Journal of Paleolimnology **27**: 353–366, 2002.

Limnological conditions in a subarctic lake (northern Québec, Canada) during the late Holocene: analyses based on fossil diatoms

Karin Ponader[1,2], Reinhard Pienitz[1,*], Warwick Vincent[1] and Konrad Gajewski[3]

*[1]Centre d'études nordiques (CEN), Université Laval, Québec, Canada G1K 7P4; [2]Patrick Center for Environmental Research, Academy of Natural Sciences, 1900 Benjamin Franklin Parkway, Philadelphia, PA 19103-1195, USA; [3]Department of Geography, University of Ottawa, Ontario, Canada K1N 6N5; *Author for correspondence (e-mail: reinhard.pienitz@cen.ulaval.ca)*

Received 13 January 2001; accepted in revised form 6 August 2001

Key words: Canada, Diatoms, Dissolved organic carbon (DOC), Northern tree-line, Paleolimnology, Québec

Abstract

A fossil diatom record covering the past 3000 cal. years BP was analyzed from a small lake in northwestern Québec near the northern limit of present-day tree-line. *Fragilaria virescens* var. *exigua* Grunow in Van Heurck was the dominant species throughout the core with abundances ranging between 13–35% of the total valve count. There was a replacement of alkaliphilous taxa by acidophilous taxa beginning ca. 1300 cal. yr ago, probably reflecting long-term, natural acidification processes. A diatom-based transfer function was used to provide quantitative estimates of variations in lakewater dissolved organic carbon (DOC). These inferred values showed that DOC concentrations have remained stable over the past 3000 years (mean ± S.D. = 5 ± 0.43 mg C l^{-1}), suggesting relatively constant allochthonous carbon inputs and underwater light conditions during the late Holocene. The reconstructed DOC data were compared to the palynological record from the same lake. Our study indicates that, in contrast to paleolimnological records from lakes in central and western Canada, climatic variations and associated vegetational shifts have been too subtle to cause pronounced variations in DOC in this northern Québec site.

Introduction

Climate warming at high latitudes during the next century is predicted to be about twice that of lower latitudes (Kattenberg et al. 1996). Due to the sensitivity of the northern tree-line ecotone to climatic change, a northward displacement of the arctic tree-line is one possible response to climatic warming (Smith et al. 1992; Monserud et al. 1993). However, to the south of the limit of spruce, climate changes may also affect the ecosystems of the forest-tundra. Potential impacts include a change in the density of trees on the landscape, in fire frequency and in the life-form of treeline populations (Payette and Gagnon 1985; Payette et al. 1989). These impacts may have ecosystem-level consequences for the forest and tundra vegetation that would also affect regional aquatic systems. To evaluate the consequences of future warming, an understanding of past effects of climate fluctuations on tree-line ecosystems is essential. Despite considerable progress in paleoclimatic research in the Arctic, knowledge about the relationships between climatic and hydrological changes and their impact on high latitude aquatic ecosystems still remains sparse (MacDonald et al. 2000).

Holocene climatic changes and the associated effects on terrestrial vegetation in northern Québec are documented through dendrochronological, palynological and anthracological studies (Gajewski et al. 1993; Payette and Morneau 1993; Lescop-Sinclair and Payette 1995; Arseneault and Payette 1997a, b). However, few studies have explored the impacts of past climatic and vegetational changes on aquatic ecosystems in this region. These impacts can be particularly pronounced in lakes near or north of the tree-line, due to low concentrations of dissolved organic carbon (DOC) that are typically found in these regions (Schindler et al. 1996; Vincent and Pienitz 1996; Fallu and Pienitz 1999). Lake-water DOC in boreal regions is composed mainly of allochthonous humic material (Schindler et al. 1992), produced by the decomposition of organic matter in the lake basin (Engstrom 1987). It colours the water and effectively screens UV-B from the water column (Vincent and Roy 1993; Milot-Roy and Vincent 1994; Schindler et al. 1996; Laurion et al. 1997). Pienitz and Vincent (2000) showed that changes in lacustrine DOC in arctic regions could have a higher impact on the exposure of aquatic organisms to UV-radiation than the present-day thinning of the ozone layer. Concentrations of lacustrine DOC and their natural variability would therefore have influenced aquatic ecosystems in the past as well as in the future. If we wish to predict future impacts of ecological changes on northern aquatic ecosystems, it is important to understand their historic variability.

Diatoms are sensitive indicators of environmental change, and their siliceous cell walls frequently allow their preservation in lake sediments. Pienitz and Smol (1993), Pienitz et al. (1999) and Fallu and Pienitz (1999) showed that in arctic tree-line regions of North America, changes in diatom assemblage composition were strongly correlated with lakewater DOC and that past variations of DOC appear to be a potential proxy of ecosystem-level response to vegetational change in lake basins. Inferred DOC may also serve to evaluate past light regimes in lakes (Pienitz and Vincent 2000; Saulnier-Talbot and Pienitz 2001).

The application of diatom-based inference models based on multivariate statistical methods is a valuable tool in the quantitative reconstruction of limnological variables (Birks 1998). Several models for the reconstruction of environmental changes in subarctic regions have been used in the Canadian Northwest-Territories (DOC; Pienitz et al. 1999), in Sweden (DOC; Korsman et al. 1994), in northern Finland (pH, TOC and water colour; Seppä and Weckström 1999), and in Siberia (alkalinity; Laing et al. 1999).

The present paleolimnological study presents the first application of a diatom-based DOC inference model (Fallu and Pienitz 1999) on the fossil diatom record from a lake located near the tree-line in northern Québec. The purpose of comparing these data with existing pollen data from the same site is to assess to what degree catchment vegetation changes are affecting the lake. This study forms part of a broader program to improve the understanding of terrestrial-aquatic links and the timing and effects of postglacial climate and vegetation change on northern freshwater ecosystems (Pienitz and Vincent 2000).

