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A diatom-based Holocene paleoenvironmental record from a lake on Boothia Peninsula, central mid Arctic, Nunavut, Canada

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Preface

The objective of this study is to present a high-resolution diatom lacustrine record from the central Canadian Arctic. The thesis is organized into seven chapters. The first chapter provides the reader with a general background of arctic paleolimnological research and of the lacustrine environment in the Canadian Arctic. The second chapter describes the region of study. The third chapter is a comprehensive explanation of methods used. The fourth chapter describes the JR01 lake sediment core and the diatom stratigraphy. The focus of the fifth chapter is to present SEM images of diatom taxa found in the core and to examine some taxa that are difficult to identify, in particular *Fragilaria*. A comprehensive list of diatoms enumerated in the JR01 lake core is also provided in chapter five. The sixth chapter includes an interpretation of the results. This record provides information on Holocene climate changes and on the past limnological states of lake JR01. Suggestions for further research are at the end of the chapter. The seventh chapter is a short summary of the thesis.

Abstract

An important source of information about climate change comes from sedimentary deposits from the arctic region. However, there are few lacustrine fossil records from the central mid Arctic region of Canada. A 485 cm sediment core, from a lake unofficially called JR01, Boothia Peninsula, Nunavut, yielded a high-resolution diatom record. Five radiocarbon dates provided the chronology. Three distinct zones are revealed in the relative percent abundance and diatom concentration diagrams. A more diverse and productive flora in the first zone implies warmer temperatures in the middle Holocene. A complete shift in diatom composition to a predominantly *Fragilaria* flora and a reduction in diversity and production suggests a cooler climate in this region after approximately 4360 years B.P. Smaller-scale climatic trends, such as the Little Ice Age (LIA) (ca. 550-150 yr. B.P.) and the Medieval Warm Period (ca. 1000-700 yr. B.P.), caused shifts in the diatom flora and production. Subtle shifts in floristic diversity within the LIA may reflect climate variability at a decadal scale. This variability is also recorded in other high-resolution paleoclimate records from the Arctic. A gradual shift to a more diverse and productive flora in the last 180 years B.P. (1790 years A.D.) suggests a response to the recent warming trend. This study permits us to address ambiguities with respect to the timing, the geographic extent and the severity of the recent warming. Changes in total diatom concentrations, magnetic susceptibility, organic and carbonate content may also reflect changes in the diatom assemblages and indicate shifts in vegetation, soil erosion, or in hydrology from the surrounding catchment. The morphological variance of *Fragilaria* and other taxonomy issues are also discussed.

Résumé

Une importante source d'informations sur le changement du climat vient des dépôts sédimentaires de la région arctique. Cependant, il y a peu de données fossiles lacustres de l'arctique moyen pour la partie centrale du Canada. Une carotte de sédiments d'une longueur de 485 cm, du lac JR01 (nom non officiel), de la péninsule de Boothia, Nunavut, a révélé une séquence sédimentaire de diatomée à haute résolution. Cinq datations radiocarbones ont fourni la chronologie. Trois zones distinctes sont indiquées dans les diagrammes d'abondances relatives et de concentrations. La première zone, de flore plus diverse et plus productive, suggère des températures plus chaudes au milieu de Holocène. Un changement complet dans la composition en diatomée, une flore dominée par *Fragilaria*, une réduction de diversité et de production suggèrent un climat plus frais pour cette région après approximativement 4360 ans B.P. Les tendances climatiques à une plus petite échelle, telles que le Petit âge glacaire (PAG) (ca. 550-180 ans B.P.) et la période chaude médiévale (ca. 1000-700 an. B.P.) ont causé des changements dans la flore et dans la production de diatomée. Les variations subtiles dans la diversité floristique du PAG peuvent refléter une variabilité climatique à une résolution décennale. Cette variabilité est également enregistrés dans d'autres séquences sédimentaires à haute résolution de l'Arctique. Le changement progressif vers une flore plus diverse et plus productive au cours des dernières 180 années B.P. (1790 an. A.D.) suggère une réponse au réchauffement récent. Cette étude permet d'adresser les ambiguïtés spatiales et temporelles ainsi que l'intensité du réchauffement récent. Les changements de concentrations totales de diatomée, la susceptibilité magnétique, la teneure en organique et en carbonates peuvent également refléter des changements d'assemblages de diatomée et aussi indiquer des changements de la végétation, de l'érosion du sol, ou de hydrologie du bassin versant. Le désaccord morphologique de *Fragilaria* et d'autres questions taxonomiques sont également abordées.

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CHAPTER ONE

1.0 Introduction

High latitude regions provide an amplified response to hemispheric changes in climate (Overpeck et al. 1997; Houghton et al. 1990). This makes the study of climate change in the arctic critical to understanding global climate change. An important source of information about climate change comes from sedimentary deposits.

A feature of the Canadian Arctic Archipelago is the widespread occurrence of freshwater lake ecosystems. These freshwater lakes are often the first to respond to environmental change (Blom et al. 2000). For instance, the observed increase in summer temperatures is predicted to affect precipitation/evaporation ratios, runoff, duration of ice cover, thickness of snow cover, and length of the growing season (Smol & Cumming 2000; Moser et al. 1998; Smol 1988).

Sediment stratigraphies archive information about past climates and provide insight into changes in the physical, biological, and geochemical properties of the lake ecosystem (Fritz 1996). Researchers are conducting paleoclimatic reconstructions in the arctic and subarctic regions of North America to record past climate trends and to determine the extent of natural and/or anthropogenic influence on the recent warming trend (Houghton et al. 1990; Overpeck et al. 1997; Smol 1988; Walsh & Crane 1992).

Diatoms are a fitting proxy for the study of arctic lake ecosystems because they are able to tolerate the extreme conditions that occur in high latitude regions. They are ecologically sensitive and are often the first organisms to respond to and recover from environmental stress. This is due to their narrow optima and tolerances to many environmental variables (Battarbee 1986; Dixit et al. 1992; Wetzel 2001). They are well-preserved in the fossil sediment record and appear to represent the entire life assemblage (Battarbee 1986; Birks & Birks 1980). Diatom stratigraphies from lakes in the arctic region are thus an important tool for reconstructing past climates and lake histories (e.g. Andreev & Klimanov 2000; Dixit et al. 1992; Gajewski et al. 1997; Houghton et al. 1990; MacDonald et al. 2000; Pienitz et al. 1999; Smol et al. 1991).

However, there are few lacustrine fossil records from the Canadian Arctic. Existing knowledge of the postglacial environmental history of the central Canadian Arctic remains insufficient (Gajewski & Frappier 2001). The few sites analysed have provided information on past climate variations. On Somerset Island two postglacial pollen diagrams suggest more productive vegetation in the early Holocene (Gajewski 1995). On Ellesmere (Douglas et al. 1994) and on Devon Island (Gajewski et al. 1997), changes of the diatom communities in the recent past appear to be due to recent global warming although the temporal resolution, geographic extent, and degree of severity is still unresolved. It is also essential to determine if other environmental changes have occurred earlier in the Holocene and to document the spatial extent of these changes in the arctic.

The objective of this study is to present a high-resolution diatom lacustrine record from the central Canadian Arctic region. The record provides information on Holocene climate variations and on the past limnological states of the southern Boothia Peninsula. This study contributes to the growing collection of paleoenvironmental records in the arctic and supplements current research on climate change and its effect on freshwater arctic lakes.

1.1 Paleolimnology and the lacustrine environment in the Canadian Arctic

Arctic lakes are subject to low water temperatures throughout the year (Lotter & Bigler 2000) and a low or absent light regime for more than half of the year. The resulting prolonged ice cover contributes to the brevity of the open water season and the subsequent low levels of productivity. Geology, vegetation, permafrost, hydrological conditions in the catchment area, as well as lake size are other factors that influence the physical and chemical condition of arctic lakes.

Temperature patterns of the Canadian Arctic are not simply determined by latitude. The coldest summer temperatures occur in regions that are governed by the northwesterly flow of the atmospheric circulation from the central Arctic Ocean. The extreme arctic ecosystem of the Queen Elizabeth Islands, for instance, is a result of the persistent flow from the central Arctic

Ocean. Conversely, areas protected from this flow have the highest summer temperatures (Edlund & Alt 1989). For instance, the intermontane zone of Axel Heiberg and Ellesmere Islands is essentially sheltered from this cold air mass. As a result, these zones are covered by a vegetation that is dense and diverse (Edlund & Alt 1989). This is also supported by the unusually high DIC and DOC concentrations found between the two mountain ranges on the Fosheim Peninsula, Ellesmere Island (Hamilton et al. 2001). Finally, the intermediate climate on the southern islands is influenced by the presence of plateaus and highlands (Edlund & Alt 1989). Therefore, as observed by Atkinson (2000), meso-scale climate patterns in the Canadian Arctic can be largely explained by physiographic factors.

The bedrock geology of the Canadian Arctic Archipelago consist largely of a metaphorphic Precambrian bedrock composed of mainly granite and gneiss and of a lower Paleozoic sedimentary rock composed of a major calcium carbonate complex (Dyke 1984, Edlund & Alt 1989). The Precambrian Shield is primarily located in the southeast with the remaining regions consisting mainly of the carbonate bedrock (Hamilton et al. 2001). Lake waters located on the Shield, such as on Baffin Island, are generally poorly buffered, low in conductivity and have lower pH values. Magnetic susceptibility values of lake sediments from this region are higher due to the leaching of aluminum and iron from the bedrock. Alternatively, lakes on carbonate bedrock are typically well-buffered with high pH values due to the presence of the calcium carbonate complex (e.g. Lim et al. 2001; Pietnitz et al. 1997 a b).

Changes in water level by means of precipitation, stream input or groundwater may also affect the lake's chemistry. Higher water levels often dilute the nutrient and ionic composition of a lake (Wolin & Duthie 1999). However, fluctuations in the water chemistry of a lake have also been related to the quality of the incoming water source. For example, Bradbury (1986) determined that the increase of acidophilous diatom taxa (low pH) in two lakes of western Tasmania was due in part to an increased flushing of the lake with low pH water. It has been hypothesized that the length of time the groundwater has contact with the surrounding soils may explain the fluctuations in water quality (e.g. increase in DIC) (Ruhland & Smol 2002). Permafrost can also restrict the amount of solute runoff from the surrounding bedrock and soil (Ruhland & Smol 1998). The size of the lake can also influence the water chemistry. For instance, the productivity of arctic lakes, especially those that are small and mid-sized, depends on allochtonous sources for nutrients (Hamilton et al. 2001; Lim et al. 2001). Larger ultra-oligotrophic lakes were found to have a poor correlation with mean summer air temperatures and chlorophyll-*a* (Hamilton et al. 2001).

A distinctive feature of lakes from the Arctic Archipelago is that many are located relatively near to the coast. Arctic lakes become typically more dilute the farther they are situated from the coast. In this case, an increase in sodium chloride brings about an increase in ionic concentrations of the lake water (Schwoerbel 1987). Evidently, it is essential to take into account the various local processes and conditions of the Arctic Archipelago when studying an arctic lake ecosystem.

Due to the extreme conditions within these arctic lakes, aquatic communities are composed of a few species with limited numbers (Burgis & Morris 1987). The aquatic plants and animals, such as cladocera, chironomids, fish, and diatoms, for instance, must be able to function in cold waters with limiting nutrients (Burgis & Morris 1987), low light levels, prolonged ice cover, varying pH levels, and restrictive habitats. As previously mentioned, diatoms are a fitting proxy for environmental research since they are sensitive to environmental change and are well-preserved in the lake sediment. It should be noted that cladocera, chironomids and other organisms are also suitable proxies for paleolimnological research in the Arctic, although they will not be treated in the discussion that follows.

Diatoms are microscopic unicellular algae (class Bacillariophyceae) that live in virtually every aquatic environment, both freshwater (such as rivers, lakes, ponds, etc.) and marine (Dixit et al. 1992; Wetzel 2000). They have an exoskeleton made of opaline silica with protoplast contained inside. The exoskeleton consists of two valves, the epivalve and the hypovalve, which fit together like a shoebox and are held together by belt-like elements, known as copulae. The valves and the bands together are called a frustule. The silica shells of diatoms are intricately designed and unique to each species and providing good preservation, they can be identified. Though they take a variety of different forms, the basic cell symmetry created during silica formation is either radial (centrics) or bilateral (pennate). They can be viewed either through a light microscope or by means of an Electron Microscope.

In freshwater lakes, diatoms are mainly categorized as either planktonic (often lightly silicified centric shapes commonly residing in the water column) or benthic (residing at the bottom or associated to substrates). Benthic diatoms occupy various habitats: epipelic (living on mud), epipsammic (attached to sand grains), epiphytic (attached to plants), epilithic (attach to rocks), epizooic (attached to animals). Each species has specific ecological requirements, compete amongst themselves and are subject to grazing. Studies have quantified the optima and tolerances of particular species to a number of chemical and physical parameters, such as temperature, light, nutrients (nitrogen, DIC, phosphorus), pH, and salinity (e.g. Hudon et al. 1986; Joynt III & Wolfe 2001; Lim et al. 2001; Pienitz et al. 1995; Wilson et al. 1996). Certain taxa, given particular adaptive traits, thrive under conditions which others may find limiting. These taxa are known as resource specialists (Smol 1990) or indicator species (Birks & Birks 1980).

Spatial variations of diatom communities in the arctic and subarctic regions of North America can be explored by means of surface sediment 'calibration' or 'training' sets. These studies attempt to establish a relationship between an entire community or individual taxa to a large number of modern environmental variables (Birks & Birks 1980; Cumming et al. 1995; Smol 1990). Surface sediment samples (e.g. top 1 cm), representing the last few years of sediment accumulation (Smol and Cumming 2000), are collected along a transect that spans the limnological gradient of interest (i.e. across an ecotonal boundary, Smol et al. 1991) and the present-day physical, chemical and biological variables are also acquired (Cummning et al. 1995). The diatoms within the sediment samples are enumerated. To explain the variation in diatom relative abundances, the species data are related to the environmental parameters using multivariate statistical methods (Smol et al. 1995). The variables explaining the highest amount of variation are used in reconstruction models (Cumming et al. 1995) through the use of transfer functions. For instance, pondwater alkalinity best explained the distribution of taxa in a series of sites on Cape Herschel, east-central Ellesmere Island. A weighted averaging regression and calibration were used to develop a transfer function to infer pondwater alkalinity from the diatom assemblages (Douglas & Smol 1995). Despite the recent growth of quantitative reconstructions, important qualitative interpretations based on diatom ecology are also being made in paleolimnological research (Battarbee et al. 2001; Douglas & Smol 1995).

The distributions of various diatom species have been correlated with temperature (Joynt & Wolfe 2001; Lim et al. 2001). Cold weather can reduce the growing season by 30% or more (Smol 1988) and extend the length of the ice coverage, thereby restricting primary production to a benthic flora in the littoral moat (Borchard 1996; Smol 1988; Smol et al. 1991). A prolonged ice cover in cold climate regions may also modify the oxygen content within shallow lakes (Smol et al. 1991). On the other hand, more extensive melting during warm summers may allow development of a planktonic population (Douglas & Smol 2000; Smol et al. 1991) or of a more complex periphytic diatom assemblage with many stalked and tube-dwelling taxa (Borchard 1996). Diatom production is also affected by an increase in temperature (DeNicola 1996; Joynt 1999; Laing & Smol 2000, Lim et al. 2001). For instance, studies in areas receiving thermal effluent, as discussed in DeNicola (1996), found that the prevention of ice cover through heating allowed increased light for winter growth. Several studies have quantified the relationship between temperature and diatom taxa in lakes in northwestern Canada (Pienitz et al. 1995), northwestern Finland (Weckström et al. 1997), Siberia (Laing & Smol 2000), Baffin Island (Joynt 1999) and Bathurst Island (Lim et al. 2001).

Indirect influences of temperature on arctic diatoms have been determined through temperature-related changes in either chemical (e.g. nutrient cycling) or in physical (e.g. degree of ice cover) states in the lake ecosystem (Bradbury 1988; Lotter & Bigler 2000; Smol et al. 1991; Smol & Cumming 2000; Wetzel 2000). For instance, polar diatom assemblages have been associated with climate-related changes in habitat down core (Smol 1988; Smol et al. 1991). Studies done by Lotter and Bigler (2000) and Smol (1988) have demonstrated the importance of ice cover in determining the diversity and productivity of diatom assemblages in high altitude and latitude lakes. Temperature-related increases in dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) have been found in numerous subarctic treeline studies. Past climatic and related movement of treeline could be linked to changes in the diatom-inferred DIC and DOC concentrations in two lakes near northern treeline in central Canada (Pienitz et al.1999).

