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Unstable early-Holocene climatic and environmental conditions in northwestern Russia derived from a multidisciplinary study of a lake-sediment sequence from Pichozero, southeastern Russian Karelia

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Abstract: A sediment core from Lake Pichozero (61°46′; N, 37°25′; E 118 m a.s.l.) provides information on the environmental and climatic conditions in the southeastern Russian Karelia during the Lateglacial and early Holocene (12 800−9300 cal. BP). The chronology of the sequence is constrained by varve counting and AMS ^{14}C measurement of terrestrial plant macrofossils. Multiproxy analyses (magnetic susceptibility, grain size, TOC, TN, TS, Rock Eval, pollen and macrofossils) imply that cold and dry regional climatic conditions with sparse Arctic vegetation immediately surrounding the site prevailed prior to 11500 cal. BP. Coincident with the transition to the Holocene at 11 500 cal. BP, air temperatures and lake productivity increased and *Betula pubescens* and *Populus tremula* started to migrate into the area, followed by *Picea abies* at 10 750 cal. BP. Although lake productivity decreased at around 11 000 cal. BP and remained low until 9600 cal. BP, pollen-based climate reconstructions imply variable climatic conditions in the region over time. Drier and colder summers prevailed from ∼11 200 to 10 900 cal. BP, followed by an interval of higher annual temperatures and precipitation from 10 900 to 10 750 cal. BP. Lower annual temperatures and drier conditions existed from 10 750 to 10 200 cal. BP, and higher temperatures and precipitation are inferred between 10 200 and 10 000 cal. BP. Finally, declining temperatures and precipitation occurred from 10 000 cal. BP onwards, with a minimum at around 9600 cal. BP. These climatic shifts are temporally coincident with those recorded in North Atlantic terrestrial, marine and ice-core archives and indicate that relatively minor climate signals were transmitted further to the east.

Key words: Northwestern Russia, Lateglacial, early Holocene, multiproxy study, palaeoenvironment, palaeoclimate, lacustrine sediments.

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Introduction

The conventional view of stable and warm climatic conditions during the early part of the present interglacial has lately been challenged by a number of high-resolution ice-core, marine and terrestrial records, mainly, but not exclusively, from around the North Atlantic region (e.g., Dahl and Nesje, 1996; Alley *et al.*, 1997; Björck *et al.*, 1997; Bond *et al.*, 1997; Klitgaard-Kristensen *et al.*, 1998; Hu, 1999; von Grafenstein *et al.*, 1999; Nesje and Dahl, 2001; Tinner and Lotter, 2001; Yu and Wright, 2001; Björck *et al.*, 2001; Nesje *et al.*, 2001). These records give evidence for the occurrence of several distinct climatic oscillations at ∼11 200, ∼10 400–10 300, ∼9400 and ∼8200 cal. BP, which were characterized by a decline in temperature, by decreased humidity or by a combination of both. The underlying causes for these fluctuations have been explained by freshwater disturbance of the thermohaline circulation (Alley *et al.*, 1997; Björck *et al.*, 1997; Bond *et al.*, 1997; Barber *et al.*, 1999), but recently solar forcing has also been put forward as a possible trigger (Muschler *et al.*, 2000; Björck *et al.*, 2001; Bond *et al.*, 2001).

Palaeoclimatological and palaeoenvironmental reconstructions have a long tradition in Russia (Khotinsky, 1984; Klimanov, 1984; Savina and Khotinsky, 1984; Elina and Filimonova, 1996; Khotinsky and Klimanov, 1997; Arslanov *et al.*, 1999; Elina *et al.*, 2000; Tarasov *et al.*, 1999; Velichko *et al.*, 2002), but regional correlations among sites and to North Atlantic records are mostly hampered by the lack of a good chronology. This, and the fact that most of the published results are not available in English, has often caused Russian records to be overlooked in western scientific literature. For example, the notion of unstable Holocene climatic conditions and cyclic recurrences of cold events during the Holocene have been common knowledge in Russia for many decades (Khotinsky, 1984; Klimanov, 1984; 1989; Arslanov *et al.*, 1999). Distinct short colder phases seem to have been characteristic of the early Holocene, especially during the Preboreal and Boreal, i.e., between 10 000 and 8000 BP (Khotinsky, 1987; Arslanov *et al.*, 1999). The oldest of these fluctuations, which is centred around 9600 BP, is separated from the Younger Dryas by a short warmer phase (Arslanov *et al.*, 1999) and might correspond to the Preboreal Oscillation of the North Atlantic region (Björck *et al.*, 1997). Three younger, shorter cooling periods occurred during the Boreal time period (Arslanov *et al.*, 1999) and, although highly speculative, might correspond with the 10 300–10 400 cal. BP and 9400 cal. BP events.

To resolve whether the observed early-Holocene climatic fluctuations in western Russia, which are mainly based upon reconstructions from pollen data, and are also evident in a number of different lake-sediment proxy records, we performed high-resolution mineral magnetic, geochemical, pollen and macrofossil analyses along a 9 m long and partly

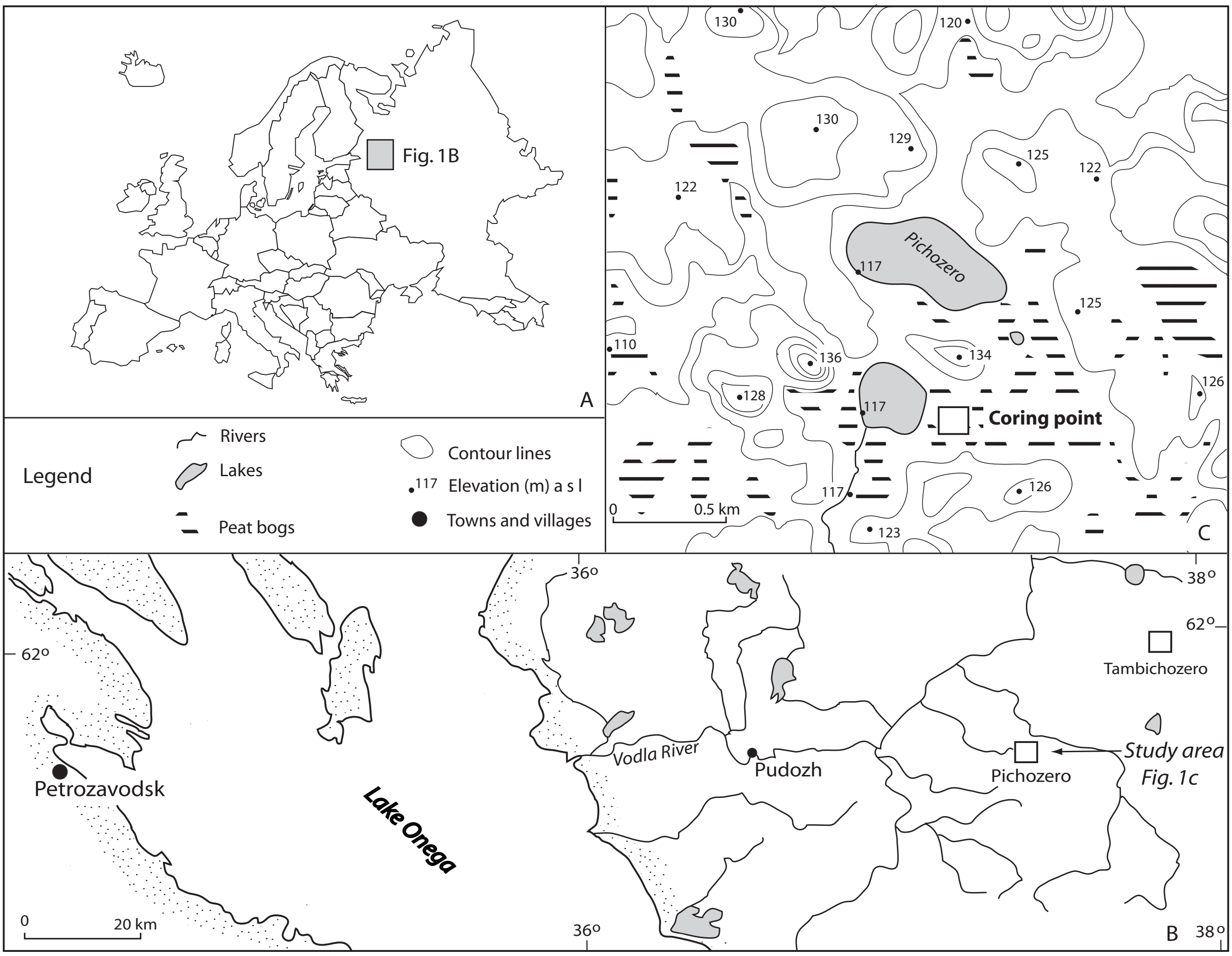

Figure 1 Location map (A), showing the position of the investigated site in eastern Russian Karelia (B), the topography around Lake Pichozero and the coring point (C).

laminated lake-sediment sequence from southeastern Russian Karelia (Figure 1). The chronology is constrained by laminae counts and AMS ^{14}C measurements on terrestrial plant macrofossils. Here, we present results for the lower part of the sequence, which comprises the Lateglacial and early Holocene (12 800–9300 cal. BP).