Study area

The study site is situated in the northern part of the forest-tundra in northwestern Québec. Lac Karinbou (unofficial name; 57°44′ N and 76°09′ W) is located about 10 km south of tree-line and 50 km east of Hudson Bay (Figure 1). This region is an outlier of tree- and shrub-form spruce populations situated in the shrub subzone of the forest tundra (Payette 1983; Arseneault and Payette 1992). Lac Karinbou is a small, shallow lake (area = 6.2 ha, maximum depth = 5.8 m) situated at an altitude of 135 m a.s.l. (Figure 2). The lake basin is oriented north–south and surrounded by three hills of 160–217 m a.s.l. (Figure 2). The basin is fed by a small inlet in the southern part and drains to the Rivière Boniface through an outlet in the northeastern part of the basin. Limnological properties recorded in the summer of 1998 are typical of an oligotrophic (total phosphorus = 7.8 μg l^{-1}), circumneutral (pH = 6.9) clearwater (Secchi depth $>$ 2.8 m) lake with summer DOC values of 2.5–2.8 mg C l^{-1}(Table 1).

The lake lies on Canadian Shield bedrock, composed of granite, granodiorite, syenite, and diorite (Avramtchev 1985), thus forming a nutrient-poor catchment area. Surface deposits are composed of tills on the hills and postglacial marine clays in depressions (Arseneault and Payette 1997a). Vegetation cover in the region is composed of tree and shrub-form black spruce (*Picea mariana*) in depressions along lake shores and river courses, and tundra on hilltops. Birch (*Betula glandulosa*), alder (*Alnus crispa*) and members of the heath family (Ericaceae) are important shrubs in the region. *Alnus* can form extensive populations on the hillslopes, and *Betula* is important in the tundra.

The subarctic climate of the region is characterized by long, cool and dry winters and by short, cool and humid summers. Meteorological data from a station taken over a period of 7–9 years during the last decade at Rivière Boniface (D. Sarrazin, personal communication, Centre d'études nordiques, Uni-

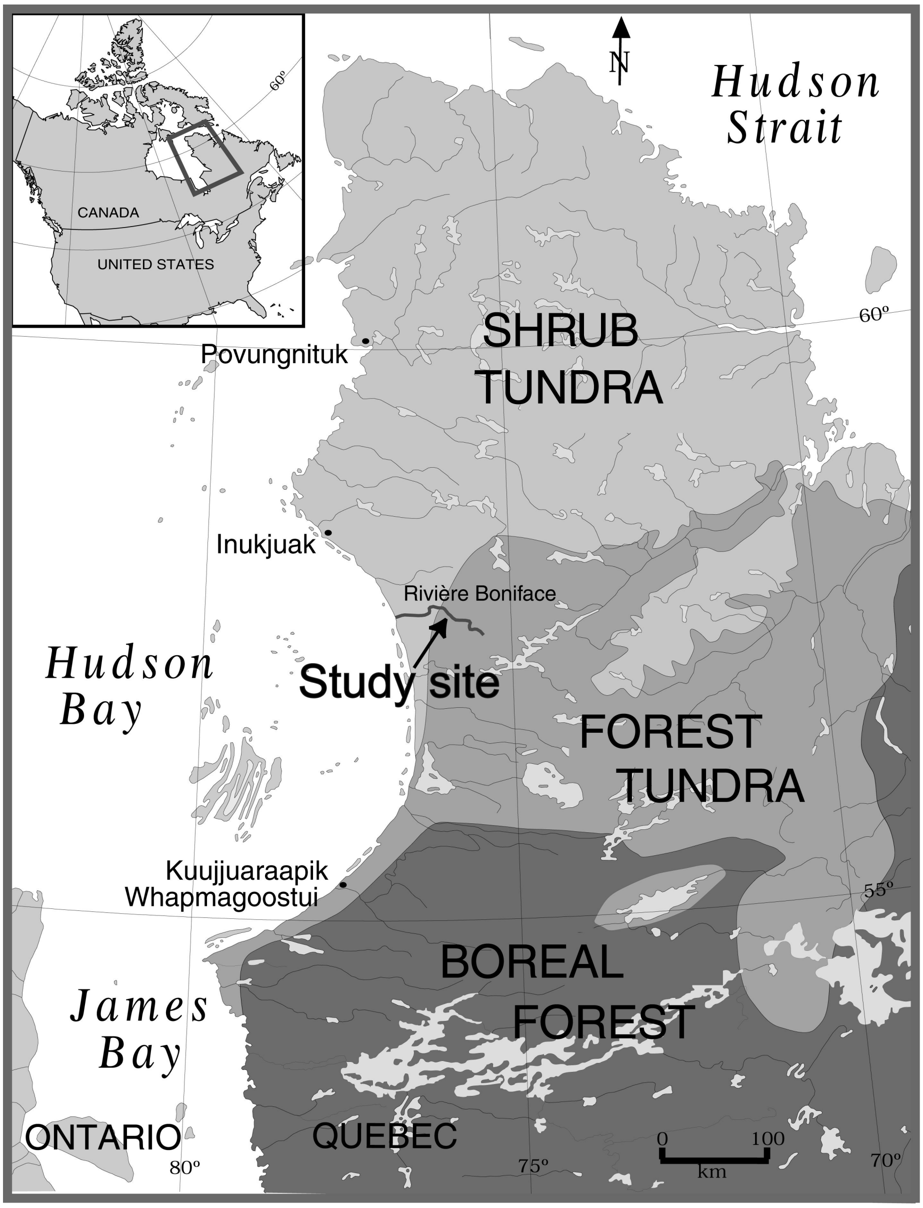

Figure 1. Map of the study area showing different vegetation zones and the location of the study site.

versité Laval) yield a mean annual temperature of −6 °C, with mean February and July temperatures of −25 °C and 12 °C, respectively. Annual mean total precipitation is 418 mm, of which 40% falls as snow (Environment Canada, 1993). The growing season is very short, with a mean frost-free period of 60 days per year (mid-June to mid-August). The study region is situated at the northern limit of discontinuous permafrost (Allard and Séguin 1987).

Paleovegetation and paleoclimate

Deglaciation of the region occurred between 7000 and 6500 BP (Lauriol 1982; Gray et al. 1993), followed by marine transgression of the Tyrrell Sea. Following the retreat of marine waters due to isostatic rebound (Gray et al. 1993), tundra plant communities were established in the region which included species of *Salix* and *Betula* (Gajewski et al.

