Heightened sensitivity of a poorly buffered high arctic lake to late-Holocene climatic change

Neal Michelutti a,b,⁎, Marianne S.V. Douglas b, Alexander P. Wolfe c, John P. Smol a

a Paleoenvironmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, Kingston, Ontario, Canada K7L 3N6
b Department of Geology, University of Toronto, Toronto, Ontario, Canada M5S 3B1
c Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2E3

Received 16 August 2004
Available online 24 March 2006

Abstract

A diatom-based paleolimnological investigation was conducted on late Holocene sediments from a poorly buffered lake, informally named “Rock Basin Lake”, on Ellesmere Island, Arctic Canada. The fossil diatom record is unlike any other obtained thus far from high arctic regions, exhibiting dynamic assemblage shifts over the entire ∼3300 yr sedimentary record. Multiple proxies (i.e., diatoms, pH reconstructions, biogenic silica, C/N ratios, total organic carbon) appear to sensitively track rapid limnological changes, which are associated with distinct climate intervals as inferred from other regional proxy records. The highly responsive nature of the diatom assemblages in Rock Basin Lake, relative to those recorded from nearby alkaline sites, appears to be related to this lake’s limited ability to buffer changes in pH. The dynamic species responses suggest that the diatoms in Rock Basin Lake are faithfully tracking climatic changes, and that low-alkalinity lakes may provide the most sensitive diatom-based paleolimnological records from high arctic regions.

© 2006 University of Washington. All rights reserved.

Keywords: Paleolimnology; Arctic Canada; Soft-water lakes; Diatoms; pH; Climate change

Introduction

Although high arctic lakes and ponds are considered highly responsive to climatic changes (Douglas et al., 1994; Douglas and Smol, 1999; Birks et al., 2004a,b), not all freshwater ecosystems will respond to climatic forcing in an identical manner (Smol and Cumming, 2000), and the most useful paleolimnological records will be obtained from sites selected with regard to their sensitivity to climatic fluctuations (Smol et al., 1991). Paleolimnological evidence from alpine and mid arctic regions suggests that diatoms in low alkalinity lakes are particularly responsive to climatic fluctuations due to a limited ability to buffer climate-driven pH shifts (Psenner and Schmidt, 1992; Sommaruga-Wögrath et al., 1997; Koinig et al., 1998; Wolfe, 2002; Schmidt et al., 2004).

Rock Basin Lake, a poorly buffered lake located on east-central Ellesmere Island (Fig. 1), was the site of the first detailed paleoecological studies in the High Arctic (Smol, 1983; Hyvärinen, 1985). Initial paleolimnological results led to hypotheses regarding mechanisms of climatic influences over arctic diatom assemblages, and provided early insights into Holocene climatic variability in this region (Smol, 1983, 1988). However, these initial studies on Rock Basin Lake do not contain the most recent environmental history, as the uppermost sediments were lost during coring procedures (Blake, 1981).

Here, we present results from a new sediment core from Rock Basin Lake that captures an undisturbed record of the lake’s most recent history. These data, in conjunction with previous research (Smol, 1983; Hyvärinen, 1985), will allow for a more complete record of Holocene environmental change from this region. Our paleoenvironmental inferences are based on primary and derived diatom data, including ecological interpretations of assemblage shifts and quantitative pH reconstructions, as well as other proxies such as biogenic silica, total organic carbon, and C/N ratios. Our reconstructions reveal dramatic changes in diatom composition and ecology that are markedly different from all other high arctic records documented to date. These results strongly suggest that poorly buffered
lakes may provide the most sensitive (diatom-based) paleoclimatic reconstructions in the High Arctic.

Site description

Rock Basin Lake (unofficial name, 78°29.5′N, 76°44.3′W) is a small (∼250 × 150 m), relatively deep (Z_{max} ≈ 15 m), single basin lake located at the head of Baird Inlet, on east-central Ellesmere Island, High Arctic Canada (Fig. 1). The lake, at an altitude of 295 m asl, occupies a steep-sided basin glacially eroded in Precambrian gneissic bedrock. The lake is surrounded by valley glaciers, and is ice-free for only a few weeks in July and August. In cooler years, it may remain partially ice-covered throughout the summer.

