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Rapid Lacustrine Response to Recent High Arctic Warming: A Diatom Record from Sawtooth Lake, Ellesmere Island, Nunavut

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Abstract

Diatoms from Sawtooth Lake (79°20′N, 81°51′W) on the Fosheim Peninsula in Central Ellesmere Island, Canada were analyzed to assess the temporal extent and magnitude of climatic change in the High Arctic during the late Holocene. Diatom results from the sediment cores show an absence of diatoms throughout the last ~2.5 ka (4.6 m) until the 1920s. However, ca. 1926 (5.3-cm depth), a rapid colonization of diatoms in the lake occurred. Within the uppermost section of the core (~1920 to ~1997), the diatom flora shift from a small *Fragilaria*-dominated assemblage to a more diverse assemblage that is dominated by large planktonic taxa (e.g., *Cyclotella bodanica*) and large raphid benthic species. The postglacial nature of this assemblage suggests a decrease in ice cover and a concomitant increase in light and nutrient availability for diatom growth over the last ~75 yr. Of particular significance is this absence of diatoms prior to the ~1920s, which indicates that environmental conditions of the last ~75 yr are unlike any of the previous ~2500 yr.

Introduction

Holocene climate fluctuations and recent warming have been reconstructed from a number of proxy climate data sets in the Northern Hemisphere. These reconstructions show pronounced warming in the last 50 yr, which is unprecedented in relation to the last 1000 yr (Mann et al., 1999). While these reconstructions provide much-needed high-resolution data for climate variability before the availability of instrumental data, it is necessary to push this application further back in time to expand our knowledge of natural climate variability throughout the Holocene, thereby placing the magnitude and rate of change in recent years within a longer perspective. This need is especially true in the High Arctic, where global circulation models (GCMs) predict an amplified response to greenhouse gas-induced warming (Zwiers, 2002), yet few long-term high-resolution climate data sets exist.

In the Arctic, recent environmental changes have been documented from many paleoclimatic records. These changes are manifested in the increased thickness of lacustrine varves (Smith, 1997; Hughen et al., 2000), in recent shifts in fossil algal assemblages preserved in lacustrine sediments (Douglas et al., 1994; Doubleday et al., 1995; Gajewski et al., 1997; Wolfe, 2000; Wolfe and Perren, 2001; Sorvari et al., 2002), and from other high-resolution paleoclimatic proxy records (reviewed in Overpeck et al., 1997). These changes are thought to represent recent warming in the Arctic that is unprecedented in the context of recent centuries. The warming is consistent with GCM predictions of climate expected under higher CO_2 levels, suggesting that it is, at least in part, the result of anthropogenic influences on global climate.

In this paper, we present a late Holocene paleolimnological record from the sediments of Sawtooth Lake, Ellesmere Island, Nunavut, Canada. The purpose of this study is to determine the nature of recent environmental change from the biological record contained within the sediments by a detailed, high-resolution analysis of the fossil diatoms.

ECOLOGICAL RESPONSE TO CLIMATE CHANGE IN THE HIGH ARCTIC

The development of calibration sets for circumarctic sites (Pienitz et al., 1995; Lim et al., 2001; Weckström and Korhola, 2001; Joynt and Wolfe, 2001) is rapidly changing the applicability of quantitative models to both high and low arctic sites; however, because of limited autecological information in the High Arctic, hindcasting climatic trends using diatoms has relied historically on qualitative models of their inferred responses to climatic change (Smol, 1983). Because high arctic lacustrine environments are dominated by low temperatures, thick and persistent ice cover, limited light, and a short (often less than 8 wk) growing season, a reduction in ice cover is expected to be the major response of arctic lakes to climatic warming (Douglas and Smol, 1999). A reduction in ice cover has many implications for the aquatic ecology of arctic lakes (Rouse et al., 1997; Douglas and Smol, 1999, Battarbee, 2000). It promotes an increased diversity of habitats for autotrophic species, such as diatoms, by increasing light in the euphotic zone for plankton growth, and allows the littoral zone to be colonized by mosses and thus epiphytic species. A longer growing season allows these species to establish themselves and reproduce for longer periods of time, thereby increasing productivity and ecological complexity. In addition, warmer climates accelerate weathering in the watershed. This increased buffering releases more nutrients and dissolved solids into the lake, which augment primary productivity (Douglas and Smol, 1999).

