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Authors: Cremer, Holger, Andreev, Andrei, Hubberten, Hans-Wolfgang, and Wischer, Frank

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# Paleolimnological Reconstructions of Holocene Environments and Climate from Lake Lyadhej-To, Ural Mountains, Northern Russia

Holger Cremer

Utrecht University, Department of Palaeoecology, Laboratory of Palaeobotany and Palynology, Budapestlaan 4, 3584 CD Utrecht, The Netherlands.  
h.cremer@bio.uu.nl

Andrei Andreev,  
Hans-Wolfgang Hubberten,  
and Frank Wischer

Alfred Wegener Institute Foundation for Polar and Marine Research, Research Department Potsdam, Telegrafenberg A43, 14473 Potsdam, Germany.

## Abstract

A sediment core recovered in Lake Lyadhej-To at the northwestern edge of the Ural Mountains reflects the complete Holocene environmental history from ~11,000 cal. yr B.P. Five limnological episodes are identified in the diatom and geochemical records. The initial lake stage, *Episode I* (~11,000–10,850 cal. yr B.P.) is characterized by the absence of biogenic production and a high influx of clastic sediments. *Episode II* (~10,850–8650 cal. yr B.P.) is characterized by ice-free conditions during summer, highest bioproductivity, strong growth of planktic diatoms and anoxic bottom waters. This period represents the Holocene climatic optimum. Deterioration of climatic conditions commenced in *Episode III* (~8650–7000 cal. yr B.P.) as indicated by distinctly lower bioproductivity and longer persistence of winter ice on the lake. During *Episode IV* (~7000–2500 cal. yr B.P.), the diatom and pollen records indicate that temperatures were cool and the growing season was short. Finally, in *Episode V* (~2500 cal. yr B.P. to present), limnological conditions, indicated by increased organic carbon and diatom deposition, initially suggest improved conditions followed by a return to modern conditions beginning ~500 cal. yr B.P. The pollen stratigraphy from Lake Lyadhej-To is consistent with other paleoclimatic records from northern Eurasia, confirming rapid postglacial warming, the presence of dense tree forests during the climatic optimum, and finally a gradual southward retreat of the treeline towards its modern location.

## Introduction

The southward extent of the Barents–Kara Sea Ice Sheet during the Last Glacial Maximum (LGM) has been a matter of discussion for some time (Mangerud et al., 2002, and references therein). During the past years many efforts have been made to clarify the position of the ice-sheet margin during the Weichselian. The most recent geomorphological and chronological results suggest a continental shelf position of the ice-sheet margin during the LGM and, consequently, an ice-free northern Russian mainland including the Pechora Lowland and the West Siberian Plain (Mangerud et al., 2001, 2002). A detailed study of terrestrial sections recovered from ice-dammed paleolake Komi in the region west of the Ural Mountains showed that maximum ice-sheet extensions occurred during the early and middle Weichselian and that the region was ice free during the Late Weichselian (Mangerud et al., 2001).

However, in northern Russia little data, particularly those including diatoms, exist on the present limnology and late Quaternary paleolimnology from areas that were possibly affected by ice. The few recently published diatom studies include (1) Laing and Smol (2000), who compared the modern diatom flora and limnology from sites in the Pechora River, Taimyr and Lena River regions; (2) Kienel (1999) and Kienel et al. (1999), who described Holocene diatom successions and their paleoecology from the North Siberian Lowland (Taimyr region); and (3) Michelutti et al. (2001), who studied the effects of mining activities on diatom assemblages in the Noril'sk region (southern Taimyr region).

Here we report on the postglacial climatic and environmental history of Lake Lyadhej-To, located at the northwestern tip of the Ural Mountains (Fig. 1), with particular focus on the diatom flora and its Holocene development. We recovered a 11.8-m-long sediment core, which consists of a basal 5-m-thick, highly consolidated till and an

overlying 7-m-thick layer of lacustrine sediments, from this High Arctic lake (Hermichen et al., 2000). Geochemical and chronological analyses on this core showed that the basal till originated from the middle Weichselian Barents–Kara Sea Ice Sheet, confirming that the region was ice free during the LGM. The lacustrine sequence of this core represents the entire Holocene history of Lake Lyadhej-To (Wischer et al., 2001).

## SITE DESCRIPTION

Lake Lyadhej-To (68°15'N, 65°47'E) is located in the Western Siberian lowlands on the northwestern edge of the Ural Mountains at the margin of the early/middle Weichselian Barents–Kara Sea Ice Sheet, the so-called Markhida Line (Fig. 1; Astakhov et al., 1999; Mangerud et al., 2001). The lake is located 150 m a.s.l., has a surface area of ~4 km<sup>2</sup> and is subdivided into two basins with a maximum water depth of 26 m (southern basin) and 21 m (northern basin), respectively (Fig. 1). The lake was visited twice, once in 1998 (end July) and again in 1999 (mid to end April), to carry out hydrological and geophysical/sedimentological surveys (Hermichen and Wischer, 1999; Hermichen et al., 2000). Both basins have a similar hydrology as indicated by the temperature, oxygen, pH, and conductivity profiles taken in July 1998 (Table 1). Lake Lyadhej-To is an oligotrophic lake with relatively low ionic content and is circumneutral to slightly alkaline. The temperature profiles in Table 1 point to the occurrence of a weak thermic stratification. The relatively intense solar radiation during summer results in a metalimnion between about 7 and 14 m water depth. During the spring 1999 expedition the lake was covered by ~1.9 m of ice and the water column below the ice had a temperature slightly above 0°C (Hermichen et al., 2000). Lake Lyadhej-To has