As noted above, observed changes in diatom assemblages (as well as other proxies) from arctic lake sediment cores have been used to infer past environments and climates. These records cover a large expanse within the Canadian Arctic Archipelago including, Ellesmere (Bourgeois et al. 2000; Brown et al. 1994; Douglas et al. 1994; Smith 2002; Smol 1983; Wolfe 2000), Devon (Gajewski et al. 1997; King 1991), Banks (Gajewski et al. 2000), Baffin (Joynt 1999; Wolfe 1991), Somerset (Gajewski 1995), and Prince of Wales (Gajewski & Frappier 2001).

The uppermost sections of many artic lake sediment cores have attributed the recent shifts in diatom flora and production to a warming trend (Doubleday et al. 1995; Douglas et al 1994; Gajewski et al. 1997; Joynt 1999; Ludlam et al. 1996; Smith 2002; Wolfe 1991, 2000). The shifts in diatom assemblages are characterized by a replacement of a mostly small benthic *Fragilaria* species (Douglas et al. 1994, 2000), or from no diatoms whatsoever (Doubleday et al. 1995), to a complex and diverse assemblage, representative of a well-developed littoral zone and/or an open-water habitat.

Climatic trends earlier than the last two centuries have also been recorded in arctic lake cores. An early Holocene warm period has been observed in a number of studies using various lines of evidence: pollen records from Ellesmere Island (Hyvarinen 1985), ice cores from the Agassiz Ice Cap (Fisher et al. 1995), paleoclimatic records from Queen Elizabeth Islands

(Bradley 1990) and pollen record from Somerset Island (Gajewski 1995). A gradual cooling in the mid-Holocene has been recorded, for example, on Ellesmere (peat deposits, Lafarge-England et al. 1991; fossil pollen records, Hyvarinen 1985; ice core, Fisher et al. 1995), and on Somerset (fossil pollen records, Gajewski 1993, 1995) Islands.

Despite the uncertainty regarding its inception, there appears to be a general agreement that a climatic deterioration occurred between 4000 and 1000 year B.P. (Ellesmere Island glacier advance, Blake 1989; diatom record on Ellesmere, Wolfe 2000; Smol 1983; fossil pollen record on Ellesmere, Hyvarinen 1985). In fact a climate transition at 4000 years B.P. has been observed in the sediment cores throughout the high latitude region (Cremer et al. 2001; Gajewski & Frappier 2001; Joynt III & Wolfe 2001; Smol & Cumming 2000; Wolfe 2000).

Aside from the recent warming trend, there is also evidence during the last 1000 years of several climatic oscillations including, the Medieval Warm Period (ca. 1000 to 700 years B.P.) and the Little Ice Age (ca. 550 to 150 years B.P.). In a review of available data (including tree-ring, ice core and documentary evidence), Hughes and Diaz (1994) show that the Medieval Warm Period had indeed occurred, although not globally nor at the same time interval in all regions. An additional review (including tree-ring, ice core, historical, oxygen isotope and pollen data) by Crowley and Lowery (2000) conclude that the Northern Hemisphere temperatures were ca. 0.2°C warmer than the Little Ice Age.

Crowley and Lowery (2000) suggest that Little Ice Age temperatures from the Northern Hemisphere records were about 0.45-0.50°C colder than the mid-20th century warm period. In northern Greenland, isotopic ($\delta^{18}O$) and chemical content from four ice cores reveal a climatic cooling from the 17th to the first half of the 19th century (Fischer et al. 1998). Also in Greenland, a lacustrine diatom record spanning the Holocene indicates cooler conditions during this period as assessed from the diatom floristic composition and productivity levels (Cremer et al. 2001). Elsewhere, in northern Quebec, high-resolution pollen diagrams detected this century-scale event in lake sediments (Gajewski 2000).

Therefore, paleoenvironmental reconstructions from diatom assemblages and other proxies may help to decipher past changes in climate or environment (Douglas & Smol 1999; Lotter et al. 1999, Wolfe 2000). However, these reconstructions are not without limitations. The lack of information regarding diatom ecology, the difficult identifications, and the conflicting life-form categories within the literature can obscure results (Battarbee et al. 2001; Dixit et al. 1992; Smol 1990). For instance, the extent to which species differ in their temperature optima and tolerances is not well known (Smol et al. 1991; Smol and Cumming 2000). Different studies show markedly different species responses to environmental variables even though species composition and the general environment are the same (Borchardt 1996; Kingston & Birks 1990). Factors other than nutrients, such as variations in depth, light, lake size, wind exposure and stability of summer stratification may be more important in determining species composition (Borchardt 1996; Douglas & Smol, 2000; Ruhland & Smol 2002; Schönfelder et al. 2002).

Multiple lines of evidence, such as magnetic susceptibility, organic content, pollen, sediment particle analysis, or various microfossils (chrysophyte cysts, cladocera, chironomids, etc.) may be used to support paleoenvironmental interpretations from diatom assemblages (Wolin & Duthie 1999).

CHAPTER TWO

2.0 Regional Setting

The Boothia Peninsula (Figure 1) is mainly composed of Precambrian Shield bedrock situated on a centrally located plateau with surrounding plains and lowlands of a mostly carbonate bedrock (Dyke 1984). The study site is located in the southwest region of the Peninsula at the middle arctic vegetation zone near the transition with the low arctic (Dyke 1984). The local landscape consists of *Dryas-Salix* tundra. Limnological properties recorded in the summer of 1998 are typical of an oligotrophic lake (Table 1). The lake is alkaline (pH 8.1) and is relatively dilute (specific conductance 220 µS/cm). Weather records from the region (Toloyoak, Pelly Bay, Shepherd Bay) show a similar climate. This region's climate is characterized by brief, cool, damp, summers and long, cold, dry winters (Atmospheric Environment Service, 1975 from Dyke 1984). Mean daily July temperatures for Taloyoak (latitude: 69.32°N; longitude: 93.31°W; altitude: 13 m) is 7.1°C and the mean total precipitation for the year is 153.4 mm (Maxwell 1982). Prevailing winds are from the south in the winter, the northeast in the spring and summer and from the northwest in the fall (Maxwell 1982).

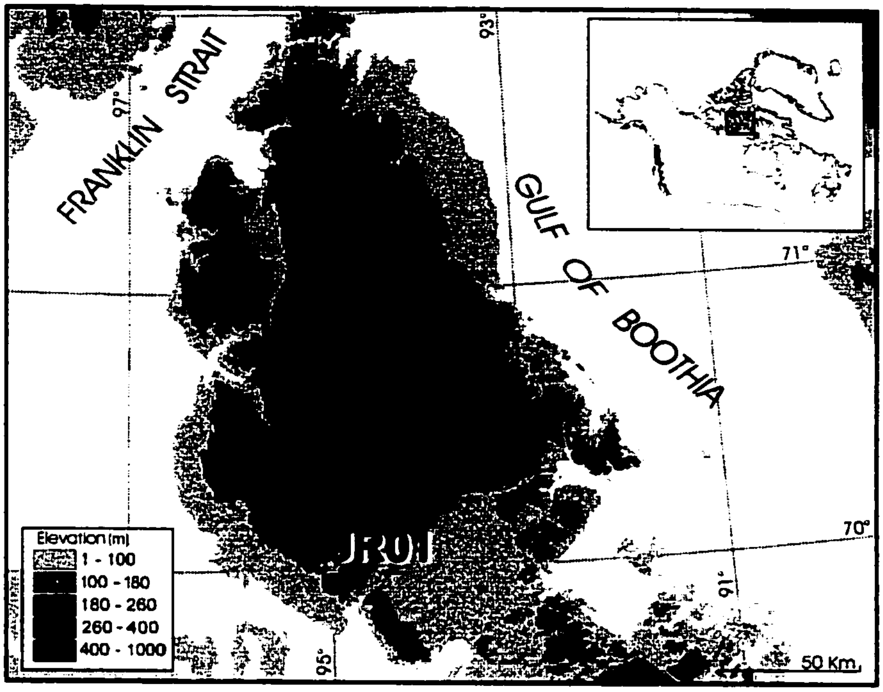


Figure 1: Location of lake JR01 on Boothia Peninsula, central mid Arctic, Nunavut. Canada.

Major Parameters	**Measurements with units**	**Major Parameters**	**Measurements with units**
Conductance	220	Total Dissolved Phosphorus (TDP)	0.01 mg l^{-1}
pH	8.1	Chlorine (Cl)	5.1 mg l^{-1}
Chlorophyll *a* (Chl *a* (unc))	0.44 µg l^{-1}	Silicate (SiO2)	1.21 mg l^{-1}
Particular Organic Carbon (POC)	0.07 mg l^{-1}	Sulfate (SO4)	2.40 mg l^{-1}
Dissolved Organic Carbon (DOC)	4.70 mg l^{-1}	Calcium (Ca)	42.40 mg l^{-1}
Dissolved Inorganic Carbon (DIC)	27.40 mg l^{-1}	Potassium (K)	0.56 mg l^{-1}
Total Kjeldahl Nitrogen (TKN)	0.81 mg l^{-1}	Sodium (Na)	2.11 mg l^{-1}
Particulate Nitrogen (PN)	0.01 mg l^{-1}	Aluminum (Al)	0.05 mg l^{-1}
Ammnonium (NH3)	0.05 mg l^{-1}	Iron (Fe)	0.03 mg l^{-1}
Total Phosphorus (TP)	0.04 mg l^{-1}	Magnesium (Mg)	21.70 mg l^{-1}
Particulate Phosphorus (PP)	0.03 mg l^{-1}	Manganese (Mn)	0.01 mg l^{-1}

Table 1: Some of the major chemical data sampled from lake JR01 (June 1999) (from Hamilton et al. 2001).

CHAPTER THREE

3.0 Field Methods

A small freshwater lake on the southern Boothia Peninsula, informally named JR01, was cored on June 24 1999 using a 5-cm diameter modified Livingstone square-rod sampler from the ice surface and in the deepest part of the lake. Two parallel series of cores were obtained reaching a depth of 5.2 m, unfortunately the base of the sediment was not reached due to a lack of driving rods. The uppermost sediment from Lake JR01 (Drives 0 and 5) was collected in a plastic tube fitted with a piston in order to ensure the retrieval of the sediment-water interface. Casing tubes were used to prevent the rods from bending when driving the sampler into the sediment.

The tubes containing the sediment-water interface were extruded back at the field basecamp. The tube was held vertically and the sediment was extruded at the top at every .5 cm for the first 20 cm. The remainder was wrapped in plastic wrap and aluminum foil, as were all other cores.

3.1 Laboratory Methods

The cores were stored at 4°C until analysis. In the summer of 2000, the cores were taken out of storage for a general description, measurement of magnetic susceptibility using a Barington MS2 meter (by Marie-Claude Roch, unpublished results on file at LPC) and for subsampling. The cores were always supported during the handling with black PVC tubes cut in half. The lengths of the drives were measured and the cores were carefully split in half. Each split core had the following labeling: the location of the top, the name of the core, and the drive number. The section of the drives not sampled were marked 'Archive' and returned to storage. General observations regarding the core's appearance, for instance organic zones, layering, stones, shells, and algae were noted. Colors were assigned using Munsell soil color charts.

Volumes of 0.3 cubic centimeter were retrieved at every 0.5 cm for the first 20 cm of the core and volumes of 1 cubic centimeter were retrieved at every 5 cm for the remainder of the core. Smaller values were used on the top 20 cm because less was available. An additional series of subsamples were extracted every 10 cm (excluding the uppermost 20 cm) for Loss-On-Ignition and Carbonate analysis (below). While subsampling, a liberal amount of distilled water was used to clean the equipment between each subsample.

3.2 Diatom Preparation

To determine the concentrations of diatoms in the subsampled sediment, the dry-weight must be calculated. To that end, the following weights were recorded: 1. initial vial weight; 2. weight of the scintillation vial with the 'wet' sediment; 3. weight of the scintillation vial and sediment after freeze-drying. The samples were always handled with tweezers. The vials were freeze-dried without their lids but covered with a tissue paper secured with an elastic band.

3.2.1 Processing

The diatoms were processed in their original vials. Carbonate was not removed by treatment with hydrochloric acid because the frustules could be enumerated satisfactorily under the light microscope without the treatment. The organic content was eliminated with a 1:1 mixture of nitric and sulphuric acid heated at high temperature with a Fisher Thermix Hotplate Model 600T. Approximately 5 ml of nitric/sulphuric acid was placed in the vials. The vials were then heated, 6 to 8 samples at a time, for approximately 25 minutes. The process was carefully supervised to prevent overflow. If the slurry appeared to boil too much, the vials were removed to cool temporarily and then returned to the hot plate. If the slurry did not change to a clear and 'whitish' color, the colors were noted. The samples were then left to cool.

The slurries were then transferred to labeled plastic Falcon® centrifuge tubes and filled to 45 ml with distilled water in order to dilute the acid solution. They were spun in the centrifuge for approximately 15 minutes. The water/acid mix was then siphoned off to the 5 ml mark. Deionized water was added again up to 45 ml for another round of centrifuging, and this was repeated five times. After the fifth rinse, samples were stored in deionized water until slides were made.

To make slides, each tube was first placed in the ultrasonic mixer for 4 minutes. The solutions were sonicated to ensure the separation of valves and to hamper valves lying in girdle views on the cover slips (Battarbee 1986). The cover slips were washed and rinsed with deionized water. The appropriate concentration was determined by diluting 1 ml of the original slurry with varying amounts of water and inspecting the solution on cover slips. Either 0.5 or 1 ml were pipetted from the solutions and deposited on the cover slips in a continuous and circular manner. The cover slips were then air-dried or heated on low temperature.

The amount derived from both the original sample and the subsample solution was marked on the receptacles. In order to retard evaporation, the vials were initially sealed with Parafilm but replaced after a couple months with a sealing tape employed by the Conservation Division of the Canadian Museum of Nature. Nonetheless, some evaporation did occur in some samples. In this event, a correction factor was applied by measuring the amount remaining after evaporation and prior to extraction.

As with the cover slips, the glass slides were washed and rinsed with deionized water. While the hot plate heated up to medium intensity, the slides were labeled. The slide was heated and a Hyrax® (20% Toluene) mounting medium with a high refractive index (1.56) was applied on top of the slide with a glass rod. The cover slip was placed deposit side down on the mounting substance with metal tweezers. After large bubbles formed and began to travel and disappear to the edge, the slide was removed from heat. It was important to have sufficient mounting substance and to not overheat the substance, otherwise it would change to a yellowish colour. Once removed from the hot plate, the cover slip was realigned. If bubbles were present, the cover slip was tapped a few times to eliminate them. Before observing the slide on the microscope, the excess hardened Hyrax was carefully scrapped with a razor blade to prevent damage to the microscope's objectives.

3.3 Diatom Enumeration and Calculations

For further study, 73 subsamples were systematically chosen along the length of the core. For each of the subsamples examined, at least 600 diatom valves were enumerated along one or more transects using oil immersion objectives with a 1000x magnification. Each valve was counted, including chains and complete frustules. All fragments that include the valve center were counted. Valves on the edge of the transect were included in the count if the center of the valve was positioned within the delineations of the transect. An eyepiece graticule was used to measure valve dimensions and to determine the transect width. Transects were either located randomly or 1/3 the distance from the edge of the diatom deposit. If additional transects were required, then transects from 2/3 of the width and in the middle of the deposit were used, respectively. If 600 diatoms were not counted by the end of the transect, then an additional whole or half - transect was counted to ensure a thorough floristic sample. This is especially necessary since the fluctuations of interesting or ecologically important taxa along the length of an arctic core may be obscured by the abundant occurrence of the common genus *Fragilaria* (Battarbee 1986).

Diatoms were identified using standard floras and regional treatments (Campeau et al 1999; Cumming et al. 1995; Fallu et al. 2000; Germain 1981; Krammer & Lange-Bertalot 1991a, b, 1997 a, b; Lange-Bertalot & Genkal 1999; Lange-Bertalot 2001; Patrick & Reimer 1975; Reavie & Smol 1998) to the lowest taxonomic level possible. Light photographs and scanning electron microscope (SEM) images were taken at the Natural Heritage Building of the Canadian Museum of Nature in order to confirm and document taxonomic identifications. Some species and varieties were combined and presented at the generic level because of their low percentage of occurrence (Anderson 1990) or uncertainties in identification. Results are presented both as relative diatom abundance (percentage), based on a sum of all halves counted in the sample, and as diatom concentrations per unit volume of sediment, based on the known quantities of sediment in the diluted slurries. Diatom concentration is expressed as the number of estimated valves of individual species per gram dry weight. Given the positive relationship between the total diatom concentrations (i.e. total number valves per gram dry weight of sediment) and the diatom floristic composition, diatom productivity is assumed to coincide with the total diatom concentraions (Battarbee et al. 2001).