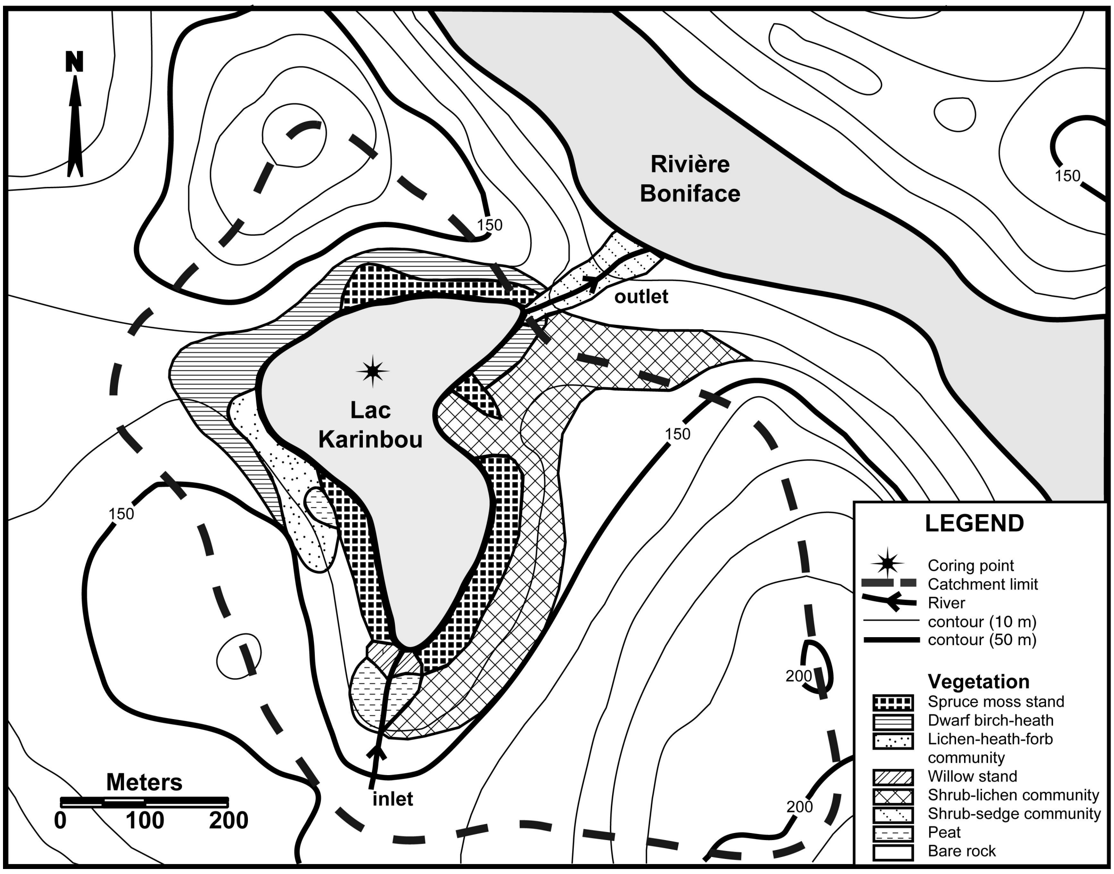

Figure 2. Map of Lake Karinbou's drainage basin showing catchment topography and vegetation.

1993). Maximum *Alnus crispa* percentages between 6200 and 3800 BP suggest a shrub tundra with no clear modern analogues in the region. Spruce arrived by 4600 BP (Payette 1993), forming a forest-tundra vegetation which reached a maximum density between 4500 and 2000 BP (Gajewski et al. 1993). Since 3000 BP, tree density has decreased in the forest-tundra as a result of the combined effects of forest fires and climatic cooling (Payette and Morneau 1993; Arseneault and Payette 1997a, b). An open forest-tundra has persisted since 1500 BP.

Methodology

Field and laboratory methods

In July 1998, one long (total length = 107 cm) and one short sediment core (total length = 27 cm) were taken from the northern part of the lake basin using a modified Livingstone (1955) piston corer and a Glew (1989) gravity corer. Subsampling for diatoms was conducted at 0.5 cm intervals on the short core using a Glew (1988) extruder and at 1 cm intervals on the long core. Sediment subsamples were oven-dried for 24 h at 65 °C to determine water content and burned at 550 °C for 2 h to determine loss-on-ignition (Bengtsson and Enell 1986). The short core sampler allowed coring with minimal disruption of the surficial sediments and therefore our analysis of the top 27 cm of the sediment record was based on the short core, while the deeper record originates from the long core. In the graphs presented in Figures 4–6, the two cores are combined into a single stratigraphy. The match of the two cores was determined from comparisons of the sediment stratigraphy and diatom counts.

Two wood fragments and one sample of organic mud selected from different depths were dated by accelerator mass spectrometry (AMS) at Isotrace Laboratories, University of Toronto (Table 2). Radiocarbon dates were converted to calendar years

Table 1. Limnological and catchment characteristics of Lake Karinbou.

Site characteristics		
Latitude	57°44′06″ N	
Longitude	76°08′89″ E	
Catchment area (km^2)	0.4	
Lake area (km^2)	0.062	
Max. water depth (m)	5.8	
Secchi depth (m)	2.8	
Chemical characteristics	Date	
	03-07-1998	10-08-1998
Conductivity (μS cm^{-1})	20.1	–
Total phosphorus (mg l^{-1})	0.0058	0.0098
Al (mg l^{-1})	0.03	–
pH	6.93	–
K (mg l^{-1})	0.26	0.5
Ca (mg l^{-1})	1.02	1.09
Na (mg l^{-1})	2.05	2.38
DIC (mg l^{-1})	1.73	1.8
DOC (mg l^{-1})	2.68	2.83
NO_3 + NO_2 (mg l^{-1})	<0.01	<0.01
SRP (mg l^{-1})	0.0005	0.0016
SiO_2 (mg l^{-1})	0.88	0.72
SO_4 (mg l^{-1})	1.97	2.3
Cl (mg l^{-1})	3.11	3.54

before present (cal. yr BP) using the program CALIB 3.03 (Stuiver and Reimer 1993). Two more dates have been added to these AMS dates from a long core taken by one of us (K.G.) at a few meters distance in the same lake basin. These gyttja dates were sampled in the same way and analysed at Isotrace. This 256-cm core dates the initial lake phase at 5870 ± 70 BP (TO-5729). The core has previously been analysed for pollen (K. Gajewski, unpublished), extracted from the sediment following methods described in Gajewski et al. (1993). These dates reveal that the core used for the diatom analysis covers about half of the history of Lac Karinbou. As there was a good correlation between the AMS dates of the two cores, we were able to compare our diatom data with the pollen data. A cubic polynomial function was used to describe the changes in sedimentation rates through time (Figure 3).