Study area

Lake Pichozero (61°47′ N, 37°25′ E; 117–118 m a.s.l.) is located in southeastern Russian Karelia (Figure 1) within the southern Boreal (middle taiga) zone, where dominating forest taxa are spruce, pine, birch and larch. Present-day climate is moderate-continental, with mean annual air temperatures of around 1.9°C (January mean: −11.8°C; July mean: 16.7°C), mean annual precipitation of 650 mm and mean runoff of 270 mm.

Bedrock in the area consists of Devonian shales and siltstones, which are overlain by Quaternary glacial, interglacial and interstadial sediments. Lake Pichozero is situated on the proximal side of a *c* 20 km wide terminal belt (Vepsovo ice marginal line), which was formed during the successive deglaciation from the last glacial maximum position of the Valdaian Ice Sheet (~17 000 cal. BP) (Larsen *et al.*, 1999). The Vepsovo ice marginal line is composed of hummocky moraines, end-moraines, kames and glaciofluvial deltas. Mapped Quaternary deposits in the surroundings of the site include mainly clayey tills. The regional deglaciation chronology is highly uncertain. but, assuming an age of 14 250 cal. BP for the deglaciation of the southern part of Lake Onega (Saarnisto and Saarinen, 2001) and an age of 15 000 cal. BP for the start of the deglaciation from the last glacial maximum (Larsen *et al.*, 1999), we conclude that the study area could have become free of active ice some time between 14 000 and 15 000 cal. BP. However, dead ice could have remained for a considerable period.

Materials and methods

Cores were obtained in October 1997 in the wetland south of Lake Pichozero (Figure 1C). Coring was performed with a strengthened Russian corer (1 m length, 7.5 cm diameter) to a depth of 9.1 m, and cores were taken with 0.5 m overlap. The sediments below 9.1 m were stiff clays and silts with some sand and gravel and could not be recovered completely. The cores between 9.1 and 3.8 m, which represent the Lateglacial and the early Holocene, were transported to the Department of Geology, Lund University, for subsampling. Based on the lithostratigraphic description, the sequence was divided into eight sediment units (Table 1). Distinct clay/silt couplets in sediment units 1–5 were counted under a dissecting microscope.

Mineral magnetic susceptibility [χ] was measured according to Walden *et al.* (1999), and grain size was determined on pretreated ($Na_4P_2O_7$ for two weeks) and wet-sieved (mesh size 0.064 mm) samples on a Micromeritic 5100 sedigraph. Both methods were employed to detect increased inwash of minerogenic material and to quantify grain-size variations. Geochemical analyses were performed to assess changes in the lacustrine environment. Total carbon (TC) and total sulphur (TS) were measured on a LECO CS-225 Carbon/Sulphur Analyzer, and total nitrogen (TN) was determined with a HEREAUS-CNS Analyser. Organic carbon (OC) content was obtained on split acidified samples. Total inorganic carbon (TIC) was then calculated as the difference between TC and OC. The C/N ratio was used as a proxy for discrimi-

Table 1 Lithostratigraphic description of the sediment sequence in the peat bog Pichozero, eastern Karelia (61°47′812″ N, 37°25′717″ E) (vgLB = very gradual lower boundary)

Depth (m) below surface	Lithological unit	Sediment description
3.80–3.845	8	Dark brown gyttja, plant fragments, vgLB
3.845–3.91		Dark brown calcareous silty gyttja, plant fragments, vgLB
3.91–3.915	7	Light brown calcareous silty gyttja, vgLB
3.915–4.01		Dark brown calcareous silty gyttja, plant fragments, vgLB
4.01–4.06		Brown-greyish calcareous silty gyttja, plant fragments, vgLB;
4.06–5.01	6	Greenish-grey calcareous silty gyttja, orange-coloured spots and horizons, plant fragments, vgLB
5.01–5.67	5	Greenish-grey calcareous silty gyttja, vgLB; 60 distinct laminae between 5.01 and 5.095 m; diffusely laminated between 5.095 and 5.27 m, ~130 laminae; 270 laminae between 5.27 and 5.67 m; estimated time of deposition for this unit: 460 years
5.67–5.89	4	Greenish-grey calcareous clayey silt, diffusely laminated, FeS colouring at *c.* 5.80, vgLB; estimated time of deposition: 90 years
5.89–6.02	3	Greenish-grey (FeS black) calcareous clayey silt, 50 distinct laminae, vgLB
6.02–6.16		Greenish-grey calcareous clayey silt, diffusely laminated (~60 laminae), vgLB; estimated time of deposition for this unit: 110 years
6.16–7.96	2	Alternating grey-greenish and reddish calcareous clayey silt with Vivia nit; organic horizons at 6.73–6.74 and 6.87 m, vgLB; 720 laminae; 16–6.36 m: grey-greenish; 6.36–6.38 m: reddish; 6.38–6.40 m: grey-greenish; 6.40–6.41 m: reddish; 6.41–6.49 m: grey-greenish; 6.49–6.56 m: reddish; 6.56–6.62 m: grey-greenish, 6.62–7.96 m: red dish; estimated time of deposition for this unit: 720 years.
7.96–9.10	1	Reddish calcareous silty clay, vgLB; diffusely laminated between 7.69 and 7.99 m (~80 laminae), 120 laminae between 7.99 and 8.42 m; diffusely laminated between 8.42 and 8.49 m (~20 laminae); 90 laminae between 8.49 and 8.73 m; diffusely laminated between 8.73 and 9.10 m (~140 laminae); estimated time of deposition for this unit: 450 years

nating terrigenic and limnic organic material (Meyers and Ishiwatari, 1993; Lami *et al.*, 1994; Dean, 1999; Meyers and Lallier-Vergès, 1999). Sulphate concentrations in lake waters are usually low (<0.1 mM), and sulphate mainly results from degradation of sulphur containing biomolecules (Mitchell *et al.*, 1990). C/S values in freshwater lake sediments vary between 8 and 50 and indicate variable degrees of sulphate availability (Berner and Raiswell, 1984). Rock Eval Analysis was performed according to Espitalié *et al.* (1977) and Bordenave *et al.* (1993) with a VINCI Rock-Eval-II Analyser. S1, S2, S3 and T_{max}-values were measured, and corresponding hydrogen index (HI [mg HC/g OC]) and oxygen index (OI [mg CO_2/g OC]) values were calculated.

Subsamples for pollen analysis were prepared according to Berglund and Ralska-Jasiewiczowa (1986) but included a cold 10% HF treatment. *Lycopodium* tablets with a known number of spores were added to enable calculation of the pollen concentration. Pollen keys and illustrations in Moore *et al.* (1991) and Reille (1992) and pollen reference collections (Department of Geology, Lund; Institute of Biology, Petrozavodsk) were used for pollen identification. Pollen percentage and concentration diagrams were constructed using TILIA and TILIAGRAPH 2 (Grimm, 1992). Sum of squares cluster analysis was performed (Grimm, 1987) to identify significant changes in the pollen stratigraphy. Based on these, the diagram was divided into seven local pollen assemblage zones (LPAZ). Samples for macrofossil analysis were sieved under running water (mesh size 0.25 mm), and remains were identified using a dissecting microscope. Owing to the small sample size, the occurrence of individual macrofossils is given as rare or common only. Given the problems that are often encountered when interpreting pollen percentage diagrams, such as long-transported pollen, regional versus local occurrence of taxa (e.g., Berglund and Ralska-Jasiewiczowa, 1986; Birks, 1993), we place stronger emphasis on the pollen concentration values for individual taxa combined with macrofossil evidence, because these allow more secure information on the local vegetation development.

Six AMS ^{14}C measurements were performed on terrestrial plant macrofossils (Table 2). The selected plant material (leaf fragments, fruits, nutlets and catkin scales of *Betula pubescens*, catkin scales of *Populus tremula*, wood fragments) was dried immediately at 105°C after sieving, and sample pretreatment followed the standard procedures at the Ångström Laboratory, Uppsala University. The ^{14}C measurements were calibrated according to Bronk Ramsey (2000).

Climate reconstructions are based on (i) the climate indicator-plant-species method, which was applied to the plant-macrofossil record to derive minimum mean summer temperature estimates (Iversen, 1954; Kolstrup, 1980; Hultén and Fries, 1986). This method, including its advantages and disadvantages, is discussed in detail in Isarin and Bohncke (1999). (ii) The best modern analogue method (Guiot, 1990) was applied to our pollen spectra to derive mean January and July temperatures, annual precipitation and runoff. This method uses a chord distance to determine the similarity between the given fossil pollen spectra and each spectrum in the reference pollen data set. PPPBase software (Guiot and Goeury, 1996; http://medias.obs-mip.fr/paleo_utils) facilitates the performance of all calculations and provides an opportunity to choose the most suitable number of best analogues (one to ten) and a solution to transform the compared taxa percentages. In the present study, we accepted eight modern analogues and performed a logarithmic transformation of taxa percentages, because this provided the best correlation between actual and pollen-reconstructed climate for surface pollen spectra from the Russian Arctic (Tarasov *et al.*, 2002). Thus, climatic variables representing the modern climate at the sites of the eight best modern analogues are averaged by a weighting inverse to the chord distance. The weight function $w_I(x)$ is defined as

$$w_I(x) = |x|^{-2}$$

where $|x|$ denotes the absolute value of x. The obtained average gives the reconstructed 'mean' value of the climatic variable for the fossil pollen spectra, and error bars for each reconstructed value are defined by the climatic variability among the eight best modern analogues. A more robust method of error estimation (Nakagawa *et al.*, 2002) would require a dense network of meteorological stations for appropriate calibration. The data set of 1110 surface pollen samples (moss pollsters, soils and core tops; representing 50–100 years) from the Former Soviet Union and Mongolia is based on an extensive data compilation (Prentice and Webb, 1998; for further details on sampling sites, sampled material, year of sample collection, see also Tarasov *et al.*, 1998; 2002; Tarasov, 2002; Edwards *et al.*, 2000). The 41 pollen taxa selected for the present palaeoclimatic analysis are listed in the Appendix. Modern climatic variables at the pollen sampling sites have been calculated from an updated version of the data base of Leemans and Cramer (1991). For northern Eurasia, the interval covered by instrumental measurements varies between 50 and 150 years. Thus, modern climatic variables and surface pollen samples represent nearly the same time interval. The choice of the climatic variable that might have greatest effect on the vegetation and thus on the composition of the pollen spectra is not an easy task. We first calculated nine conventional and bioclimatic variables, which can be potentially reconstructed from pollen records. Then the correlation coefficients between reconstructed and calculated climatic variables at the surface pollen sites were defined. Based on the results of this test, Tarasov *et al.* (2002) found that mean July temperature (T_{Jul}) and annual sum of mean daily temperatures above 5°C, known as growing-degree days (*GDD5*), can be