The diatom concentration calculations (valves per gram dry weight) are computed as follows:

Total number of valves of species 'X' per gram dry weight =

$$\left(A * (B * C)/(D * (C * E)) * F/G * H/F * (I / G)/J\right) / K$$

Where,

A = Total number of species 'X' counted from all transects on cover slip
B = Measured width of diatom deposit on slide (mm)
C = Length of cover slip (mm)
D = # of transects
E = Width of transects (mm)
F = Total original volume (mL)
G = Subsample from original (mL)
H = Evaporated original (mL)
I = Total dilution (mL)
J = Final settled volume on slip (mL)
K = Sample dry weight (g)

Therefore,

(B * C) = Area of diatom deposit on cover slip
D * (C * E) = Total area counted for diatoms
(C * E) = Area of transect
F/G = Volume removed from original slurry
H/F = Evaporation correction factor (see explanation below)
I/G = Dilution volume

The following two corrections were applied for a more accurate representation of the number of diatom valves within the volume subsampled. First, the width of the actual diatom deposit was measured on the cover slip to account for the fewer diatoms present on the edge of the cover slip. The fewer diatoms along the margins of the cover slip were considered to be a non-random representation of valve quantity. Preferential sorting of various taxa during evaporation was minimal. Nonetheless the margins located on the top and bottom end of the slip were included in the count and could therefore account for any non-random representation of taxa. Therefore, this method takes into consideration the non-representative proportions of valve quantity and of various taxa. Second, some of the original volumes underwent minimal evaporation in spite of their sealed containers. The volumes were consequently measured and accounted for in the calculation (i.e. H/F).

3.4 Radiocarbon Dating

Chronological control was provided by five accelerator mass spectrometer (AMS) radiocarbon dates of aquatic macrofossils at various depths along the length of the core. The basal date was retrieved from the second series obtained and the cores correlated using magnetic susceptibility. The organic material was picked using a Leica WILD M3C microscope from 5 cm segments of the core that had been previously sieved. The samples were wrapped in Aluminum foil, labeled, weighed and sent to Beta Analytic Inc.

3.5 Loss-on-Ignition and Carbonate content

A series of porcelain crucibles were cleaned by lightly wiping the interior and weighed (CW). Plastic tweezers were used to handle the crucibles since the oil from the hands could alter the total weight of the crucible. One cubic centimetre of sediment was then placed in the crucible. The crucible was weighed once again (Fresh Weight; FW). The crucibles were then placed in the gravity oven overnight at 95°C. The samples were taken out and cooled to room temperature in a dessicator. The dry samples were weighed to obtain the Dry Weight (DW). The muffle furnace was preheated for a couple of hours to 550°C. The crucibles were then placed in the furnace for three hours. The samples were taken out and cooled to room temperature in a dessicator, and weighed for the Ignition Weight (IW). Next, the muffle furnace was again preheated for 3 hours to a temperature no less than 850°C. The samples were returned to the furnace for three hours, removed and allowed to cool to room temperature in a dessicator. The samples were then weighed for Carbonate Weight (CaW).

The following calculations were used to estimate organic and carbonate content:

$$\%\text{ Organic content} = \frac{(DW - CW) - (IW - CW)}{(DW - CW)} * 100$$

$$\%\text{ Carbonate content} = \frac{(IW - CW) - (CaW - CW)}{(IW - CW)} * 100$$

(methodology modified from Heiri et al. 2001).

CHAPTER FOUR

4.0 Sediment Stratigraphy

The 485 cm core consists of a relatively organic gyjjta that is homogeneous in colour with no rapid transitions. Many small organic fragments as well as shiny white particles were found throughout the core. The lower sediment seems to be less moist than the upper sediment though this may be an artifact of storage and wrapping.

Drive 0 (0 - 84 cm) - As mentioned in the methodology, 20 intervals of 0.5 cm from Drive 0 were extruded and bagged in the field. Two mollusc shells were found in Drive 0 at 20.8 cm and 57.5 cm from the surface, respectively. There was a higher concentration of organic detritus between 46 cm and 51 cm. The Munsell soil color chart was 2.5y 4/2.

Drive 1 (84 - 184cm) – A small white stone (~1-2 mm diameter) was found at 105.5 cm and a few light brown stones (~1-2 mm diameter) were found between 183 and 184 cm. There was a higher concentration of organic fragments between 98 and 101 cm, between 138 and 141.5 cm and between 156 and 157 cm. The Munsell soil color chart was 5Y 4/2.

Drive 2 (184 – 284cm) – Small white stones (~1-2 mm diameter) were found scattered throughout Drive 2. There was a higher concentration of organic fragments between 195 and 215 cm and between 271 and 275 cm. There was some light banding at the following intervals: 223-223.5 cm, 226-227 cm, 229.2-229.6 cm, 231.2-231.6 cm, 263.5-265 cm and darker banding at 236-237 cm and at 239-240 cm. There appeared to be an increase in plant fragments in this section. The Munsell soil color chart was 5Y 4/2.

Drive 3 (284 – 384 cm) - From 284 to 303 cm, layering and black fragments were not present. After 303 cm, there is a layering of light and dark bands. There was a higher concentration of organic fragments between 293 and 294 cm, between 299 and 301 cm, and between 349 and 350 cm. A blue-green algae, identified as *Nostoc*, was found at 360 cm. The Munsell soil color chart was 2.5Y 4/2.

Drive 4a (384 – 434 cm) - There was a higher concentration of organic fragments between 386.5 and 398 cm, between 414.5 and 146.5 cm and between 425.5 and 428.5 cm. As with Drive 3, Drive 4a has alternate light and dark layering. There was an orange powder (~2-3 mm thick) between 419 and 419.5 cm, which was speculated as being the remnants of a *Nostoc* mass (Paul Hamilton, personal communication). There were several plant fragments and small mollusc shells in this core. The Munsell soil color chart was 2.5y 4/2.

Drive 4b (434 - 484cm) - Drive 4b contained many organic fragments. As with Drive 4a, Drive 4b had numerous layers though the banding increases down the drive (esp. between 468-478 cm). There were no small white shells present. There was a higher concentration of organic fragments at 438 cm. The Munsell soil color chart was 2.5y 4/2.

4.1 Chronology

The five accelerator mass spectrometer (AMS) radiocarbon dates analyzed by Beta Analytic Inc. are presented in chronological order (Table 2). The samples, taken at different depths along the length of the core, consisted of aquatic macrofossils (Bryophytes) and plant detritus. Identification of the fragments by Linda Ley, aquatic plant specialist, Canadian Museum of Nature (personal communictation, Feb 2002) revealed at least 10 species of moss (Table 3). It should be noted that the basal date is retrieved from the second series and the diatom record only extends to 5800 yr. B.P. A cubic polynomial equation was applied to the radiocarbon dates to estimate an age/depth curve (Figure 2).

Lake	**Hole**	**Drive**	**Depth (cm)**	**Measured Radiocarbon Age (BP)**	**Conventional Radiocarbon Age (BP)**	**Material**	**Lab #**
JR01	1	0	30-35	1310 +/- 40	1290 +/- 40	Bryophytes, leaf and branch fragments	Beta - 156532
JR01	1	1	95-100	2460 +/- 40	2410 +/- 40	Bryophytes, leaf and branch fragments	Beta - 156533
JR01	1	2	220-225	4340 +/- 40	4290 +/- 40	Bryophytes, leaf and branch fragments	Beta - 156534
JR01	1	3	295-300	4930 +/- 40	4890 +/- 40	Bryophytes, leaf and branch fragments	Beta - 156535
JR01	3	10	544-549	6370 +/- 40	6320 +/- 40	Bryophytes, leaf and branch fragments	Beta - 156536

Table 2: Radiocarbon dates from the JR01 sediment core.

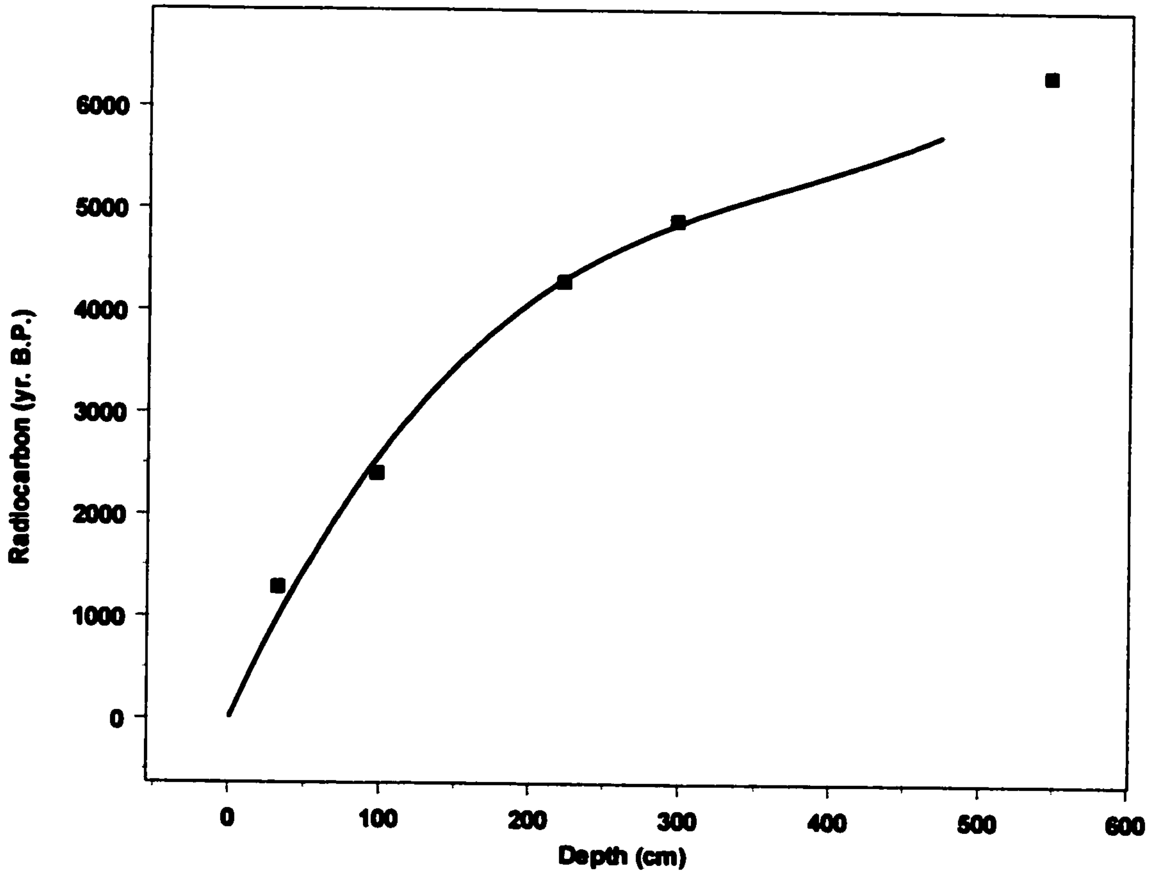


Figure 2: Age/Depth curve (cubic polynomial) derived from 5 AMS radiocarbon dates from the JR01 sediment core.

Depth (cm)	Leaf debris	*Bryum* sp.	*Calliergon giganteum*	*Ceratodon* sp. or *Ditrichum* sp.	*Ceratodon purpureus*	*Depranocladus* sp.	*Depranocladus* cf. *lycopodioides* var. *brevifolius*	*Depranocladus* cf. *revolvens*	*Dicranum* sp.	*Hypnum* sp.	*Scorpidium* sp.	*Tomenthypnum* sp.	Unknown
30-35	mostly leafless stem and branch fragments; some stems with leaves or leaf bases; some leaf fragments			√		√						cf.	√
95-100	mostly detached leaves and leaf fragments; a few short branch segments with and without leaves					√				√	cf.	cf.	
100-105	leafless stem fragments; stem/branch fragments with shredded leaves; detached entire leaves; leaf fragments		cf.				√	√			cf.		√
215-220	leafless stem fragments; leafy branch tips; detached entire leaves; leaf fragments		cf.				√				cf.	cf.	
220-225	mostly leaf fragments; a few detached entire leaves		√			√					√		
290-295	mostly stem fragments, with and without leaves				cf.		√				cf.		√
295-300	mostly detached leaves and leaf fragments; some leafless stem and branch fragments		√			2						cf.	√
373.5-378.5	mostly detached entire leaves and leaf fragments; some leafless branch fragments					√			√	cf	cf.		
475-480	mostly leaf fragments; some detached entire leaves; some stem fragments with leaves	1 stem fragment with a few leaves	cf.			√							√
Drive 10 52-57 Base of 2nd series	a few detached entire leaves and some leaf fragments					√							

Table 3: A preliminary list of bryophytes from the JR01 sediment core

4.2 Diatom Record

The sediments from lake JR01 provided a continuous record of abundant and well-preserved diatom data. One hundred and sixty-three species in 36 genera were identified (Table 6 in Chapter 5), most of which have been documented in the Canadian Arctic Archipelago (Hamilton et al. 1994).

In this thesis, *Fragilaria (sensu lato)* Lyngbye (1819) refers to the following genera: *Pseudoconstruens*, *Staurosira*, *Staurosirella*. These recently ascribed synonymies will be used to describe the individual species only. The *Fragilaria* species are present and prevalent throughout the entire core (Figure 3, 4). The diatom stratigraphy was divided into three zones discernible in both the relative percentage abundance diagram (Figure 3), the diatom concentrations (Figure 5), and the total diatom concentration diagrams (Figure 6).

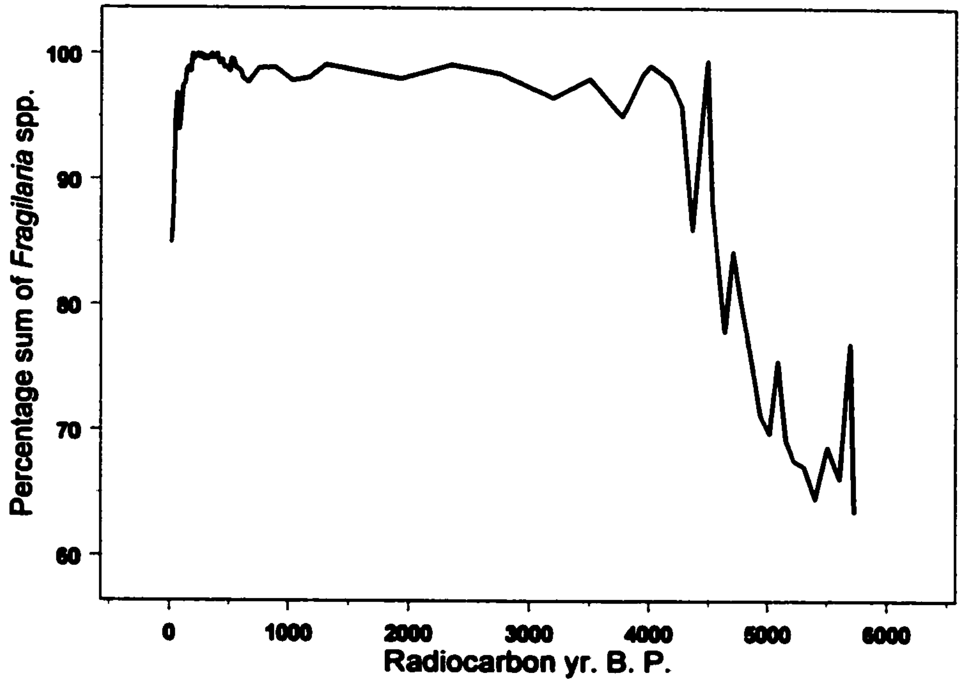


Fig 4: Relative abundance (%) of *Fragilaria* spp. in the JR01 sediment core.

Zone 1: (473 cm – 173 cm; 5730 to 4360 yrs. B.P.) Zone 1 has the highest species diversity. All of the 163 species enumerated in the core (Table 6) are present with the exception of the following species: *Achnanthes ziegleri*, *Amphora thumensis* and *Synedra parasitica*. *Fragilaria* spp. shows the lowest relative abundance values in the entire core (minima at 64%) (Figure 4). Percentages of the *Fragilaria* spp. irregularly increase from 5400 yr. B. P. (65%) to 4000 yr. B. P. (99%).

From 5030 to 5540 B. P. and from 4660 to 5080 B. P., the following species seem to occur together: *Psammothidium abundans* f. *rosenstockii*, *Achnanthidium minutissimum*, *Cymbella diluviana*, *Encyonema silesiaca*, *Denticula kuetzingii*, *Navicula* sp., *Navicula hustedtii* f. *obtusa*, *Nitzschia* spp., *Nitzschia bacillum*, *Nitzschia fonticola*, *Nitschia perminuta*, *Pseudostaurosira brevistriata*, *Pseudostaurosira pseudoconstruens* and *Staurosira construens* var. *venter* (Figure 3, 5)

Total diatom concentrations are the highest and the most variable in Zone 1 (Figure 6). Concentrations vary widely with mean concentrations greater than in the subsequent zones. With the exception of 5700 yr B.P., peak values are above 3 x 10^9 valves per gram dry weight (i.e. VGW).