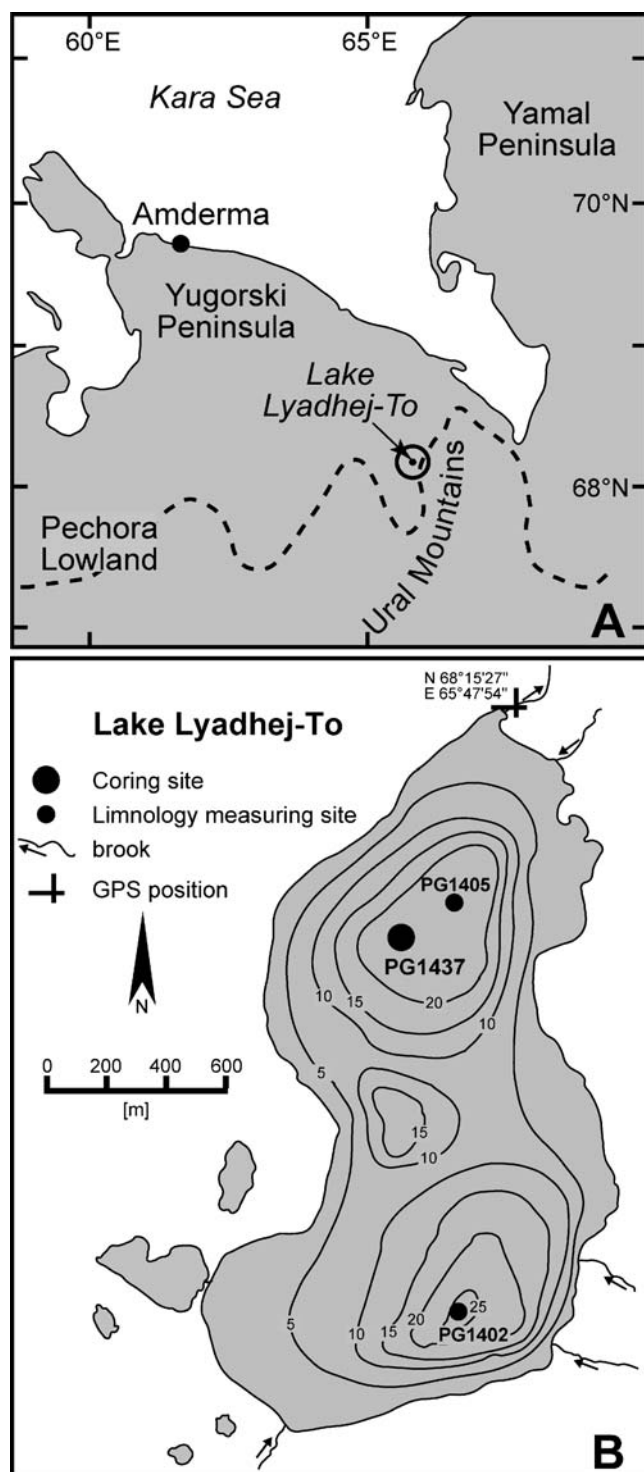


FIGURE 1. Geography of the study area. A. Map of Yugorski Peninsula, northern Russia, and adjacent regions. The dashed line is the so-called Markhida Line which marks the early to middle Weichselian ice-sheet limit in the region (after Astakhov et al., 1999). B. Bathymetry and sampling sites in Lake Lyadhej-To. The bathymetry was surveyed by single-point measurements along several longitudinal and latitudinal transects.

several inflows into the southern basin and one major outflow at the northern end of the lake (Fig. 1).

The geology of the region is characterized by igneous Paleozoic rocks that are overlain by 3000- to 6000-m-thick Mesozoic-Cenozoic sedimentary deposits and 50- to 300-m-thick Quaternary sediments of

TABLE 1

Vertical temperature, conductivity, pH-values and oxygen concentration profiles at sites PG1402 and PG1405 in Lake Lyadhej-To (taken from Hermichen and Wischer, 1999)

Water depth [m]	Temperature [°C]	Conductivity [ $\mu\text{S cm}^{-1}$ ]	pH	Oxygen concentration [ $\text{mg l}^{-1}$ ]
Site PG1402, southern basin				
0.1	16.3	62	7.8	9.6
5	16.4	68	8.0	8.8
10	12.9	49	7.9	8.8
15	10.3	57	7.5	9.1
20	10.2	57	7.5	10.5
24	9.2	58	7.6	10.0
Site PG1405, northern basin				
0.1	16.2	55	8.3	9.4
10	13.9	59	7.9	8.0
15	10.0	56	7.5	8.1
20	9.6	55	7.5	8.5
21	9.8	56	7.7	7.8

different facies (Astakhov, 1992; Kremenetski et al., 2003). The glacially formed hummock-and-lake landscapes around the Polar Urals are highly diverse, and include, for example, different types of moraines (Astakhov et al., 1999). At present, the Western Siberian lowlands are the world's largest high-latitude wetlands; they are characterized by diverse periglacial features, including permafrost, peat and swamp formation, and solifluction processes (Astakhov et al., 1999; Kremenetski et al., 2003).

The climate in this region is dry and cold, with a mean precipitation of 400 to 600  $\text{mm yr}^{-1}$  and mean temperatures for the coldest (January) and warmest (July and August) months of  $-16$  to  $-24^\circ\text{C}$  and  $+4$  to  $+8^\circ\text{C}$ , respectively (Treshnikov, 1985). Lake Lyadhej-To is ice-covered 8 to 9 mo and becomes ice free by June. The vegetation in the lake catchment is dominated by grass and low shrub tundra.

## Material and Methods

### CORING AND SEDIMENTOLOGY

Sediment core PG1437 was taken in April 1999 in the northern basin of Lake Lyadhej-To in 21 m of water (Fig. 1). Coring was carried out using a piston corer (UWITEC Corp.; see Melles et al., 1994, for a detailed description of the coring technique). Core PG1437 is 11.80 m long. The basal part of the core (11.80–7.00 m) consists of a highly consolidated, pre-Holocene till (Fig. 2), which contains no diatoms. Therefore, the basal core section is not discussed further in this paper. The upper 7.00 m of core PG1437 consists of a stratified to laminated clayey-silty gyttja (Fig. 2) with an increased organic carbon content. A well-preserved diatom flora is present in the upper 6.70 m of the core.

### RADIOCARBON DATING

Age control is provided by 14 radiocarbon dates on samples of cleaned terrestrial plant detritus and one piece of shrubwood (Table 2). Dating was carried out by accelerator mass spectroscopy (AMS) at the AMS laboratory in Kiel, Germany. The obtained radiocarbon ages were converted into calibrated ages (cal. yr B.P.) by using the INTCAL'98 calibration data set (Stuiver et al., 1998).

