

**An Examination of the Limnology and Freshwater Diatom Autoecology of  
Bathurst Island, N. W. T., Canadian High Arctic**

**by**

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**A thesis submitted in conformity with the requirements  
for the degree of Master of Science  
Graduate Department of Geology  
University of Toronto**

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## **Abstract**

Limnological analysis of 38 lakes and ponds on Bathurst Island, N.W.T., Canada revealed that the sites were alkaline (pH = 8.0-8.6), and that the major ion concentrations were relatively high, reflecting the calcareous nature of local geology.

Total nitrogen ranged from 247 $\mu$ g/L-1065.2 $\mu$ g/L. Total (unfiltered) phosphorus ranged from 3.2 $\mu$ g/L-64.0 $\mu$ g/L. PON:POP and TN:TPU analysis found 63% of the sites to most likely be N-limited. Linear regression analysis of chlorophyll *a* vs. TN revealed a significant correlation for N-limited sites, indicating that nitrogen may be limiting algal growth in most sites. Principle Components Analysis identified dominant limnological gradients.

148 diatom taxa were identified from surface-sediment of 29 lakes and ponds. Dominant species were small, pennate and benthic. *Fragilaria* and *Pinnularia* species dominated colder, larger sites; warmer, more nutrient-rich sites supported larger diatom assemblages. Canonical Correspondence and Weighted-Averaging analyses identified the potential to build diatom-based transfer functions for paleoreconstructions on Bathurst Island.

*For Jessica . . . the Rant Queen*

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## **Chapter 1:                   General Introduction**

### **1.1 Global Climate Change & Anthropogenic Inputs**

Up until our current industrial age, causes of climate changes could be entirely attributed to natural processes affecting the Earth. These included both internal and external processes. Internal processes include plate tectonics, which lead to the redistribution of land masses and topography, and increases in volcanic activity leading to changes in the amount of atmospheric aerosols and gases (PICKERING & OWEN 1997). External processes include changes in solar radiation and sunspot activity, which have been linked to flood and drought frequencies (CURRIE & FAIRBRIDGE 1985). Other external processes include those summarized by the Milankovitch Theory, which takes into account the combined effects of shifts in the tilt of the Earth's axis of rotation, changes in the eccentricity of the Earth's orbit, and the precession of the equinoxes. All of these vary in a cyclical manner (MANNION 1991) and cause fluctuations in the amount of solar radiation reaching the Earth's surface (PICKERING & OWEN 1997), thus altering the atmosphere-ocean system.

These internal, external and random processes continue to affect the Earth's climate. Although these effects may not be realized within a human lifetime, understanding these processes on longer-term time scales will enable us to better predict future global natural climate changes that could be realized within our lifetimes, and help us to differentiate between natural and human-induced climate change and variability.

With human development has come our ability to dramatically impact the global environment. The onset of the post-1700 Industrial Age has brought on a myriad of new processes that play a role in affecting the Earth's biota and climate. Increased global carbon budgets, acidification, greenhouse gas emissions, and both toxic and domestic waste are a few of the by-products of human domination. They have all been shown to affect the environment on both a local and global level.

Multidisciplinary studies (e.g. OVERPECK et al. 1997) and international taskforces, such as the United Nations Intergovernmental Panel on Climate Change (UN IPCC), have shown documentation for a warming trend over the past century. However, the delineation between anthropogenic and natural warming processes has not been clear. Therefore, further research is clearly warranted.

## 1.2 Climate Change in the Canadian High Arctic

Variance in both external and internal climate forces from one region of the Earth to another have resulted in distinct differences in geology, geography, biota, and level of industrial development throughout the globe (ROOTS 1990). The Canadian High Arctic, in particular, is a very distinct region of this planet in the way that it supports life, responds to shifts in the climate, and affects the environments of the rest of the globe. This is the result of several factors that set the Arctic apart from other regions. The three most important characteristics are: (a) planetary surface heat flux; (b) planetary geography; and (c) snow and ice levels (i.e. albedo surfaces) (ROOTS 1990; ROUSE 1993). More specifically, these factors are manifested in the High Arctic as low overall incoming radiation, small land

mass area (one tenth the size of tropical regions), and high-albedo surfaces (as a result of the longevity and high reflectivity of the snow and ice cover). The Arctic is therefore considered an extremely vulnerable environment characterized by highly specialized, simple, low energy ecosystems with short food chains (ROOTS 1990).

As a result of this vulnerability, the effects of hemispheric temperature trends are exacerbated in the High Arctic. This has led to the rate of climate change in the central Arctic since 1976 to be in excess of  $0.75^{\circ}\text{C}$  per decade, while mid-latitude figures are typically less than  $0.50^{\circ}\text{C}$  per decade (JONES 1988). Furthermore, over the 20<sup>th</sup> century, increases in average arctic temperatures have exceeded those recorded for the hemisphere as a whole (OVERPECK et al. 1997). The prediction that Canada's cold environments will be affected by greater climatic change than experienced elsewhere is a likely occurrence given the most reliable simulations on general circulation models (GCMs) (LEDREW 1993). These simulations predict temperature increases as great as  $4.0^{\circ}\text{C}$  in the summer and  $9.0^{\circ}\text{C}$  in the winter for a  $2 \times \text{CO}_2$  scenario (ROUSE 1997). The High Arctic has therefore become an important reference area for environmental change research, and of critical interest to many paleoecologists.

The High Arctic was once considered to be the last 'untouched' region of the world. However, we now know that it is not immune to the effects of human activity. Arctic haze, which is a well-defined case of air pollution in polar regions, is one of several stressors leading to the environmental alteration of this once pristine region (HEINTZENBERG 1989). Documentation of the trace substances associated with arctic haze, such as  $\text{SO}_4$ , elemental carbon (the main component of soot),  $\text{NH}_4$  and Al, is captured in the polar snow and ice. In many respects, the Arctic has become a "sink" for airborne contaminants, where



they will likely continue to accumulate and persist (DOUBLEDAY 1995). Fluctuations in the concentration and composition of the arctic haze components have been linked to episodic transport from areas of high industrial activities in middle latitudes of the globe (SHERIDAN & SCHNELL 1990). However, the full effects of Arctic haze on the climate and biosphere of the High Arctic are still being resolved.

It is also known that the High Arctic is strongly tied to general circulation due to its inherent role as an energy sink (LEDREW 1993). It is predicted that any changes to the High Arctic's climate will inevitably affect intrinsic low latitude climate systems (OVERPECK et al. 1997). For example, changes in river run-off affected by atmospheric temperature increases could have altering effects on global thermohaline circulation patterns (OVERPECK et al. 1997). With the need to better understand the far reaching effects of high arctic climate change, comes the demand for continued immediate and long-term monitoring of the High Arctic. However, this is a difficult region to monitor on a frequent basis due to financial and logistical constraints (DOUGLAS & SMOL 1993), and relatively little ecological baseline data exists for many areas throughout the High Arctic (DOUGLAS & SMOL 1994). This situation is slowly being rectified with the use of paleoecological approaches.

### 1.3 High Arctic Limnology

Until recently, there has been a lack of limnological information on the high arctic lakes and shallow ponds. However, several recent studies have been initiated. These data have allowed for new insights into the responses of arctic lakes and ponds to climate change (e.g. VINCENT & PIENITZ 1996; PIENITZ et al. 1997).

Multivariate statistical analysis was used to explore the limnology of Bathurst Island. Multivariate ordination analyses can be either unconstrained or constrained to be a linear combination of environmental variables (ter Braak 1988). Ordinations unconstrained by environmental variables, such as principal components analysis (PCA) or correspondence analysis (CA), are used to reduce the variation in the environmental dataset amongst sites, for example, to a scatter on an ordination diagram (TER BRAAK 1988). PCA and CA provide a strong approximation to the problem of ordinating samples (e.g. lake/pond sites) and environmental variables in two or more dimensions (TER BRAAK 1988). Clusters of sample points associated with the PCA or CA axes allow researchers to detect patterns of variation visually and spatially.

Specific to this thesis, a PCA was used to project site scores (as marked by points) onto environmental arrows in order to detect key patterns of variation in the limnological dataset, and infer the chemical composition of any given site (JONGMAN et al. 1987; TER BRAAK & PRENTICE 1988). This projection forms a biplot. Each environmental arrow will orient in the direction of maximum variation in the site scores, and its position (by quadrat) and length demonstrated its correlation with the relevant axes (TER BRAAK 1990). The length of the arrow, in particular, demonstrates the relative “strength” or weight

of each environmental variable in determining the axes (TER BRAAK & PRENTICE 1988). By examining the angles between environmental arrows, we can also gain an understanding of the correlations between variables. Angles between environmental arrows that are more acute represent highly positive correlations between variables (JONGMAN et al. 1987).

PCA biplot axes are constructed by carrying out a least-squares regression exercise that weighs all environmental variables equally (PIELOU 1984). Therefore, the variables with the higher values amongst sites will have a greater affect on the construction of the axis gradient, since they will tend to have higher variances (and means) than the uncommon components (PIELOU 1984). In this study, I have limited my analysis only to the first two axes of the ordination, since the patterns of variation are usually best explained by these axes (JONGMAN 1987). Axes higher than two are usually so constrained as to become almost insignificant in the analysis of major environmental gradients.

The eigenvalues of the PCA axes, when multiplied by 100, represent the “percentage variance accounted for” by each ordination axis (JONGMAN 1987; TER BRAAK 1988). The goal of the PCA ordination is not to account for 100% of the variance, since part of the total variance is due to noise in the dataset (TER BRAAK & PRENTICE 1988).

Chapter 2 of this thesis examines the limnology of 38 lakes and ponds from Bathurst Island, N. W. T., Canadian High Arctic. This includes an investigation of the modern physical, chemical and biological limnology of each site. A modified version of this chapter will be submitted shortly for publication. The authors are D. S. S. LIM, M. S. V. DOUGLAS, J. P. SMOL, and D. S. LEAN.

## 1.4 Diatoms as Bioindicators for Reconstructing Past Environmental Conditions in the High Arctic

Diatoms are a dominant algal group in arctic lakes and ponds, and have considerable potential as biomonitors. There is little to no documented historical climate data for the High Arctic, which makes tracking and interpreting environmental changes difficult if not impossible. By using paleolimnological tools and approaches (e.g. proxy data, calibration sets), researchers can potentially use the information preserved in the sediment record to reconstruct this missing climate record in a quantifiable, reproducible manner (SMOL 1992).

In order to use diatoms to infer paleoenvironmental reconstructions, a quantitative relationship should ideally be established between limnological and/or physical variables and the dominant species assemblages. This link can be established by creating calibration or training sets using a four-step process. First, lakes and ponds that span a wide environmental gradient (e.g. temperature, altitude, proximity to sea, etc.) are selected. Second, from these sites, surface sediment samples and environmental data (i.e. physical, chemical and biological) are collected. This surface sediment ( $\approx$  top 1 cm) represents the last few years of deposition, and will contain an integrated sample of the recent diatom communities (reviewed by CHARLES & SMOL 1994). Third, the diatom remains from each surface sediment sample are identified and enumerated. Fourth, using multivariate direct-gradient analysis (e.g. CCA, RDA), the environmental factors that influence the distributions of the diatom assemblages can be identified (STEVENSON et al. 1989).

Subsequently, this statistical correlation can be used as a model for inferring past environmental changes from fossil diatom assemblage shifts.

Specific to this thesis, constrained multivariate statistical analysis was used to explore the relationship between diatom taxa distribution, sites and environmental variables, and weighted averaging regression techniques were used to develop a transfer function using modern diatom taxa.

Constrained analyses, such as canonical correspondence analysis (CCA), are commonly used to interpret the unconstrained PCA ordination with the aid of external data (TER BRAAK 1988). It is used to detect patterns of diatom species variation in relation to the ordination axes that represent environmental gradients. This analysis does not assume that the relationship between diatoms and environmental variables is linear, but rather that the response is unimodal (TER BRAAK 1986). CCA takes into account the optima and tolerances of diatom assemblages by assuming that individual taxa respond in a unimodal manner over long ( $S.D. > 2.5$ ) environmental gradients (TER BRAAK & VAN DAM 1989).

Once the key environmental variables driving diatom distributions amongst sites have been established, a transfer function can be developed. Using weighted averaging (WA), which is a regression-calibration technique, the optima and tolerances (autoecology) of modern diatom taxa can be estimated for specific environmental variables, and applied to the fossil diatom record. This technique allows for the quantitative estimation of past environmental conditions.

Chapter 3 of this thesis examines the relationship between the physical and chemical limnic properties and the diatom assemblages of 29 lakes and ponds from Bathurst Island. Furthermore, a temperature (TEMP) reconstruction model is explored for the dataset. A

modified version of this chapter will be submitted shortly for publication. The authors are  
D. S. S. LIM, M. S. V. DOUGLAS and J. P. SMOL.

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## **Chapter 2:                    Limnological Characteristics of 38 High Arctic Lakes and Ponds from Bathurst Island, N. W. T., Canada**

### **Abstract**

This chapter presents an overview of the limnology of 38 lakes and ponds from Bathurst Island, N. W. T., Canada (75°42'N, 97°21'W). Limnological information from High Arctic lakes and shallow ponds, such as these, provides an effective means of documenting and monitoring environmental change in this remote area of the world.

The geology of Bathurst Island consists of sedimentary Ordovician to Late Devonian rocks. All of the sampled sites fell within a tight pH range (pH = 8.0-8.6), which reflects their geographic position along the highly alkaline (pH>7.8) eastern section of Bathurst Island. A total of 23 shallow ponds (<2m deep) and 15 deeper lakes (>2m deep) were sampled along this eastern transect. The ponds had a mean surface temperature of 12.2°C, while the lakes had a mean temperature of 6.2°C. This striking difference in mean temperature values can mostly be attributed to differences in thermal inertia and bathymetry.

The major ion concentrations were relatively similar amongst all sites. The relative average concentration of the major cations in descending order was Ca>Mg>Na>K, while the major anions were CO<sub>3</sub>>SO<sub>4</sub>>Cl. All sites were oligotrophic. Particulate organic nitrogen to particulate organic phosphorus (PON:POP), total nitrogen to total unfiltered phosphorus (TN:TPU), Redfield C:N:P, chlorophyll *a* unfiltered to TPU (CHLAU:TPU), and CHLAU:TN ratio analysis revealed that nitrogen may be limiting algal growth to a greater degree than phosphorus in over 63% of the Bathurst Island sites.

Multivariate statistical analysis was used to explore key patterns of variation in the limnological dataset. The dominant limnological gradients affecting site distribution on the PCA ordination were: (a) components affecting the water hardness such as calcium and magnesium, (b) major ion content, and (c) dissolved organic carbon (DOC) levels along Axis 1, and pH along Axis 2. DOC and temperature differences were most likely driving the differences between the shallow ponds and the deeper lakes.

The limnological information presented in this chapter will be incorporated into a larger effort to construct a limnological database of the Canadian High Arctic. Furthermore, this analysis will aid in the interpretation of an array of biological, limnological and paleolimnological studies on and near Bathurst Island.

## **Chapter 2:                   Limnological Characteristics of 38 High Arctic Lakes and Ponds from Bathurst Island, N. W. T., Canada**

### **2.1 Introduction**

The High Arctic is a critical area for environmental and climatic research, as the effects of hemispheric temperature trends are exacerbated in this region (ROUSE et al. 1997). For example, warming in the central Arctic since 1976 has been in excess of 0.75°C per decade, while mid-latitude increases are typically less than 0.50°C per decade (JONES 1988). Furthermore, over the 20<sup>th</sup> century, increases in average arctic temperatures have exceeded those recorded for the hemisphere as a whole (OVERPECK et al. 1997). The prediction that Canada's cold environments will be affected by greater climatic change than experienced elsewhere is also a likely occurrence given the most reliable simulations on general circulation models (LEDREW 1993). These simulations predict temperature increases as great as 4°C in the summer and 9°C in the winter for a 2 x CO<sub>2</sub> scenario (ROUSE et al. 1997). It is known that the High Arctic is strongly tied to general circulation patterns due to its inherent role as an energy sink (LEDREW 1993), and therefore the effects of arctic climate change will not be isolated to this extreme area of the globe. Instead, it is predicted that any changes to the high arctic's climate will inevitably affect low latitude climate systems. For example, changes in river run-off affected by atmospheric temperature increases could alter global thermohaline circulation patterns (OVERPECK et al. 1997). With the need to better understand the far reaching effects of

high arctic climate change, comes the demand for continued immediate and long-term monitoring of this region.

Limnological information from tundra lakes and shallow ponds that are found throughout the High Arctic provides a means to monitor environmental change in this region. These small bodies of water are sensitive to such environmental influences as global warming (SMOL et al. 1991), increased UV-B penetration (VINCENT & PIENITZ 1996), local pollution inputs (DOUGLAS & SMOL in press), and most likely other anthropogenic effects such as arctic haze. Furthermore, ecological and genetic information from relatively undisturbed polar freshwater biota may help develop our understanding of various basic biological concepts (e.g. speciation, top-down trophic control, etc.), which could also assist in the eco-management of temperate lakes (HAMMAR 1989). However, arctic environments are difficult to monitor on a frequent basis due to financial and logistical constraints (SMOL & DOUGLAS 1996), and, as a result, relatively little ecological baseline data exist for many areas of the High Arctic (DOUGLAS & SMOL 1994).

Earlier limnological analyses from other high latitude regions were published by FOGED (1958), LAMAR (1966), LIVINGSTONE (1967), HOBBIE (1980), SHEATH (1986), and DENYS & BEYENS (1987). The collection and analyses of North American arctic limnological data have continued with, for example, the following works: ALEXANDER et al. (1989), KLING et al. (1992), CORNWELL & BANAHAN (1992), all in arctic Alaska; DOUGLAS & SMOL (1994) on Cape Herschel, Ellesmere Island; LUDLAM (1996) on Cornwallis and Ellesmere Island, N. W. T.; PIENITZ et al. (1997a,b) in the (a) Yukon and Tuktoyaktuk Peninsula, N. W. T., and (b) the Yellowknife region;

RÜHLAND & SMOL (1997) on arctic treeline lakes in the central N. W. T., and ongoing researcher at INSTAAR (Boulder, Colorado, U. S. A.).

Despite this recent surge of limnological activity in the Arctic, we are still lacking limnological data from many parts of the High Arctic, including the Bathurst Island region. Although some preliminary temperature records from a shallow pond have been published for Bathurst Island, N. W. T. (DANKS 1971), a more thorough documentation of the limnology of the lakes and ponds on this island has yet to be completed. This information could eventually play a key role in the successful interpretation of paleolimnological data for climate change studies.

This study presents an overview of the water chemistry data of 38 lakes and ponds from Bathurst Island, N. W. T., situated in the Canadian High Arctic. These chemical and physical data will be used in the interpretation of an array of biological, limnological and paleolimnological studies on and near Bathurst Island. This limnological information will also form part of a larger effort to create a limnological database of the Canadian High Arctic. Furthermore, the results reported here will be used to describe the relationships between dominant diatom taxa found in the ponds and the limnological gradients that are outlined in this paper. These findings will help to construct quantitative transfer functions that will be used in biomonitoring efforts and in paleoenvironmental reconstructions (LIM et al. *in prep.*). Moreover, as a newly designated Canadian National Park area, part of Bathurst Island will likely become a focal point for high arctic environmental issues, which increases the need for the collection of baseline data for future biomonitoring and research programs.

## 2.2 Site Description

Bathurst Island (75° 42'N, 97° 21'W) is situated near the geographic center of the Canadian High Arctic (Fig.1, Table 1). The geology is similar to most other areas of the High Arctic in that it is covered by sedimentary Ordovician to Late Devonian rocks. Bathurst Island is characterized geologically by its folded strata consisting mostly of limestone and siltstone (BUDKEWITSCH et al. 1996). The eastern-most segment of the Parry Islands Fold Belt is exposed on this island (HARRISON et al. 1991). The stratigraphic record in this area starts above the base of the Eleanor River Formation, which is a Lower to Middle Ordovician shelf carbonate unit (HARRISON et al. 1991).

On Bathurst Island, the lithology and mineralogy encompasses shale, anhydrite, siltstone, sandstone, limestone, and dolostone (HODGSON 1989). This underlying geology has resulted in low relief with few areas being more than 300m asl; however, the island is also marked by areas of rugged topography with deeply incised streams and V-shaped valleys (KERR 1981). Large portions of the island are also covered by felsenmeer or by glacial sands and gravels (KERR 1981).

The surficial material is dominated by weathered and colluviated bedrock (HODGSON 1989; TARNOCAL 1976), and is highly alkaline (pH>7.8) in the eastern portion of Bathurst Island (EDLUND 1990). The texture of the surficial materials to the east of Bathurst (where all the sampling took place for this study) usually have sufficient fines for the rooting of vascular plants (EDLUND 1990).

Table 1. Legend for map numbers and corresponding site names

Map Number	Corresponding Sites
1	BC
2	BD, BE
3	BF
4	BG
5	BH
6	BI, BJ
7	BK, BL
8	BN
9	BO
10	BP, BQ, BR
11	BS, BT
12	BU
13	BV, BW, BX
14	BY
15	BZ
16	BAA, BAB
17	BAC
18	BAD
19	BAE, BAF, BAG, BAH, BAI
20	BAJ, BAK, BAL
21	BAM, BAN

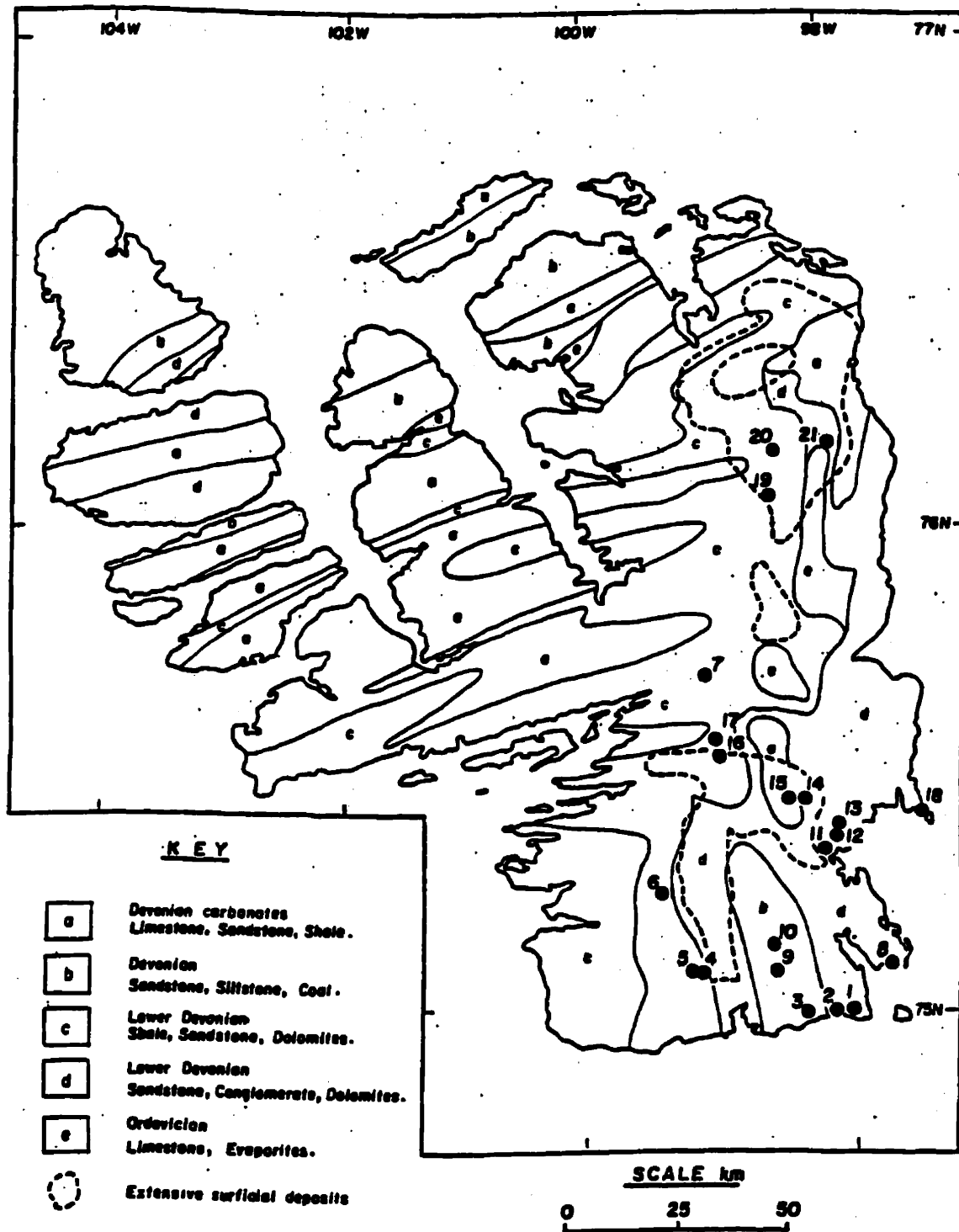


Fig.1 Bathurst Island, N. W. T. site map



The soils on Bathurst Island are much more developed and wetter compared to other high arctic islands in the region, and are highly affected by cryogenic processes that have helped to rejuvenate soil surface nutrients by continuous addition of new materials (TARNOCAI 1976). Along the eastern side of the island, drainage characteristics range from poorly drained, highly saturated soils, to moderately to imperfectly drained slopes (EDLUND 1990). This level of soil development directly affects vegetation, as Bathurst Island is much more lush than other nearby islands. This distinguishing characteristic is noteworthy given the similarity in short growing season and harsh winter conditions that Bathurst Island shares with its less vegetated, neighboring islands. *Saxifraga oppositifolia*, herbaceous plant communities, and a few local shrubs and sedges (EDLUND & ALT 1989) characterize the vegetated areas in the eastern part of the island. Some eastern areas are also completely unvegetated and drain through highly alkaline ( $\text{pH} > 8.0$ ) silt, sand, or gravel conditions (EDLUND & ALT 1989).

The sandstone formations on Bathurst Island (Fig.1, sections a, b, c, d) are commonly covered by green and black lichen, while the limestone and dolomite are nearly bare of any vegetation (KERR 1974). Around my limnological sample sites, there was often abundant submerged mosses and grasses, which most likely affects the nutrient content of each water body. Other vegetation, such as *Saxifraga oppositifolia* (purple saxifrage) and *Papaver lapponicum* (Arctic poppy) flowers, grow during the summer months of late June through early August.

The mean annual temperatures in the Bathurst Island region hover around  $-15.0^{\circ}\text{C}$ . The warmest summer month (July) has a mean temperature as high as  $5.0^{\circ}\text{C}$ , although summer temperatures can, for short periods of time, reach the mid-teens ( $^{\circ}\text{C}$ ).

During these summer months, low lying stratus clouds and fog due to the open sea water are common (GEALE 1980). Lakes and ponds begin to thaw in late June, whereas freeze-up and winter snows usually begin in late August or early September.

## 2.3 Materials and Methods

### 2.3.1 Sample Collection and Analysis

A total of 38 lakes and ponds were sampled using a helicopter on Bathurst Island, N. W. T., Canada (Fig. 1, Table 1) over the period of July 14, 1994 – July 20, 1994. All lake and ponds names are unofficial, and are given a letter designation of BC to BZ, and then BAA to BAN. A total of 39 limnological variables (both field and laboratory) were measured for each site. Latitudes and longitudes for all sites were recorded using a handheld GPS. All of the aforementioned data are listed in the field notes (see Appendix 1).

Water samples were collected from a wide variety of both freshwater lakes and ponds. These sites were selected in order to cover as wide an environmental gradient as possible (e.g. proximity to sea, altitude, size, drainage characteristics, vegetation, etc.). Sampling techniques for all abiotic and biotic components followed routine procedures as detailed by PIENITZ et al. (1997a) and DOUGLAS & SMOL (1994). Sampling took place over a short period of time (one week) in order to minimize seasonal differences that might obfuscate some of the spatial trends in limnological variables.

Water temperature at approximately 0.3m water depth was measured to the nearest 0.5°C at each site using a handheld thermometer. As well, the pH of the surface water was recorded at each site using a Hanna field pH meter.