Summer water chemistry measurements from various intervals between 1979 and 2004 indicate that the lake is generally acidic (Table 1) but experiences large fluctuations in pH (range from pH 5.2 to 7.0, mean = 6.04, standard deviation = 0.72, n = 6). The lake is very dilute (range in specific conductance from 5 to 23 μS/cm), ultraoligotrophic (total phosphorus ∼5 μg/L) and has low alkalinity (dissolved inorganic carbon = 1.1 mg/L). Vegetation on the south-facing slopes above the lake is relatively lush and includes mainly Empetrum nigrum (crowberry), Vaccinium uliginosum (bog whortleberry), and Cassiope tetragona (arctic white heather) (Blake, 1981). Bridgland and Gillet (1983) provide a more detailed list of vascular plants from this region.

Methods

Water chemistry

Measurements of lakewater pH and specific conductance were obtained during the summers of 1987, 1983, and 1979 (Table 1). Water samples collected during the summers of 1998, 2001, and 2004 were analyzed at the National Laboratory for Environmental Testing at the National Water Research Institute (NWRI) for major and minor ions, phosphorus, nitrogen,
chlorophyll a, dissolved organic carbon, dissolved inorganic carbon and metals. Protocols for bottling and filtering, and methods for chemical analyses are given in Environment Canada (1996a,b). Measurements of pH, temperature, and specific conductance were performed in the field.

**Sediment core recovery**

On July 12, 1998, a 49-cm-long sediment core was obtained from the centre of Rock Basin Lake using a large diameter gravity corer (7.62 cm inner diameter), specifically designed to collect high-resolution surface sediment cores (Glew, 1989). The core was extruded on-site and sectioned into 0.5-cm intervals for the first 5 cm, and 1-cm intervals thereafter (Glew, 1988).

**Sediment core chronology**

Sediment chronology was established using both $^{210}$Pb and $^{14}$C dating techniques. Alpha spectroscopy $^{210}$Pb determinations were performed at NWRI, and the dates were calculated using the constant rate of supply model (Yang and Turner, 2000) (Table 2). Accelerator mass spectroscopy (AMS) $^{14}$C measurements, based on bulk sediment increments 1 cm thick, were performed at Isotrace Radiocarbon Laboratory. The results were corrected for natural and sputtering isotope fractionation to a base $\delta ^{13}C = -25\%$o, using the measured $^{13}C/^{12}C$ ratios. Sediment ages were calibrated to calendar years (cal yr B.P.) (Table 3) following Stuiver et al. (2005) and, in order to match the timescale of the $^{210}$Pb dates, adjusted for zero age at 1998 (the date of sediment core recovery).

**Statistical procedures and pH inference model development**

The pH inference model from Joynt and Wolfe (2001), derived from 61 low pH lakes from Baffin Island, was considered applicable to our study because it was designed to maximize the climate-driven pH relationship by selecting lakes not influenced by carbonate catchments, and was also based on arctic lakes of similar size and morphology to Rock Basin Lake. Only those sediment core (fossil) taxa with relative abundances greater than 1% at any one interval and calibration (modern) taxa with relative abundances greater than 1% in at least 3 sites were included in the statistical analysis. In an effort to ensure taxonomic consistency between the modern and fossil datasets, diatom micrographs from both datasets were reviewed for potentially problematic taxa. The taxonomic consistency between the two datasets was excellent, with only minor adjustment needed to match the fossil dataset. These “adjustments” primarily involved the grouping together of taxa that were split in one, but not the other, diatom dataset.

Taxonomic changes made to the modern dataset necessitated re-running the original Joynt and Wolfe (2001) pH inference model. Additionally, one site in the calibration set was deemed an outlier, based on its site scores falling outside of the 95% confidence limits for both species assemblages (run from a Detrended Correspondence Analysis) and environmental variables (run from a Principal Components Analysis). The resulting model, slightly modified from its original form in Joynt and Wolfe (2001), included 100 taxa and 60 sites and was developed with $^{13}$C (Juggins, 2003) using weighted-averaging (WA) regression and calibration with classical de-shrinking. Diatom-inferred pH (DI-pH) reconstructions were compared to the site scores from the first axis of a Correspondence Analysis (CA), which captures the main direction of species variability in the absence of any a priori ecological constraint(s).

The program ANALOG ver. 1.6 (Line and Birks, unpublished program) was used to calculate the degree of dissimilarity between modern and fossil assemblages. The squared Euclidean distance, an unweighted dissimilarity coefficient (DC) whose values are most influenced by common and dominant taxa, was used to compare each fossil sample with all modern samples. Fossil diatom assemblages with minimum DCs greater than the 95th percentile of the minimum DCs calculated from the calibration taxa were considered to have poor analog matches.