Zone 2: (173 cm – 39 cm; 4360 to 1170 yrs. B.P.) Zone 2 has the least diverse diatom flora with only 23 species represented (Figure 3, 5). *Fragilaria* spp. is the most abundant within this zone and can comprise >95% of the valves (Figure 4). Other species encountered in this zone include *Rossithidium pusillum*, *Psammothidium abundans* f. *rosenstockii*, *Achnanthes ziegleri*, *Amphora* spp., *Amphora inariensis*, *Amphora pediculus*, *Amphora thumensis*, *Cocconeis* spp, *Cymbella hustedtii*, and *Synedra parasitica*. Several species appear in trace amounts: *Aneumastus tusculus*, *Cymbella* spp., *Encyonema minutum*, *Navicula* spp., *Navicula hustedtii* f. *obtusa*, *Navicula reinhardtii*, *Psammothidium marginulatum*. *Achnanthes ziegleri*, *Amphora thumensis*, and *Synedra parasitica* are mostly found in Zone 2.

In general, total diatom concentrations are the lowest (<10^9 valves/gram dry weight) and least variable in Zone 2 (Figure 6). Maximum values are above 2 x 10^9 valves per gram dry weight.

Zone 3 : (39 cm to surface; 1170 yrs. B.P. to present day) This zone was sampled at a higher resolution and is subdivided into three subzones (Figure 10, 11): **Zone 3A** (1170 to 660 yr. B.P.; 540 to 1210 yr. A.D.), **Zone 3B** (660 B.P. to 150 yr. B.P.; 1210 to 1830 yr. A.D.) and **Zone 3C** (150 yr. B.P. to present; 1830 yr. A.D. to present).

Zone 3A (1170 to 660 yrs. B.P.; 540 to 1210 yr. A.D.)

There is a slight increase in floristic diversity between 1170 yr. B. P. and 660 yr. B. P. (540 to 1210 yr. A.D.). The taxa present in Zone 3A are *Achnanthes* spp., *Amphora* sp., *Amphora inariensis*, *Amphora ovalis* var. *affinis*, *Amphora pediculus*, *Amphora thumensis*, *Achnanthes ziegleri*, *Pseudostaurosira pseudoconstruens*, *Pseudostaurosira brevistriata*, *Staurosira construens* complex, *Staurosirella pinnata* complex, and araphid frustules (Figure 10, 11). From 1030 yr. B.P. to 890 yr. B.P. (725 to 910 yr. A.D.), total diatom concentrations rise from 4.69 x 10^8 valves per gram dry weight (i.e.VGD) to 7.29 x 10^8 VGD (Figure 6). Values above 7 x 10^8 VGD are maintained until 660 yr. B.P. (1210 yr. A.D.) (Figure 6).

Zone 3B (660 to 180 yrs. B.P.; 1210 to1790 yrs. A.D.)

In general, from 660 yrs B. P. to 180 yr. B. P. (1210 to 1790 yr. A.D.), there is decrease in floristic composition and the usual subsequent increase in *Fragilaria* spp. The percent relative abundance values for *Fragilaria* spp. are high from 660 to 150 yr B. P. (1210 to 1830 yr. A.D.) (above 98%) and they dominate the diatom composition (Figure 4). For instance, between 445 and 180 yr. B.P. (1475 to 1790 yr. A.D.), the percent relative abundance values of the *Fragilaria* spp. do not fall below 99%.

This period is marked by smaller-scale fluctuations, especially noticeable in the concentration diagram (Figure 11). Between 530 and 260 yr. B.P. (1360 and 1700 yr. A.D.), the floristic composition is characterized by the following taxa: *Achnanthes* spp., *Amphora pediculus*, *Brachysira vitrea*, *Cymbella* spp., *Denticula* spp., *Navicula hustedtii* f. *obtusa*, *Nitzschia perminuta*, *Nitzschia frustulum*, *Psammothidium abundans* f. *rosenstockii*, and araphid frustules.

Between 660 and 490 yr. B.P. (1210 and 1420 yr. A.D.), total diatom concentrations are generally below 6.2 x 10^8 VGD (Figure 6). From ca. 490 to 240 yr. B.P. (1420 to 1720 yr. A.D.), total diatom concentrations increase and are above 8 x 10^8 VGD. From approximately 240 to 100 yr. B.P. (1720 to 1890 yr. A.D.), concentrations decrease and range between 2.69 to 6.60 x 10^8 VGD.

Zone 3C (150 yrs. B.P. to present; 1830 yrs. A.D. to present)

After 150 yr. B. P. (1830 yr. A.D.), a more diverse floristic composition, similar to Zone 1, begins to appear (Figure 10, 11). After 100 yr. B.P. (1890 yr. A.D.), the present day diatom composition is established. Several taxa other than *Fragilaria*, such as, *Navicula hustedtii* f. *obtusa*, *Cymbella* spp. and *Nitzschia* species, increase in concentration over the last 50 years B.P. (1940 years A.D.). Although a few raphid diatoms appear at 180 yr. B.P. (1790 yr. A.D.) (*N. vulpina*, *Neidium* spp., *Nitzschia* spp.), *N. vulpina* and *Neidium* spp., in particular, no longer appear in the diatom record after 150 yr. B.P. (1830 yr. A.D.).

All the taxa present in the last 180 years B.P. (1790 yr. A.D.) were found in the Zone 1 flora, although Zone 3C assemblage has a lower floristic composition. For instance, the following taxa are present in Zone 1 but not present in the last 150 years B.P. (1830 yr. A.D.): *Achanthes laevis*, *Amphora inariensis*, *Amphora pediculus*, *Brachysira* spp, *Caloneis* spp., *Cymbella designata*, *Cymbella diluviana*, *Cymbella incerta*, *Cymbella subaequalis*, *Gomphonema* spp., *Melosira* spp., *Navicula leptostriata*, *Psammothidium* cf. *bioretii* and *Sellaphora pupula*.

Total diatom concentrations generally increase, with average values of 9 x 10^8 VGD (Figure 6). Similarly, after 150 yr. B.P. (1830 yr. A.D.), relative percentage abundance of *Fragilaria* spp. fall below 98% and gradually decrease to present day values at 85% (Figure 4).

4.3 % Organic and % Carbonate content

The organic and carbonate contents generally show an inverse relationship along the length of the JR01 lake core (Figures 8, 9). Between 5800 and 5400 yr. B.P., organic content is generally above 28%. However, organic content rapidly increases from 5450 yr. to 5400 yr. B.P. from 31.5% to 38%. Loss-on-ignition values are maintained above 37% until 4800 yr. B.P. and reach maxima up to 42% between 5000 and 4800 yr. B.P.. Conversely, the carbonate content is low between 5800 and 4800 yr. B.P., between 4 and 10%. The negative relationship between carbonate and organic content is maintained from 5400 to 4800 yr. B.P. with carbonate having the lowest values of the entire JR01 lake core (e.g. values range between 4.04 and 5.29%) and organic matter having the highest values. From 4800 yr. B.P to 660 yr. B. P., the organic values decrease in tandem with an increase of carbonate values.

4.3 Magnetic Susceptibility

The highest magnetic susceptibility values are between 5700 and 5500 yr. B.P. (e.g. maximum 0.85) (Figure 7). From 5500 yr. B.P. until approximately 5250 yr. B.P., values decrease and become negative at 5400 yr. B.P.. The decreasing magnetic susceptibility values coincide with the increase in organic content and decrease in carbonate and mineral content. For the remainder of the core, values remain negative except for one peak between 3160 and 3125 yr. B.P.. Three unusually high values account for this peak, which is probably caused by a pebble. After the peak, magnetic susceptibility values are the lowest from approximately 3100 and 2400 years B. P.. Between 2400 to 2300 yr. B.P., values increase. The rapid increase in values do not appear to correspond with variations in the organic and carbonate content. This may be due in part to a difference in resolution. For instance, subsamples for the organic and carbonate content were taken at every 10 cm from the JR01 lake core, whereas the magnetic susceptibility values were read at every centimeter. From 2300 yr. B.P. to the end of the record at approximately 1090 yr. B.P., magnetic susceptibility values remained relatively stable ranging between –0.34 and –0.66.

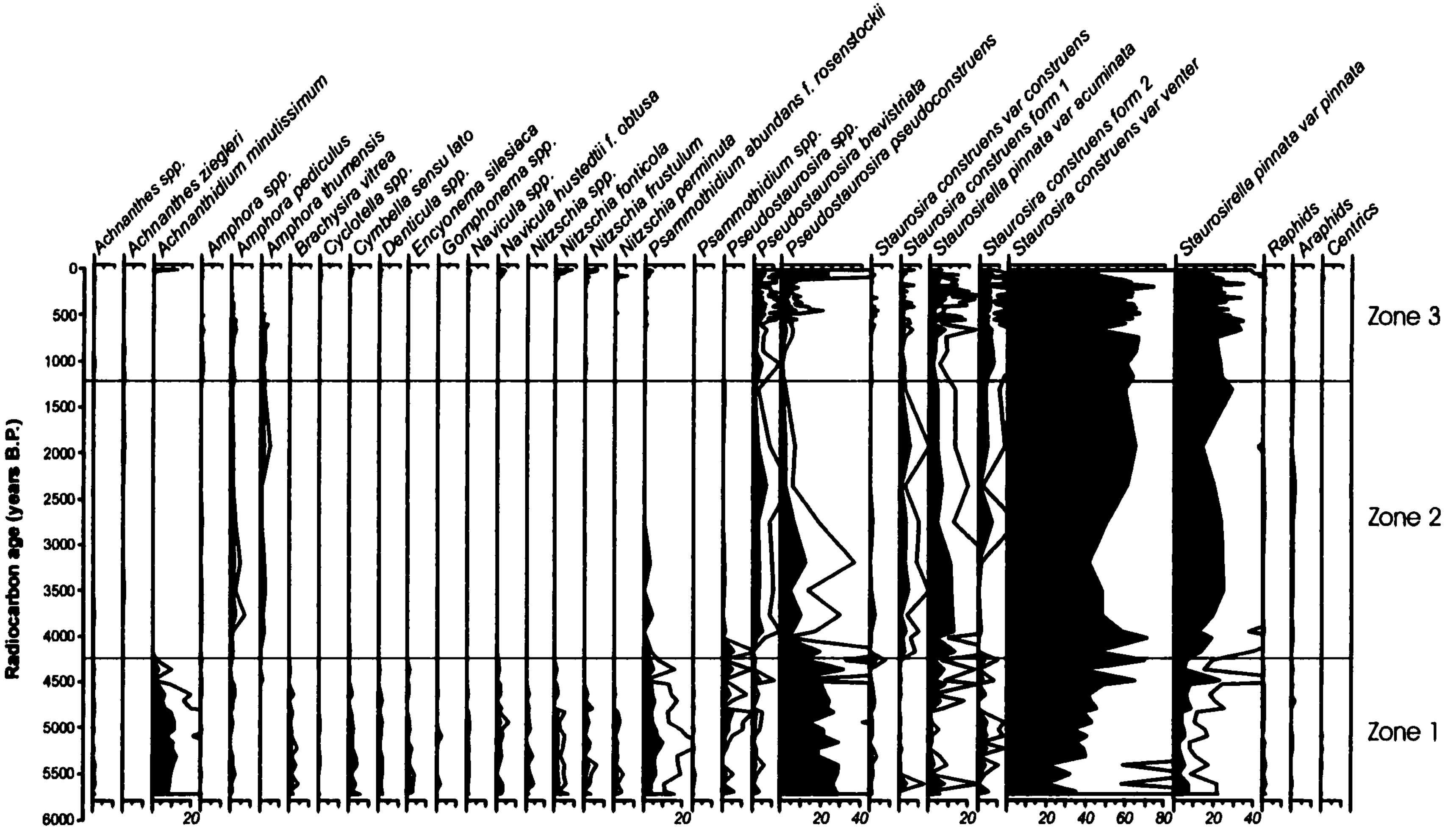


Figure 3: Relative abundance (%) of diatoms in the JR01 sediment core.

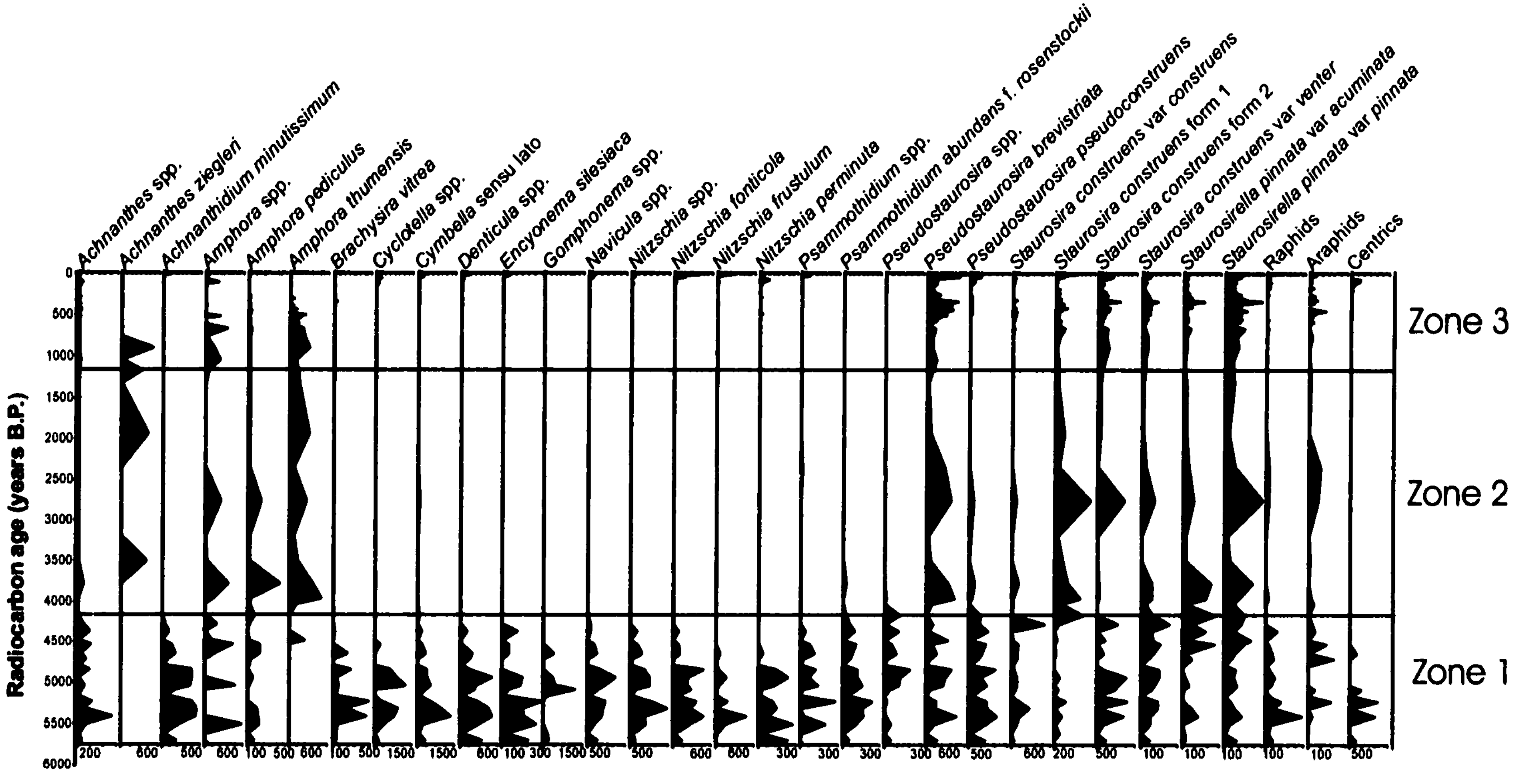
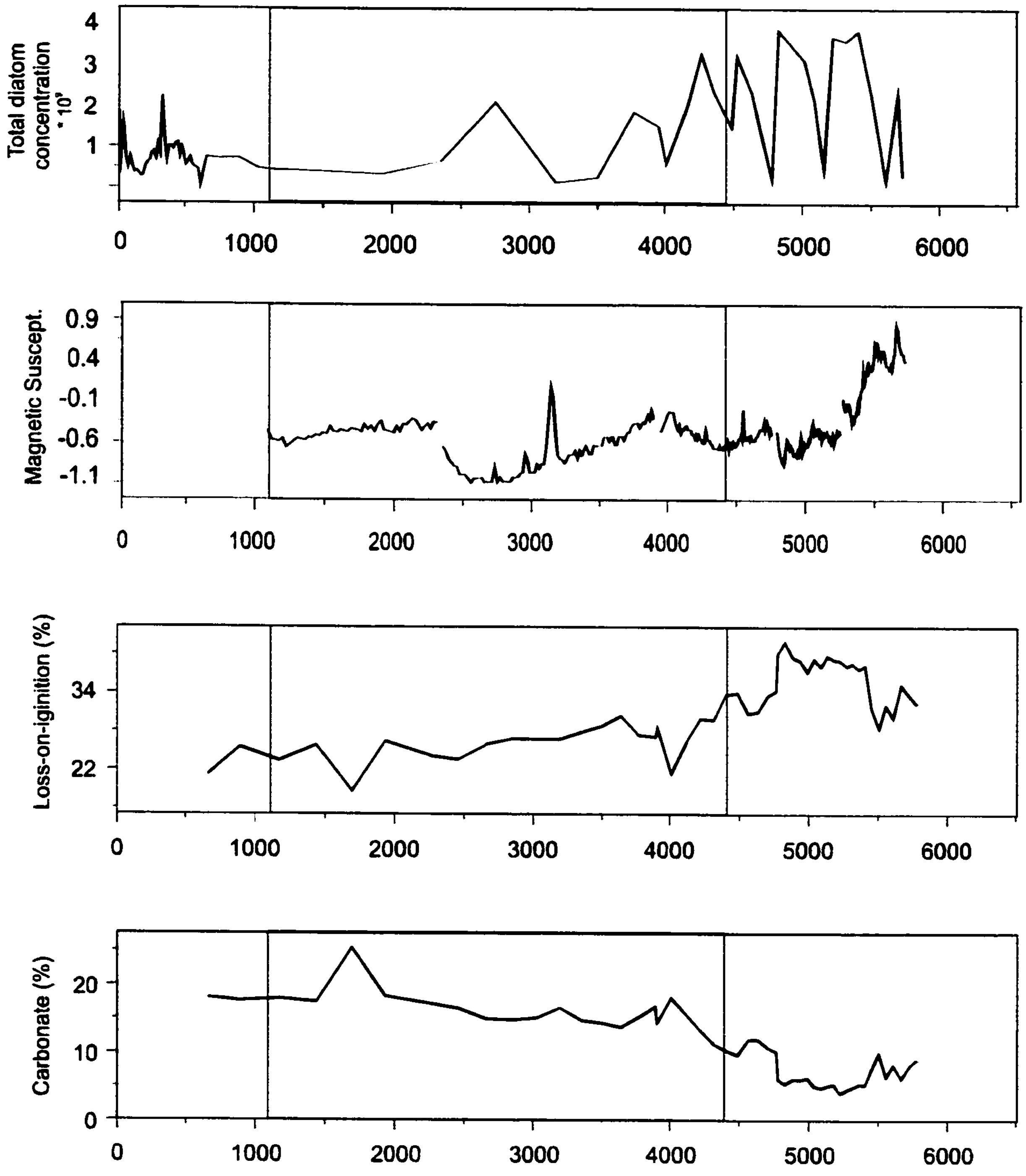


