Climate and environment on the Karelian Isthmus, northwestern Russia, 13 000–9000 cal. yrs BP

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Sediment sequences retrieved from Lake Medvedevskoye (60°13′N; 29°54′E) and Lake Pastorskoye (60°13′N; 30°02′E), Karelian Isthmus, northwestern Russia, were analysed for lithology, pollen and diatom stratigraphy, total organic carbon content and mineral magnetic parameters. Age control for both sequences was provided by AMS ^{14}C measurements and the Vedde Ash tephra. The reconstructed climatic and environmental development shows the deglaciation of the sites and the establishment of sparse shrub and herb/grass vegetation before 12 650 cal. yrs BP ('Allerød'; GI-1a). Steppe tundra and cold, dry conditions prevailed until about 11 000 cal. yrs BP, i.e. throughout the 'Younger Dryas' (GS-1) and the earliest Holocene. The establishment of open *Picea–Pinus–Betula* forest around the lakes at about 11 000 cal. yrs BP coincides with the first distinct change towards gradually warmer and more humid climatic conditions. Boreal forest with *Picea, Pinus, Betula, Alnus incana* and *Corylus* was present at the lower altitude site between *c.* 10 700 and 10 200 cal. yrs BP, while open *Betula–Pinus* forest continued to dominate the vegetation around the higher altitude site. After a short, possibly colder, phase around 10 200–10 000 cal. yrs BP, which is expressed by a marked reduction in vegetation cover and decreased lake productivity, climatic conditions became significantly warmer and possibly more humid. Boreal forest with *Pinus, Betula, Picea, Alnus incana, Corylus* and *Ulmus* became widespread in the region after 10 000 cal. yrs BP. The delayed environmental response of the lakes and their catchment to hemispheric warming at the Pleistocene/Holocene boundary may be explained by a sustained blocking of westerly air masses due to the presence of the Scandinavian ice sheet and associated strengthened easterlies and anticyclonic circulation and/or extensive permafrost.

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The lateglacial and Holocene climatic and environmental development in areas bordering the North Atlantic is relatively well known (Walker 1995). Little information, however, is available from regions situated farther east, such as northwestern Russia, where most of the studies have only been published in Russian (see e.g. Tarasov *et al.* 1996). The few overviews that have recently been published in English address the palaeogeographic development (Kvasov 1979), lake status changes and vegetation history (Davydova & Servant-Vildary 1996; Davydova *et al.* 1996; Elina & Filimonova 1996; Arslanov *et al.* 1999). The low sampling resolution and poor dating control, which characterize most of these data sets, make it impossible to address questions about the exact timing of, and environmental response to, the lateglacial and early Holocene warm and cold events seen in North Atlantic records.

To fill this gap, a Swedish–Russian collaboration project was initiated in 1997 with the aim of reconstructing the palaeoclimatic and palaeoenvironmental development in northwestern Russia during the last 15 000 years, based on lake sediment studies on Kola Peninsula, the Karelian Isthmus, eastern Karelia, the Valdai region and the area around Jaroslavl–Rostov. Here, we present the first results from two sites, Lake Medvedevskoye and Lake Pastorskoye on the Karelian Isthmus (Fig. 1). Lake sediments from the two sites were analysed for pollen, diatoms, organic carbon and mineral magnetic parameters, and were dated using the Vedde Ash (Wastegård *et al.* 2000b) and AMS ^{14}C measurements. Together, these data provide a picture of the changes in the lakes and surrounding vegetation during the later part of the lateglacial (Allerød or GI-1a and Younger Dryas or GS-1) and the early Holocene (Preboreal and Boreal). Our reconstruction shows that shrub and herb/grass communities became established soon after deglaciation of the sites around 13 000 cal. yrs BP and that this type of vegetation persisted until *c.* 11 000 cal. yrs BP, when distinctly warmer climatic conditions may have favoured an expansion of open *Picea–Betula–Pinus* forests, followed by boreal forest.

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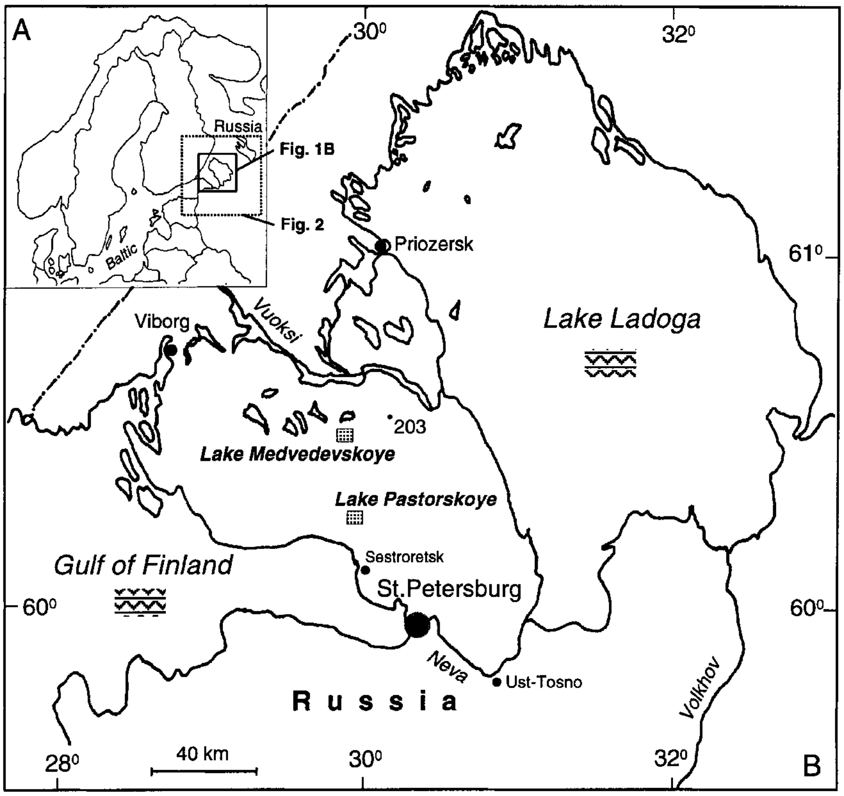

Fig. 1. Index map (A) and location of the study sites on Karelian Isthmus (B). Lake Medvedevskoye and Lake Pastorskoye are marked by dotted squares.

Geographic and geological setting

The Karelian Isthmus, which is situated between the Gulf of Finland and Lake Ladoga (Fig. 1) can be divided into three landscape units: the lowland area in the north with more than 800 lakes; the central highland, which reaches up to 203 m a.s.l.; and the Neva Lowland (15–25 m a.s.l.) in the south, which is characterized by numerous Holocene terraces. The region has a maritime climate, with mean January temperatures of −9°C, mean July temperatures of +16°C and a mean annual temperature of +3°C. Precipitation is around 600 mm yr^{-1}.

At the Last Glacial Maximum (LGM), the southeastern margin of the Scandinavian ice sheet was located in the Valdai region, southeast of the Karelian Isthmus (Fig. 2), and extended northwards towards the Barents Sea (Svendsen *et al.* 1999). The LGM is attributed to the Late Valdai stage, which is conventionally correlated to the European Late Weichselian, based on radiocarbon ages of *c.* 25 000 ^{14}C yrs BP and 22 000 ^{14}C yrs BP on interstadial sediments underlying till (Gey & Malakhovskiy 1998). Recently, the LGM was dated by Optical Stimulated Luminescence (OSL) to 17 000 yrs BP, east of the White Sea and deglaciation in this area is assumed to have started 15 000 yrs ago (Larsen *et al.* 1999). Several lateglacial ice marginal formations (Veps, Krestsy, Luga and Neva) (Faustova 1984) and intervening interstadial sediments have been identified and mapped in the area between the Valdai Hills and the Karelian Isthmus (Fig. 2), but their ages are not well established. Saarnisto & Saarinen (in press) assign ages of ~14 250 cal. yrs BP for the Luga stage, 13 300 cal. yrs BP for the Neva stage, ~12 250 cal. yrs BP for the Salpausselkä I and ~11 600 cal. yrs BP for the Salpausselkä II stages, based on a combination of varve chronological investigations and AMS ^{14}C ages from eastern Karelia.

It is generally assumed that the central part of the Isthmus became deglaciated fairly early, at a time when the active ice margin was situated south of the Gulf of Finland (Kvasov 1990) (Fig. 2). Hang's (1997) revision of Markov & Krasnov's (1930) varve-diagram correlations suggests that deglaciation of the western part of the Karelian Isthmus, below the level of the Baltic Ice Lake, took *c.* 450 varve years. During the formation of the Salpausselkä I ice marginal zone, areas below 60 m a.s.l. in the central part of the Karelian Isthmus and below 80 m a.s.l. in the northern part, were covered by the Baltic Ice Lake, whereas higher areas were probably connected with the mainland.

The study sites, Lake Medvedevskoye (LM) (60°31′N; 29°54′E) and Lake Pastorskoye (LP) (60°13′N; 30°02′E), are located on the central highland at the outer margin of the Neva marginal formation, at elevations of 102.2 m and 76.6 m a.s.l., respectively

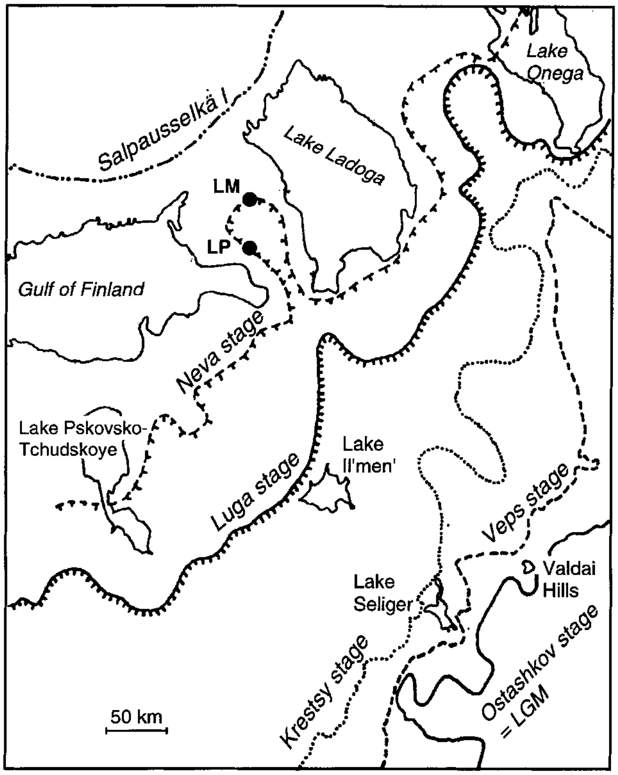

Fig. 2. The main lateglacial ice marginal positions in northwestern Russia, taken mainly from Faustova (1984). Lake Pastorskoye (LP) and Lake Medvedevskoye (LM) are located close to the Neva stage ice marginal position.