**Diatoms and geochemical proxies**

Preparation of the sediment for diatom analyses followed standard protocols for siliceous microfossils (Wilson et al., 1996). A minimum of 400 diatom valves were identified and enumerated at each interval. Diatom species were identified primarily following Krammer and Lange-Bertalot (1986/1991), and Patrick and Reimer (1966, 1975). Biostratigraphic zones in our fossil diatom profile were constructed by cluster analysis using constrained incremental sum of squares (CONISS; Grimm, 1991), with square chord distance as the measure of dissimilarity.

Biogenic silica (BSiO₂) is a measure of silica production by diatoms and chrysophytes, commonly the dominant phototrophs in arctic lakes (Douglas and Smol, 1999), and therefore is a reasonably good proxy for whole-lake production (Conley and Schelske, 2001). BSiO₂ concentrations were determined using a wet alkaline extraction, as summarized by Conley and Schelske (2001). Sediments were leached with a weak base (Na₂CO₃),

---

**Table 2** $^{210}$Pb dates for the 1998 Rock Basin Lake sediment core as derived from the constant rate of supply (CRS) model

<table>
<thead>
<tr>
<th>Core depth (cm)</th>
<th>Uncompacted mid-depth (cm)</th>
<th>Cumulative dry mass (g/cm²)</th>
<th>Unsupported activity (pCi/g)</th>
<th>CRS year (A.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.5</td>
<td>0.64</td>
<td>0.02</td>
<td>9.293</td>
<td>1989</td>
</tr>
<tr>
<td>0.5–1</td>
<td>2.18</td>
<td>0.04</td>
<td>4.752</td>
<td>1966</td>
</tr>
<tr>
<td>1–1.5</td>
<td>5.17</td>
<td>0.08</td>
<td>1.338</td>
<td>1929</td>
</tr>
<tr>
<td>1.5–2</td>
<td>8.39</td>
<td>0.10</td>
<td>0.153</td>
<td>1906</td>
</tr>
</tbody>
</table>

---

**Table 3** AMS radiocarbon dates for the Rock Basin Lake sediment core

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>$^{14}$C yr B.P.</th>
<th>Two sigma ranges (cal. yr B.P.)</th>
<th>Cal yr B.P.</th>
<th>$\delta ^{13}$C</th>
<th>IsoTrace Lab no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–21</td>
<td>1150 ± 40</td>
<td>970–1172</td>
<td>1071</td>
<td>−32.20</td>
<td>TO–9663</td>
</tr>
<tr>
<td>28–29</td>
<td>2210 ± 50</td>
<td>2114–2342</td>
<td>2228</td>
<td>−32.37</td>
<td>TO–9664</td>
</tr>
<tr>
<td>36–37</td>
<td>2280 ± 40</td>
<td>2297–2352</td>
<td>2325</td>
<td>−32.99</td>
<td>TO–9665</td>
</tr>
<tr>
<td>48–49</td>
<td>3110 ± 50</td>
<td>3213–3415</td>
<td>3314</td>
<td>−34.09</td>
<td>TO–9668</td>
</tr>
</tbody>
</table>
and aliquots were withdrawn after 2, 3, 4, and 5 h. The aliquots were then measured for the amount of total extracted silica (mineral and biogenic), using a LKB Ultraspec II spectrophotometer. BSiO₂ determinations were calculated as the y-intercept of a least squares regression line of absorbency vs. extraction time. A calibration curve constructed from known silica standards was used to convert absorbency readings to mg/L, which in turn were converted to % BSiO₂ based on sediment density measurements for each interval. The % BSiO₂ values below 24.5 cm depth were calculated using an average sediment density of 2.05 g/cm³ (the mean value from 0 to 24.5 cm depth), as density measurements were not available for this portion of the core.

The C/N ratios of lake sediments can provide insight into changes of source organic matter over time. C/N ratios between 4 and 10 are indicative of aquatic organic matter, whereas terrestrial organic matter has a C/N ratio greater than 20 (Meyers and Teranes, 2001). Total organic carbon (TOC) reflects the balance between organic matter production and decomposition, and as such, partially tracks aquatic production (Meyers and Teranes, 2001). Preparation of the sediment for TOC and C/N determinations involved involving leaching the samples overnight in 2 N HCl at room temperature, followed by 4 washes with deionised water to remove any remaining acid. Following freeze-drying, TOC and C/N ratios were determined by pyrolysis using a Leco® CNS-2000 Elemental Analyzer.