### DIATOM AND POLLEN SLIDE PREPARATION

Diatom slides of 103 subsamples of 1 cm thickness were prepared using 0.2 to 1.5 g of freeze-dried bulk sediment that was treated

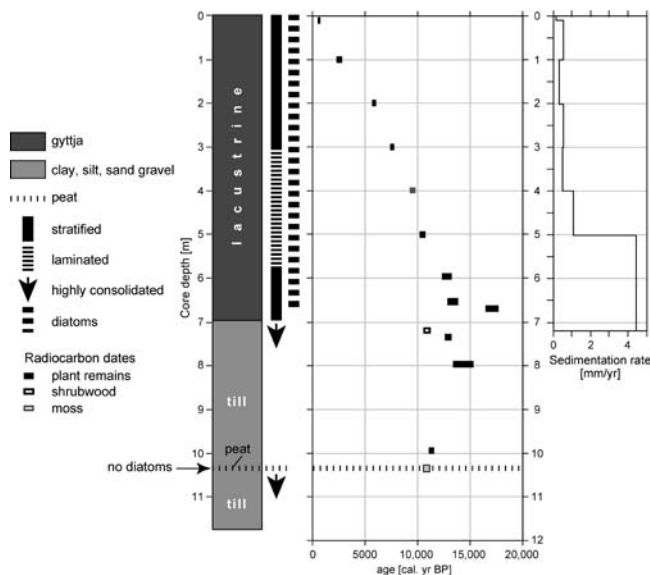


FIGURE 2. Sedimentology and chronology of core PG1437 from Lake Lyadhej-To (see also Table 2 for datings).

subsequently with hydrogen peroxide, hydrochloric acid, and nitric acid in order to remove all organic and carbonate components (Cremer et al., 2001). Slides were prepared employing the sedimentation tray method described by Battarbee (1973) and the high refraction mountant Naphrax<sup>®</sup> was used to mount the cover-glasses on slides. Diatom identification and counting were performed at  $\times 1000$  magnification using a Zeiss-Axioplan-microscope equipped with differential interference contrast (Nomarski) optics. Generally, a minimum of 500 diatom valves were counted. The identification of diatom species was mainly based on Krammer and Lange-Bertalot (1991, 1999a, 1999b, 2000).

Pollen samples were prepared according to the method described in Andreev et al. (2001) and included treatment with fluoric and hydrochloric acid, acetolysis, staining with a solution of safranin, and sieving. Counting was performed at a magnification of  $\times 400$ . Generally, 300 to 400 pollen grains were counted on each slide.

## GEOCHEMICAL ANALYSES

The total organic carbon content (TOC) was measured with a Metalyt-CS-1000-S apparatus (ELTRA Corp.), whereas the total sulphur (TS) and total carbon (TC) contents were analyzed with a CHNS-932 determinator (LECO Corp.). The calcium carbonate ( $\text{CaCO}_3$ ) percentage of the samples was calculated from the carbonate content (difference between TC and TOC) and the atomic weights of the elements.

## Results

### CHRONOLOGY

Table 2 and Figure 2 report the radiocarbon dates obtained for core PG1437. Based on plant remains of aquatic origin, the base of the lacustrine sequence has an age of  $\sim 17,000$  cal. yr B.P.; however, the age of a piece of shrubwood in the uppermost till layer (718 cm core depth) is  $\sim 11,000$  cal. yr B.P. Consequently, the older dates obtained in the lacustrine core sequence at 597 cm, 653 cm, and 671 cm core depth probably resulted from contamination with older, redeposited terrestrial plant detritus or "old" glacial meltwaters from the Ural Mountains (Table 2; Fig. 2). The assumed age of the onset of lacustrine sedimentation is also supported by a date obtained on moss detritus

from a peat layer recovered in the lower third of the till sequence (Fig. 2). This peat was also formed at  $\sim 11,000$  cal. yr B.P. (Table 2).

The sedimentary sequence in Lake Lyadhej-To and the available radiocarbon dates support the following conclusions: after the deposition of a basal till layer before 11,000 cal. yr B.P., a short-term, shallow-water environment developed and led to the formation of a thin peat layer at  $\sim 11,000$  cal. yr B.P. Subsequently, the shallow lake was rapidly filled up by more than 3 m of till. The onset of lacustrine sedimentation probably took place soon after the till deposition. Autochthonous planktic diatoms were deposited from  $\sim 10,850$  cal. yr B.P. The initial stage of the lake was characterized by a relatively high sedimentation rate (Fig. 2) probably supported by large inputs of allochthonous material, which is indicated by the relatively high percentages of re-deposited diatom valves (Fig. 3; *Paralia siberica* (Schmidt) Crawford et Sims) and pollen grains (Fig. 4).

### THE DIATOM RECORD

In the Holocene sequence of core PG1437 a total of 153 diatom taxa from 42 genera were identified. *Achnanthes* (20 taxa), *Fragilaria* (17 taxa, including *Pseudostaurosira*, *Staurosira* and *Staurosirella*), and *Navicula* (19 taxa) are the most diverse genera. Diatom assemblages, however, are generally dominated by a few planktic species belonging to the genera *Aulacoseira* and *Stephanodiscus* and by small *Staurosira* and *Staurosirella* species (Fig. 3).

The diatom record of core PG1437 can be subdivided visually into seven biostratigraphical diatom units (informally named Diatom Unit A–G; Fig. 3) which are briefly described in chronological order.

#### Diatom Unit A ( $\sim 11,000$ – $10,850$ cal. yr B.P.)

The initial Holocene stage of Lake Lyadhej-To is characterized by the presence of *Paralia siberica* (Schmidt) Crawford et Sims, a taxon that is known only from Paleocene and Eocene deposits. Its occurrence indicates a relatively high terrestrial input into the lake basin, which is also suggested by the occurrence of re-deposited pollen (Fig. 4). The nearly complete absence of autochthonous planktic diatoms at the same time shows that there was no significant pelagic bioproductivity in the lake (Fig. 3).