Water samples for chemical analyses were collected from approximately 0.3 m water depth. At each site, pre-cleaned 250 ml Nalgene® bottles were rinsed three times with lake/pond water prior to water collection. Unfiltered samples for major and minor ion analysis were collected in these bottles. Similar samples were collected for trace metals. 1 ml of concentrated nitric acid was added to the trace metal bottles.

Unfiltered samples for total unfiltered phosphorus (TPU) were collected in pre-washed 250 ml glass bottles. A 1L Nalgene® bottle was filled with lake/pond water that would be subsequently partitioned and prepared for future analysis of: total chlorophyll *a*, particulate organic carbon (POC), particulate nitrogen (PON), further nutrient analysis, pH, and conductivity (COND) measurements.

Upon return to base camp, unfiltered samples were used to measure pH with a Hannah pH meter that was calibrated to buffers daily. Conductivity and salinity levels were measured using a Yellow Springs Instrument (YSI model 33) temperature/conductivity/salinity meter corrected to 25.0°C.

Some of the water samples were filtered in preparation for subsequent nutrient analysis by the National Water Research Institute (NWRI) in Burlington, Ontario (i.e. total “dissolved” phosphorus (TFP), nitrite (NO<sub>2</sub>), nitrate (NO<sub>3</sub>), ammonia (NH<sub>3</sub>), soluble reactive phosphate-phosphorus (SRP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and total Kjeldahl nitrogen (TKN)). Samples were filtered through

47mm diameter cellulose acetate Sartorius filters (pore size = 0.45  $\mu\text{m}$ ), and the filtrate was placed in acid rinsed 125 ml glass bottles.

In order to estimate primary production, on average 300 ml of each water sample were also filtered through glass microfiber filters for analysis of total chlorophyll (CHLAU and CHLAC (uncorrected and corrected for phaeophytin, respectively)). Filters were folded once, and stored in plastic petri dishes wrapped in aluminum foil. An additional 100ml of each water sample was filtered through pre-ashed 25mm diameter Whatman GF/F glass microfiber filters (particle retention = 0.7 $\mu\text{m}$ ). The filters were stored in plastic petri dishes that were wrapped in aluminum foil. These were used for future analysis of POC and PN. All filters, once wrapped in aluminum, were kept frozen during storage and transportation for analysis.

All filtered and unfiltered samples were kept chilled and in the dark for the duration of the field period. Subsequently, samples were shipped directly to the NWRI for all additional nutrient and major ion analysis, following standard methods (ENVIRONMENT CANADA 1994 a & b).

### 2.3.2 Statistical Analysis

The statistical analyses used are summarized in BIRKS (1995). Principal Components Analysis (PCA), using the computer statistical program CANOCO v.3.15 (TER BRAAK 1997, 1990), was performed to ordinate the site and environmental data. PCA was deemed appropriate given the continuous nature of the abiotic dataset.

From the 39 environmental variables measured, those chemical concentrations that were recorded as being below the detection limit in more than half the study sites were eliminated from the active dataset (i.e.  $[\text{Be}^{2+}]$ ,  $[\text{Cd}^{2+}]$ ,  $[\text{Co}^{2+}]$ ,  $[\text{Cr}^{2+}]$ ,  $[\text{Cu}^{2+}]$ , and  $[\text{Pb}^{2+}]$ ). These variables were treated as passive elements in the standard analyses. Therefore, the final environmental dataset comprised a total of 33 variables measured for each site (see Table 2 for a list of the active variables).

Pairs of significantly ( $p \leq 0.05$ ) correlated environmental variables were identified from a Pearson correlation matrix (Table 3). In order to check for skewedness in the distribution of each environmental variable, CALIBRATE v.0.3 (JUGGINS & TER BRAAK 1992) was used. If necessary, the data were normalized through either a  $\log(x)$ ,  $\log(x+1)$ , or square root transformation. A list of each variable and the type of transformation performed is listed in Appendix 2. These transformations were performed, in order to reduce the 'clumping' of sites with similar environmental characteristics in two-dimensional ordination space. Therefore, the PCA was performed using this transformed dataset.

In an effort to understand the nutrient relationships of the study sites, PON:POP, TN:TPU, POC:POP, C:N:P and POC:CHLAU ratios were calculated (Table 2). As well, a linear regression of CHLAU Vs TPU was performed and compared to the DILLON & RIGLER (1974) results. Finally, in order to discern differences in N-limitation amongst the sites, a series of separate CHLAU Vs TN linear regressions were performed for (1) all 38 sites, (2) sites with  $\text{PON:POP} \leq 10:1$ , and (3) sites with  $\text{PON:POP} > 10:1$ .

Table 2. Dataset of environmental variables for Bathurst Island, N. W. T. sites (n=38)

Sites	Ca	Mg	Na	K	SO4	Cl	Al	Ba	Fe	Li	Mn
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
BC	36.6	8.0	4.6	0.6	4.9	8.50	0.00	0.0667	0.012	0.001	0.0013
BD	43.2	18.9	3.9	0.6	2.1	7.14	0.00	0.0746	0.239	0.004	0.0081
BE	43.9	14.8	6.1	0.5	3.9	12.90	0.00	0.0851	0.243	0.003	0.0044
BF	9.2	4.1	0.7	0.0	0.6	1.16	0.00	0.0047	0.015	0.001	0.0007
BG	24.7	1.7	1.1	0.4	4.6	1.79	0.02	0.0159	0.048	0.002	0.0031
BH	19.4	2.4	1.4	0.5	6.7	1.48	0.00	0.0068	0.018	0.002	0.0019
BI	35.9	5.7	6.0	0.9	8.1	9.48	0.00	0.0672	0.026	0.004	0.0051
BJ	35.1	6.8	5.7	1.3	6.8	10.00	0.00	0.0567	0.038	0.004	0.0059
BK	53.3	10.5	6.2	1.3	15.8	10.50	0.94	0.1190	2.420	0.008	0.0797
BL	29.9	2.8	1.9	0.4	5.8	3.31	0.02	0.0261	0.060	0.002	0.0042
BM	29.1	4.5	3.6	0.5	3.6	5.41	0.00	0.0855	0.053	0.002	0.0038
BN	28.8	4.7	3.2	0.5	4.8	5.63	0.02	0.0736	0.064	0.002	0.0035
BO	27.1	2.6	0.8	0.0	1.4	1.46	0.00	0.0057	0.008	0.001	0.0016
BP	33.0	4.4	1.3	0.2	1.7	2.38	0.01	0.0177	0.052	0.002	0.0107
BQ	28.9	4.2	1.2	0.2	2.2	2.54	0.01	0.0162	0.021	0.002	0.0010
BR	29.1	4.0	1.0	0.0	0.8	1.89	0.00	0.0090	0.031	0.001	0.0009
BS	34.5	0.9	1.1	0.2	1.0	2.26	0.00	0.0156	0.011	0.002	0.0009
BT	25.6	2.1	0.9	0.0	0.8	1.82	0.00	0.0133	0.034	0.002	0.0005
BU	21.9	8.2	6.3	0.3	3.8	10.70	0.19	0.0657	1.280	0.002	0.0107
BV	23.1	8.4	6.5	0.2	6.9	10.10	0.02	0.0437	0.361	0.002	0.0037
BW	26.9	8.9	5.2	0.3	2.4	9.85	0.04	0.0441	0.249	0.001	0.0035
BX	26.4	7.4	6.5	0.3	3.7	10.20	0.00	0.0514	0.103	0.002	0.0018
BY	24.2	6.2	6.4	0.5	3.5	15.20	0.10	0.1070	0.382	0.002	0.0064
BZ	33.8	8.6	7.9	0.9	5.0	19.10	0.29	0.1750	0.774	0.004	0.0107
BAA	30.1	3.2	0.9	0.2	5.2	2.19	0.00	0.0326	0.017	0.001	0.0009
BAB	37.6	4.8	1.1	0.3	10.4	2.28	0.00	0.0351	0.017	0.002	0.0000
BAC	41.8	5.2	1.5	0.4	18.6	2.83	0.01	0.1310	0.040	0.001	0.0017
BAD	19.9	5.2	2.9	0.5	2.5	4.66	0.09	0.0196	1.410	0.002	0.0174
BAE	32.0	2.9	1.5	0.2	7.0	2.87	0.00	0.0391	0.029	0.001	0.0017
BAF	26.2	3.1	1.4	0.3	7.8	2.49	0.00	0.0294	0.046	0.002	0.0009
BAG	28.3	2.6	1.5	0.2	7.0	2.88	0.00	0.0337	0.042	0.000	0.0007
BAH	33.8	6.1	1.6	0.3	16.2	1.97	0.04	0.0249	0.066	0.003	0.0014
BAI	38.0	6.9	1.8	0.4	22.0	2.83	0.00	0.0318	0.043	0.002	0.0008
BAJ	43.7	7.8	3.2	0.9	18.7	4.46	0.00	0.1610	0.139	0.003	0.0043
BAK	15.7	2.1	1.1	0.2	2.8	1.40	0.00	0.0561	0.096	0.002	0.0033
BAL	36.7	5.7	2.5	0.5	13.6	3.48	0.00	0.1210	0.079	0.001	0.0021
BAM	28.6	2.7	3.3	0.3	2.4	8.53	0.01	0.0876	0.035	0.001	0.0017
BAN	33.1	3.9	2.8	0.3	3.6	5.24	0.01	0.0563	0.140	0.001	0.0017
Mean	30.8	5.6	3.1	0.4	6.3	5.60	0.05	0.0554	0.230	0.002	0.0056
Max.	43.9	18.9	7.9	0.4	22.0	19.10	0.94	0.1750	2.420	0.004	0.0797
Min.	9.2	0.9	0.7	0.0	0.6	1.16	0.00	0.0047	0.008	0.001	0.0000

N/A = [CHLA] reported only as &lt;0.001 mg/L

Table 2. (Cont'd) Dataset of environmental variables for Bathurst Island, N. W. T. sites (n=38)

Sites	Mo	Ni	Sr	V	Zn	SiO <sub>2</sub>	DOC	DIC	POC	SRPF	TPU	TPF
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
BC	0.001	0.000	0.0769	0.000	0.005	0.15	3.3	26.2	347.9	1.1	7.2	5.9
BD	0.001	0.000	0.0588	0.000	0.002	4.68	11.2	39.9	679.7	1.6	14.0	10.0
BE	0.001	0.000	0.0689	0.001	0.001	3.36	10.7	35.8	695.7	0.9	11.6	10.0
BF	0.000	0.000	0.0052	0.000	0.007	0.18	2.5	9.3	392.4	1.4	17.5	3.8
BG	0.002	0.002	0.0967	0.000	0.002	0.23	1.5	14.3	357.8	1.0	5.5	4.3
BH	0.001	0.000	0.0816	0.000	0.001	0.15	1.7	11.8	286.4	1.4	3.3	3.6
BI	0.000	0.000	0.1520	0.000	0.003	1.40	2.7	23.6	462.6	1.1	7.1	5.4
BJ	0.001	0.002	0.1790	0.000	0.008	0.40	5.8	23.7	473.3	1.0	7.0	5.4
BK	0.001	0.007	0.4260	0.003	0.014	2.12	5.8	29.2	1100.0	1.1	64.0	8.8
BL	0.000	0.004	0.1390	0.000	0.005	0.55	2.7	17.9	421.9	3.1	4.7	7.7
BM	0.000	0.004	0.0628	0.000	0.015	0.13	2.6	19.2	450.6	1.2	7.9	2.8
BN	0.001	0.000	0.0558	0.000	0.006	0.49	1.9	18.9	366.1	0.9	4.8	3.1
BO	0.000	0.002	0.0644	0.000	0.002	0.25	1.8	17.1	363.3	0.9	4.3	3.0
BP	0.001	0.003	0.0302	0.000	0.003	0.05	6.7	20.9	608.3	1.2	15.1	8.6
BQ	0.002	0.003	0.0313	0.000	0.041	0.18	5.1	18.9	488.9	0.9	8.3	6.9
BR	0.003	0.000	0.0409	0.000	0.007	0.06	5.9	20.1	705.0	1.8	17.3	11.5
BS	0.000	0.002	0.0230	0.000	0.007	0.54	1.9	19.6	342.1	1.5	3.2	6.3
BT	0.000	0.000	0.0213	0.000	0.002	0.44	1.7	15.8	389.9	1.1	3.7	3.9
BU	0.001	0.009	0.0317	0.002	0.006	0.85	6.2	18.8	1334.2	1.4	38.2	9.4
BV	0.001	0.000	0.0268	0.000	0.001	0.91	6.5	18.8	925.7	1.5	14.0	6.9
BW	0.001	0.000	0.0281	0.000	0.001	0.14	10.9	21.7	527.3	1.4	8.7	6.5
BX	0.001	0.000	0.0346	0.000	0.001	0.62	4.9	19.7	595.8	4.3	9.8	5.6
BY	0.002	0.002	0.0607	0.000	0.008	0.34	3.2	16.2	707.1	2.7	21.8	7.6
BZ	0.002	0.003	0.0954	0.002	0.004	0.50	3.7	22.1	1195.8	2.3	45.4	9.0
BAA	0.000	0.000	0.3600	0.000	0.000	0.67	1.1	17.9	375.5	1.4	4.9	4.0
BAB	0.001	0.000	0.5300	0.000	0.001	2.58	2.1	22.6	403.7	1.4	6.5	4.0
BAC	0.002	0.005	0.1280	0.001	0.003	0.86	3.8	22.5	503.0	1.8	4.0	10.5
BAD	0.000	0.000	0.0225	0.001	0.029	2.08	5.1	15.1	833.1	1.4	28.0	11.5
BAE	0.001	0.000	0.2510	0.000	0.000	0.21	1.8	18.3	469.0	1.4	4.8	4.3
BAF	0.001	0.000	0.1700	0.000	0.001	0.48	2.4	15.2	516.7	1.4	5.7	4.2
BAG	0.000	0.000	0.2150	0.000	0.002	0.15	1.6	15.9	447.2	1.4	5.8	5.4
BAH	0.000	0.000	0.2830	0.000	0.001	0.55	3.2	19.7	473.3	1.4	15.1	4.4
BAI	0.001	0.000	0.3510	0.000	0.004	0.89	3.8	21.2	586.5	1.4	7.6	4.5
BAJ	0.003	0.003	0.1530	0.001	0.017	1.12	6.9	26.6	640.3	1.4	16.0	8.8
BAK	0.001	0.004	0.0351	0.000	0.004	0.15	2.2	10.1	515.8	1.4	9.7	4.3
BAL	0.003	0.003	0.1060	0.000	0.005	0.66	4.8	22.2	630.9	1.4	9.6	4.6
BAM	0.001	0.003	0.0408	0.000	0.005	0.20	1.8	16.4	474.3	1.4	7.3	1.7
BAN	0.000	0.004	0.0320	0.000	0.002	0.76	2.7	20.2	725.3	1.4	12.3	3.6
Mean	0.001	0.002	0.1202	0.000	0.006	0.79	4.1	20.1	574.0	1.5	12.7	6.1
Max.	0.003	0.009	0.5300	0.003	0.041	4.68	11.2	39.9	1334.2	4.3	64.0	11.5
Min.	0.000	0.000	0.0052	0.000	0.000	0.05	1.1	9.3	286.4	0.9	3.2	1.7

N/A = [CHLA] reported only as &lt;0.001 mg/L

Table 2. (Cont'd) Dataset of environmental variables for Bathurst Island, N. W. T. sites (n=38)

Sites	NO2 (mg/L)	NO3NO2 (mg/L)	NH3 (mg/L)	TKN (mg/L)	PON (µg/L)	TN (µg/L)	ChlaU (µg/L)	ChlaC (µg/L)	TEMP °C	pH	COND (µS)
BC	0.001	0.010	0.000	0.158	13.0	420.50	0.2	0.0	11.0	8.2	211.0
BD	0.001	0.000	0.006	0.898	39.0	986.60	0.9	0.0	19.5	8.4	282.0
BE	0.001	0.000	0.020	0.948	42.0	1015.70	0.5	0.0	19.5	8.3	276.0
BF	0.001	0.000	0.000	0.099	9.0	323.60	0.9	0.2	16.5	8.3	69.0
BG	0.001	0.000	0.000	0.123	7.0	357.70	0.4	0.0	4.0	8.1	111.0
BH	0.001	0.000	0.000	0.065	8.0	263.00	N/A	N/A	10.0	8.0	109.0
BI	0.001	0.000	0.000	0.149	30.0	416.00	N/A	N/A	7.0	8.2	213.0
BJ	0.001	0.000	0.006	0.473	22.0	709.80	1.3	0.3	18.0	8.4	211.0
BK	0.001	0.000	0.000	0.389	117.0	740.70	0.1	0.0	16.0	8.1	266.0
BL	0.002	0.000	0.005	0.106	19.0	344.60	N/A	N/A	7.0	8.1	153.0
BM	0.001	0.000	0.005	0.206	19.0	472.90	N/A	N/A	3.5	8.2	139.0
BN	0.001	0.000	0.000	0.164	11.0	416.00	N/A	N/A	5.0	8.1	131.0
BO	0.001	0.000	0.000	0.085	14.0	305.50	N/A	N/A	2.5	8.1	115.0
BP	0.001	0.000	0.013	0.681	44.0	869.20	N/A	N/A	9.0	8.3	137.0
BQ	0.001	0.000	0.017	0.483	20.0	715.00	1.3	1.1	10.0	8.3	131.0
BR	0.002	0.000	0.011	0.504	54.0	763.90	0.4	0.0	8.5	8.3	131.0
BS	0.001	0.000	0.000	0.056	11.0	247.60	0.8	0.0	6.0	8.2	121.0
BT	0.002	0.000	0.000	0.075	18.0	291.90	0.7	0.0	6.0	8.2	112.0
BU	0.001	0.000	0.005	0.543	196.0	932.90	3.4	1.1	7.5	8.1	152.0
BV	0.002	0.000	0.007	0.627	92.0	883.80	0.8	0.2	9.0	8.2	160.0
BW	0.000	0.000	0.017	1.080	26.0	1065.20	0.2	0.0	13.0	8.3	176.0
BX	0.000	0.019	0.000	0.517	45.0	783.00	0.8	0.0	9.5	8.3	168.0
BY	0.000	0.000	0.000	0.212	52.0	512.40	0.7	0.0	7.5	8.3	159.0
BZ	0.001	0.000	0.000	0.258	134.0	641.90	1.6	1.0	7.0	8.2	215.0
BAA	0.001	0.124	0.010	0.085	12.0	427.50	1.6	0.9	3.0	8.2	140.0
BAB	0.001	0.014	0.006	0.137	10.0	394.10	0.8	0.2	9.0	8.4	182.0
BAC	0.001	0.000	0.006	0.339	18.0	600.20	1.1	0.8	8.0	8.3	200.0
BAD	0.001	0.000	0.005	0.450	72.0	742.80	2.0	1.3	9.0	8.3	128.0
BAE	0.000	0.000	0.013	0.107	23.0	350.10	1.3	1.0	4.0	8.3	140.0
BAF	0.001	0.000	0.007	0.169	23.0	434.10	1.6	1.2	8.0	8.4	120.0
BAG	0.001	0.000	0.005	0.094	21.0	327.60	1.7	1.1	8.0	8.4	135.0
BAH	0.001	0.000	0.011	0.317	13.0	576.00	1.6	1.0	9.0	8.5	110.0
BAI	0.002	0.000	0.009	0.324	31.0	600.20	2.5	2.0	10.5	8.5	196.0
BAJ	0.003	0.000	0.035	0.752	43.0	910.20	1.6	0.9	12.0	8.6	216.0
BAK	0.001	0.000	0.007	0.144	30.0	409.50	N/A	N/A	5.0	8.3	88.0
BAL	0.003	0.000	0.007	0.488	40.0	738.60	0.8	0.0	12.0	8.5	173.0
BAM	0.001	0.000	0.005	0.129	16.0	375.20	N/A	N/A	5.0	8.3	149.0
BAN	0.002	0.000	0.006	0.264	54.0	567.80	0.3	0.0	8.0	8.5	169.0
Mean	0.001	0.004	0.006	0.334	38.0	577.19	0.8	0.4	9.0	8.3	160.4
Max.	0.003	0.124	0.035	1.080	196.0	1065.20	3.4	2.0	19.5	8.6	282.0
Min.	0.000	0.000	0.000	0.056	7.0	247.60	N/A	N/A	2.5	8.1	69.0

N/A = [CHLA] reported only as &lt;0.001 mg/L



Table 2. (Cont'd) Dataset of environmental variables for Bathurst Island, N. W. T. sites (n=38)

Sites	ELEV m asl	PON:POP	POC:ChlaU	TN:TPU
BC	91	10:1	1740:1	58:1
BD	30	10:1	755:1	70:1
BE	30	26:1	1391:1	88:1
BF	21	1:1	436:1	18:1
BG	21	6:1	895:1	65:1
BH	122	27:1	N/A	80:1
BI	0	18:1	N/A	59:1
BJ	0	14:1	346:1	101:1
BK	91	2:1	11000:1	12:1
BL	91	6:1	N/A	73:1
BM	0	4:1	N/A	60:1
BN	0	6:1	N/A	87:1
BO	152	11:1	N/A	71:1
BP	335	7:1	N/A	58:1
BQ	335	14:1	376:1	86:1
BR	335	9:1	1763:1	44:1
BS	61	4:1	428:1	77:1
BT	61	90:1	557:1	79:1
BU	30	7:1	392:1	24:1
BV	152	13:1	1157:1	63:1
BW	152	12:1	2637:1	122:1
BX	152	11:1	745:1	80:1
BY	0	4:1	1010:1	24:1
BZ	0	4:1	747:1	14:1
BAA	183	13:1	235:1	87:1
BAB	183	4:1	505:1	61:1
BAC	122	3:1	457:1	150:1
BAD	0	4:1	417:1	27:1
BAE	61	46:1	361:1	73:1
BAF	61	15:1	323:1	76:1
BAG	61	53:1	263:1	56:1
BAH	61	1:1	296:1	38:1
BAI	61	10:1	235:1	79:1
BAJ	122	6:1	400:1	57:1
BAK	122	6:1	N/A	42:1
BAL	122	8:1	789:1	77:1
BAM	61	3:1	N/A	51:1
BAN	61	6:1	2418:1	46:1
Mean	93	13:1	871:1	64:1
Max.	335	90:1	11000:1	150:1
Min.	0	1:1	235:1	12:1

N/A = [CHLA] reported only as &lt;0.001mg/L



## 2.4 Results and Discussion

### 2.4.1 Physical Variables

The 38 study sites, which ranged in elevation (ELEV) from sea level to a maximum of 335m asl (mean ELEV = 93m asl), were all shallow ponds (<2m deep), except for 15 lakes that were deeper (>2m deep) (i.e. BC, BG, BH, BK, BL, BM, BN, BO, BS, BY, BZ, BAA, BAE, BAF, BAJ).

Temperatures of all samples sites ranged from 2.5°C to 19.5°C. One of the most striking differences noted in the Bathurst sites is the relatively higher temperatures in the shallow pond sites versus the deeper lakes. All shallower pond sites (n=23) freeze solid to the bottom during the winter, and had an average temperature of 12.2°C, while the deeper lakes (n=15) had an average temperature of 6.2°C. As shown by, for example, DOUGLAS & SMOL (1994), HOBBIE (1980, 1984), and reviewed by SMOL et al. (1995), this is not surprising, as shallow sites will have lower thermal capacities and will therefore heat up or cool down much faster than deeper lakes.

The correlation matrix (Table 3) helped to identify correlations amongst several of the 33 variables. Elevation (ELEV) was not correlated with temperature (TEMP). Therefore, temperature variation amongst sites during the week of sampling was most likely driven by the differences in thermal inertia and bathymetry, and not the slight elevation gradient present on the island.

#### 2.4.2 Trends in pH, Conductivity and Major Ions

All Bathurst Island sites were within a tight pH range (pH = 8.0-8.6) (Table 2) reflecting their geographic position along the eastern section of Bathurst Island, which is characterized by highly alkaline (pH  $\leq$  8.0) surficial material (e.g. sand, gravel, silt, clay) (Edlund 1987). Relatively higher pH and alkalinity levels are similar to those recorded for ponds on Ellesmere Island draining calcareous deposits (DOUGLAS & SMOL 1994). BAI, BAJ, and BAL had slightly elevated pH levels relative to all other sites (Table 2). This could be attributed to the argillaceous limestone formations draining large amounts of calcium carbonates into these particular sites.

The specific conductivities (COND) of the study ponds ranged from 88 - 282  $\mu$ S/cm, with a mean of 160  $\mu$ S/cm (Table 2). The highest conductivity was in pond BD (282  $\mu$ S/cm), which lies in close proximity to the sea (Fig.1, Table 1). Ponds BY (159  $\mu$ S/cm) and BZ (215  $\mu$ S/cm), which are also located near sea level (Fig.1, Table 1), similarly had elevated ion concentrations (Table 2). Sites BF (69  $\mu$ S/cm) and BAK (88  $\mu$ S/cm) had the lowest conductivities recorded. Given that ELEV is negatively correlated with increasing COND levels ( $r=-0.32$ ;  $P<0.05$ ), it is not surprising that BF was 213m asl, and BAK was 122m asl, both sites being at greater elevations than the mean of 93m asl (Table 2). Furthermore, drainage through a surrounding snow-bank may also have decreased conductivity levels in BF.

Overall, the concentrations (mg/L) of the major ions were relatively high (Table 2).  $\text{Ca}^{2+}$ ,  $\text{Na}^{+}$  and  $\text{Mg}^{2+}$  are the major cations, while  $\text{CO}_3^{-}$  (i.e. DIC),  $\text{SO}_4^{-}$  and  $\text{Cl}^{-}$  are the major anions. The major ion concentrations are relatively similar amongst all sites; a gradient,

however, does exist that shows a distinction between the shallower vs. deeper sites with respect to ionic concentration.

The relative concentration (mg/L) of cations amongst sampled sites was  $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$  (Table 2), with means of 30.8mg/L, 5.6mg/L, 3.1mg/L, and 0.4mg/L respectively. These ratios are similar to those of KLING et al. (1992), EILERS et al. (1993), DOUGLAS & SMOL (1994), PIENITZ et al. (1997a,b) (although Mg was not considered), and RÜHLAND & SMOL (1998). The relative concentration of anions amongst the sites was, on average,  $\text{CO}_3 > \text{SO}_4 > \text{Cl}$ . The dominance of calcium and bicarbonate ions reflects the calcium-carbonate rich limestone bedrock or dolostone tills in the drainage basins of all the sample sites.

Concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$  were largely a function of proximity to the Arctic Ocean. From the correlation matrix (Table 3), it is apparent that elevation (ELEV) was negatively correlated with [Na], and [Cl]. More inland and higher sites would be less subject to sea spray inputs carrying  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Cl}^-$ , and  $\text{Ba}^{2+}$  than those sites closer to the ocean. For example, sites such as BE, BI, BJ, and BK are all located near the ocean and have elevated conductivity levels. BY and BZ are both located close to sea level near Polar Bear Pass (Fig.1, Table 1), and have the highest [Na] (6.4mg/L, 7.9mg/L respectively) and [Cl] (15.2mg/L, 19.1mg/L respectively).

Varying levels of [K] might be related to the abundance of vascular plants that are thought to leak out this cation (PRENTKI et al. 1980). Similar to the findings of DOUGLAS & SMOL (1994), those sites with grasses, mosses and other vascular plants growing within their drainage had higher [K] (Table 2).

SO<sub>4</sub> concentrations were usually high, ranging from 0.80 mg/L (site BR) – 22.0 mg/L (site BAI), with a mean concentration of 6.3 mg/L (Table 2). High SO<sub>4</sub> concentrations were also found in the PIENITZ et al. (1997a) study lakes that were in areas of prevalent limestone-dolomite, sandstone, siltstone, and conglomerate rock (i.e. bedrock similar to that of Bathurst Island). PIENITZ et al. (1997a) attributed the elevated SO<sub>4</sub> levels to weathering from this bedrock. There did not appear to be a link between SO<sub>4</sub> levels and proximity to the ocean amongst the Bathurst Island samples.