Figure 5: Diatom concentrations (valves/per gram dry weight) in the JR01 sediment core.



Figures 6-9: (from top to bottom) **Figure 6:** Total concentration (valves/per gram dry weight) of diatoms in the JR01 sediment core. **Figure 7:** Magnetic Susceptibility of the JR01 sediment core. **Figure 8:** Organic content (% loss-on-ignition) of the JR01 sediment core. **Figure 9:** Carbonate content (%) of the JR01 sediment core. Delineated zones are: **Zone 1** (ca. 5800 to 4360 yrs. B.P.), **Zone 2** (ca. 4360 to 1170 yrs. B.P.), **Zone 3** (ca. 1170 yrs. B.P. to present).

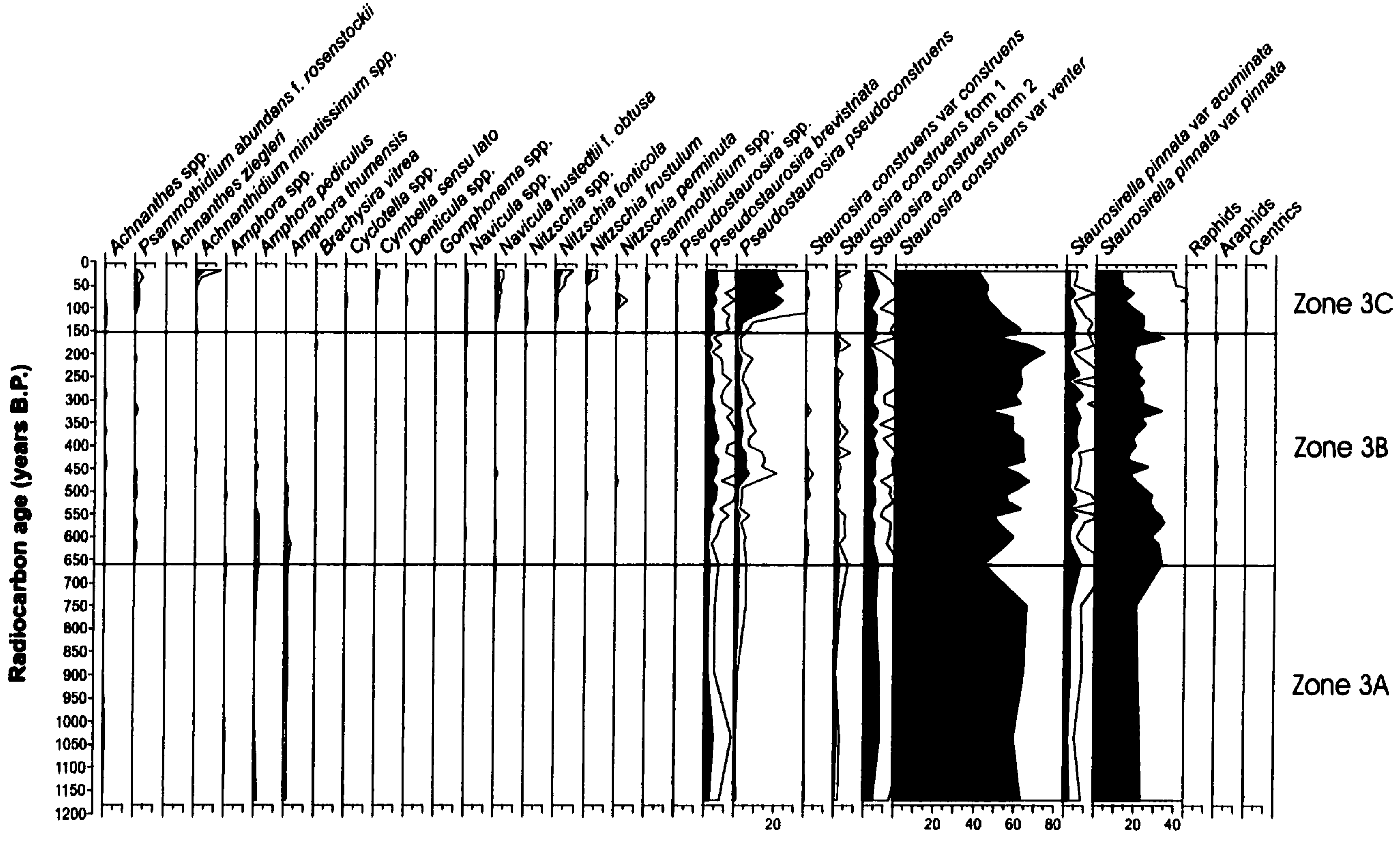


Figure 10: Relative abundance (%) of diatoms in Zone 3 of the JR01 sediment core.

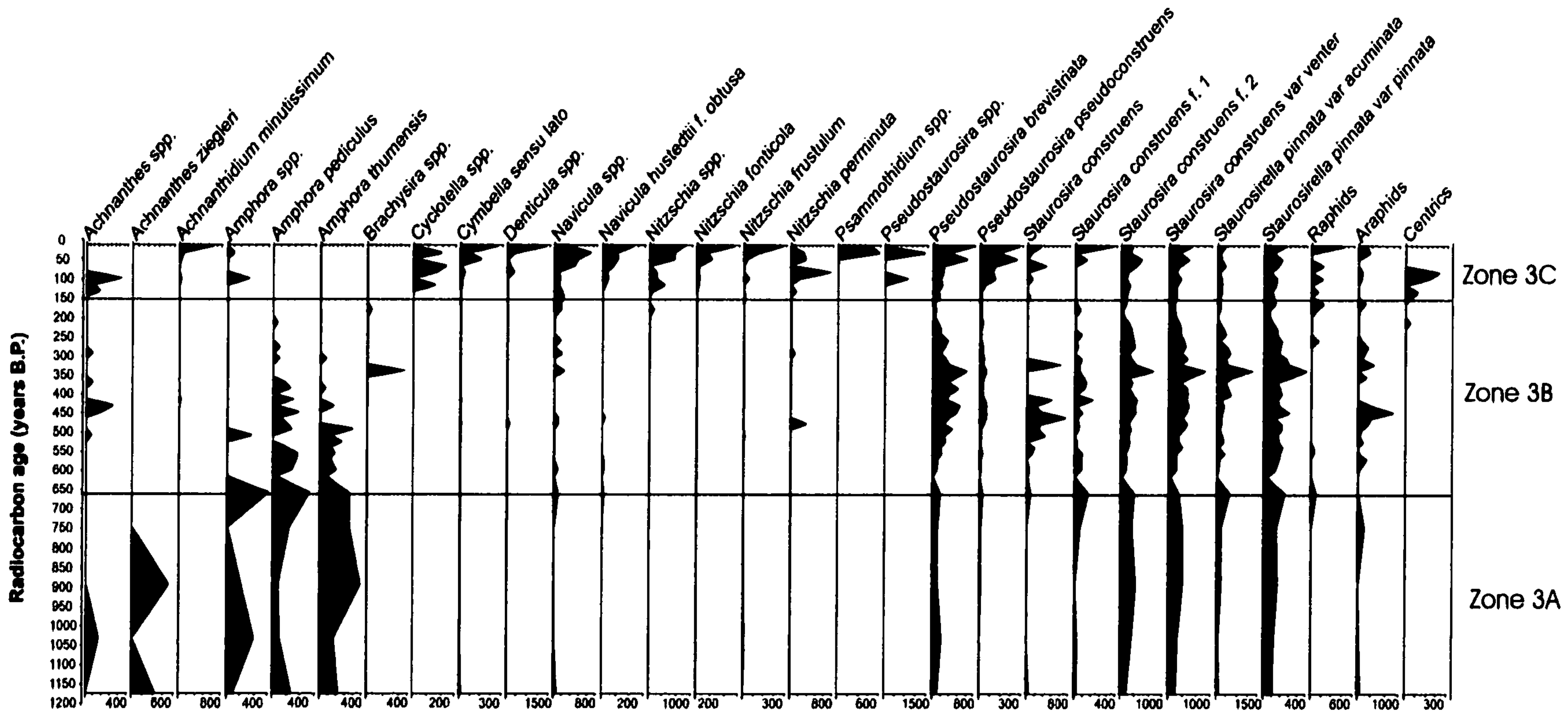


Figure 11: Diatom concentrations (valves/per gram dry weight) in Zone 3.

CHAPTER FIVE

5.0 Diatom identification

Diatoms were identified using standard floras (Germain 1981; Krammer & Lange-Bertalot 1991, 1997; Lange-Bertalot & Genkal 1999; Lange-Bertalot 2001; Patrick & Reimer 1975) and regional compilations (Campeau et al 1999; Cumming et al. 1995; Fallu et al 2000; Reavie and Smol 1998) to the lowest taxonomic level possible. One hundred and sixty-three species in 36 genera were identified (Table 4), most of which have been documented in the Canadian Arctic Archipelago (Hamilton et al. 1994). Light microscope (LM) photographs and Scanning electron microscope (SEM) images were taken in order to confirm and document taxonomic identifications. Although SEM images show some evidence of silica dissolution in samples from the JR01 sediment core, fine details could still be observed in the diatom frustules under LM. Plate 1 illustrates some of the diverse, well-preserved taxa found in the JR01 lake core. However, some genera presented particular identification problems under the LM: *Fragilaria* Lyngbye (*sensu lato*), *Nitzschia* Hasall and *Navicula* Bory de St.-Vincent.

Generally, two criteria best differentiate *Staurosira construens* (Ehrenberg) Williams & Round from *Staurosirella pinnata* (Ehrenberg) Williams and Round: the structure of the apical pore fields and the structure of the striae and areolae (Figures 12, 13). Other criteria such as the presence, shape and location of spines appear to be more difficult to use since the diagnostic characters are not always applicable nor can they be easily recognised under the LM (Figures 12, 13). The morphological diversity of the fragilarioid diagnostic characters can significantly frustrate identifications, thereby not only reducing the quality of the study but also comparison between studies. Several SEM images taken from the JR01 core demonstrate this morphological diversity (Plates 2, 3).

The fragilarioid diatoms in the JR01 core, namely *S. pinnata* and especially *S. construens*, resembled those illustrated and described by Morales (2001). In an extensive morphological study of fragilarioid diatoms retrieved from Connecticut waters, Morales (2001) provides a written synopsis of selected SEM features of freshwater *Fragilaria* Lyngbye (*sensu lato*) based on the information provided by Flower et al. (1996), Round et al. (1990), Williams and Round (1987) and Williams (1986). *Staurosira construens* is mainly described as having round or elliptical areolae, well developed apical pore fields composed of rimmed poroids, and spines of variable shape situated between the striae. In his study, Morales (2001) discusses a morphological character not previously described in the published literature, that is, the shape of the areolae. Aside from being round or elliptical, the shape of the areolae was found to be sometimes linear and wide, which could lead to it being missidentified as a *Staurosirella pinnata* under the LM. Frustules within the JR01 core resemble both the proper description provided above (Plate 2: 1-2) and the morphological variances (esp. shape of areolae) as described by Morales (2001) (Plate 2: 3-7).

On the other hand, *Staurosirella pinnata* is mainly described as having linear areolae, a well developed apical pore field composed of several rows of simple poroids (at least on one valve pole) and spines of intricate shapes located between the areolae. In addition, Morales (2001) observes: "... the structure (of the axial area) gives the impression that the areolae are single elliptical "holes" on the valve crossed by siliceous bars." Many frustules within the JR01 core resemble the above definition (Plate 3: 1-4), though there appears to be some differences.

Morales (2001) points out a couple of diagnostic traits from the *Staurosirella pinnata* form that are considered to be fundamentally different from *Staurosira construens*, that is, a narrower central sternum and profusely branched solid spines. Conversely, frustules found within the JR01 core can have a central sternum wider than that found in *S. construens* (Plate 3: 1) and the location or structure of spines may prove to be a fruitless diagnostic trait given their absence on some valves found in the JR01 core (Plate 3: 1-2, 4). In addition, some of the frustules within the core do not appear to have a well-developed apical pore field at either valve pole (Plate 3: 1), while others appear to show two parallel spines located between the striae (Figure 13, Plate 3: 3). As with *Staurosira construens*, there appear to be morphological variations within *Staurosirella* *pinnata*, though the most reliable trait appears to be the elliptical "holes" with the siliceous bars as described by Morales (2001). Frustules found to have the latter trait in the JR01 core were identified as *S. pinnata* despite the morphological variances noted above.

Therefore, fragilarioid specimens having morphological variance, such as *S. construens* and *S. pinnata*, can still be identified to the generic level because they retain a sufficient number of character traits belonging to either form. However, certain specimens proved to be difficult to identify since they appeared to share a mixture of character traits unique to both species. For example, frustules resembling Plate 3: 4, appear to be, on many accounts, *S. pinnata*, however the shape of the areolae appear to extend into the morphological range of *S. construens*.

Conversely, the JR01 diatom record contained several round frustules smaller than *S. construens* or *S. pinnata* (Plate 3:5-6). The areolae along the striae are few (1-3), fairly round and/or mishappen and relatively large. The areolae appear to especially resemble those found in the genus *Pseudostaurosira* (Grunow) Williams & Round (Plate 3:7). Identification to species was not possible.

A molecular study of the genus *Fragilaria* Lyngbye (*sensu lato*) is evidently required. It will be interesting to see whether or not molecular research will be able to substantiate the argument set forth by Lange-Bertalot (1989), that is, to retain the *construens* and *pinnata* taxa within one genus (Morales 2001).

It was also difficult to assign species names to certain *Navicula* Bory de St.-Vincent taxa. This is because the measurements offered in the literature to differentiate one species from another often overlap. For instance, similar dimensions are shared by two pairs of species which closely resemble each other: *Navicula vulpina* Kützing and *Navicula radiosa* Kützing, and *Navicula cryptocefalsa* Lange-Bertalot (synonym: *Navicula cryptocephala* Kützing) and *Navicula cryptotenella* Lange-Bertalot (Table 4).