#### Diatom Unit B ( $\sim 10,850$ – $9350$ cal. yr B.P.)

This unit shows the highest diatom valve concentrations ( $2$ – $5 \times 10^9$  valves per gram sed.) and is dominated by small *Stephanodiscus* taxa (*S. hantzschii* Grunow, *S. minutulus* (Kützing) Cleve et Möller, *S. parvus* Stoermer et Håkansson). Three other species, *Aulacoseira islandica* (Müller) Simonsen, *Staurosira construens* (Ehrenberg) Williams et Round and *Staurosirella pinnata* (Ehrenberg) Williams et Round are of minor importance. Towards the end of Unit B, the significance of these species gradually decreases, whereas the relative abundance of *A. islandica* increases.

#### Diatom Unit C ( $\sim 9350$ – $8650$ cal. yr B.P.)

The diatom assemblage in this unit consists mainly of *A. islandica*, *S. construens*, *S. pinnata*, and the small *Stephanodiscus* species. Compared to the previous unit, the latter group occurs with distinctly lower relative abundances. Unit C has also the highest concentration of *Cyclotella ocellata* Pantocsek during the entire Holocene. The total diatom abundance is lower than  $2 \times 10^9$  valves per gram of freeze-dried sediment (Fig. 3).

#### Diatom Unit D ( $\sim 8650$ – $7000$ cal. yr B.P.)

This period was characterized by further decrease of total diatom concentration and the *Stephanodiscus* group. The dominating diatom

TABLE 2  
Results of  $^{14}\text{C}$  dating and calibrations in core PG1437

Laboratory No	Depth [cm]	Conventional $^{14}\text{C}$ age [yr BP]	$^{14}\text{C}$ error [+/- yr BP]	Carbon dated	Calibrated age [cal. yr BP]	Cal. age error [+/- yr BP]
KIA10040	9	690	30	Plant detritus	620	55
KIA8915	99	2460	40	Plant detritus	2550	200
KIA10041	201	5135	60	Plant detritus	5870	125
KIA8916	299	6730	70	Plant detritus	7580	105
KIA8920	399	8550	100	Plant detritus	9520	190
KIA8917	501	9230	90	Plant detritus	10450	230
KIA12131	597	10780	140	Plant detritus	12750*	390
KIA8759	653	11230	150	Plant detritus	13340*	450
KIA8760	671	14210	90	Plant detritus	17060*	510
KIA8761	718	9600	60	Shrubwood	10940	235
KIA12132	735	10940	90	Plant detritus	12910*	255
KIA12133	794	11850	80	Plant detritus	14370*	865
KIA 12134	994	9880	50	Plant detritus	11370*	180
KIA 12135	1035	9490	60	Moss	10830	265

\* Samples probably contaminated by older plant detritus.

Used calibration method: CALIB 4.3, Method 1, intercept ages, errors at  $2\sigma$  probability (Stuiver et al., 1998).

species in Unit D is *Aulacoseira subarctica* (Müller) Harworth, whereas *S. construens* and *S. pinnata* are of secondary importance. *Achnanthes* spp. gradually increase in relative abundance in this unit.

#### Diatom Unit E (~7000–2500 cal. yr B.P.)

This unit represents the longest period of relative stability in terms of the composition of the diatom community. The assemblage in Unit E is dominated by the periphytic species *Staurosira construens* and *Staurosirella pinnata*, and *Achnanthes* spp. (Fig. 3). Planktic diatoms generally play a minor role in this unit. The total diatom abundance has lowest values in this unit (below  $1 \times 10^9$  valves per gram sed.).

#### Diatom Unit F (~2500–0 cal. yr B.P.)

Similar to Unit D, *A. subarctica* dominates this unit, whereas the significance of *S. construens*, *S. pinnata*, and *Achnanthes* spp. is slightly reduced. The abundance of *Cyclotella tripartita* Håkansson increases at the end of Unit F. The total diatom valve concentration is slightly higher than in the previous unit. The youngest period in Lake Lyadhej-To (from ~350 cal. yr B.P.) shows a similar diatom assemblage to those of Unit E: planktic diatoms are of minor importance and *S. construens*, *S. pinnata* and *Achnanthes* spp. dominated (Fig. 3).

### THE GEOCHEMICAL AND POLLEN RECORDS

The calcium carbonate and total sulphur content show distinct Holocene patterns, whereas changes in the total organic carbon content are relatively small (Fig. 4). Unit A has the lowest TOC content ( $0.97 \pm 0.54\%$ ). Maximum TOC values of  $3.55 \pm 0.66\%$  were recorded in Units B and C, while Units E, D and F are characterized by TOC values of  $2.09 \pm 0.52\%$ . The TS content in core PG1437 also has its maximum in Unit B, gradually decreases in Units C and D and remains extremely low from ~7000 cal. yr B.P. to the present. Furthermore, there is a clear calcium carbonate peak in early Unit B that subsequently rapidly decreases. From Unit C (~9350 cal. yr B.P.), the carbonate content in the core remains very low.

The abundance of the most important pollen groups is also displayed in Figure 4. Unit A is characterized by the dominance of spruce (*Picea*), herb (Cyperaceae, Poaceae, *Artemisia* spp., *Thalictrum* spp.), and redeposited pollen. These groups occur in low abundances in

Unit B, which is dominated by *Betula alba* pollen. The abundance of *Betula alba* decreases in Units C and D and remains relatively low during the mid and late Holocene with a maximum relative abundance of 20% (Fig. 4). Spruce, herb, and pine (*Pinus sylvestris*) pollen are equally represented in these latter units. *Betula nana* pollen have a relative abundance between 10 and 20% throughout the entire sediment core.