The correlation between higher levels of pH, conductivity and major ions amongst all of the sample sites is similar to the findings of RÜHLAND & SMOL (1998) for their TUNDRA sites in the central arctic mainland, and for those sites sampled by DOUGLAS & SMOL (1994) on Ellesmere Island.

#### 2.4.3 Nutrients: N & P

Nutrient concentrations in all of the sampled sites were below the averages for uncontaminated surficial waters listed by MCNEELY et al. (1979), which reflects the characteristic oligotrophic aquatic environments typical for high arctic lakes and ponds.

Five different nitrogen variables were measured and analyzed. These are total Kjeldahl nitrogen (TKN), nitrite (NO<sub>2</sub>), nitrate-nitrite (NO<sub>3</sub>-NO<sub>2</sub>), ammonia (NH<sub>3</sub>), and particulate nitrogen (PON). TKN was the most variable, with a range from 56.0 µg/L to 1080.0 µg/L, and a mean of 334.0 µg/L. These values are similar to those reported by PIENITZ et al. (1997a). The NO<sub>2</sub>, NO<sub>3</sub>-NO<sub>2</sub>, and NH<sub>3</sub> values for the Bathurst Island sites are all near or below detection limits (<0.001 mg/L) (Table 2).

Total nitrogen (TN) (sum of TKN,  $\text{NO}_3\text{NO}_2$ , PON) ranged from  $247.6\mu\text{g/L}$  to  $1065.2\mu\text{g/L}$  (mean =  $577.19\mu\text{g/L}$ ); values typical for oligotrophic waters WETZEL (1983).

Three phosphorus variables (total phosphorus unfiltered (TPU), total phosphorus filtered (TPF), and soluble reactive phosphorus filtered (SRPF)) were measured for all 38 sites (Table 2). TPU and TPF were highly correlated ( $r = 0.51$ ,  $P < 0.01$ ) (Table 3). TPU ranged from  $3.2\mu\text{g/L}$  –  $64.0\mu\text{g/L}$ , and had an average of  $12.7\mu\text{g/L}$ , which is comparable to values reported by Pienitz *et al.* (1997a) for their western arctic sites. TPF ranged from  $1.7\mu\text{g/L}$  –  $11.5\mu\text{g/L}$  (mean =  $6.1\mu\text{g/L}$ ), which is comparable to those values reported by other limnological studies in arctic tundra regions (DOUGLAS & SMOL 1994; WHALEN & CORNWELL 1985; MCNEELY & GUMMER 1984). SRPF concentrations were all near detection limits, which is not uncommon given its rapid uptake, and the difficulty in properly measuring it (MCNEELY & GUMMER 1984). Values for SRPF ranged from  $0.9\mu\text{g/L}$  –  $4.3\mu\text{g/L}$  (mean =  $1.5\mu\text{g/L}$ ), which is comparable to the results of PRENTKI *et al.* (1980), and PIENITZ *et al.* (1997a, b).

The low TPU levels may not, however, necessarily indicate that phosphorus is the limiting nutrient for algae in the Bathurst Island sites. In order to discern if (a) the sample sites are all P limited, and (b) which sites are more P limited than others, the ratios of PON to particulate organic phosphorus ( $\text{POP} = \text{TPU} - \text{TPF}$ ) (i.e. PON:POP), TN:TPU, and C:N:P were examined.

According to SCHANZ and JUON (1983), ambient N:P ratios greater than 20:1 are characteristic of significantly P-limited aquatic environments. If, however, the N:P ratio is less than 10:1, then the environment is N-limited. Ratios between 10:1 and 20:1 may indicate limitation by either nutrient. However, these nutrient ratios are useful only in cases

where the ambient concentrations are near growth-limiting concentrations (BORCHARDT 1996). The oligotrophic Bathurst Island lakes and ponds appear to conform to this criterion. PON:POP ratios ranged from 1:1 to 90:1 (mean = 13:1). Overall, 63% of the sites had ratios of  $\leq 10:1$ , 13% had ratios of  $\geq 20:1$ , while 24% fell in the intermediate zone of 10:1 to 20:1. Sites such as BF, BK, BU, BY, BZ, and BAD, which have PON:POP ratios  $\leq 10:1$ , all have [TPU] greater than the reported mean of  $12.7 \mu\text{g/L}$ , and were characterized by a 'greenish' tinge in the field notes. The elevated TPU values of these sites may be attributed to the large quantity of excrement left both in and around the watersheds of these particular sites by the local wildlife (e.g. caribou, lemmings, muskox, and arctic terns), which was recorded. These six sites in particular are grouped along the TPU gradient on the Principle Components Analysis (PCA) ordination (Fig.2; see below). Those sites with PON:POP ratios  $\geq 20:1$ , such as BE, BH, BT, BAE, and BAG, all had [TPU] below the mean, and were characterized by rocky drainage areas. With the exception of BT and BAG, all of these sites were larger, deeper lakes, which may account for the more dilute concentrations of TPU.

TN:TPU ratios ranged from 12:1 to 150:1, with a mean of 64:1. These ratios are comparable to those reported by PIENITZ et al. (1997a) (i.e. 13:1 to 103:1) for their 59 lakes along a southern Yukon to Tuktoyaktuk Peninsula transect, and SHORTREED & STOCKNER (1986) (i.e. 38:1 to 109:1) for 19 lakes in the Yukon Territory. Those sites which had PON:POP ratios  $\leq 10:1$ , also had TN:TPU ratios below the mean for the Bathurst Island dataset (Table 2). This may indicate that, instead of being P-limited, algae may be limited to a greater degree by nitrogen. Nitrogen was found to be the dominant limiting agent to phytoplankton growth in subarctic lakes when the lakes were P-fertilized alone



(SMITH et al. 1984). The TN:TPU ratios reported for Bathurst Island, as well as by PIENITZ et al. (1997a) and by SHORTREED & STOCKNER (1986), are much higher than those reported by SMITH (1983) for lakes dominated by nitrogen-fixing cyanobacteria. This may account for the N-limitation in certain Bathurst Island sites. However, it should be noted that nitrogen-fixation may not be the most important source of N to arctic waters, since, aside from blue-greens such as *Nostoc*, N-fixing bacteria is lacking in the High Arctic aquatic systems. Instead, as was demonstrated by ALEXANDER et al. (1989), in shallow ponds wind agitation of the sediment may be the dominant source of pond water N. In larger lakes, N levels may be even lower, since the sediment recharge of N is very low due to the low rate of sedimentation, low water temperature, and year-round oxic conditions (ALEXANDER et al. 1989). Most of the sites with TN:TPU ratios below the mean were either larger, deeper lakes and/or they drained through snow-banks with diluted nutrient concentrations. This observation supports the findings of Alexander *et al.* (1989), and suggests that these sites may rely upon the recycling of N through zooplankton excretion (LEHMAN 1980) to support any primary production. Given this characteristic, the sample sites most likely support simple, low-diversity food chains that could be easily altered by disrupting the limited N input into the water column.

Finally, by comparing the average C:N:P ratios for the Bathurst Island sites to those of other studies, we can make an overall assessment of whether or not these sites are more N or P limited. The average C:N:P ratio for Bathurst Island is 107:6:1, which is lower than the ratio of 137:18:1 reported by SHORTREED & STOCKNER (1986) for 19 Yukon lakes, and lower than the REDFIELD (1958) ratio of 106:16:1 reported for marine phytoplankton. Based on the average ratio for Bathurst Island, it appears that N is the critical factor which

is much lower than other reported values. Therefore, we could conclude that most of the sites are in fact N-limited. However, it should be noted that the range of the C:N:P ratios was large, ranging from 29:1:1 for site BF to 1950:90:1 for site BT. Therefore, some sites, as discussed earlier, are either severely or moderately P-limited as compared to those which are N-limited.

#### 2.4.4 Carbon

Three different carbon species were measured and analyzed for this study: DIC, DOC, and POC. DIC values ranged from 9.3mg/L to 39.9mg/L (mean = 20.1mg/L). These values are comparable to the [DIC] from the PIENITZ et al. (1997a) arctic study sites, and likely reflect similarities in bedrock geology.

DOC concentrations were generally low on Bathurst Island, which is common in oligotrophic waters that are outside of treeline. For example, average DOC concentrations in the PIENITZ et al. (1997a) study were lowest in unforested arctic tundra sites, whereas they were highest in boreal forest and forest-tundra sites. The [DOC] for Bathurst Island ranged from 1.1mg/L to 11.2mg/L (mean = 4.1mg/L). PIENITZ et al. (1997a) found that there is often a significant correlation between watershed vegetation and DOC levels, which could account for the differences in my DOC concentrations. Those sites (e.g. BD, BJ, BP, BV, and BW) with [DOC] greater than the mean drained through relatively lush vegetation such as grasses and mosses, and also supported abundant submerged mosses. Furthermore, the shallower pond sites on Bathurst Island were typically found in lush valley areas that supported various species of sedges and grasses, whereas deeper sites usually had more rocky drainage areas than the ponds. Of course, deeper sites would also more likely dilute

any terrestrial/detrital DOC. DOC levels play a critical role in controlling the depth of ultraviolet (UV) penetration into the lake or pond, which has an impact on the aquatic biota. Given the relatively low [DOC] on Bathurst Island lakes, any slight changes in the environmental that may affect [DOC] may potentially have far reaching consequences (VINCENT & PIENITZ 1996).

#### 2.4.5 Chlorophyll *a*

CHLAU is a common measure of phytoplankton standing crop and hence trophic status (DILLON & RIGLER 1974). CHLAU concentrations for the 38 Bathurst Island sites ranged from below detection limits to 3.4µg/L (mean = 0.8µg/L). In an effort to understand whether the POC in the water was mostly derived from either algal or terrestrial/detrital sources POC:CHLAU ratios were calculated (Table 1). Furthermore, in order to compare this dataset to the DILLON & RIGLER (1974) linear regression of summer CHLA Vs. TP, the slope and r-value for the linear regression of CHLAU Vs TPU for the Bathurst Island sites were calculated. Some POC:CHLAU ratios were not calculated, since CHLAU values were sometimes below the detection limit (<0.001mg/L). Those POC:CHLAU values that were available for calculation ranged from 11000:1 to 235:1, with a mean of 871:1. However, with the reduced sample size, this mean value should be treated cautiously. The range is indicative of a variance in detrital input amongst the sites. Sites which drained through lush, vegetated areas where detrital material could be transported in the run-off, usually had POC:CHLAU ratios above the mean. However, it was surprising to find that sites such as BK, which have elevated [TPU] relative to other sites, would still have POC:CHLAU ratios far above the mean. One possible explanation lies in the observation

that site BK, for example, is most likely N-limited rather than P-limited. Another possible explanation is that phosphorus can form strong bonds with Fe and DOC, rendering it inaccessible to algae. Site BK, in particular, had [Fe] and [DOC] levels (2.42mg/L and 5.8mg/L, respectively) far above the reported means. This characteristic, coupled with a highly vegetated drainage basin, could drive the POC:CHLAU ratio up.

According to DILLON & RIGLER (1974), those sites which lie on or deviate only slightly from the CHLA-TP slope of 1.583, which was derived from a linear regression of the SAKAMOTO (1966) dataset, will most likely be P-limited. However, those sites that have low N:P ratios would show much larger deviations from the trend line. The CHLAU-TPU slope calculated for Bathurst Island was 3.784 ( $P > 0.01$ ). Therefore, the Bathurst Island sites are, in general, not severely P-limited. Instead, as has been documented throughout this study, the sites are most likely either slightly P-limited or N-limited.

As a final check, the relationship between CHLAU and TN was also examined for all 38 sites. These two variables did not show a strong correlation with each other ( $P > 0.01$ ) when the dataset was considered in total (Appendix 10). However, given that the relationship between CHLAU and TPU was also not significant, it is possible that nutrient factors other than N or P were playing a significant role in limiting algal growth. As stated earlier (see section 2.4.3), 63% of the sites are considered to be N-limited, having PON:POP ratios  $\leq 10:1$ , while 37% of the sites had ratios  $> 10:1$ , and were considered to be either influenced by other nutrient factors or P-limited. Therefore, by running separate CHLAU Vs TN regressions on those sites with (a) PON:POP ratios  $\leq 10:1$ , and (b) PON:POP ratios  $> 10:1$ , I was able to discern differences in nutrient limiting factors amongst the sites. From these regressions, it was apparent that the N-limited sites showed a

significant correlation with the CHLAU values ( $R=0.45$ ;  $P\leq 0.01$ ) (Appendix 11).

Conversely, those sites which are most likely not N-limited were not significantly correlated with CHLAU ( $R=0.10$ ;  $P\geq 0.01$ ) (Appendix 12). This indicates, that, similar to the aforementioned findings, the prominent limitation for algal growth in approximately two thirds of the Bathurst Island sites is most likely nitrogen. Therefore, any disruptions to the nitrogen budget of these sites could cause a significant change in the algal biota.

#### 2.4.6 Statistical Analysis – PCA

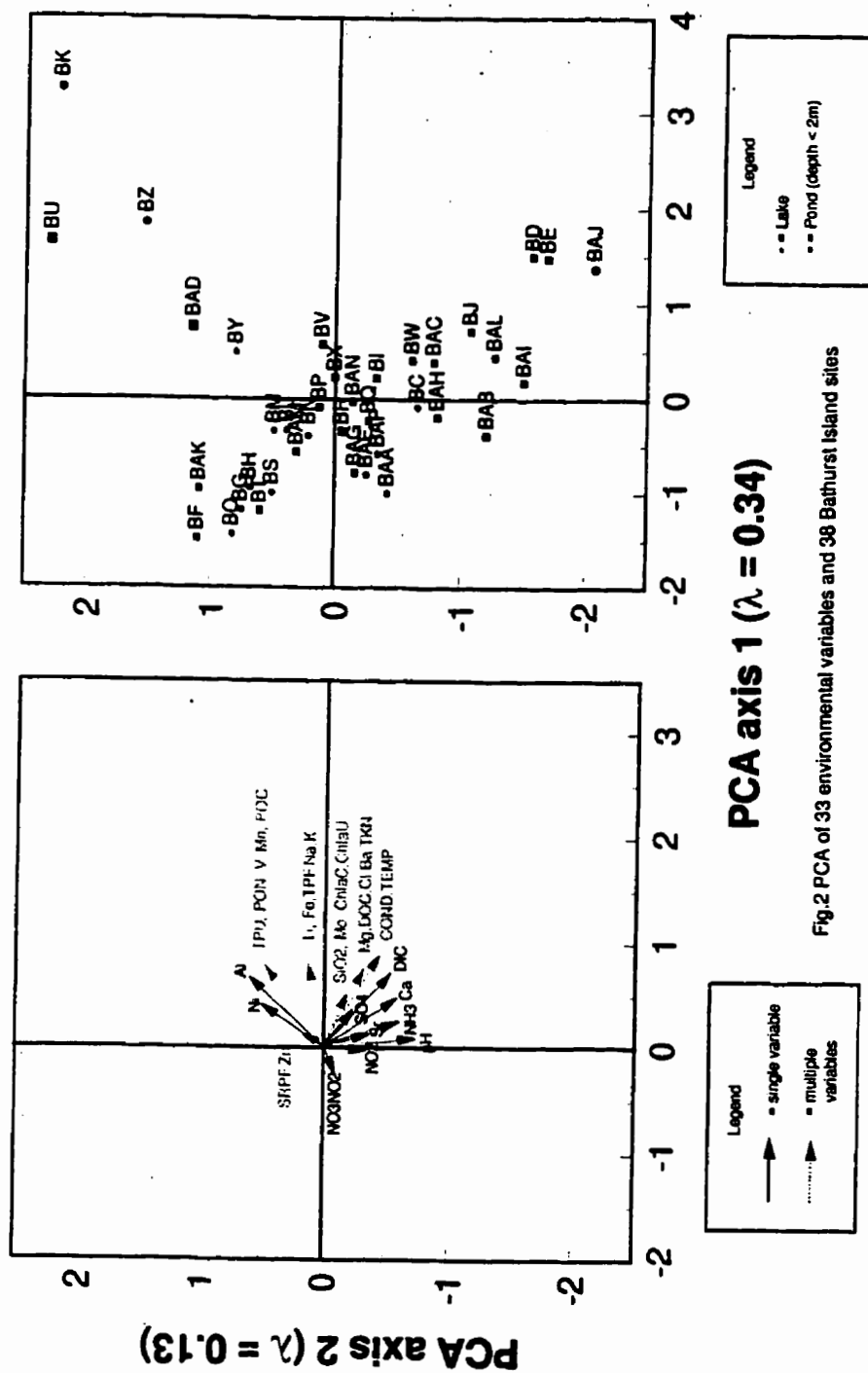
Axes 1 and 2 of the PCA accounted for 34.4% and 12.7%, respectively, of the variance (Table 4). Axes 3 and 4 captured only 18.1% of the total cumulative percentage variance (Table 4), and are therefore not discussed further here.

Axes lengths were less than 4 standard deviations (SD), which indicates that the sites will share many common attributes (JONGMAN et al. 1987). This is reflected by the similarity amongst all of the sampled sites in their climate, as well as underlying bedrock.

The dominant gradients identified in the PCA ordination (Fig.2) of the measured limnological variables indicate that differences in: (a) the components affecting water hardness such as calcium and magnesium, (b) major ion content, and (c) DOC levels along Axis 1, and pH along Axis 2, mostly influence the distribution of the 38 lake and pond sites on the ordination. However, shallower pond sites tend to cluster separately from the deeper lakes. For example, ten of the thirteen deeper sites are clustered in the two left quadrats of the PCA ordination. For reasons described earlier in this paper, as well as the discussion by DOUGLAS & SMOL (1994), this is not surprising.

Table 4. PCA summary output for 33 environmental variables

Axes	1	2	3	4	Total Variance
Eigenvalues	.344	.126	.095	.087	1.000
Cumulative percentage variance of species data	34.4	47.1	56.6	65.2	
Sum of all unconstrained eigenvalues					1.000



Also, conductivity (COND), [Ca], and [Mg] show a high positive correlation along the first axis of the PCA (Fig.2). This relationship is also clear in the correlation matrix (Table 3), with positive correlation between COND and [Ca] and [Mg]. Those sites (e.g. BD, BE, BAJ) which have relatively elevated Ca and Mg levels are most strongly influenced by this cluster of environmental variables (Fig.2).

Aluminum, iron, and manganese also show high positive correlations with Axis 1 (Fig.2), and share high correlations to each other (Table 3). This is to be expected, given that water containing elevated levels of calcium and magnesium salts are commonly associated with polyvalent metals, such as iron, aluminum, and manganese (LIND 1974). Sites BK, BU, BY, BZ and BAD, located in the upper right-hand quadrat of the PCA, all had high levels of these metals (Table 2). In acidic lakes, with high aluminum levels, Al has been correlated with pH levels (DIXIT et al. 1993). Aluminum did not, however, have a significant correlation with pH in this study (Table 3), which is not surprising, since the Bathurst Island sites are highly alkaline (pH = 8.0 – 8.6). Al concentrations were fairly similar and relatively low amongst all Bathurst sites (mean of 0.0479mg/L), which is to be expected given the similarity in catchment geology amongst the sites.

The DOC gradient is most likely driving the differences between the shallower ponds and the deeper lakes (Fig.2). Shallower pond sites (e.g. BD, BE, and BJ) are ordinated closely to the DOC gradient extremity, while deeper sites (e.g. BG, BH, and BO) are ordinated in the opposite quadrat. The projection of site scores onto environmental arrows allows for the detection of key patterns of variation in the limnological dataset, and for the inference of the chemical composition of any given site (JONGMAN et al. 1987). Therefore, we can infer that the shallower sites had higher organic input relative to the



deeper sites. Small, oligotrophic water bodies such as these shallow tundra ponds can still receive a significant amount of dissolved organic carbon loading from the catchment vegetation and soils, even in the absence of trees. Field observations indicated that the ponds tended to have more grasses and mosses in their catchments relative to what was recorded for the lakes. The small, shallow ponds would also have less volume with which to dilute the humic and fulvic acid inputs, thereby resulting in increased DOC concentrations relative to the deeper sites.

The pH gradient is most closely related to Axis 2, but it also shares a relationship with the Ca-Mg and polyvalent metal gradient driving Axis 1 (Fig.2). Those sites (e.g. BAI, BAJ, BAL) ordinated at the end of the pH arrow have higher alkalinity levels and elevated Ca and Mg levels (Table 2). Sites located in the upper left-hand quadrat (Fig.2) (i.e. BF, BG, BH, BL, BN, BO, BT) all have lower pH, Ca and Mg levels relative to other sample sites (Table 1). This pH trend is not correlated with size nor elevation (ELEV), and in fact only slight differences exist amongst the pH levels of the sites, given the short pH gradient length and the similarity in underlying bedrock amongst all the sites.

## 2.5 Conclusions

Major ion concentrations of the Bathurst Island ponds and lakes were relatively high, which is consistent with the calcareous, limestone, and dolomite bedrock of the drainage basins of all sites. Differences in Na and Cl concentrations were primarily related to the proximity of each site to the sea. Overall, this limnological dataset was similar to those reported by other studies from similar geological settings in the subarctic and arctic

regions of North America (see RÜHLAND & SMOL 1998; PIENITZ *et al.* 1997; DOUGLAS & SMOL 1994; EILERS *et al.* 1993; KLING *et al.* 1992) (Table 5).

Nutrient concentrations amongst all sites were typical for high arctic oligotrophic aquatic environments. Total unfiltered phosphorus (TPU) ranged from 3.2  $\mu\text{g/L}$  – 64.0  $\mu\text{g/L}$  (mean = 12.7  $\mu\text{g/L}$ ), which is comparable to the reported values from other arctic sites (e.g. Pienitz *et al.* 1997a). Examination of PON:POP, TN:TPU and REDFIELD (C:N:P) ratios, showed that although certain sites were P-limited, most were N-limited. Sixty-three percent (63%) of the sites, which had PON:POP ratios  $\leq 10:1$ , also had TN:TPU ratios less than the mean ratio of 64:1, indicative of N-limitation. Those sites with PON:POP ratios  $\geq 20:1$ , all had [TPU] under the mean, and drained through rocky areas that were relatively less vegetated. Finally, by looking at the C:N:P ratios, I was able to make an overall assessment of whether or not most sites were N or P limited. The average C:N:P ratio for Bathurst Island is 107:6:1, which indicates less nitrogen than that reported by SHORTREED & STOCKNER (1986) (137:18:1) for 19 Yukon lakes, and REDFIELD (1958) (106:16:1) for marine phytoplankton. From this comparison, it is most likely that most of the Bathurst Island sites are in fact N-limited. However, the range of C:N:P ratios amongst the sites (e.g. 29:1:1(BF) – 1950:90:1(BT)) indicates that the extent of N-limitation may be variable.

Comparison of the slope of the CHLA Vs TP linear regression for Bathurst Island to that calculated by DILLON & RIGLER (1974) for summer values, also indicated that, in general, most of my sites are not highly P-limited, but rather range from slightly P-limited to N-limited. The linear regression of CHLAU Vs TN for those sites with PON:POP  $\leq 10:1$

Table 5. Comparisons of limnological results of North American arctic region studies.

↑ = increased; ↓ = decreased

Researcher	Location	No. of sites	Analysis	Major Ions	Key Trends
Kling 1992	arctic Alaska, USA	45 (lakes)	N/A	$\text{Ca}^{2+}$ , $\text{HCO}_3^-$ , $\text{NH}_4^+$	$\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ ; Surface waters within 20km of coast dominated by Na, Ca, Cl, $\text{HCO}_3^-$ ; surface waters further inland dominated by $\text{HCO}_3^-$ , Ca, Mg
Eilers 1993	Kenai Peninsula, Alaska, USA	59	nonhierarchical cluster analysis	$\text{Ca}^{2+}$ , $\text{Na}^+$ , $\text{Mg}^{2+}$ , $\text{Cl}^-$	$\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ ; $\text{Cl}^-$ ↓ with distance from the coast; low alkalinity lakes were at higher elevations than high-alkalinity lakes
Douglas & Smol 1994	Ellesmere, NWT, Canada	36	Average-linking agglomerative clustering algorithm	$\text{Ca}^{2+}$ , $\text{Na}^+$ , $\text{Cl}^-$	$\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ ; [Na] & [Cl] ↑ with ↑ in proximity to ocean; sites with vascular plants in drainage had relatively higher [K]; low TPF, DOC and nitrogen species concentrations; highly alkaline waters
Pienitz <i>et al.</i> 1997a	Yukon & NWT, Canada	59	PCA	$\text{Ca}^{2+}$ , $\text{Na}^+$ , $\text{Cl}^-$ , $\text{K}^+$ , $\text{SO}_4^{2-}$	$\text{Ca} > \text{Na} > \text{K}$ ; Na, Cl, K, Ca, $\text{SO}_4$ , DIC all highly correlated ( $P < 0.01$ ) with conductivity; elevated $\text{SO}_4$ levels due to weathering from sedimentary bedrock; $\text{Cl}^-$ ↓ with distance from the coast
Pienitz <i>et al.</i> 1997b	Yellowknife, NWT, Canada	24	PCA	$\text{Ca}^{2+}$ , $\text{Na}^+$ , $\text{Cl}^-$ , $\text{K}^+$ , $\text{SO}_4^{2-}$	$\text{Ca} > \text{Na} > \text{K}$ ; nitrogen species concentrations were near or below detection limit
Ruhland & Smol 1998	arctic treeline, NWT, Canada	70	PCA	$\text{Ca}^{2+}$ , $\text{Na}^+$ , $\text{Mg}^{2+}$ , $\text{K}^+$	$\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ ; correlation between elevated levels of pH, conductivity, and major ions; $\text{Cl}^-$ ↓ with distance from the coast

N/A = Not Applicable

revealed a significant ( $P \leq 0.01$ ) correlation, while those site with PON:POP  $>10:1$  were not significantly correlated ( $P \geq 0.01$ ). This indicates that the limiting algal nutrient for almost two-thirds of the Bathurst sites is most likely nitrogen, and not phosphorus.

DOC concentrations ranged from 1.1 mg/L – 11.2 mg/L, which is typical for oligotrophic waters outside of treeline (VINCENT & PIENITZ 1996). Variance in [DOC] could be partially explained by differences in surrounding vegetation for each site, as well as the volume of the site. Sites with [DOC] greater than the mean were typically smaller ponds, which drained through relatively lush, vegetated areas. In order to clarify whether the organic carbon source was mostly derived from algae or from terrestrial/detrital inputs, POC:CHLAU ratios were calculated. POC:CHLAU ranged from 11000:1 to 235:1 (mean = 871:1), which is indicative of significant detrital input. Sites draining through lush, vegetated areas, where detrital material could be transported in the run-off, usually had POC:CHLAU ratios above the mean.

PCA provided an effective ordination of lake and pond sites, and environmental variables in two or more dimensions (TER BRAAK & PRENTICE 1988). The eigenvalues revealed that the first two axes of the ordination could explain most of the limnological variation amongst the sites. Conductivity, DOC and variables related to water hardness such as Ca-Mg ions and other polyvalent metals, contributed primarily to Axis 1, while Axis 2 was driven primarily by pH. Differences between the shallow vs. deeper sites were especially clear in their spread in the ordination relative to the DOC gradient.

Future work on Bathurst Island will hopefully include a detailed limnological analysis of the western portion of the island. Surficial material on western Bathurst Island is much less alkaline ( $\text{pH} < 4.0$ ) than in the east. A comparison of the water chemistry of the

lakes and ponds in these two areas could help expand our understanding of the dominant limnological trends governing Bathurst Island.

The results of this and future studies will be incorporated into a growing database of baseline water chemistry from sites throughout the High Arctic. By understanding the differences in limnological processes that govern in this extreme environment, we will be able to better predict how future changes in the climate could affect these water bodies.

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**Chapter 3:                    The Relationship Between Diatom Assemblages and  
Environmental Variables from Lakes and Ponds on Bathurst  
Island, N. W. T., Canadian High Arctic**

**Abstract**

Multivariate statistics was used to explore the relationship between the physical and chemical limnic properties and the diatom assemblages from the surface sediment of 29 lakes and ponds from Bathurst Island, N. W. T., Canada. Furthermore, weighted averaging regression techniques were used to develop a temperature (TEMP) transfer function using modern diatom species.