(Figs 1, 2). The lakes are shallow (<4 m water depth), open basins with surface areas of ~0.5 km^2 (LM) and 0.18 km^2 (LP). LM is situated in an area of hummocky moraine landscape, whereas LP is surrounded by low sandy hills. Groundwater input plays a significant role in the water balance of LP. Several springs were observed along the eastern sandy slope, close to the lake surface. *Pinus sylvestris, Picea abies*, dwarf shrubs, shrubs, lichens and mosses dominate the vegetation (middle taiga type) around both lakes.

Methods

The lakes were cored from ice in March 1997 (LM) and March 1998 (LP) with a strengthened Russian corer (chamber length 1 m, inside diameter 5 cm), close to the deepest part of the basins. At both lakes, two parallel sediment sequences with 0.5 m overlap were obtained. A preliminary lithostratigraphic description of the sediments was carried out in the field. The cores were wrapped in plastic, placed in half PVC tubes and transported to the Department of Quaternary Geology, Lund University, where they were stored at 4°C in a cold room.

In the laboratory, the sediments were described in detail and the overlapping cores from each lake were visually correlated using lithological marker horizons. The lower part of the sediment sequence from LM was divided into 7 lithological units (Table 1, Fig. 3) and the correlative part of the sequence from LP was divided into 4 lithological units (Table 2, Fig. 4). The core intervals 3.5–4.86 m in LM and 8.0–10.07 m in LP were sub-sampled for mineral magnetic properties, total organic carbon, pollen, diatoms, AMS ^{14}C dating, and tephra.

Mineral magnetic measurements made on contiguous sub-samples included saturation isothermal remnant magnetization (SIRM) and mineral magnetic susceptibility (χ). Remnant magnetism was measured with a Molspin 'Minispin' magnetometer using a DC field of 1T, with the results expressed in $mAm^2\,kg^{-1}$. Susceptibility measurements were made with a Digital Voltmeter Kopparbridge KLY-2 and are expressed in $\mu m^3\,kg^{-1}$. After the measurements were made, the

Table 1. Lithostratigraphic description of the sediment sequence from Lake Medvedevskoye. LB = lower boundary; s = sharp; g = gradual.

Lithological unit	Depth (m) below water surface	Sediment description
7	2.50–3.725	Dark brown detritus gyttja with a moss layer between 3.71 and 3.694 m, sLB
6	3.725–3.795	Olive brown clayey silty algae gyttja, gLB
5	3.795–3.85	Brown silt gyttja, gLB
4	3.85–3.91	Olive brown silty gyttja clay; brown lamina between 3.885 and 3.87 m, sLB
	3.91–4.20	Olive brown gyttja silt, with FeS laminae in the bottom and brown laminae between 4.00–3.993 m, 3.97–3.955 m 3 and 3.93–3.91 m, sLB
	4.20–4.215	Grey, slightly sandy gyttja silt, sLB
	4.215–4.52	Olive brown gyttja silt with moss remains, FeS laminae in the lower part, gLB
	4.52–4.607	Grey sandy silt with organic material, gLB
2	4.607–4.695	Grey, thinly laminated fine sand/silt; organic material in sand layers, gLB
	4.695–4.76	Grey sandy silt with FeS stains, sLB
	4.76–4.765	Grey coarse sand, sLB
1	4.765–4.835	Grey silty sand, erosive LB
	4.835–4.84	Beige sand, sLB
	4.84–4.86	Grey silty sand

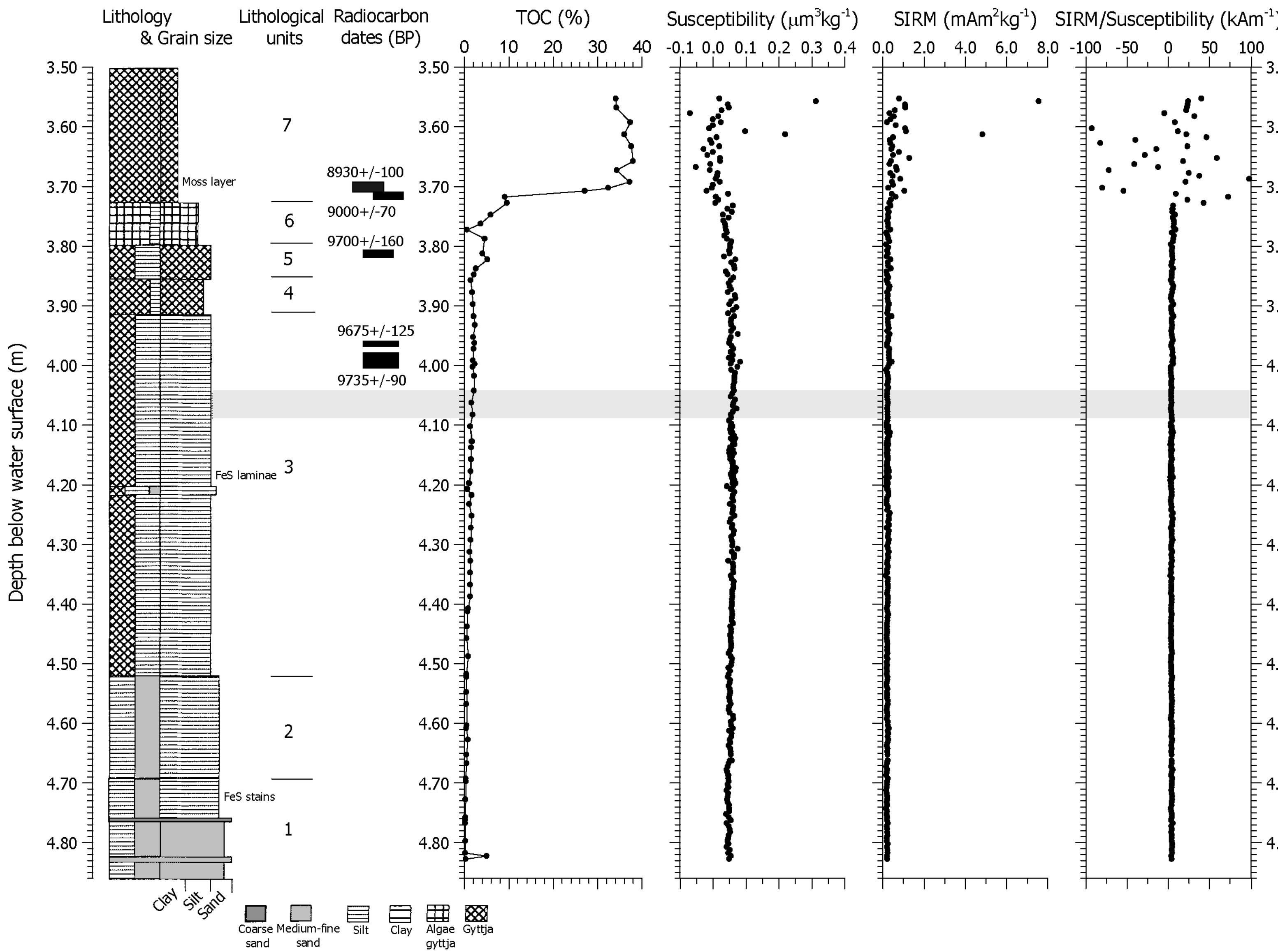

Fig. 3. Lithology, grain size, radiocarbon measurements, TOC and mineral magnetic properties of the sediment sequence from Lake Medvedevskoye. The grey horizontal bar indicates the position of the Vedde Ash. See Table 1 for a description of the lithological units and Table 6 for details on the radiocarbon dates.

Table 2. Lithostratigraphic description of the sediment sequence from Lake Pastorskoye. LB = lower boundary; s = sharp; g = gradual.

Lithological unit	Depth (m) below water surface	Sediment description
4	3.50–8.895	Dark brown gyttja with plant fragments, sLB
3	8.895–9.17	Reddish, brown, black and blue, weakly laminated silty gyttja with some moss remains (*Fontinalis antipyretica*) and vivianite; gLB (fresh sediment: dark grey)
	9.17–9.225	Black, blue, orange gyttja silt, gLB
	9.225–9.345	Yellow, blue and black laminated clayey silt with organic material, gLB
	9.345–9.44	Weakly laminated bluish-yellow, moss-rich (*Fontinalis antipyretica*) clayey silt; gLB
2	9.44–9.475	Blue, black and orange laminated clayey silt, gLB
	9.475–9.65	Weakly laminated, bluish-yellow, moss-rich (*Fontinalis antipyretica*) clayey silt, gLB
	9.65–9.795	Black, yellow, grey, laminated clayey silt with fine sand lenses and clay laminae, gLB
1	9.795–9.925	Yellowish-grey sandy silt, with clay laminae, FeS spots, gLB (fresh sediment: yellow-black laminated)
	9.925–10.07	Yellowish-grey silty sand, slightly laminated

samples were dried at 45°C to calculate mass specific SI units (Figs 3, 4).

Sub-samples for total organic carbon (TOC) were dried overnight at 105°C, crushed to powder and measured by stepwise heating in a LECO RC-412 multiphase carbon/hydrogen/moisture analyzer. The stepwise heating allows different carbon phases to be discriminated. The major carbon component in the sediments of both lakes is organic carbon. Inorganic carbon makes up <1% of the measured TOC (Figs 3, 4).