Results

Water chemistry

Low dissolved inorganic carbon (DIC) concentrations (1.0 mg/L) and an acidic pH (6.03) recorded during the summer of 2004 were consistent with previous measurements (Smol, 1983), reconfirming that Rock Basin Lake is a poorly buffered, slightly acidic lake (Table 1). Although only pH and specific conductance are available for most years, the data illustrate that pH experienced relatively large fluctuations (range from pH 5.2 to 7.0), whereas specific conductance remained relatively dilute (range from 5 to 23 μS/cm).

Sediment core chronology

An age-depth model was developed using two linear regressions constrained between (1) the oldest ²¹⁰Pb date and youngest ¹⁴C date and (2) the ¹⁴C dates at 20.5, 36.5 and 48.5 cm depths (Fig. 2). Contamination of the ¹⁴C measurement at 28.5 cm depth was suspected as this age produced a sedimentation rate over the interval between 28.5 cm and 36.5 cm that is over ten times greater than (1) other sections of this core; (2) an independently ¹⁴C-dated core from Rock Basin Lake (Smol, 1983); and 3) arctic lakes in general (Korhola and Weckström, 2004). Moreover, there are no sedimentological or biostratigraphic indications to suggest highly nonlinear sedimentation during this interval. Thus, the age at 28.5 cm depth is reported but not included in the construction of our age model.

Figure 2. Age model used for the chronology of Rock Basin Lake, showing ²¹⁰Pb dates (triangles) and ¹⁴C ages adjusted for zero age at 1998 (squares). Data on the ²¹⁰Pb dates and ¹⁴C ages can be found in Tables 2 and 3, respectively.

Overall, sedimentation rates appear largely uniform over time, with a slightly higher rate during the early part of the record (Fig. 2). Due to the absence of calcareous rocks in the catchment, and low alkalinity in the water column, a reservoir effect was not suspected and thus no age corrections were deemed necessary to the reported ¹⁴C ages.

Model performance and DI pH reconstructions

The modified model of Joynt and Wolfe (2001) showed a relatively good relationship between the measured and DI-pH values ($r²_{boot} = 0.44$, $P < 0.01$, RMSE$_{boot} = 0.34$), and the lack of any statistically significant trends in the residuals ($r² = 0.00$) suggests that WA with classical deshrinking is suitable to track overall trends in pH from Rock Basin Lake (Figs. 3A, B). Our DI-pH reconstructions ranged from pH 6.15 to 7.08, which is nearly twice as large as the pH ranges inferred from soft-water alpine (Koinig et al., 1998) and mid-arctic (Wolfe, 2002) lakes.

Over 70% of Rock Basin Lake fossil taxa also occur in the calibration dataset, with all but two of these taxa (Gomphonema parvulum and Achnanthes saccula) present in at least 25% of the calibration lakes (Table 4). Only 17% of the fossil samples were deemed to have good modern analogs with the calibration taxa. However, the analog approach only indicates that differences exist between the fossil and calibration taxa and does not affect the reliability of our pH reconstructions, when using WA techniques, provided that a large number of the fossil taxa are present in sufficient frequencies in the calibration dataset (Birks, 1998). Thus, we are confident that our reconstructions reliably track pH trends over time, with the possible exception of diatom zones 1 and 2, where G. parvulum, a taxon represented in less than 4% of the calibration lakes, dominates the fossil assemblage (Fig. 4). In fact, pH appears to be tracking the main direction of variation in the fossil assemblages (excluding pH reconstructions from diatom zones 1 and 2), as indicated by a significant correlation between DI-pH and CA axis 1 ($r² = 0.71$, $P < 0.01$).
Diatoms and geochemical proxies

Fifteen fossil diatom taxa were categorized as dominant (relative abundance $\geq 10\%$ in any one interval) and were plotted in a stratigraphy in order of their CA axis 1 scores (Fig. 4). The diatom zones constructed in Figure 4 provide a common framework to discuss taxa shifts and facilitate comparisons between proxy records.