Navicula species	Length (µm)	Width (µm)	Striae (/10µm)	Lineolae (/10µm)
Navicula vulpina	(50) 75-140	(10) 14-20	8-11	c.22
Navicula radiosa	40-120	8-12	10-12	c.28-32

(*Diatoms of Europe*, Lange-Bertalot 2001)

	Length (µm)	Width (µm)	Striae (/10µm)	Lineolae (/10µm)
Navicula cryptocefalsa	20-40	5-7	14-18	c.40
Navicula cryptotenella	12-40	5-7	14-16	c.38

(*Diatoms of Europe*, Lange-Bertalot 2001)

Table 4: Dimensions of two species pairs of *Navicula* Bory de St. Vincent.

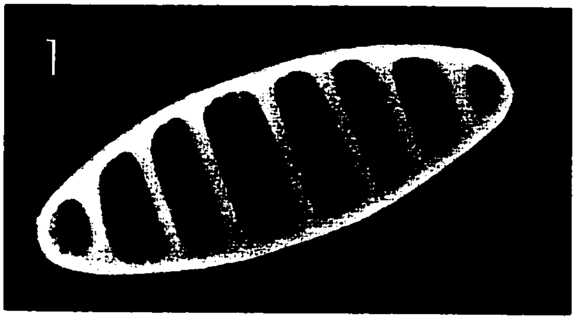
A similar problem was encountered with the following *Nitzschia* species: *N. frustulum*, *N. perminuta*, *N. lacuum*, *N. bacillum* and *N. fonticola* (Table 5). The general size and shape of the frustule (including the ends), the distribution of the fibulae (often related to the space taken by the central raphe endings), and the density of the striae were the main diagnostic traits used:

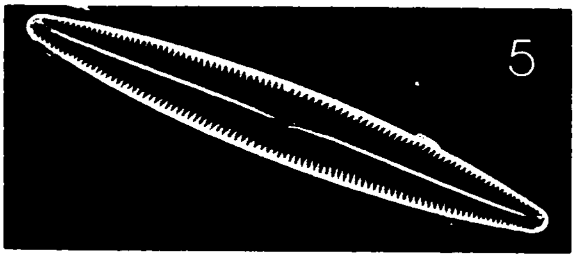
Nitzschia species	Fibulae distribution	Shape of frustule	Length (µm)	Width (µm)	Striae (/10µm)	Fibulae (/10µm)
N. frustulum	uneven	varied	5-60	2-4,5	19-30	10-16
N. lacuum	even	like an *N. bacillum* but ends more pinched	10-20	2-3	35-40 (density too high for LM)	13-18
N. bacillum	even	curved sides	12-20(24)	2-3.5(5)	27-32	12-16
N. perminuta	even	straight sides,ends capitate.	8-45	2,5-3	26-32(36)	10-16
N. fonticola	space in center	curved sides	10-65	2,5-5	23-33	9-16

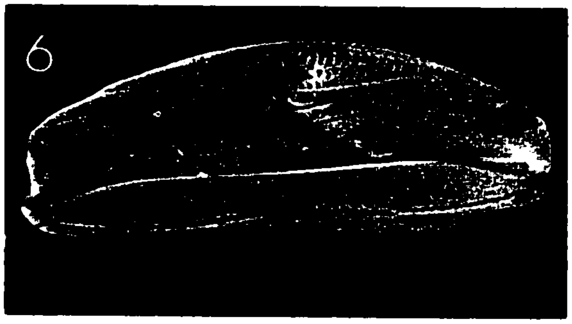
(Lange-Bertalot 1997; Fallu et al. 2000; Reavie & Smol 1998)

Table 5: Traits and dimensions used to distinguish five *Nitzshia* species.

LM identification of the *Nitzschia* species in the JR01 lake core was mainly based on information provided by Lange-Bertalot (1997), Fallu et al. (2000) and Reavie and Smol (1998).







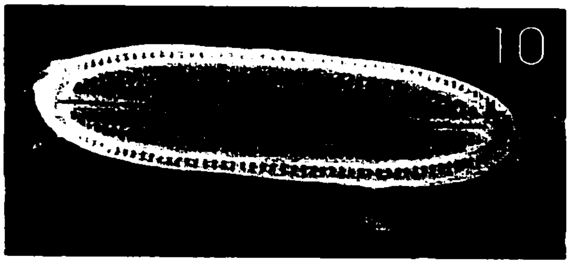


Plate 1: SEM images of diatoms from JR01 sediment core 1. *Denticula elegans* Kützing (L. 11.6, W. 4.36, Fib. 7/10 µm) (JRD4310.tif) 2. *Aneumastus tusculus* (Ehrenberg) Mann & Stickle (L. 53.3, W. 18.5, Str. 11/10 µm) (JRD4309.tif) 3. *Cymbella incerta* (Grunow) Cleve (L. 34.2, W. 7.91, Str. 15/10 µm) (JRD4306.tif) 4. *Brachysira vitrea* (Grunow) Ross (L. 19.1, W. 5.2, Str. 35/10µm) (JRD4307.tif) 5. *Navicula radiosa* Kützing (L. ca. 100, W. ca. 15, Str. 9/10µm) (JRD0501.tif) 6. *Amphora copulata* (Kutzing) Schoeman & Archibald (L. 48.6, W. 18.9, Str. 13/10 µm) (JR046512.tif) 7. *Nitzschia* cf. *perminuta* (Grunow) M. Perag. (L. 24.2, W. 4.58, Str. 22/10 µm) (JR046513.tif) 8. *Achnanthidium minutissimum* (Kützing) Czarn. (L. 14.7, W. 4.02, Str. 23/10 µm) (JR046515.tif) 9. *Psammothidium abundans* f. *rosenstockii* (Lange-Bertalot) Bukhtiyarova & Round (L.14.4, W. 4.73 µm, Str. 22/10 µm) (JR046517.tif) 10. *Brachysira* sp. (L. 17.5, W. 4.37, L. 19.8, W. 5.6, Str. 25/10 µm (outer edge) (JR04658.tif) 11. *Encyonema silesiacum* (Bleisch ex Rabeen.) Mann (L. 44.5, W. 11.1, Str. 12/10 µm) (JR04657.tif)

SEM diagnostic features
(*Staurosira construens* and *Staurosirella pinnata*)

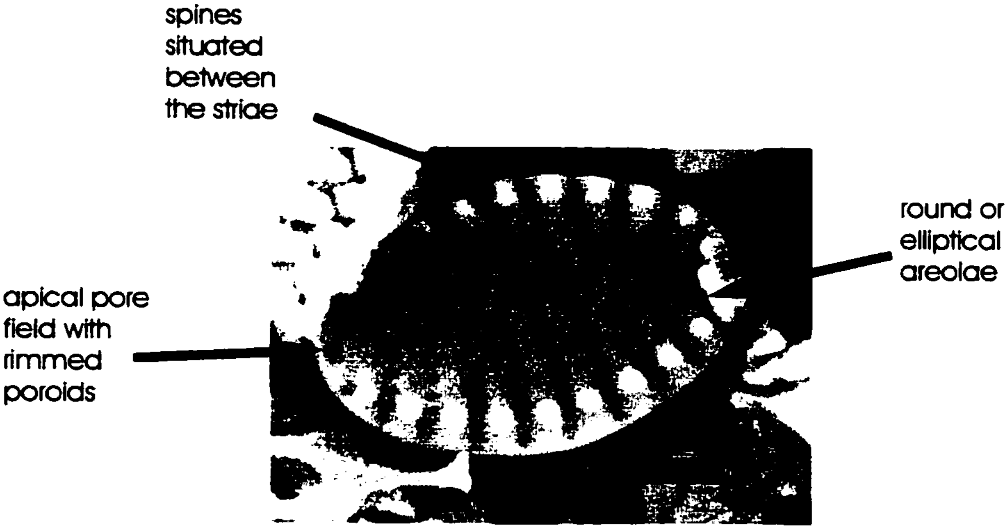


Figure 12: Diagnostic features used to identify *Staurosira construens* (Ehrenberg) P.B. Hamilton in Hamilton, Poulin, Charles & Angell as reviewed in Morales (2001) (Images : JR000013.tif)

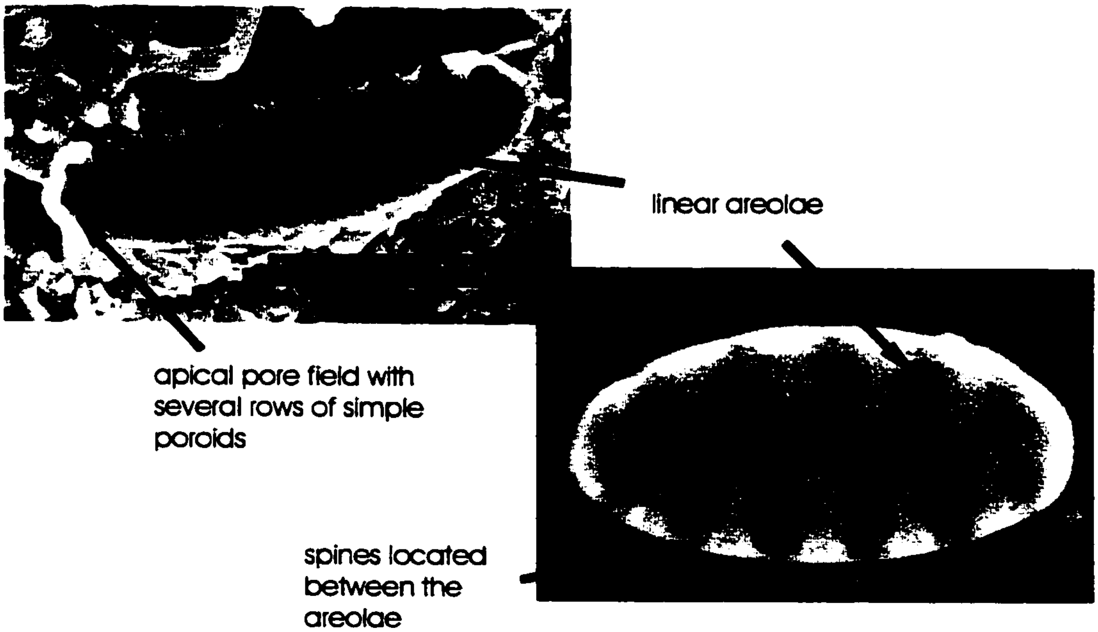


Figure 13: Diagnostic features used to identify *Staurosirella pinnata* (Ehrenberg) Williams & Round as reviewed in Morales (2001) (Images: JR0000017.tif; JR0000019.tif)

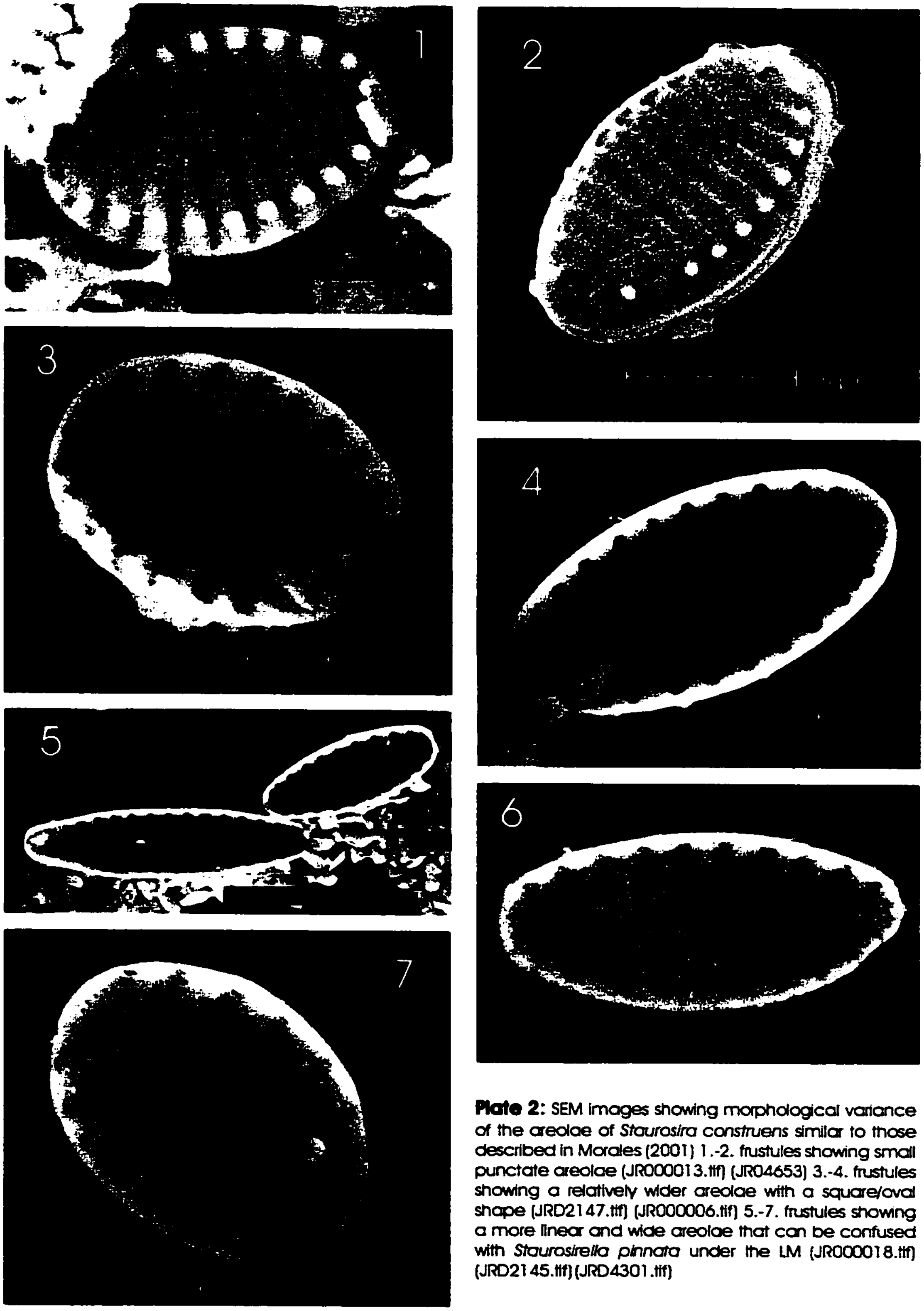
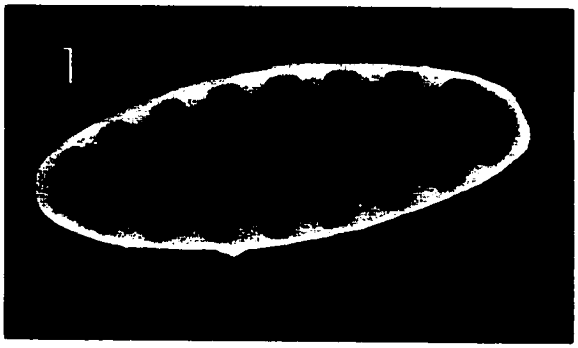
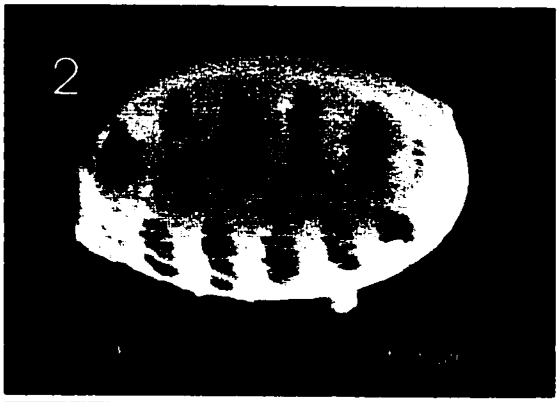
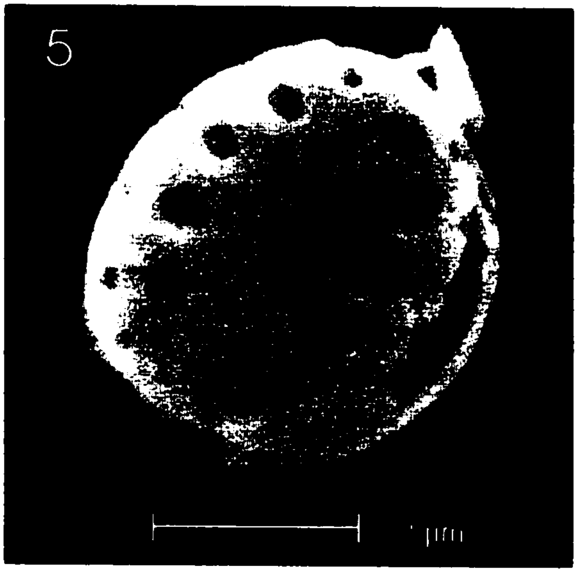
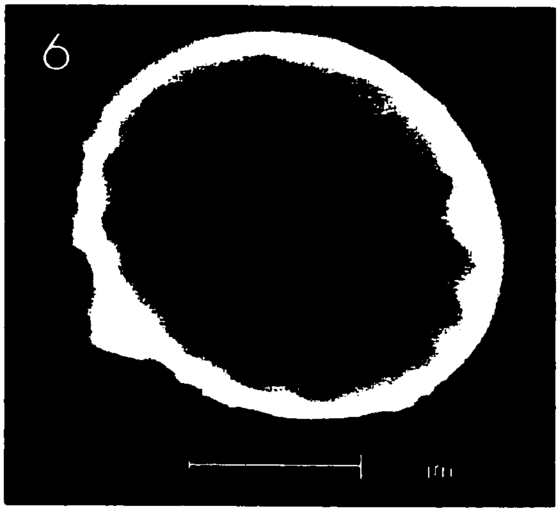


