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Late-Glacial and Early Holocene Environmental and Climatic Change at Lake Tambichozero, Southeastern Russian Karelia

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High-resolution lithostratigraphy, mineral magnetic, carbon, pollen, and macrofossil analyses, and accelerator mass spectrometry ^{14}C measurements were performed in the study of a sediment sequence from Lake Tambichozero, southeastern Russian Karelia, to reconstruct late-glacial and early Holocene aquatic and terrestrial environmental changes. The lake formed ca. 14,000 cal yr B.P. and the area around the lake was subsequently colonized by arctic plants, forming patches of pioneer communities surrounded by areas of exposed soil. A minor rise in lake productivity and the immigration of *Betula pubescens* occurred ca. 11,500 cal yr B.P. The rise in summer temperatures probably led to increased melting of remnant ice and enhanced erosion. The distinct increase in lake productivity and the development of open *Betula-Populus* forests, which are reconstructed based on plant macrofossil remains, indicate stable soils from 10,600 cal yr B.P. onward. *Pinus* and *Picea* probably became established ca. 9900 cal yr B.P.

Key Words: **Northwestern Russia; late-glacial; paleoclimate; lake sediments.**

INTRODUCTION

The environmental response of terrestrial, marine, and ice-core records to the climatic fluctuations of the last Termination and to the rapid warming at the beginning of the Holocene is well established for the circum–North Atlantic region. However, the rapidity with which the regional vegetation and the lakes responded to these climatic shifts has been an ongoing debate (e.g., Ammann *et al.*, 2000), mainly due to poor time resolution, chronological problems, and an outdated chronostratigraphic framework. Björck *et al.* (1998), Walker *et al.* (1999), and Lowe *et al.* (2001) therefore recommended comparing the environmental development of chronologically well-constrained sites to the Greenland Ice Project (GRIP) event stratigraphy and discussing leads/lags in relation to this reference profile. Such

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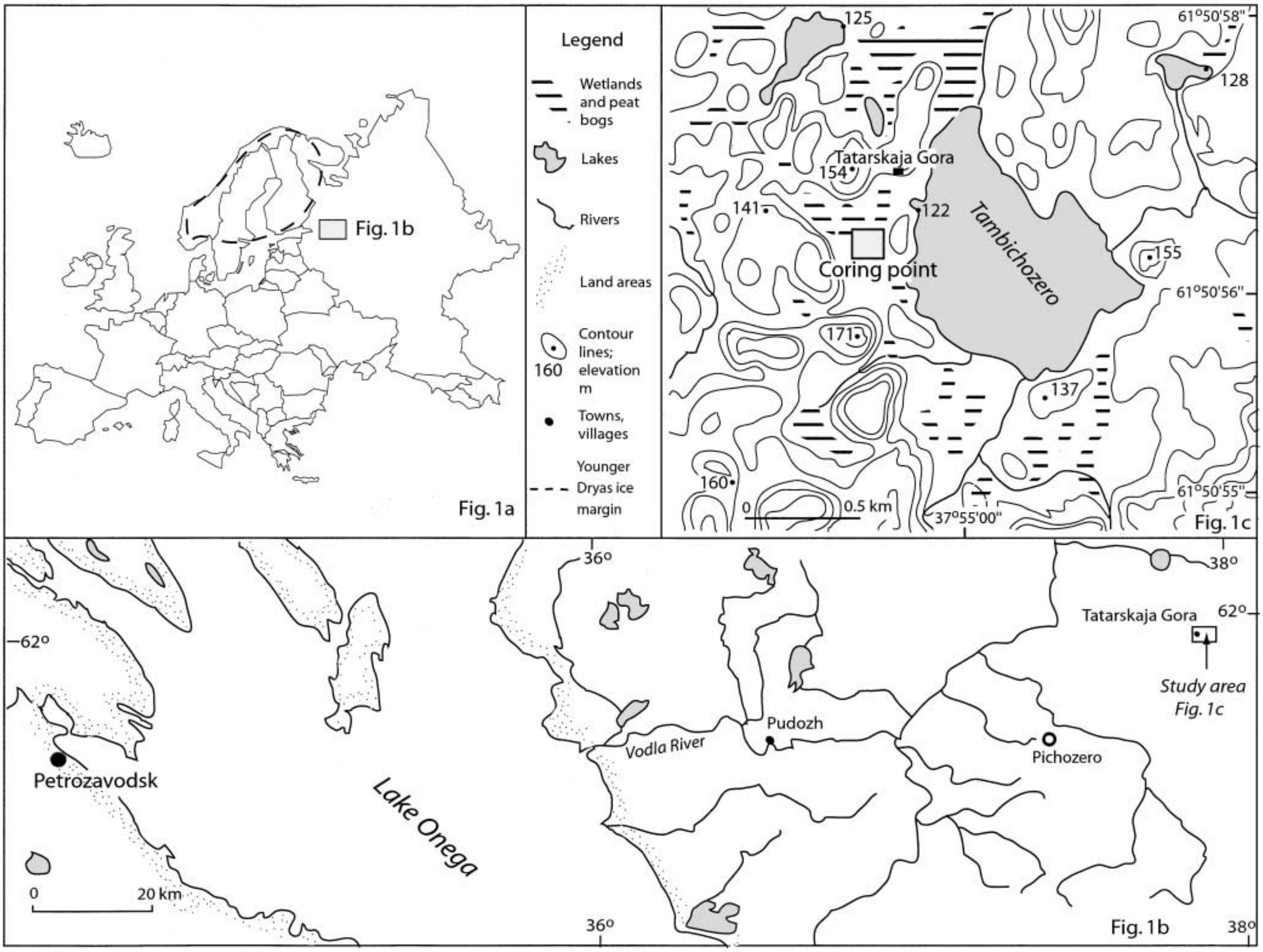


FIG. 1. Maps showing location of the study area in southeastern Russian Karelia (a), east of Lake Onega (b), and topographic map showing details of the coring site (c). The approximate position of the Younger Dryas ice margin of the Scandinavian Ice Sheet is indicated by the dashed line.

comparisons showed rapid responses of terrestrial and aquatic systems to the beginning and end of the Younger Dryas interval in, for example, central Europe (Litt *et al.*, 2001), Scandinavia (Björck *et al.*, 1996; Birks *et al.*, 2000) and Switzerland (Ammann *et al.*, 2000), independent of the altitudinal position of the studied sites or of their position in relation to the receding ice margin (Björck *et al.*, 1996; Ammann *et al.*, 2000).

Information on late-glacial and early Holocene environmental changes is scarce for northwestern Russia, and the temporal resolution of most of the available data sets (e.g., Davydova and Servant-Vildary, 1996; Davydova *et al.*, 1996; Elina and Filimonova, 1996; Subetto *et al.*, 1998; Arslanov *et al.*, 1999; Tarasov *et al.*, 1999) is not sufficient for discussing the development of the area in great detail. In particular, a rapid environmental response to the warming at the Pleistocene–Holocene transition, which had up to now been assumed, has recently been questioned by Subetto *et al.* (2002).