Preparation of the sediments for diatom analysis was done following strong-acid-digestion techniques using a solution of 50:50 of sulfuric and nitric acid (Wilson et al. 1996). A minimum of 500 diatom valves were counted at 2-cm intervals at 1000× magnification using a Leica DMRB microscope. Diatom identification was mainly based on the floras of Camburn et al. (1984–1986), Lange-Bertalot and Krammer (1989), Krammer and Lange-Bertalot (1986–1991), Krammer (1992), Lange-Bertalot and Moser (1994), Cumming et al. (1995), Lange-Bertalot and Metzeltin (1996) and Fallu et al. (2000). Stratigraphic diatom zones were determined by stratigraphically constrained cluster analysis of the most abundant diatoms (>1% in at least one level) using CONISS (Grimm 1987). In addition, two-way ANOVA (SigmaStat version 1.0) analysis was used to evaluate the statistical significance of the diatom zones.

Statistical analyses

A weighted-averaging (WA) inference model was

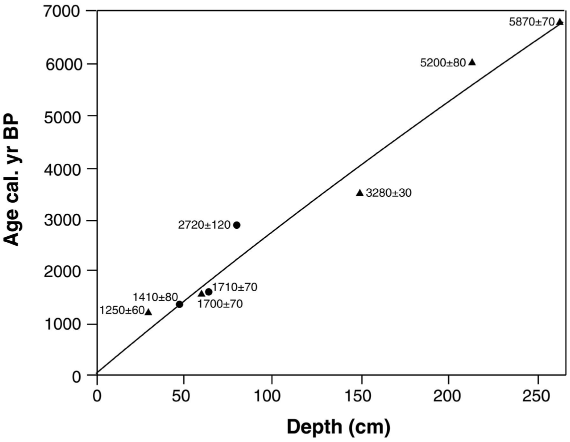

Figure 3. Depth-age model for the two sediment cores. The solid line was plotted using a cubic polynomial function. Dates obtained by K. Gajewski are indicated by triangles (▲). The three dates from the core obtained by K. Ponader and R. Pienitz are indicated by points (●).

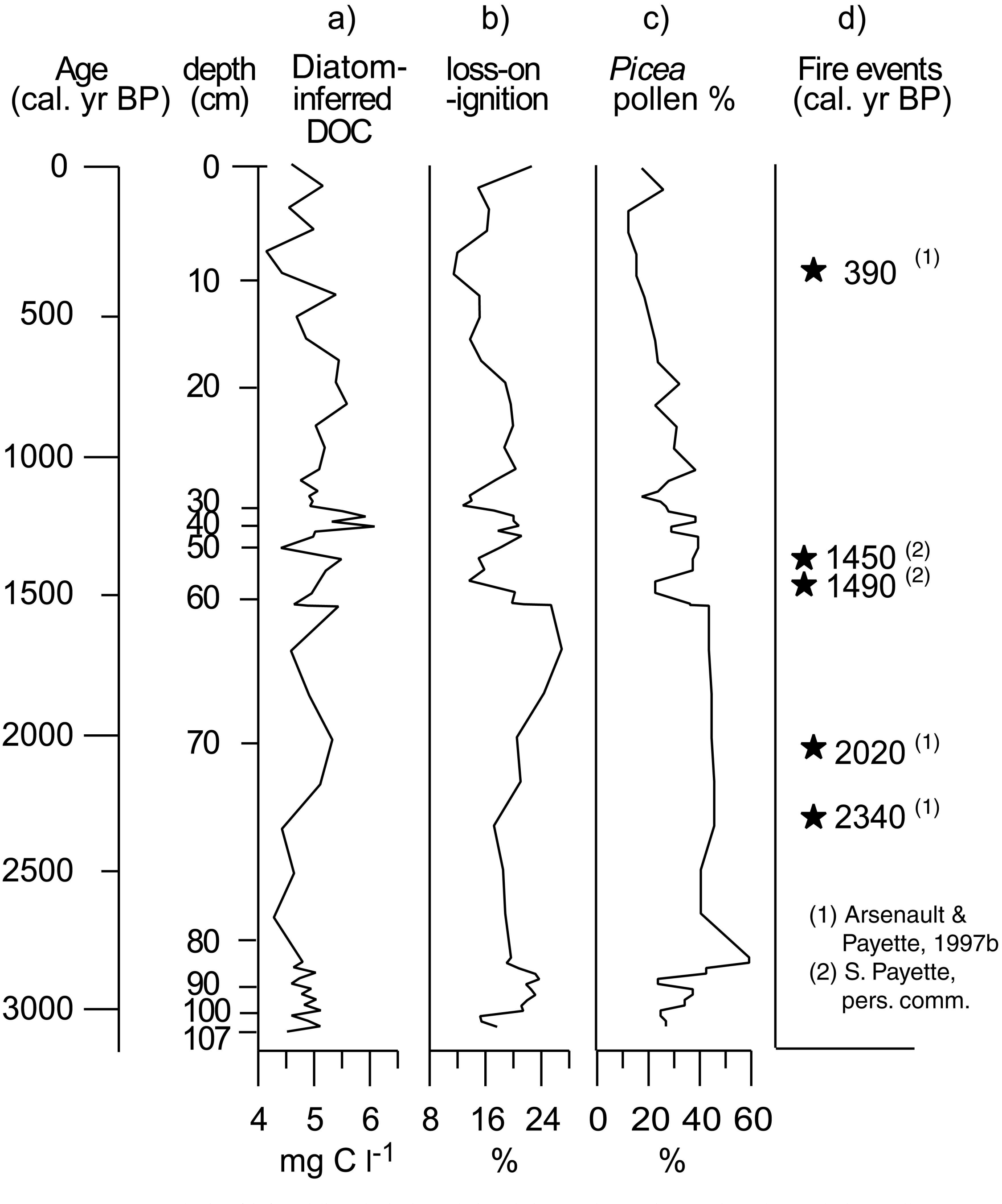

Figure 4. Synthesis of inferred limnological trends in relation to changes in organic carbon and Picea pollen.