## Discussion

The diatom species records fit well with the main trends in the stratigraphy of selected geochemical and pollen parameters (Fig. 4). The TOC signature in core PG1437 shows a clear maximum in Units B and C that occurred contemporaneously with the maximum TS content, the total diatom concentration, and the proportion of planktic diatoms. This points to the presence of a thermal optimum northwest of the Ural Mountains during the early Holocene between ~10,800 and 8600 cal. yr B.P. that resulted in greater productivity in Lake Lyadhej-To. The relatively high TS content in Units B to D indicates the dominance of anoxic conditions on the lake bottom during this period as a result of increased deposition of algal and terrestrial organic detritus. However, C:N ratios between 8:1 and 16:1 support the idea that most of the TOC in core PG1437 is derived from algal productivity in Lake Lyadhej-To. High sedimentation of organic matter on the lake bottom causes decomposition processes that use up oxygen and result in an increased production of sulphides. Further decrease of oxygen could also be caused by an increase in thermal stratification as a result of warmer temperatures or decreased influence of wind (Moser et al., 2002). The high deposition of authigenic carbonate in Unit B likely reflects alkaline pH conditions possibly resulting from increased photosynthesis in Lake Lyadhej-To that allowed the precipitation and preservation of calcium carbonate (Fig. 4).  $\delta^{18}\text{O}$  values of carbonate range from  $-16$  to  $-12\text{‰}$  PDB before ~9500 cal. yr B.P. and from  $-10$  to  $-7\text{‰}$  PDB between ~9500 and ~8800 cal. yr B.P., indicating distinct hydrological changes at this transition. An early Holocene climatic optimum is also supported by the pollen record, which indicates an increase in the abundance of *Betula alba*. A peak in *Betula alba* in the early Holocene has also been reported in many other pollen records from northern Eurasian regions (e.g., Kaakinen and Eronen, 2000; Pitkänen et al., 2002; Solovieva and Jones, 2002), among them

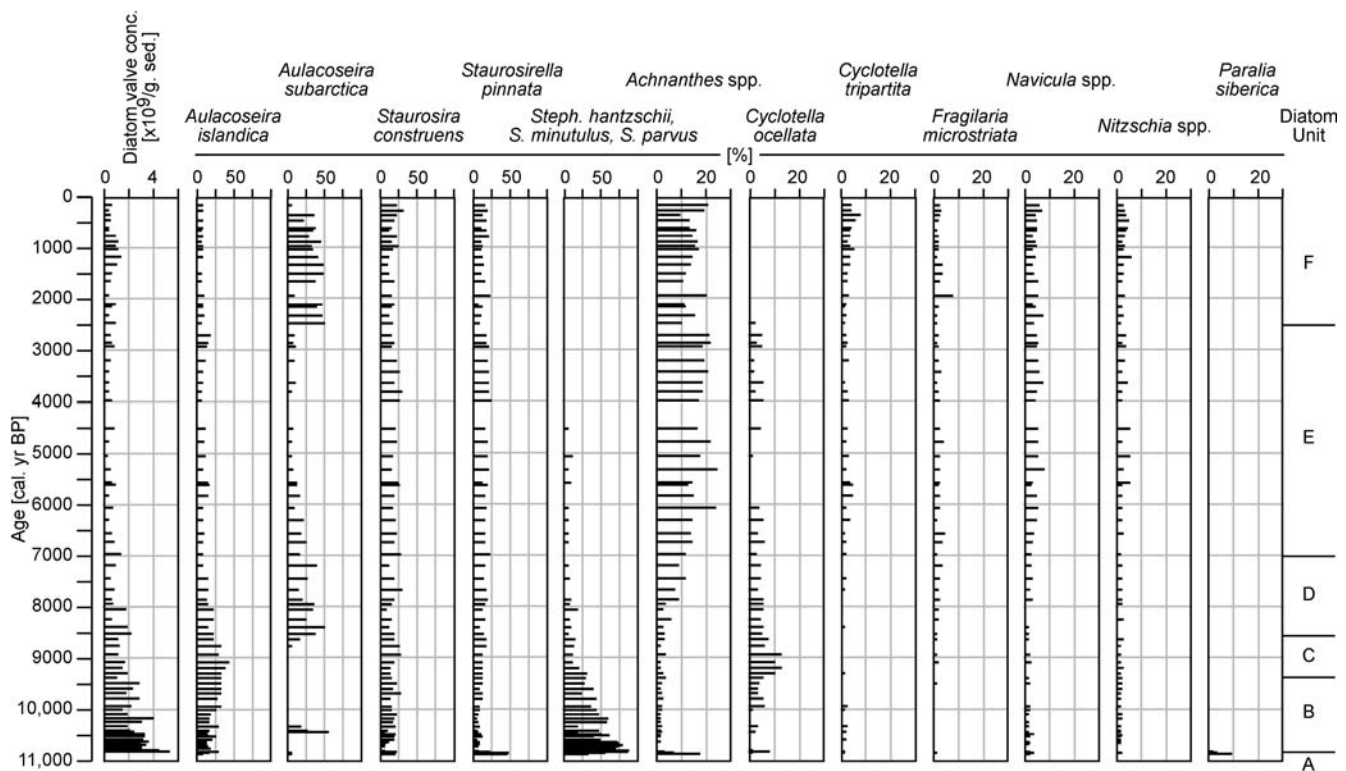


FIGURE 3. Holocene diatom stratigraphy of core PG1437 from Lake Lyadhej-To. Diatom units are defined based on major changes in the diatom assemblage.

a sedimentary profile at Cape Shpindler, northern Yugorski Peninsula, which is closely located to Lake Lyadhej-To (Andreev et al., 2001). These records support generally warm climatic conditions during the early Holocene across northern latitudes in West Siberia. Productivity rapidly decreased in Units C and D, which indicates a deterioration in climatic conditions. This is also evidenced by decreases in TOC content, total diatom valve concentration, and proportions of planktic diatoms and *Betula alba* pollen (Fig. 4). The distinct decrease in TS content in Units C and D might indicate improved ventilation of bottom waters and hence reduced anaerobic decomposition of organic matter. Unit E, lasting from ~7000 to ~2500 cal. yr B.P., probably reflects the coolest period in the northern Polar Urals during the Holocene. All sedimentary indicators reflecting productivity and warmer temperatures (TOC, total diatom concentration, planktic diatom abundance) show minimum values, whereas the abundance of spruce (*Picea*), pine (*Pinus*), and herb pollen distinctly increase. Climatic and environmental conditions likely improved again during Unit F indicated by a distinct increase of the relative abundance of planktic diatoms, mainly *A. subarctica* (Figs. 3, 4). As well, the total abundance of organic carbon and concentration of diatom valves slightly increase, supporting a climatic amelioration. Increased summer temperatures might have reduced the extent of ice cover on Lake Lyadhej-To and, hence, led to an extended open water season, higher water temperatures and stronger diatom growth in the lake's pelagic zone (Smol, 1988; Douglas and Smol, 1999; Cremer et al., 2001; Rühland et al., 2003). Vegetation during this period probably continued to be mainly Arctic tundra with few spots covered by conifer forests. However, towards the end of Unit F (from ~350 cal. yr B.P.) diatom and pollen data reflect again a cooling that led to reduced diatom productivity and the dominance of herb vegetation in the catchment of the lake.