Table 2 AMS radiocarbon dates for Pichozero. Bp = *Betula pubescens*, P = *Populus tremula*. The midpoint was chosen where the calibration results showed highest significance

Depth (m)	Material	^{14}C yr BP	Cal. BP		Lab. no.	
			95% Probability	68% Probability	Midpoint	Ua-
8.50–8.30	Wood	10500 ± 125	12900–11950	12850–12150	12575	14805
6.87–6.71	Wood	10110 ± 85	12350–11250	11950–11300	11625	14806
5.67–5.39	Bp, P	9640 ± 205	11650–10250	11250–10600	10925	14807
5.10–4.90	Bp, P	9095 ± 140	10700–9750	10500–9950	10225	16173
4.75–4.55	Bp	8965 ± 135	10500–9600	10240–9790	10065	16174
3.85–3.8	Bp	8255 ± 90	9470–9020	9420–9030	9270	14808

reconstructed with reasonably high confidence ($r > 0.80$; $r^2 = 0.75$ and 0.73, respectively) at sites from the Russian Arctic (north of 60°N). The reconstruction of mean January temperature (T_{Jan}) may be reasonable for the European part of northern Russia only, because the vegetation in Siberia is controlled mainly by summer temperatures ($r^2 = 0.50$). Among the other tested variables, annual precipitation (P) and runoff (defined as the difference between annual precipitation (P) and evaporation (E)) were reconstructed at Arctic sites with relatively high accuracy ($r = 0.68$ and 0.61, and $r^2 = 0.67$ and 0.60). However, the root mean square error of prediction (RMSEP) is low for all variables (e.g., 63.8°C-day for *GDD5*, 0.58°C for T_{Jul}, 0.45°C for T_{Jan} and *c*. 30 mm for *P* and *P-E*). Assuming that the correlation between T_{Jul} and *GDD5* is almost 1 (Nakagawa *et al*., 2002), we chose for the present reconstruction four variables: mean T_{Jul} and T_{Jan}, P_{ann} and *P-E*.

Chronology

Sediment units 1–5 are composed of silt/clay couplets (1.4–4.4 mm thick), which were examined and counted under a dissecting microscope (Table 1). The regular appearance of the silt/clay couplets and their distinct boundaries led us to assume that they represent annually deposited sediments. To test this hypothesis, we compared our pollen stratigraphy with a pollen record from the Karelian Isthmus (Subetto *et al*., 2002). Reconstructions of Lateglacial vegetation changes on the Karelian Isthmus and in southeastern Russian Karelia (Wohlfarth *et al*., 2002) indicate that *Betula* and, to some extent, *Artemisia* pollen are long-distance transported and represent vegetation changes in source regions further south or west, rather than in the catchment. Changes in these pollen taxa thus can be regarded as a regional, time-synchronous signal. The decrease in arboreal pollen percentages and the concomitant increase in *Artemisia* and herb pollen percentages on the Karelian Isthmus at 12 650 cal. BP (Subetto *et al*., 2002) correlate well with the transition between local pollen zones PI-1 and PI-2 in Pichozero. The rise in *Betula* and decrease in *Artemisia* pollen percentages are dated to 12 000 cal. BP on the Karelian Isthmus (Subetto *et al*., 2002) and are comparable to the transition between pollen zones PI-2 and PI-3 in Pichozero. The age estimate of ~650 years between the pollen zone transitions PI-1/PI-2 and PI-2/PI-3 is in good agreement with the number of silt/clay couplets between 8.70 m and 7.10 m and gives support for annual laminations (Figure 2). To constrain the upper nonlaminated part of the sequence, the pollen stratigraphy was compared to the neighbouring site Tambichozero (Wohlfarth *et al*., 2002) (Figure 1B), where the rise in *Pinus* pollen percentages, dated to 9900 cal. BP, is comparable to the pollen zone transition PI-6/PI-7. The six calibrated AMS ^{14}C measurements (Table 2) fall, with one exception, at 5.50 m, on the tentative age-depth curve established by laminae counts and pollen stratigraphic correlations (Figure 2) and provide independent evidence that the suggested age-depth curve serves as a good approximation.

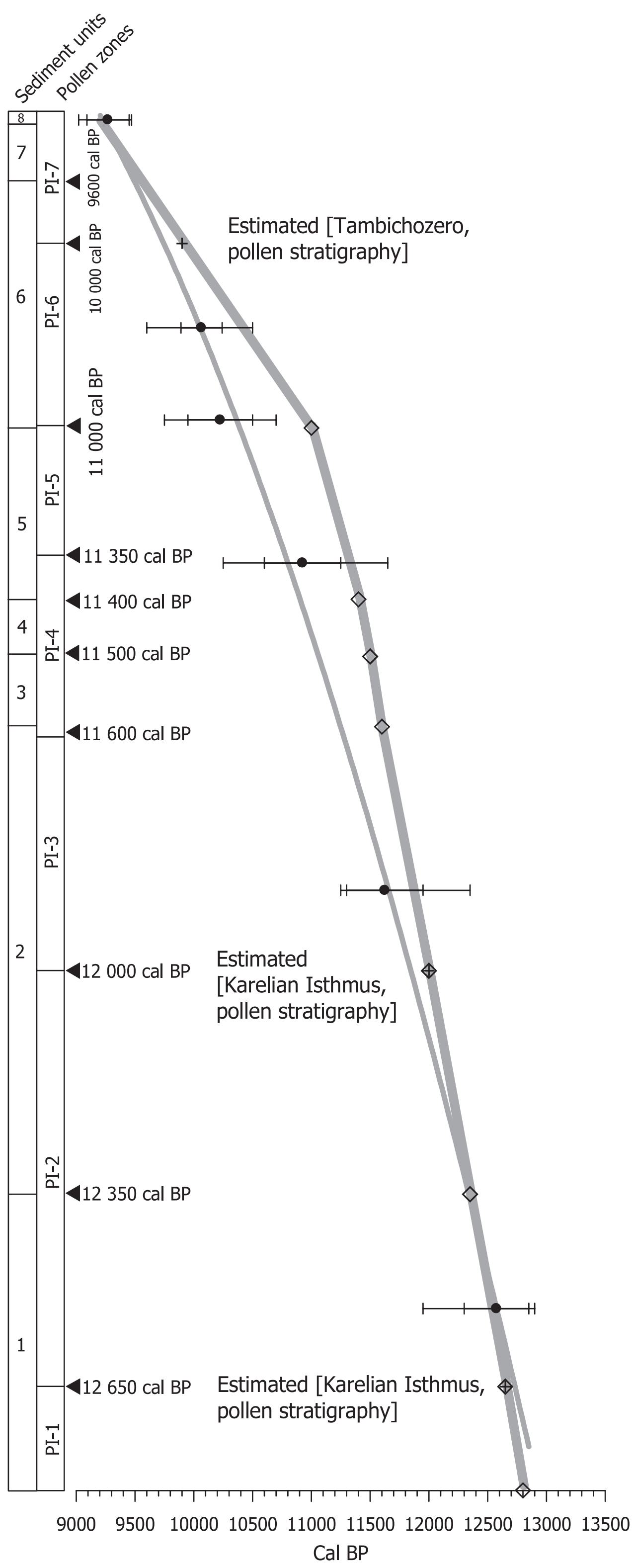

Figure 2 Age-depth curve based on calibrated ^{14}C measurements (see Table 2) (Bronk Ramsey, 2000), on laminae counts in sediment units 1–5 and on pollen stratigraphic correlations to the Karelian Isthmus (Subetto *et al*., 2002) and to Lake Tambichozero (Wohlfarth *et al*., 2002). The radiocarbon dates are displayed with 1 and 2 standard deviations, and the midpoint of each date represents the point of highest probability. + = age inferred from sites on the Karelian Isthmus and from Tambichozero; ◇ = age obtained through laminae counting. The age points used for the construction of the age-depth curve are indicated.