applied to the core in order to reconstruct past lakewater dissolved organic carbon (DOC). The model for the reconstruction of lakewater DOC was developed from a calibration set of 59 lakes distributed along a latitudinal gradient in the James Bay and Hudson Bay regions of northwestern Québec (Fallu and Pienitz 1999). The model is based on regions extending from the boreal forest to the arctic tundra and it shows a strong relationship between diatom assemblages and DOC (r^2_{jack} = 0.81; $RMSEP_{jack}$ = 1.23 mg C l^{-1}). The program WA-PLS (Weighted-averaging partial least squares), version

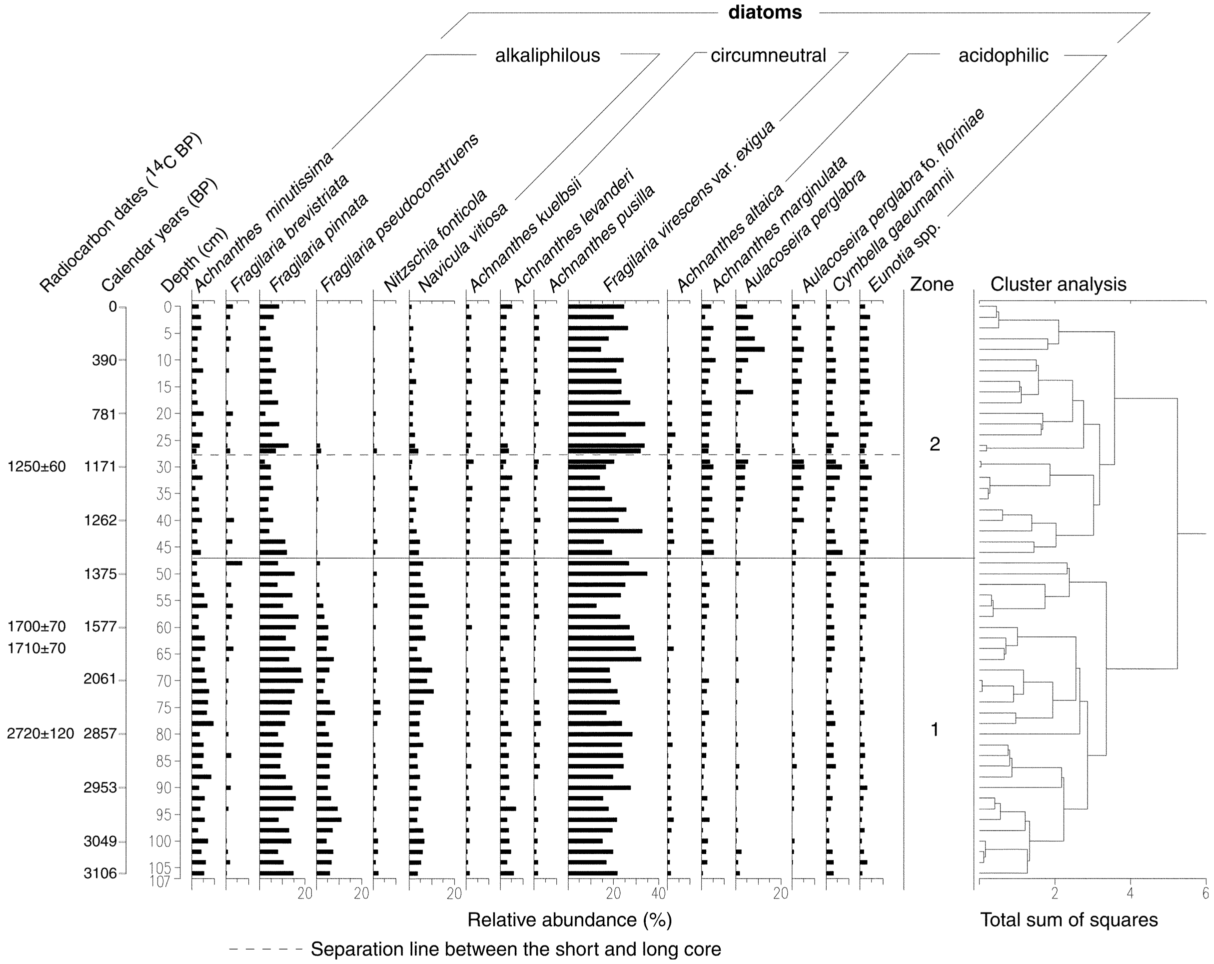

Figure 5. Diatom percentage for Lac Karinbou. Diatoms are ranged according to pH-preferences.

1.0 (ter Braak and Juggins 1993) was used to create the reconstructions.

Assessment of the reliability of diatom-based reconstructions followed the methods of Laing et al. (1999). First, we used the program ANALOG, version 1.6 (Birks and Line, unpublished) to evaluate the degree of dissimilarity between the fossil core assemblages and the assemblages contained in the models. A dissimilarity coefficient (DC) based on squared chord distance was selected (Overpeck et al. 1985). The mean minimum DC distance between samples in the calibration set was calculated, and used to determine confidence limits for cut-off criteria (Laird et al. 1998). All levels in the core with minimum DC distances which were situated between the upper 75% and 95% confidence intervals of the calibrated set were considered to be 'poor analogs' with the calibration set. Core samples beyond the upper 95% confidence limit have no analogs in the model.

A goodness-of-fit analysis was used to evaluate how reliably the model predicted environmental variables at each depth in the core (Birks 1995). We used the computer program CANOCO version 4 (ter Braak 1998) to apply a CCA (canonical correspondence analysis) constrained to the environmental variable to be reconstructed (DOC; axis 1) for the calibration model samples. The 95% confidence limits were determined based on the squared residual distances of calibration model samples to axis 1. The fossil samples were plotted passively on the same CCA diagram and the squared residual distances of each fossil sample to axis 1 were calculated. All fossil levels with squared residual distances greater