Plate 2: SEM images showing morphological variance of the areolae of *Staurosira construens* similar to those described in Morales (2001) 1.-2. frustules showing small punctate areolae (JR000013.tif) (JR04653) 3.-4. frustules showing a relatively wider areolae with a square/oval shape (JRD2147.tif) (JR000006.tif) 5.-7. frustules showing a more linear and wide areolae that can be confused with *Staurosirella pinnata* under the LM (JR000018.tif) (JRD2145.tif)(JRD4301.tif)









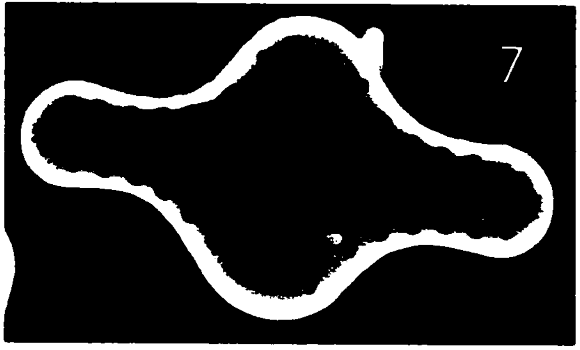


Plate 3: SEM images showing morphological variance of the fragilarioid species 1. Long, oval form of *Staurosirella pinnata* showing a wide axial area and an absence of spines (JR000011.tif) 2. smaller round form of *Staurosirella pinnata* showing a relatively more narrow axial area and an absence of spines (JR046516.tif) 3. *Staurosirella pinnata* showing two parallel spines between the striae (JRD2144.tif) 4. frustule resembling a hybrid between *Staurosirella pinnata* and *Staurosira construens* (JR046516.tif) 5.-6. *Pseudostaurosira* spp. showing the characteristic areolae with a wide range in shape commonly found with either *Pseudostaurosira brevistriata* or *Pseudostaurosira pseudoconstruens* (JR1D3737.tif) (JR1D3735.tif - interior valve view) 7. *Pseudostaurosira pseudoconstruens* showing characteristic striae structures (JRD4303.tif - interior valve view)

Table 6: Complete list of diatoms enumerated in the JR01 lake core.

Taxon Nomenclature	Synonym
Achnanthes sp. Bory de St.-Vincent	
Achnanthes ziegleri Lange-Bertalot	
Achnanthidium minutissimum (Kützing) Czarn.	*Achnanthes minutissima* Kützing
Amphora sp. Ehrenberg ex Kützing	
Amphora inariensis Krammer	
Amphora pediculus (Kützing) Grunow ex A. Schmidt	*Amphora ovalis* var. *pediculus* (Kützing) van Heurck
Amphora thumensis (Mayer) A.Cleve	
Ampiphleura sp. Kützing	
Aneumastus tusculus (Ehrenberg) D.G.Mann & Stickle in Round, Crawford & Mann	*Navicula tuscula* Ehrenberg
Aulacoseira sp. Thwaites	
Aulacoseira ambigua (Grunow) Simonsen	
Aulacoseira crenulata (Ehrenberg) Thwaites	*Gaillonela crenulata* ?
Aulacoseira distans (Ehrenberg) Simonsen	
Aulacoseira granulata (Ehrenberg) Simonsen	
Brachysira neoexilis (?)	
Brachysira vitrea (Grunow) Ross in Hartley	
Caloneis sp. Cleve	
Caloneis silicula (Ehrenberg) Cleve	
Caloneis tenuis (Gregory) Krammer	
Cocconeis sp. Ehrenberg	
Cocconeis neodiminuta Krammer	
Cocconeis neothumensis Krammer	
Cocconeis placentula Ehrenberg	
Cocconeis placentula var. *lineata* (Ehrenberg) Van Heurck	
Cocconeis placentula Ehrenberg	
Craticula cuspidata (Kützing) D.G.Mann in Round, Crawford & Mann	*Navicula cuspidata* (Kützing) Kützing
Craticula halophila (Grunow) D.G.Mann in Round, Crawford & Mann	*Navicula halophila* (Grunow) Cleve
Cyclotella sp. (Kützing) Brébisson	
Cyclotella antiqua W. Smith	
Cyclotella bodanica var. *lemanica* (O. Müller in Schröter) Bachmann	
Cyclotella glabriuscula (Grunow) Håkansson	
Cyclotella ocellata Pantocsek	
Cyclotella pseudostelligera Hustedt	
Cyclotella radiosa Grunow	
Cyclotella rossii (Grunow) Håkansson	

Cymbella sp. Agardh	
Cymbella affinis Kützing	
Cymbella alpina Grunow	
Cymbella amphicephala Naegeli	
Cymbella angustata (W. Smith) Cleve	
Cymbella arctica (Lagerstedt) Schmidt	
Cymbella cesatii (Rabenhorst) Grunow ex A.W.F.Schmidt	
Cymbella delicatula Kützing	
Cymbella descripta (Hustedt) Krammer & Lange-Bertalot	
Cymbella designata Krammer in Krammer & Lange-Bertalot	
Cymbella diluviana (Krasske) Florin	*Navicula diluviana* Krasske
Cymbella gaeumannii Meister	
Cymbella helvetica Kützing	
Cymbella hillardii Manguin	
Cymbella hustedtii Krasske	
Cymbella hybrida Grunow	
Cymbella incerta (Grunow) Cleve	
Cymbella incerta var. *crassipunctata* Krammer	
Cymbella cf. *latareolatum* (?)	
Cymbella mesiana Chonolky	
Cymbella microcephala Grunow	
Cymbella cf. *paucistriata* Cleve-Euler	
Cymbella reinhardtii Krammer	
Cymbella silesiaca Bleisch	
Cymbella subaequalis Grunow	
Cymbella turgidula Grunow	
Cymbella tumidula Grunow	
Denticula sp. Kützing	
Denticula elegans Kützing	
Denticula ketzingii Grunow	
Denticula tenuis Kützing	
Encyonopsis (nov.) spec. (?)	
Encyonema brehmii (Hustedt) D.G.Mann in Round, Crawford & Mann	*Cymbella brehmii* Hustedt
Encyonema gracile Rabenhorst	*Cymbella gracilis* (Rabenhorst) Cleve
Encyonema minutum (Hilse ex Rabenhorst) D.G.Mann in Round, Crawford & Mann	*Cymbella minuta* Hilse
Encyonema neomuelleri Krammer	
Eucocconeis flexella (Kützing) Cleve	*Achnanthes flexella* (Kützing) Brun.
Eunotia sp. Ehrenberg	
Eunotia bilunaris (Ehrenberg) Mills	
Eunotia exigua (Brébisson) Rabenhorst	

Epithemia sorex Kützing	
Epithemia sorex var. *gracilis* Hustedt	
Fragilaria sp. (Lyngbye)	
Fragilaria capucina Desmazières	
Fragilaria capucina var. *gracilis* (Oestrup) Hustedt	
Fragilaria cyclopum (Brutschy) Lange-Bertalot	
Fragilaria exigua Grunow	
Fragilaria fascilutata (Agardh) Lange-Bertalot	
Fragilaria parasitica (W. Smith) Grunow	
Gomphonema sp. Ehrenberg	
Gomphonema angustatum (Kützing) Rabenhorst	
Gomphonema parvulum (Kützing) Kützing	
Melosira sp. Agardh	
Navicula sp. Bory de St.-Vincent	
Navicula cf. *braetzii* (?)	
Navicula bryophila J.B.Peterson	
Navicula concentrica Carter	
Navicula cryptocefalsa Lange-Bertalot	*Navicula cryptocephala* Kützing
Navicula cryptotenella Lange-Bertalot	
Navicula densilineolata (Lange-Bertalot) Lange-Bertalot	
Navicula digitoradiata (Gregory) Ralfs in Pritchard	
Navicula explanata Hustedt	
Navicula helensis Schulz	
Navicula hustedtii f. *obtusa* (Hustedt) Hustedt	
Navicula impexa Hustedt	
Navicula minima Grunow	
Navicula molestiformis Hustedt	
Navicula leptostriata Joergensen	
Navicula perminuta (Grunow)	
Navicula pseudolanceolata Lange-Bertalot	
Navicula radiosa Kützing	
Navicula reinhardtii Grunow	
Navicula rhynchocephala Kützing	
Navicula riparia Hustedt	
Navicula soehrensis Krasske f. 1	
Navicula stroemii Hustedt	
Navicula submolesta Hustedt	
Navicula suchlandtii Hustedt	
Navicula trivialis Lange-Bertalot	
Navicula viridula (Kützing) Ehrenberg	
Navicula vulpina Kützing	
Neidium sp. Pfitzer	
Neidium affine (Ehrenberg) Pfitzer	

Neidium affine var. *longiceps* (Gregory) Cleve	
Neidium alpinum Hustedt	
Neidium ampliatum (Ehrenberg) Krammer in Krammer & Lange-Bert.	
Neidium iridis (Ehrenberg) Cleve	
Nitzschia sp. Hassall	
Nitzschia amphibia Grunow	
Nitzschia bacillum Hustedt	
Nitzschia fonticola Grunow	
Nitzschia frustulum (Kützing) Grunow	
Nitzschia inconspicua Grunow	
Nitzschia lacuum Lange-Bertalot	
Nitzschia perminuta (Grunow) M. Peragallo	
Pinnularia sp. Ehrenberg	
Pinnularia mesolepta (Ehrenberg) W.Smith	
Placoneis elginensis (Gregory) E.J.Cox	*Navicula elginensis* (Gregory) Ralfs
Psammothidium abundans f. *rosenstockii* (Lange-Bertalot) Bukhtiyarova & Round	*Achnantes rosenstockii* Lange-Bertalot
Psammothidium cf. *bioreti* (Germain) Bukhtiyarova & Round	*Achnanthes* cf. *bioreti* Germain
Psammothidium levanderi (Hustedt) Bukhtiyarova & Round	*Achnanthes levanderi* Hustedt
Psammothidium marginulatum (Grunow) Bukhtiyarova & Round	*Achnanthes marginulata* Grunow
Pseudostaurosira sp. (Grunow) D. M Williams & Round	
Pseudostaurosira brevistriata (Grunow in Van Heurck) D.M.Williams & Round	*Fragilaria brevistriata* Grunow in Van Heurck
Pseudostaurosira (Marciniak) D. M. Williams & Round *pseudoconstruens*	*Fragilaria pseudoconstruens* Marciniak
Reimeria sinuata (Gregory) Kociolek & Stoermer	*Cymbella sinuata* Gregory
Rossithidium pusillum (Grunow) Round & Bukhtiyarova	*Achnanthes pusillum* (Grunow) De Toni
Sellaphora pupula (Kützing) Mereschk.	*Navicula pupula* Kützing
Sellaphora vitabunda (Hustedt) D.G.Mann	*Navicula vitabunda* Hustedt
Stauroneis anceps f. *gracilis* Rabenhorst	
Stauroneis phoenicenteron (Nitzsch) Ehrenberg	
Staurosira construens Ehrenberg f. 1	*Fragilaria construens* (Ehrenberg) f. 1
Staurosira construens Ehrenberg f. 2	*Fragilaria construens* (Ehrenberg) f. 2
Staurosira construens var. *construens* (Ehrenberg) Grunow	*Fragilaria construens* (Ehrenberg) f. *construens*
Staurosira construens var. *venter* (Ehrenberg) Hamilton	*Fragilaria construens* var. *venter* (Ehrenberg) Grunow

Staurosira construens f. *subsalina* (Hustedt) Bukhtiyarova	*Fragilaria construens* var. *subsalina* Hustedt
Staurosirella lapponica (Grunow in Van Heurck) D.M.Williams & Round	*Fragilaria lapponica* Grunow
Staurosirella pinnata (Ehrenberg) D. M. Williams & Round (long form)	
Staurosirella pinnata (Ehrenberg) D. M. Williams & Round (short form)	
Staurosirella pinnata var. *acuminata* (Ehrenberg) D. M. Williams & Round	*Fragilaria pinnata* (Ehrenberg) var. *acuminata*
Tabellaria sp. Ehrenberg	
Tabellaria flocculosa (Roth) Kützing	*Conferva flocculosa* Roth

(Krammer & Lange-Bertalot 1991, 1997; retrieved (08/15/02) from the Integrated Taxonomic Information System (ITIS) on-line database http://www.itis.usda.gov.)

CHAPTER SIX

6.0 Discussion

The JR01 sediment core is divided into three segments. There is a more diverse diatom flora and higher productivity at the uppermost and lowermost section of the core. The central segment, between 4360 and 1170 yrs. B.P., is less productive, having fewer taxa and lower diatom concentrations. Three sections divide the uppermost sediments and consist of the Medieval Warm Period, the Little Ice Age, and the recent warming trend. Within this uppermost segment of the core, the high rate of sedimentation within the lake and the fine-interval sampling provide a high-resolution record. Other sedimentary evidence (e.g. magnetic susceptibility, carbonate and organic content) is essentially in agreement with the diatom record and provides information on the lake environment and surrounding catchment.

Climate variation identifed in the JR01 sediment core, such as an early Holocene warm period, Neoglacial cooling, and the Little Ice Age, are seen in other proxy-climate records. For example, the Neoglacial cooling, between approximately 4000 and 1000 yrs. B.P., and the recent warming trend have been generally reported in arctic and subarctic lake cores (Douglas et al. 1994, Gajewski et al. 1997, Ponader et al. 2002, Wolfe 2000, Smith 2002).

6.0.1 Comparisons between arctic lakes and ponds

This study will be comparing the data acquired from ponds on Cape Herschel, Ellesmere Island (Douglas & Smol 1995; Douglas et al. 2000) to the JR01 lake core. However, comparisons between lakes and ponds may be limited by their inherent differences. According to Sheath (1986), a pond may be distinguished from a lake by means of depth and ice thickness. A pond is defined as a shallow water body that freezes completely to the bottom in the winter, whereas a lake is sufficiently deep to allow water below the winter ice (Sheath 1986).

However, there are also similarities between the water bodies in the two regions. Many of the diatoms in the ponds on Ellesmere Island, as identified by Douglas & Smol (1995), are similar to those found in the JR01 diatom record, especially in the littoral habitats (Figure 3, 5).

Therefore, the ability to tolerate freezing and thawing processes, required by the diatoms living in ponds, may not be the sole reason for their presence in these shallow water bodies. However, changes in water chemistry, such as depletion in oxygen, may be a factor to consider.

6.1 Zone 1 – (ca. 5800 to 4360 yrs. B.P.) - Paleolimnological manifestations of climatic warmth

Warmer temperatures can cause higher levels of productivity within a lake for several reasons. Increasing lake water temperatures affect the rate of photosynthesis and therefore productivity. In addition, by reducing the length of ice cover, higher water temperatures prolong the growing season. This affects, in turn, photosynthetic production, successional development, and habitat availability (Smol & Cumming 2000). The diatom floristic composition (Figure 3, 5), the total diatom concentrations (Figure 6), and the high organic content of the sediment (Figure 8) point to a period of higher productivity caused by an amelioration in climate between ca. 5800 and 4360 years B.P..

The Zone 1 diatom assemblage is indicative of a more productive environment and of a well-developed littoral zone. This hypothesis is supported by the positive relationship between climate and microhabitat substrates and between microhabitat substrate and diatom composition (Douglas et al. 2000; Schönfelder et al. 2002). In arctic lakes especially, warmer temperatures can bring about increased growth of wetland and aquatic plants (e.g. bryophytes). When a lake environment becomes warmer and more nutrient rich, more diverse substrates are made available.

Microhabitat substrates, in turn, have been found to largely affect the composition of diatom assemblages. For instance, in a surface sediment study on Cape Herschel, east-central coast of Ellesmere Island, microhabitat accounted for 10.2 % of the total variance exhibited by the diatom species composition (Douglas et al. 2000). Schönfelder et al. (2002) also determined a relationship between diatom communities and microhabitat substrates in a study of lakes and rivers from northeastern Germany. In an ecological study on diatom assemblages from

Mackenzie Delta lakes, Northwest Territories, epiphytic species, such as *Gomphonema*, *Cocconeis* and *Encyonopsis*, were related to an increase in summer production (Hay et al. 2000).