Sub-samples for pollen analysis comprised 1 cm^3 of organic-rich sediment and 2 cm^3 of minerogenic sediment. *Lycopodium* spore tablets with a known number of spores were added to each sample to enable calculation of the pollen concentration. Minerogenic sediments from the base of the sequence from LM were treated with a heavy liquid ($CdI_2 + KI$) to remove

Table 3. Description of local pollen zones at Lake Medvedevskoye. See Fig. 5 for the pollen percentage and concentration diagram.

Pollen zone	Depth	Description
ME-5	3.71–3.55 m	High percentages of *Betula* and *Pinus*, increasing values of *Alnus incana*, low percentages of *Picea abies, Betula nana*, Cyperaceae and Poaceae. *Ulmus* and *Corylus* pollen appear for the first time. In comparison with zone ME-4, *Pinus* and *Alnus incana* percentages are higher, *Betula* values are lower and *Ulmus* and *Corylus* are present with higher values. Total pollen concentrations increase markedly at the beginning of the zone and reach >1.2 million grains/cm^3.
ME-4	3.83–3.71 m	High percentages of *Betula*, fluctuating values of *Pinus*, marked decline of *Betula nana, Artemisia*, Cyperaceae and Chenopodiaceae percentages. *Pediastrum* spores peak in the lower part of the zone and decline upwards. Compared to zone ME-3, *Betula* and *Pinus* percentages are higher and herbaceous pollen are lower. Pollen concentrations increase from 33,000 grains/cm^3 at 3.81 m to 200 000 grains/cm^3 at 3.72 m, peak at 700 000 grains/cm^3 at 3.75 m, but decline between 3.76 and 3.71 m.
ME-3	4.09–3.83 m	Increasing percentages of *Betula*, Cyperaceae and *Pinus*, decreasing percentages of *Artemisia* and low values of *Picea abies* and *Alnus incana*. *Pediastrum* spores increase from *c*. 4.09 m upwards. In comparison with ME-2, *Betula* and to a lesser extent Cyperaceae percentages are higher and *Artemisia* percentages lower. Total pollen concentrations are low (15 000–32 000 grains/cm^3), although *Artemisia*, Chenopodiacea and Cyperaceae have relatively high values.
ME-2	4.415–4.09 m	High percentages of *Artemisia*, significant values of Chenopodiaceae and Cyperaceae and low values of *Pinus, Picea abies, Alnus incana, Betula* and Poaceae. In comparison with zone ME-1, *Pinus, Betula* and to some extent *Picea abies* percentages are low, whereas *Artemisia* and to a lesser extent Chenopodiaceae and Cyperaceae percentages are high. Total pollen concentrations are generally low (11 000–41 000 grains/cm^3); only *Artemisia* and Chenopodiaceae have relatively high pollen concentrations.
ME-1	4.80–4.415 m	High percentages of *Pinus sylvestris*, fairly high percentages of *Betula* and low values of *Picea abies, Betula nana, Artemisia*, Chenopodiaceae, Cyperaceae and Poaceae. *Pediastrum* spores peak in the middle part of the zone. Towards the top, *Betula* and *Pinus* percentages decline, while *Artemisia* and Chenopodiaceae percentages increase slightly. Total pollen concentrations are low (<65 000 grains/cm^3), although *Artemisia* and Chenopodiaceae concentrations increase in the upper part of the zone.

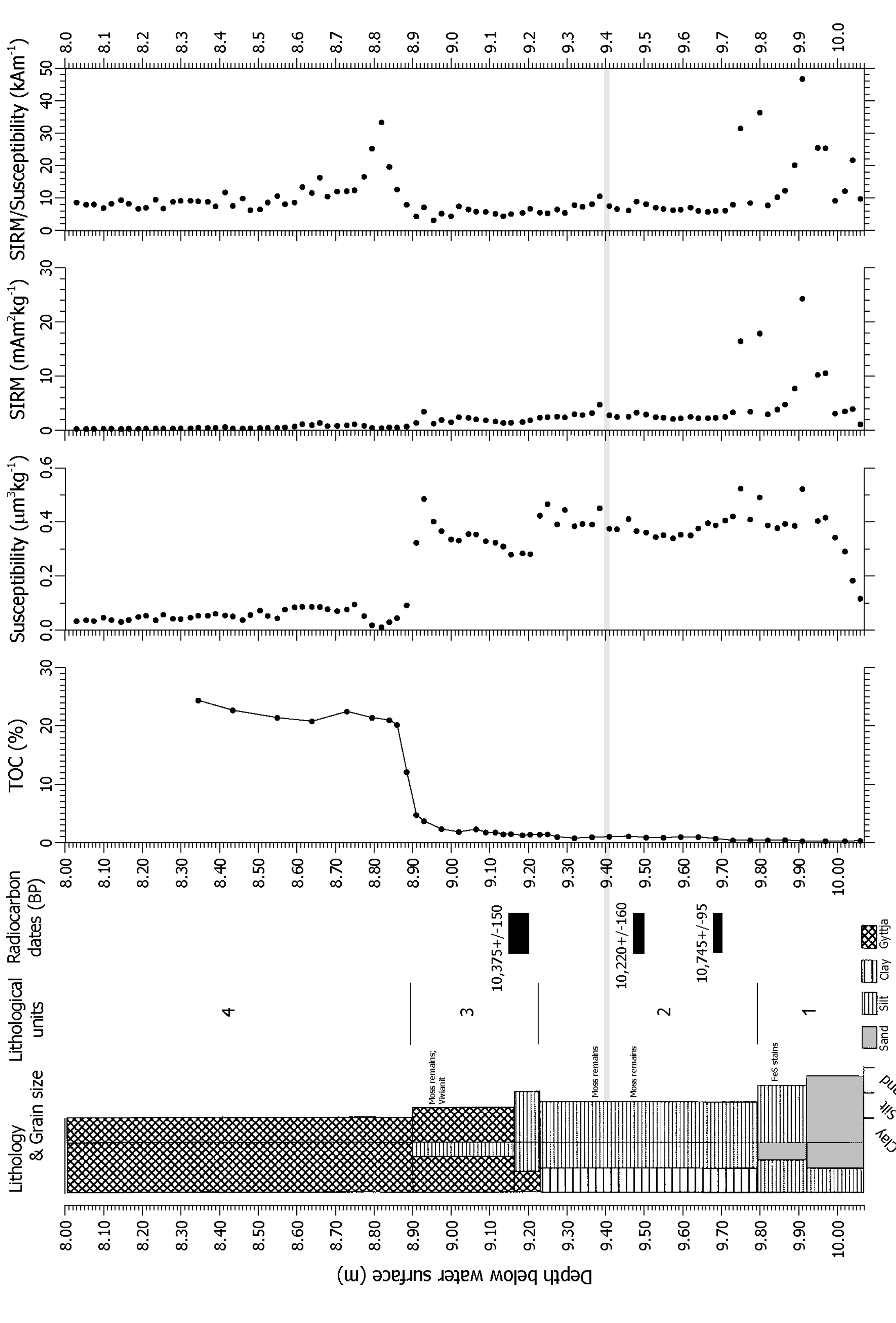

Fig. 4. Lithology, grain size, radiocarbon measurements, TOC and mineral magnetic properties for the sediment sequence from Lake Pastorskoye. The grey horizontal line indicates the position of the Vedde Ash. See Table 2 for a description of the lithological units and Table 6 for details on the radiocarbon dates.

Table 4. Description of local pollen zones at Lake Pastorskoye. See Fig. 6 for the pollen percentage and concentration diagram.

Pollen zone	Depth	Description
PA-6	8.69–8.00 m	High, but declining percentages of *Betula*, high values of *Pinus* and Cyperaceae, low, but significant values of *Alnus incana*, low values of Poaceae and *Corylus*. In comparison to zone PA-5, *Betula* has decreased, while *Pinus* and especially *Alnus* have increased. Total pollen concentrations fluctuate from 1.4 to 19 million grains/cm^3 between 8.66 and 8.22 m, but increase subsequently to 10–20 million grains/cm^3.
PA-5	8.80–8.69 m	High values of *Betula*, low values of *Picea*, *Pinus*, *Alnus incana*, Cyperaceae and Poaceae. Scattered grains of *Ulmus* and *Corylus* pollen. Total pollen concentrations reach 14 million grains/cm^3 and concentrations of *Picea*, *Betula*, *Ulmus*, *Corylus*, Cyperaceae and Poaceae are high.
PA-4	8.97–8.80 m	High percentages of *Pinus* and *Betula*, low values of *Picea,* Chenopodiaceae, Cyperaceae and Poaceae. In comparison to zone PA-3, *Pinus* and *Betula* percentages are higher, while Cyperaceae values are low. *Artemisia* is absent. Total pollen concentrations range from 800000 to >3 million grains/cm^3; *Picea*, *Pinus*, *Betula* and Chenopodiaceae values are high.
PA-3	9.40–8.97 m	High *Artemisia*, *Betula* and Cyperaceae values and low, but significant *Pinus*, Chenopodiaceae and Poaceae values. Chenopodiaceae and *Artemisia* percentages gradually decline towards the top of the zone, while *Betula* values gradually increase. In comparison with zone PA-2, *Artemisia* and Chenopodiaceae percentages are lower and *Betula* and Cyperaceae pollen values are higher. Total pollen concentrations are low, but start to increase between 9.20 and 9.14 and reach 300000 grains/cm^3 at 9.02 m.
PA-2	9.65–9.40 m	Fluctuating, but high percentages of *Artemisia* and Chenopodiaceae, significant values of *Betula*, Cyperaceae and Poaceae and low values of *Picea* and *Pinus*. Compared to zone PA-1, *Pinus* and *Picea* values are lower, while *Artemisia*, Chenopodiaceae, Cyperaceae and Poaceae percentages are higher. Total pollen concentrations are low (25000–50000 grains/cm^3), although *Artemisia* has relatively high values.
PA-1	10.07–9.65 m	Increasing pollen percentages of *Pinus sylvestris*, fairly high values of *Betula* and low, but significant percentages of *Picea abies*, *Artemisia*, Chenopodiaceae and Cyperaceae. Total pollen concentrations are 15000–40000 grains/cm^3.

minerogenic particles. All other samples were prepared according to the method described by Berglund & Ralska-Jasiewiczowa (1986), but including a cold 10% HF treatment. 400–600 pollen grains were counted for most samples, but the low pollen concentrations in the basal part of the LM sequence resulted in counts of no more than 100 pollen grains. Pollen and spore identification was carried out using pollen keys and photographs of Kuprianova & Alyoshina (1972) and Moore *et al*. (1991) and by comparison with pollen reference slides at the Department of Quaternary Geology in Lund and the Institute of Limnology in St. Petersburg. The results are plotted in diagrams constructed using the TILIA2 and TILIA GRAPH2 programs of Grimm (1991) (Figs 5, 6). The CONISS zonation of the TILIA program supports the visually defined local pollen assemblage zones. The total pollen sum was calculated as the sum of tree, shrub and herb pollen. Pollen zones are described in Tables 3 and 4.