Here, we combine high-resolution lithostratigraphy, mineral magnetic, carbon, pollen, and macrofossil analyses, and accelerator mass spectrometry (AMS) ^{14}C measurements in the study of a ca. 6-m-long lake-sediment sequence from southeastern Russian Karelia (Fig. 1) to reconstruct late-glacial and early Holocene aquatic and terrestrial environmental changes between ca. 14,000 and 9500 cal yr B.P. Our reconstructions show that pioneer arctic vegetation and cold-climatic conditions persisted until ca. 11,500 cal yr B.P. Temperatures rose rapidly at the beginning of the Holocene, and *Betula pubescens*, and later also *Populus tremula,* started to immigrate into the catchment.

MATERIALS AND METHODS

Study Region

Lake Tambichozero (~0.7 km^2, 122 m altitude, 61°56′N, 37°54′E) is situated in southeastern Russian Karelia (Fig. 1a, 1b) within a hummocky moraine landscape (Niemelä *et al.*, 1993) commonly associated with the Vepsovo–Krestets ice-marginal zone (>14,000 ^{14}C yr B.P.) (Ekman and Iljin, 1991). The maximum position of the Late Weichselian ice sheet, which was attained at ~17,000 cal yr B.P., lies about 150 km east of the study area. Deglaciation from this position is assumed to have begun ca. 15,000 cal yr B.P. (Larsen *et al*., 1999) and was likely rapid, for the Lake Onega basin became free of ice between 14,250 and 12,750 cal yr B.P. (Saarnisto and Saarinen, 2002).

The climate of the region is moderate-continental. Mean annual air temperatures are ca. +2.1°C (January T_{mean} − 12.1°C; July T_{mean} + 14°C) and annual precipitation is 650–700 mm. The area belongs to the southern Boreal zone, and pine forests with some larch, spruce, poplar, and tree birch grow around the lake.

Cores were obtained in a former bay in the western part of the lake at an altitude of 123 m (Fig. 1c). Coring was performed with a strengthened Russian corer (1 m long, 7.5 cm diameter); cores were taken with 0.5 m overlap. The cores between 11.1 and 5.3 m depth, which represent late-glacial and early Holocene lake development, were transported to the Department of Quaternary Geology in Lund for subsampling. The cores between 0 and 6 m (peat and lake sediments) are stored at the Institute of Biology, Russian Academy of Sciences (RAS), Petrozavodsk, for further analyses.

Analyses

Based on the lithostratigraphic description and correlation of overlapping cores, the sequence was divided into 16 sediment units (Table 1, Fig. 2). In units 9–16, the sediments show alternating layers with distinct laminae, diffuse laminae, and massive horizons. The distinct laminae, which were examined and counted using a dissecting microscope, consist of alternating light-colored calcite-rich and dark-colored, organic-rich layers. Their composition, appearance, and regularity suggest that each couplet may represent 1 yr. Although this assumption could not be tested by further analyses, the laminated sections were tentatively used to estimate the sedimentation rate for the intercalated weakly laminated and massive layers (Table 1).

Subsamples for grain-size measurements were placed in $Na_4P_2O_7$ for 2 weeks, wet sieved (mesh size: 0.064 mm), and analyzed in a Micromeritic 5100 sedigraph. In sediment units 1–7, the sand fraction is composed of quartz grains, whereas calcite dominates in units 8–16 (Fig. 2).

Contiguous subsamples (2 cm^3) for mineral-magnetic parameters (susceptibility [χ] and saturation isothermal remnant magnetization [SIRM]) were analyzed according to Walden *et al.* (1999). Measured values are generally low (Fig. 2), although SIRM fluctuates from 2 to 7.5 mAm^2kg^{-1} between 9.30 and 8.40 m and χ shows a distinct peak between 7.82 and 7.675 m. SIRM/χ indicates that the fluctuating SIRM values in the lower part and the χ peak at 6.45 m are likely caused by the presence of greigite (Oldfield, 1999). The χ peak at 7.82–7.675 m is related to the increased sand fraction in unit 6 and the fluctuating mineral magnetic values from ~6.40 m upward could be explained by minor minerogenic input.

Total carbon (TC) was determined by stepwise heating in a LECO RC-412 multiphase analyzer, which permits separation

TABLE 1
Lithostratigraphic Description of the Sediment Sequence from Lake Tambichozero

Depth (m)	Unit	Sediment description
5.34–6.095	16	Greenish-grey diffusely laminated calcareous silty clay gyttja, gLB; approx. sedimentation rate: 0.25 cm/yr; estimated time of deposition: 300 yr
6.095–6.37	15	Black/light-brown, diffusely laminated calcareous silty clay gyttja, 12 laminae between 6.09–6.12 m; gLB; approx. sedimentation rate: 0.25 cm/yr; estimated time of deposition: 112 yr
6.37–6.455	14	Black massive calcareous silty clay gyttja, gLB
6.455–6.615	13	Black/light-brown laminated calcareous silty clay gyttja, 120 laminae, sLB; approx. sedimentation rate: 0.13 cm/yr; estimated time of deposition: 120 yr
6.615–6.63	12	Black massive calcareous silty clay gyttja, sLB
6.63–6.935	11	Black/grey laminated calcareous silty clay gyttja, 29 laminae between 6.63–6.67 m; diffuse laminations between 6.67–6.705 m; 132 laminae between 6.705–6.92 m; massive between 6.92–6.935 m; approx. sedimentation rate: 0.15 cm/yr; estimated time of deposition: 194 yr
6.935–7.385	10	Black/grey, calcareous silty clay gyttja; 67 laminae between 6.935–7.095 m; massive between 7.095–7.11 m; 79 laminae between 7.11–7.28 m; diffuse laminations between 7.28–7.30 m; gLB; approx. sedimentation rate: 0.22 cm/yr; estimated time of deposition: 200 yr
7.385–7.63	9	Black/grey, diffusely laminated calcareous clayey gyttja silt; gLB; approx. sedimentation rate: 0.22 cm/yr; estimated time of deposition: 110 yr
7.63–7.655	8	Greyish-brown massive silt, sLB
7.655–7.675	7	Grey clayey silt, sLB
7.675–7.82	6	Dark-grey massive silty fine sand, fining upward into silt, organic material between 7.69–7.70 m, sLB
7.82–7.985	5	Dark-grey to light-brown silty gyttja clay with diffuse FeS laminae, sLB
7.985–8.80	4	Light-brown sandy, clayey silt with dark grey massive sand layers between 7.985–7.99 m, 8.13–8.14 m; FeS laminae between 8.14–8.445 m; sLB
8.80–10.125	3	Light-brown sandy, clayey silt with some FeS laminations, gLB; sand layers at 9.895–9.885 m, 9.825–9.823 m, 9.755–9.75 m, 9.62–9.615 m, 9.505–9.50 m, 39.37 m, 9.28–9.25 m, 9.235 m, 9.19–9.18 m, 9.10–9.085 m (dark brown sand layer with organic material), 9.06 m, 9.00–8.985 m, 8.905–8.895 m, 8.84 m, 8.81 m
10.125–10.40	2	Light-brown clayey silt with few thin sand layers, gLB

Note. The black-green colors disappeared immediately after opening of the cores and became beige–white. gLB = gradual lower boundary; sLB = sharp lower boundary.