ICE COVER MODEL

The main model used in the Arctic relates diatom species assemblages to changes in ice cover (Smol, 1983). As warming occurs, the ice pan on the lake shrinks, thereby allowing more photosynthetically active radiation to penetrate the lake. The moat (the area between the shore and the ice pan) becomes wider, allowing for the proliferation of deeper water and epiphytic taxa. Convective circulation in the ice-free areas and increased nutrients allow for larger phytoplankton to thrive in the euphotic zone and for larger epiphytic taxa to colonize the littoral zone of the lake. Thus, with warming, a shift from small shallow-water taxa (e.g., *Fragilaria pinnata*) to larger epiphytic benthic species (e.g., *Navicula* spp.) and planktonic taxa (e.g., *Cyclotella* spp., *Stephanodiscus* spp.) should be apparent (Lotter and Bigler, 2000). Indeed, this species transition is also a noted sequence in the glacial/postglacial ontogeny of lakes at lower latitudes (reviewed in Round, 1981).

While this model provides the means by which diatom records can be interpreted, it cannot be directly tied to any single meteorological

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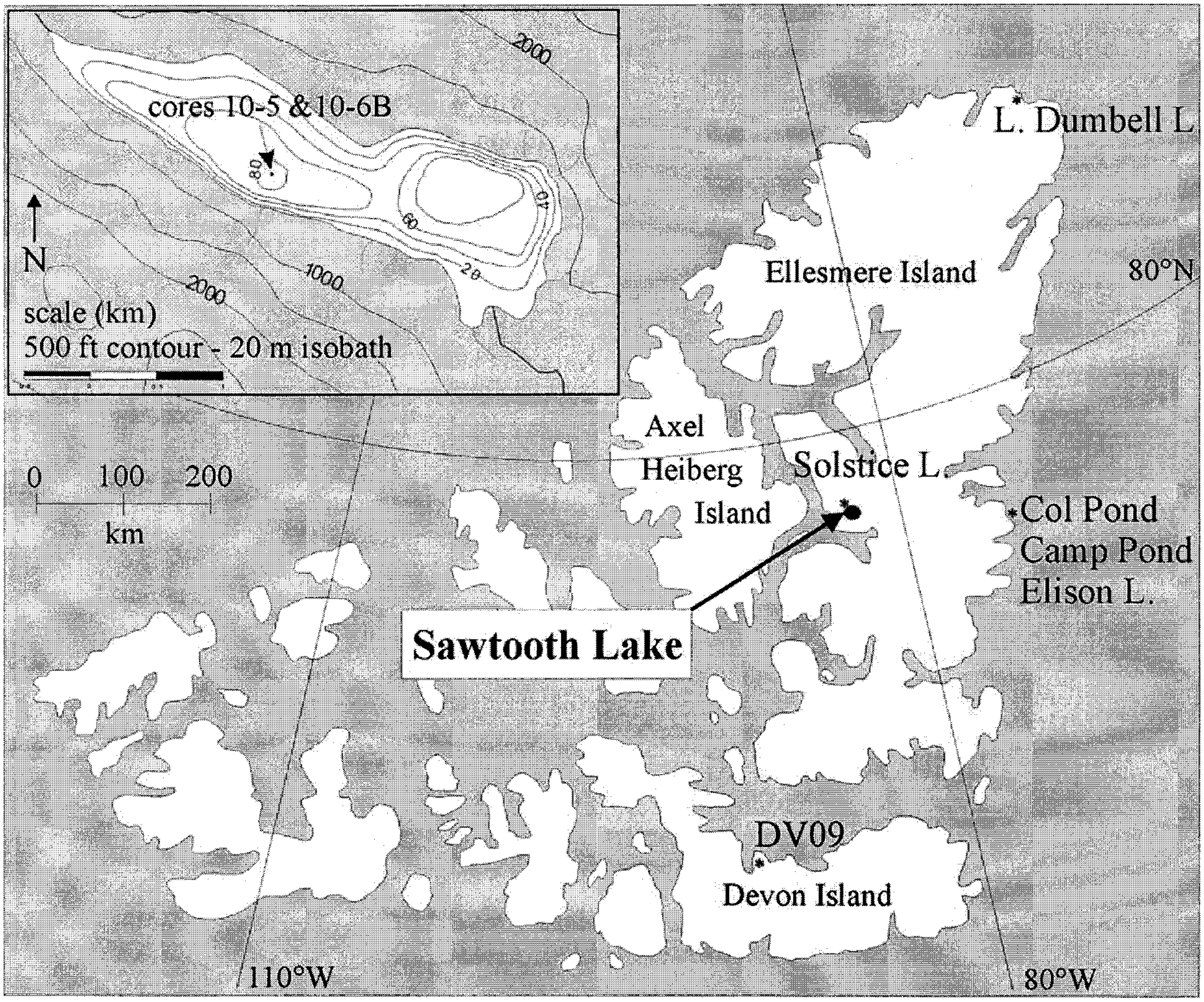