Sub-samples for diatom analysis (1 cm^3) were taken

Table 5. Description of the diatom zones ME-1D to ME-4D distinguished in Lake Medevedskoye (A) and Lake Pastorskoye (B). See Figs 7 and 8 for the percentage diagrams.

Diatom zone	Depth	Description
A. Medvedevskoye		
ME-4D	3.725–3.00 m	Marked change towards lower species diversity (70 species) and a dominance of planktonic species. Epiphytic diatoms are present at lower values than in zone ME-3D and percentages of benthic species increase gradually upwards. Acidophilous species dominate this zone.
ME-3D	4.32–3.725 m	Distinct increase in diatom abundance and species diversity relative to zone ME-2D (up to 139 different species and varieties). High percentages of epiphytic diatoms and significant values of benthic diatoms. Planktonic diatoms are present in very low numbers, but start to increase at 3.76 m. Alkalibiontic and alkaliphilous species dominate the assemblages.
ME-2D	4.71–4.32 m	Few, mainly epiphytic species.
ME-1D	4.80–4.71 m	No diatoms.
B. Pastorskoye		
PA-4D	8.92–7.98 m	Increase in diatom concentrations. Benthic diatoms dominate the lowest two samples. Planktonic and epiphytic species increase upwards. Most of the diatoms are alkaliphilous.
PA-3D	9.57–8.92 m	Few diatoms, dominantly planktonic and benthic.
PA-2D	9.72–9.57 m	Few diatoms, dominantly planktonic and benthic.
PA-1D	10.07–9.72 m	No diatoms.

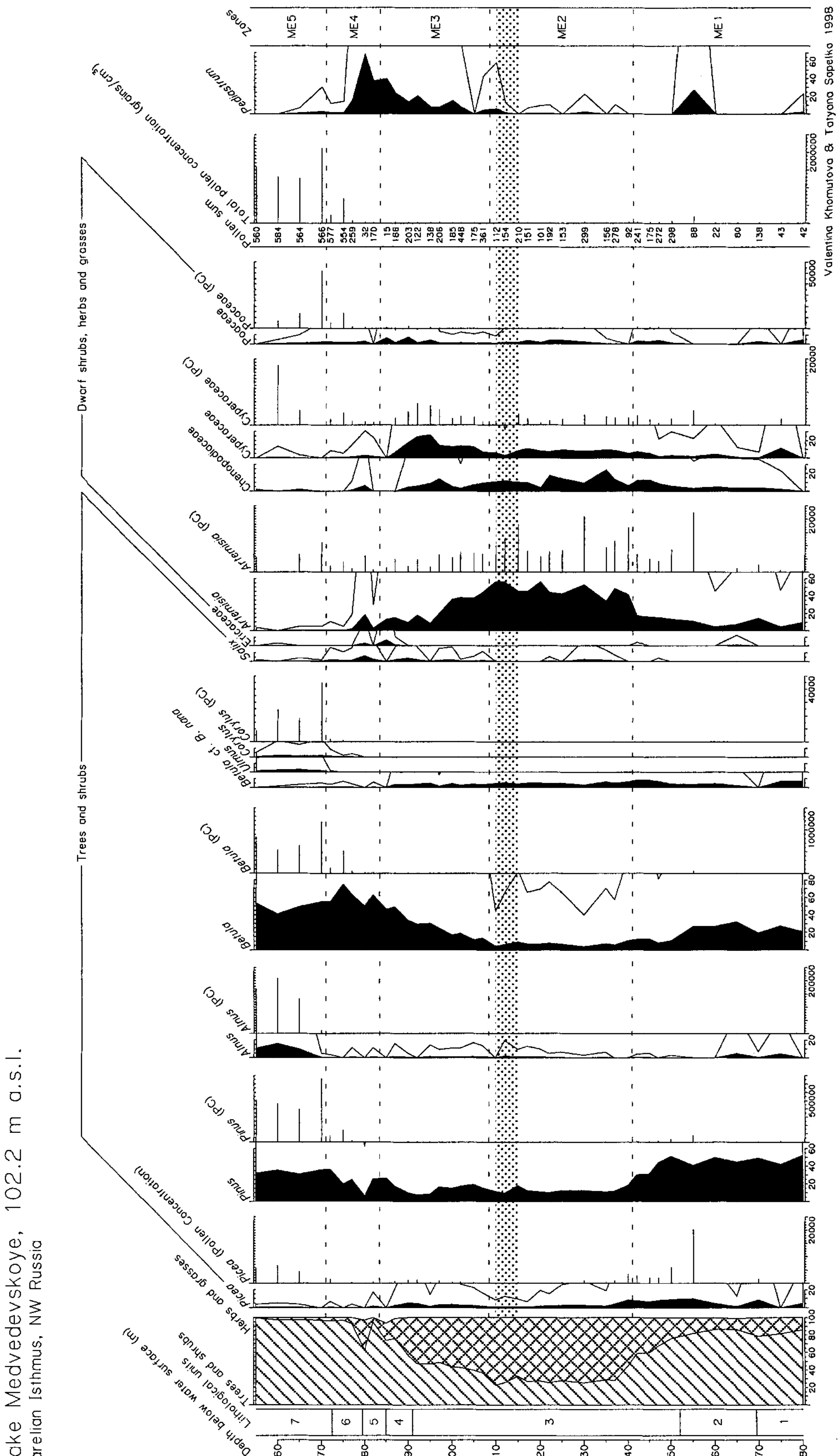

Fig. 5. Pollen percentage and concentration diagram of selected taxa for the Lake Medvedevskoye sediment sequence. The dotted bar indicates the position of the Vedde Ash.

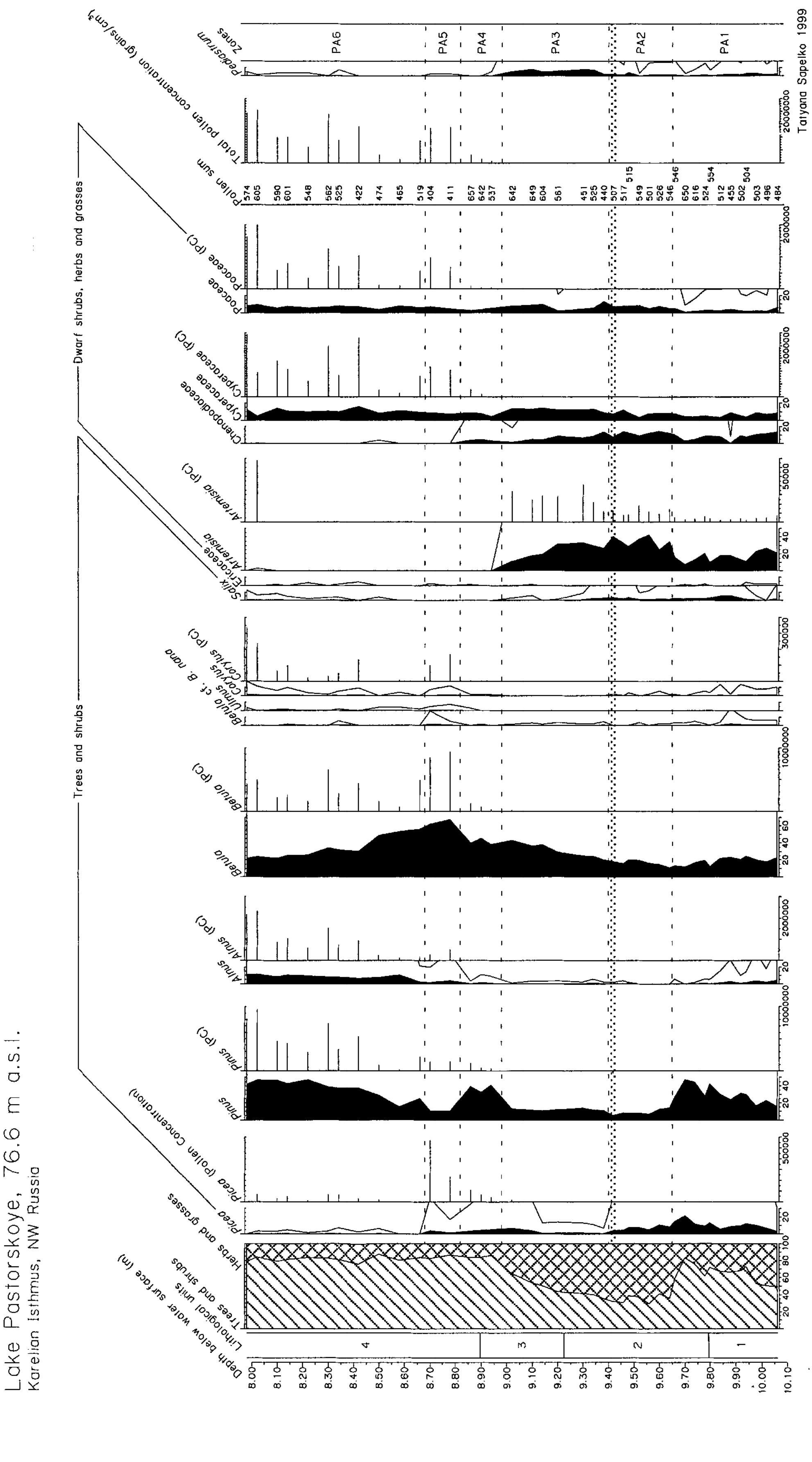

Fig. 6. Pollen percentage and concentration diagram of selected taxa for the Lake Pastorskoye sediment sequence. The dotted bar indicates the position of the Vedde Ash.