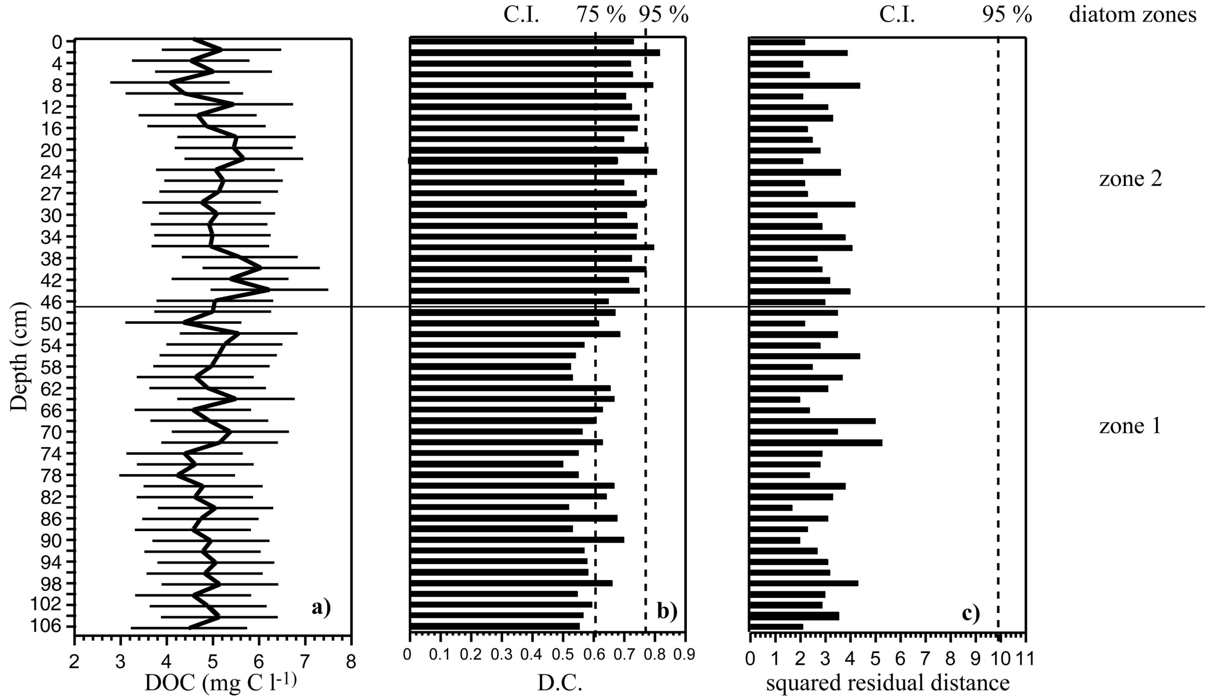

Figure 6. Reconstructions of diatom-inferred DOC (a), analogs between diatom assemblages in the sediment cores and calibration model (b) and DOC analogs of diatom assemblages in the sediment cores (c). Horizontal lines in (a) show the margin errors. Dotted lines in (b) and (c) show the 75% and 95% confidence limits.

than the upper 95% confidence limit were not considered to have a good fit to the model (Birks et al. 1990; Laing et al. 1999).

Results

Sediment stratigraphy and chronology

The sediment sequence is composed entirely of organic gyttja. The loss-on-ignition (LOI; Figure 4) varies between 12 and 24% and shows a slight decrease through time during the last 3000 years. The dating chronology shows only slight variations from a constant mean sedimentation rate of 0.39 mm/year over the same period (Figure 4).

Diatom stratigraphy

A total of 204 taxa in 24 genera were identified within the sediments. The diatom flora was dominated by small benthic taxa of *Fragilaria* (*F. pseudoconstruens* Marciniak, *F. pinnata* Ehrenberg, *F. virescens* var. *exigua* Grunow in Van Heurck) and *Achnanthes* (*A. levanderi* Hustedt, *A. marginulata* Grunow, *A. minutissima* Kützing) together with taxa

Table 2. AMS radiocarbon dates from Lac Karinbou sediments.

Lab. number	Depth (cm)	Material	Age (^{14}C yr BP)	Age (cal. yr BP)
TO-5734	27–30	gyttja	1250 ± 60*	1171*
TO-8182	47–48	gyttja	1410 ± 80	1334
TO-5733	58–60	gyttja	1700 ± 70*	1577*
TO-7550	64	wood	1710 ± 70	1584
TO-7551	80–81	wood	2720 ± 120	2857

The calibrated dates in calendar years BP are the midpoint of the probability range of dates using CALIB 3.03 (Stuiver and Reimer 1993). Two dates from a long core sampled by K. Gajewski* have been added to the dates from the core used for diatom analysis.

belonging to the genera *Aulacoseira*, *Navicula*, *Cymbella* and *Eunotia* (Figure 5). *Fragilaria virescens* var. *exigua* was the dominant species throughout the core with abundances ranging between 13–35%. It seems to prefer circumneutral to slightly acidic waters (Krammer and Lange-Bertalot 1986–1991; Pienitz and Smol 1993; Pienitz et al. 1999) and reflects the measured pH of the lake water (Table 1).

Two diatom zones can be distinguished in the core from the cluster analysis, the first from the surface to 46 cm depth and the second from 48 to 106 cm depth (Figure 5). Two-way ANOVA for the 16 species in Figure 5 confirmed that there was a significant difference in species composition between the two zones (F = 13.1, p = 0.00031). Individual *t*-test comparison showed that for 12 of these species there was a significant difference ($p < 0.05$) between the upper and lower portions of the core. Between ca. 3100 and 1300 cal. yr BP (diatom zone 1), Lac Karinbou was dominated by benthic, circumneutral to alkaliphilous taxa (Figure 5). The dominant taxon was *Fragilaria virescens* var. *exigua* with 12–35% abundance and it occurred in association with the alkaliphilous taxa *Fragilaria pinnata* (8–19%) and *Navicula vitiosa* Schimanski (3–11%). The autecology of *Navicula vitiosa* is not well known. Our classification is based on the data of Pienitz et al. (1995), who found this taxon in circumneutral to alkaline lakes in the Yukon (pH range from 6.9 to 9.3). Other autecological data from subarctic Scandinavia confirm the classification of this species as circumneutral to slightly alkaliphilous with estimated pH optima of 6.8 (Rosén et al. 2000) and 7.3 (Weckström 2001). With 1–11% abundance, the alkaliphilous *Fragilaria pseudoconstruens* also formed an important component of the assemblage. Sub-dominant taxa were benthic alkaliphilous *Achnanthes minutissima* (1–8%), *Fragilaria brevistriata* Grunow (0.2–7%) and tychoplanktonic *Nitzschia fonticola* Grunow (0.2–3%), as well as benthic circumneutral to acidophilic species of the genera *Achnanthes* and *Navicula*.