FIGURE 1. Location of Sawtooth Lake and other sites referred to in text. Bathymetric map and location of the sediment cores.

variable, which is necessary for the use of a transfer function. Ice cover does relate to summer warmth (Doran et. al., 1996; Schindler et al., 1996), but not linearly. Several factors such as winter temperature, windiness, and internal lacustrine thermal feedbacks complicate the relationship (Doran et al., 1996), as do changes in snow depth, which affect sub-ice circulation, diatom suspension, and photosynthesis (Kelley, 1997). In addition, caution must be used in ascribing changes solely to ice cover. A reduction in ice cover is merely one factor among others, such as the increases in nutrient supply, light, and habitat availability that result from climatic warming.

Study Area

Sawtooth Lake (79°20′N, 83°51′W, 280m a.s.l.) is the highest of a chain of three lakes situated within a col in the Sawtooth Mountain Range on the Fosheim Peninsula in central Ellesmere Island (Fig. 1). The surrounding unglacierized landscape is considerably high in relief, with the steep-sided, east-west-trending valley walls reaching 1000 m in elevation. It is a large (260 ha), deep (>90 m) lake that retains considerable ice cover during the summer months and is rarely ice free.

The prevalence of lake ice sharply contrasts with the relatively warm climatic and vegetational characteristics of this intermontane region. Summer temperatures (June, July, and August) average 5.5°C in nearby Eureka (60 km to the north). Mean annual temperature averages −20°C. The area is an extreme polar desert where annual precipitation, which falls mainly as snow, averages 68 mm, making it the driest place in Canada (Environment Canada, 2003). The catchment is largely unvegetated: the silt and clay-rich lowlands support an enriched prostrate shrub flora (Edlund and Alt, 1989), whereas the felsenmeer highlands, predominantly composed of the highly erodable carbonate bedrock of the Eureka Sound Group (Miall, 1991), support only a sparse saxifrage-dominated community.

The lake is situated well above Holocene marine limit (<140 m a.s.l.: Bell, 1996) and is slightly alkaline (pH 8) and dilute with concentrations of major cations ranging from ~0–4.5 mg L^{-1} for Na^{3+}, K^{+}, Mg^{+}, and Si^{4+}, with higher concentrations of Ca^{2+} (~20 mg L^{-1}) derived from the surrounding bedrock. Lake water temperatures range between 0 and 2°C, and oxygen levels range between over 15 mg L^{-1} at the surface to 4 mg L^{-1} at depth in the distal basin (see Table 1).

The mixing regimen of Sawtooth Lake is complicated. The predominance of ice on the lake prevents classic cold monomictic overturn. However, the inflowing streams from the eastern end of the watershed deliver considerable sediment to the lake in the form of overflows, interflows, and underflows (Patridge, 1999) and effectively mix the lake. A sill (60-m depth) in the middle of the lake acts as a barrier to communication between the two basins and creates an

TABLE 1

Major cation water chemistry

		Concentration (ppm)				
Basin	depth	Ca^{2+} (ppm)	Mg^{+} (ppm)	K^{+} (ppm)	Na^{3+} (ppm)	Si^{4+} (ppm)
Proximal	1 m	20.91	4.489	0.824	2.428	0.562
	80 m	20.67	4.432	0.781	2.101	0.770
Distal	1 m	19.94	4.320	0.774	2.162	0.513
	80 m	25.40	5.22	0.838	2.218	1.450

isolated trough in the distal basin. This trough is depleted in oxygen, has relatively higher concentrations of hypolimnetic cations, and allows for the preservation of laminae from which a high-resolution record may be obtained.

