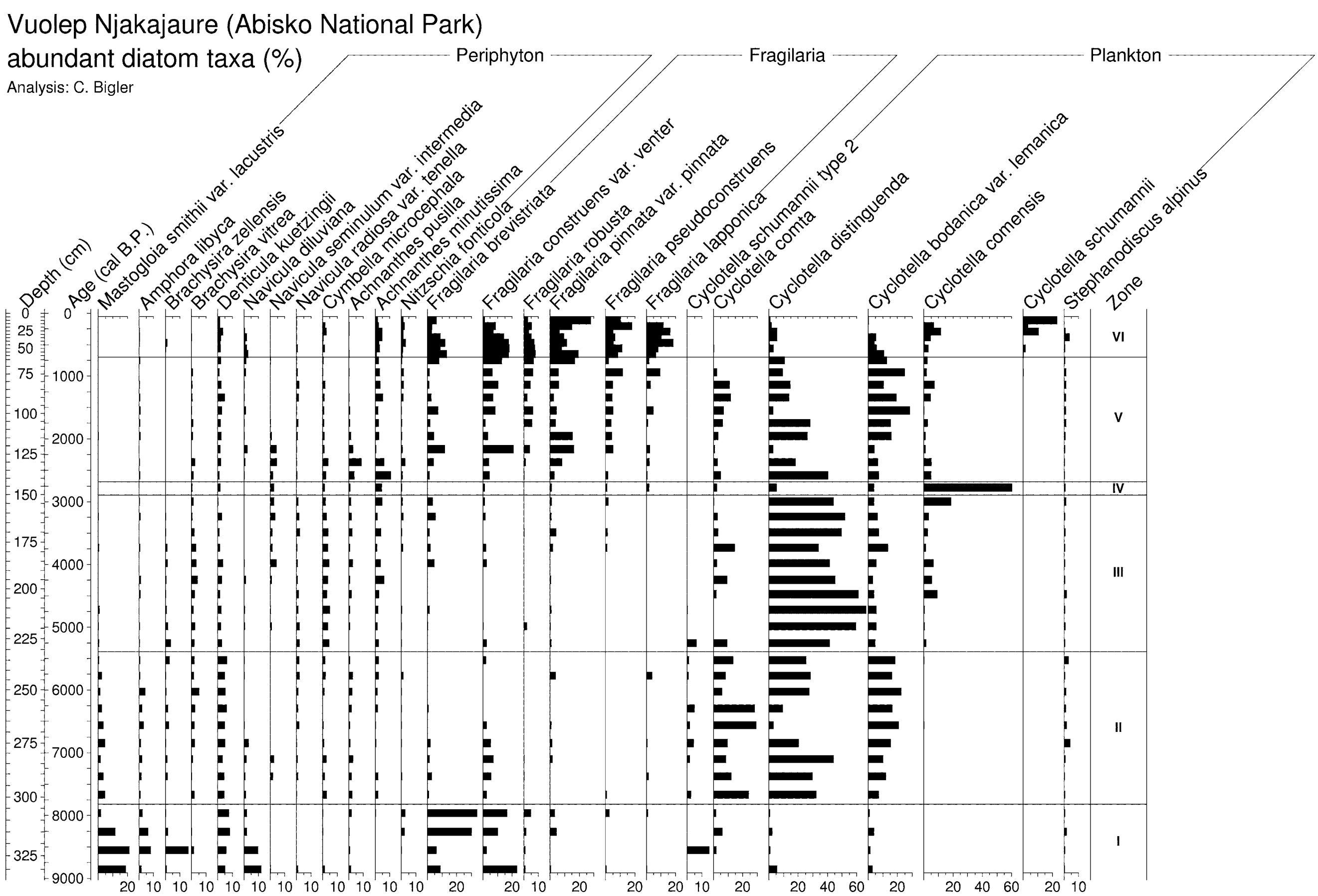

Fig. 5 Stratigraphical record of abundant diatom taxa in the sediment core from Vuolep Njakajaure (expressed as percentage abundance)

Barnekow 2000). The original zonation differs in having additional divisions during the earliest part of the Holocene.