Based on the data presented in the Figures 3 and 4, the Holocene

limnological history of Lyadhej-To can be subdivided into five limnological episodes (Fig. 5).

#### Episode I (~11,000–10,850 cal. yr B.P.)

During this period, consistent with the Preboreal (Haas et al., 1998; Pitkänen et al., 2002), Lake Lyadhej-To was characterized by the deposition of mainly clastic material from glacial meltwaters which would have been draining off the Ural Mountains. This is also indicated by the occurrence of redeposited pollen and diatoms in sediments from this period. The absence of autochthonous algal growth and terrestrial organic detritus, indicated by low TOC content, during this initial episode point to turbid and nutrient-poor lake conditions.

The catchment vegetation was dominated by plants typical for Arctic tundra (Fig. 4) which indicate that a cool and dry climate existed northwest of the Ural Mountains. These findings are similar to results from other localities from West Siberia (e.g., Hahne and Melles, 1997; Andreev et al., 2001; Pitkänen et al., 2002).

#### Episode II (~10,850–8650 cal. yr B.P.)

The Boreal in northern Siberia is characterized by the highest TOC and total diatom concentrations, and a distinct dominance of planktic diatoms, indicating that Episode II has the longest growing season, lowest lake-ice coverage and highest bioproductivity in Lake Lyadhej-To of all five episodes (Fig. 3). This period is undoubtedly the warmest postglacial episode and marks the Holocene climatic optimum in northern Eurasia (MacDonald et al., 2000; Andreev et al., 2001).

The diatom assemblage is initially predominated by *Stephanodiscus* taxa, which later co-occur with *A. islandica* and *C. ocellata* (Fig. 3). All three *Stephanodiscus* taxa are alkalibiontic species, which occur

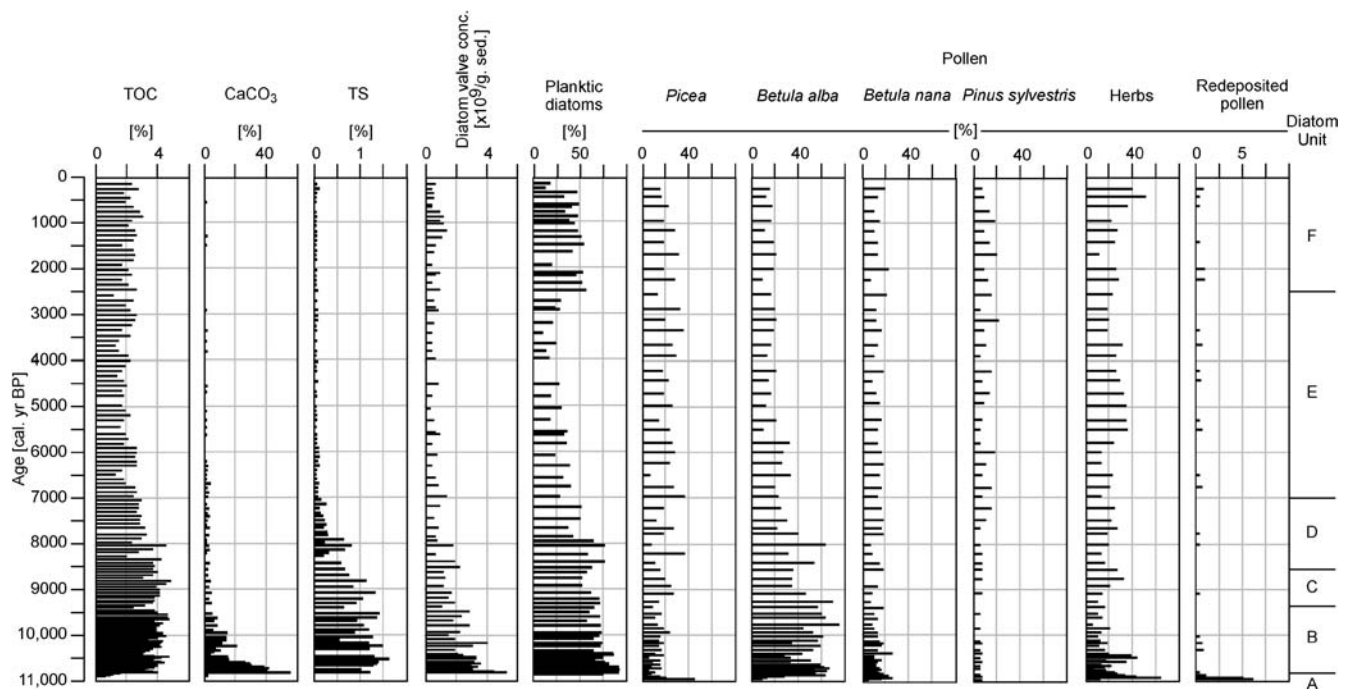


FIGURE 4. Selected geochemical and palynological parameters in core PG1437 from Lake Lyadhej-To compared to the total diatom valve concentration and the proportion of planktic diatoms. Herb pollen counts include Cyperaceae, Poaceae, Ericales, Artemisia, Thalictrum, and Polygonum.

exclusively at pH values  $>7$  (van Dam et al., 1994). High calcium carbonate precipitation at the beginning of Episode II support high alkalinity at this time (Fig. 4). *Stephanodiscus hantzschii* and related species are also known as eutrathentic species (van Dam et al., 1994) which support the presence of nutrient-rich conditions in Lake Lyadhej-To during Boreal summers, possibly caused by increased terrestrial nutrient input as a consequence of less and shorter ice and snow cover. Bottom waters and sediments were probably anoxic, as reflected by the remarkable sulphur deposition, suggesting stratification of the water column. The dominance of *A. islandica* and *C. ocellata* from  $\sim 10,000$  cal. yr B.P.—both are classified as circumneutral and alkaliphilous taxa, respectively (van Dam et al., 1994)—and the contemporaneous decrease of *Stephanodiscus* abundance might indicate a slight shift towards lower pH in Lake Lyadhej-To. The lower  $\text{CaCO}_3$  content in the core from  $\sim 10,000$  cal. yr B.P. supports lower alkalinity of the lake water or changed diagenetic conditions within the upper sediment layers. The simultaneous gradual decrease of both the total sulphur content and the increase in *Aulacoseira* abundance towards the end of Episode II (Figs. 3, 4) demonstrate that both parameters likely were linked together and might reflect an increased ventilation possibly caused by increased wind activity and, consequently, mixing of the water column.