Of the one-hundred forty eight (148) diatom species identified from the surface sediment, fifty-nine (59) met screening requirements and were included in the transfer function development. The dominant diatom species were small, pennate and benthic. Species that appeared in over 80% of the sites included *Achnanthes flexella*, *Achnanthes minutissima*, *Cymbella angustata*, *Cymbella arctica*, *Nitzschia frustulum*, *Nitzschia perminuta*, and *Nitzschia perminuta* T1. *Fragilaria pinnata* and *Pinnularia balfouriana* accounted for over 50% of the diatom assemblage in many of the colder, larger sites. A greater variety of periphytic diatom species were present in the warmer, more nutrient-rich sites.

Canonical correspondence analysis (CCA) constrained only to temperature demonstrated that surface water temperature accounted for a significant proportion of the diatom species variance. Exploratory weighted averaging (WA) analysis identified the potential for deriving paleotemperature inferences from the modern diatom assemblages on Bathurst Island. Given that other factors such as grazing, parasitism, turbidity and microhabitat distribution may also be influencing species variation as a function of temperature influences, the use of this model should be limited to other sites falling within the temperature range of the Bathurst Island sites (i.e. 2.5°C – 19.5°C).

Overall, the development of this temperature model demonstrated the potential for future thermal and other environmental paleoreconstructions in the Canadian High Arctic. Furthermore, this study contributes to a growing diatom autoecological database spanning the High Arctic.

**Chapter 3:                    The Relationship Between Diatom Assemblages and  
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**3.1 Introduction**

The lakes and ponds that dot the high arctic landscape are extremely sensitive to environmental changes, both natural and introduced or accelerated by human activity (SMOL et al. 1991). In order to effectively monitor change in these aquatic systems, we need to: (a) understand the natural variability of past environments; (b) determine the environmental conditions prior to anthropogenic influences; and (c) be able to make predictions about future climate change (SMOL & DOUGLAS 1996). For these reasons, historical limnic data are needed to reconstruct past aquatic environmental conditions. In the High Arctic, these data are impossible to procure without the use of paleoenvironmental techniques. Fossilized freshwater algal remains, which are present in lake and pond sediments, are reliable bioindicators of past physical and chemical limnic conditions. The most commonly used algal indicators are diatoms (class Bacillariophyceae).

In the oligotrophic lakes and ponds of the High Arctic, diatoms often are a significant part of the algal community (DOUGLAS & SMOL 1993). It has been proposed that their minute size facilitates the uptake of nutrients and growth factors in nutrient poor waters (KALFF 1970). They play a key role in aquatic food chains, and shifts in their assemblages, particularly in the wake of any environmental change, may affect the biotic balance in the aquatic environments. Since each diatom species exhibits characteristic

optima and tolerances to specific environmental variables, and because they are usually well preserved in lake and pond sediment due to siliceous cell walls, diatoms are useful bioindicators in reconstructing past salinity, pH, nutrient, and lake levels, as well as other environmental variables. Furthermore, diatoms have rapid immigration and reproduction rates (DIXIT et al. 1992).

Surface sediment samples (~ top 1 cm) for high arctic lakes and ponds represent an integrated sample of diatom communities, both spatially (i.e. from various habitats) and temporally (i.e. ~ last few years of deposition). One method of effectively using diatoms to infer past aquatic environments is to establish a quantitative relationship between present-day limnic properties and the dominant surface sediment diatom assemblages. This link can be explored through the use of direct multivariate gradient analysis techniques such as Canonical Correspondence Analysis (CCA). This approach has previously been used to examine arctic freshwater diatoms by, for example, PIENITZ & SMOL (1993) near Yellowknife, N. W. T., PIENITZ et al. (1995) between Whitehorse in the Yukon and Tuktoyaktuk, N. W. T., WECKSTRÖM et al. (1997) in Fennoscandian subarctic lakes, and GREGORY-EAVES (1998) in Alaska.

This study examines the relationship between 33 environmental variables and the distribution of surface sediment diatom assemblages from 29 lakes and ponds on Bathurst Island, N. W. T. with the use of CCA. In order to develop a potential calibration model to infer past surface-water temperatures, the autoecology (optimum and tolerance) of 59 dominant diatom species was estimated for surface temperature (TEMP) using weighted-averaging regression analysis.

### 3.2 Site Description

Twenty-nine lakes and ponds along the eastern section of Bathurst Island (75° 42'N, 97°21'W), N. W. T., Canada (Fig.1, Table 1) were sampled for both limnological (physical, chemical, and biological) data (see Chapter 2) and surface sediment collections. All of the sites share similar Ordovician to Late Devonian geology, and their bedrock consists of shale, anhydrite, siltstone, limestone and dolostone (HODGSON 1989). The island is characterized by low relief, with few areas rising above 300m asl, although there are certain areas marked by deeply incised streams and valleys (KERR 1980). A detailed geological and topographical description can be found in Chapter 2 of this thesis.

Bathurst Island is different from other High Arctic islands, in that its soils are much more moist, developed, and highly cryoturbated (TARNOCAI 1976). The drainage characteristics along the eastern end of the island range from poorly drained, highly saturated soils, to moderately to imperfectly drained slopes (EDLUND 1990). These soil characteristics have given rise to a more vegetated environment, as compared to other high arctic islands in the vicinity. Plants such as *Saxifraga oppositifolia* and *Papaver lapponicum* dominated the study area during the July 1994 summer collection period (see field notes, Appendix 1).

The climate of Bathurst Island is typical of other high arctic islands, with a mean annual temperature of approximately -15.0°C. Summer months (June – August) may see an increase to mid-teen (°C) temperatures, although they usually remain around 5.0°C. It is during this short span of time that the lakes and ponds are either partially or fully ice-free.



### 3.3 Methods and Materials

#### 3.3.1 Sample Collection and Field Techniques

Of the total 38 sites sampled for limnological analysis on Bathurst Island (see Chapter 2), nine sites (BI, BL, BO, BQ, BS, BY, BAA, BAB, BAF) could not be sampled for surface sediments for either logistical reasons (e.g. tenuous ice cover) or because sediments were not accumulating in some of the shallow ponds. Therefore a total of 29 sites were available for the modern diatom assemblage analysis. Of these sites, 9 were lakes (i.e. BC, BG, BH, BK, BM, BN, BZ, BAE, BAJ), and the remaining 20 were ponds (depth < 2m). The 29 lakes and ponds were sampled using a helicopter on Bathurst Island, N. W. T., Canada from July 14, 1994 – July 20, 1994. The location of each site was recorded using a handheld GPS (Appendix 1). A total of 39 limnological variables (field and laboratory) were collected for each site, although 6 variables that were consistently below the detection limit were eliminated from the active dataset, leaving a total of 33 active variables (see Chapter 2 for details). For a detailed description of the abiotic sample collection and preparation techniques, please refer to Chapter 2 (section 2.3.1).

The uppermost 1cm of lake or pond surface sediment was sampled, often by hand, and placed in a 15ml plastic scintillation vial. Depending on the bathymetry, sediment was collected several meters from the edge of the shore, or as close to the center of the site as possible.

Other biotic components were also collected, which allow for the option to expand upon the analysis of each site (see DOUGLAS & SMOL 1995 for a list of additional

collections). Epiphytic algal communities were sampled by collecting mosses (sampled across moisture gradients), and any emergent or submerged plants. In addition, epilithic algal communities were sampled by collecting five submerged rocks from each site and brushing the attached algae into a 15ml plastic scintillation vial with a soft toothbrush. Phytoplankton and zooplankton tows were collected using a 55µm mesh plankton net. These samples were stored in 15ml plastic scintillation vials, preserved in Lugol's iodine solution and Formalin (LIND 1974), respectively, and kept cool both in the field and upon return to the lab.

### 3.3.2 Laboratory Analyses

Sample preparation adhered to procedures outlined in PIENITZ & SMOL (1993), and is summarized in this section.

Preparation of the diatom slides involved placing approximately 1cm<sup>3</sup> of each lake/pond surface sediment sample in a 15ml polypropylene centrifuge tube. Next, 9ml of a strong solution of sulphuric (H<sub>2</sub>SO<sub>4</sub>) and nitric (HNO<sub>3</sub>) acids (1:1) was added to each centrifuge tube in order to digest any organic material. The digestion process took place over a period of approximately 5 days, at the end of which the samples were placed in a hot water bath for two hours in order to accelerate the digestion of any residue.

These digested samples were then centrifuged. The supernatant was aspirated, and the remaining pellet was resuspended in distilled water. Centrifuging-washing was performed eight times on all samples until they were acid-free.

After these centrifuge-washings, the slurry of siliceous material contained in each tube was pipetted out onto a set of four coverslips, in a series of dilutions. Each coverslip had been washed in 10% ethanol. The slurries were left to evaporate, over a period of 24 hours, on the coverslips that were placed on slide warming trays at very low heat.

Once dry, the coverslips were mounted on glass microscope slides with Naphrax®, a permanent mounting medium with a high refractive index (R.I. = 1.74).

### 3.3.3 Microscopy and Diatom Identification and Enumeration

A Nikon Optiphot-2 microscope equipped with differential interference contrast optics (1000X; N.A.= 1.25) was used to examine samples under oil immersion. For each lake/pond sample, one cover slip of the appropriate dilution was examined, and a minimum of 300 diatom valves was identified and enumerated along central transects following counting procedures outlined by KINGSTON (1986). However, it should be noted that in two samples (BH & BZ), the concentration of diatom valves was too low to reach a minimum count of 300 valves.

Diatom species were identified mainly using the following references: KRAMMER & LANGE-BERTALOT (1988-1991 & 1997), LANGE-BERTALOT & KRAMMER (1989), KRAMMER (1992), LANGE-BERTALOT (1996), FOGED (1974), FOGED (1981), CUMMING et al. (1995), GERMAIN (1981), and DOUGLAS & SMOL (1993). Furthermore, the 1997 & 1998 Arctic – Antarctic Working Group annual sessions provided a great deal of taxonomic assistance.

Nomenclature of the diatom taxa follows these resources, and the descriptive terms follow BARBER and HAWORTH (1981). Undefined species have been given a designation of 'sp.'. Those diatoms with a 'T1' listing are considered to be unknown subtypes of a species. This designation was given at the 1997 Arctic-Antarctic Diatom Symposium. All the dominant diatom taxa have been arranged alphabetically, and relevant information is summarized in Table 7.

Using a Nikon FDX-35 camera, photographs were taken of the various diatom valves using high-resolution black and white Tech Pan film (exposed at 50ASA). A reference catalogue of all the observed diatom taxa was compiled. From this catalogue, a total of 5 photographic plates were arranged to document the key diatom assemblages for this thesis. The plates were constructed with Sprint Scan 35 Polaroid® electronic imaging systems software, which allowed for images to be scanned directly from the black and white negatives. Subsequently, the images were arranged using Adobe Photoshop®.

### 3.3.4 Statistical Data Analyses

#### Data Preparation

One hundred and forty-eight diatom taxa were identified for the 29 lake and ponds sampled for surface sediment. Only those diatom taxa that had a relative abundance >1% in a minimum of three lakes were included in the ordination analysis. From the 29 calibration lakes and ponds, 59 taxa met these criteria (see Appendix 3 for species dataset).

### Ordination

Principle Components Analysis (PCA) was performed using CANOCO v.3.15 (TER BRAAK 1997, 1990), for the purpose of ordinating the site and environmental data. The projection of site scores onto environmental arrows allows for the detection of key patterns of variation in the limnological dataset, and for the inference of the chemical composition of any given sites (JONGMAN et al. 1987). For a full description of the PCA methods, see Chapter 2 (section 2.3.2).

Detrended Correspondence Analysis (DCA) was used as part of the analyses. These analyses were conducted to assess whether a unimodal method, such as Canonical Correspondence Analysis (CCA), would be appropriate to use in the interpretation of the environmental data and diatom species data. DCA calculates the species gradient length, which can be used to estimate whether the species distributions follow unimodal or linear patterns. More specifically, a standard deviation (SD) greater than 2.5 indicates a relatively long gradient, and is indicative of a unimodal species distribution (JONGMAN et al. 1987). DCA results showed that the gradient length for the 29 lake training set was 2.90 SD for axis 1 and 3.95 SD for axis 2 (Appendix 4). Therefore, most of the diatom taxa would have unimodal distributions along these axes, and CCA (a unimodal technique) was deemed appropriate for further analyses.

CCA is a constrained ordination technique that is commonly used to identify patterns of distribution and influence amongst diatom species, sites and environmental variables. It is not uncommon to find that the greatest percentage of variance amongst all the variables is accounted for by the first two axes of the CCA. The length of the CCA biplot arrows demonstrates the relative importance of each environmental variable, while

the placement of each arrow relative to the other arrows and to the ordination axes represent their approximate correlation to each of these factors. The dominant environmental variables driving the construction of the CCA axes are represented by the longest arrows in the ordination (TER BRAAK, 1986).

### Data Screening

In order to run a CCA for the 29 lake/pond dataset, the size of the environmental dataset had to be reduced to a maximum of  $n-1$ , where  $n$  is the number of sample sites. First, a series of CCAs were run. With each CCA run, the variable with the highest variance inflation factor (VIF) (indicating high collinearity with other variables) was removed from subsequent CCAs (TER BRAAK 1988). This was done to eliminate variables with unstable canonical coefficients (TER BRAAK 1988). CCAs were run until all remaining environmental variables had VIFs less than 20.

Next, forward selection was used to identify the minimum number of environmental variables that could effectively explain the greatest amount of variance in the species dataset. The significance of each variable was determined by testing the significance of the first canonical axis using implicit Monte Carlo testing (based on 99 unrestricted permutations) (TER BRAAK 1988). This process produces a reduced environmental dataset that explains the species data almost as well as the full set (TER BRAAK 1990).

To reduce distortion in the CCA ordination, rare and dominant species were given less weight (i.e. downweighted) in proportion to their frequency (TER BRAAK 1988), while retaining them in the analysis.

In order to understand the relative importance of each of the significant environmental variables identified through forward selection in explaining additional variation in the diatom distribution, a series of constrained CCA's were run. The significance of each of these variables in explaining the first CCA axis was determined using Monte Carlo testing with 999 unrestricted permutations (TER BRAAK 1990). By measuring the ratio of the first constrained eigenvalue ( $\lambda_1$ ) to the second unconstrained eigenvalue ( $\lambda_2$ ) (i.e.  $\lambda_1/\lambda_2$ ) for each variable, the relative strength of each variable was quantified (Appendix 5).

#### Regression and Calibration

Using the program WACALIB version 3.3 (LINE et al. 1994), weighted averaging (WA) regression analysis was used to explore the viability of developing a temperature (TEMP) transfer function for Bathurst Island, N. W. T. The construction of this calibration set would enable surface-water temperature reconstructions to be made for this island using diatom remains in lake and pond sediments. This technique assumes that the diatom taxa will be the most abundant in the lakes or ponds that have TEMP values at or near their optima.

Non-linear least-squares regression or maximum-likelihood estimations are two other methods of building a calibration set, however WA regression techniques have been shown to be computationally simpler and equally as robust in estimating indicator values (TER BRAAK & VAN DAM 1989).

### 3.4 Results and Discussion

#### 3.4.1 Limnological Trends

The limnology of all the 38 Bathurst Island sites is described in detail in Chapter 2. A list of all measured variables is summarized in Table 2. Only 29 of these lakes and ponds could be sampled for surface sediment. Overall, the lakes and ponds sampled were oligotrophic, and within a small pH range of 8.0 to 8.6 (Table 2). The major cations in descending order of concentration (mg/L) were  $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ , while the major anions, also in descending order, were  $\text{CO}_3 > \text{SO}_4 > \text{Cl}$ .

The nutrient analysis presented in Chapter 2 demonstrated that the Bathurst Island sites are most likely nitrogen (N) limited. By examining the PON:POP, TN:TPU and Redfield (C:N:P) ratios, it was apparent that of the 29 sites included in this diatom analysis, 66% of the sites are most likely N-limited, while 17% are most likely phosphorus (P) limited, and the final 17% fall into an intermediate zone. N-limited sites such as BF, BK, BU, BZ and BAD, all had total unfiltered phosphorus (TPU) concentrations greater than the mean ( $12.7 \mu\text{g/L}$ ) (Table 2). Sites that were most likely P-limited, all had [TPU] under the mean, and were, with the exception of BT and BAG, all deeper, larger lake sites.

Dissolved organic carbon (DOC) concentrations ranged from  $1.1 \text{ mg/L} - 11.2 \text{ mg/L}$ , which falls within a typical range for oligotrophic lakes and ponds outside of treeline (VINCENT & PIENITZ 1996). Variance in [DOC] amongst sites could be attributed to differences in vegetation in the drainage area.



Axes 1 and 2 of the PCA accounted for 34.4% and 12.7%, respectively, of the variance (Table 3). PCA (Fig.2) revealed two dominant gradients driving the variance amongst sites: (a) variables related to water hardness (i.e. Ca-Mg ions, other polyvalent metals), and DOC along Axis 1; and pH along Axis 2.

Differences between shallower vs. deeper sites were apparent (Fig.2), and were attributed to the variance in DOC concentrations amongst these sites. We can make the inference that the shallower sites received a greater amount of organic input than the deeper sites, and that given their smaller capacity, are unable to dilute the effects of this input as would a lake of greater volume.

Along Axis 2, sites ordinated along the pH gradient (Fig.2). Those sites with relatively elevated alkalinity levels were found at the end of the pH arrow projection. However, since all the sites share similar bedrock, they fell within a tight pH range, which accounts for the short pH gradient.

#### 3.4.2 Diatom Assemblage Data

The dominant diatom species identified were small, pennate and benthic, which is typical for high latitude, oligotrophic lakes and ponds (KALFF 1970; DOUGLAS & SMOL 1993; PIENITZ et al. 1995; DOUGLAS & SMOL 1995; WECKSTRÖM et al. 1997). The only centric species identified was *Cyclotella antiqua* (Plate E). This centric diatom is considered to be benthic, and is typical of arctic regions (DOUGLAS & SMOL 1993). However, it did not meet the criteria outlined in section 3.3.4 to be considered as a dominant diatom species, and is not included in the CCA analysis.

The dominant diatom species, which appeared in over 80% of the sites, were *Achnanthes flexella*, *Achnanthes minutissima*, *Cymbella angustata*, *Cymbella arctica*, *Nitzschia frustulum*, *Nitzschia perminuta*, and *Nitzschia perminuta* T1. All of these species had a total number of occurrences above 23, and a high effective number of occurrences (i.e. high N2 values) (Table 7), indicating a fairly even distribution amongst the Bathurst Island sites. Furthermore, these species are generally considered to be cosmopolitan diatoms (FOGED 1981, PATRICK & REIMER 1975). In particular, *Achnanthes minutissima* is a common diatom to many freshwater environments (KRAMMER & LANGE-BERTALOT 1986-1991), whereas *Cymbella arctica* has been abundantly reported in various high arctic sites (K. MOSER (Cornwallis Island), D. ANTIONADES (Axel Heiberg Island) pers. comm.).

Comparing my diatom flora specifically to that described for Cape Herschel, Ellesmere Island, N. W. T. (DOUGLAS & SMOL 1993), there are a great deal of similarities. Over 50% of the dominant species reported for Cape Herschel were also reported as common diatoms on Bathurst Island. Similarities also exist between the Cape Herschel diatoms and those described by FOGED (1953, 1955) on Western Greenland, which points to the possibility of a diatom flora specific to the High Arctic (DOUGLAS & SMOL 1993). Undoubtedly, all of these diatoms share the common trait of being able to survive extreme physical and chemical (e.g. oligotrophy) conditions, short growing seasons, and unpredictable temperature fluctuations (DOUGLAS & SMOL 1993).

Two species, *Fragilaria pinnata* and *Pinnularia balfouriana*, although not commonly distributed amongst all sites, accounted for over 50% of the diatom assemblage in certain lakes and ponds. More specifically, *F. pinnata* dominated in BAJ, BAK, BAL

and BAM, all of which were either lakes (BAJ) or large ponds (BAK, BAL, BAM), while *P. balfouriana* dominated in lakes BM and BN, and constituted nearly 32% of site BAM (Appendix 3). These two species are known to be able to survive in ultraoligotrophic waters by associating themselves with sediment and/or moss substrata (DOUGLAS & SMOL 1995). *P. balfouriana* is generally considered to be a moss epiphyte (DOUGLAS et al. 1994a). Those sites dominated by *P. balfouriana* had relatively more mosses growing both along their shoreline and within their littoral zone than other sites (Appendix 1). *Fragilaria pinnata* is considered to be an epipellic diatom, and the availability of nutrients from the interstitial waters of the loosely aggregated sediment in the lake and pond littoral zones, could have created a significant nutritional advantage for this species (WETZEL 1996).

### 3.4.3 CCA

Overall, the data screening process reduced the environmental dataset from 33 to a total of 6 significant variables. Al, Mn, SRPF, and NO<sub>3</sub>-NO<sub>2</sub> were first removed through the process of identifying highly collinear variables, leaving a total of 29 environmental variables to be considered. The first two axes of the CCA performed for these 29 variables and 59 dominant diatom taxa accounted for 31.6% of the diatom-environment cumulative percentage variance (Appendix 6). The eigenvalues for Axis 1 (0.61) and Axis 2 (0.36) of the CCA represent 32% of the cumulative variance in the weighted averages of the diatom taxa. Monte Carlo permutation tests (99 unrestricted permutations) of the first two axes indicated that both were statistically significant ( $P \leq 0.05$ ).

Next, forward selection and Monte Carlo permutation tests reduced the environmental dataset from 29 to a total of 6 variables (i.e. TPF, Zn, Ba, pH, TEMP, DIC) that significantly ( $p \leq 0.05$ ) explained the species variation. Each one of these variables is significantly correlated with one or more environmental variables as shown by the weighted correlation matrix for 29 variables (Appendix 8), and represents a group of correlated variables. For example, Ba represents the combined effects of various major ions and trace metals, as shown by its positive correlation with such variables as Ca, K, Mg, Mo, V, and conductivity (COND). This subset of variables accounted for 41.3% of the variance explained by the initial 29 variables (i.e. TEMP 10.1%, TPF 8.5%, Zn 6.5%, Ba 5.5%, pH 5.5%, DIC 5.2%).

Although the remaining 23 variables did not explain a significant amount of variance of the taxon-weighted averages, I chose to include 7 other variables (i.e. Fe, Cl, K, NH<sub>3</sub>, DOC, COND, SiO<sub>2</sub>) in the CCA due to their limnological importance, and their ability to add further explanatory insight into the ordination.

Therefore, a final CCA was performed for a total of 13 environmental variables (TPF, **Zn**, **Ba**, **pH**, **TEMP**, **DIC**, Fe, Cl, K, NH<sub>3</sub>, DOC, COND, SiO<sub>2</sub>) and 59 dominant diatom taxa (Fig.3, 4, Table 6) (**bold** = significant  $P \leq 0.05$ ).

The first two axes of this CCA captured 40.3% of the cumulative diatom-environment relation (Appendix 7). This value is in fact higher than that reported for the initial CCA featuring 29 environmental variables, which indicates that this subset of environmental variables gives a strong representation of the overall trends in the dataset. The diatom-environment correlations for CCA axis 1 (0.90) and axis 2 (0.95) indicate a strong relationship between the 59 diatom species and the 13 environmental variables. The

Table 6. Summary of Dominant Diatom Species and Relevant Optima Information for TEMP (°C).

Taxon Code	Taxon Name and Authority	Plate Letter	Max. Abund.	Mean Abund.	TEMP (°C) optimum	Num. Of Occurrences	Hill's N2
1	<i>Amphora inariensis</i> Krammer	A	8.09	0.79	8.41	11	53
2	<i>A. libyca</i> Ehrenberg	A	4.02	0.45	10.14	9	5.8
3	<i>A. aequalis</i> Krammer	A	2.05	0.30	8.97	11	8.6
4	<i>A. veneta</i> var. <i>capitata</i> Haworth	A	3.33	0.33	7.79	4	3.7
5	<i>A. pediculus</i> (Kützing) Grunow	A	9.09	0.77	8.45	8	3.6
6	<i>Achnanthes</i> sp.1	A	3.27	0.28	14.09	7	4.3
7	<i>A.</i> sp.2	A	2.26	0.29	8.09	8	5.9
8	<i>A. chlidanos</i> Hogn & Hellermann	A	4.75	1.13	8.35	19	13.6
9	<i>A. flexella</i> Kützing	A	21.05	3.05	13.04	23	9.3
10	<i>A. minutissima</i> Kützing	A	39.62	8.23	11.64	26	13.5
11	<i>A. kryophila</i> var. <i>petersenii</i> Peterson	A	7.84	0.64	11.79	8	4.0
12	<i>A. oestrupii</i> var. <i>oestrupii</i> (Cleve-Euler) Hustedt	A	8.33	0.44	6.68	6	2.2
13	<i>A. ventralis</i> (Krasse) Lange-Bertalot	A	6.96	0.68	8.44	9	5.2
14	<i>A. laevis</i> var. <i>laevis</i> (Oestrup)	A	3.61	0.84	12.13	14	10.4
15	<i>A. subatamoides</i> (Hustedt) Lange-Bertalot & Archibald	A	5.57	0.37	16.99	4	2.4
16	<i>A. marginulata</i>	A	9.09	1.39	10.03	14	6.6
17	<i>Caloneis</i> sp.1	B	3.20	0.54	11.29	15	10.2
18	<i>C. bacillum</i> (Grunow) Cleve	B	3.77	0.69	11.53	13	9.6
19	<i>C. silicula</i> (Ehrenberg) Cleve	B	3.88	0.24	8.42	4	2.5
20	<i>Cymbella angustata</i> (W. Smith) Cleve	B	15.72	3.20	11.18	23	11.9
21	<i>C. arctica</i> (Langerstedt) Schmidt	B	11.01	3.70	10.81	26	17.8
22	<i>C. arctica</i> T1	B	19.94	1.32	9.37	12	3.3
23	<i>C. cesatii</i> (Rabenhorst) Grunow	B	6.50	1.61	12.15	19	12.9
24	<i>C. designata</i> Krammer	B	9.80	1.16	12.31	19	8.2
25	<i>C. latens</i> (Krasske) Reimer	B	4.38	1.07	10.14	20	13.2
26	<i>C. microcephala</i> Grunow	B	21.90	2.63	12.50	21	6.7
27	<i>C. minuta</i> Hilse	B	31.82	2.24	10.41	18	3.8
28	<i>C. silesiaca</i> Bleisch	B	9.09	1.02	9.86	16	7.1
29	<i>C. similis</i> Krasske	B	2.93	0.55	10.57	15	9.6
30	<i>C. subaequalis</i> Grunow	B	5.66	0.37	11.85	5	2.6
31	<i>C. tumidula</i> Grunow	B	9.15	0.80	11.73	13	3.8
32	<i>Denticula elegans</i> Kützing	C	22.19	1.40	10.37	11	3.0
33	<i>D. kuetzingii</i> Grunow	C	37.94	3.05	11.52	16	4.6
34	<i>Diadesmis</i> Round sp.1	C	23.44	2.20	8.12	15	5.3
35	<i>Diatoma</i> cf. <i>moniliformis</i> Kützing	C	6.56	0.44	11.79	4	2.3
36	<i>Diploneis oculata</i> (Brébisson) Cleve	C	3.91	0.78	8.33	12	8.8
37	<i>Eunotia arcus</i> Ehrenberg	C	6.83	0.65	14.50	9	5.2
38	<i>Fragilaria capucina</i> var. <i>capitellata</i> (Desmazières)	C	31.27	5.01	10.68	22	7.9
39	<i>F. construens</i> var. <i>construens</i> (Ehrenberg) Hustedt	C	7.29	0.75	6.71	6	4.2
40	<i>F. pinnata</i> var. <i>pinnata</i> Ehrenberg	C	55.84	11.34	7.39	12	8.0
41	<i>Navicula hilliardii</i> var. <i>pseudosiliculoides</i> Foged	C	2.61	0.29	7.35	5	4.2
42	<i>N. cryptocephala</i> Kützing	C	5.00	0.73	10.06	15	8.3
43	<i>N. cryptotenella</i> Lange-Bertalot	C	7.03	0.79	11.03	11	5.1
44	<i>N. jaernefeltii</i> Hustedt	C	5.00	0.38	6.20	4	2.6
45	<i>N. pseudoscutiformis</i> Hustedt	C	5.63	0.34	9.15	7	2.7
46	<i>N. salinarum</i> Grunow	D	2.39	0.41	8.52	11	8.0
47	<i>N. soehrensii</i> var. <i>soehrensii</i> Krasske	D	5.38	0.35	12.02	7	3.0
48	<i>N. vulpina</i> Kützing	D	4.79	0.76	11.28	15	9.1
49	<i>N. bryophila</i> Boye Peterson	D	4.40	0.41	7.04	9	5.1
50	<i>Neidium umiatense</i> Foged	D	9.09	0.94	10.62	7	3.9
51	<i>Nitzschia alpina</i> Hustedt	D	9.09	1.08	10.00	12	6.8
52	<i>N. frustulum</i> (Rabenhorst) Grunow	D	30.87	4.23	9.63	25	10.0
53	<i>N. perminuta</i> (Grunow) Peragallo	D	26.05	4.24	9.18	26	11.3
54	<i>N. perminuta</i> T1	D	15.09	2.82	9.51	23	10.9
55	<i>N. inconspicua</i> Grunow	D	11.64	1.01	9.31	12	5.0
56	<i>N. palea</i> Kützing	D	4.10	0.53	7.59	11	6.4
57	<i>Pinnularia balfouriana</i> Grunow	D	58.50	9.62	6.21	16	7.9
58	<i>P. subrostrata</i> A. Cleve	D	9.09	0.93	8.93	13	5.5
59	<i>Siauroneis anceps</i> Ehrenberg	D	1.71	0.31	11.62	9	8.0