The pollen assemblage from the first zone (335–273 cm; >6800 cal B.P.) is dominated by *Betula pubescens*-type pollen, reaching values greater than 80%. Based on evidence from Lake Badsjön (Barnekow 2000), a small lake nearby, mountain birch was already established regionally when organic sedimentation started in Vuolep Njakajaure. Organic sedimentation was considerably delayed, probably caused by dead-ice occupying the basin of this kettle lake (Barnekow 2000). The *Pinus sylvestris* pollen curve shows a slow rise in percentage abundance throughout the zone. The pollen-influx values indicate that single pine trees could have been present locally, even though most of the pollen probably arrived by long-distance wind transport (Barnekow 2000). Beside these two pollen types, the first pollen zone contains a relatively high abundance of *Hippophaë rhamnoides* pollen in the oldest sediments. Pteridophyte spores are present and relatively abundant mainly during the first part of the zone, whereas increasing values of *Alnus* and decreasing values of *Betula nana*-type pollen occurred in the second part of the zone (Fig. 6).

The second zone (273–129 cm; 6800–2300 cal B.P.) is characterised by relatively high *Pinus sylvestris* pollen abundances and a concomitant reduction of *Betula pubescens*-type pollen, indicating that pine-birch forest had developed regionally. In addition, *Alnus*, *Juniperus* and pteridophyte values decrease, in contrast to an increase in Ericales. From ca. 4300 cal B.P., spruce (*Picea abies*) pollen was continuously recorded at low percentage abundance in the pollen assemblages, even though spruce probably never colonised the lake catchment. At present, spruce reaches the Kiruna area, ca. 85 km east-southeast of Vuolep Njakajaure.

In the third zone (129–0 cm; <2300 cal B.P.), *Pinus sylvestris* pollen decreases, while *Betula pubescens*-type pollen increases. In addition, *Betula nana* and to some extent Ericales and Poaceae increase. Thus the vegetation understorey was composed mainly of heath species, whereas during the early part of the Holocene herbs and ferns dominated.

The chironomid record

In Heinrichs et al. (in press), the chironomid record is divided into three zones, whereas zonation based on the optimal partitioning approach, including broken stick significance evaluation, identified only two significant zones (Fig. 6).

The first zone (331–111 cm, >1900 cal B.P.) is dominated by 15–50% Tanytarsini (Fig. 6), however, *Psectrocladius* is also notably abundant throughout. The Tanytarsini are identified as having broad ecological tolerances to environmental variables in northern Sweden (Larocque et al. 2001), thus little information regarding climate or limnological state can be derived from the overwhelming abundance of this taxon. *Sergentia*, *Microtendipes* and *Dicrotendipes* are also present in the first zone and show a decreasing trend, while at the same time *Chironomus* and *Cricotopus* increase. This notable shift could possibly be related to changes in oxygen conditions, as a survey in Canada identified *Chironomus* as tolerant of low oxygen conditions, which is not the case for *Sergentia* (Quinlan and Smol 2001). Consequently, this shift within the first zone may suggest lower oxygen conditions in the lake. Furthermore, an increased abundance of littoral taxa (e.g.