Results & interpretation

Lake system, vegetation and climate >~11 500 cal. BP

Lake system

The laminated, slightly calcareous silty clays and clayey silts (sediment units 1–3) are the lowermost sediments of the sequence, because the underlying stiff clays and silts could not be recovered. The sediments have overall low magnetic susceptibility values, whereas the grain size displays a decrease

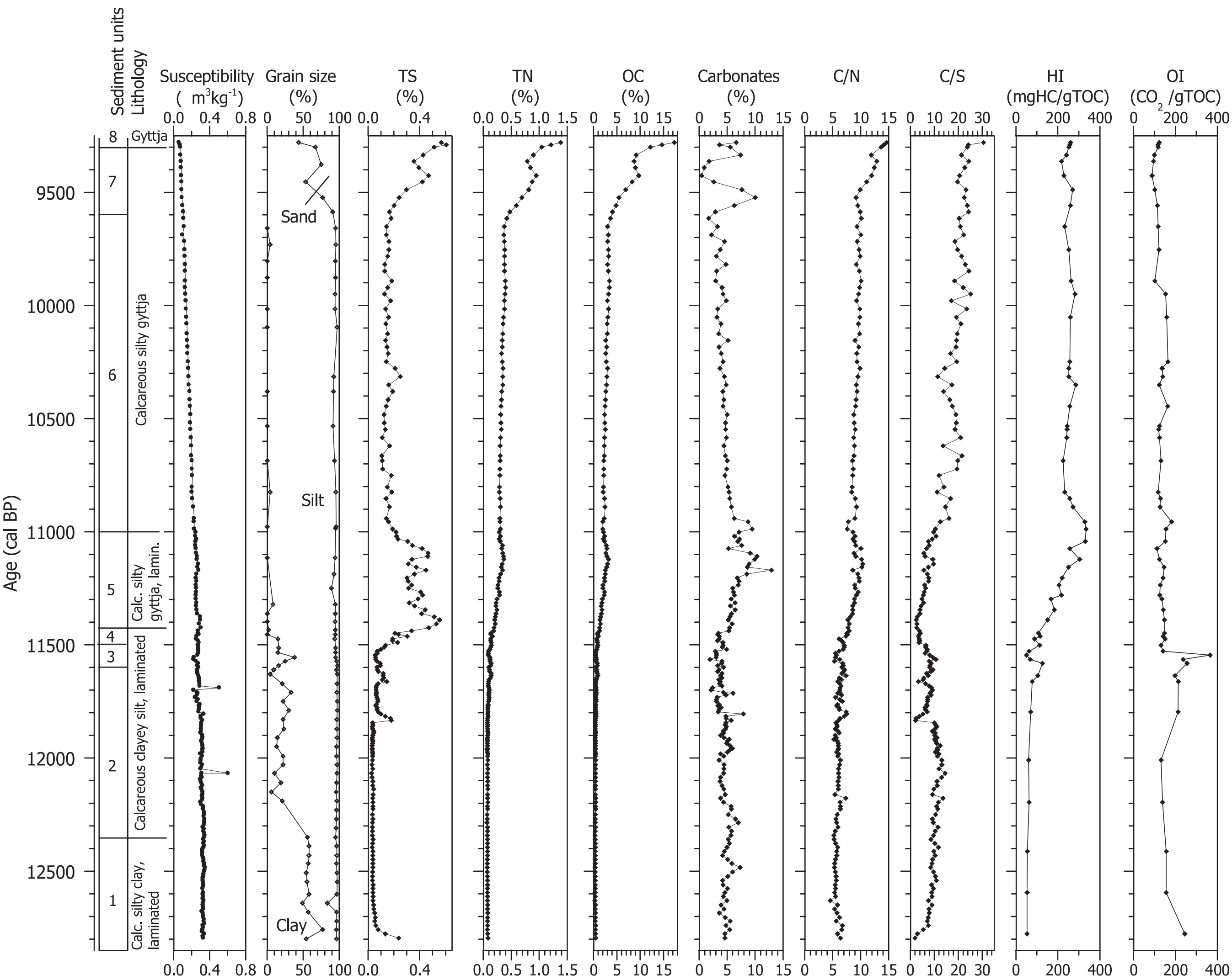

Figure 3 Lithology, magnetic susceptibility, grain size and geochemical parameters for Lake Pichozero between 3.8 and 9.1 m. See Table 1 for a detailed lithostratigraphic description.

in the clay fraction and an increase in silt-sized particles (Figure 3). Vivianite and FeS laminae occur in sediment units 2 and 3. TN and OC contents are low throughout, while TS increases from values of $<0.1\%$ to around 0.2–0.1% at ~11 850 cal. BP. Carbonates are present at around 2–5%.

The mainly minerogenic sediments indicate input of predominantly allochthonous mineral matter, and the low OC, TN and TS contents imply only minor lake productivity (Figure 3). This is corroborated by scarce macrofossil finds of *Chara* sp. and *Nitella* sp., *Callitriche hermaphroditica*, *Potamogeton filiformis*, *Daphnia* sp., Chironomidae, *Pisidium* sp. and *Cristatella mucedo* (Figure 4). A primarily autochthonous origin of the organic material is indicated by the C/N ratio, which is well below 10 (Lami *et al.*, 1994; Dean, 1999; Meyers and Lallier-Vergès, 1999). On the other hand, Rock Eval HI and OI point towards a preferential terrigenous organic matter source, albeit that terrigenous, as well as limnic, organic matter underwent heavy oxidative degradation (Figure 3). Anoxic bottom-water conditions are indicated by the presence of laminations, vivianite and FeS colourings (Table 2) and could have been caused by long-lasting lake-ice cover. The C/S ratios are exceptionally low at the very base of the sequence, pointing towards a high proportion of allochthonous sulphur supply. Sulphur became limited very rapidly, and C/S ratios remain around 10 throughout, except for one interval at around 11 800 cal. BP, where they decline quickly to values around 2. The sharp increase and gradual decrease of TS at ~11 800 cal. BP point to a pulse of allochthonous sulphur supply, which facilitated enhanced bacterial sulphate reduction and accumulation of reduced sulphur species in the sediment. A major increase in minerogenic detritus is not recognizable in grain size or susceptibility, but a slight increase in C/N ratios may support an episodic increase in terrigenous matter input.

Terrestrial vegetation and climate reconstruction

The pollen spectra (zones PI-1 to middle part of PI-4) (Figure 5) show higher percentages for tree pollen (mainly *Betula*, *Alnus*, *Pinus*), compared to herb pollen, in the lowermost zone PI-1 (12 800–12 650 cal. BP). Herb pollen percentages, mainly *Artemisia*, increase in PI-2 (12 650–12 000 cal. BP) but start to decline again in PI-3 (12 000–11 650 cal. BP), coincident with a rise in tree pollen values. The lower part of PI-4 (11 650–11 500 cal. BP) is characterized by a further rise in tree pollen, an increase in shrub pollen and a gradual decline in herb percentages, mainly *Artemisia*. Pollen concentrations for trees (*Picea*, *Pinus*, *Betula*) remain generally low in all pollen zones. The plant macrofossil finds are composed of dwarf shrubs (*Betula nana, Dryas octopetala*), herbs (*Sagina* sp.,

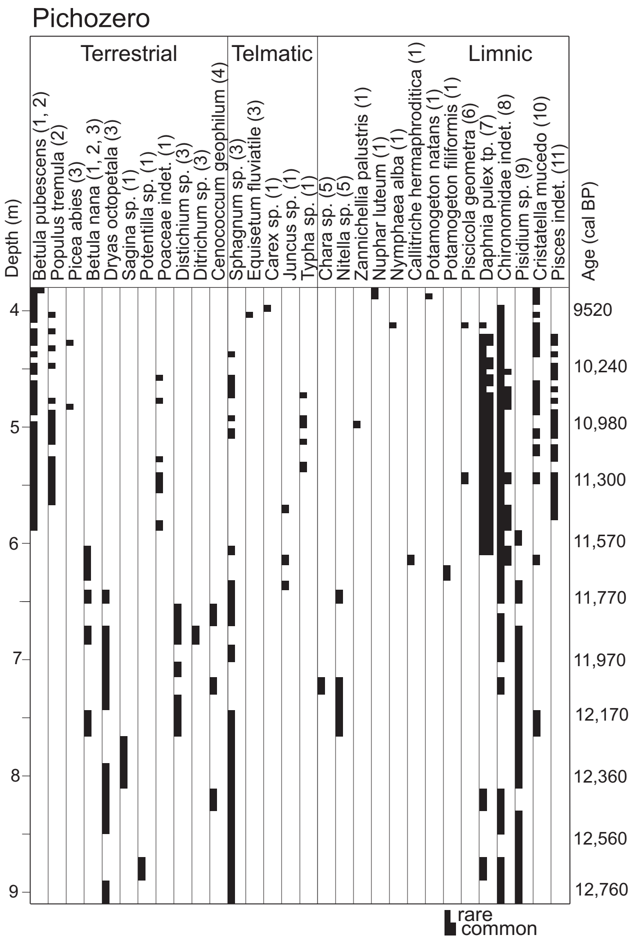

Figure 4 Simplified macrofossil diagram. (1) Seeds, fruits; (2) catkin scales; (3) leaves and other vegetative remains; (4) sclerotia; (5) oospores; (6) coccoons; (7) ephippia; (8) head capsules; (9) shells; (10) statoblasts; (11) bones, scales.