Diatom zones 1 and 2 ($\sim 3300$ to $2500$ yr ago) are characterized by an overwhelming dominance of the moss epiphytes *Gomphonema parvulum* and *Pinnularia biceps* (Fig. 4). DI-pH exhibited the least amount of variability in these zones; however, these values should be viewed with caution as low frequencies of *G. parvulum* in the calibration dataset prevented a reliable estimate of pH optimum for this dominant taxon. BSiO$_2$ values were highest in these zones and steadily decreased until stabilizing at 36.5 cm depth (Fig. 5C). C/N ratios and TOC showed no consistent trends during this period (Figs. 5D, E).

Diatom zones 3–7 ($\sim 2500$ to $140$ yr ago) are characterized by dynamic assemblage shifts, with most of the dominant taxa exhibiting quasi-periodic shifts in abundance (Fig. 4). DI-pH fluctuates but shows a slight decreasing trend from about 20 cm depth ($\sim 1100$ yr ago) upwards (Fig. 5A). BSiO$_2$ concentrations are generally low, with the exception of two peaks centred at 24.5 cm ($\sim 1400$ yr ago) and 12.5 cm ($\sim 650$ yr ago) depths (Fig. 5C). C/N ratios and TOC values showed no consistent trends during this period (Figs. 5D, E).

Diatom zone 8 ($\sim 140$ yr ago to present) shows an increasing dominance of *Achnanthes marginulata* and the (tycho) planktonic *Aulacoseira distans* complex (Fig. 4). DI-pH reached its lowest values on record, although it increases slightly at the very surface (Fig. 5A). BSiO$_2$ values were the

---

**Table 4**

Species occurrences ($N$) and effective number of occurrences ($N2$) for the fossil diatom taxa that also occurred in the calibration dataset

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Fossil</th>
<th>Calibration set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$</td>
<td>$N2$</td>
</tr>
<tr>
<td><em>Achnanthes saccula</em> Carter in Carter and Watts 1981</td>
<td>54</td>
<td>45.7</td>
</tr>
<tr>
<td><em>Achnanthes helvetica</em> (Hust.) Lange–Bertalot 1989</td>
<td>36</td>
<td>26.1</td>
</tr>
<tr>
<td><em>Achnanthes kriegerii</em> Krasske 1943</td>
<td>44</td>
<td>39.5</td>
</tr>
<tr>
<td><em>Achnanthes marginulata</em> Grun. in Cleve and Grun. 1880</td>
<td>54</td>
<td>39.8</td>
</tr>
<tr>
<td><em>Achnanthes minutissima</em> Kütz. 1844</td>
<td>27</td>
<td>22.8</td>
</tr>
<tr>
<td><em>Achnanthes pusilla</em> Grun. in Cleve and Grun. 1880</td>
<td>39</td>
<td>26.2</td>
</tr>
<tr>
<td><em>Aulacoseira distans</em> complex (Ehrenb.) Simonsen 1979</td>
<td>47</td>
<td>34.1</td>
</tr>
<tr>
<td><em>Aulacoseira perglabra</em> (Oestrup) Haworth 1988</td>
<td>48</td>
<td>40.7</td>
</tr>
<tr>
<td><em>Cymbella gauemannii</em> Meister 1934</td>
<td>47</td>
<td>32.9</td>
</tr>
<tr>
<td><em>Encyonema minutum</em> (Hilse in Rabenhorst) Mann 1990</td>
<td>27</td>
<td>23.0</td>
</tr>
<tr>
<td><em>Eunotia praerupta</em> Ehrenb. 1843</td>
<td>35</td>
<td>28.6</td>
</tr>
<tr>
<td><em>Staurosira construens</em> v. <em>venter</em> (Ehrenb.) Hamilton 1992</td>
<td>17</td>
<td>15.4</td>
</tr>
<tr>
<td><em>Fragilariaforma exiguisformis</em> (Lange–Bertalot) Flower, Jones and Round</td>
<td>52</td>
<td>43.2</td>
</tr>
<tr>
<td><em>Fragilaria pinnata</em> (Ehrenb.) Williams and Round 1987</td>
<td>26</td>
<td>24.0</td>
</tr>
<tr>
<td><em>Fragilaria pseudocostatissima</em> (Marciniak) Williams and Round 1987</td>
<td>33</td>
<td>24.4</td>
</tr>
<tr>
<td><em>Gomphonema parvulum</em> (Kütz.) Kütz. 1849</td>
<td>43</td>
<td>23.2</td>
</tr>
<tr>
<td><em>Nitzschia palea</em> (Kütz.) W. Sm. 1856</td>
<td>52</td>
<td>43.0</td>
</tr>
<tr>
<td><em>Nitzschia perminuta</em> (Grun.) Peragallo 1903</td>
<td>33</td>
<td>26.3</td>
</tr>
<tr>
<td><em>Pinnularia balfouriana</em> Grun. ex Cleve 1896</td>
<td>38</td>
<td>31.3</td>
</tr>
<tr>
<td><em>Pinnularia biceps</em> Greg. 1856</td>
<td>54</td>
<td>46.4</td>
</tr>
<tr>
<td><em>Stauroneis aniceps</em> Ehrenb. 1843</td>
<td>37</td>
<td>27.9</td>
</tr>
<tr>
<td><em>Tabellaria flocculosa</em> (Roth) Kütz. 1844</td>
<td>51</td>
<td>44.3</td>
</tr>
</tbody>
</table>