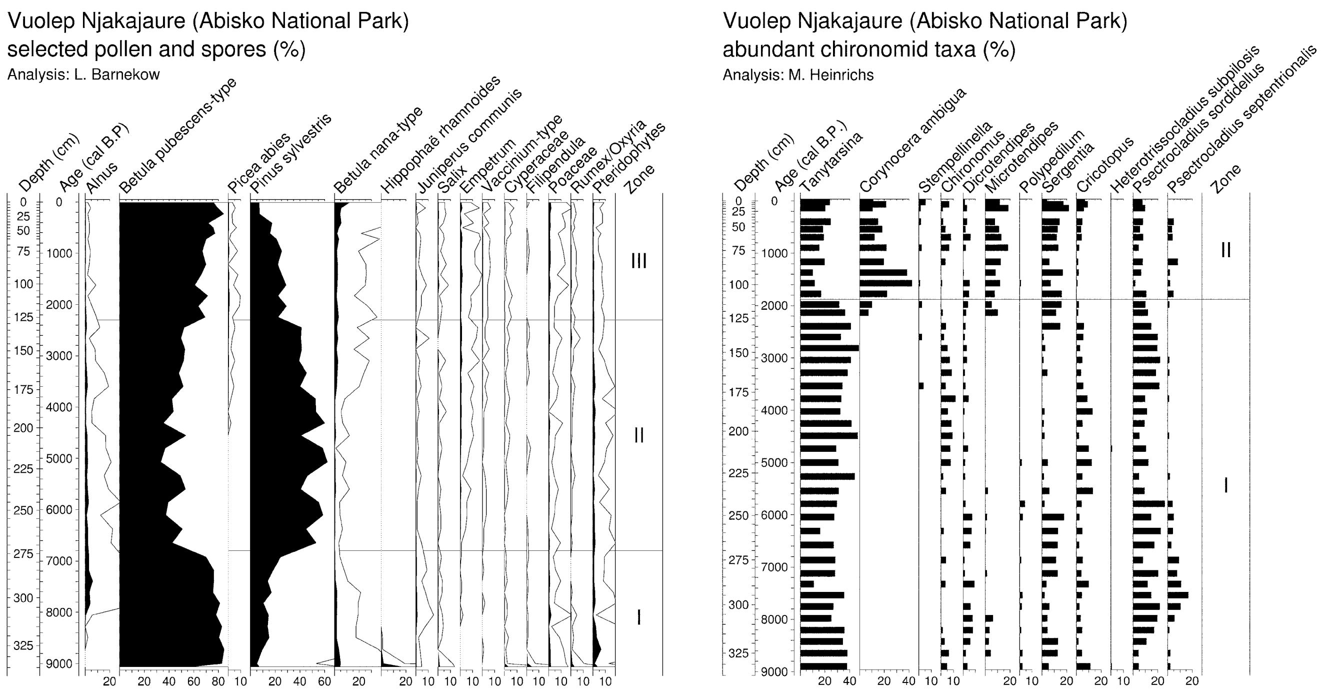

Fig. 6 Stratigraphical record of abundant pollen and spores (*left panel*, unshaded silhouettes are exaggerated at ×10 scale) and chironomid head capsules (*right panel*) in the sediment core of Vuolep Njakajaure (expressed as percentage abundance)

Cricotopus) was observed. *Sergentia* is often associated with cold conditions (Brooks and Birks 2000), but in cooler alpine or subarctic environments it is of little indicative value (Lotter et al. 1997; Olander et al. 1999). Overall, the chironomid assemblage composition suggests oligo-mesotrophic conditions.

The second zone (111–0 cm, <1900 cal B.P.) is characterised by a sudden and dominant appearance of *Corynocera ambigua*. Tanytarsini decline to values around 20%, whereas *Microtendipes* and *Sergentia* increased to 5–20% and 10–20%, respectively. *Cricotopus* and *Psectrocladius* were less abundant than in the previous zone. *Microtendipes* indicates warmer temperatures in northern Sweden (Larocque et al. 2001), but may also reflect an expanded littoral region in subarctic lakes.

Compositional turnover as assessed by correspondence analysis

The diatom sample scores of a Detrended Correspondence Analysis (DCA) show highest variability during the early Holocene, indicating that diatom assemblages experienced the most dramatic compositional changes during the earliest lake development stage (Fig. 7). Subsequently, stable and high DCA scores are recorded on the first DCA axis (eigenvalue $\lambda = 0.31$) ca. 3800 cal B.P., after which values decrease. The second DCA axis ($\lambda = 0.10$) shows high scores during the early Holocene, reach lower scores afterwards, and display no clear trend after ca. 7000 cal B.P.

The pollen DCA scores follow in general the established zones in Fig. 6. On the first axis ($\lambda = 0.14$), the scores initially show high values that decrease quickly and reach their lowest values between 6800 and 2300 cal B.P. (note that axes are presented in inverse order for pollen to maximize concordance of patterns among the proxies). Subsequently, the scores increase slightly until present. The second axis ($\lambda = 0.05$) shows first low values that increase moderately and culminate around 6800 cal B.P. In the remainder of the record, the scores on the second axis decrease linearly, showing the lowest values in the uppermost samples.

The main patterns of chironomid DCA axis 1 scores (Fig. 7) are to some extent related to the established zones (Fig. 6), and seem mainly driven by the appearance of *Corynocera ambigua*. The first axis ($\lambda = 0.32$) shows high scores initially, decreasing distinctly around the established zone boundary. The second DCA axis ($\lambda = 0.08$) shows no particular trend throughout the Holocene.