Potentilla sp.) and mosses (*Distichium* sp., *Ditrichum* sp.), as well as few telmatic remains (*Sphagnum* sp., *Juncus* sp.) and some *Cenococcum geophilum* sclerotia (Figure 4).

The probably sparse vegetation in the close surroundings of the site included Arctic and hypoarctic pioneer plants, such as *Betula nana* and *Dryas octopetala*, as well as grasses and mosses. The low pollen concentration values for trees throughout the whole time interval show that these were not growing near to the site and that pollen of *Picea*, *Pinus* and tree *Betula* have to be regarded as long-distance transported. However, shrubs, such as *Salix*, and herbs and grasses could have colonized the soils already before 12 650 cal. BP and especially *Artemisia* may have been common. Inferred minimum mean summer temperatures based on the presence of *Betula nana* and *Potamogeton filiformis* may have been around 4°C (Hultén and Fries, 1986; Bennike, unpublished data). Pollen-based climate reconstructions (Figure 7) give evidence for a three-phased development: (i) an earlier phase (< 12 000 cal. BP) with T_{jan} of $\sim < -25$°C, T_{jul} of $\sim 12-16$°C and $P \cong 400$ mm/yr; *P-E* decreases gradually to its lowest values between 12 500–12 000 cal. BP; (ii) a middle phase (around 12 000 cal. BP) with distinctly lower temperature and precipitation values; (iii) a later phase (12 000–11 500 cal. BP) with higher, but fluctuating T_{jan}, T_{jul} and P and rising *P-E* values. Compared to present, winters were probably > 10°C and summers 3–6°C colder. The low values for P and *P-E* show that conditions must have been distinctly drier than today.

Lake System, vegetation and climate between ~11 500 and 9300 cal. BP

Lake system

The calcareous clayey silts (sediment unit 4) change at ~11 400 cal. BP into calcareous silty gyttja (sediment units 5–7), which is overlain by gyttja (sediment unit 8) at 9300 cal. BP. Grain-size analysis shows a dominance of the silt fraction and an increase in sand-sized particles at ~9600 cal. BP. Given the presence of carbonates and the overall low mineral magnetic susceptibility values, this probably reflects an increase in silt and sand-sized carbonate particles, rather than increased minerogenic runoff (Figure 3). Most geochemical parameters display marked changes at ~11 500 cal. BP, compared with the previous time interval (Figure 3). TS values rapidly attain 0.3–0.55% between 11 500 and 11 100 cal. BP but decline thereafter to stable values of 0.2%. The second increase in TS at ~9600 cal. BP is interrupted by a short decline at ~9400 cal. BP. TN and OC values mirror this trend with a very gradual increase until ~11100 cal. BP, low but stable values between 11100 and 9600 cal. BP, a renewed increase to 1% and 10%, respectively, at around 9600 cal. BP and a short decline at ~9400 cal. BP (Figure 3). Carbonate percentages rise gradually between 11 200 and 10 900 cal. BP, are stable between 10950 and 9600 cal. BP, but fluctuate from 9600 cal. BP onwards. The C/N ratio is generally below or around 10 and increases to 10–15 only after 9400 cal. BP. The C/S ratio rises gradually and fluctuates at 20–30 between 11000 and 9300 cal. BP. Limnic macrofossils (Figure 4) become slightly more diverse at ~11 500 cal. BP and include abundant *Daphnia* sp., chironomids, fish remains and sparse finds of *Pisicola geometra*, *Cristatella mucedo* and *Zannichellia palustris*. Finds of *Nymphaea alba*, *Nuphar luteum* and *Potamogeton natans* appear at around 9700 cal. BP.

All geochemical parameters and the slightly increased diversity of limnic macrofossil remains point to enhanced lake productivity starting at 11 500 cal. BP. The increasing TS content at ~11 500 cal. BP shows that the lake rapidly changed from an extremely low-productivity stage into a stage of enhanced autochthonous biomass production. This assumption is also supported by the position of the samples in the HI/OI diagram, which indicates a primary hydrogen-enriched source that underwent significant oxidation (samples A in Figure 6b). The remarkably high TS content between 11 400 and 11 000 cal. BP can, to a certain extent, be explained by enhanced productivity in the lake as indicated by the hydrogen richness of organic matter, which increases by a factor of 2 (Figure 3). A higher proportion of autochthonous algae preserved in the sediment (samples B in Figure 6b) is not in contradiction with the slightly elevated C/N ratios, approaching values of 10. Higher productivity and sulphur availability may have stimulated bacterial sulphate reduction and the establishment of anoxic porewater. Better overall preservation conditions also would enhance the amount of preserved nitrogen. A decline in sulphur availability and consequently an increase in the C/S ratio, resulting from sulphur limitation, are visible already at around 11 000 cal. BP (Figure 3). However, the high TS values between 11 400 and 11 000 cal. BP need to be attributed to an external source, at least in part. If all sulphur originated from biogenic sources, it would be accompanied by higher OC values. It is also evident from Figure 6a that OC and TS are decoupled in the sediments of this interval (samples B), whereas all remaining samples (samples C–E) show different, but linear, OC versus TS relationships. It remains open whether the additional sulphur input occurred via surface runoff or resulted from aeolian input of aerosol sulphate.

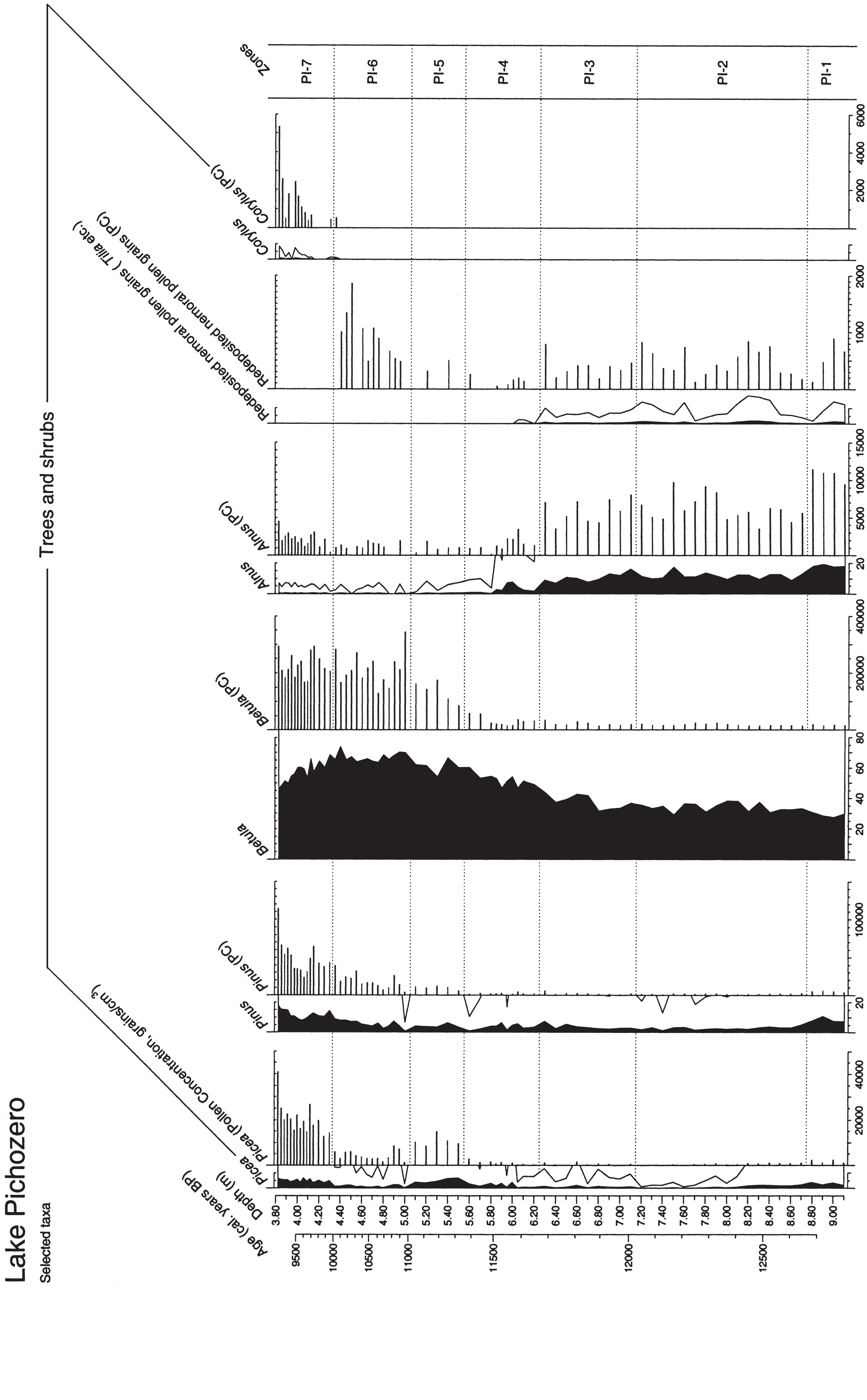

Figure 5 Simplified pollen percentage and pollen concentration diagram; PC = pollen concentration (grains/cm^3).