The pollen assemblage during Episode II was dominated by tree birch pollen (Fig. 4), indicating that the region was widely covered by birch forests during Preboreal and early Boreal times. This interpretation is in agreement with other records from the region (e.g., Andreev et al., 2001; Solovieva and Jones, 2002), confirming that the birch treeline was located farther north during Episode II than it is today (Khotinskiy, 1984; MacDonald et al., 2000). According to Kremenetski et al. (1998, 2003) the period between 9000 and 7500  $^{14}\text{C}$  yr B.P., corresponding to  $\sim 10,200$  to 8500 cal. yr B.P., was most favorable for tree growth in northern Russia. Another indicator that Lake Lyadhej-To was surrounded by forests is the relatively low abundance of the fragilarioid diatoms *Staurosirella pinnata* and *Staurosira construens* (Fig. 3), which, according to Laing and Smol

(2000), generally have low abundances in forested lakes of high latitudes.

#### Episode III ( $\sim 8650$ – $7000$ cal. yr B.P.)

This period, representing the early and middle Atlantic, has to be regarded as a transition between the climatic optimum during Episode II and the long period of relatively cooler climatic conditions of the following Episode IV. All biological and geochemical records point to a deterioration of the climate and cooler temperatures than before. The deposition of diatom valves, TOC and sulphur gradually decreased (Fig. 4) confirming a lower bioproductivity in Lake Lyadhej-To. The abundance of *Stephanodiscus* further decreased and *A. islandica* was replaced by *A. subarctica* (Fig. 3), probably proving that the lake water showed a slight tendency to further acidification. *Aulacoseira subarctica* is characterized as an acidophilous diatom (van Dam et al., 1994), indicating a pH in Lake Lyadhej-To below 7. During Episode III there was also a distinct gradual increase of the relative abundance of *Achnanthes* spp. which might be a result of decreased availability of open water habitats as a result of extended or prolonged ice cover on Lake Lyadhej-To.

The pollen assemblage in Episode III shows a decline of birch pollen and a contemporaneous rise of spruce and pine pollen (Fig. 4) during the early Atlantic indicating that the birch-dominated forests of the climatic optimum were replaced by conifer-dominated forests. A similar pattern is also reported from other sites in northern Siberia (Hahne and Melles, 1997; Pitkänen et al., 2002).

#### Episode IV ( $\sim 7000$ – $2500$ cal. yr B.P.)

The mid-Holocene in the northern Ural Mountains was a relatively long and climatically stable period with minor variation in the diatom, pollen and geochemical records. Lowest concentrations of TOC and diatom valves in sediments of Episode IV confirm that the terrestrial nutrient influx was decreased and, consequently, bioproductivity in