Quantitative reconstruction of July temperature using diatoms

The temperature inferred from the diatoms appears related to the ratio of planktonic diatoms to *Fragilaria* taxa (Fig. 8). Rises in *Cyclotella* abundance indicate, in general, high temperatures in northern Sweden, whereas *Fragilaria* taxa have rather lower temperature optima (Rosén et al. 2000; Bigler and Hall 2002). The diatom assemblages imply relatively low temperatures during the early Holocene (9000–8000 cal B.P.), reaching values around 12–13 °C. Subsequently, temperature increased distinctly, and during the major part of the Holocene, the diatom assemblages indicate high temperatures (14–15 °C). At ca. 3000 cal B.P., a gradual temperature decrease is reconstructed with low temperatures culminating at around 2000 cal B.P. and during the past millennium (ca. 2 °C cooler than during the major part of the Holocene). Interestingly, the most recent sample suggests the lowest temperature (Fig. 8).

Discussion

Holocene lake development phases: early succession, climate optimum and climate deterioration

The early Holocene is probably the most difficult time-period for reconstructing past climatic and environmental conditions in northern Sweden. It is likely that ecosystems, both aquatic and terrestrial, were not in balance with the prevailing climatic conditions. During deglaciation, the melting of ice masses probably led to patchy landscapes, with notable spatial differences in environmental conditions. This is illustrated by the different timing of the onset of organic sedimentation, which was delayed in Vuolep Njakajaure by ca. 900 years compared to Lake Badsjön, a small lake located only a few hundred meters further to the east (Barnekow 2000). Vegetation was rather open during this time, and pollen spectra suggest wetter and warmer conditions than today (Barnekow 2000). During the early Holocene, remains of glaciers in the catchment were likely to have had a major impact on lake features such as stratification of the water column, light penetration and water temperature. For example, melting water could have affected Vuolep Njakajaure during the warm summer months, hampering the development of a stable stratification in the water column. This process is to some extent supported by the diatom record, as *Fragilaria* taxa, favouring a higher minerogenic input (Smol 1983) are abundant, whereas at the same time planktonic *Cyclotella* taxa, which require a stratified water column, show low abundances.

A major shift in both the pollen and diatom stratigraphy occurred at around 7800 cal B.P. *Alnus* begins to become established, and pollen abundance and influx increase and reach the highest values recorded during the Holocene (Barnekow 2000). At the same time, the *Fragilaria* dominated diatom assemblage was replaced by a *Cyclotella* dominated community (Fig. 5). This shift probably indicates a reduction in minerogenic input and the development of stable lake stratification, allowing an increase of planktonic taxa. The ratio between planktonic and benthic diatoms in lake sediments has been used to reconstruct the effects of climate on lakes, based on the assumption that a high proportion of planktonic diatoms represents a prolonged season of open water (Lotter and Bigler 2000; Sorvari et al. 2002). In addition to increasing catchment stability, the establishment of *Alnus* also plays a major role