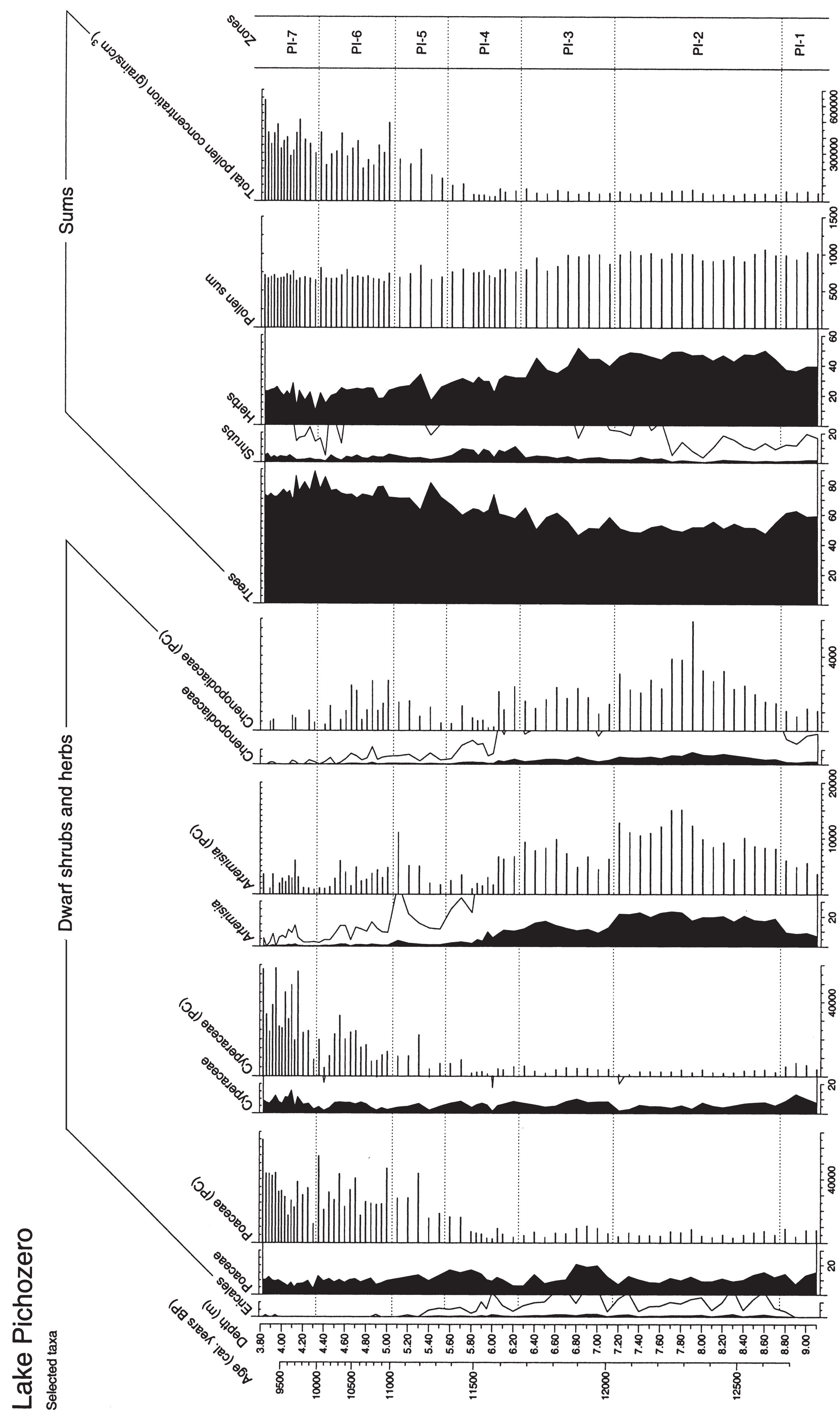

Figure 5 *(continued)*

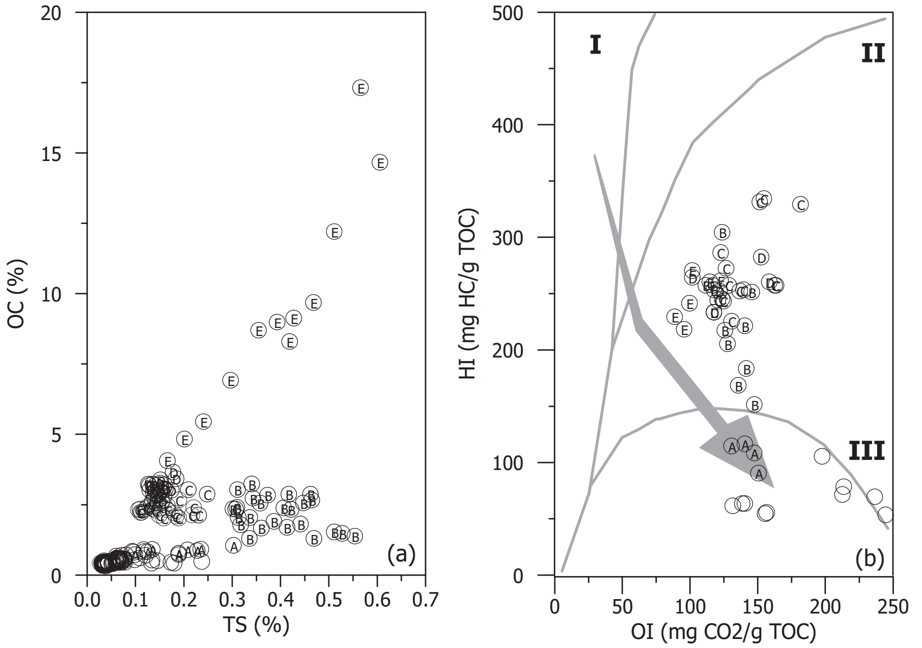

Figure 6 (a) Discrimination diagram for total sulphur (TS) versus organic carbon (OC). A linear relationship exists for samples $>$11 500 cal. BP, for samples originating from 11 500–11 400 cal. BP (phase A) with a C/S ratio of 8.6 and for samples between 11 000 and 9300 cal. BP (phases C–E) with an average C/S ratio of 18.65. The lack of correlation between OC and TS between 11 400 and 11 000 cal. BP (phase B) is attributed to external sulphur sources. (b) Pseudo van Krevelen diagram plotting Hydrogen index (HI) versus oxygen index (OI) obtained from Rock Eval analysis. The diagram allows for organic matter typing, thermal maturation and oxidative degradation processes. Evolution pathways are shown for Type I organic matter derived from monospecific limnic algae and bacteria, type II from mixed algal sources and type III from land plants. Oxidative degradation will shift values along the indicated arrow.

The rise of TN, OC and carbonate percentages until 11 000 cal. BP and the following and concomitant decline in all parameters shows that the trend of increasing lake productivity very likely became interrupted. Lake productivity remained low between 11 000 and 9600 cal. BP, and a remarkably stable lake system must have been present, given that TN, OC and carbonate contents display only very minor changes. The only significant variation is indicated by Rock Eval indices of organic matter at ~11 000 cal. BP with HI values of almost 350 [mgHC/gOC] (Figure 3). A high contribution of algal-derived organic matter to the sediments is not evident from the constant C/N ratios. If changes in organic input do not account for the HI increase, enhanced anoxia in the sediment may be invoked. Owing to sulphate limitation, anoxia was not accompanied by enhanced bacterial sulphate reduction.

A dramatic shift in the lake ecosystem occurred around 9600 cal. BP and was initiated by strongly enhanced input of terrestrially derived organic matter, which served as a nutrient base for simultaneously increasing autochthonous production. The strong increase in OC is not paralleled by higher Rock Eval HI and equivalent TN values (Figure 3). Enhancement of planktonic productivity in the lake therefore must be considered unlikely, but a shift toward predominantly higher contributions of terrigenous organic matter is supported by both proxy parameters. The concomitant decline of TS, TN and OC at ~9400–9300 cal. BP could possibly give indications of a short phase of decreased terrestrial organic matter input, which in turn may have limited the organic production in the lake.

Terrestrial vegetation

The rise in *Betula* pollen percentages and concentrations at around 11 500 cal. BP (upper part of PI-4) coincides with the first appearance of *Betula pubescens* and *Populus tremula* plant macrofossils (Figures 4 and 5) and with a decrease in *Artemisia* pollen values. During PI-5 (11 350 and 11 000 cal. BP), pollen values for *Betula* rise steadily and *Picea* starts to increase. Pollen percentages for herbs and grasses remain constant, but their concentration values, especially those for *Artemisia*, rise around 11 200 cal. BP (Figure 5). *Betula pubescens* and *Populus tremula* remains are frequent and indicate that both trees were growing around the site (Figure 4). During PI-6 (11 000–10 000 cal. BP), *Betula* pollen have constant percentage and concentration values, while those for *Pinus* increase gradually (Figures 5 and 6). A marked decline in percentage and concentration values for *Picea* is observed between 10 700 and 10 000 cal. BP, although the occurrence of *Picea abies* needles shows that it was present around the site at ~10 750 cal. BP and at ~10 000 cal. BP (Figures 4 and 5). Poaceae and Cyperaceae have constant pollen percentages and high concentration values during PI-6 and PI-7, but concentrations for *Artemisia* start to decline around 10 200 cal. BP. Redeposited pollen are again frequent between 10 900 and 10 100 cal. BP and attain highest concentration values at ~10 250 cal. BP (Figure 5). During PI-7 (10 000–9300 cal. BP) *Betula* has values similar to those before, while *Picea* and *Pinus* increase again (Figure 5). However, a minor decrease in pollen concentrations for *Pinus* can be observed around 9600–9500 cal. BP (Figure 5). The first pollen grains of *Corylus* appear at ~10 100 cal. BP, and pollen concentrations start to increase at ~9600 cal. BP (Figure 5). Cyperaceae and *Artemisia* concentration values are again higher between 9800 and 9300 cal. BP.