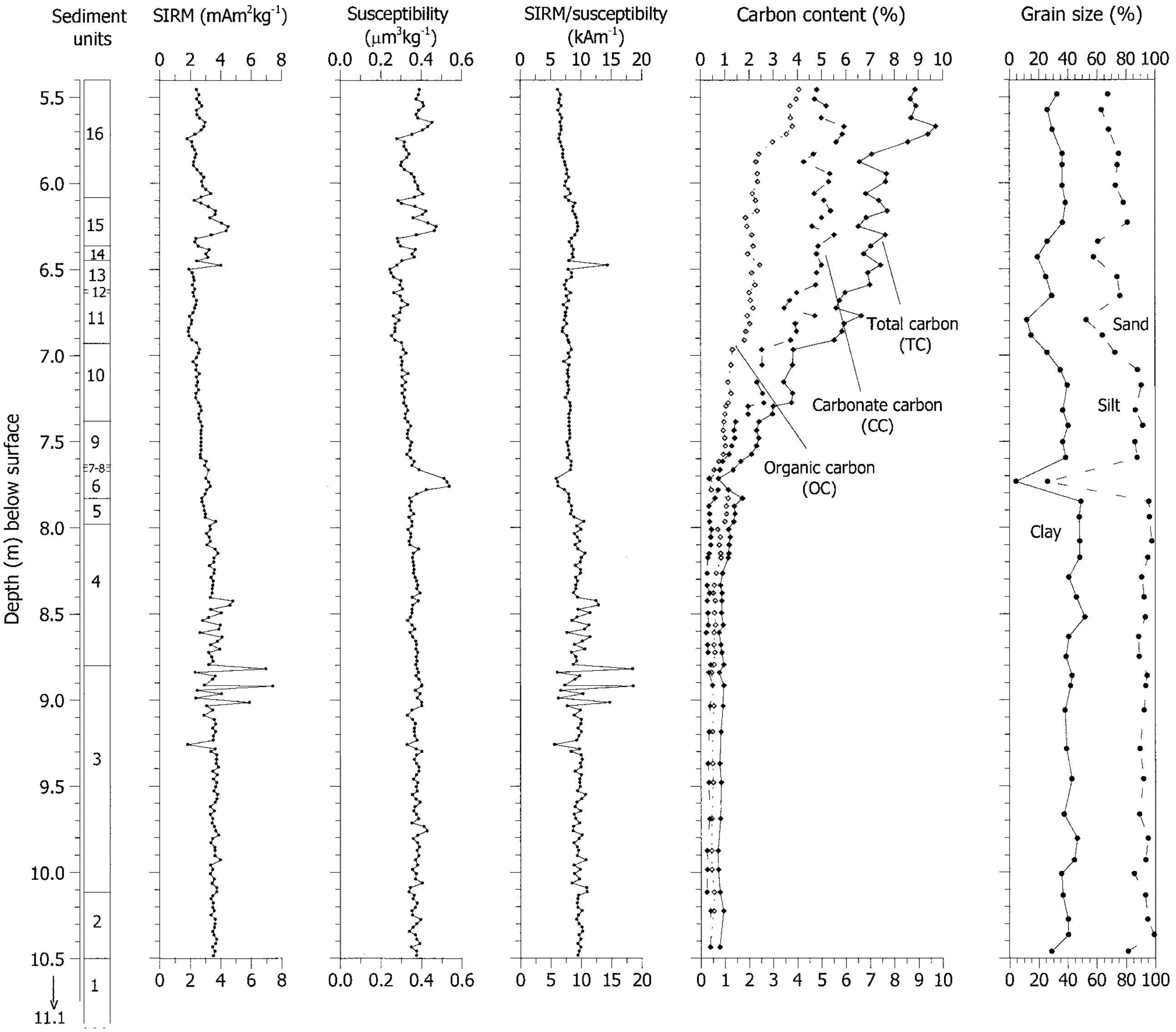


FIG. 2. Stratigraphy, mineral-magnetic parameters, total carbon, and grain size for the sediment sequence from Lake Tambichozero. See Table 1 for a detailed lithostratigraphic description. SIRM = Saturated isothermal remnant magnetization.

of organic carbon (OC) and minerogenic carbon phases. The minerogenic carbon phase is here almost entirely composed of carbonate carbon (CC) (Fig. 2).

Due to the scarcity of plant macrofossils, only four AMS ^{14}C measurements could be performed (Table 2, Fig. 3). The selected plant material was immediately dried at 105°C after sieving. Sample pretreatment followed the standard procedures at the Ångström Laboratory, Uppsala University, Sweden.

Samples for pollen analysis (2 cm^3) were treated according to Berglund and Ralska-Jasiewiczowa (1986) and included a cold 10% hydrofluoric acid (HF) treatment. *Lycopodium* tablets with a known number of spores were added to each sample to estimate pollen concentration. Pollen keys and illustrations in Moore *et al.* (1991) and Reille (1992), as well as pollen reference collections at the Department of Quaternary Geology, Lund, and the Institute of Biology, Petrozavodsk, were used for identification. Pollen percentage and concentration diagrams were constructed using TILIA and TILIA-GRAPH (Grimm, 1992) (Figs. 4 and 5). However, influx values were not calculated, given the uncertainties of the age-depth curve (see below). The group of redeposited tree pollen includes *Larix*, *Ulmus*, *Quercus*, *Tilia*, *Carpinus*, and *Corylus*, which are common in underlying interglacial deposits. The pollen diagram was subdivided into eight local pollen assemblage zones (LPAZ), using sum-of-squares cluster analysis (Grimm, 1987). Here, we present a simplified pollen diagram only, since the detailed vegetation history will be discussed elsewhere (L. Björkman *et al.*, unpublished data).

Macrofossil samples (5- to 10-cm slices) were sieved under running water (mesh size: 0.25 mm) and were identified using a dissecting microscope. Due to the small sample size, the occurrence of individual macrofossils is given as rare or common (Fig. 6).

TABLE 2
Sample Depth, Type of Material Selected for Dating, AMS ^{14}C Measurements, and Resulting Calibrated Ages ($\pm 2\sigma$)[a]

Sample ID Ua-	Depth (m)	Dated material	AMS ^{14}C (yr B.P.)	Calibrated age (yr B.P.)
14015	6.565–6.355	*Betula* sp., *Populus tremula*	8915 ± 190	9975 (+525/−475)
14660	9.75–9.65	*Salix* sp., *Betula* sp., *Dryas octopetala*	9935 ± 150	11,425 (+925/−375)
16707	10.00–9.89	*Dryas octopetala, Betula* sp.	11,250 ± 260	13,225 (+825/−675)
14013	10.40–10.35	*Salix* sp., *Betula* sp., *Dryas octopetala*	11,635 ± 225	13,575 (+775/−625)

[a] According to OxCal v.3.5 (Bronk Ramsey, 2000).
AMS = accelerator mass spectrometry.

Age-Depth Curve and Chronology

The chronological control for the sequence is based on calibrated AMS ^{14}C measurements and varve counting. Figure 3 shows two alternative age-depth curves. Alternative A envelops the 95% confidence interval of the radiocarbon dates and gives a wide range of possible age points for the base and top of the sequence and for the different sediment units and pollen zones.