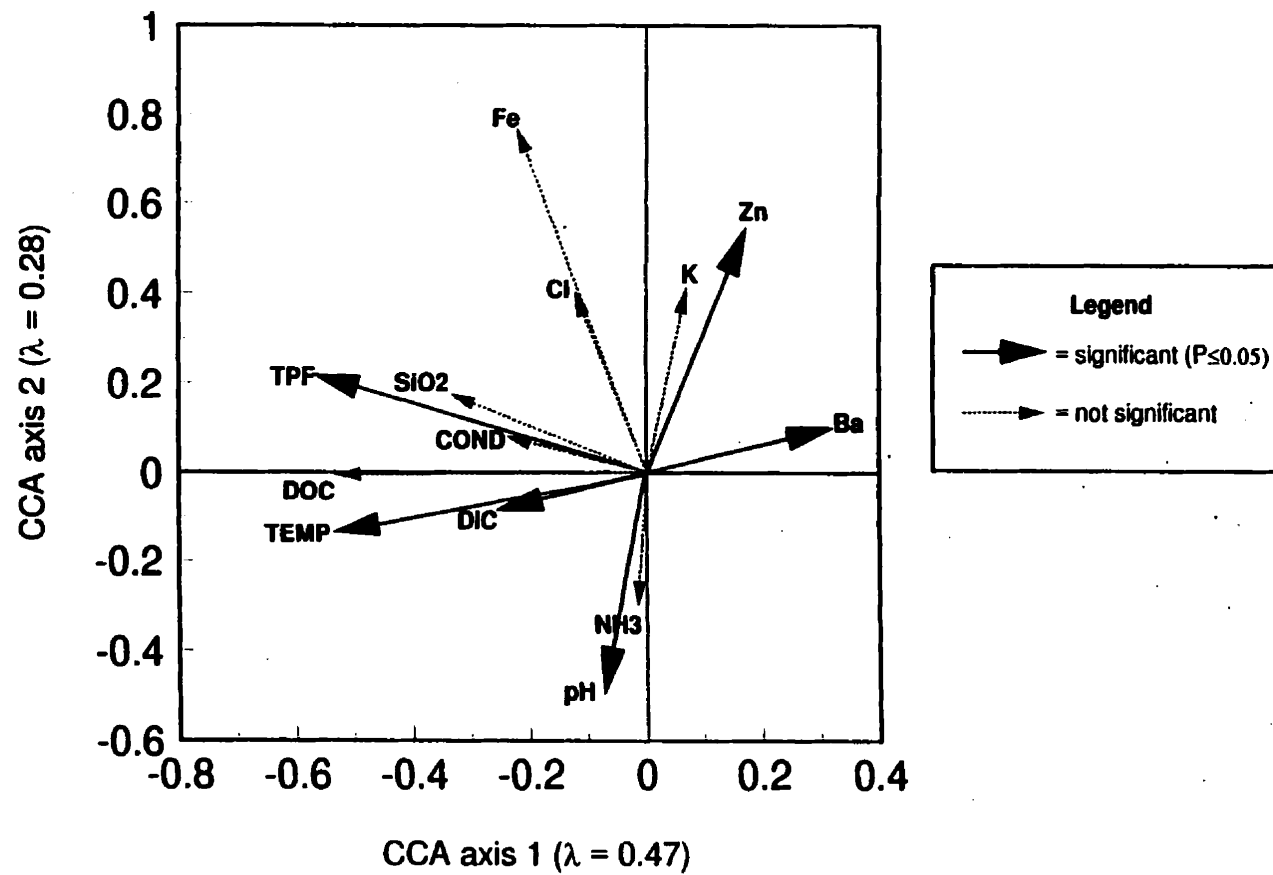


Fig.3 CCA biplot of environmental variables from the 29 lake and pond set

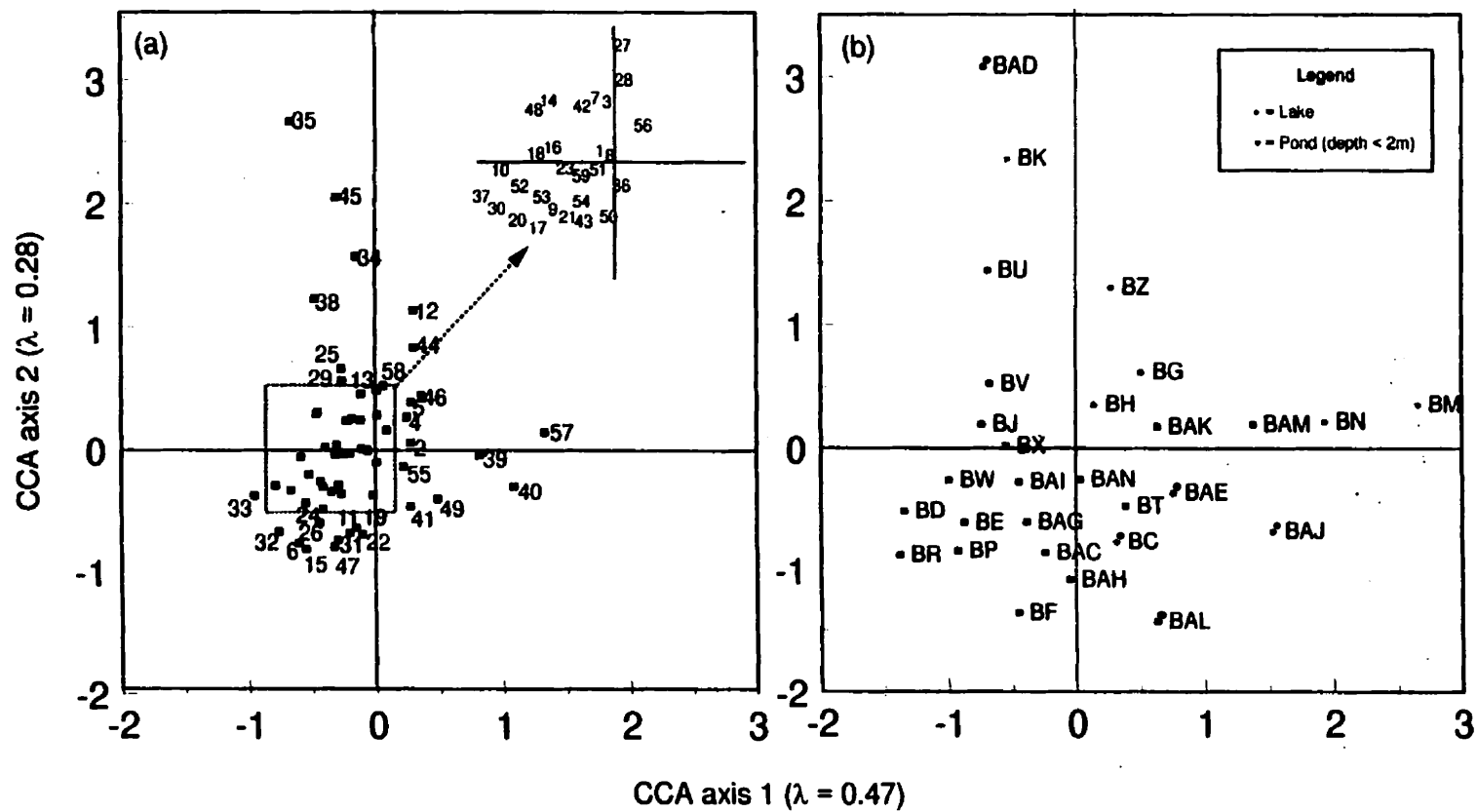


Fig.4 CCA biplot of (a) 59 dominant diatom species, and (b) 29 Bathurst Island lakes and ponds

eigenvalues for Axis 1 (0.47) and Axis 2 (0.28) accounted for 24.5% of the cumulative variance in the weighted averages of the diatom taxa. The regression/canonical coefficients, their approximate t-values, and the intra-set correlations of the environmental variables with the axes are listed in Table 7.

Figures 3 and 4 show the CCA environmental ordination and the CCA diatom species and site ordination, respectively. The major limnological trends, represented by the CCA arrows (Fig.3), affecting the 29 sample sites, are very similar to those identified in the PCA ordination (Fig.2). As identified by the inter-set correlations, Axis 1 is most strongly driven by Ba concentrations ([Ba]) (0.31), temperature (TEMP)(-0.52) and total filtered phosphorus (TPF) (-0.55). Axis 2 is strongly related to ionic concentrations (e.g. [Fe] (0.75), [Zn] (0.53)) and pH (-0.47)).

Similar to the PCA, the CCA ordination shows that the deeper lakes and larger ponds (BM, BN, BAM, BAE) are negatively correlated with the DOC, DIC, TPF, and TEMP gradients. Each of these sites was characterized by rocky drainage, with limited vegetation both in and around the catchment area. These characteristics, coupled with the larger area of these sites, may have caused a dilution of incoming nutrients such as, phosphorus, and other constituents such as, dissolved inorganic and organic carbon, resulting in lower [TPF], [DIC] and [DOC] relative to their means (6.1 µg/L, 20.1 mg/L, 4.1 mg/L, respectively). The colder temperatures of sites such as BM, BN, BAE, and BAM (mean of 4 sites = 4.4°C), relative to the overall temperature mean (9.0°C), can be attributed to their thermal inertia and bathymetry. That is, deeper, larger sites such as these will take longer to heat up and cool down than will shallower sites (HOBBIE 1980, 1984;



Table 7. Canonical coefficients of the 13 environmental variables included in the CCA, their t-values, and their intra-set correlations

Environmental variable	Canonical coefficients		t-values of canonical coefficients		Intra-set correlations	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
Ba	0.55	-0.39	2.59	-2.64	0.31	0.10
Fe	-0.23	0.31	-1.09	2.12	-0.22	0.75
K	-0.08	0.52	-0.30	2.85	0.06	0.39
Zn	0.45	0.20	2.36	1.49	0.17	0.53
Cl	0.00	0.26	0.01	1.65	-0.12	0.39
SiO <sub>2</sub>	0.11	0.50	0.44	2.97	-0.32	0.18
DOC	-0.25	0.29	-0.74	1.22	-0.52	-0.01
DIC	0.54	-0.89	1.17	-2.75	-0.24	-0.09
NH <sub>3</sub>	0.28	-0.05	1.27	-0.32	-0.01	-0.29
TPF	-0.72	0.01	-3.56	0.05	-0.56	0.23
TEMP	-0.26	-0.66	-1.06	-3.94	-0.52	-0.14
pH	-0.36	-0.08	-1.92	-0.64	-0.07	-0.47
COND	-0.40	0.44	-0.77	1.20	-0.22	0.08

DOUGLAS & SMOL 1994b; SMOL et al. 1995;). *Pinnularia balfouriana* (57), *Fragilaria pinnata* (40), and *F. construens* var. *construens* (39) dominate these larger, colder, less nutrient rich sites. This finding is in agreement with other ecological information given for these species by FOGED (1981) and KRAMMER & LANGE-BERTALOT (1986-1991). These small, benthic species are able to thrive in the ultraoligotrophic conditions of these sites by remaining in the warmer littoral zone where various plant substrates, for example, are present. Mosses grew sparsely around and within the littoral zone of each of these sites (Appendix 1), and most likely supported the bulk of the epiphytic *Pinnularia balfouriana* community. Furthermore, DOUGLAS & SMOL (1995) found that *P. balfouriana* could live on a variety of substrates such as rocks and sediment, both of which were in abundance around each of these sites (Appendix 1). PIENITZ et al. (1995) and WECKSTRÖM et al. (1997) also found *Fragilaria* species to dominate colder-temperature lakes. The lack of variety in the diatom composition and the dominance of the hardy *Fragilaria* and *Pinnularia* species in these larger sites, suggests that the lakes and large ponds are perhaps too cold and nutrient poor to support other diatom species that are unable to fully exploit their benthic resources.

Those sites ordinated in the lower left-hand quadrant of the CCA (Fig.4) are mostly smaller, shallower sites. These sites drain through lush, highly vegetated areas, populated by such vascular plants as *Saxifraga oppositifolia* (purple saxifrage) (EDLUND 1987), which may account for their elevated TPF and DOC concentrations relative to the means (6.1 µg/L, 4.1 mg/L, respectively). Although the ordination of the diatom species against the DOC gradient does not clearly demonstrate that certain taxa are affected by higher DOC inputs, it does demonstrate that species such as *Fragilaria pinnata*, *F. construens*, and *P. balfouriana*

are found in greater abundance in those sites with relatively lower levels, as seen by their position at the opposite end of the gradient arrowheads (Fig.4). Such larger taxa as *Navicula vulpina* (48), *N. cryptocephala* (42), and *Caloneis bacillum* (18) are ordinated at the head of the TPF arrow. It is possible that greater phosphorus input into a lake or pond may afford larger diatoms, such as these, adequate nutrient levels to grow and reproduce.

TEMP levels are also elevated in the sites having higher TPF, DOC, and DIC concentrations (i.e. those sites ordinated in the lower left-hand quadrant), as compared to the deeper, larger sites. As mentioned earlier, these smaller, shallower sites heat up faster than deeper sites. Furthermore, sunlight is usually able to penetrate to the deepest sections, which do not exceed 2m in depth, thereby increasing the photic zone.

These warmer, shallower, nutrient-rich sites, relative to the deeper, colder, phosphorus and nutrient limited sites, may support a greater diversity of substrates, such as mosses, grasses, etc. Consequently, a greater diatom assemblage composition may be supported by these different substrates. Increased chemical weathering as a result of warmer temperatures could increase nutrient supply (WECKSTRÖM et al. 1997). *Eunotia arcus* (37), *Denticula* species (e.g. *D. elegans* (32), *D. kuetzingii* (33)), and various *Cymbella* species (e.g. *C. angustata* (20), *C. arctica* T1 (22), *C. designata* (24), *C. microcephala* (26), *C. subaequalis* (30), and *C. tumidula* (31) constitute the main taxa. WECKSTRÖM et al. (1997) also found *Eunotia* species associated with warmer surface waters, however there exists few species similarities between this and other studies (e.g. PIENITZ et al. 1995) from which further comparisons could be drawn. DOUGLAS & SMOL (1995) found *Eunotia* species to be associated with mosses, which were abundant throughout many of the warm, shallow ponds on Bathurst Island. This substrate would confer a source of phosphorus,

calcium, and potassium, for example, to the *Eunotia* species living on them, hence creating an advantageous nutritional environment. Furthermore, *Eunotia* species such as *E. exigua* and *E. praerupta* are typically found in shallow, circumneutral to slightly acidic, low electrolyte environments (PIENITZ & SMOL 1993). In the case of my CCA results, the only dominant *Eunotia* species identified, *E. arcus*, was found in the lower-left quadrant, closely associated with Axis 1 (Fig.4). From its position on the CCA biplot, it can be inferred that *E. arcus* also predominates low electrolyte waters. Although the pH gradient along Axis 2 was short (pH = 8.1 – 8.6), *E. arcus* was more common in the less alkaline sites (Fig.3, 4).

The association between increasing TEMP and diatom assemblage variety may help explain the shift reported by DOUGLAS et al. (1994a) from a near mono-culture of *Fragilaria* species in pre-18<sup>th</sup> century sediment samples to a present-day assemblage of diverse benthic diatom species in the Col Pond and Alison Lake cores (Cape Herschel, Ellesmere Island, N. W. T.). DOUGLAS et al. (1994a) hypothesized that this represented a change from colder conditions, with longer periods of ice-cover, to warmer conditions, with extended growing seasons able to support a flourishing and more diverse periphytic diatom population. The lack of a present-day *Fragilaria* species analogue in the surface sediment of the DOUGLAS et al. (1994a) study stymied efforts to identify the environmental change that may have affected this assemblage shift. Information from the Bathurst Island CCA, including modern *Fragilaria* analogues, may help to further elucidate some possibilities as to why this occurred. Since DOUGLAS & SMOL (1994b) demonstrated that surface-water temperatures track ambient air temperature, it is possible that an increase in incoming solar radiation may have not only affected aquatic temperatures, but also other related factors such as littoral zone area, increase in surrounding vegetation, and changes in incoming humus and

nutrient loading. All of these factors attributed to a warming trend may account for the dramatic assemblage shift in Col Pond and Elison Lake (DOUGLAS et al. 1994a).

More specifically, the abundance of *F. pinnata* and *F. construens* at the bottom (representing approximately 8000 (Col Pond) and 4000 (Elison Lake) years B. P.) (DOUGLAS et al. 1994a) through to approximately 150 years ago in the Col Pond and Elison Lake cores, may indicate that these sites once had continued periods, possibly extending through the summer months, of near-zero (°C) temperatures, and low ionic and nutrient input. Ultraoligotrophic conditions, such as these, would favor small, epipelagic diatoms such as *F. pinnata*, which, for example, could derive a great deal of their nutrients from the sediment substrate in the ice-free areas of the littoral zone.

Possibly around 150 years B.P., an increase in temperatures, and a subsequent increase in meltwater run-off, may have began washing more nutrients into Col Pond and Elison Lake. Furthermore, an increase in ambient air temperatures during the summer months may have increased evaporation rates, thus concentrating the major ions and nutrients, as well as introduced more diverse substrates to the lake or pond, such as different moss species, grasses, etc. Increased levels of DOC, SiO<sub>2</sub>, phosphorus, and substrate diversity in Col Pond and Elison Lake may have made it possible for larger benthic diatoms to proliferate. These diatoms may be more specialized and more efficient at uptaking nutrients from substrates and the surrounding water than the smaller *Fragilaria* species. Thus, a shift in dominant diatom flora would ensue.

Species clustered around the origin of the CCA (Fig.4), such as *Achnanthes minutissima* (10), *Achnanthes flexella* (9), *Cymbella cesatii* (23), *Nitzschia frustulum* (52), *Nitzschia perminuta* (53), and *Nitzschia inconspicua* (55), are common to all sites, and are

considered to be cosmopolitan or eurytopic (FOGED 1981; KRAMMER & LANGE-BERTALOT 1986-1991; PIENITZ et al. 1995; WECKSTRÖM et al. 1997).

Axis 2 primarily represents an ionic and pH gradient. However, the pH range for all the sites was small (pH = 8.1-8.6), which reflects similarities in the underlying bedrock of all the sample sites. Those sites in the upper left-hand quadrat of the CCA all had elevated ionic concentrations relative to other sites, and pH levels either at or below the mean (pH = 8.3). DOUGLAS & SMOL (1995) also found that ionic concentrations were important, and specifically found that sodium concentrations ([Na]) explained a significant proportion of the variation in the diatom distribution. Differences in ionic content amongst the DOUGLAS & SMOL (1993) sites were attributed to proximity to the sea. This trend is also reflected amongst the Bathurst Island sites.

Diatom species associated with the pH gradient shifted from predominantly smaller *Navicula* (e.g. *N. pseudoscutiformis* (45) and *N. jaernefeltii* (44)) and *Achnanthes* (e.g. *A. oestrupii* (12) and *A. ventralis* (13)) species in the upper portion of Axis 2, to larger *Cymbella* species (e.g. *C. silicula* (19) and *C. tumidula* (31)) in the lower portion of Axis 2. This spread along the pH gradient indicates that the smaller *Navicula* and *Achnanthes* species may prefer less alkaline conditions, while the larger diatom species are more common in higher pH waters. However, the pH range was relatively small (pH = 8.1 – 8.6), therefore any ecological conclusions inferred about the diatom flora against this short gradient should be treated with caution.

Although the 13 variables considered in the CCA are significantly correlated with one or more variables, not all of them account significantly for the variation in the diatom distribution. By constraining a series of CCAs to those variables identified through forward

selection (i.e. TPF, TEMP, pH, Ba, Zn, DIC), it was determined that only TPF and TEMP, and not the pH or ionic variables, were significant ( $P \leq 0.01$ ) in explaining species variance. The CCA ordination (Fig.3) clearly demonstrates the strong influence of TEMP, coupled with TPF, along the first axis. According to the weighted-average correlation matrix (Appendix 8), TPF is significantly correlated ( $P \leq 0.05$ ) to TEMP. With higher surface-water temperatures, a greater abundance of aquatic plant life, greater decomposition rates, and more animal life would flourish, and introduce more phosphorus into the lake or pond. Therefore, this analysis focuses on the development of a calibration set for surface-water temperature alone, although optima values are listed for TPF in Appendix 9.

Temperature is known to affect a variety of ecological, physiological and metabolic algal processes, as summarized by WECKSTRÖM et al. (1997), but is not commonly selected when constructing calibration sets, since freshwater diatoms are expected to possess a wide tolerance range for temperature fluctuations, making them poor thermal indicators (WECKSTRÖM et al. 1997). However, in recent studies by STOERMER & LADEWSKI (1976), PIENITZ et al. (1995), and WECKSTRÖM et al. (1997) surface-water temperature transfer functions were developed, which, although limited in their geographic applicability, show diatom taxa can potentially be used to track past trends in temperature, as this environmental variable captures some of the variance in other important variables, such as nutrient concentrations, extent of ice cover, etc.

### 3.4.4 Weighted Averaging (WA) Regression Models

In order to test quantitatively whether or not a strong statistical relationship existed between TEMP and the dominant diatom taxa, a CCA was performed constrained only to this variable. The greater the ratio of the eigenvalues from Axis 1 to Axis 2 (i.e.  $\lambda_1/\lambda_2$ ), the more important the single variable is at explaining species variance in the dataset (TER BRAAK 1988). The temperature-constrained CCA revealed that the ratio of the first eigenvalue ( $\lambda_1 = 0.22$ ) to the second eigenvalue ( $\lambda_2 = 0.48$ ) was 0.46, with the first axis accounting for a statistically significant ( $P \leq 0.01$ ) proportion of the species variance (7.0%), as determined by Monte Carlo permutation testing (99 unrestricted permutations; TER BRAAK 1988). Therefore, theoretically, it should be possible to develop a temperature transfer function to track overall trends in past surface-water temperatures on Bathurst Island using diatoms.

The WA regression model presented in this thesis predicts inferred temperatures for the 29 Bathurst Island lakes and ponds that approximate the actual observed summer surface water temperatures (Fig. 5, 6). Classical and inverse regression techniques were performed on the dataset for comparative purposes. The apparent root mean square error (RMSE) for surface-water temperatures is 4.79°C for classical deshrinking, and 3.27°C for inverse deshrinking, while the bootstrapped RMSE values are 5.39°C for classical deshrinking, and 4.34°C for inverse deshrinking (Fig. 5, 6).

Inverse deshrinking was deemed less reliable for building a WA model due to the trend that it produced in the residuals ( $R^2 = 0.54$ ;  $P \leq 0.01$ ) (Fig. 6). The significant correlation indicates that this regression method is overestimating low and underestimating



### Classical Deshrinking; WA; TRUE # OCCURRENCES

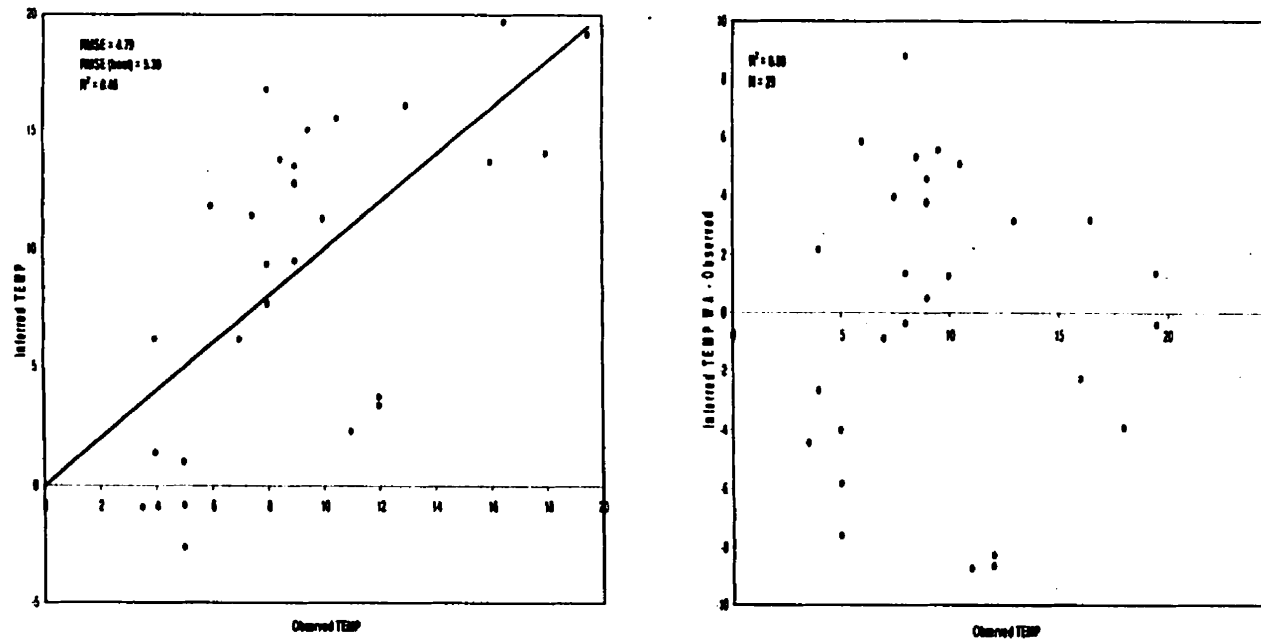
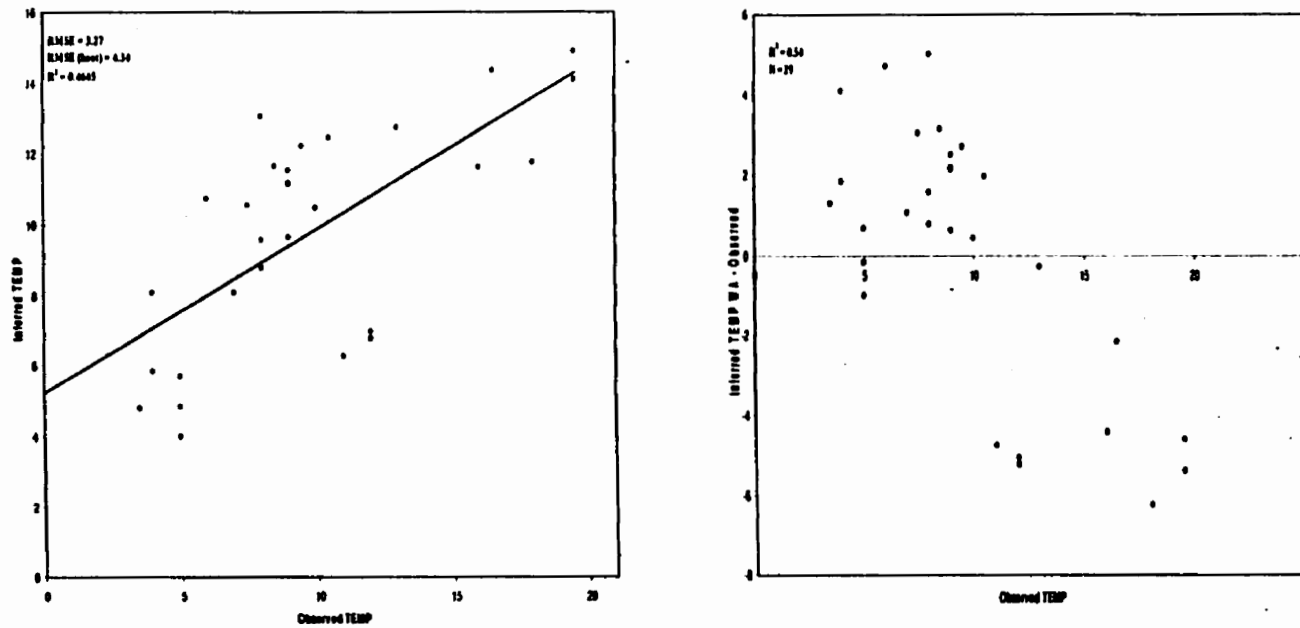


Fig.5 Classical deshrinking optima regression for TEMP

# **Inverse Deshrinking; WA; TRUE # OCCURRENCES**



**Fig.6 Inverse deshrinking optima regression for TEMP**

high temperature values (HAY et al. 1997; PIENITZ et al. 1995). Classical deshrinking, however, did not produce any trends in the residuals ( $R^2 = 0.00$ ;  $P > 0.05$ ) (Fig. 5). These results indicate that there is a potential to use the classical deshrinking WA models to infer past surface-water temperature changes. It is important to consider that these temperature transfer functions were derived from 29 lakes and ponds, which not only spanned across a large temperature range ( $2.5^{\circ}\text{C} - 19.5^{\circ}\text{C}$ ), but also across a variety of physical and limnological gradients listed in Table 2. Therefore, although we may be able to apply these equations to other high arctic lake and pond surface-water temperature reconstructions, the chosen sites should fall within the limnological ranges of the Bathurst Island sites. In any event, this transfer function would at best indicate trends in past temperatures.