The pollen and plant macrofossil record implies that the vegetation was initially composed of mainly shrubs and herbs, but included some *Betula pubescens* and *Populus tremula*. The gradual rise in pollen concentrations for *Betula* and the frequent occurrence of *Betula pubescens* and *Populus tremula* macro remains shows that open *Betula-Populus* forests became established around the site at ~11 500–11 400 cal. BP. *Picea* and also possibly *Pinus* may have been present in the region, as indicated by their increasing pollen and concentration values. The rise in herb and grass pollen concentrations around ~11 200 cal. BP points to an expansion of herbs and grasses, which could have been caused by an expansion of wetlands and/or by a change in climatic conditions. Finds of *Picea abies* needles show that it was present around the site at ~10 750 cal. BP and at 10 000 cal. BP. The absence of macroscopic finds between 10 700 and 10 000 cal. BP cannot prove the absence of these trees, but based on lower pollen concentration values we speculate that *Picea* became reduced in the area. The increase in redeposited pollen between 10 900 and 10 000 cal. BP may indicate increased erosion from the surrounding soils. Between 10 000 and 9300 cal. BP the forests around the site were probably still rather open and composed mainly of *Betula pubescens*, *Populus tremula*, *Picea abies* and *Pinus*. *Corylus* may have been present from 9600 cal. BP onwards. However, herbs and grasses must have been rather common in the area.

Climate reconstructions

Pollen-based climate reconstructions suggest a distinct increase in all reconstructed climate variables around and shortly after 11 500 cal. BP (Figure 7). T_{jan} gradually attains ~−20°C between ~11 000 and 10 800 cal. BP, but decreases again to ~−22° to −25°C between 10 800 and 10 200 cal. BP. The second rise to −20°C at 10 100 cal. BP is followed by a minor decline between 9700 and 9500 cal. BP and temperatures of ~−21°C thereafter. Throughout the whole time interval reconstructed T_{jan} are ~10°C below present-day mean January temperatures. Reconstructed T_{jul} increases rapidly from ~11°C at ~11400 cal. BP to ~15°C at 11 200 cal. BP, but declines again between 11 200 and 10 900 cal. BP. Highest T_{jul} of ~16°C at around 10 900–10 800 cal. BP were followed by generally lower, but fluctuating, values between 10 800 and 9300 cal. BP. Slightly lower T_{jul} were reconstructed between 10 700 and 10 400 cal. BP, during 10 000–9750 cal. BP and after 9700 cal. BP, whereas higher T_{jul} may have been attained at 10 200–10 000 cal. BP and at 9700 cal. BP (Figure 7). The reconstructed summer temperatures for the area are below present-day July temperatures and imply that summers were generally 2–4°C cooler than today, except for around 10 900–10 800 cal. BP. Reconstructed *P-E* is ~150 mm at ~11 500 cal. BP and ranges, apart from a short decrease at 11 000 and 10 800 cal. BP, between 150 and 170 mm, which also is considerably lower than today's 270 mm. *P* mirrors, more or less, the curve for T_{jul} with a rise until 11 300–11 200 cal. BP, a drop in values between 11 200 and 10 900 cal. BP and a second increase at 10 900–10 800 cal. BP. Lower values for *P* are reconstructed between 10 800 and 10 200 cal. BP, during 10 000–9750 cal. BP and after 9700 cal. BP. Reconstructed values are 100–200 mm lower than the present-day mean annual precipitation of 650 mm and indicate that conditions must have been generally drier.

Minimum mean summer temperatures, based on the immigration of *Betula pubescens* may have reached ≥10°C (Iversen, 1954; Bos, 1998; Birks, 2000) at 11 500 cal. BP, which is in good accordance with the pollen-based reconstructions (Figure 7). However, inferred minimum mean summer temperatures of ≥10°C between 11 500 and 9700 cal. BP are slightly below those reconstructed based on the pollen record. Plant macrofossil finds of *Nymphaea alba* and *Nuphar luteum* at 9700 cal. BP give evidence for a second increase in mean summer temperature to ≥12–13°C (Iversen, 1954; Kolstrup, 1980), while pollen-based climate reconstructions indicate that summer temperatures did not change markedly between 10 800 and 9300 cal. BP.

Independent of the differences between summer temperature reconstructions based on the indicator-species method and those based on pollen, both methods indicate that summer temperatures were probably lower than at present throughout the whole time period. The pollen-based climate reconstructions also give evidence for shorter time intervals with higher/lower temperatures, precipitation and runoff. T_{jan} seem to have increased gradually between 11 500 and ~10 750 cal. BP, while the rapid rise in T_{jul} may have been interrupted by a decrease between 11 200 and 10 900 cal. BP. Coincident with the decline in T_{jul}, mean annual precipitation may have decreased, which implies that summers may have been cooler and conditions generally drier between 11 200 and 10 900 cal. BP. Highest T_{jan}, T_{jul} and *P* are reconstructed at around 10 900–10 750 cal. BP, pointing to warmer and more humid conditions. The decline in all parameters between 10 750 and 10 200 cal. BP indicates a return to cooler and drier winters and summers. Higher winter and summer temperatures and higher precipitation may have occurred again around 10 200–10 000 cal. BP. However, from *c.* 10 000 cal. BP onwards, reconstructed T_{jan}, T_{jul} and *P* decline again, except for one event at 9700 cal. BP, when T_{jul} and *P* increase shortly, pointing to a phase with cooler winters, but warm summers and higher precipitation.

Discussion

The geochemical and biological proxy data give evidence for four major stages in the environmental development of the lake and its catchment between 12 800 and 9300 cal. BP. Superimposed on these were several minor climatic and environmental changes.

Low lake productivity, anoxic conditions and long-lasting lake-ice cover characterized the lake before 11 500 cal. BP. The sparse vegetation on unstable soils was composed of Arctic and hypoarctic shrubs, herbs and grasses, and inferred climatic conditions were cold and dry (Figure 7). However, reconstructed minimum mean summer temperatures of ~4°C, as indicated by plant macrofossil remains, are in contrast with pollen-based reconstructed T_{jul}, which indicate that summers must have been warm enough to support tree vegetation. If the assumption of summer temperatures of ≥10°C holds true, we speculate that the inferred low winter temperatures, thin snowcover, low *P* and low *P-E*, as well as unstable soil conditions and possibly strong winds, may have been the limiting factors for tree establishment in the area.

The distinct increase in T_{jan}, T_{jul}, *P* and *P-E* around 11500 cal. BP led to substantial environmental changes in the lake and its catchment. Autochthonous production in the lake increased, and the first *Betula pubescens* and *Populus tremula* trees started to colonize the surroundings of the site. Although *Artemisia* and Chenopodiaceae probably became less abundant, herb-grass communities (Poaceae, Cyperaceae) remained important components of the vegetation. The re-expansion of *Artemisia* at ~11 200 cal. BP and inferred cooler summer temperatures and slightly lower precipitation between 11 200 and 10900 cal. BP may indicate a minor climatic fluctuation.

The change in lake system from higher to lower productivity, which started at around 11000 cal. BP, coincided with increased erosion from the surrounding slopes lasting until ~10 000 cal. BP (Figure 7). Furthermore, *Picea abies*, which had now become established close to the lake, seems to have become reduced in abundance between 10 700 and 10 000 cal. BP. Pollen-based climate reconstructions imply increasing winter temperatures until 10 750 cal. BP, while summer temperatures and precipitation were initially low and only