Over 70% ($22/30$) of the fossil taxa occurred in the calibration dataset, and only *G. parvulum* and *A. saccula* were present in less than 25% of the calibration lakes.
Figure 4. The fossil diatom record from Rock Basin Lake spanning the last ~3300 yr, showing dominant taxa arranged in order of their CA axis 1 scores. DI pH reconstructions are plotted on the far right.
highest since ~2500 yr ago (Fig. 5C), whereas C/N ratios and TOC were amongst the lowest concentrations on record (Figs. 5D, E). Due to a lack of surface sediment, BSiO₂, C/N, and TOC could not be determined on the upper 2 cm of core.

Discussion

The fossil diatom record from Rock Basin Lake is unlike any other documented thus far in the High Arctic. The highly variable nature of assemblages shifts over time are in marked contrast to the relatively stable, low-diversity assemblages recorded in nearby alkaline sites that are pervasively dominated by small Fragilaria taxa in pre-19th century sediments (e.g., Blake et al., 1992; Douglas et al., 1994; Wolfe, 2000; Smith, 2002; Antoniades et al., 2005).

The primary mechanism invoked to explain shifts in arctic diatom assemblages is physical constraints on habitat availability and length of growing season imposed by the duration and extent of ice cover, which, in turn, is directly modulated by climate (e.g., Smol et al., 2005 and references therein). The length and degree of ice cover can also drive changes in key limnological variables including nutrient levels, mixing regimes, gas exchange, and, in poorly buffered sites such as Rock Basin Lake, fluctuations in lakewater pH (Douglas and Smol, 1999). As evidenced by the significant relationship between DI-pH and CA axis 1, our data indicate that the majority of variation in our diatom assemblages is governed by changes in pH. In fact, the fossil diatom assemblages from Rock Basin Lake are most similar to those documented in soft-water lakes in alpine (Psenner and Schmidt, 1992; Sommaruga-Wögrath et al., 1997; Koinig et al., 1998) and mid arctic (Wolfe, 2002) regions, where climate-driven pH changes have been implicated as the main mechanism driving taxa shifts.

In low-alkalinity lakes, pH shifts may be caused by several climate-related processes including changes in: (1) weathering rates, which release base cations into the lake; (2) snow cover in the catchment, which in turn influences the amount of acid neutralizing dust into the lake; and (3) catchment vegetation (Psenner and Schmidt, 1992; Sommaruga-Wögrath et al., 1997; Koinig et al., 1998). However, the most significant process believed to effect pH shifts in poorly buffered alpine and arctic lakes is dissolved inorganic carbon (DIC) speciation (i.e., CO₂ (±H₂CO₃), HCO₃⁻, and CO₃²⁻) driven by within-lake processes (i.e., photosynthesis and respiration), which is ultimately governed by the duration and extent of ice cover (Wolfe, 2002).

Previous research has coupled cool periods with low pH levels, as extended ice coverage traps CO₂ produced from decomposition processes and decreases photosynthesis by restricting the availability of photosynthetically active radiation. Conversely, warm intervals have been associated with increased pH levels, as longer ice-free seasons allow respired CO₂ to equilibrate freely with the atmosphere and also result in increased photosynthetic activity, which further removes CO₂ from the water column and shifts the relative proportions of DIC species towards HCO₃⁻ (Psenner and Schmidt, 1992; Sommaruga-Wögrath et al., 1997; Koinig et al., 1998; Douglas and Smol, 1999; Wolfe, 2002).