Although a significant proportion of the diatom variance was accounted for by the temperature variable, we must also consider that other measured related variables, such as TPF, and unmeasured variables, such as grazing and microhabitats, may also influence diatom distributions.

### 3.5 Summary & Conclusions

Similarly to other sites (DOUGLAS & SMOL 1993; DOUGLAS & SMOL 1995; WECKSTRÖM et al. 1997), the 59 dominant diatom taxa in the 29 lakes and ponds on Bathurst Island were small, benthic species. A temperature and nutrient gradient strongly influenced the first axis of the CCA ordination, and affected the diatom assemblage composition amongst the sites. More specifically, *Fragilaria pinnata*, *F. construens* var. *construens* and *Pinnularia balfouriana* dominated the colder, larger sites, in some cases

comprising nearly 50% of the assemblage (Fig.3, 4; Appendix 3). A greater variety of periphytic diatom species were present in the warmer, more nutrient-rich sites (Fig.3, 4).

Constrained CCA demonstrated surface-water temperature (TEMP) to be significant in explaining species variation, while exploratory weighted averaging (WA) analysis identified the potential for reconstructing past thermal conditions from the modern diatom assemblages on Bathurst Island. However, other measured and unmeasured factors may also influence the species variance, and should be taken into account when assessing the applicability of this temperature model. For example, biotic and abiotic features such as grazing, parasitism, turbidity, light penetration, microhabitat, and silica availability may potentially explain some of the diatom species variance (SMOL et al. 1991; PIENITZ et al. 1995). Although the 29 sites ranged across a wide temperature spectrum (2.5°C – 19.5°C), which would allow for a valid approximation of species autoecology, the trends identified from these data should only be extrapolated to other sites falling within this temperature range.

Overall, this study demonstrated that a strong relationship exists between measured environmental variables and distinct diatom assemblages in these high arctic sites. Moreover, the CCA and WA analyses quantitatively demonstrated that surface-water temperature explained some of the variance in diatom distributions along a set gradient. Whether temperature directly or indirectly influences diatom assemblages is still, however, not certain (PIENITZ et al. 1995). Nevertheless, the results from this study add important data for possible temperature and other environmental paleoreconstructions in the High Arctic. As calibration studies are completed for other high arctic islands, we will be able to

expand our autoecological database, and potentially generate transfer functions applicable over a wider thermal and environmental spectrum.

Plate A. Light micrographs of diatoms recovered from the surface sediment of lakes and ponds on Bathurst Island, N. W. T., Canada. A scale bar is shown on the plate. See Table 6 for a summary of taxon codes, names and authorities.

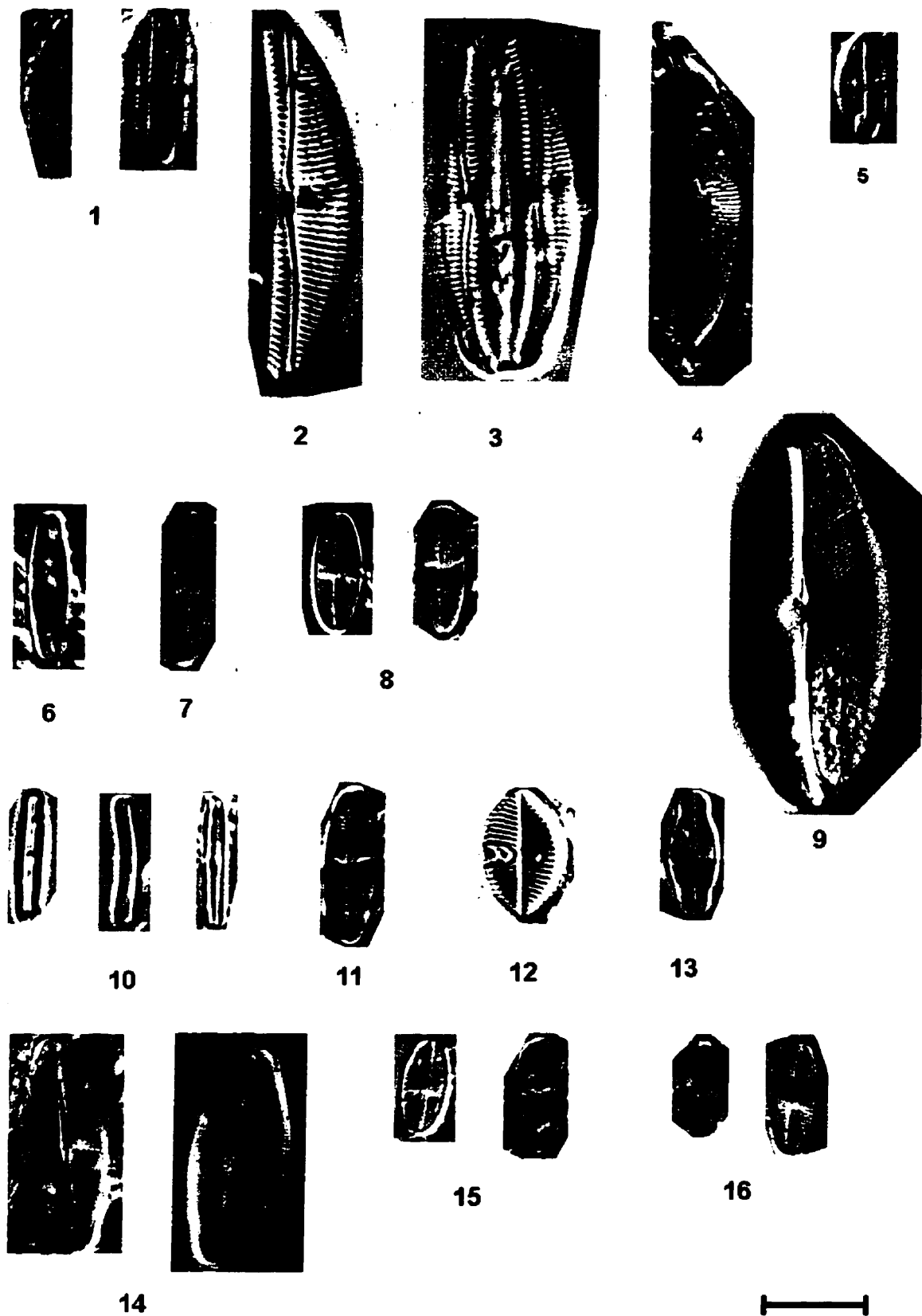


PLATE A

Plate B. Light micrographs of diatoms recovered from the surface sediment of lakes and ponds on Bathurst Island, N. W. T., Canada. A scale bar is shown on the plate. See Table 6 for a summary of taxon codes, names and authorities.





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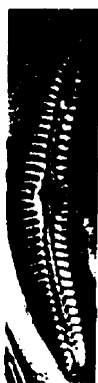
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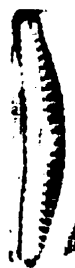
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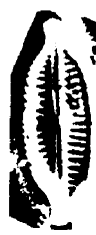
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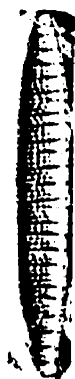
PLATE B

10µm

Plate C. Light micrographs of diatoms recovered from the surface sediment of lakes and ponds on Bathurst Island, N. W. T., Canada. A scale bar is shown on the plate. See Table 6 for a summary of taxon codes, names and authorities.



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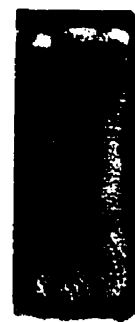
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gv



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gv



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PLATE C

10µm

Plate D. Light micrographs of diatoms recovered from the surface sediment of lakes and ponds on Bathurst Island, N. W. T., Canada. A scale bar is shown on the plate. See Table 6 for a summary of taxon codes, names and authorities.



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PLATE D

10µm

Plate E. Light micrograph of *Cyclotella antiqua* (W. Smith). A scale bar is shown on the plate.



*Cyclotella antiqua*

10µm

**PLATE E**

### 3.6 References

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## **Chapter 4:                      Summary of Findings**

Overall, the following conclusions were made from the findings of this thesis:

### **(1)     Chapter 2:**

Bathurst Island limnology resembles the limnology of other subarctic and arctic areas in North America, which have similar underlying bedrock.

The major ion concentrations were relatively high, and relative to each other, the cations and anions ranged, respectively, as follows:  $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ ,  $\text{CO}_3 > \text{SO}_4 > \text{Cl}$ . Differences in Na and Cl concentrations, in particular, were mostly driven by the proximity of each site to the sea. This trend has also been reported in other limnic studies in both the subarctic and arctic, as well as other regions (WETZEL 1983).

Lake and pond nutrient concentrations on Bathurst Island were congruent with other high arctic oligotrophic water bodies. The examination of PON:POP, TN:TPU and REDFIELD (C:N:P) ratios revealed that sixty-three percent (63%) of the Bathurst Island sites were most likely nitrogen (N) limited. These sites drained through areas that had a high concentration of wildlife, and all had [TPU] greater than the mean ( $12.7\mu\text{g/L}$ ). Sites which were most likely phosphorus (P) limited drained through sparsely vegetated, rocky areas, and had [TPU] under the mean.

A linear regression of CHLAU vs. TN for those sites considered to be N-limited showed a significant ( $P \leq 0.01$ ) correlation. Those sites most likely not limited by nitrogen did not show a significant correlation between CHLAU and TN. Therefore, nitrogen is most likely the limiting algal growth factor in nearly two thirds of the Bathurst Island sites.

Variance in DOC concentrations amongst the sites could be partially explained by differences in surrounding vegetation, as well as lake or pond volume. Sites with [DOC] greater than the mean (4.1 mg/L) were typically shallow, small ponds which drained through highly vegetated areas.

Principle Components Analysis (PCA) revealed that conductivity (COND), DOC and variables related to water hardness, such as Ca-Mg ions and other polyvalent metals, drove the construction of Axis 1. Differences in pH amongst the sites drove the construction of Axis 2. The PCA biplot revealed a distinct spread between the shallow vs. deeper sites.

This study adds to the growing database of limnological data from the High Arctic, and provides critical baseline data that will enable researchers to predict how future changes in the environment could alter these lakes and ponds.

(2) Chapter 3:

A strong relationship exists between the measured environmental variables and the dominant diatom taxa from 29 lakes and ponds on Bathurst Island.

Similar to other arctic and subarctic oligotrophic sites, the dominant diatom taxa from 29 Bathurst Island lakes and ponds were all small, benthic species. Over 50% of the dominant species recorded on Cape Herschel, Ellesmere Island (DOUGLAS & SMOL 1993) were also common to the Bathurst Island diatom assemblage. These diatom species are all able to withstand oligotrophic and ultraoligotrophic conditions, short growing seasons, and sharp temperature fluctuations (DOUGLAS & SMOL 1993). *Fragilaria pinnata* and *Pinnularia balfouriana* were two species that dominated in lakes and larger ponds. These diatoms are possibly more competitive in these deep, nutrient poor sites by associating themselves with substrates along the shoreline and in the littoral zone.

Canonical Correspondence Analysis (CCA) revealed a strong temperature and nutrient gradient along Axis 1, which affected the diatom assemblage distribution amongst the sites, and a weaker pH gradient along the second axis (Fig.3,4).

Consistent with the aforementioned findings, *F. pinnata* and *P. balfouriana* ordinated at the opposite end of the temperature spectrum, in close proximity to the larger sites. A greater variety of periphytic diatoms ordinated in close proximity to those sites that were warmer, shallower and less oligotrophic (Fig.3, 4).

Through constrained CCA, surface-water temperature (TEMP) was shown to be significant ( $P \leq 0.01$ ) in explaining diatom species variation, and was chosen as the key variable for the development of a transfer function. Weighted-averaging (WA) was used to test the potential of this temperature model to reconstruct past thermal conditions from the modern diatom assemblages identified on Bathurst Island. Although the results of these analyses demonstrate the potential of this dataset to reconstruct past lake/pond surface temperatures, caution should be exercised in the application of this inference model. Other measured and unmeasured variables may also be influencing species variation. However, they may not be as apparent, and may be masked by the dominance of the temperature gradient.

The results from this study demonstrate that surface-water temperature accounted for a portion of the diatom assemblage variance amongst the sites. Furthermore, the results add to the growing diatom autoecological database for the High Arctic, and increase the possibility of conducting quantitative temperature (and other environmental) paleoreconstructions in the High Arctic.

Appendix I. Bathurst Island Field Notes (July 14, 1994 – July 20, 1994) with site descriptions

Lake/ Pond	Location	Physical Description
BC	75°03.74N 97°59.74W 300'asl	<ul style="list-style-type: none"> <li>• Large lake, just across from Bahn Island; one of the first ones you see</li> <li>• Big pancakes of ice</li> <li>• Most of it is still ice covered</li> <li>• On western shore, 'tennis ball' sized <i>Nostoc</i> balls in the water</li> <li>• Mosses come up to the shore, but almost 100% rock</li> <li>• Don't see mosses in the water, yet hard to get sediment, almost all rock.</li> </ul>
BD	75°04.63N 98°02.96W 100'asl	<ul style="list-style-type: none"> <li>• lush meadow</li> <li>• helicopter landed by 2 sites</li> <li>• ~ 1/2 of next pond (i.e. BE)</li> <li>• little moss island in the middle (30m x 30m)</li> <li>• moss right to the edge, and right into the site</li> </ul>
BE	same as BD; about 100m East of BD	<ul style="list-style-type: none"> <li>• about 2x size of BD</li> <li>• gently rolling terrain; water in the middle of the field</li> <li>• in lush vegetation with muskox dung, etc.</li> <li>• very shallow</li> <li>• no real rocks; <i>Lepidurus arcticus</i></li> </ul>
BF	75°08.25N 98°28.94W 700'asl	<ul style="list-style-type: none"> <li>• still has a snow band</li> <li>• very different from the last 2 ponds</li> <li>• higher elevation</li> <li>• whiter, light coloured rock</li> <li>• some <i>Nostoc</i></li> <li>• looks quite shallow (~20cm)</li> <li>• pavement of black crusted rock</li> <li>• almost all rocks</li> </ul>
BG	75°27.43N 99°26.67W 700'asl	<ul style="list-style-type: none"> <li>• ~90% ice covered; candling ice; most is ~5m wide</li> <li>• very rocky, some detrital moss</li> <li>• cobbles of small boulders pushed up on shore by ice</li> <li>• seems to get deep very quickly</li> <li>• quite rocky terrain, but can see purple saxifrage</li> <li>• this lake is on the map (one of the larger sites)</li> <li>• Sediment = loose material between rocks</li> </ul>
BH	75°27.16N 99°32.12W 400'asl	<ul style="list-style-type: none"> <li>• also on the map</li> <li>• ~90% ice covered</li> <li>• not far from pond we were at</li> <li>• very rocky drainage with some purple saxifrage</li> <li>• ~100% rock substrate</li> <li>• moat ~ 40m</li> <li>• much bigger than last site</li> <li>• one moss just at water line ~1cm of moss is submerged</li> </ul>
BI	75°37.64N 99°38.30W near sea level	<ul style="list-style-type: none"> <li>• next to BJ ~80m apart</li> <li>• not far from the sea; ~80% moat around (BJ is ice free)</li> <li>• gently to moderately sloping terrain</li> <li>• lots of grasses, some mosses</li> <li>• seashells in water</li> <li>• mosses come right to the edge; ~100% rock covered though ~10m of water to moat</li> <li>• some <i>Nostoc</i> balls; can't find mosses in lake</li> <li>• moss island to one side</li> </ul>
BJ	same as BI; ~80m East of BI	<ul style="list-style-type: none"> <li>• ice-free as opposed to BI; ~200m in diameter</li> <li>• a lot of mosses along the edge, grasses</li> <li>• completely ice-free</li> <li>• dung from caribou, shells in the water</li> <li>• as opposed to BI, very few rocks in BJ, moss and sediment</li> <li>• red net and fairy shrimp</li> <li>• little tiny balls in the water (<i>Nostoc</i>?)</li> </ul>
BK	75°78.63 99°20.20W	<ul style="list-style-type: none"> <li>• next to BL (very large)</li> <li>• 300M long</li> <li>• white caps</li> <li>• lush vegetation (moss &amp; grass)</li> <li>• lots of caribou and muskox near here</li> <li>• water high turbated by wind; induced mixing of sediments</li> </ul>



## Appendix 1. (Cont'd) Bathurst Island Field Notes (July 14, 1994 – July 20, 1994) with site descriptions

Lake/ Pond	Location	Physical Description
BL	same as BK; ~300m from BK	<ul style="list-style-type: none"> <li>enormous lake in pass; ~60-80% ice-covered</li> <li>drainage - relatively moderate slope of clay/med. rocks</li> <li>protected from wind (unlike BK)</li> <li>a lot of pebbles around shore; very rocky, quite different from the mosses we saw at the other site; mainly rocks</li> <li>very little moss - might be above in ~5m of water</li> </ul>
BM	75°08.26N 97°47.42W	<ul style="list-style-type: none"> <li>2 lakes, ~300m apart</li> <li>helicopter in middle when I got coordinator; both lakes are large and on map.</li> <li>cape just W of Bahn Island</li> <li>ice to south blown over; gently rolling terrain with mosses and medium in drainage; looks like it has an (2?) island in the middle; relatively big lakes</li> <li>around shore a lot of mosses, grasses, scats, fern colony on island</li> <li><i>Nostoc</i> washed up on shore; almost a rock pavement</li> <li>just detrital moss in the pond; moss bank with ice push</li> <li>very large <i>Daphnia</i></li> <li>goose scats</li> </ul>
BN	same as BM	<ul style="list-style-type: none"> <li>see BM for more details</li> <li>80% ice covered; we are sampling in a large bog that is ice free</li> <li>rocks go right to the edge, but a little moss edges here and there</li> <li>don't see any mosses in the water; near shore ~100% rock covered; some clayey sediment deeper with lots of shell bits</li> </ul>
BO	75°09.40N 98°51.29W 500'asl	<ul style="list-style-type: none"> <li>we are on one of the rocky and somewhat open bogs; big lake, on map</li> <li>90% ice covered; some mosses but very rocky drainage with lots of bugs, can't see any mosses on sediment</li> <li>rock scrape is covered with brown sediment, so not true scrape and could be used almost as a sediment sample</li> </ul>
BP	75°19.02N 98°50.58W 100'asl	<ul style="list-style-type: none"> <li>due N from BO</li> <li>it was very dry, but now we stopped where there are 3 small ponds ~30m radius of each other (BP, BQ, BR)</li> <li>helicopter in middle, ~5x8m long - smallest of 3, water levels lower</li> <li>mostly sediment with rocks; few mosses shore and a few in the water.</li> <li>Can't pull net, ~5cm? deep; may be ephemeral; <i>Nostoc</i></li> <li>surface sediment = detrital organic moss; not real sediment</li> </ul>
BQ	same as BP	<ul style="list-style-type: none"> <li>~40m to N of BP</li> <li>2mx10m long</li> <li><i>Nostoc</i>; water levels dropped</li> <li>we are standing on mosses that were once submerged; water levels are quite low; some mosses covered with sediment, rocks; surrounded by rocks and mosses.</li> <li>no rock scrape - everything is covered by this organic/algal/moss crust</li> <li>no other substrate; light reddish brown algal crust</li> </ul>
BR	Same as BP	<ul style="list-style-type: none"> <li>largest of the 3; still not very big 15mx10m</li> <li>moss in pond as well; lots of sediment and little rocky</li> <li>~20-30cm deep</li> <li>organic brown sediment</li> </ul>
BS	75°31.42N 98°11.90W 200'asl	<ul style="list-style-type: none"> <li>W part of Bathurst; 2 lakes ~200-300m on map, more westerly of 2</li> <li>nearly ice-free except some ice accumulations that have been blown</li> <li>white caps on lake; large lake; very rocky and muddy drainage with some mosses; fairly high relief to one side</li> <li>very rocky ~ 100% near shore; some mosses near shore; probably gets quite deep in the middle</li> <li>could be a good core lake</li> <li>can't find sediment</li> <li>some mosses along shore are now submerged under some water, but maybe not if wind was in the other direction</li> </ul>
BT	same as BS	<ul style="list-style-type: none"> <li>rocky terrain; turn over the rocks in the shallow area, and the bottom of the rock is covered by what looks like blue-green algae</li> <li>frost boils around it</li> <li>rocks covered by brownish-black frost; much shallower than BS; BT is the one closer to the ocean (but can't see the ocean b/c of relief); smaller too than BS; no ice at all, and no moss in lake</li> </ul>

## Appendix 1. (Cont'd) Bathurst Island Field Notes (July 14, 1994 – July 20, 1994) with site descriptions

Lake/ Pond	Location	Physical Description
BU	75°38.79N 98°05.65W 100'asl	<ul style="list-style-type: none"> <li>• greenish colour; secchi depth around 20-30cm</li> <li>• a lot of lemming holes</li> <li>• draining an organic, muddy area</li> <li>• lot of mosses along the edge; very hard to see what is in the water; largely rock covered bottom (but can't see due to green)</li> <li>• little bit of coarse sand near shore</li> </ul>
BV	75°39.14N 98°02.59W 500'asl	<ul style="list-style-type: none"> <li>• a few 100m away (~500+m); 3 sites near each other on the map</li> <li>• very grassy, rich vegetation area, lush; unlike gravelly areas we have been sampling lately;</li> <li>• a lot of moss along the edge</li> <li>• hunks of detrital moss; largely sediment, some rocks, mosses/grasses right to edge</li> <li>• a lot of Nostoc along the edge; water level down.</li> <li>• lot of grasses and sedges; ~40-50cm deep; ~100m diameter.</li> </ul>
BW	same as BV	<ul style="list-style-type: none"> <li>• 20m to S of BV; very small pond; 15m long</li> <li>• at higher water levels, puddles probably connect BW to BV</li> <li>• lush vegetation</li> <li>• some loose mosses in the water and some moss islands</li> <li>• no rocks at all</li> <li>• ~10cm water depth</li> <li>• lots of scats of birds and other animals</li> </ul>
BX	same as BV	<ul style="list-style-type: none"> <li>• 50m SW of BV; about same size as BU - about 100m S of BU</li> <li>• looks similar to BU, grasses, etc., but maybe a bit more of a rocky bottom; rock and sediment and some detrital mosses along the edge</li> <li>• waves on this pond (1st one towards the wind of 3)</li> <li>• almost all sediment, some rock, mosses along the edge</li> </ul>
BY	75°43.29N 98°31.03W near sea level	<ul style="list-style-type: none"> <li>• Polar Bear Pass - Big lake in Pass</li> <li>• lush vegetation, very low lying area, a lot of sites to the E (polygon type)</li> <li>• looking like overflow ponds, inundated near it; no ice</li> <li>• sediment is hard to get, and mostly between rocks</li> </ul>
BZ	75°43.25N 98°40.68W	<ul style="list-style-type: none"> <li>• smaller lake to the W, in Polar Bear Pass; connected by what looks like pools of water to BY</li> <li>• topography, etc. similar, but this one is very green (not BY) with suspended, very rocky shore</li> <li>• some mosses (seems fewer than BY); a sandy sort of beach</li> <li>• hard to get sediment</li> </ul>
BAA	75°55.43N 99°05.53W 600'asl	<ul style="list-style-type: none"> <li>• NW part of island; NW part of Polar Bear Pass; helicopter in middle of 2 lakes; both are on map</li> <li>• western part is ice covered by ice blown over (pancakes); ~15% covered</li> <li>• drainage med. and rocks &amp; some mosses; ~100% rock covered; don't see mosses in lake; some green 'clouds' of algae</li> </ul>
BAB	same as BAA	<ul style="list-style-type: none"> <li>• got good and stuck walking over from BAA; 500m and walk due E</li> <li>• both lakes on map</li> <li>• very loose mud at one end, but found a part with rocks; this is smaller and shallower than BAA, completely ice free short, med. boulders; very little vegetation in drainage; a lot of mud, some grass and moss</li> <li>• ~100% rock covered – rocks have sediment on top of them; probably goes for maybe 50cm deep</li> <li>• ~100% rock covered – rocks have sediment on top of them</li> <li>• found one moss in water and used it (12°C if you stick bulb inside moss)</li> </ul>
BAC	75°56.66N 99°04.76W 400'asl	<ul style="list-style-type: none"> <li>• 2km N of the ones we just did</li> <li>• rocky, muddy terrain; very rocky in pond</li> <li>• 30cm deep in the middle; one moss, just rocks</li> <li>• rock scrape = organic crust; could use as sediment</li> </ul>
BAD	75°36.01N 97°50.99W sea level	<ul style="list-style-type: none"> <li>• E of Polar Bear Pass</li> <li>• Surrounded by moss bank going into the pond; seems to get fairly deep</li> <li>• greenish colour to water; bird scats, etc.</li> </ul>