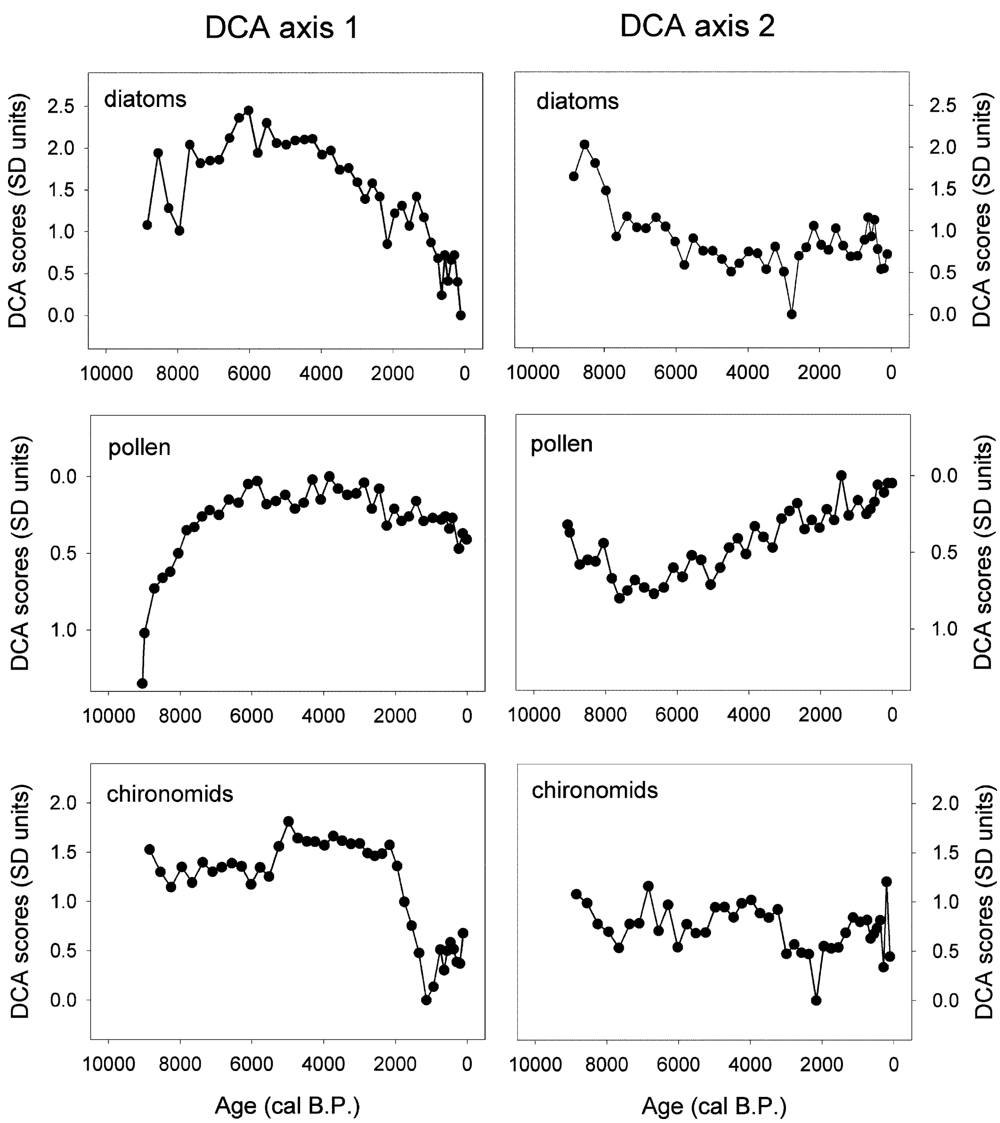

Fig. 7 Detrended Correspondence Analysis (DCA) sample scores illustrating the compositional species turnover during the Holocene of the biological proxy-indicators in sediments from Vuolep Njakajaure

in the nitrogen budget. *Alnus* is able to fix atmospheric nitrogen, and as a result nitrogen concentrations in soils and at the lake shore probably increased. In an investigation of a chronosequence of newly deglaciated lakes in Alaska, the establishment of *Alnus* has been shown to have a major influence on lake chemistry and nutrient availability, with pronounced consequences for the diatom assemblage composition (Engstrom et al. 2000). From 7000–2500 cal B.P., the high abundance and influx of *Pinus sylvestris* pollen suggest maximum extension of pine-birch forest in the area, indicating particularly warm summer temperatures and dry conditions (Barnekow 1999b). This is in agreement with the July air temperatures inferred from the diatoms (Fig. 8) and from chironomids (Heinrichs et al. in press).

The pollen record suggests a climatic cooling at 4500 cal B.P., when *Pinus* influx decreases abruptly for a short time in Vuolep Njakajaure and also in nearby Badsjön (Barnekow 2000). Both diatoms and chironomids seem unaffected at this time. Pollen data suggest a further substantial temperature decrease at 2500 cal B.P., as the abundance of *Pinus* pollen decreases and, concomitantly, the abundance of heath species such as *Betula nana*, Poaceae and Ericales increase (Barnekow 2000). Contrary to the first temperature decrease inferred from pollen, at this time the diatoms and chironomids also show major changes in species composition patterns and temperature indications. The prevailing *Cyclotella* community is partly replaced by *Fragilaria*, which could be a result of reduced stratification and longer ice-cover duration. Subsequently, temperatures inferred from diatoms remain relatively low, indicating that the past two millennia were colder than the mid-Holocene (Fig. 8). Simultaneously, chironomids show a major change in community composition, as Tanytarsini decrease, whereas *Corynocera ambigua* appears and *Microtendipes* and *Sergentia* increase.