Table 6. AMS ^{14}C measurements from Lake Medvedevskoye and Lake Pastorskoye. Calibrated ages are given with 95.4% probability (2σ uncertainty). B = *Betula*, Pi = *Pinus*, Po = *Populus tremula*. The dated mosses from Lake Pastorskoye are *Fontinalis antipyretica*.

Lab. no. Ua-	Core depth (m)	^{14}C age (years BP) $\pm 1\sigma$	$\delta^{13}C$ (‰ PDB)	Dated material range (years BP)	Calibrated age
A. Lake Medvedevskoye					
13485	3.695–3.71	8930 ± 100	−29.52	mosses	10250–9650
12583	3.712–3.717	9000 ± 70	−28.65	bulk sediment	10250–9890
12627	3.807–3.813	9700 ± 160	−22.80	bulk sediment	11650–10550
12626	3.96–3.965	9675 ± 125	−24.40	bulk sediment	11300–10550
13175	3.98–4.005	9735 ± 90	−22.90	bulk sediment	11350–10700
B. Lake Pastorskoye					
14012	4.48–4.50	480 ± 70	−28.10	bark indet.	570–420
14011	5.48–5.50	2055 ± 65	−29.00	B, Pi	2160–1870
14010	6.48–6.50	3175 ± 70	−26.46	B, Pi	3570–3240
14009	7.48–7.52	5065 ± 70	−28.11	B, Pi, Po	5940–5650
14804	9.15–9.20	10375 ± 150	−29.1	mosses	12950–11550
13486	9.475–9.495	10220 ± 160	−33.53	mosses	12650–11250
14803	9.68–9.70	10745 ± 95	−33.5	mosses	13150–12600

at 5-cm intervals and prepared according to the method of Davydova (1985). Air-dried sediment was treated with H_2O_2 at 60°C for 8–12 h, washed in distilled water and centrifuged with a heavy liquid ($CdI_2 + KI$) with a specific gravity of 2.6 g. The liquid containing the diatoms was separated and centrifuged twice with distilled water; 0.02–0.04 ml of the decanted sample was placed on a glass slide, allowed to dry and mounted with Hyrax. The diatom taxonomy used here follows that of Hustedt (1930), Krammer & Lange-Bertalot (1986–1991) and Simonsen (1987). Diatom percentage diagrams were constructed using the TILIA2 and TILIA GRAPH2 programs (Grimm 1991) (Figs 7, 8). Diatom zones are described in Table 5. Past changes in lake pH were reconstructed using the AL:PE diatom-pH model (Cameron *et al.* 1999). However, the diatom taxa from the sampled lakes have few modern analogues in the AL:PE training set, which decreases the reliability of the pH reconstructions.

Sub-samples for tephra analysis consisted of contiguous 5-cm slices from LM and 1-cm samples from LP. The samples were ashed at 550°C for 4 h, treated in 10% HCl for 8–12 h and then sieved using 24-µm and 80-µm screens. The 24–80-µm fraction was chosen for further extraction of rhyolitic tephra following the method of Turney (1998). Once tephra was found in a sample, an equivalent unashed master sample was processed to recover glass for microprobe analysis. Treatment of high temperatures is known to alter the geochemical signature (Dugmore *et al.* 1995). The lithostratigraphic position of the tephra shards is shown in Figs 3, 5 and 7 for LM and in Figs 4, 6 and 8 for LP. Bulk sediment, terrestrial plant macrofossils and aquatic mosses were selected for AMS ^{14}C age determination (Table 6). Plant macrofossils were extracted from enclosing sediment by wet sieving. All samples were dried at 70°C before they were submitted to the Uppsala radiocarbon laboratory, where they were processed according to standard AMS techniques.

Chronology and age model

Colourless tephra shards were found in LM sediments at a depth of 4.10–4.15 m (unit 3) and in LP sediments at a depth of 9.40–9.41 m (unit 2) (Figs 3, 4). Microprobe analysis confirmed that these shards belong to the rhyolitic part of the Vedde Ash (Wastegård *et al.* 2000b), which has been dated to 10 400–10 300 ^{14}C yrs BP (Birks *et al.* 1996; Gulliksen *et al.* 1998; Wastegård *et al.* 2000a) in lacustrine sediments and to *c.* 12 000 GRIP yrs BP in the GRIP ice core from central Greenland (Grönvold *et al.* 1995).

Five AMS ^{14}C measurements were obtained from bulk sediments and aquatic mosses from LM (Table 6). The ages range from 9735 ± 90 ^{14}C yrs BP in the upper part of unit 3 (3.98–4.005 m) to 8930 ± 100 ^{14}C yrs BP at the base of unit 7 (3.695–3.71 m) (Fig. 3). The seven AMS ^{14}C dates from LP were more or less evenly spaced along the whole sediment sequence and comprised terrestrial plant macrofossils and aquatic mosses. The ages range from 10 745 ± 95 ^{14}C yrs BP in unit 2 at 9.68–9.70 m to 480 ± 70 ^{14}C yrs BP in unit 4 at 4.48–4.50 m to (Fig. 4). All ^{14}C ages were calibrated using the OxCal v3.5 calibration program (Bronk Ramsey 2000), which is based on the data used by Stuiver *et al.* (1998) (Table 6).

Ua-13485 (8930 ± 100 ^{14}C yrs BP) and Ua-12583 (9000 ± 70 ^{14}C yrs BP) slightly predate the increase in *Alnus incana* pollen values and concentrations at *c.* 3.65 m at LM (beginning of pollen zone ME-5) (Fig. 5, Table 6). These dates correspond closely to dates of *c.* 9000 ^{14}C yrs BP on the increase in *Alnus incana* pollen percentages at other sites on the Karelian Isthmus (Arslanov *et al.* 1999) and in southernmost Finland (Bondestam *et al.* 1994). Because the increase was probably synchronous within the study area, the ages obtained at LM can also be used to date the rise of *Alnus incana* pollen concentration values at *c.* 8.45 m at LP (PA-6) (Figs 6, 9a).

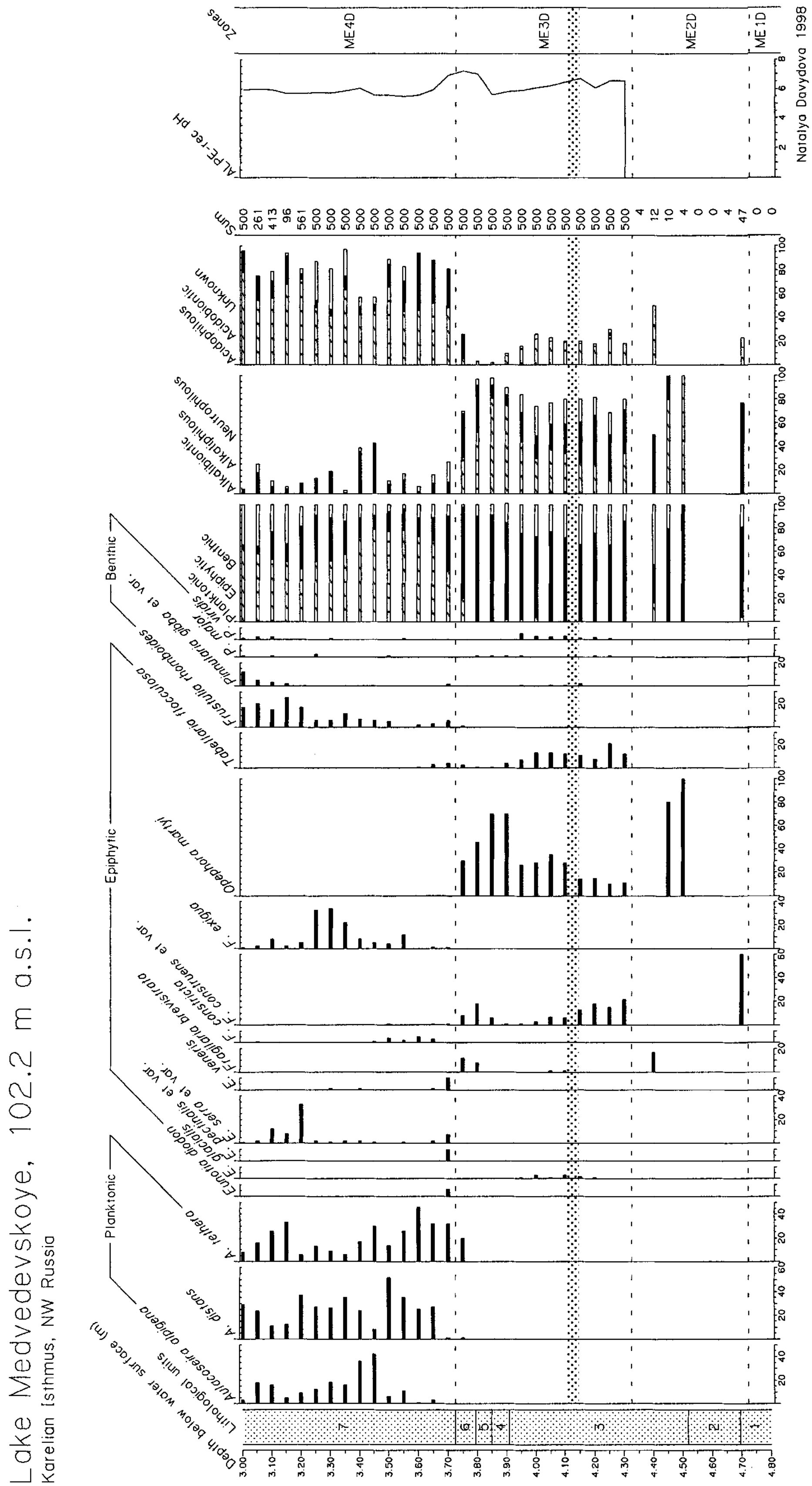

Fig. 7. Diatom percentage diagram and pH reconstruction for Lake Medvedevskoye. The dotted bar indicates the position of the Vedde Ash.