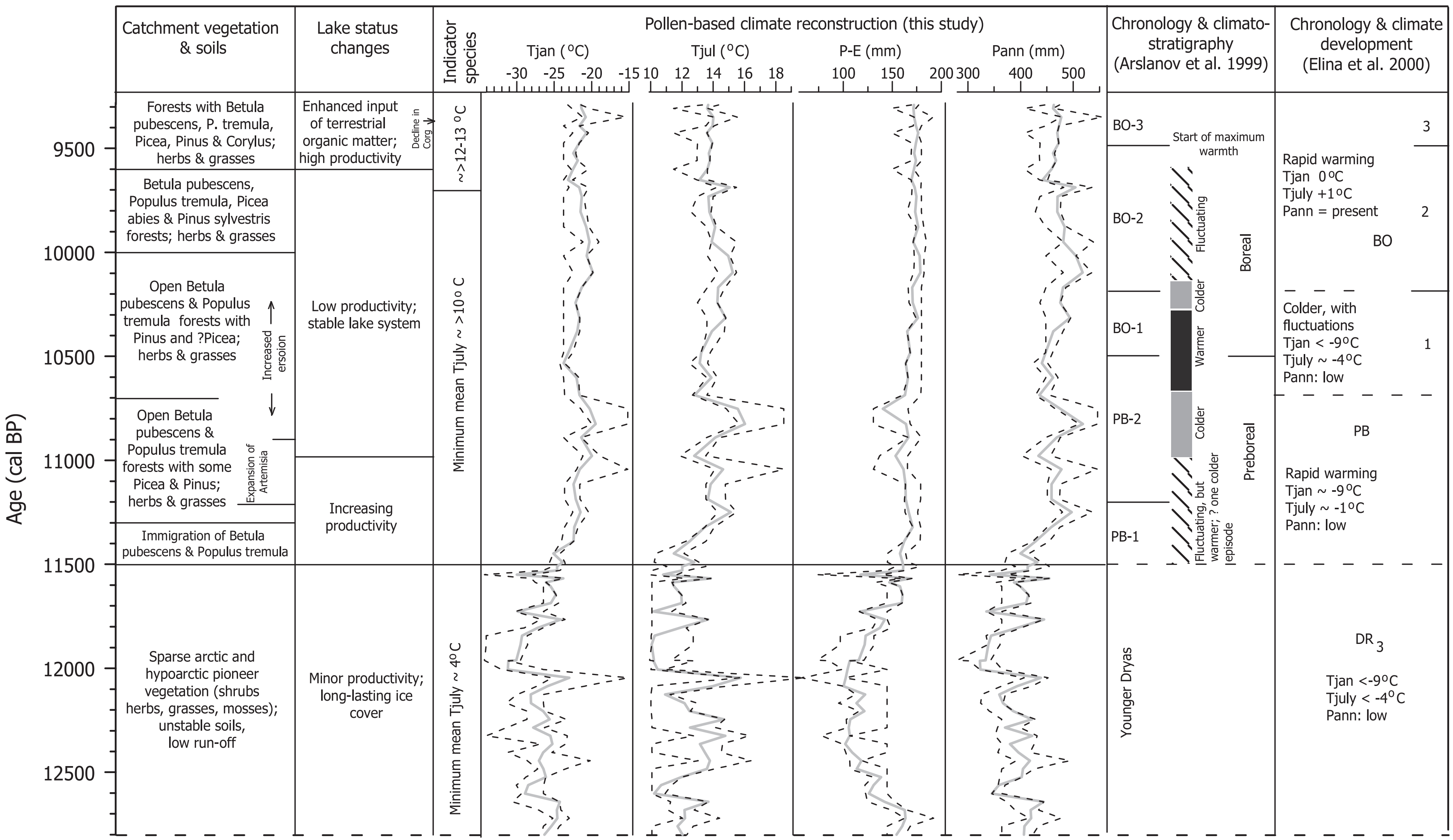

Figure 7 Summary chart of the climatic and environmental development between 12 500 and 9300 cal. BP as reconstructed from Lake Pichozero and comparison to other data sets from northwestern Russia. T_{jan} = mean January temperature; T_{july} = mean July temperature; P_{ann} = mean annual precipitation. The dashed line represents minimum and maximum values (error bars) for each reconstructed value and the dark grey line shows the mean values (see text).

increased shortly between 10 900 and 10 750 cal. BP. Thereafter, temperatures and precipitation declined, pointing to cooler and drier winters and summers until ~10 100 cal. BP. Although the phase of low lake productivity continued until 9600 cal. BP, the inferred catchment vegetation shows that *Picea abies* and *Pinus* were probably rather common in the open *Betula pubescens-Populus tremula* forests from 10 000 cal. BP onwards. It seems difficult to reconcile the long-lasting, low-productivity phase between 11 000 and 9600 cal. BP with the changes seen in the catchment vegetation and with the climatic fluctuations inferred from the pollen record. One possibility is that overall warmer summers and higher precipitation may have led to increased melting of remnant ice, to erosion from the surrounding slopes and to increased inflow of meltwater. Cold meltwater could have kept the lake water cool and turbid, and rapid sedimentation could have caused temporary anoxia in the sediments.

Around 9600 cal. BP, the lake experienced a dramatic shift, which was initiated by enhanced input of terrestrial organic material forming a nutrient base for increasing the autochthonous production. While pollen-based climate reconstructions imply fairly stable temperatures and precipitation, except for a short increase in summer temperature and precipitation around 9700 cal. BP, plant macrofossil-derived minimum mean summer temperature estimates indicate a second rise at 9700 cal. BP, approximately coincident with the renewed rise in lake productivity (Figure 7). Theoretically, the expanding vegetation cover and denser forests in the catchment should have stabilized the surrounding soils and reduced runoff. Reduced inwash of minerogenic matter also can be inferred from low magnetic susceptibility and absence of redeposited pollen grains. However, as shown by the geochemical parameters, input of terrigenous organic matter increased distinctly. This could be explained either by a marked decrease in the sedimentation rate, which is indicated by gyttja formation, or by a rise in lake level, which led to the inundation of the surrounding wetlands and to subsequent terrestrial matter flux into the lake.

The development reconstructed for Lake Pichozero corresponds well with that inferred from the study of a sediment sequence at nearby Lake Tambichozero (Figure 1B), where a first rise in summer temperatures and in lake productivity occurred around 11 500 cal. BP, coincident with the immigration of *Betula pubescens* (Wohlfarth *et al.*, 2002). The second distinct change is reconstructed for around 9900–9800 cal. BP, which is slightly earlier than compared with Pichozero.

The recent study by Elina *et al.* (2000), which included a large number of lake-sediment sequences in northwestern Russia, also indicates rapid warming at around ~11 500 cal. BP, but here the reconstructed values for T_{jan}, T_{jul} and P differ considerably from our results, both before and after 11 500 cal. BP (Figure 7). The compilation by Arslanov *et al.* (1999) gives evidence for a number of colder/warmer fluctuations between ~11 500 and 9500 cal. BP, but these do not correlate with those seen at Pichozero (Figure 7). On the other hand, both studies indicate stepwise warming at 11 500 cal. BP and at ~9500 cal. BP and an intermediate phase with more variable climatic conditions. A slightly different picture emerges from two lakes on the Karelian Isthmus, where pollen stratigraphic, diatom and organic carbon evidence indicate that major environmental changes did not occur until around 11 000 cal. BP (Subetto *et al.*, 2002), when a shift from shrub and herb/grass communities to open *Betula-Pinus-Picea* forests occurred. Similar results were obtained in southeastern Finland, where at *c.* 10 700–10 600 cal. BP the Arctic-Subarctic vegetation was replaced by boreal-temperate *Populus-Pinus-Betula* forest, coincident with an increase in summer temperatures from 7–10°C to 16–22°C (Bondestam *et al.*, 1994). It is interesting to note that the vegetation and temperature changes reconstructed on the Karelian Isthmus and in southeastern Finland broadly correspond to the time interval around 10 900–10 800 cal. BP, for which highest T_{jan}, T_{jul} have been reconstructed at Pichozero (Figure 7).

The distinct climatic and environmental changes seen in our data set at 11 500 cal. BP correspond in time to the hemispheric warming, which marked the transition into the Holocene. The rapid response of the limnic and terrestrial ecosystem shows that the warming signal was also rapidly transmitted towards the east, to areas at some distance from the North Atlantic. The early-Holocene short-term cooling periods at 11 200, 10 400–10 300 and ~9400 cal. BP, which are recorded in a number of North Atlantic marine, terrestrial and ice-core archives (e.g., Bond *et al.*, 1997; Björck *et al.*, 1997; Yu and Wright, 2001; Björck *et al.*, 2001; Nesje *et al.*, 2001), are, however, weakly registered. The pollen-inferred summer temperature decline and decrease in mean annual precipitation at ~11 200–10 900 cal. BP may correspond to the colder period at around 11 200 cal. BP. Also lower winter and summer temperatures between ~10 750 and 10 200 cal. BP and at 9600 cal. BP may be equivalent with the North Atlantic cooling phases at 10 400–10 300 cal. BP and 9400 cal. BP, respectively. While pollen-based climate reconstructions thus may give indications that these minor climatic shifts were transmitted further to the east, the response of the limnic environment was probably entirely related to local conditions.

Conclusions

The reconstructed terrestrial and limnic development at Lake Pichozero, southeastern Russian Karelia, differs from earlier palaeoenvironmental investigations in the region and emphasizes the need for more multiproxy studies in areas where only limited information is available. These would not only place earlier investigations into a regional climatic and environmental framework, but also expand the present knowledge of Lateglacial and early-Holocene variability, which is well known from around the North Atlantic, further towards the east into the continental interior.

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Appendix

Pollen taxa from Lake Pichozero used for climate reconstructions. *Alnus*, Apiaceae, *Artemisia*, Asteraceae (including Asteraceae and Cichoriaceae), *Betula*, Boraginaceae, Brassicaceae, Caryophyllaceae, Chenopodiaceae, Convolvulaceae, *Cornus*, *Corylus*, Cyperaceae, *Dryas*, *Ephedra*, Ericales, Fabaceae, *Juniperus*, Lamiaceae, *Larix*, *Picea*, *Pinus*, Plumbaginaceae, Poaceae, Polemoniaceae, Polygonaceae (including *Polygonum*), *Populus*, Primulaceae, Ranunculaceae (including Ranunculus), Rosaceae (including *Filipendula*), Rubiaceae (including *Galium*), *Rubus chamaemorus*, *Rumex*, *Salix*, Saxifragaceae (including *Parnassia*), Scrophulariaceae, *Thalictrum*, *Ulmus*, Urticaceae (including *Urtica*), *Viburnum*, Violaceae.

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