External factors affecting Vuolep Njakajaure: land-uplift, insolation patterns

The glacio-isostatic land-uplift may have had an influence on prevailing climate and therefore on the quantitative

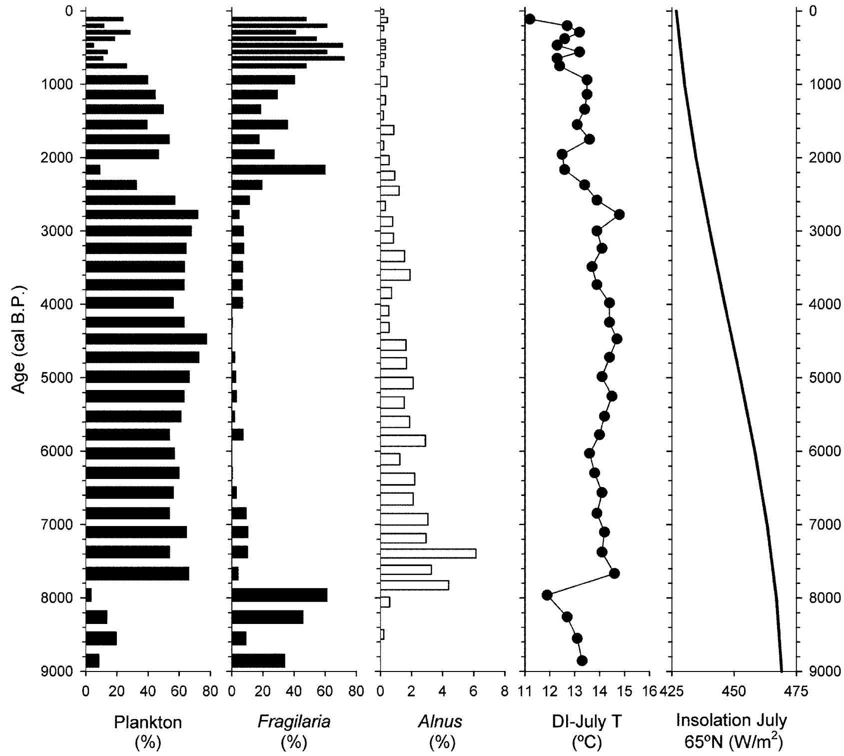

Fig. 8 The abundance of *Fragilaria* and planktonic diatoms (mainly *Cyclotella*), pollen percentage abundance of *Alnus*, and mean July air temperature inferred from diatoms (DI-July T) in the Vuolep Njakajaure record. July insolation at 65 °N is based on Berger and Loutre (1991)

diatom based summer temperature reconstruction. Since 9000 cal B.P., the magnitude of regional land-uplift has been estimated to be ca. 100 m based on shore-line displacement (Renberg and Segerström 1981; Møller 1987). Applying the lapse rate for Fennoscandia of 0.57 °C per 100 m (Laaksonen 1976), the cooling due to land-uplift may account for some of the changes indicated by diatoms (Fig. 8). Our reconstruction is, however, not corrected for land-uplift.

Orbital forcing, the so-called Milankovitch-cycles, has a strong influence on latitudinal insolation patterns. Detailed reconstructions are available for periods exceeding the Holocene (Berger and Loutre 1991). Due to the location of Vuolep Njakajaure north of the Arctic Circle, the summer insolation was considerably higher during the early Holocene than today (Fig. 8), whereas the winter insolation remained consistently low. The change in summer insolation patterns certainly affected local climatic conditions, and was, in combination with the glacio-isostatic land-uplift, a major external factor regulating Holocene ecosystem dynamics in northern Sweden.