## Appendix 1. (Cont'd) Bathurst Island Field Notes (July 14, 1994 – July 20, 1994) with site descriptions

Lake/ Pond	Location	Physical Description
BAE	76°23.18N 98°52.05W 200'asl	<ul style="list-style-type: none"> <li>• N part of Bathurst Island; not far from sea</li> <li>• large in surface area, good waves, very rocky base; drains muddy gravel</li> <li>• water a little murky; some mosses, but just along the edge; mainly rock or mud; not far out there is sediment, the rocks look like they may have been pushed by the ice; ~200m x 100m</li> <li>• very windy, no mosses in lake itself; mosses only at edge; clay-like sediment not far out; rock scrape could be a sediment sample as a loose sediment; littoral moss</li> <li>• ~60-70% ice covered, but 40m+ moat; lot of ice still on lake</li> </ul>
BAF	same as BAE	<ul style="list-style-type: none"> <li>• ~300m away from BAE</li> <li>• completely ice-free, but about the same size as BAE; over a ridge, walking parallel to sea; small island in the middle; distinct moss bank that goes right to rocks</li> <li>• ~100% rock cover after that can see near shore washed up "clouds of green algae"</li> <li>• unlike BAE, this pond is not covered by silt/sediment; seems to be covered by round brown colonies</li> <li>• no real submerged moss; few mosses in drainage; gravelly drainage; might be a bit bigger than BAE</li> <li>• no ice, but can't get sediment</li> </ul>
BAG	same as BAE	<ul style="list-style-type: none"> <li>• a few 100m; BAE flows into BAG, and then flows into the ocean; also drains stripped mosses and gravel like BF</li> <li>• ~100% rock covered; little bit of snow on one bank; little smaller than last 2 but not much; some sediment in whirlpak - but really sediment around rocks, maybe ice scour</li> <li>• rocks covered by silt like the first pond, so the rock sample could be used as a sediment sample</li> <li>• no moss bank on BAG; some 20-30cm from water edge are mosses; a lot of caribou prints</li> <li>• ~30cm from shoreline find a wet moss</li> </ul>
BAH	same as BAE	<ul style="list-style-type: none"> <li>• still part of BAE – BAI</li> <li>• other side from BF; BAE and BAG in the middle; BAF to the other side, note BAH (and soon BAI) are on the other side (i.e. the side where BAE was)</li> <li>• other ridge</li> <li>• very small; 20m diam.; irregular shape; what seems to be a lot of sediment but MSVD says really moss carpet type with sediment</li> <li>• very shallow, few rocks; wind swept; pond was bigger before; some grasses to one side</li> </ul>
BAI	same as BAE	<ul style="list-style-type: none"> <li>• 5th in area; area to far right could be outlets to BAE and BAF; BAG is directly behind us when S took picture</li> <li>• appears to be a closed basin, draining mosses, etc.; lots of mosses in drainage; seems to be a more organic drainage, etc.</li> <li>• rocks covered by organic material; smaller than BAE, BAF, BAG, but still a big pond</li> <li>• &lt;100m; circular; sea not far</li> <li>• Rock Scrape - mossy organic greenish crust</li> <li>• some detrital moss is water; don't see any real attached mosses; just along bank; mainly rock covered</li> <li>• Sediment = organic crust in everything, wherever you walk is this crust (i.e. on rocks, etc.); zoop. tow may have sediment in it.</li> </ul>
BAJ	76°39.52N 98°52.82W 400'asl	<ul style="list-style-type: none"> <li>• to the SE, larger of 3 sites; both looked similar from air</li> <li>• a lot of foam along edge; drains a very mossy area, but the lake has a lot of (~100%) rocks</li> <li>• Elison lake size; more sediment as you get deeper - don't see any mosses; <i>Nostoc</i> balls (tiny); lot of <i>Daphnia</i> &amp; fairy shrimp</li> <li>• maybe sediment btw. rocks &amp; mud - whirl pak</li> <li>• rocks very clean - took more than usual to get a rock scrape; waves</li> </ul>
BAK	same as BAJ	<ul style="list-style-type: none"> <li>• next one over from BAJ; smaller than last one ~200mx100m</li> <li>• more mosses along the edge; this one seems protected by a relief</li> <li>• ~200m from last one; mosses right to the edge; some detrital mosses in water; ~100% rock cover</li> <li>• few clouds of algal filaments; <i>Nostoc</i> balls</li> <li>• submerged moss in moss bank didn't look like it was in great shape</li> <li>• found some sediment</li> </ul>

## Appendix I. (Cont'd) Bathurst Island Field Notes (July 14, 1994 – July 20, 1994) with site descriptions

Lake/ Pond	Location	Physical Description
BAL	same as BAJ	<ul style="list-style-type: none"> <li>• moss beds in the middle with moss islands</li> <li>• rocks - lots and some sediment; can't find mosses in water where we are; rocks have a brownish tinge; quite a bit of sediment over there</li> <li>• pond drains a lot of mosses; looks shallow - a little island in middle; mosses in drainage could be a significant source of diatoms; low, gently rolling terrain</li> </ul>
BAM	76°30.14N 98°10.05W 200'asl	<ul style="list-style-type: none"> <li>• the last of previous sites, moss banks right up to the edge and into the water; a few mosses in the water; very rocky, no ice</li> <li>• large pond; BAN is right next to it with maybe ~2m of land in between them - at higher levels will be connected to each other</li> <li>• 200-300m roughly circular in shape; draining stripes</li> <li>• Sediment = should be ok, but between rocks; near shore all rocks</li> <li>• could use rocks as main substrate in water</li> </ul>
BAN	same as BAM	<ul style="list-style-type: none"> <li>• actually bigger than we first thought; like last pond is protected by a modest relief; has a peninsula coming out into it</li> <li>• can't really tell if BAM or BAN flow into each other - looks like at same level</li> <li>• scats, etc. (all the lakes we seemed to sample had this)</li> <li>• caribou in area</li> <li>• rocks seemed to be covered by BG algae (the brownish stuff) (<i>Gomphocystis</i>, <i>Nostoc</i>, lots of diatoms)</li> <li>• ~100% rock, mosses pushed up; moss bank in distance</li> <li>• mosses in drainage</li> <li>• submerged moss very rare, but sampled one</li> <li>• a few meters out is some clayey sediment</li> </ul>

Appendix 2. Transformation list for environmental variables

<i>Environmental Variable</i>	<i>Transformation</i>
Al	$\text{Al}(x) = \log(\text{Al} + 1)$
Ba	$\text{Ba}(x) = \log(\text{Ba} + 1)$
Ca	$\text{Ca}(x) = \log(\text{Ca} + 1)$
Fe	$\text{Fe}(x) = \log(\text{Fe})$
K	$\text{K}(x) = \log(\text{K} + 1)$
Li	$\text{Li}(x) = \log(\text{Li} + 1)$
Mg	$\text{Mg}(x) = \log(\text{Mg} + 1)$
Mn	Square root
Mo	No transformation required
Na	$\text{Na}(x) = \log(\text{Na} + 1)$
Ni	$\text{Ni}(x) = \log(\text{Ni} + 1)$
Sr	Square root
V	$\text{V}(x) = \log(\text{V} + 1)$
Zn	$\text{Zn}(x) = \log(\text{Zn} + 1)$
Cl	$\text{Cl}(x) = \log(\text{Cl} + 1)$
SO <sub>4</sub>	$\text{SO}_4(x) = \log(\text{SO}_4 + 1)$
SiO <sub>2</sub>	$\text{SiO}_2(x) = \log(\text{SiO}_2)$
Dissolved organic carbon (DOC)	$\text{DOC}(x) = \log(\text{DOC} + 1)$
Dissolved inorganic carbon (DIC)	No transformation required
Soluble reactive phosphorus filtered (SRPF)	Square root
NO <sub>2</sub>	No transformation
NO <sub>3</sub> NO <sub>2</sub>	No transformation
NH <sub>3</sub>	$\text{NH}_3 = \log(\text{NH}_3 + 1)$
Total Kjeldahl nitrogen (TKN)	Square root
Total phosphorus (unfiltered) TPU	No transformation
Total phosphorus (filtered) TPF	No transformation
Total Chlorophyll <i>a</i> (uncorrected for phaeophytin) ChlaU	No transformation
Total Chlorophyll <i>a</i> (corrected for phaeophytin) ChlaC	No transformation
Particulate organic carbon (POC)	Square root
Particulate organic nitrogen (PON)	No transformation
Temperature (TEMP)	No transformation
PH	$\text{pH}(x) = \log(\text{pH} + 1)$
Conductivity (COND)	$\text{COND}(x) = \log(\text{COND} + 1)$
Elevation (ELEV)	No transformation

Appendix 3. Raw relative species abundance data for 59 dominant diatom species.

Site	<i>Amphora inariensis</i>	<i>A. libyca</i>	<i>A. aequalis</i>	<i>A. veneta</i>	<i>A. pediculus</i>	<i>Achnanthes sp.1</i>	<i>A. sp.2</i>	<i>A.chlidanos</i>	<i>A. flexella</i>	<i>A.minutissima</i>	<i>A.krophila</i>
BC	0.50	4.02	0.50	2.26	2.76	0.25	0.00	0.50	0.00	2.01	1.01
BD	0.00	0.00	0.68	0.00	0.00	0.00	0.00	0.00	9.22	18.43	0.34
BE	0.00	0.00	0.00	0.00	0.00	1.55	0.00	1.24	21.05	12.69	0.62
BF	0.00	0.00	0.00	0.00	0.00	3.27	0.00	0.33	1.63	7.52	7.84
BG	3.41	0.00	2.05	1.37	0.00	0.00	0.00	2.39	1.37	0.68	3.07
BH	0.00	0.00	0.00	0.00	9.09	0.00	0.00	0.00	0.00	0.00	0.00
BJ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	0.98	14.10	0.00
BK	2.61	1.30	0.98	0.00	0.00	0.00	0.00	0.00	0.33	4.56	0.00
BM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.59	4.41	0.00
BN	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	1.96	0.00	0.00
BP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	14.79	0.00
BR	0.00	0.00	0.00	0.00	0.00	0.64	0.00	1.93	0.00	6.43	0.00
BT	0.63	0.63	0.63	0.00	0.31	0.94	0.00	1.89	3.77	4.09	1.26
BU	0.65	0.32	0.00	0.00	0.00	0.00	2.26	0.65	0.00	17.74	0.00
BV	0.00	0.00	0.63	0.00	0.00	0.63	0.63	2.53	6.01	20.89	1.27
BW	0.00	0.00	0.00	0.00	0.00	0.96	0.32	0.00	6.39	39.62	0.00
BX	0.61	0.00	0.61	0.00	0.00	0.00	1.83	2.74	9.76	16.77	0.00
BZ	0.00	0.00	0.00	3.33	6.67	0.00	0.00	3.33	3.33	5.00	0.00
BAC	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	1.89	17.30	0.00
BAD	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.63	1.56	2.50	0.00
BAE	0.00	0.00	0.63	0.00	1.26	0.00	0.00	1.26	1.57	0.63	0.00
BAG	8.09	0.00	0.65	0.00	0.00	0.00	0.97	1.94	0.32	0.65	0.00
BAH	1.90	0.00	0.00	0.00	0.63	0.00	0.63	4.75	2.85	2.22	3.16
BAI	0.00	2.24	0.64	0.00	0.00	0.00	0.00	0.00	2.56	11.50	0.00
BAJ	0.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	1.25	5.64	0.00
BAK	0.95	0.00	0.00	0.00	0.95	0.00	0.00	1.89	0.00	3.79	0.00
BAL	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.85	1.18	0.00
BAM	0.00	1.55	0.00	0.00	0.00	0.00	1.24	0.93	0.62	0.00	0.00
BAN	2.93	0.98	0.65	2.61	0.00	0.00	0.00	1.95	0.00	3.58	0.00

Appendix 3. (Cont'd) Raw relative species abundance data for 59 dominant diatom taxa.

Site	<i>A. oestrupii</i>	<i>A. ventralis</i>	<i>A. laevis</i>	<i>A. subatamoides</i>	<i>A. marginulata</i>	<i>Caloneis sp.1</i>	<i>C. schumanniana</i>	<i>C. silicula</i>	<i>C. angustata</i>	<i>C. arcica</i>	<i>C. arcica T1</i>
BC	0.00	0.00	0.00	0.00	0.00	0.00	1.51	0.00	0.00	6.53	0.00
BD	0.00	0.00	2.05	0.00	0.00	0.34	2.73	0.00	9.22	6.48	1.71
BE	0.00	0.00	3.41	5.57	0.00	1.55	2.17	0.00	5.88	4.02	0.62
BF	0.00	0.00	0.00	3.92	2.29	0.65	0.00	0.00	2.29	6.21	0.00
BG	0.00	0.00	0.00	0.00	0.34	0.00	0.68	0.00	0.68	2.05	0.00
BH	0.00	0.00	0.00	0.00	9.09	0.00	0.00	0.00	9.09	0.00	0.00
BJ	0.00	0.00	3.61	0.00	0.66	1.31	1.31	0.00	1.31	3.61	0.00
BK	0.00	0.00	0.65	0.00	1.63	0.00	1.30	0.00	1.95	5.21	1.30
BM	0.88	0.00	1.18	0.59	0.00	0.00	0.00	0.00	0.00	0.59	0.00
BN	0.33	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.65	0.00
BP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.97	7.07	0.00
BR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.75	2.57	0.00
BT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.46	2.83	1.26
BU	1.94	0.00	1.57	0.00	0.00	0.94	2.20	0.00	0.32	0.97	0.00
BV	0.32	6.96	2.85	0.00	0.00	0.00	0.00	0.00	1.27	0.00	0.00
BW	0.00	0.00	0.96	0.00	8.86	0.00	0.63	0.00	4.79	2.56	0.00
BX	0.00	1.22	1.52	0.00	1.92	1.28	0.64	0.00	2.13	3.05	0.00
BZ	8.33	3.33	0.00	0.00	0.83	0.00	1.52	0.00	0.00	3.33	0.00
BAC	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	15.72	11.01	5.03
BAD	0.00	1.25	0.94	0.00	0.00	0.00	0.94	0.00	0.63	1.88	0.00
BAE	0.00	0.00	0.00	0.00	0.94	0.63	3.77	0.00	1.26	1.89	1.89
BAG	0.00	0.65	0.00	0.00	2.91	0.65	0.00	3.88	1.94	5.83	0.65
BAH	0.00	0.00	0.32	0.00	7.59	0.95	0.00	0.63	6.01	9.18	19.94
BAI	0.00	0.00	0.64	0.64	0.00	3.19	0.64	0.00	5.75	8.31	1.92
BAJ	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.63	1.88	0.63
BAK	0.95	2.52	1.89	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.63
BAL	0.00	1.77	0.00	0.00	0.59	0.00	0.00	0.59	1.18	0.59	0.00
BAM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.48	0.00
BAN	0.00	1.30	0.00	0.00	1.30	0.65	0.00	1.95	0.65	6.51	2.61

**Appendix 3. (Cont'd) Raw relative species abundance data for 59 dominant diatom taxa.**

Site	<i>C. cesatii</i>	<i>C. designata</i>	<i>C. latens</i>	<i>C. microcephala</i>	<i>C. minuta</i>	<i>C. silesiaca</i>	<i>C. similis</i>	<i>C. subaequalis</i>	<i>C. tumidula</i>	<i>Denticula elegans</i>	<i>D. kuetzingii</i>
BC	0.00	0.75	1.76	1.26	0.25	0.75	0.25	0.00	0.00	0.00	0.00
BD	3.41	1.71	0.00	6.14	0.00	0.00	0.68	3.07	0.00	1.37	8.19
BE	6.50	0.93	1.24	1.55	0.00	0.62	0.62	0.31	0.62	1.24	6.19
BF	0.65	9.80	1.96	21.90	0.33	1.96	0.33	0.00	9.15	0.00	0.00
BG	0.68	0.68	2.73	0.00	3.07	2.05	0.68	0.00	0.68	0.00	0.00
BH	0.00	0.00	0.00	0.00	31.82	9.09	0.00	0.00	0.00	0.00	0.00
BJ	2.62	0.66	0.66	3.28	4.59	0.66	0.00	0.00	0.00	0.00	5.90
BK	5.21	1.63	2.61	1.63	3.91	1.30	2.93	0.00	0.33	0.00	4.56
BM	1.18	0.00	0.00	0.00	0.00	1.76	0.00	0.00	0.00	0.00	0.00
BN	0.65	0.65	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00
BP	0.00	3.22	0.00	0.32	0.00	0.00	0.00	0.00	0.00	22.19	0.64
BR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	37.94
BT	4.40	0.63	0.63	3.14	0.00	0.63	0.00	0.00	0.63	0.00	0.00
BU	1.29	0.00	0.65	0.32	1.29	3.87	0.00	0.00	0.00	0.00	2.26
BV	1.27	0.63	1.27	0.63	0.00	0.63	2.53	0.00	0.63	0.00	1.90
BW	1.92	1.28	1.92	2.56	1.92	0.64	0.00	0.00	0.00	5.75	0.00
BX	3.66	1.22	3.05	2.74	0.00	2.44	1.22	0.61	0.61	0.61	3.66
BZ	0.00	1.67	3.33	3.33	1.67	0.00	1.67	0.00	0.00	0.00	0.00
BAC	1.57	0.00	0.00	16.04	0.00	0.00	0.00	5.66	7.55	1.89	0.63
BAD	0.00	0.00	4.38	0.31	3.75	0.00	0.63	0.94	0.63	0.00	0.63
BAE	1.26	0.63	0.63	0.00	0.63	0.00	0.63	0.00	0.00	0.00	0.00
BAG	2.59	1.94	1.29	5.18	0.00	1.29	1.94	0.00	0.65	1.29	2.59
BAH	1.58	3.16	0.00	2.53	1.27	0.63	0.63	0.00	0.63	2.53	5.70
BAI	4.79	1.92	0.64	1.92	1.60	0.00	0.00	0.00	0.00	1.92	3.19
BAJ	0.00	0.00	0.00	0.31	2.82	1.25	0.00	0.00	0.00	0.63	2.51
BAK	0.00	0.00	0.32	0.00	1.26	0.00	0.00	0.00	0.00	0.00	0.00
BAL	0.00	0.00	0.59	0.59	1.18	0.00	0.59	0.00	0.59	1.18	0.00
BAM	0.00	0.00	0.62	0.00	0.62	0.00	0.00	0.00	0.62	0.00	0.00
BAN	1.30	0.65	0.65	0.65	2.93	0.00	0.00	0.00	0.00	0.00	1.95



Appendix 3. (Cont'd) Raw relative species abundance data for 59 dominant diatom taxa.

Site	<i>Diadomesis sp. 1</i>	<i>Diatoma moniliformis</i>	<i>D. oculata</i>	<i>Eunotia arcus</i>	<i>F. capucina</i>	<i>F. construens</i>	<i>F. pinnata</i>	<i>N. sp. 2</i>	<i>N. cryptocephala</i>	<i>N. cryptotenella</i>
BC	0.00	0.00	3.02	0.00	0.00	7.29	18.84	1.51	0.75	0.25
BD	0.00	0.00	0.00	6.83	5.46	0.00	0.00	0.00	0.00	0.00
BE	0.00	0.00	0.00	1.24	2.48	0.00	0.00	0.00	1.24	0.62
BF	0.00	0.00	0.98	0.00	0.00	0.00	0.00	0.00	1.96	1.96
BG	6.83	0.00	3.41	0.00	13.65	5.80	7.17	0.00	0.00	0.00
BH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BJ	0.00	0.00	0.33	2.30	6.89	0.00	0.00	0.00	0.66	1.31
BK	2.28	5.21	0.00	0.00	31.27	0.00	0.00	0.00	0.00	0.00
BM	0.59	0.00	0.00	0.00	1.76	0.00	23.82	0.00	0.59	0.00
BN	1.31	0.00	0.00	0.00	0.33	2.61	25.16	0.00	0.00	0.00
BP	0.00	0.00	0.00	0.00	2.57	0.00	0.00	0.00	0.00	0.00
BR	0.00	0.00	0.00	0.00	1.29	0.00	0.00	0.00	0.00	0.00
BT	0.00	0.00	1.26	1.89	0.00	0.63	0.00	2.52	0.00	0.00
BU	3.23	0.65	1.61	0.00	28.71	0.00	0.00	0.00	0.65	0.00
BV	6.65	0.32	1.27	1.27	12.97	0.00	0.00	0.00	1.27	0.63
BW	0.00	0.00	0.00	0.00	3.19	0.00	0.00	0.00	0.64	0.64
BX	0.00	0.00	0.61	1.52	0.61	0.00	0.00	0.00	3.66	2.74
BZ	10.00	0.00	1.67	0.00	0.00	0.00	0.00	0.00	5.00	0.00
BAC	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.63	0.00
BAD	23.44	6.56	0.00	0.00	19.06	0.00	0.00	0.00	0.63	0.00
BAE	1.26	0.00	0.00	0.00	0.94	1.57	39.94	1.26	0.63	0.00
BAG	0.65	0.00	3.24	0.00	0.97	0.00	12.94	0.65	0.00	0.00
BAH	0.00	0.00	0.00	0.63	1.27	0.00	0.32	0.00	0.00	0.00
BAI	1.28	0.00	1.28	2.56	1.92	0.00	0.00	0.00	2.24	7.03
BAJ	1.25	0.00	0.00	0.00	0.63	0.00	49.53	0.00	0.00	0.94
BAK	0.00	0.00	0.00	0.00	3.15	0.00	55.84	0.00	0.00	0.00
BAL	1.77	0.00	0.00	0.00	2.36	0.00	52.21	0.00	0.00	0.59
BAM	1.86	0.00	0.00	0.00	0.00	3.72	42.41	0.00	0.62	0.00
BAN	1.30	0.00	3.91	0.00	3.91	0.00	0.65	2.61	0.00	6.19

Appendix 3. (Cont'd) Raw relative species abundance data for 59 dominant diatom taxa.

Site	<i>N.jaernefeltii</i>	<i>N.pseudoscutiformis</i>	<i>N.salinarum</i>	<i>N.soehrensii</i>	<i>N.vulpina</i>	<i>N.bryophila</i>	<i>Neidium umlatense</i>	<i>N.alpina</i>	<i>N.frustulum</i>	<i>N.perminuta</i>
BC	0.00	0.00	0.50	0.50	0.25	0.00	0.00	0.00	2.01	1.01
BD	0.00	0.00	0.00	0.34	2.39	0.00	0.00	0.00	1.71	0.34
BE	0.00	0.00	0.00	1.24	0.62	0.00	0.00	0.00	1.24	0.00
BF	0.00	0.00	0.65	0.65	0.00	0.00	8.17	0.00	0.00	0.00
BG	0.00	0.00	2.39	0.00	0.00	0.00	1.37	1.37	1.37	0.68
BH	0.00	0.00	0.00	0.00	0.00	0.00	9.09	9.09	0.00	0.00
BJ	0.00	0.00	0.00	0.66	0.33	0.00	0.00	4.59	9.84	5.25
BK	0.00	0.65	1.95	0.00	1.63	0.00	0.00	0.00	1.30	1.95
BM	0.00	0.59	0.00	0.00	0.00	0.00	0.00	0.00	2.94	0.59
BN	0.00	0.00	0.00	0.00	0.65	1.31	0.00	0.00	0.65	1.31
BP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.97	26.05
BR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	30.87	8.36
BT	0.00	0.00	0.63	0.00	0.00	4.40	5.97	3.77	8.18	2.52
BU	1.29	1.29	0.65	0.00	0.00	0.00	0.00	0.65	7.74	5.16
BV	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	2.53	3.16
BW	0.00	0.00	0.00	0.00	1.92	0.00	0.00	0.00	6.71	3.83
BX	0.00	0.00	0.30	0.00	2.44	0.00	0.61	2.13	2.74	9.45
BZ	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00
BAC	0.00	0.00	0.00	0.00	1.57	0.63	0.00	0.63	2.52	3.77
BAD	0.00	5.63	0.00	0.00	2.50	0.00	0.00	0.00	3.13	0.63
BAE	0.00	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00	1.26
BAG	0.00	0.00	0.00	0.00	0.00	0.65	0.65	0.65	4.85	12.62
BAH	0.00	0.00	0.00	5.38	0.00	1.90	0.00	1.27	1.27	7.59
BAI	0.00	0.00	0.00	1.28	4.79	0.00	0.00	2.56	7.03	7.03
BAJ	0.00	0.31	0.63	0.00	0.00	0.00	0.00	0.00	3.13	1.88
BAK	4.42	0.00	0.95	0.00	0.63	0.00	0.00	0.00	0.63	1.26
BAL	0.00	0.59	0.00	0.00	0.00	0.59	0.00	0.00	1.18	1.18
BAM	0.31	0.00	1.86	0.00	0.31	1.24	0.00	0.00	3.41	1.24
BAN	0.00	0.65	1.30	0.00	1.30	0.65	1.30	2.61	5.86	9.77

Appendix 3. (Cont'd) Raw relative species abundance data for 59 dominant diatom taxa.

Site	<i>N.perminuta</i> T1	<i>N.inconspicua</i>	<i>N.palea</i>	<i>Pinnularia balfouriana</i>	<i>P. subrostrata</i>	<i>Stauroneis anceps</i>
BC	1.51	1.01	0.00	28.39	0.75	1.01
BD	0.00	0.00	0.00	0.34	0.00	1.71
BE	0.00	1.24	0.31	0.00	0.00	0.00
BF	0.00	0.00	0.00	0.00	0.00	0.65
BG	1.71	0.68	4.10	10.92	1.37	0.68
BH	0.00	0.00	0.00	0.00	9.09	0.00
BJ	13.77	1.64	0.00	1.31	0.00	0.00
BK	0.00	0.65	0.00	2.28	0.65	0.00
BM	1.76	0.00	0.00	55.59	0.00	0.00
BN	0.00	0.00	0.00	58.50	1.31	0.00
BP	2.57	0.00	0.00	0.00	0.00	0.00
BR	1.29	0.00	0.00	0.00	0.00	0.00
BT	15.09	11.64	1.26	0.00	0.00	0.00
BU	2.58	2.58	0.65	4.19	0.32	0.00
BV	1.90	0.00	0.63	0.00	0.63	0.00
BW	1.28	0.00	1.92	0.00	2.56	0.00
BX	5.18	1.22	0.00	0.00	0.00	0.00
BZ	3.33	0.00	0.00	6.67	5.00	0.00
BAC	3.14	0.00	0.00	0.00	0.00	0.00
BAD	0.63	0.63	0.63	7.19	1.25	1.25
BAE	1.89	0.00	0.00	26.73	0.31	0.00
BAG	5.18	0.00	0.65	7.77	0.00	0.65
BAH	0.63	0.00	0.00	0.00	0.32	0.00
BAI	0.64	0.00	0.00	0.00	0.00	1.28
BAJ	5.02	3.76	0.00	12.23	0.00	0.00
BAK	2.52	0.00	0.00	13.88	0.00	0.63
BAL	1.77	2.36	0.59	11.21	0.00	1.18
BAM	1.24	0.00	1.24	31.89	0.00	0.00
BAN	7.17	1.95	3.26	0.00	3.26	0.00

Appendix 4. DCA summary output for 13 environmental variables and full species dataset

Axes	1	2	3	4	Total Inertia
Eigenvalues	.607	.337	.198	.146	3.061
Lengths of gradients	2.895	3.949	2.168	1.740	
Species – environment correlations	.858	.837	.888	.765	
Cumulative percentage variance					
● of species data	19.8	30.9	37.3	42.1	
● of species – environment relation	20.2	32.9	42.7	47.6	
Sum of all unconstrained eigenvalues					3.061
Sum of all canonical eigenvalues					1.862

Appendix 5. CCAs constrained to a single environmental variable for 6 forward selected variables.  
(**bold** = significant  $P \leq 0.01$ )

Environmental variable	$\lambda_1$	$\lambda_2$	$\lambda_1/\lambda_2$	P-value
<b>TEMP</b>	<b>.216</b>	<b>.483</b>	<b>.450</b>	<b>0.01</b>
<b>TPF</b>	<b>.257</b>	<b>.524</b>	<b>.490</b>	<b>0.01</b>
pH	.165	.607	.270	0.07
DIC	.141	.594	.240	0.24
Zn	.169	.586	.290	0.13
Ba	.141	.546	.260	0.18

Appendix 6. CCA summary output for 29 environmental variables

Axes	1	2	3	4	Total Inertia
Eigenvalues	.607	.362	.300	.260	3.061
Species-environment correlations	1.000	1.000	1.000	1.000	
Cumulative percentage variance					
• of species data	19.8	31.7	41.5	50.0	
• of species – environment relation	19.8	31.6	41.4	50.0	
Sum of all unconstrained eigenvalues					3.061
Sum of all canonical eigenvalues					3.062

**Appendix 7. CCA summary output for 13 environmental variables**

<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total Inertia</b>
Eigenvalues	.474	.276	.250	.151	3.061
Species-environment correlations	.903	.949	.884	.862	
Cumulative percentage variance					
• of species data	15.5	24.5	32.7	37.6	
• of species – environment relation	25.5	40.3	53.7	61.8	
Sum of all unconstrained eigenvalues					3.061
Sum of all canonical eigenvalues					1.862

Appendix 8. CCA Weighted correlation matrix (weight = sample total) for 29 environmental variables.