Ua-14803 (10 745 ± 95 ^{14}C yrs BP) dates the increase in *Artemisia* and the concurrent decrease in arboreal pollen percentages at the transition of pollen zones PA-1 and PA-2 at LP. Since these changes are also likely synchronous within the Karelian Isthmus, the age can be used to date the ME-1/ME-2 pollen zone transition at LM (Figs 5, 9). Furthermore, it can be assumed that the increase in *Artemisia* pollen values was not only synchronous throughout the Karelian Isthmus, but that it coincided with the beginning of the GS-1 cold period (~12 650 ice core yrs BP) in the GRIP ice core and in numerous marine and terrestrial records from around the North Atlantic region (Björck *et al.* 1998).

Construction of precise age-depth curves for the two study sites, however, is limited by the scarcity of reliable ^{14}C dates and the large errors of the calibrated ages. The age-depth curves shown in Fig. 9A and B, therefore, have been built with a number of assumptions: (1) The sedimentation rate in LP was fairly constant throughout the middle and later part of the Holocene. (2) The increase in *Alnus incana* pollen percentages and concentration values occurred more or less synchronously at LM (3.65 m) and LP (8.42 m) (Figs 5, 6) at about 10 000 cal. yrs BP. (3) The Vedde Ash at a depth of 9.40–9.41 m in LP (Fig. 4) and 4.10–4.15 m in LM (Fig. 3) was deposited *c.* 12 000 calendar/ice core yrs BP. (4) The sedimentation rate during the deposition of unit 2 at LP (weakly laminated clayey silt) was more or less constant at about 0.037 cm/yr. This rate was calculated based on the position of the Vedde Ash and by assuming that sediment at 9.65 m in LP is 12 650 cal. yrs BP old (Ua-14803). (5) The increase in *Artemisia* pollen values at 9.65 m in LP and at 4.41 m in LM was synchronous, coincided with the beginning of the GS-1 cold period and occurred *c.* 12 650 calendar/ice core yrs BP. (6) AMS ages on samples Ua-13175 and Ua-12626 from LM are slightly too young (Fig. 9B).

Environmental and climatic reconstruction

Based on the age-depth curves for LM and LP (Fig. 9A, B), tentative ages (cal. yrs BP) were assigned to the lithostratigraphic units and to the pollen and diatom zones (Fig. 10). Three major phases are recognized in the environmental and climatic development of the region: >12 650 cal. yrs BP, 12 650–11 000 cal. yrs BP and <11 000 cal. yrs BP.

>12 650 cal. yrs BP

Sediments deposited between *c.* 13 000 and 12 650 cal. yrs BP comprise partly laminated sands and silts with FeS-rich laminae and/or stains and TOC values of <1% (unit 1 and lower part of unit 2 in LP; units 1–2 and lower part of unit 3 in LM) (Figs 3, 4, 10). Diatoms are absent in most of these sediments (diatom zones PA-1D and ME-1D), but appear sporadically and in low numbers in zones PA-2D and ME-2D (Figs 7, 8). These characteristics indicate rapid in-wash of minerogenic sediment, reduced conditions and a turbid water column. We infer an environment affected by melting of glacier ice, with barren, unstable soils in the catchment. Anoxic conditions in the lakes could have been caused by rapid sedimentation and burial or could be related to long ice cover.

Pinus, Betula and to some extent *Picea* herbs and grasses display fairly high pollen percentages (ME-1, PA-1) and concentration values. *Artemisia* pollen concentrations are slightly elevated at both sites, whereas increased concentrations of *Pinus, Picea* and Cyperaceae are apparent only in the upper part of pollen zone ME-1 at LM (Fig. 5). It is, therefore, most likely that the higher concentration values of these latter taxa in the minerogenic sediments of unit 2 are due to redeposition of older pollen and do not indicate the presence of the taxa close to the site. The tree pollen may be derived both from older sediment and by long transport by winds from areas to the south, southwest and southeast, where forests were already established. The upland vegetation probably only consisted of very sparse shrub and herb/grass communities ('arctic tundra') on barren and unstable soils (Fig. 10).

Taken together, the proxy data indicate melting of stagnant glacier ice in the catchment, which could have led to the formation of the lake basins. Ice probably covered the lakes for much of the year, and the lakes were surrounded by barren, unstable soils with sparse shrub, herb and grass vegetation (Fig. 10). Overall, cold climatic and environmental conditions must have prevailed.

12 650–11 000 cal. yrs BP

Laminated, moss-rich clayey silt (middle and upper part of unit 2) and laminated silty gyttja (lower part of unit 3), both with FeS laminae and stains, were deposited in LP during this period. A slow, but gradual increase in TOC to values of 2% can be observed from *c.* 11 600 cal. yrs BP onwards, coincident with the lithological change from unit 2 to unit 3 (Figs 4, 10). The scarcity of diatoms in the sediments (diatom zone PA-3D) (Fig. 8) may be related to high turbidity of the water column or to dissolution due to anaerobic conditions. Both factors are suggested by the high minerogenic content of the sediments and common FeS laminae and stains. Anaerobic conditions were likely due to long winter ice cover. At LM, deposition of gyttja silt with FeS stains was followed at 11 200 cal. yrs BP by deposition of silty gyttja clay (unit 4); both units have TOC values of *c.* 2% (Figs 3, 10). *Pediastrum* spores increase from *c.* 12 000 cal. yrs BP onwards. The number of diatoms increases dramatically at *c.* 12 400 cal. yrs BP (diatom zone ME-3D), and the dominance of epiphytic com-

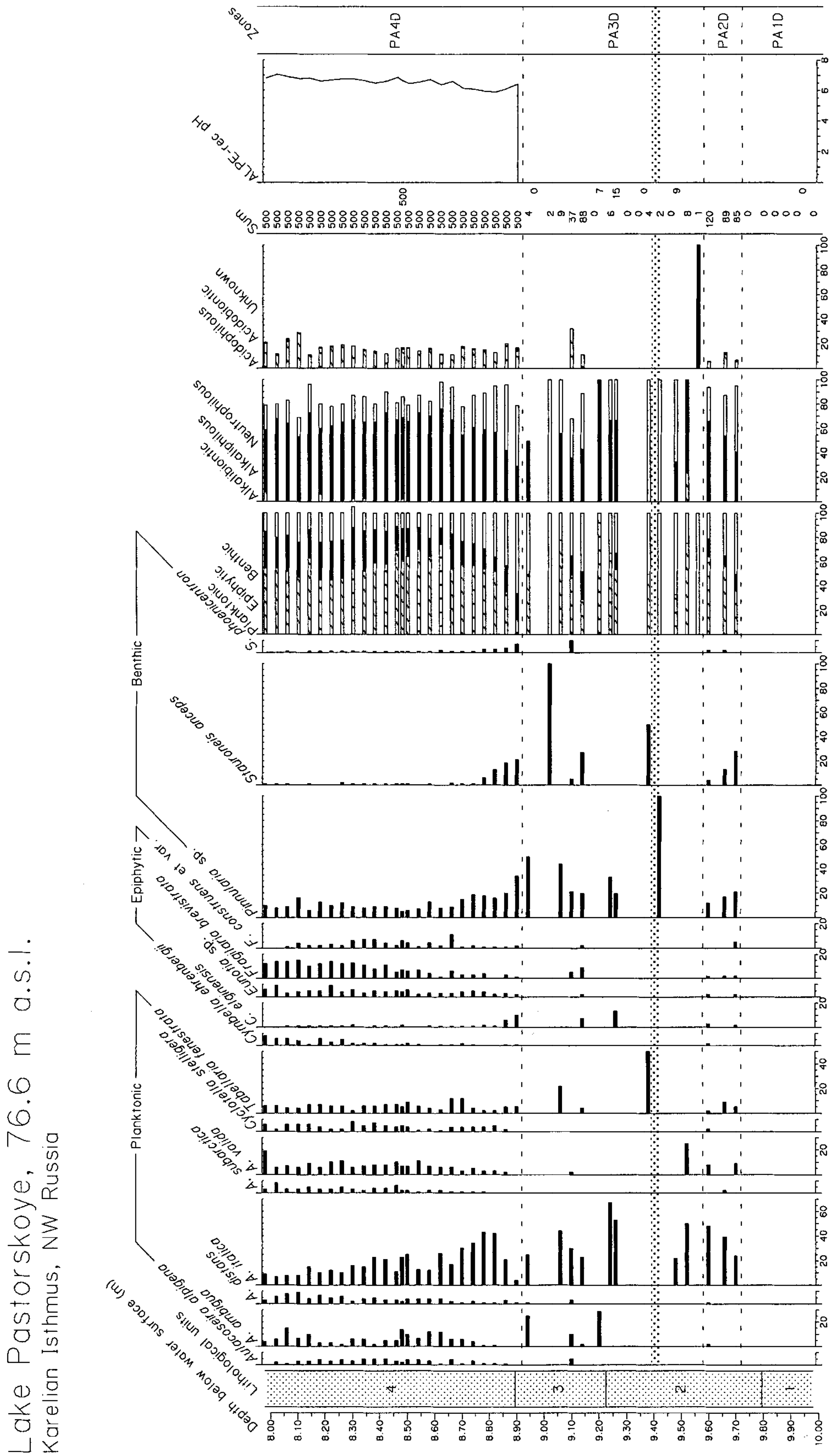

Fig. 8. Diatom percentage diagram and pH reconstruction for Lake Pastorskoye. The dotted bar indicates the position of the Vedde Ash.

munities indicates a shallow lake (Fig. 7). Inferred lake water pH is around 6–6.5 indicating slightly acid waters.

The pollen spectra at both sites have high percentages of *Artemisia*, Chenopodiaceae and Cyperaceae pollen. *Betula* pollen percentages increase from *c.* 12 000 cal. yrs BP onwards (PA-2, PA-3; ME-2, ME-3). However, total pollen concentrations are low, and only *Artemisia* and Cyperaceae display higher concentrations (Figs 5, 6). The increasing *Betula* pollen percentages are thus attributed to long transport reflecting vegetation changes in areas to the south. *Artemisia* and Cyperaceae were possibly common near the study sites, suggesting a cold and dry environment.