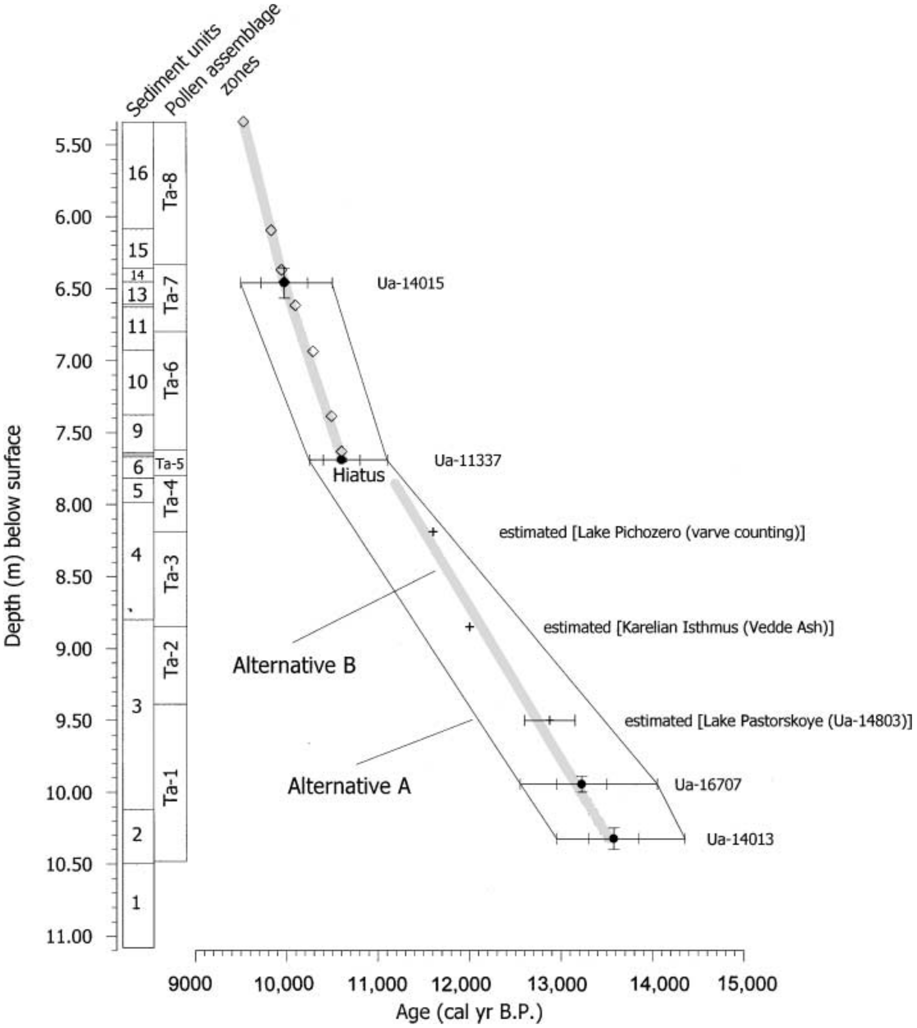


FIG. 3. Age-depth curve, based on the calibrated ^{14}C dates shown in Table 2 (filled circles), on the sedimentation rate estimated from laminae counting (open diamonds), and on pollen stratigraphic correlations with the nearby site Lake Pichozero (B. Wohlfarth, unpublished data) and sites on the Karelian Isthmus (Subetto *et al.*, 2002) (crosses). The calibrated dates are displayed with 2σ error bars. The two alternative age-depth curves, A and B, are discussed in the text.

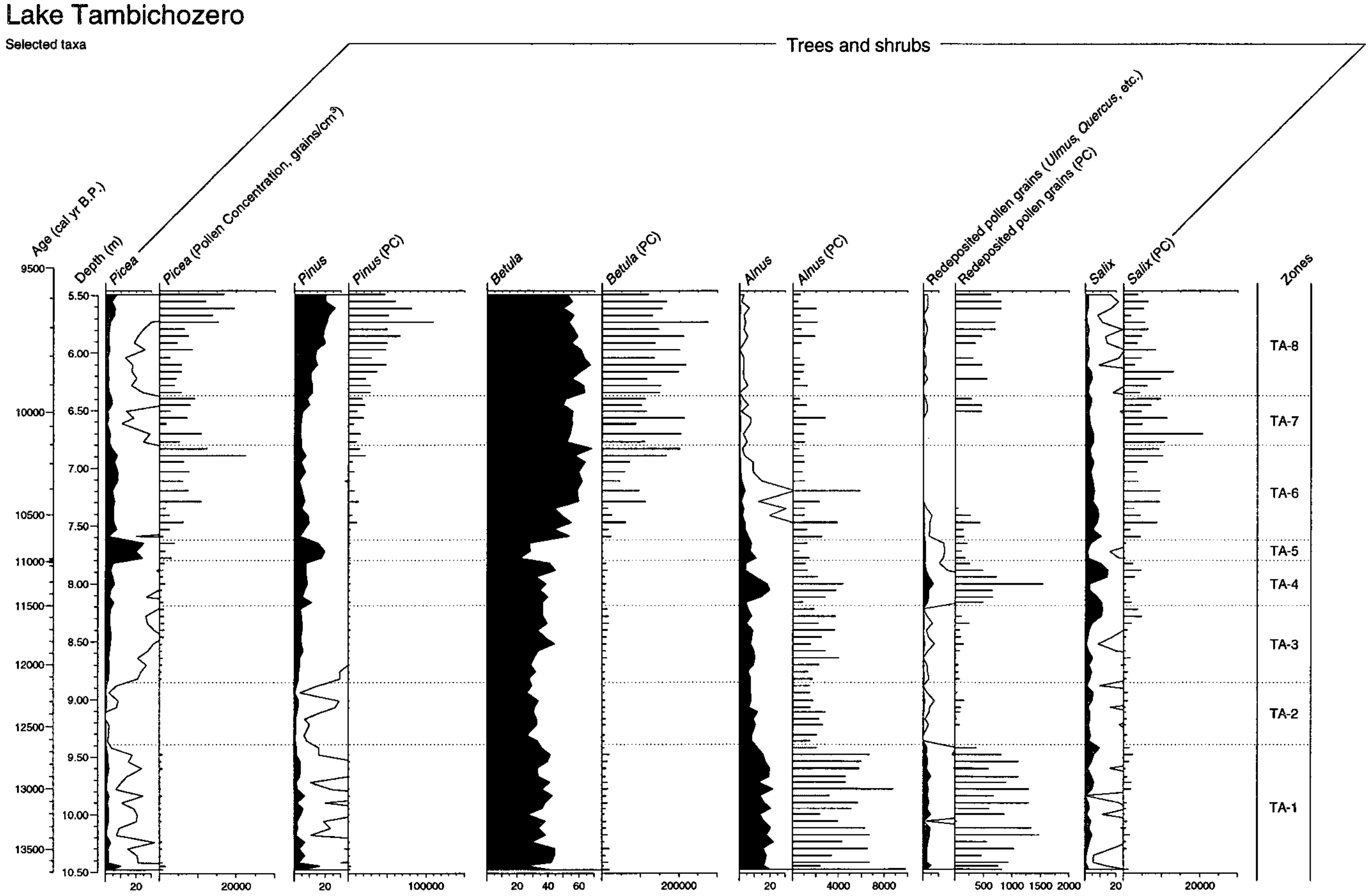
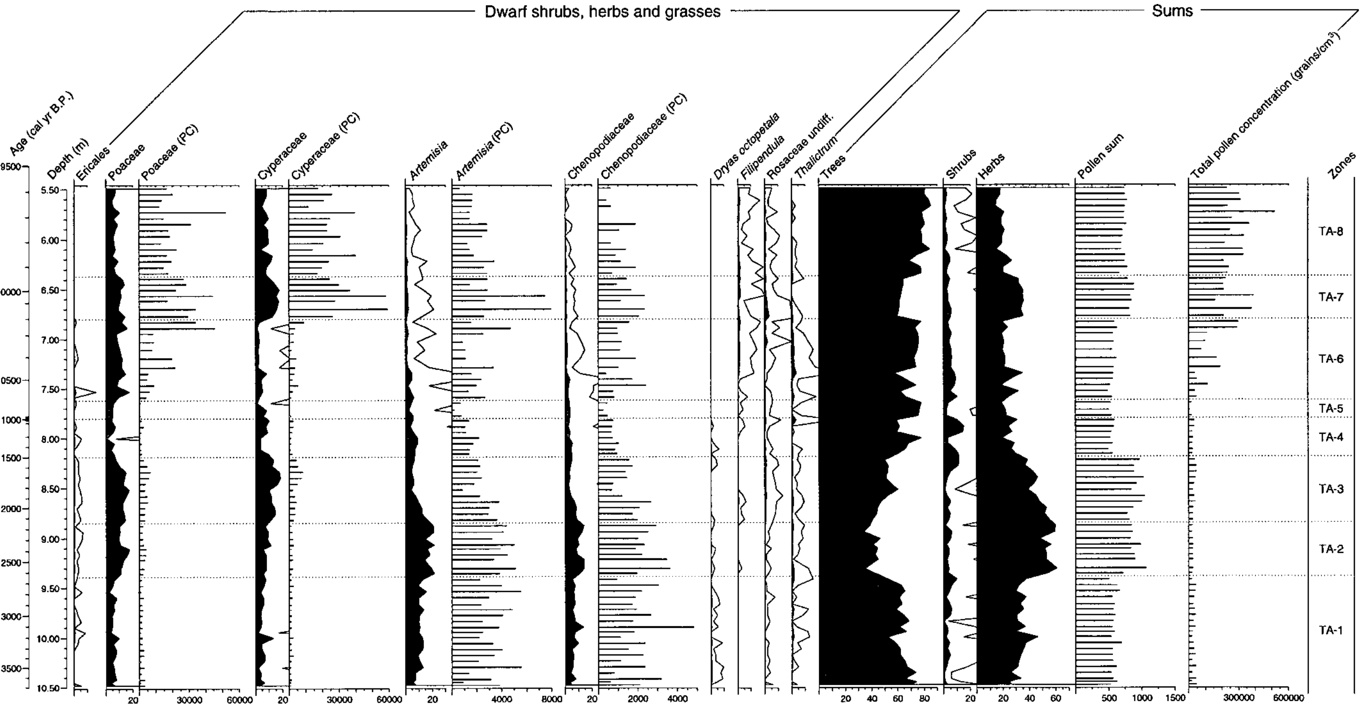