Below, we discuss our DI-pH inferences in relation to autecological shifts in diatom taxa and the other measured proxies including BSiO₂, C/N ratios, and TOC. We interpret our data in light of distinct climate intervals including local expression of the Holocene thermal maximum, Neoglacial cooling and the Little Ice Age, and recent warming, as inferred from previous paleoenvironmental research from this region.

Termination of the Holocene thermal maximum (diatom zones 1 and 2)

The onset and termination of the Holocene thermal maximum (HTM) throughout the Arctic was highly spatially
variable and showed no apparent systematic latitudinal pattern. On eastern Ellesmere Island, the termination of the HTM is estimated to have occurred between ∼4500 and 2000 yr ago (Kaufmann et al., 2004). Hyvärinen (1985) suggested the onset of cool conditions at Rock Basin Lake began at ∼4000 yr ago, based on increased pollen assemblages of bare-ground and fell-field vegetation (Saxifraga, Ranunculus, Papaver, Caryophyllaceae, Dryas) and declines in pollen influx. Analyzing fossil diatom assemblages from the same sediment core, Smol (1983) provided independent evidence of climatic cooling commencing at ∼4000 yr ago, based on declining diatom abundances and decreases in deep-water epiphytic taxa, particularly Pinnularia biceps. The P. biceps recorded in diatom zones 1 and 2 of our sediment core likely corresponds to the tail end of the declining abundances of P. biceps (from a maximum of over 90% relative abundance) documented by Smol (1983), and as such might represent an approximate point of overlap between the two diatom records.

Our pH reconstructions within diatom zones 1 and 2 must be viewed with caution as G. parvulum, which composed roughly half of the total diatom relative abundance throughout this period, was not present in sufficient quantities in the calibration dataset to reliably estimate pH optima. However, the autecology of diatoms in zones 1 and 2, particularly G. parvulum and Pinnularia biceps, can provide much insight into the environmental conditions during this period. For example, both of these taxa have known affinities to moss substrates (Douglas et al., 1994; Michelutti et al., 2003a) and the dominance of moss epiphytes implies warm conditions, as aquatic mosses are predicted to increase during warm periods (Douglas and Smol, 1999).

While no discernible trends in C/N ratios and TOC occur within diatom zones 1 and 2, the highest BSiO2 values of our entire late Holocene record occur during this period, providing further evidence for warm conditions, as longer open water periods result in extended growing seasons for diatom and chrysophyte populations. It should be noted that the % BSiO2 values recorded in Rock Basin Lake (range <1 to 5%) are extremely low, even when compared to other arctic locations. For example, research on Baffin Island has shown BSiO2 can range from 7 to 65% within a single sediment core (Michelutti et al., 2005), and elsewhere diatoms have been estimated to compose from 20 to 90% of the sediment volume matrix (Wolfe, 2003). Nonetheless, the highest BSiO2 values on record, coupled with dominance by moss-epiphyte diatom taxa, indicate that zones 1 and 2 correspond to the transition period from warm to cool conditions that existed during the late stages of the HTM in this region.

Neoglacial cooling and the Little Ice Age (diatom zones 3–7)

Several independent lines of evidence from this arctic region suggest Neoglacial cooling began ∼3000 yr ago and persisted until its culmination in the Little Ice Age (LIA) at ∼AD 1450 to 1850 (Bradley, 1990; Bradley et al., 2003). For example, glaciers on Greenland and Ellesmere Island experienced substantial Neoglacial advances (Blake, 1989; Weidick et al., 1990), the Agassiz ice core record shows declining δ18O and percent-melt records (Fisher et al., 1995; Koerner and Fisher, 1990), and lake sediment records show decreased sedimentation rates (Lamoureux and Bradley, 1996) and low diatom abundances (Smith, 2002).

The dramatic declines in G. parvulum and, to a lesser extent, P. biceps, and the coeval decrease in % BSiO2 at ∼2500 yr ago appear to mark the end of the HTM and onset of cooler conditions. Inferences of environmental conditions based on diatom autecology are difficult for this period, as the fossil record contains numerous, rapid assemblage shifts with no clear dominant taxa. Regardless, we conclude that changes in pH are most likely driving these assemblage shifts, given the significant correlation between DI-pH and CA axis 1.