Methods

CORING AND DIATOM PREPARATION

A suite of gravity and vibracores was collected from the distal basin of Sawtooth Lake in the summer of 1999. Diatoms were sampled from the 36-cm-long gravity core (10–5) at 1–2-mm intervals to approximate an annual record in the uppermost 6 cm and at 1-cm intervals thereafter to 36 cm. The vibracore (10–6B) was sampled at 10-cm intervals to 4 m; thereafter it was sampled at 5-cm intervals to the base at 4.6 m.

Diatom samples from the short core were freeze-dried and then digested in 30% hydrogen peroxide following standard oxidative techniques (Battarbee, 1986). They were repeatedly rinsed, and then aliquots were evaporated at room temperature on round coverslips in evaporation trays. Coverslips were permanently mounted on plain glass slides using Naphrax® mounting medium (RI = 1.74). At least 300 diatoms were enumerated from the uppermost samples using an Olympus HB microscope equipped with phase optics. Where diatom concentrations declined, at least 5 transects of the slide were counted. For several of these (below 5-cm depth), total diatom counts were less than 5. Diatom species are expressed as relative percentages and as estimated concentrations within the sediment based upon the known weight of the original sample, the volume of the subsequent aliquots taken, and the area of the slide surface counted (Battarbee, 1973). Taxonomic assignations were made using reference literature (Krammer and Lange-Bertalot, 1986–1991).

CHRONOLOGY

The chronology of Sawtooth Lake is complicated. An additional surface lamina recovered in each successive year of coring suggests that the sediments are annually laminated (varved). However, a large erosive turbidite at 2-cm depth and several sections where laminae are disturbed preclude a definitive varve chronology for the uppermost section. Two approaches to this chronological uncertainty were produced.

First, we used ^{210}Pb and ^{137}Cs as a guide to the chronology. However, due to dilution, the ^{210}Pb curve for Sawtooth Lake does not decay exponentially with depth. Rather, the ^{210}Pb profile tends to oscillate with lamina thickness, suggesting that old Pb has been washed in from the watershed. However, a strong ^{137}Cs peak stratigraphically correlated with ~4.0-cm depth in core 10–5 anchors the chronology and is believed to be valid due to the prevalence of clays, which retard the vertical migration of Cs in the sediments (Crusius and Anderson, 1995). In addition, the constant rate of supply (CRS) model (Appleby and Oldfield, 1978) produced a date of 1964, which closely matches that of the ^{137}Cs-inferred date of 1963. These factors suggest that the Pb-based chronology provides a reliable estimate of age within the uppermost 6 cm.

Second, we counted and measured varve thickness as outlined in Francus et al. (2002). Given that samples for radiometric analysis spanned 0.5 cm of sediment, and the time interval represented by each sample must range over a decade in places, one would not expect exact correspondence between the varve count and the radiometric peaks. Nevertheless, the correspondence that we found is quite consistent with the interpretation of the varve chronology (compare Francus et al., 2002). These varve counts place the base of the core at least 2550 varve yr BP. In spite of these uncertainties, the timing of the major changes in diatom assemblages, as we will discuss further, can be constrained within a decade. Diatom samples were taken from individual laminae in an effort to approximate an annual record and were assigned ages based on linear interpolation between ^{210}Pb-generated dates.

STATISTICAL METHODS

Diatom species >1% abundance in any one sample were employed in statistical analyses. Gradient lengths were assessed using detrended correspondence analysis (DCA) on CANOCO software (ter Braak, 1990). Principle Components Analysis (PCA) was chosen for further analysis due to the linear response of the data, indicated by the short gradient length (1.896) of the DCA 1 axis. The PCA was run using a centered covariance data matrix and then plotted as both a species scatter (Fig. 4) and as downcore first-axis scores (Fig. 5).