Zone 2 (ca. 1300 cal. yr BP to present) is characterized by a shift from pennate alkaliphilous to centric acidophilous diatom taxa, dominated by *Aulacoseira* spp. (Figure 5). With 14–34% abundance, *Fragilaria virescens* var. *exigua* remained the most abundant species. The most pronounced changes in this zone were the decrease of *Fragilaria pinnata* to 2–13% and of *Navicula vitiosa* to 1–5%, accompanied by a significant increase in the acidophilous centric taxon *Aulacoseira perglabra* (Østrup) Haworth (up to 13%). Other acidophilic species also increased, such as *Cymbella gaeumannii* Meister (1–7%), *Achnanthes marginulata* (2–6%), *Aulacoseira perglabra* var. *floriniae* (Camburn) Haworth (1–5%), *A. distans* (Ehrenberg) Simonsen (0.4–3%), and *A. distans* var. *nivalis* (W. Smith) Haworth (0.2–3%), as well as *Eunotia* spp. (1–5%). Subdominant taxa were small, circumneutral to acidophilous species dominated by *Achnanthes* spp.

Evaluation of model fit

Statistical analyses showed that the application of the diatom-based model to the core assemblages is valid, with some restrictions for diatom zone 2. Goodness-of-fit analyses indicated a good fit of core samples to the reconstructed variable DOC, with all core residuals falling within the 95% confidence intervals (Figure 6c). The analogs between diatom assemblages in the DOC model and those in the core samples, as evaluated by ANALOG, were generally good, with a great majority (89%) of the core samples falling within the 95% confidence interval (Figure 6b). This result, in addition to that of the goodness-of-fit, suggests that the application of the DOC model to the fossil data is justified. However, analogs between the model and the core species are relatively weak in diatom zone 2, where 9% of the core samples were judged non-analogs, due to the higher abundances of *Aulacoseira perglabra, Achnanthes altaica* (Poretzky) Cleve-Euler and *Achnanthes levanderi* relative to the model. Therefore, the absolute values for reconstructed DOC should be interpreted with caution in this zone (from ca. 1300 cal. yr BP to present).

Diatom-based paleolimnological reconstructions

Reconstructed concentrations of lakewater DOC were reasonably constant (~5 mg C l^{-1}) over the past 3000 years (variation from 4.1 to 6.2 mg C l^{-1}) (Figure 6a). Between 106 and 76 cm (3100–2500 cal. yr BP), DOC is particularly constant with variations around a mean value of 4.8 mg C l^{-1} (SD = 0.27). DOC levels then increased slightly between 74 and 12 cm (ca. 2400–500 cal. yr BP) (mean = 5.1 mg C l^{-1}; SD = 0.42). From 500 cal. yr BP to the present, DOC decreased again to a minimum of

4.1 mg C l^{-1} at ca. 300 cal. yr BP, with an inferred value of 4.6 mg C l^{-1} for the most recent sediments.

Pollen stratigraphy

In Lake Karinbou sediments, maximum *Picea* percentages occurred between ca. 2900 and 1600 cal. yr BP and have declined since that time (Figure 4). There was a notable decrease beginning around 1300 cal. yr BP and *Picea* percentages have been steadily decreasing over the past 1100 years. Variations in the % *Picea* pollen and LOI curves were similar for the past 1800 years (Figure 4). The overall pollen stratigraphy broadly resembles that of Lake LB1 (Gajewski et al. 1993), located a few tens of kilometers to the east, in an area with much less abundant *Picea* in the landscape.

Discussion

The diatom community remained relatively constant throughout the course of the last 3000 years, with no evidence of major changes (Figure 5). The predominance of *Fragilaria virescens* var. *exigua* is typical of northern Canadian Shield lakes (Fallu and Pienitz 1999; Pienitz et al. 1999; Fallu et al. 2000; Saulnier-Talbot and Pienitz 2001; Laing and Pienitz, unpublished) and its continuous downcore abundance suggests that no abrupt limnological changes have occurred over the last 3000 years.

Diatom-inferred reconstructions show relative stability in DOC (about a mean of 5 mg C l^{-1}) throughout the late Holocene. The actual values of DOC measured in Québec forest-tundra lakes vary between 2.7 and 6.5 mg C l^{-1}(Fallu and Pienitz 1999), thus inferred concentrations correspond to typical lake conditions within this vegetation zone. The difference between the DOC concentration measured during the summer of 1998 (2.5–2.9 mg C l^{-1}) and the inferred value (4.6 ± 1.23 mg C l^{-1}) may be explained by the tendency of the applied training-set to over-estimate reconstructed DOC values at the lower 'edge' of its range (2.3–19.4 mg C l^{-1}) (Fallu and Pienitz 1999). Also, DOC concentrations in subarctic lakes show some seasonal and interannual variation (Gibson et al. 2001).

Of secondary importance after *F. virescens* var. *exigua*, diatom assemblages were dominated by alkaliphilous taxa, such as *Fragilaria pinnata*, *F. pseudoconstruens* and *Navicula vitiosa* between ca. 3100 and 1300 cal. yr BP (diatom zone 1, Figure 5). These *Fragilaria* species are abundant in tundra lakes, as they are competitive under oligotrophic conditions in high latitude lakes with extended periods of ice cover (Smol 1988; Pienitz and Smol 1993; Laing et al. 1999). The abundance of these taxa in Lac Karinbou indicates that alkalinity was higher during this period, which may be due to successional shifts in the weathering of soluble carbonate minerals from surficial glacial till deposits in the catchment (e.g. Pienitz et al. 1999; Engstrom et al. 2000). In addition, more alkaline conditions may have resulted from short-term alkalinity pulses due to increased fire activity in the study area between ca. 2340 and 1450 cal. yr BP (Arseneault and Payette 1997a, b; S. Payette, personal communication; Figure 4). Korsman and Segerström (1998) and Korhola et al. (1996) reported short-lived inputs of alkaline ashes following fire events in northern lakes which are accompanied by shifts in diatom community composition.

Based on the *Picea* pollen profile (Figure 4), we infer that spruce trees reached their maximum abundance in the catchment about 2900 cal. yr BP and since then gradually decreased. Payette and Morneau (1993) and Arseneault and Payette (1997a, b) provided evidence for a gradual opening in the forest-tundra cover of the Rivière Boniface region after about 3200 cal. yr BP in response to the combined effect of more frequent forest fires and climatic cooling. Qualitative estimates of charcoal in the lake sediments revealed higher occurrences of particles (size $< 200\ \mu m$, data not shown) between ca. 2300 and 1400 cal. yr BP, thereby also suggesting increased fire activity.