The combined proxy data show a continued supply of minerogenic sediment into the lakes and also provide evidence for anoxic conditions, likely caused by long-lasting lake ice cover. The dramatic rise in diatom percentages at 12 400 cal. yrs BP and the increase in *Pediastrum* spores at 12 000 cal. yrs BP indicate the beginning of organic production in LM. This could be interpreted as a response to the increased insolation at that time or to low competition by other aquatic plants. At LP, organic production began *c.* 11 600 cal. yrs BP, at least several hundred years later than at LM. The upland vegetation probably consisted mainly of shrub–herb–grass communities ('steppe tundra') and barren soils may still have been widespread. The inferred climate was cold and dry (Fig. 10).

<11 000 cal. yrs BP

At LP, laminated silty gyttja with FeS stains (unit 3) is at 10 800 cal. yrs BP followed by gyttja (unit 4) with a sharp lower boundary. TOC increases rapidly from 2% at 11 100 cal. yrs to 23% at 10 300 cal. yrs BP (Fig. 4). Around 10 200–10 000 cal. yrs BP, TOC values drop briefly to 20%, but increase thereafter to 25%. Initially, diatoms are still sparse (uppermost part of diatom zone PA-3D), but at *c.* 10 800 cal. yrs BP, benthic species increase in numbers (diatom zone PA-4D). From 10 700 cal. yrs BP onwards, planktonic and epiphytic species dominate, indicating the development of a deeper lake with a lake water pH of 6–6.5. Reconstructed pH for PA-4D in LP (unit 4) shows a gradual increase from *c.* 6.5–6.6 to 7.0–7.1, which may be an indication of progressive eutrophication of the lake during the Holocene (Fig. 8).

At LM, the silty gyttja (unit 5) grades at 10 600 cal. yrs BP into an algae gyttja (unit 6), which is replaced by a gyttja at 10 200 cal. yrs BP (unit 7). TOC increases rapidly to 6% between 10 900 and 10 600 cal. yrs BP and to 10–38% *c.* 10 200 cal. yrs BP (Fig. 3). The rise is interrupted at about 10 400 cal. yrs BP, when TOC values drop to $<1\%$. The diatom assemblages are initially characterized by shallow water species indicating a lake water pH of $\sim$7 (diatom zone ME-3D), but at *c.* 10 300 cal. yrs BP, planktonic species start to appear (Fig. 7). After 10 200 cal. yrs BP, the assemblages are dominated by acidophilous, planktonic species (diatom zone ME-4D), indicating the gradual development of a deeper lake with an inferred pH of 5.5–6. *Pediastrum* reaches a peak at around 10 600 cal. yrs BP.

The marked rise in TOC values at *c.* 11 100 cal. yrs BP in LP and 10 900 cal. yrs BP in LM reflects a rapid increase in organic production in the lakes and a concomitant decrease in inwash of minerogenic sediment. These changes result from stabilization and maturation of soils in the catchments (Fig. 10). The absence of FeS stains in the sediments indicates aerobic conditions. The decrease in TOC values between $\sim$10 400 and 10 000 cal. yrs BP could be due to an increased supply of minerogenic sediment into the lake, due for example to increased snow-melt or erosion, or it may be evidence of a short-term reduction of organic production in the lakes. The sediment composition (algae gyttja) and the mineral magnetic parameters, however, give no indication of an increase in minerogenic input.

Total pollen concentrations increase at both lakes at around 11 000 cal. yrs BP (PA-4, ME-4) (Figs 5, 6). At LP *Picea, Pinus, Betula* (PA-4), *Corylus, Alnus incana,* Cyperaceae and Poaceae (PA-5) achieve high percentages and concentrations between 10 700 and 10 200 cal. yrs BP. The dramatic decrease in *Artemisia* percentage and concentration values at 11 000 cal. yrs BP indicates that it was no longer an important component of the vegetation (Fig. 6). The rapid rise in *Picea, Alnus* and *Corylus* pollen percentage and concentration values in zones PA-4 and PA-5 could be taken as evidence for erosion and re-deposition of older sediments, since these assemblages have no counterparts at LM. However, neither the sediment composition nor the magnetic parameters support erosion and re-deposition or a hiatus during this period. Therefore, the pollen spectra are tentatively interpreted as reflecting a change from shrub–herb–grass communities to open *Picea–Pinus–Betula* forests at about 11 000 cal. yrs BP and the successive development of boreal forests at 10 700 cal. yrs BP (Fig. 10). The drop in pollen concentrations at *c.* 10 200–10 000 cal. yrs BP is evidence of a short, but significant reduction in the vegetation cover that, at *c.* 10 000 cal. yrs BP, was followed by a renewed spread of boreal forest. At LM, only *Pinus* and *Betula* show increasing pollen concentration values after 11 000 cal. yrs BP, while *Artemisia* has still fairly high pollen concentrations (ME-4). Total pollen concentrations drop briefly around 10 350–10 300 cal. yrs BP, implying a reduction in vegetation cover (Fig. 10). The reduction in vegetation cover at LM correlates to a similar event at LP around 10 200–10 000 cal. yrs BP. At about 10 200 cal. yrs BP, however, *Pinus, Betula, Picea, Alnus incana* and *Corylus* have high concentration values and seem to have become established around the lake (ME-5) (Fig. 5). The pollen spectra for LM indicate a replacement of shrub–herb–grass vegetation by open

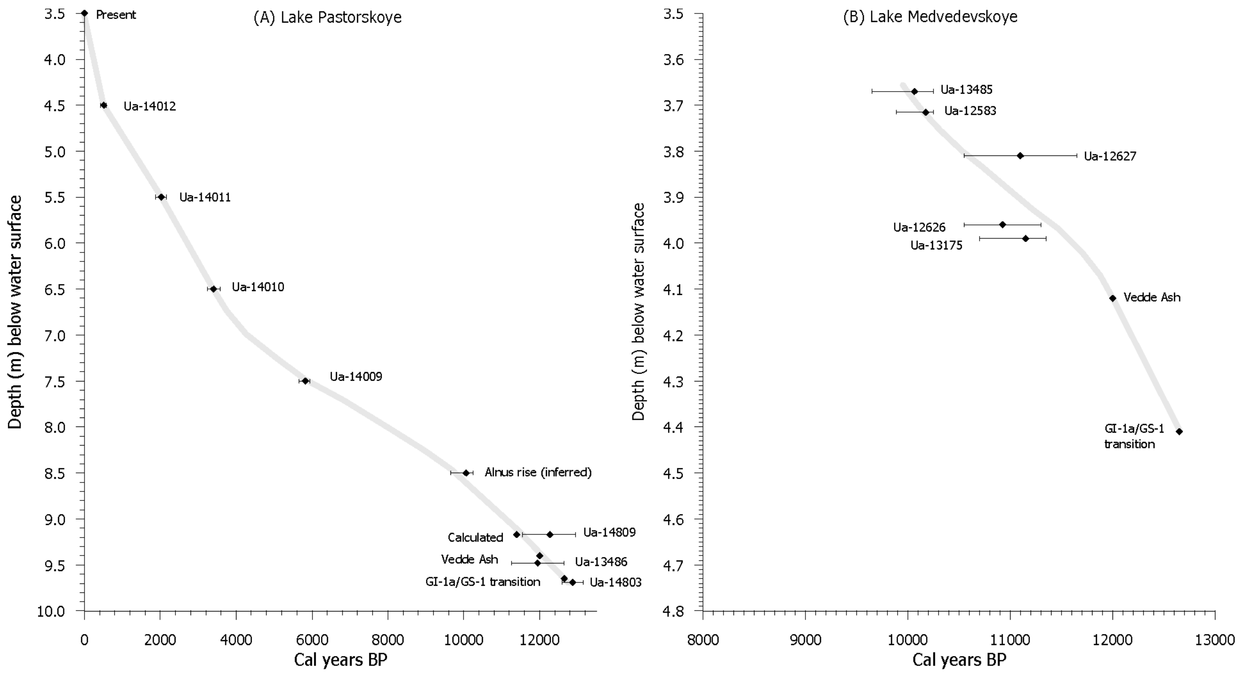

Fig. 9. Age-depth models for (A) Lake Pastorskoye and (B) Lake Medvedevskoye. Radiocarbon dates are displayed with 1σ uncertainties. See Table 3 for details on radiocarbon dates.

Pinus–Betula forests at *c.* 10 900 cal. yrs BP, which is more or less synchronous with the similar vegetation change seen at LP. *Picea* does not seem to have been an important element of the vegetation around LM.

The combined proxy data clearly indicate marked environmental changes at the two study sites during this interval. The increase in the lakes' organic production at *c.* 11 000 cal. yrs BP and the establishment of open *Picea–Pinus–Betula* forests in the catchments show that climate warmed and more stable soils developed (Fig. 10). The slight acidification of the lakes may be explained by an increase in humic substances due to a more extensive vegetation cover, and corresponds to similar changes in lakes in southern Finland at about the same time (Bondestam *et al.* 1994). The appearance of *Betula* and the change towards deeper lake waters may reflect increasing humidity. These favourable climatic conditions were briefly interrupted around 10400–10000 cal. yrs BP, by a return to colder conditions inferred from a decrease in the lakes' organic production and a marked reduction in vegetation cover (Fig. 10).

Discussion and regional comparisons

The two studied lake basins formed before 12 650 cal. yrs BP, possibly due to melting of stagnant glacier ice. Although the chronology of this early part of the record is too uncertain to attribute an exact age to the beginning of minerogenic sedimentation in the basins, it is likely that the sediments accumulated fairly rapidly. The low pollen concentrations and the sediment properties imply sparse shrub, herb and grass vegetation on barren and unstable soils, and cold climatic conditions (Fig. 10). This interval may correspond to the later part of the South Scandinavian Allerød pollen zone and to the GI-1c interval as defined in the GRIP ice core record (Björck *et al.* 1998; Walker *et al.* 1999).