BIOVOLUME

Diatom biovolume (μm^3 g^{-1} dry sediment) was estimated for diatom species using the BIOVOL program (Kirschtel, 1996). Size ranges were estimated from reference photographs from Sawtooth Lake and other girdle views from other high arctic lakes (usually smaller than temperate-cell size ranges). In cases where girdle views were unavailable, volumes were estimated from similarly sized species. Due to the inherent uncertainty in estimating cell volumes, the values are used to provide a rough estimate of changes in diatom production over time rather than absolute numbers. Despite these uncertainties, volumes calculated here were comparable to other, published diatom biovolumes (compare Joynt and Wolfe, 2001).

Results

GENERAL DIATOM STRATIGRAPHY

Diatoms are absent from the entire retrieved sedimentary record of Sawtooth Lake below 5.3-cm depth (~1926). However, in the uppermost 5.3 cm, diatom concentrations increase rapidly and oscillate between 0 and 3.5×10^7 valves g^{-1} dry sediment. Of a total of 66 species seen in the lake sediments, only 21 diatom species were recorded in >2% relative abundance (Table 2). The siliceous remains of chrysophytes are equally variable and appear periodically throughout the core, but are most abundant at the top, where they range from 0 to 1×10^7 cysts g^{-1} dry sediment (Fig. 2) and below 4-m depth, where they were inconsistently observed.

A trend in the diatom stratigraphy is apparent over the last 80 yr (Fig. 3). In general, diatoms increase in both size and diversity toward the surface: from the early dominance of small *Fragilaria* species to larger planktonic *Cyclotella* species and larger benthic taxa (*Navicula*, *Cymbella*, etc.) in recent decades. This general trend is superimposed upon the higher-frequency oscillations in species dominance, which punctuate the record.

When diatoms first appear in the lake ca. 1926, it is as a low concentration and low biovolume population of *Fragilaria pinnata*. *Fragilaria* species diversify quickly and are replaced by larger taxa, both benthic and planktonic, which reach a maximum circa 1980. In

TABLE 2

Diatom species >2% abundance in any sample

Achnanthes marginulata Grun. in Cleve & Grun. 1880
Achnanthes minutissima Kutz. 1833
Amphora inariensis Krammer
Amphora libyca Ehr.
Amphora pediculus (Kutz.) Grun.
Campylodiscus noricus Ehrenb. ex Kutz. 1844
Cyclotella bodanica var. *lemanica* (O. Muller ex Schroter) Bachmann 1903
Cyclotella comensis Grun. in Van Heurck 1882
Cyclotella pseudostelligera Hust. 1939
Denticula tenuis Kutz. 1844
Diploneis cf. *parma* Cleve 1891
Fragilaria capucina var. *vaucheriae* (Kutz.) Lange-Bertalot 1980
Fragilaria construens var. *venter* (Ehrenb.) Grun. in Van Heurck 1881
Fragilaria pinnata var. *intercedens* (Grun.) Hust. 1931
Fragilaria pinnata var. *pinnata* Ehrenb. 1843
Fragilaria pseudoconstruens Marciniak 1982
Hannaea arcus (Ehrenb.) Patr. in Patr. and Reimer 1966
Navicula cincta (Ehrenb.) Ralfs in Pritch. 1861
Navicula cryptocephala Kutz. 1844
Nitzschia perminuta (Grun.) M. Perag. 1903
Stephanodiscus alpinus Hust.

the early 1990s, concomitant with a large turbidite, diatom species diversity and concentration within the sediments plummet. The mid- to late 1990s are marked by a return to high species diversity and concentration.

ORDINATION

The PCA of diatom species highlights trends within the data (Fig. 4). Negative values on the first axis ($\lambda = 64\%$) represent "warmer"-condition taxa: large, high-biomass, centric diatoms (*Cyclotella bodanica* and *Stephanodiscus alpinus*) and larger benthic, epiphytic species belonging to the genera *Achnanthes*, *Cocconeis*, *Cymbella*, *Denticula Diploneis*, *Navicula*, *Pinnularia*, and *Nitzschia.* The positive, "colder" side of the axis is dominated by the presence of small *Fragilaria pinnata* (and the occasional *Campylodiscus noricus*), which is typically associated with late glacial lakes at more temperate latitudes (Haworth, 1976; Stabell, 1985; Marciniak, 1986). The second axis ($\lambda = 17\%$) shows intermediate species: other *Fragilaria* and small benthic taxa (e.g., *Amphora pediculus*, *Caloneis* spp.). These groupings can therefore be seen as a gradient from "cold" to "warm. "The downcore diatoms appear to follow this "ice-cover" gradient with the transition from cold, ice-covered conditions to warmer conditions in the last few decades (see Fig. 5). Indeed, this trend echoes the climate trends of the region where 6 of the warmest years on record were in the last decade (Environment Canada, 2003).