The most evident change in diatom assemblages occurred ca. 1300 cal. yr BP (diatom zone 2), marked by an increase of acidophilous diatoms including the periphytic *Achnanthes marginulata*, *Cymbella gaeumannii* and *Eunotia* spp., as well as the centric tychoplanktonic *Aulacoseira* spp. (Figure 5). This shift implies a trend towards less alkaline waters in Lac Karinbou from 1300 cal. yr BP until the present day, which may be related to a natural acidification process combined with the effect of decreasing in fire activity since about that time. Natural acidification usually occurs as a result of successional changes in lakes on granitic bedrock characterized by poor soil development in North America (e.g., Whitehead et al. 1989; Charles et al. 1989; Ford 1990; Laing et al. 1999; Engstrom et al.

2000; Saulnier-Talbot and Pienitz 2001) and in Scandinavia (Renberg and Hellberg 1982; Renberg et al. 1993; Korsman and Segerström 1998; Korsman 1999).

During the same time period, *Picea* pollen abundances and loss-on-ignition continued to decrease (Figure 4). However, in contrast to paleolimnological studies at the northern tree-line, documenting changes in lakewater DOC in relation to shifts in catchment vegetation (Pienitz et al. 1999; Seppä and Weckström 1999), no such clear response in diatom-inferred DOC to decreasing *Picea* abundances emerges from our study (Figure 4). Several possible reasons may explain this. A gradual paludification process in a small peatland near the inlet of Lac Karinbou has occurred in the lake watershed since ca. 1500 cal. yr BP, as suggested by increases in peat-associated taxa in the diatom record (*Eunotia* spp.) and *Sphagnum* spores. This would have caused an increase in nutrients and DOC and may have muted the expected decrease in DOC caused by less spruce trees in the catchment. The most likely explanation is that changes in the spruce pollen abundances reflect regional changes in vegetation density and that these changes were less pronounced in the immediate lake basin. The size of Lac Karinbou (diameter of ca. 300 m) suggests that the pollen source area would be more regional than local (Jacobson and Bradshaw 1981). Also, Neoglacial cooling and fire events may have more strongly affected vegetation cover on the upland regions, while trees growing in the immediate lake basin were less affected. The lake's small drainage basin is located in a depression, which likely provided protection from fires for trees growing on the immediate slopes as they are covered by spruce stands today (Figure 2). Since inputs of allochthonous DOC and nutrients originate mostly from the immediate catchment, less pronounced vegetational change on the slopes resulted in no major change in the water chemistry. However, some of the short-lived oscillations in diatom-inferred DOC and LOI during the past 3000 years may be associated with changes in spruce (Figure 4). Short-lived decreases in LOI and DOC at 2200 cal. yr BP, 1600 cal. yr BP, 1300 cal. yr BP and 400 cal. yr BP coincide with similar changes in *Picea* pollen percentages.

Given that DOC exerts a major control on the penetration of solar ultraviolet radiation (UVR) and photosynthetically available radiation (PAR) in northern lake waters (Laurion et al. 1997), these results also suggest that underwater spectral irradiance has remained constant in this lake throughout the late Holocene. Water transparency for UV radiation ($1/K_{d320}$, where K_{d320} is the diffuse attenuation coefficient for downwelling UV radiation at 320 nm) can be calculated from the inferred DOC values using the equations in Gibson et al. (2000) for northern lakes, revealing a mean value of 0.1 m for Lac Karinbou during the last 3000 years (coefficient of variation (CV) = 16.7%). During the same period, water transparency for PAR ($1/K_{dPAR}$) averaged 1.7 m with a CV of only 9.4% (data not shown). This contrasts markedly with the two order-of-magnitude changes in the UVR and PAR transparency over the Holocene found in tree-line lakes further to the west (Pienitz and Vincent 2000).

Conclusions

Fossil diatom assemblages from Lac Karinbou were dominated by the taxon *Fragilaria virescens* var. *exigua* from ca. 3000 cal. yr BP to the present, indicating that limnological conditions at this site have changed little over time. The diatom record shows a gradual replacement of initially dominant alkaliphilous taxa by acidophilous taxa beginning ca. 1300 cal. yr ago. This shift probably reflects a long-term natural acidification process of the lake due to progressive loss of base cations from weathered soils and rocks. Decreasing fire activity since 1300 cal. yr. and reduced inputs of alkaline ash may also have contributed to this trend. Diatom-inferred DOC concentrations remained stable over the past 3000 years and displayed a weak response to vegetation change as indicated by decreasing *Picea* pollen abundances since ca. 1300 cal. yr BP. Despite the gradual opening of regional forest cover occurring since that time, these changes were not pronounced enough to have had a major impact on organic matter inputs into Lac Karinbou. Our paleolimnological data confirm previous palynological studies suggesting little variation in vegetational conditions near tree-line in northwestern Québec despite evidence of Neoglacial cooling (Gajewski et al. 1993; Lavoie and Payette 1996). Our results are in sharp contrast to paleolimnological studies from northwestern Canada and the Canadian High Arctic (e.g., Douglas et al. 1994; Overpeck et al. 1997; Rouse et al. 1997; Hughen et al. 2000), which associate abrupt limnological changes in surface sediments with recent global warming trends. Lac Karinbou fossil records reveal no such changes in its recent history but instead indicate climatic stability. This is in agreement with measured (Allard and Seguin 1987; Environment Canada 1997; International Arctic Science Committee 1999) and inferred (Lavoie and Payette 1996; Payette and Gagnon 1985) temperature trends for the Québec-Labrador Peninsula region. Similar research is presently ongoing at a broader regional scale, in order to provide a more complete image of past limnological changes in northern Québec and to preview the impact of future climatic change on northern freshwater ecosystems.

Acknowledgements

This project was funded by research grants from Natural Sciences and Engineering Research Council Canada to R.P., W.F.V. and K.G., from Fonds pour la formation de Chercheurs et de l'Aide à la Recherche to R.P. and W.F.V., and by logistic support from CEN. A scholarship (Government of Canada Awards) from the International Council for Canadian Studies (ICCS) to K.P. is gratefully acknowledged. We wish to thank S. Boudreau, S. Campeau, M.-A. Fallu, J. Gibson, T. Laing, É. Saulnier-Talbot and K. Swadling for their assistance in the field and in the laboratory.

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