SPEC AX1	1.0000							
SPEC AX2	.0000	1.0000						
SPEC AX3	.0003	.0002	1.0000					
SPEC AX4	.0000	.0000	.0000	1.0000				
ENVI AX1	1.0000	.0000	.0002	.0000	1.0000			
ENVI AX2	.0000	1.0000	.0001	.0000	.0000	1.0000		
ENVI AX3	.0001	.0001	1.0000	.0000	.0000	.0000	1.0000	
ENVI AX4	.0000	.0000	.0000	1.0000	.0000	.0000	.0000	1.0000
Ba	.3458	-.1083	.0931	-.1818	.3458	-.1083	.0931	-.1818
Ca	-.0403	-.3248	.0712	.1150	-.0402	-.3249	.0714	.1151
Fe	-.1525	.1485	.7524	-.2215	-.1526	.1484	.7525	-.2214
K	.0891	.1896	.3117	-.0376	.0891	.1896	.3117	-.0376
Li	-.1840	.1037	.3656	-.0764	-.1840	.1036	.3657	-.0763
Mg	-.3161	-.2486	.2022	-.1930	-.3162	-.2487	.2024	-.1930
Mo	.1436	-.1380	.0312	.3465	.1435	-.1381	.0312	.3465
Na	-.0878	-.0035	.4799	-.1682	-.0878	-.0035	.4799	-.1682
Ni	.1294	-.0293	.3170	-.0472	.1293	-.0295	.3171	-.0472
Sr	-.0396	-.0101	.0432	.0158	-.0395	-.0101	.0433	.0159
V	-.1358	.1147	.5280	-.2304	-.1359	.1146	.5282	-.2303
Zn	.2247	.0372	.5210	-.1194	.2246	.0372	.5210	-.1194
Cl	-.0699	-.0122	.4240	-.1820	-.0699	-.0123	.4240	-.1820
SO4	-.0114	-.0161	-.1054	-.0613	-.0114	-.0162	-.1053	-.0613
SiO2	-.2636	-.1494	.2759	-.2460	-.2637	-.1495	.2761	-.2460
DOC	-.4255	-.3705	.2399	.0367	-.4255	-.3705	.2400	.0367
DIC	-.1747	-.3815	.1245	.0333	-.1747	-.3816	.1247	.0333
NO2	.0941	-.0734	-.0087	.2268	.0941	-.0735	-.0086	.2268
NH3	.0437	-.3634	-.0926	.2333	.0437	-.3634	-.0925	.2333
TKN	-.3815	-.4059	.2268	.0784	-.3815	-.4059	.2270	.0784
TPU	-.2051	.0758	.6044	-.1675	-.2052	.0756	.6046	-.1674
TPF	-.4578	-.2572	.4486	.0587	-.4579	-.2573	.4488	.0587
ChlaU	-.2399	-.0660	.2782	-.1874	-.2400	-.0661	.2783	-.1874
ChlaC	-.1085	-.0134	.1777	-.1612	-.1086	-.0135	.1778	-.1612
POC	-.2149	.0328	.6668	-.0914	-.2151	.0327	.6670	-.0913
PON	-.2042	.0229	.6789	-.0381	-.2044	.0228	.6790	-.0381
Temp	-.4997	-.1018	-.0694	-.1739	-.4997	-.1018	-.0693	-.1739
pH	-.0359	-.4842	-.2344	.0450	-.0358	-.4842	-.2343	.0450
Cond	-.1611	-.2335	.2220	-.0492	-.1611	-.2335	.2222	-.0492
	SPEC AX1	SPEC AX2	SPEC AX3	SPEC AX4	ENVI AX1	ENVI AX2	ENVI AX3	ENVI AX4



Appendix 8. (Cont'd) CCA Weighted correlation matrix (weight = sample total) for 29 environmental variables.

Ba	1.0000							
Ca	.6034	1.0000						
Fe	.2583	.2259	1.0000					
K	.6027	.6085	.4578	1.0000				
Li	.3699	.5277	.6653	.7519	1.0000			
Mg	.3781	.5575	.3233	.4240	.5240	1.0000		
Mo	.4784	.3396	-.0723	.2220	.0404	.1015	1.0000	
Na	.4877	.2875	.4785	.5365	.4763	.6304	.0519	1.0000
Ni	.4996	.2072	.5114	.3157	.3196	-.0030	.1706	.2351
Sr	.1760	.5789	.3035	.4617	.4819	.0923	.0220	-.0165
V	.5613	.3947	.8622	.5331	.6512	.3589	.1658	.5116
Zn	.2058	.0407	.5080	.3924	.2718	-.0002	-.0004	.0656
Cl	.5288	.2952	.4284	.5006	.4305	.5950	.0647	.9582
SO4	.4214	.5732	.1108	.3921	.2647	.0979	.3139	-.0504
SiO2	.2513	.4904	.3791	.3245	.5063	.8320	-.0184	.3204
DOC	.1929	.3986	.2353	.2350	.3203	.8272	.2350	.4937
DIC	.4875	.8408	.1952	.5082	.4932	.8794	.2518	.4823
NO2	.2435	.2105	-.0912	.0500	-.0224	-.0482	.4328	-.1978
NH3	.2446	.3447	-.1593	.0552	-.0332	.2329	.3641	-.0271
TKN	.2033	.3712	.1606	.1777	.2280	.7324	.2864	.4587
TPU	.3569	.2462	.9043	.4429	.6931	.3524	.0613	.4959
TPF	.2397	.3535	.4650	.1981	.2943	.5353	.3720	.2877
ChlaU	.0619	.0041	.2502	.0446	-.0040	.1552	-.0116	.1408
ChlaC	.0651	.0772	.1669	.0425	-.0526	-.0240	-.0573	-.0597
POC	.3708	.1382	.7661	.2687	.4463	.3870	.1347	.6255
PON	.3162	.0844	.7424	.2175	.3902	.3425	.1295	.6101
Temp	.1069	.3894	.1894	.4327	.4420	.7258	.0477	.3252
pH	.1665	.3192	-.3185	.0062	-.1542	.1320	.1284	-.1915
Cond	.6218	.8465	.3235	.6621	.5523	.8304	.2821	.6193
	Ba	Ca	Fe	K	Li	Mg	Mo	Na

Appendix 8. (Cont'd) CCA Weighted correlation matrix (weight = sample total) for 29 environmental variables.

Ni	1.0000							
Sr	.1055	1.0000						
V	.6409	.3261	1.0000					
Zn	.2195	.0423	.3875	1.0000				
Cl	.2100	-.0476	.5219	.0027	1.0000			
SO4	.1896	.7572	.2758	.0881	-.1225	1.0000		
SiO2	-.0151	.0922	.3431	.1662	.2993	.0758	1.0000	
DOC	-.0123	-.1077	.2296	.0425	.4433	-.0329	.6377	1.0000
DIC	.0451	.2328	.3051	-.0085	.4757	.2259	.7539	.7289
NO2	.1060	.0227	-.0112	.2079	-.2345	.3728	.0456	-.0077
NH3	-.0267	.1004	.0111	.1289	-.0482	.3111	.1596	.5068
TKN	-.0059	-.1365	.1672	.0399	.3926	.0229	.5363	.9727
TPU	.5332	.2842	.8778	.4053	.4939	.0992	.2951	.2411
TPP	.1657	-.0264	.5553	.3126	.2848	.0648	.5220	.6536
ChlaU	.1538	.2772	.3315	.1706	.1103	.3554	.1467	.0823
ChlaC	.0214	.4858	.2558	.2168	-.0439	.5363	.0192	-.1093
POC	.5937	.0616	.7993	.2073	.6139	.0294	.2807	.3175
PON	.5949	.0131	.7570	.2064	.5784	-.0093	.2327	.3093
Temp	-.1383	.1527	.1860	.0471	.2814	.1162	.6153	.6903
pH	-.1469	.2219	-.2580	.0505	-.1945	.4044	.1405	.2088
Cond	.1644	.3193	.4622	.0449	.6223	.3261	.6899	.6483

Ni                      Sr                      V                      Zn                      Cl                      SO4                      SiO2                      DOC

Appendix 8. (Cont'd) CCA Weighted correlation matrix (weight = sample total) for 29 environmental variables.

DIC	1.0000							
NO2	.0879	1.0000						
NH3	.3487	.3036	1.0000					
TKN	.6575	.0484	.6051	1.0000				
TPU	.2213	-.0060	-.1031	.1657	1.0000			
TPF	.5060	.0623	.3150	.6096	.4940	1.0000		
ChlaU	.0227	.1183	.1551	.0962	.2593	.3195	1.0000	
ChlaC	-.0747	.0671	.2141	-.0777	.1611	.2098	.8602	1.0000
POC	.2183	.0666	-.0452	.2789	.8432	.5342	.4845	.2684
PON	.1743	.0732	-.0358	.2820	.8047	.5255	.4917	.2536
Temp	.6238	.0581	.2125	.5851	.2209	.3770	.0570	-.1174
pH	.2541	.4251	.5896	.2931	-.2137	.0360	.2868	.3378
Cond	.9277	.0751	.2638	.5719	.3246	.4853	.0817	.0209
DIC		NO2	NH3	TKN	TPU	TPF	ChlaU	ChlaC

Appendix 8. (Cont'd) CCA Weighted correlation matrix (weight = sample total) for 29 environmental variables.

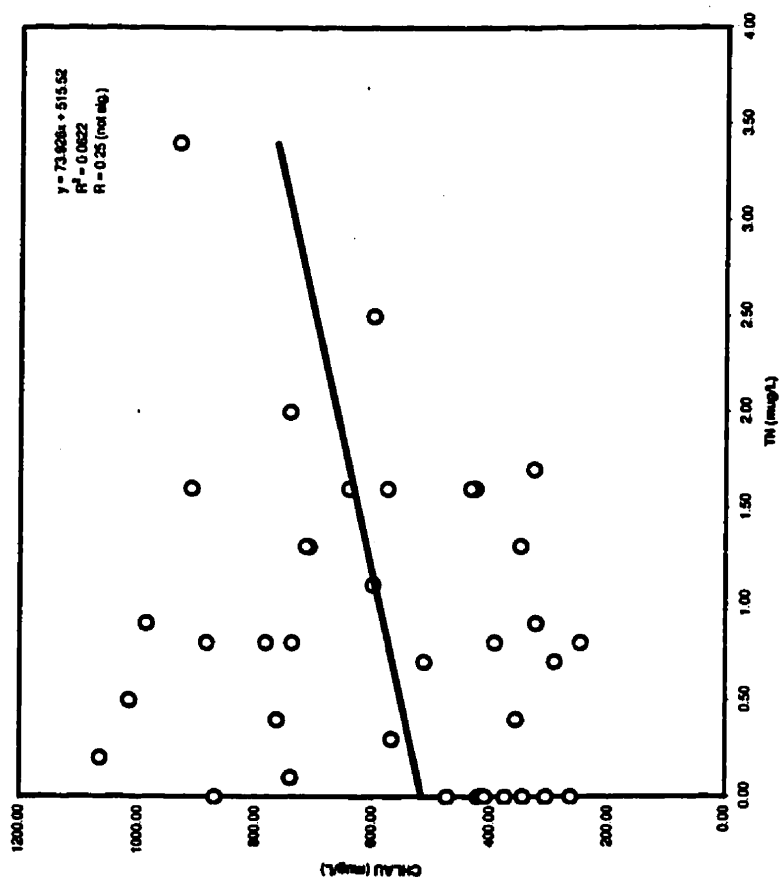
	POC	PON	Temp	pH	Cond
POC	1.0000				
PON	.9912	1.0000			
Temp	.0810	.0447	1.0000		
pH	-.2147	-.2233	.2681	1.0000	
Cond	.3289	.2785	.6136	.1956	1.0000

Appendix 9. Ba, Zn, pH, DIC, TPF Optima for 59 Dominant Diatom Taxa.

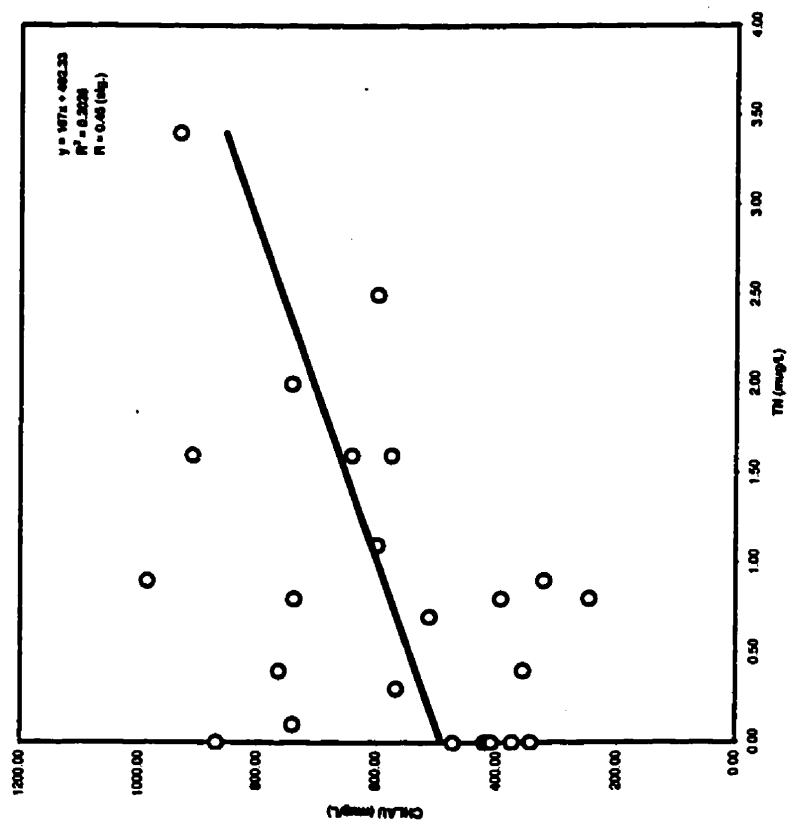
Taxon Code	Taxon Name and Authority	Ba (mg/L)	Zn (mg/L)	pH	DIC (mg/L)	TPF (mg/L)	Num. Of Occurrences
1	<i>Amphora inariensis</i> Krammer	0.048	0.004	8.32	18.373	0.005	11
2	<i>A. libyca</i> Ehrenberg	0.072	0.008	8.32	22.819	0.006	9
3	<i>A. aequalis</i> Krammer	0.047	0.003	8.26	20.880	0.006	11
4	<i>A. veneta</i> var. <i>capitata</i> Haworth	0.094	0.003	8.27	21.438	0.006	4
5	<i>A. pediculus</i> (Kützing) Grunow	0.071	0.003	8.13	17.440	0.006	8
6	<i>Achnanthes</i> sp.1	0.031	0.004	8.28	18.547	0.006	7
7	<i>A.</i> sp.2	0.062	0.003	8.27	18.763	0.006	8
8	<i>A. chlidanos</i> Hogn & Helleermann	0.054	0.003	8.31	19.033	0.006	19
9	<i>A. flexella</i> Kützing	0.071	0.003	8.33	25.740	0.007	23
10	<i>A. minutissima</i> Kützing	0.061	0.004	8.30	22.735	0.007	26
11	<i>A. kryophila</i> var. <i>petersenii</i> Peterson	0.021	0.004	8.28	15.348	0.005	8
12	<i>A. oestrupii</i> var. <i>oestrupii</i> (Cleve-Euler) Hustedt	0.138	0.005	8.19	20.342	0.008	6
13	<i>A. ventralis</i> (Krasse) Lange-Bertalot	0.078	0.005	8.29	18.615	0.007	9
14	<i>A. laevis</i> var. <i>laevis</i> (Oestrup)	0.059	0.005	8.28	23.185	0.007	14
15	<i>A. subatamoides</i> (Hustedt) Lange-Bertalot & Archibald	0.053	0.004	8.31	24.326	0.007	4
16	<i>A. marginulata</i>	0.036	0.002	8.25	17.416	0.005	14
17	<i>Caloneis</i> sp.1	0.048	0.003	8.36	21.570	0.006	15
18	<i>C. bacillum</i> (Grunow) Cleve	0.054	0.004	8.29	24.551	0.007	13
19	<i>C. silicula</i> (Ehrenberg) Cleve	0.046	0.002	8.45	17.957	0.005	4
20	<i>Cymbella angustata</i> (W. Smith) Cleve	0.054	0.003	8.30	22.531	0.008	23
21	<i>C. arctica</i> (Langerstedt) Schmidt	0.061	0.005	8.34	22.085	0.007	26
22	<i>C. arctica</i> T1	0.051	0.002	8.43	21.360	0.006	12
23	<i>C. cesatii</i> (Rabenhorst) Grunow	0.061	0.004	8.30	24.148	0.007	19
24	<i>C. designata</i> Krammer	0.040	0.004	8.32	18.769	0.006	19
25	<i>C. latens</i> (Krasske) Reimer	0.062	0.008	8.26	19.798	0.007	20
26	<i>C. microcephala</i> Grunow	0.061	0.004	8.32	19.557	0.007	21
27	<i>C. minuta</i> Hilse	0.039	0.005	8.17	16.409	0.005	18
28	<i>C. silesiaca</i> Bleisch	0.042	0.005	8.17	17.139	0.005	16
29	<i>C. similis</i> Krasske	0.074	0.005	8.25	22.058	0.007	15

Appendix 9. (Cont'd) Ba, Zn, pH, DIC, TPF Optima for 59 Dominant Diatom Taxa.

Taxon Code	Taxon Name and Authority	Ba (mg/L)	Zn (mg/L)	pH	DIC (mg/L)	TPF (mg/L)	Num. Of Occurrences
30	<i>C. subaequalis</i> Grunow	0.099	0.005	8.33	27.120	0.010	5
31	<i>C. tumidula</i> Grunow	0.059	0.005	8.30	16.544	0.007	13
32	<i>Denticula elegans</i> Kützing	0.038	0.003	8.34	22.069	0.008	11
33	<i>D. kuetzingii</i> Grunow	0.042	0.006	8.33	23.730	0.009	16
34	<i>Diadesmis</i> Round <i>sp. I</i>	0.063	0.013	8.25	18.068	0.008	15
35	<i>Diatoma</i> cf. <i>moniliformis</i> Kützing	0.063	0.021	8.21	21.149	0.010	4
36	<i>Diploneis oculata</i> (Brébisson) Cleve	0.051	0.003	8.29	18.830	0.005	12
37	<i>Eunotia arcus</i> Ehrenberg	0.057	0.003	8.37	28.404	0.007	9
38	<i>Fragilaria capucina</i> var. <i>capitellata</i> (Desmazières)	0.063	0.009	8.21	21.519	0.008	22
39	<i>F. construens</i> var. <i>construens</i> (Ehrenberg) Hustedt	0.054	0.004	8.19	19.562	0.004	6
40	<i>F. pinnata</i> var. <i>pinata</i> Ehrenberg	0.086	0.007	8.35	18.919	0.005	12
41	<i>Navicula hilliardii</i> var. <i>pseudosiliculoides</i> Foged	0.041	0.002	8.32	19.357	0.004	5
42	<i>N. cryptocephala</i> Kützing	0.080	0.004	8.28	20.535	0.007	15
43	<i>N. cryptotenella</i> Lange-Bertalot	0.050	0.004	8.44	20.519	0.005	11
44	<i>N. jaernefeltii</i> Hustedt	0.112	0.004	8.23	16.743	0.007	4
45	<i>N. pseudoscutiformis</i> Hustedt	0.050	0.020	8.29	17.931	0.009	7
46	<i>N. salinarum</i> Grunow	0.065	0.006	8.24	18.757	0.005	11
47	<i>N. soehrensii</i> var. <i>soehrensii</i> Krasske	0.038	0.002	8.44	22.470	0.005	7
48	<i>N. vulpina</i> Kützing	0.059	0.007	8.35	23.012	0.007	15
49	<i>N. bryophila</i> Boye Peterson	0.046	0.003	8.29	17.885	0.004	9
50	<i>Neidium umiatense</i> Foged	0.012	0.003	8.18	12.732	0.004	7
51	<i>Nitzschia alpina</i> Hustedt	0.030	0.003	8.25	17.429	0.005	12
52	<i>N. frustulum</i> (Rabenhorst) Grunow	0.042	0.006	8.32	20.526	0.008	25
53	<i>N. perminuta</i> (Grunow) Peragallo	0.048	0.004	8.34	20.172	0.007	26
54	<i>N. perminuta</i> Tl	0.059	0.005	8.33	19.760	0.006	23
55	<i>N. inconspicua</i> Grunow	0.06	0.006	8.30	20.306	0.006	12
56	<i>N. palea</i> Kützing	0.043	0.003	8.28	18.013	0.005	11
57	<i>Pinnularia balfouriana</i> Grunow	0.076	0.008	8.24	19.237	0.004	16
58	<i>P. subrostrata</i> A. Cleve	0.059	0.004	8.17	17.558	0.006	13
59	<i>Stauroneis anceps</i> Ehrenberg	0.052	0.007	8.35	22.038	0.007	9

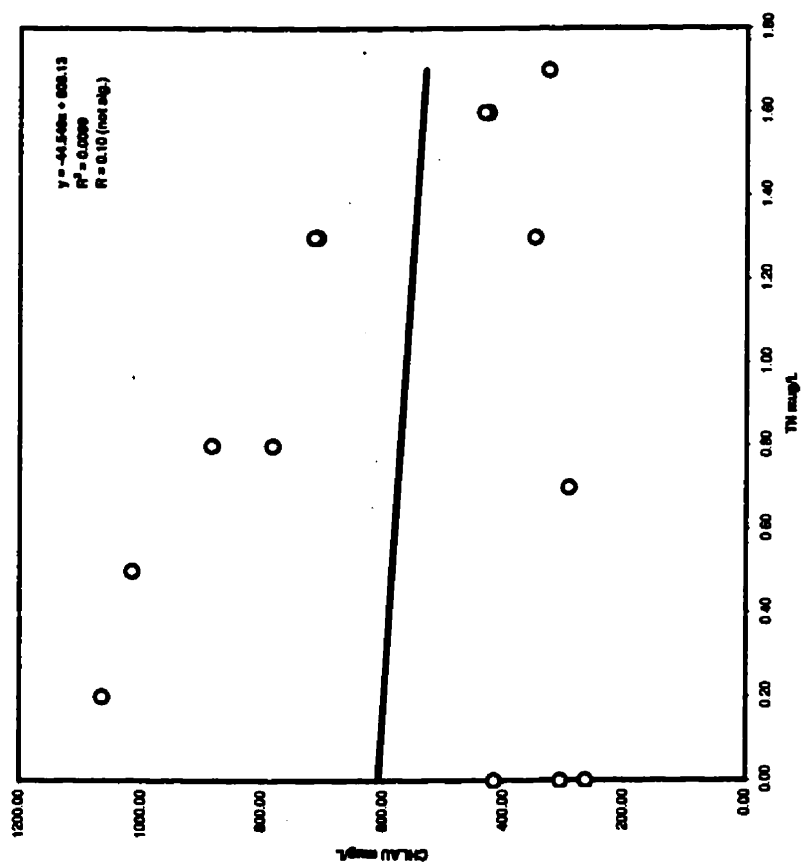


Appendix 10. CHLAU vs. TN linear regression for 38 sites



Appendix 11. CHLAU vs TN for sites with PON:POP <10:1





Appendix 12. CHLAU vs TN for sites with PON:POP &gt; 10:1



## **CURRICULUM VITAE**

### **DARLENE SZE-SHIEN LIM**

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#### **FORMAL EDUCATION/CERTIFICATION**

- |                         |   |
|-------------------------|---|
| Sept. 1996 – Present    | Master's of Science (M.Sc.) in Geology<br><i>University of Toronto, Dept. of Geology</i><br>Thesis: An examination of the limnology and freshwater diatom autoecology of Bathurst Island, N. W. T., Canadian High Arctic.<br>Supervisors: Dr. M. S. V. Douglas & Dr. J. P. Smol |
| Sept. 1990 – April 1994 | Bachelor of Science - Honours (B.Sc.H) in Biology<br><i>Queen's University, Dept. of Arts and Science</i>   |
| Sept. 1997 - June 1998  | Private Pilot's License<br><i>The Toronto Flight Centre - Toronto Island</i>  |

#### **GRADUATE STUDENT WORK EXPERIENCE**

- |                      |  |
|----------------------|--|
| Sept. 1996 - Present | <u>University of Toronto - Dept. of Geology, Paleoenvironmental Assessment Laboratory (PAL)</u><br><i>Toronto, Ontario</i> |
|----------------------|--|

##### **Research Assistant**

- 1998-99 school year: supervision of 4<sup>th</sup> year thesis student projects
- assist with overall lab organization of in-coming undergraduate students joining Paleoenvironmental Assessment Lab (PAL)
- coordinate bi-monthly PAL meetings
- manage ordering of supplies, and other equipment

##### **Teaching Assistant**

- teach student laboratory sessions for various classes
- mark and compile student papers and exams

- attend to student inquiries and concerns

## EXTERNAL FUNDING & SUPPORT

- Ontario Graduate Scholarship 1998-99
- Northern Studies Training Grant 1997
- University of Toronto Open Scholarship 1997/98
- University of Toronto Open Scholarship 1996/97

## CONTRIBUTIONS – ORAL PRESENTATIONS & POSTERS

All listed contributions resulted from work done in the process of completing master's degree.

### Oral Presentations

- (1) LIM, D. S. S., DOUGLAS, M. S. V. & SMOL, J. P. *Dominant Trends driving the Surface Sediment Diatom Distributions from 29 sites on Bathurst Island, NWT, Canada*; 1997/98 Rockfest Departmental Seminar Series; Dept. of Geology - University of Toronto, Toronto, ONT, Canada (received Rockfest Award for Best Presentation of the Year)

### Conference Presentations: With Published Abstracts

- (1) LIM, D. S. S., DOUGLAS, M. S. V. & SMOL, J. P. *Surface sediment diatom assemblages from Bathurst Island, NWT, Canadian High Arctic – A Calibration Project*; 28<sup>th</sup> Arctic Workshop: Mar. 12-14, 1998; Institute of Arctic & Alpine Research, University of Colorado, Boulder, Colorado, U.S.A. (Poster)
- (2) LIM, D. S. S. & DOUGLAS, M. S. V. *An Examination of the Relationship between the Limnology and Aquatic Moss Epiphytes from Canadian High Arctic Ponds (Bathurst Island, NWT, Canada)*; 5th National Students' Conference on Northern Studies: Nov. 28 - 30, 1997; Simon Fraser University, Vancouver, BC, Canada (Poster)
- (3) LIM, D. S. S. & DOUGLAS, M. S. V. *Aquatic Moss Epiphytes from Bathurst Island, NWT, Canadian High Arctic*; 14th North American Diatom Symposium: Sept. 24 - 27, 1997; Univ. of Michigan Biological Station, Pelleston, Mich., U.S.A. (Poster)
- (4) LIM, D. S. S., DOUGLAS, M. S. V., SMOL, J. P. & LEAN, D. S. *Limnology of High Arctic Ponds (Bathurst Island, NWT, Canada)*; 27th Arctic Workshop: Feb. 27 - Mar. 1, 1997; University of Ottawa, Ottawa, Canada. (Poster)

**ADDITIONAL WORKSHOPS ATTENDED:**

1998 Annual Geological Society of America (GSA) Meeting and Exposition, Toronto, Ontario; October 26-29, 1998 (convener)

8<sup>TH</sup> Annual Arctic – Antarctic Diatom Symposium, Canadian Museum of Nature, Ottawa, Ontario; June 2-6, 1998 (participant)

7<sup>TH</sup> Annual Arctic – Antarctic Diatom Symposium, University of Laval, Quebec City, Quebec; June 5-8, 1998 (participant)