FIG. 4. Simplified pollen percentage and concentration (PC) diagram of selected tree and shrub taxa from Lake Tambichozero.



Analysts: L. Filimonova, N. Lavrova

FIG. 5. Pollen percentage and concentration (PC) diagram of selected dwarf shrub, herb, and grass taxa from Lake Tambichozero.

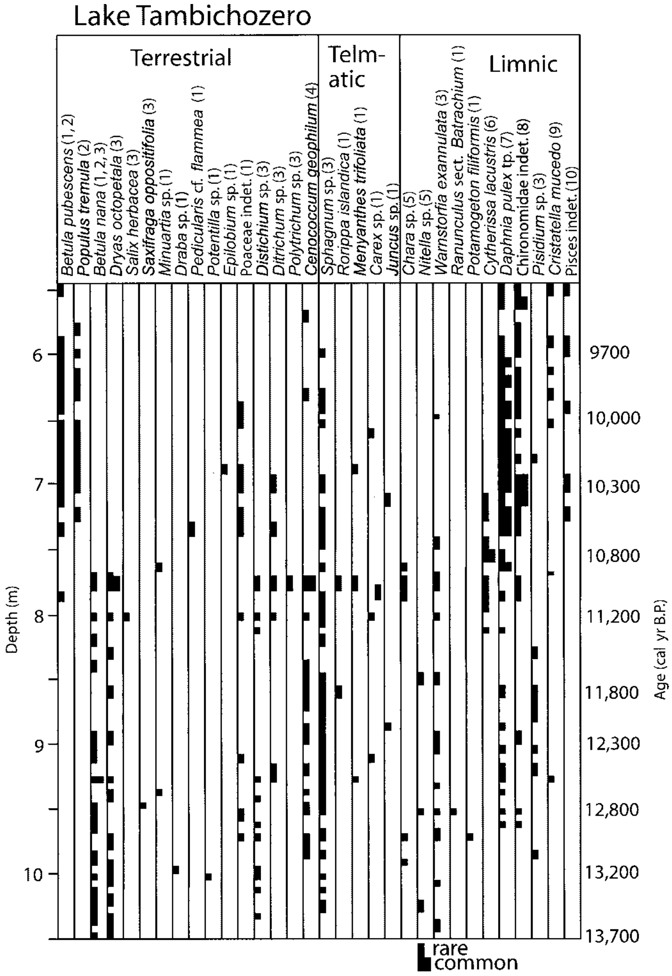


FIG. 6. Macrofossil diagram for Lake Tambichozero. 1: seeds, fruits; 2: catkin scales; 3: vegetative remains; 4: sclerotia; 5: oospores; 6: shells; 7: ephippia; 8: head capsules; 9: statoblasts; 10: bones, scales.

Alternative B assumes that the midpoints of the radiocarbon dates have highest probability and that the laminated intervals (sediment units 9–16) are correctly anchored at the midpoint of ^{14}C dates Ua-14015 and Ua-11337. However, the large error margins of these latter dates would allow several different solutions. Alternative B also includes pollen-stratigraphic correlations to the nearby site of Pichozero (B. Wohlfarth, unpublished data) (Fig. 1b) and to two sites on the Karelian Isthmus (Subetto *et al.*, 2002). The transition between pollen assemblage zones TA-1 and TA-2 is characterised by a distinct increase in herb–grass pollen percentages and a concomitant decrease of arboreal pollen values (Fig. 5). This development compares nicely with the pollen records of Lake Pichozero and Lake Pastorskoye on the Karelian Isthmus, where it has been estimated to occur about 12,650 cal yr B.P. The increase in tree pollen and the decrease in herbaceous pollen percentages at the boundary between TA-2 and TA-3 is similar to the data sets from the Karelian Isthmus, where the occurrence of Vedde Ash tephra dates the increase in tree pollen to ca. 12,000 cal yr B.P. (Wastegård *et al.*, 2000). The pollen spectra at the transition between pollen zones TA-3 and TA-4 (further decrease in herb/grass pollen, rise in tree pollen percentages) correlate well with Lake Pichozero, where an age of about 11,600 cal yr B.P. may be suggested, based on counting of annual layers (B. Wohlfarth, unpublished data). The age-depth curve for alternative B points to a hiatus of ~500 yr between the lower and upper part of the sequence. The presence of a hiatus is supported by the sharp contact between the sediments in units 5 (gyttja clay) and 6 (sand). Distinctly increased values of *Pinus* and *Picea* pollen in LPAZ TA-5 (Fig. 5) and fairly high numbers of *Cenoccocum geophilum* sclerotia in sediment unit 6 (Fig. 6) point to erosion from surrounding slopes, and the lithology of the sediments in units 6–8 (sand, silt) indicates rapid deposition. It is likely, therefore, that underlying sediments were eroded prior to or in connection with the deposition of unit 6 and that units 6–8 may represent only a short time interval.