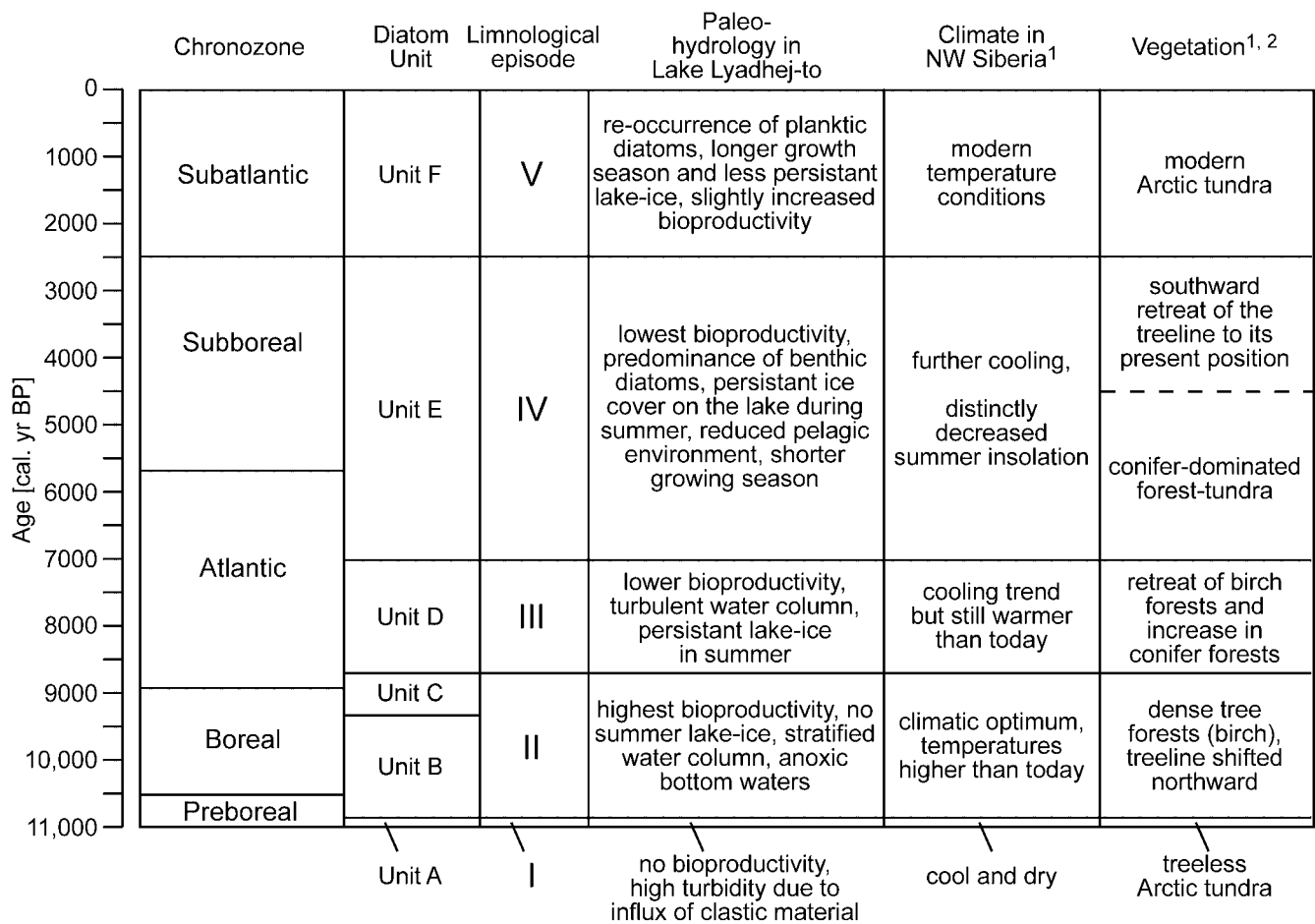


FIGURE 5. Summary of limnological and climatic changes reflected in core PG1437 from Lake Lyadhej-To. Chronozone boundaries according to Haas et al. (1998) and Pitkänen et al. (2002). <sup>1</sup>Considering also data from MacDonald et al. (2000); <sup>2</sup>Considering also data from Andreev et al. (2001).

Lake Lyadhej-To was low (Fig. 4). The relative increase of benthic diatoms (*Achnanthes*, *Navicula*, *Staurosira*, *Staurosirella*) and the lower proportion of planktic diatoms point to relatively short growing seasons and longer persistence of ice on the lake during summer leading at least to an ice-free moat of the lake (Smol, 1988; Cremer et al., 2001). There is no evidence that the acidity in Lake Lyadhej-To changed from Episode III. The most abundant taxa during Episode IV, *Staurosirella pinnata* and *Staurosira construens*, are alkaliphilous taxa (van Dam et al., 1994).

The vegetation during Episode IV was relatively uniform and can be characterized as a mix of grass-low shrub tundra and *Picea-Pinus-Betula* forests. In the middle of this period, corresponding to the Atlantic-Subboreal transition, herb pollen became more significant (Fig. 4) reflecting that Arctic tundra vegetation was more widespread than before. Synchronous increases in the abundance of *Staurosirella pinnata* and *Staurosira construens* further supports an increase in tundra vegetation at this time (Laing and Smol, 2000). This vegetational shift, occurring at the Atlantic-Subboreal boundary, is also visible in a profile recovered from Yugorski Peninsula some 100 km north of Lyadhej-To (Andreev et al., 2001) and in adjacent regions (e.g., Pitkänen et al., 2002). From ~4500 cal. yr B.P., the vegetation in the Lyadhej-To region was probably similar to the modern vegetation cover. The mid-Holocene was a period of rapid change of treeline in northern Siberia, which resulted in a southward shift of treeline to its present position (Kaakinen and Eronen, 2000; MacDonald et al., 2000).

#### Episode V (~2500 cal. yr B.P. to present)

The Subatlantic period initially shows some distinct changes in the diatom record which might have been a result of altered limnological conditions. There is an increase in both the TOC and total diatom valve contents indicating slightly higher nutrient supply and bioproductivity in Lake Lyadhej-To. Warmer temperatures are also indicated by the re-occurrence of *A. subarctica*, which is the dominant planktic diatom in the Subatlantic, and slightly lower relative abundances of benthic diatoms (Figs. 3, 4). Both observations suggest an extended growing season during Subatlantic summers, possibly accompanied by reduced and/or shorter ice cover on the lake. These conditions, as well as a relatively low lakewater pH, enabled *A. subarctica* to increase in abundance. A low lakewater pH is also supported by the occurrence of *C. tripartita*, another acidophilous diatom.

The Subatlantic pollen record from Lake Lyadhej-To initially shows no changes, but from ~1000 cal. yr B.P., there is an increase in the abundance of herbs and a decrease in the relative abundance of *Picea* and *Pinus* pollen (Fig. 4), reflecting the dominance of arctic tundra vegetation and probably the farther southward shift of treeline. This trend is less notable in the diatom record, but is reflected in a decreased total diatom concentration and proportion of planktic diatoms.

A distinct late Holocene climatic amelioration, as reflected by the diatom record from Lake Lyadhej-To, is contrary to most other available paleoecological records from northern Siberia which,



however, are based mostly on vegetation studies. All these studies generally report a treeline retreat in northern Eurasia from ~4000 cal. yr B.P. and a replacement of boreal forests by arctic tundra vegetation (Khotinskiy, 1984; MacDonald et al., 2000). However, the climatic deterioration that is recorded since the Atlantic-Subboreal boundary was regularly interrupted by warmer phases during which boreal forests remigrated to the north (Khotinskiy, 1984).

## Concluding Remarks

Diatom, geochemical, and pollen records in sediment core PG1437 reflect both limnological and climatic trends around Lake Lyadhej-To during the past 11,000 cal. yr B.P. (Fig. 5). These trends are indicated by changes in diatom assemblage composition, which document long-term changes in lakewater pH, lake-ice cover, and habitat availability. A climatic optimum from ~10,850 to 8650 cal. yr B.P. is clearly confirmed by the diatom record, which indicates rapid climatic warming after the last deglaciation. The pollen record also indicates changes in the vegetation cover northwest of the Ural Mountains, which are in good accordance with previously published results (see review by MacDonald et al., 2000). According to MacDonald et al. (2000) northern Eurasia was forested to or near the current arctic coastline between ~9000 and ~7000 <sup>14</sup>C yr B.P., corresponding to ~10,000 to 7800 cal. yr B.P. All available vegetation data confirm a southward treeline shift and cooler temperatures since the mid-Holocene in northern Eurasia (e.g., Andreev et al., 2001; Khotinskiy, 1984).

However, taking into account the large surface of northern Eurasia the available data base, particularly on aquatic biota (e.g., diatoms, chironomids), is rather small and has to be improved in future. This might lead to a more detailed picture of past climatic and environmental changes and also reveal regional differences and peculiarities in limnological conditions and treeline positions.

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