Shrub, herb and grass communities ('steppe-tundra') and cold and dry climatic conditions dominated in the area until about 11 000 cal. yrs BP (Fig. 10). The inferred vegetation for the period 12 650–11 500 cal. yrs BP agrees well with that suggested by earlier researchers working on the Karelian Isthmus (Arslanov *et al.* 1999) and in Russian Karelia areas (Elina & Filimonova 1996). These results imply that steppe-tundra vegetation was widespread in the region. The presence of sparse *Betula–Pinus* forest shortly after 11 500 cal. yrs BP on the Karelian Isthmus (Arslanov *et al.* 1999) is not supported by this study. The interval 12 650–11 500 cal. yrs BP corresponds to the South Scandinavian Younger Dryas pollen zone or to the GS-1 interval defined in the GRIP ice core (Björck *et al.* 1998; Walker *et al.* 1999). The rapid environmental response to warming at the Pleistocene/Holocene boundary, which is evident in many North Atlantic records at *c.* 11 500 cal. yrs BP (e.g. Björck *et al.* 1996), is not apparent in our two data sets from the Karelian Isthmus. Rather, shrub, herb and grass vegetation seems to have dominated the landscape

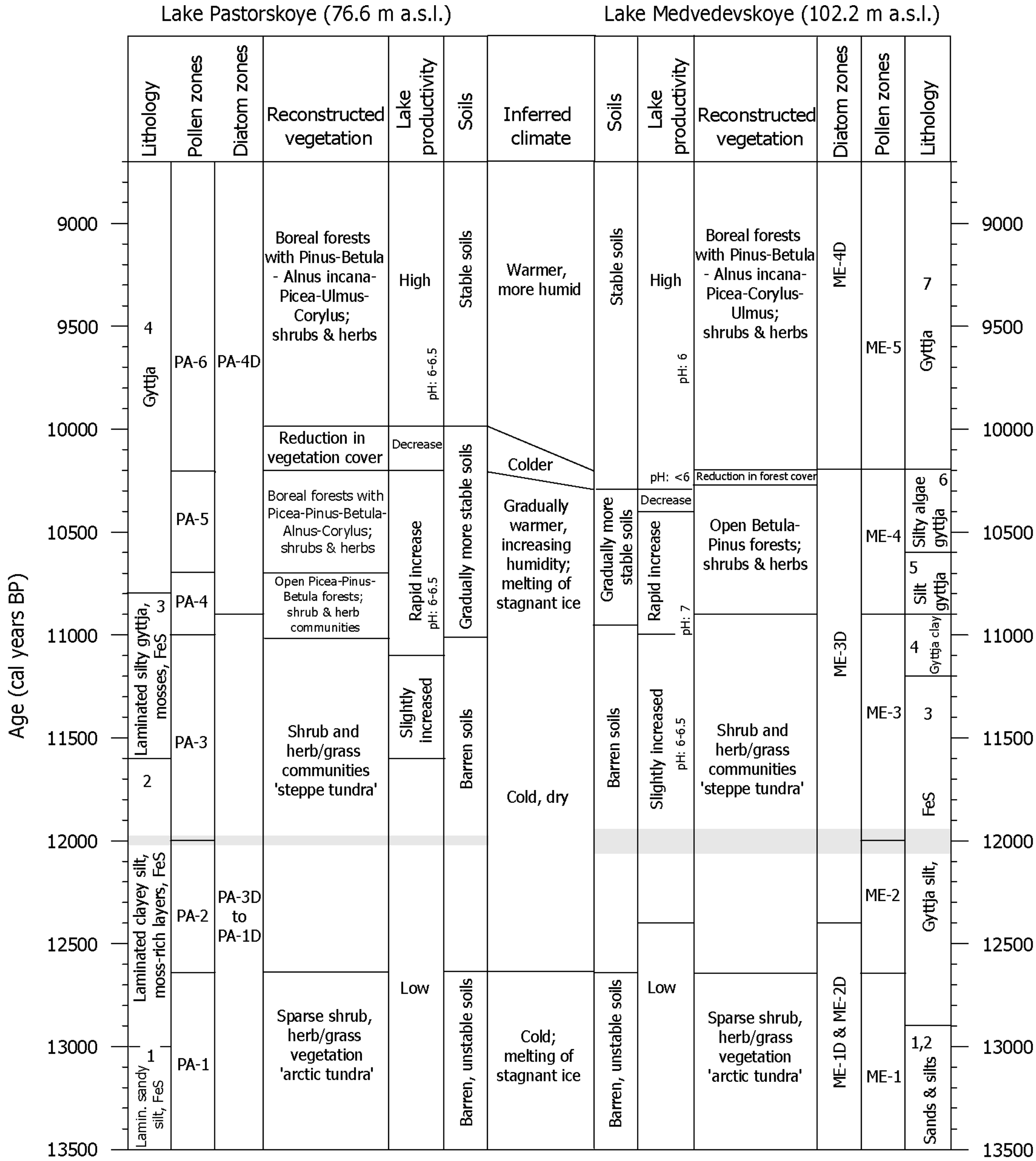

Fig. 10. Summary of lateglacial and early Holocene climatic and environmental development on the Karelian Isthmus, based on sediment properties, pollen, diatoms, and the age models. The grey horizontal bar indicates the position of the Vedde Ash.

until about 11 000 cal. yrs BP, corresponding approximately to the middle part of the Scandinavian Preboreal pollen zone. Although organic production increased briefly around 11 600 cal. yrs BP at one of the study sites, the climate remained cold and dry (Fig. 10).

Major climatic and vegetation changes on the Karelian Isthmus were probably delayed until 11 000 cal. yrs BP, when open forests gradually became established (Fig. 10). Open *Picea–Pinus–Betula* forest, together with shrub, herb and grass communities, seem to have dominated the lower elevation site, until about 10 700 cal. yrs BP, when they were replaced by closed boreal forest. At the higher elevation site, open *Betula–Pinus* forest became established about 10 900 cal. yrs BP and was not replaced by boreal forest until 10 200 cal. yrs BP. The immigration of trees into the area coincides with a rapid rise in the lakes' organic production, both of which point to distinctly warmer climatic conditions, melting of remnant ice in the area and gradual stabilization of the soils in the catchments. The presence of *Betula* may indicate increased humidity. A similar marked change in climate and vegetation has been inferred from southernmost Finland, where alpine and *Betula nana*-dominated, arctic-subarctic vegetation was replaced by boreal–temperate *Populus–Pinus–Betula* forest at *c.* 10 700–10 600 cal. yrs BP (Hyvärinen 1972; Bondestam *et al.* 1994). Inferred summer temperatures increased at about this time from 7–10°C to 16–22°C (Bondestam *et al.* 1994).

A reduction in vegetation cover and colder climatic conditions between *c.* 10 400 and 10 000 cal. yrs BP (Fig. 10), which corresponds approximately to the transition between the Scandinavian Preboreal–Boreal pollen zones, may coincide with a pronounced cooling event, which is inferred to have occurred at about 10 200 cal. yrs BP from North Atlantic marine (Bond *et al.* 1997) and terrestrial records. Early Holocene colder events also have been recognized in northwestern Russia based on vegetation-inferred paleoclimatic reconstructions (e.g. Khotinsky 1984; Arslanov *et al.* 1999; Elina *et al.* 2000). High organic production in the lakes and the establishment of widespread boreal forest on the Karelian Isthmus indicates warm and humid climatic conditions and stable soils after 10 000 cal. yrs BP (Fig. 10).

The delayed response of the sites on the Karelian Isthmus to the dramatic temperature rise at the Pleistocene–Holocene transition, which is regarded as a synchronous event in the North Atlantic region (Björck *et al.* 1996) and more broadly in the Northern Hemisphere (Severinghaus *et al.* 1998), may be due to several factors. The presence of widespread permafrost and/or stagnant ice, the proximity of the Scandinavian ice sheet, the cold surface waters of the Baltic Sea and regional circulation patterns may all have contributed to this delay. According to Global Circulation Model experiments, strong seasonal contrasts, with winters colder than today and summers warmer and drier than present, characterized the period between 12 000 and 9000 cal. yrs BP in northeastern Europe (Kutzbach *et al.* 1993; Webb III *et al.* 1993). Extensive permafrost may have been preserved in western Russia under this extreme continental climate. The permafrost kept the ground cold and may have had a marked influence on atmospheric circulation and heat transport by creating a high-pressure cell, which in turn could have blocked warm westerly air masses. Strengthened easterlies south of the Scandinavian ice sheet could have enhanced anticyclonic circulation (Yu & Harrison 1995; Harrison *et al.* 1996). Only about 10 000–9000 cal. yrs BP, coincident with the final disintegration of the Scandinavian ice sheet, did the zone of drier conditions and influence of easterlies disappear (Kutzbach *et al.* 1993; Yu & Harrison 1995; Harrison *et al.* 1996), giving way to a spread of warm North Atlantic air masses over the western part of Russia (Peterson 1993). Although these model experiments are not based on high resolution records, the approximate times of events and the suggested scenarios are consistent with the inferences derived from our data set – specifically dry and cold conditions until about 11 000 cal. yrs BP, slightly warmer and more humid conditions between 11 000 and 10 200 cal. yrs BP and increasing warmth and humidity after 10 000 cal. yrs BP (Fig. 10).

Conclusions

- Arctic climatic and environmental conditions with stagnant ice, permafrost and sparse shrub, herb and grass vegetation growing on barren soils characterized the central highland of the Karelian Isthmus prior to 12 650 cal. yrs BP. Steppe-tundra and cold, dry climatic conditions are inferred between 12 650 and 11 000 cal. yrs BP.
- The organic production in Lake Medvedevskoye and Lake Pastorskoye started to increase about 11 000 cal. yrs BP, when climate began to warm and became humid. Open *Pinus–Betula* forests, in some areas with *Picea,* became established. These favourable climatic conditions may have led to the melting of stagnant ice and permafrost and to stabilization and maturation of soils.
- Vegetation cover was reduced and organic production decreased in the lakes between about 10 400 and 10 000 cal. yrs BP during a brief cold phase.
- Closed boreal forest developed about 10 000 cal. yrs BP when climate became distinctly warmer and more humid. High organic productivity in the lakes indicates that soils around the lakes were stable.
- The delayed response of the lakes and the vegetation to the distinct temperature rise at the Pleistocene/Holocene transition may be explained by a different circulation pattern in this part of Europe compared to that around the North Atlantic. The extreme continentality shown in GCMs and strong anticyclonic circulation due to strengthened easterlies south of the Scandinavian ice sheet could have preserved extensive stagnant ice and permafrost in western Russia. The high pressure cell over permafrost regions and/or strengthened easterlies south of the ice sheet could have blocked warm air masses coming from the west as long as 2000 years.

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