The available ^{14}C dates for Tambichozero alone do not constrain the chronology and would argue for alternative A. However, by including the pollen stratigraphic correlations with the nearby site of Pichozero and the Karelian Isthmus, and by assuming that the laminations are annual and correctly anchored, alternative B may be proposed as a working hypothesis. Until more ^{14}C dated stratigraphies are available for the area, we base the following discussion on alternative B and conclude that sediment units 2–5 were likely deposited between ~13,300 and ~11,100 cal yr B.P. and units 9–16 between ~10,600 and ~9500 cal yr B.P.

CLIMATIC AND ENVIRONMENTAL RECONSTRUCTION

>ca. 12,650 cal yr B.P.

The coarse bottom sediments (units 1, 2, lower part of unit 3) and their low TC content (<1%) reflect high input of minerogenic sediment into the lake, likely due to the melting of remnant ice and permafrost in the area (Table 1, Figs. 2 and 7). The few limnic remains between 10.50 and 9.40 m (*Chara, Nitella, Warnstorfia exannulata, Ranunculus* sect. *Batrachium, Potamogeton filiformis, Daphnia pulex,* Chironomidae, *Pisidium*) indicate limited lake productivity (Fig. 6).

The pollen assemblages (TA-1) show a considerable amount of tree, dwarf shrub, and herb pollen percentages and redeposited pollen (Figs. 4 and 5). *Betula* and *Alnus* dominate the tree pollen, and *Artemisia*, Chenopodiaceae, Cyperaceae, and Poaceae dominate the herb pollen assemblages. Total pollen concentrations are low, although *Betula, Alnus, Artemisia*, and Chenopodiaceae have slightly elevated values. Plant macrofossil remains include *Betula nana, Dryas octopetala, Saxifraga oppositifolia, Minuartia* sp., *Potentilla* sp., Poaceae, and mosses (10.50–9.40 m) (Fig. 6). The overall low pollen concentrations and the similar shape of the percentage curve for *Pinus*, *Picea*, *Alnus*, *Betula*, and redeposited pollen suggest that most of the tree pollen should be regarded as long-distance-transported and/or reworked. The surrounding environment was likely characterized by barren ground and a mosaic of different pioneer communities in more

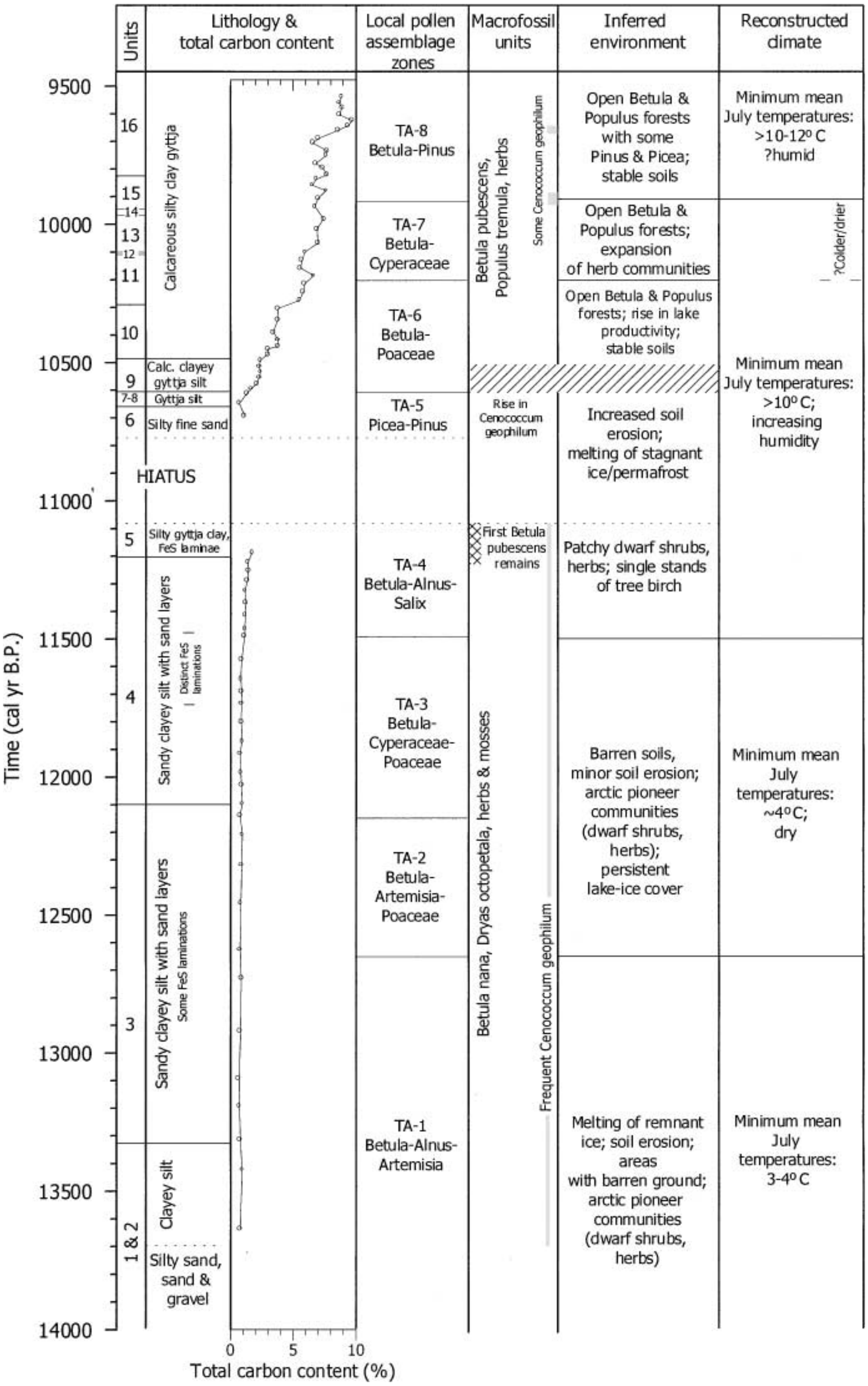


FIG. 7. Summary chart of the paleoenvironmental and paleoclimatic development reconstructed for Lake Tambichozero between 14,000 and 9500 cal yr B.P.

favorable habitats. Bare ground communities included, for example, *Dryas octopetala* and *Potentilla* sp., while *Betula nana*, Poaceae, and other herbs colonized more stable soils. The plant assemblages, together with the presence of *Cenococcum geophilum* sclerotia, show that organic soils may already have developed, but also that soil erosion was common.