Comparison with regional quantitative climate reconstructions

Numerous palaeoecological studies have been carried out reconstructing past environmental conditions and climate in northern Sweden, particularly in the Abisko area. In this section, we compare our record with other quantitative reconstructions. At Lake Njulla, located above the present-day treeline (Fig. 2), chironomids and diatoms indicate warm summers during the early Holocene (Bigler et al. 2003). Elevated temperatures are suggested as well by fossil wood remains buried near the lake shore (Kullman 1999), a finding that is also supported by the pollen and macrofossil records of mountain birch from the same lake (Barnekow 1999a). At Lake 850 (Fig. 2), chironomids suggest a progressive temperature decline during the Holocene, whereas diatoms do not show any remarkable long-term trend (Larocque and Bigler 2004). At Lake Tibetanus (Fig. 2), summer temperatures were quantitatively reconstructed using pollen, and indicate a climate optimum during the mid-Holocene (Barnekow 1999a; Hammarlund et al. 2002). In Lake Vuoskkujávri, located today within the birch-forest (Fig. 2), chironomids suggest decreasing temperatures since the early Holocene. Both pollen and diatom indicators suggest similar patterns, but due to the lack of a good modern analogue, the reconstructions are tentative prior to 8000 (pollen) and 6000 (diatoms) cal B.P. (Bigler et al. 2002).

A similar study using quantitative multi-proxy reconstructions was carried out at Lake Sjuodjijaure in the Sarek Mountains (150 km south of our study area) where unstable and fluctuating climatic conditions were reconstructed for the early Holocene, followed by a mid-Holocene climatic optimum and progressively colder conditions during the past millennia (Rosén et al. 2001). In Lake Tsuolbmajavri, northern Finland, diatom-based reconstructions indicate only moderate temperature changes during the Holocene, suggesting that the coldest periods occurred during the early Holocene, at 4000 cal B.P., 3000 cal B.P. and during the past millennium (Korhola et al. 2000). Pollen-based reconstructions from the same core suggest a cool early Holocene, a mid-Holocene climate optimum and cooler

temperatures since ca. 5700 cal B.P. (Seppä and Hammarlund 2000). Due to methodological constraints, a tree-ring record from the Torneträsk area showed no long-term Holocene climate trend, but accurately dated annual to centennial fluctuations (Grudd et al. 2002). However, a combination of low- and high-resolution proxies has a high potential for climate reconstructions in the Northern Hemisphere (Moberg et al. 2005) and this approach could probably lead to a more detailed synopsis of Holocene climate change in northern Sweden.

Precipitation reconstructions from Lake Tibetanus, based on pollen and oxygen isotopes, suggest relatively moist conditions during the early Holocene (600–800 mm annual precipitation) that subsequently decrease reaching present-day values from 4000 cal B.P. onwards (Hammarlund et al. 2002). Similarly, evidence from pollen from Lake Vuoskkujávri indicated a decreasing amount of annual precipitation since 7000 cal B.P. (Bigler et al. 2002). In a regional context, comparable pollen-based precipitation patterns were reconstructed from Lake Tsuolbmajavri, northern Finland (Seppä and Birks 2001). An overall shift in dominating air masses is proposed for northern Scandinavia during the Holocene. Whereas moist Atlantic air masses dominated during the early Holocene, leading to relatively high precipitation, the influence of continental Arctic air masses increased progressively during the Holocene, leading to relatively dry conditions (Seppä and Hammarlund 2000; Seppä and Birks 2001; Shemesh et al. 2001; Hammarlund et al. 2002).

Our study confirms the patterns of Holocene climate and environmental conditions in northern Sweden described by many paleoenvironmental studies. During the early Holocene, pteridophytes indicate relatively moist conditions and diatom assemblages suggest relatively cool temperatures. The latter could be considerably affected by cold melting water and remaining ice in the lake catchment. As consequence, the largest differences between quantitative summer temperature reconstructions in northern Sweden based on biological proxy indicators in lake sediments exist during the early Holocene. After ca. 8000 cal B.P., diatoms in Vuolep Njakajaure suggest warm conditions, consistent with other regional temperature reconstructions that are all in relatively good agreement during the mid-Holocene. A regional climate deterioration, starting at ca. 4000 cal B.P., is considerably delayed in the Vuolep Njakajaure record. Whereas diatoms indicate a temperature deterioration starting around ca. 3000 cal B.P., the pollen and chironomid record show a considerably delayed response (ca. 2300 cal B.P. and 1900 cal B.P., respectively), demonstrating differences of response, both in timing and magnitude, among the proxies. It seems that lakes above the tree-line tend to respond more immediately than lakes within forested areas, highlighting the roles of the catchment properties of a lake and its position relative to ecotonal boundaries of the biota (Bigler et al. 2003). Unfortunately, dating uncertainties are considerable in many records and the resolution is relatively low, hampering an evaluation of the timing of colder and warmer periods on a finer temporal scale (Heegaard et al. 2006) .

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