Our pH reconstructions are highly variable throughout most of the above period, which is a reflection of the dynamic shifts in diatom taxa (Fig. 4). One trend of interest is the steadily declining pH values beginning at 10.5 cm depth (∼550 yr ago) (Fig. 5A), which corresponds roughly to when cooler LIA conditions would have began. The DI-pH values during this period are amongst the lowest on record, which is what would be predicted during cool conditions, given our current knowledge of climate-driven pH relationships in arctic regions (Wolfe, 2002). In addition, the steady decreases in aquatic primary production proxies, TOC and BSiO2, post ∼550 yr ago indicate cool conditions.

Recent warming (Diatom zone 8)

An extensive body of paleolimnological literature from circumpolar regions has documented striking changes in diatom species composition, production and diversity, attributable to recent climate warming (Douglas et al., 1994; Wolfe, 2000; Sorvari et al., 2002; Rühland et al., 2003; Michelutti et al., 2003b; Smol et al., 2005). For example, at Cape Herschel, approximately 30 km from Rock Basin Lake (Fig. 1), marked changes in diatom assemblages, associated with longer growing seasons and increased habitat availability, were recorded in several small ponds beginning in the mid ∼1850s (Douglas et al., 1994). Non-biological proxies, such as varve thickness, have similarly recorded evidence of warming commencing in the 19th century on Ellesmere Island (Smith et al., 2004).

Several proxies within the Rock Basin Lake sediment core indicate the onset of warmer conditions within the past ∼150 yr. For example, the highest % BSiO2 values in over 2500 yr, indicating increased whole-lake production, and two of the lowest C/N ratios on record, indicating increased contribution of organic matter from aquatic sources, support recent warming (Figs. 5C, D). Although DI-pH values are low, we interpret the small rise in the most recent sediments (last ∼100 yr) as a response to recent warming. The timing and magnitude of this recent pH increase is entirely consistent with those recorded from several poorly buffered lakes on Baffin Island (Wolfe, 2002; Briner et al., in press). In fact, the general pattern of gradually declining pH levels throughout the Neoglacial and LIA followed by slight increases during the last ∼100 yr is a trend that is remarkably consistent between Rock Basin Lake and the Baffin Island lakes.
The diatom response to recent warming in Rock Basin Lake does not appear as marked as that recorded in several ponds from nearby Cape Herschel (Douglas et al., 1994). However, the uppermost zone is very different ecologically from previous sections of the core. For example, _Aulacoseira distans_, a planktonic species in most arctic systems, reaches its highest abundances in this section, suggesting longer ice-free seasons. Although _A. distans_ was present earlier in the profile, over the last ~150 yr, it represented a combined average of 34% of the diatom assemblage, far greater than previously. It is likely that Rock Basin Lake may not have registered as dramatic an ecological response to recent warming as the small, low-elevation ponds of Cape Herschel, due to its larger size, high elevation, and proximity to large glaciers. Nonetheless, the changes in response to recent warming occurred during roughly the same time in Rock Basin Lake as they did in the Cape Herschel ponds, further highlighting the sensitivity of this poorly buffered lake to climatic fluctuations.

**Conclusions**

We believe that the dynamic nature of the species changes recorded in Rock Basin Lake is largely a result of the lake’s limited ability to buffer changes in pH. It is these climate-driven pH shifts that make the fossil diatom record from Rock Basin Lake so unique compared to other high arctic records obtained from well-buffered sites. Our diatom-based paleoclimatic inferences are supported by additional proxies, which all track aquatic responses to distinct climatic intervals of the late Holocene, including the termination of the HTM and onset of Neoglacial cooling, and post-LIA warming. One implication of our data relates to site selection for future paleolimnological studies, as diatoms in poorly buffered lakes appear to react more sensitively to climatic changes compared to those in well-buffered locations.

**Acknowledgments**

This work was funded by Natural Science and Engineering research Council (NSERC) grants awarded to NM, JPS, MSVD, and APW as well as an Ontario Graduate Scholarship (OGS) and Northern Scientific Training Programme (NSTP) awarded to NM. We are especially grateful to the Polar Continental Shelf Project (PCSP) for logistical and financial support for field work. Water chemistry was provided by D. Muir and X. Wang from the National Water Research Institute in Burlington, Ontario. We thank John Glew for assisting in field work and for drafting Figure 1. Thanks to Weston Blake Jr. and Bronwyn Keatley for providing helpful comments on the manuscript. This is Cape Herschel Project No. 67 and PCSP contribution #01904.

**References**