Based on the combined proxy data, it is inferred that the lake basin could have formed about 14,000 cal yr B.P., likely due to melting of remnant ice, and that a mosaic of different arctic dwarf shrub and herb pioneer communities gradually colonized the surroundings. The reconstructed vegetation pattern points to arctic climatic conditions, and the presence of *Betula* *nana*, *Potamogeton filiformis*, and *Ranunculus* sect. *Batrachium* may indicate minimum mean July temperatures of ca. 3° to 4°C (Hultén and Fries, 1986) (Fig. 7).

~12,650 to ~11,500 cal yr B.P.

The sandy clayey silt with intercalated sand layers (upper part of unit 3, lower and middle part of unit 4) implies continued supply of minerogenic sediment (Table 1, Fig. 2). FeS laminations are common between ~11,700 and 11,500 cal yr B.P. and give evidence for anaerobic conditions that may have been caused by persistent lake ice cover (Fig. 7). The sparse limnic flora and fauna (9.40–8.20 m) include *Nitella* sp., mosses, *Daphnia pulex*, chironomidae, and *Pisidium* and imply, together with the low TC content, only minor lake productivity (Fig. 6).

Between 12,650 and 12,100 cal yr B.P., herb pollen types (mainly *Artemisia*, Chenopodiaceae, Poaceae) dominate the pollen assemblages (TA-2). However, from ~12,100 cal yr B.P. onward tree pollen values increase gradually (TA-3), coincident with a decrease in *Artemisia*, while Cyperaceae and Poaceae continue to dominate the herb pollen assemblages (Figs. 4 and 5). Redeposited pollen values decrease distinctly in both zones. Total pollen concentrations are low, although a minor increase can be observed in TA-3, between ~12,150 and 11,500 cal yr B.P. The scarce terrestrial and telmatic plant macrofossil remains between 9.40 and 8.20 m include *Betula nana, Dryas octopetala*, Poaceae, mosses, *Rorippa islandica, Menyanthes trifioliata, Carex* sp., and *Juncus* sp. (Fig. 6). The dwarf shrub-herb vegetation likely was patchy and confined to small areas.

The proxy records point to continued minerogenic sediment supply, which was possibly facilitated by unstable and barren surfaces in the catchment. Arctic pioneer communities likely colonized more protected habitats. Low pollen concentration, low lake productivity, and long-lasting lake ice cover imply cold climatic conditions (Fig. 7). The marked decrease in redeposited pollen percentages and concentrations, compared with the previous period, could be interpreted as evidence of decreased soil erosion and runoff, which in turn could indicate drier conditions. Inferred minimum mean July temperatures, based on the presence of *Betula nana*, were ~4°C (Hultén and Fries, 1986).

~11,500 to ca. 11,100 (?) cal yr B.P.

At 11,500 cal yr B.P., TC increases for the first time from stable values of about 0.8–0.9% to values of 1.4–1.7%. The minor increase in TC, which is mainly due to an increase in OC, coincides with a lithologic change from sandy silty clay (unit 4) to silty gyttja clay with FeS laminations (unit 5) (Figs. 2 and 7). The limnic flora and fauna between 8.20 and 7.82 m include *Chara* remains, mosses, *Cytherissa lacustris, Daphnia pulex*, and chironomidae, and are slightly more diverse than during the previous time interval (Fig. 6). This, together with the slowly increasing TC content, shows gradually increasing lake productivity.

Tree, shrub, and redeposited pollen show increasing percentages, while herb pollen values start to decrease (TA-4). However, total pollen concentrations are still low (Figs. 4 and 5) and the marked increase in redeposited pollen values points to soil erosion. Macrofossil finds of *Betula nana, Dryas octopetala, Salix herbacea*, Poaceae, and mosses confirm their presence around the lake and first remains of *Betula pubescens* (8.20–7.82 m) show that it started to colonize the surroundings (Fig. 7).

The gradual rise in lake productivity ca. 11,500 cal yr B.P. and the immigration of *Betula pubescens* suggest higher minimum mean July temperatures (>10°C) (Bos *et al.*, 2001) and gradually increasing humidity (Fig. 7). This may have subsequently led to the melting of remaining ice and/or permafrost in the catchment. Anoxic conditions were probably still common, and, given the low organic content of the sediments, could have been related to persistent lake ice cover.

11,100 (?) to ~10,600 cal yr B.P.

The sharp lower boundary of the sand in sediment unit 6 (Table 1) suggests erosion of the underlying sediments, possibly causing a hiatus between sediment units 5 and 6, and the low TC values in the massive sand and silt (units 6–8; Fig. 2) point to rapid deposition. *Pinus* and *Picea* pollen percentages increase distinctly (TA-5; Figs. 4 and 5) in these sediments. This increase cannot be observed in the pollen diagram from nearby Lake Pichozero (B. Wohlfarth, unpublished data) and indicates that the pollen spectra in TA-5 very likely are reworked. Together with the occurrence of a large number of *Cenococcum geophilum* sclerotia in sediment unit 6 (Fig. 6), it may thus be assumed that units 6–8 are composed of eroded and reworked sediment from the surrounding slopes. Possibly melting of remnant ice in the area had accelerated as a response to higher summer temperatures, leading to unstable soils and greater runoff (Fig. 7).

~10,600 to 9900 cal yr B.P.

From 10,600 cal yr B.P. onward, the sediments are partly laminated calcareous clayey gyttja silt (unit 9) and calcareous silty clayey gyttja (units 10–14, lowermost part of unit 15) (Table 1, Figs. 2 and 7). TC continuously increases, but fluctuates between 3 and 7%. The limnic fauna and flora become more diverse between 7.675 and 6.095 m, and the larger number of *Cytherissa lacustris, Daphnia pulex*, and chironomidae, and the appearance of fish remains (probably *Perca fluviatilis*) point to a distinct change in the lake environment (Fig. 6). The occurrence of laminated sediments could indicate deeper lake water, but the alternation between distinctly and diffusely laminated parts could also be explained by shifting anaerobic–aerobic bottom-water conditions due to increased decomposition of organic matter, given the increasing TC content of the sediments. Taken together, the sediments imply increasing lake productivity, more stable soil conditions in the catchment, and a change in lake status (Fig. 7).

Tree pollen values (mainly *Betula*) dominate the pollen spectra (TA-6) and the amount of redeposited pollen decreases markedly (Figs. 4 and 5). Total pollen concentrations rise for the first time at ~10,600 cal yr B.P. and *Betula* concentrations remain generally high from ~10,500 cal yr B.P. onward. The plant macrofossil record shows the appearance of frequent *Betula pubescens* and *Populus tremula* remains at ~10,500 cal yr B.P. The concomitant decline of dwarf shrubs mirrors this change nicely (Figs. 6 and 7) and indicates the nearby development of open *Betula-Populus* forests from ~10,500 cal yr B.P. onward. While shrubs may have been a minor component of the regional vegetation, herbs and grasses were still important, especially around the margin of the lake. Between ~10,200 and 9900 cal yr B.P., tree pollen percentages decline and herbs, mainly Cyperaceae, show a marked increase (TA-7). These changes are also expressed in the individual pollen concentration curves, which display somewhat lower values for *Pinus* and higher values for *Salix, Artemisia*, Chenopodiaceae, Cyperaceae, and Poaceae (Figs. 4 and 5). The distinct increase in herb pollen percentages (mainly Poaceae and Cyperaceae) implies reexpansion of these taxa in the otherwise open *Betula-Populus* forests, or the development of an extensive herb vegetation around the shore of the lake.