BIOMASS

Two main features are apparent in the diatom stratigraphy of Sawtooth Lake. Years with low diatom concentrations are dominated by the small diatom *Fragilaria pinnata.* Those years with high diatom concentrations have higher diatom diversity and a larger relative abundance of large diatom taxa. These features are evident in the stratigraphic changes in diatom biovolume (see the right column on Fig. 3). *Cyclotella bodanica* is roughly 10–15 times the volume of small *Fragilaria pinnata* and thus requires considerably more resources for proliferation. This change in biomass, from a few small diatoms to a lot of larger diatoms, illustrates the degree to which the diatom production in Sawtooth Lake has exponentially increased within the last 100 yr.

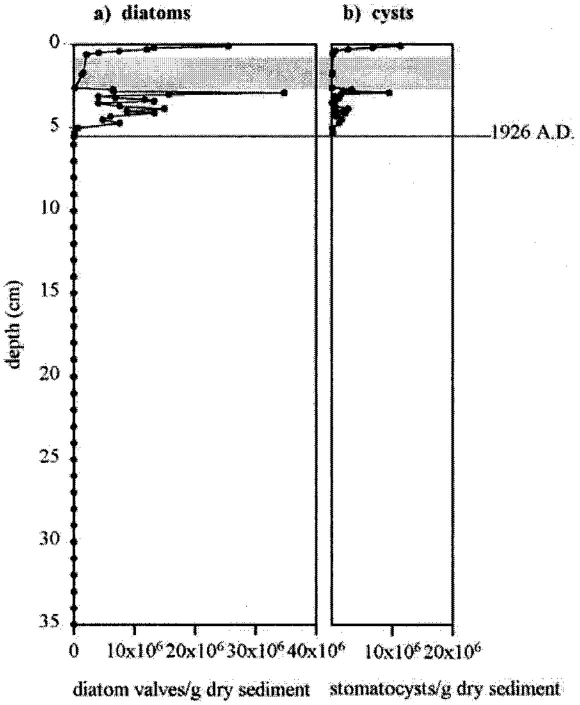

FIGURE 2. Concentration of (a) diatoms and (b) chrysophyte cysts within core 10–5. Diatoms are absent below 6 cm. The gray band marks the presence of a turbidite.

Discussion

Due to the lack of pitting or etching on the valve surfaces, repetitions in laboratory preparations of diatoms, and the oscillations in diatom concentration at the top of the core, the sedimentary sequence is interpreted as recording an environmental rather than taphonomic signal. First-order changes in both the relative abundance and concentration of diatoms suggest that major changes have occurred within the lake environment over the last 100 yr.

Furthermore, the record of annual median grain size at Sawtooth Lake, interpreted as the early-summer snowmelt intensity (Francus et al., 2002) shows a clear coarsening in the 20th century, from ~1900 until the 1960s. Unlike the record for diatoms, the coarsening recorded is not unprecedented in the last 400 yr. Nevertheless, both of these independent proxies, i.e., grain size and diatoms, from the same site clearly demonstrate a response to warming during the latter half of the 20th century.

LAKE ONTOGENY

The change in diatoms reflects the ontogeny of Sawtooth Lake and the evolution of diatom production within it. The small *Fragilaria pinnata* is considered a pioneering species, commonly found in late glacial sediments (Haworth, 1976; Stabell, 1985; Marciniak, 1986), whose adaptation to marginal environments allows it to outcompete larger species in marginal environments (Lotter et al., 1999; Lotter and Bigler, 2000). The autecology of other *Fragilaria* species is less well known. However, the diatom record from nearby Solstice Lake (Wolfe, 2000) suggests that *F. pseudoconstruens* may be viewed as an intermediate species on a gradient between "glacial" conditions represented by *F. pinnata* and interglacial conditions marked by larger diatom taxa in high arctic environments.

Indeed, the changes seen over the last 80 yr in Sawtooth Lake are similar in character to changes seen at lower latitudes in the transition