Overall, the proxy data indicate increasingly stable soil conditions in the catchment, the presence of open *Betula-Populus* forests, and an expansion of herb vegetation. The occurrence of *Betula pubescens* macrofossils suggests minimum mean July temperatures of >10°C (Bos *et al*., 2001) and possibly also higher humidity. There is a suggestion that the forest development was interrupted between ~10,200 and 9900 cal yr B.P. Although speculative, the slight increases in herb pollen percentages and/or concentrations may indicate decreased air temperatures and humidity (Fig. 7).

~9900 to 9500 cal yr B.P.

In the laminated calcareous silty clay gyttja (units 15–16), TC values fluctuate initially at around 6.5–7.5% and increase from 9700 cal yr B.P. onward to about 9–10%. This latter increase is mainly due to a rise in OC. SIRM and susceptibility, which until this time have been fairly stable, fluctuate slightly (Fig. 2).

At ~9900 cal yr B.P., tree pollen percentages and concentration values rise again (TA-8). Concentrations of *Betula* pollen increase more-or-less gradually and values for *Pinus* and *Picea* rise at 9900 and 9800 cal yr B.P., respectively. The rise in *Pinus* (likely *Pinus sylvestris*) and *Picea* pollen may suggest the presence of scattered individuals in the open *Betula-Populus* forest, although these were probably not growing close to the site (Fig. 7). While Cyperaceae and Poaceae still have high concentration values, dwarf shrubs and *Artemisia* decline gradually (Fig. 5). Redeposited pollen grains are still present, but show large variations between samples (Fig. 4). Plant macrofossils include frequent *Betula pubescens* and *Populus tremula* remains, whereas *Cenococcum geophilum* sclerotia appear infrequently (Fig. 6).

Given the presence of *Betula pubescens*, and possibly also *Pinus sylvestris*, inferred minimum July temperatures may have ranged from >10° to 12°C (Bos *et al*., 2001). Although the surrounding soils seem to have been rather stable, mineral magnetic parameters, redeposited pollen grains, the fluctuating CC content, and the presence of *Cenococcum geophilum* give evidence for short phases with increased soil erosion.

DISCUSSION

The reconstructions presented here compare in general terms with earlier pollen (Elina and Filimonova, 1996) and plant macrofossil records (Wohlfarth *et al*., 1999; B. Wohlfarth, unpublished data) from Russian Karelia, although the presence of scattered *Betula pubescens* forests >12,650 cal yr B.P. (Elina and Filimonova, 1996) could not be confirmed by macrofossil finds. Instead, and in accordance with investigations on sediment sequences from Pudozh (Wohlfarth *et al*., 1999), Lake Pichozero (B. Wohlfarth, unpublished data) (Fig. 1b), and the Karelian Isthmus (Subetto *et al*., 2002), the vegetation, between ~14,000 and ~11,500 cal yr B.P., was composed mainly of sparse dwarf shrubs, herbs, and grasses. Lake productivity was low and inferred minimum mean July temperatures, based on plant macrofossils, were about 3° to 4°C.

This development is in contrast to, for example, circum–North Atlantic sites, where warmer (Allerød/GI-1c-a; 13,900–12,650 cal yr B.P.) and colder temperatures (Younger Dryas/GS-1; 12,650–11,500 cal yr B.P.) led to distinct environmental changes (Walker *et al*., 1999; Björck *et al*., 1998). These changes are even seen at sites in southwestern Sweden, close to the former margin of the Scandinavian Ice Sheet (Björck *et al*., 1996), because of their proximity to the North Atlantic Ocean. However, along the eastern and southeastern margin of the ice sheet, strengthened easterlies could have blocked the spread of warm Atlantic air masses into western Russia (Yu and Harrison, 1995; Harrison *et al*., 1996), thereby leading to significantly lower temperatures in this region. In addition, permafrost and remnant ice could have kept summer temperatures locally relatively cold, due to wet soil conditions (Renssen *et al*., 2000). Only with the final disintegration of the Scandinavian Ice Sheet about 10,000–9000 cal yr B.P. did the influence of the easterlies disappear (Kutzbach *et al*., 1993; Yu and Harrison, 1995; Harrison *et al*., 1996) and warm North Atlantic air masses could reach the western part of Russia (Peterson, 1993). These Global Circulation Model experiments (Kutzbach *et al*., 1993) agree well with our data, although an influence of warmer air masses might already be seen at or shortly after ~11,500 cal yr B.P., when the immigration of *Betula pubescens* suggests a rapid rise in minimum mean summer temperatures to >10°C (Fig. 7). Higher mean summer temperatures likely led to melting of remnant ice/permafrost and increased runoff from the surrounding slopes, which in turn may have caused the hiatus in Lake Tambichozero between ~11,100 and 10,600 cal yr B.P. (Fig. 7).

The minor reexpansion of herbaceous communities between ~10,200 and ~9900 cal yr B.P., although speculative, may indicate that forest development was interrupted and that air temperatures and humidity decreased (Fig. 7). A marked cooling event at 10,300 cal yr B.P. was first recognized in North Atlantic marine sediments (Bond *et al*., 1997), but recently, Björck *et al*. (2002) showed that this event is a distinct feature in many types of archives. Although this so-called 10.3 event seems to have been the most pronounced, a number of other short cooling episodes can be recognized in tree-ring and ice-core records between 10,500 and 10,000 cal yr B.P. (Fig. 4 in Björck *et al*., 2002). However, given the local nature of the environmental record and the uncertainties in our chronology, it cannot be confirmed whether the expansion of herbaceous taxa between ~10,200 and 9900 cal yr B.P. in Tambichozero represents a real climatic event and correlates with the 10.3 event or to any of the other cooling episodes between 10,500 and 10,000 cal yr B.P.

CONCLUSIONS

Lithostratigraphy, mineral magnetic, carbon, pollen, and macrofossil analyses, and AMS ^{14}C measurements of a ~6-m-long lake-sediment sequence from Lake Tambichozero, southeastern Russian Karelia, permit the reconstruction of late-glacial and early Holocene aquatic and terrestrial environmental changes.

The lake probably formed about 14,000 cal yr B.P. due to the melting of remnant ice, and its surroundings were subsequently colonized by arctic pioneer plant communities that persisted until ~11,500 cal yr B.P. The immigration of *Betula pubescens* shortly after ~11,500 cal yr B.P. suggests rapidly increasing minimum mean summer temperatures from 3° to 4°C to >10°C. The late-glacial development in eastern Russian Karelia may have been strongly influenced by the presence of the Scandinavian Ice Sheet, which seems to have weakened at ~11,500 cal yr B.P. when warmer Atlantic air masses began to reach the region. Open forests of *Betula pubescens* and *Populus tremula* are recorded from 10,500 cal yr B.P. onward and *Pinus* and *Picea* likely appeared in the region at 9900 cal yr B.P.

The record from Tambichozero gives evidence for a change in vegetation and minimum mean summer temperatures at ~11,500 cal yr B.P., coinciding with the beginning of the Holocene. However, the chronological resolution and the presence of a hiatus prevent drawing further conclusions on the rapidity of this change.

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