Many stalked and tube-dwelling taxa such as, *Gomphonema*, *Cymbella* and *Encyonema* species, are present in the Zone 1 diatom assemblage (Figure 3, 5). Tychoplanktonic species, such as *Aulacoseira* sp., are also present (Ponader et al. 2002). The presence of aquatic plants provide a suitable habitat for not only epiphytic and tychoplanktonic species but also for epipelic taxa by damping out wind and wave activity in the littoral zone (Burgis & Morris 1987). In accordance with this hypothesis, diatoms common to rock, moss and sediment microhabitats in lakes on Cape Herschel, Ellesmere Island, were also present in Zone 1. Some of these taxa are *Achnanthidium minutissimum*, *Cymbella cesatii*, *Cymbella designata*, *Cymbella microcephala*, *Cymbella subaequalis*, *Denticula kuetzingii*, *Denticula tenuis*, *Navicula bryophila*, *Navicula radiosa*, *Navicula tuscula*, *Navicula vulpina*, and *Nitzschia frustulum* (Douglas & Smol 1995). Similarly, several studies have reported *Achnanthes minutissima* to be most prominent in littoral communities (Douglas & Smol 1993; Hamilton et al. 1994; Ludlam et al. 1996). Thus, the many moss epiphytes, epipelics, tychoplanktons in Zone 1 of the JR01 diatom record are indicative of a favourable climate and indicate the existence of a more complex habitat structure (Burgis & Morris 1987; Smol & Cumming 2000; DeNicola 1996; Douglas & Smol 1995, 1999).

In numerous ecological preference studies, certain diatom taxa are related to warmer, more nutrient-rich sites. Many of these taxa are common in Zone 1 (Figure 3, 5). For instance, in a Canonical Correspondance Analysis (CCA) plot, Rühland & Smol (2002) found that *Cocconeis placentula*, *Nitzschia* sp. (e.g. *N. fonticola*, *N. frustulum*, *N. perminuta*), *N. radiosa*, *N. crytocephala*, *N. cryptotenella* were more commonly found in boreal lakes. Conversely, *Achnanthes*, *Fragilaria*, *Gomphonema* and *Navicula* were found to characterize productive freshwaters (Goldsborough & Robinson 1996).

Two arctic diatom inference models, one on Baffin Island (Joynt III & Wolfe 2001) and the other on Bathurst Island (Lim et al. 2001), identified summer lake water temperature as a significant environmental control over diatom assemblages. Many of the taxa indicative of warmer water temperatures in these studies are also found in Zone 1 of the JR01 diatom record. For instance, the following taxa from the JR01 diatom record were found in the Baffin Island assemblages having summer lake water temperature optima above 7°C: *Cymbella cesatii, Sellaphora pupula, Cyclotella rossii, Stauroneis phoenicenteron, Cymbella angustata, Nitzschia perminuta, Achnanthes pusilla, Achnanthes minutissima, Cylotella stelligera, Brachysira vitrea, Navicula radiosa* var. *tenella, Achnanthes flexella,* and *Cyclotella bodanica* var. *lemanica.* Conversely, species that are present in Zone 1 of the JR01 lake core, such as, *Achnanthes flexella, Achnanthes laevis, Cymbella cesatii, Cymbella subaequalis, Denticula küetzingii, Denticula elegans* and *Nitzschia frustulum,* were found to be closely associated with higher temperature gradients and with increased levels of total nitrogen in an ecological diatom study on Bathurst Island (Lim et al. 2001). *Achnanthes flexella* and *Cymbella cesatii* may be considered as more reliable indicators of warmer water temperatures since both studies present a similar ecological preference for these particular taxa.

The high values of total diatom concentrations in Zone 1 (Figure 6) also indicate a period of warmth since a longer and warmer growing season not only influences the diatom floristic composition, or the organic content of the sediment, but can influence the rate of diatom valve production as well (Battarbee et al. 2001; Williams 1990). The interpretation of high productivity in Zone 1 assumes that the sedimentation rate is constant and that dissolution is not a determining influence. Dissolution is not a factor in this core because SEM images show only minor diatom dissolution down core. However, there are sharp fluctuations in total diatom concentrations in the lowermost sediments of the core. According to Battarbee et al. (2001), "sharp changes in diatom concentration are more likely to be the result of diatom preservation changes or changes in sediment accumulation rates rather than changes in production." However, errors in determination of diatom concentrations may also contribute to these sharp changes. Nonetheless, it is possible that the variable diatom concentrations are due to dilution of authochtonous sediments from a rapid inwashing of an allochtonous sediment source (Battarbee et al. 2001; Birks & Birks 1980). The higher influx of sediment may be derived from either soil erosion from a climate-induced destabilization of the terrain (Edlund & Alt 1989) or inwashing due to intense precipitation events (Paul Hamilton, personal communication).

Other studies in high latitude regions have reported a similar positive relationship between a warmer climate and diatom production. For instance, in a study on four small lakes on northeastern Ellesmere Island, Smith (2002) used variations in diatom abundances to reconstruct past changes in summer lake-ice covers. Smol (1983) recorded higher concentrations and accumulation rates of diatoms during warmer periods on Ellesmere Island, as did Blake et al. (1992) in Northwestern Greenland and Williams (1990a) on Baffin Island. Therefore the more diverse and productive flora and high organic values in Zone 1 of the JR01 lake core imply warmer temperatures in the middle Holocene, and the presence of epiphytic, epipelic, epilithic and tychoplanktonic species suggest a complex community with a well-developed littoral habitat (Douglas & Smol 1994, 1995; Ludlam et al., 1996; Smol & Cumming, 2000)

The diatom assemblage in Zone 1 of the JR01 lake core may also have been influenced by changes in pH. Zone 1 flora, such as *Caloneis bacillum* and *Brachysira vitrea*, appear to prefer circumneutral lake waters. Studies on Baffin Island (Joynt III & Wolfe 2000) and in the Ocala National Forest, Florida, U.S.A., (Shayler & Siver submitted) showed *Brachysira vitrea* to have a pH optima around 6.7 and 7.0, respectively. Similarly, *Caloneis bacillum* showed a pH optima around 6.5 on Baffin Island (Joynt & Wolfe 2000). These taxa are in agreement with the lowest carbonate values (i.e. between 4 and 10%, Figure 9) recorded in this section of the core. It should be noted that these circumneutral taxa do not appear in Zone 3C. This is likely due to the considerably higher carbonate values that occur after approximately 4000 yr. B.P. and are maintained up to the last carbonate estimate at ca. 600 yr. B.P. (ca. 1290 yr. A.D.)

The changes in magnetic susceptibility values in the early section of the core (Figure 7) prompt the development of several hypotheses regarding the JR01 lake ontogeny and the possible environmental changes that may have taken place in the late/mid Holocene. First, the high magnetic susceptibility values occurring before 5500 year B.P. may imply the presence of minerals that are typically found in high concentrations in the metamorphic rock of the Pre-Cambrian Shield (e.g. between 0.1 and 1μm^3 kg^{-1} in Dearing 1994; Moser et al. 1998).

Second, according to Battarbee et al. (2001), a positive relationship between magnetic susceptibility and total diatom concentrations may indicate an increased input of dissolved silica (SiO_2) with the enhanced clastic sedimentation (Figures 7, 6). This can increase diatom production and outweigh the diluting effects of sedimentation (Battarbee et al. 2001). This scenario is an agreement with the presence of *Aulacoseira* spp. and *Melosira* spp. during this period (Figures 3, 5). These centrics are highly silicified taxa that are generally recognized to flourish in waters that receive a high supply of silicon (Smol 1988; Wolfe 1994).

Third, the changes in magnetic suceptibillity and organic content point to an alteration of either vegetation or hydrology within the surrounding catchment between 5500 and 5400 yr. B.P. This alteration may be climate related since a climatic shift has been also recorded in millenial-scale climate studies (e.g. O'Brien et al. 1995; Viau et al. 2002).

Fourth, following a peak in organic content (42%) ca. 4800 years B.P., the organic content decreases in tandem with an increase in carbonates (Figures 8, 9). This change in sedimentation may also have been due to an alteration of the surrounding catchment (e.g. vegetation and hydrology). For example, the increase in carbonate content may have been due to the increased weathering of carbonate minerals from the surrounding carbonate bedrock or glacial till deposits (Hamilton et al. 2001; Moser et al. 1998; Pietnitz et al.1997; Wetzel 2000).

6.2 Zone 2 – (ca. 4360 to 1170 yrs. B.P.) – Neoglacial cooling

The shift in diatom composition to predominantly *Fragilaria* flora (Figures 3, 4), the reduction in diversity (Figures 5) and production (decrease in valve concentrations, Figure 6), and other sedimentary evidence (decrease in organic content, Figure 8) suggests a cooler climate in this region after approximately 4360 years B. P.. A climatic deterioration, between 4000 and

1000 years B.P. has also been recognized in several sediment and ice core studies from North America (Blake et al. 1992; Cremer et al. 2001; Douglas et al. 2000; Gajewski 1993, 1995; Lavoie & Payette 1996; O'Brien et al. 1995; Viau et al. 2002; Wolfe 2000).

The diatom flora between 4360 and 1170 years B.P. appears to be indicative of a low nutrient, highly alkaline, and cold environment. The species composition is reduced to a handful of taxa (Figure 5) and a predominance of *Fragilaria* spp. Lyngbye (*sensu lato*) (Figure 4), though the latter genus is present in large numbers throughout the core. *Fragilaria* (*sensu lato*) is a cosmopolitan genus with a wide environmental tolerance (Veres et al. 1995), thereby often outcompeting other taxa. A study on Baffin Island showed *Fragilaria brevistriata*, *Fragilaria pinnata*, *Staurosira construens*, *Staurosira construens* var. *venter* to prefer summer lake water temperatures below 6°C (Joynt III & Wolfe 2000). *Amphora pediculus*, another species prevalent in Zone 2, has also been associated with cooler conditions (T. Laing, unpublished data in Lotter et al. 1999).

Cocconeis spp., a taxon present in Zone 2, is also considered to be opportunistic with a broad tolerance of a number of environmental variables (Veres et al. 1995). As with *Fragilaria* spp., they are associated with alkaline environments (Joynt III & Wolfe 2000). These alkaline taxa indicators are in agreement with the increase in carbonate values (Figure 9).

The diatom flora and concentrations do not begin to change until approximately 450 years (ca. 4360 years B. P) after the increase in carbonate and the related decrease in organic values. A 'system crash' hypothesis described in Wetzel (2000) and a similar hypothesis described in Miller (1995) may explain the 450-year resilience of the diatom composition to the gradual changes in water chemistry, as would be expected from the changes in carbonate and organic content. Under this threshold effect model, populations would seem relatively stable until the carrying capacity of the system is exhausted. The whole system would then 'crash', resulting in abrupt changes until a new equilibrium is reached.

The limited floristic composition (Figure 3), the dominance of *Fragilaria* (Figure 4), and the decrease in valve production (Figure 6) within this zone are also likely indicative of an oligotrophic environment. Low diversity assemblages and a dominance of *Fragilaria* has been reported in surface-sediment assemblages and in postglacial sediment cores in lakes across arctic and subarctic regions (e.g. Northwest Territories, Pietnitz et al. 1995; Devon Island, Gajewski et al. 1997, King 1991, Sai & King 1999; Ellesmere Island, Douglas et al. 1994, 2000; Smith 2002; Swiss Alps, Lotter & Bigler 2000; Bathurst Island, Lim et al. 2001). These studies have reported a relationship between oligotrophy and diatom composition. This is in agreement with other species found within this period (Figures 3, 5), namely *Psammothidium abundans* f. *rosenstockii* and *Amphora inariensis*, which also suggest an oligotrophic environment (Dixit et al. 1992; Smith 2002).

Because of its affect on nutrient cycling, low water temperatures can partially explain the increase in oligotrophy in the diatom record. However, the increase in carbonate during this period may also have affected the cycling of nutrients in the lake. Nutrients are adsorbed by carbonate and through coprecipitation are removed from the trophogenic zone (Wetzel 2000). For example, in southern Michigan, a eutrophic hardwater lake experienced a similar decrease in productivity due to low temperature and the coprecipitation of phosphorus with $CaCO^3$ (Manny et al. 1978 in Wetzel 2000). Many studies in North America have determined carbonate to be responsible for the paucity of nutrients, both inorganic and organic, in the study lakes (DIC, Pietnitz & Smol 1993; DOC, Otsuki & Wetzel 1973 in Wetzel 2000; Phosphorus, Hamilton et al. 2001, Manny et al. 1978 in Wetzel 2000). Therefore, the deficiencies in the supply of nutrients may not only be due to a decrease from the surrounding catchment or a decrease in nutrient cycling but to a decrease in nutrient availability within the lake itself (Wetzel 2000).

Achnanthes zieglerii and *Amphora thumensis* are also of particular interest, since they mainly appear in this zone. These species, especially *A. zieglerii*, do not often appear in diatom records and based on the JR01 assemblages, seem to grow when others (even *Fragilaria* spp.) are less able. On the other hand, they may have been unable to grow in Zones 1 and 3 due to some limiting competitive factor. Also apparent in Zone 2 is the absence of certain life form categories (i.e. epiphytic and planktonic taxa) that are present in Zones 1 and 3. According to Smol (1988) and Prather & Hickman (2000), the absence of planktonic species is an indication of longer ice covers, shorter growing seasons and lower nutrients in the water column. This relationship has also been observed in a Siberian lake where Flower et al. (1998) related the abundance of centric diatoms to the length of the ice-free season.

6.3 Zone 3 – (ca. 1170 yrs B.P. to present)

The JR01 diatom record reveals smaller scale climatic shifts within the last ca. 1170 years B.P. where the temporal resolution of the sampling is greatly increased. These smaller scale climatic shifts are more evident in the diatom concentrations diagram (Figure 11) than in the relative abundance (%) diagram (Figure 10) of diatoms in Zone 3.

Enumerations were completed at every 0.5 cm up to 19.5 cm, which represents the last ca. 610 radiocarbon years B.P. (1270 years. A.D.). As a result, there is a sample within this period at approximately every 15 years. This can allow for interpretations based on known smaller-scale climatic shifts. Errors in radiocarbon dating, as well as the interpolations calculated from depth, necessitate a cautionary note with respect to the interpretations obtained from this particular diatom record. However, these fluctuations in diatom assemblages can be related to other high-resolution records from the Arctic (Overpeck et al. 1997; Fisher et al. 1998; Wolfe 2000).

In a review article, Smol and Cumming (2000) discuss two recent diatom-based studies: a diatom-inferred salinity study in Moon lake, North Dakota (Laird et al. 1996a, 1998b) and a multiproxy paleolimnological study of Lake Navaisha, Kenya (Verschuren et al. 2000). From high-resolution records, these studies were able to record centennial-scale climatic fluctuations in the late Holocene.

6.3.1 Zone 3A - Medieval Warm Period (ca.1170 to 660 yrs. B.P.; ca. 540 to 1210 yrs. A.D.)

The JR01 diatom record contributes to the existing body of knowledge on this period where there are widespread differences of opinion with respect to the timing and extent of the warmth (see Backman et al. 1999; Crowley & Lowery 2000; Hughes & Diaz 1994). In a review of individual records (including tree-ring, ice core, historical, oxygen isotope and pollen data), Crowley & Lowery (2000) show that the Medieval Warm Period temperatures were only 0.20°C warmer than the subsequent Little Ice Age (1580-1840 A.D.). Similarly, several pollen diagrams from the Northern Québec treeline show a decrease in spruce pollen production and transport beginning around 1000 yrs B.P. (Gajewski 2000).

The extent of the Medieval Warm Period, based on the floristic composition and production of diatoms in the JR01 sedimentary record, is also subtle (Figures 6, 10, 11). Although present, the increase in floristic diversity between 1170 and 660 yrs. B.P. (540 and 1210 yrs. A.D.) is slight (Figures 10, 11), which may be partially due to a lower-resolution sampling interval. For instance, many of the species distributed throughout Zone 2 (Figures 3, 5), seem to appear together in Zone 3A (Figures 10, 11). These diatom taxa are the following: *Achnanthes* spp., *Amphora* sp., *Amphora inariensis*, *Amphora ovalis* var. *affinis*, *Amphora pediculus*, *Amphora thumensis*, *Achnanthes ziegleri*, *Pseudostaurosira pseudoconstruens*, *Pseudostaurosira brevistriata*, *Staurosira construens* complex, *Staurosirella pinnata* complex, and araphid frustules. Diatom productivity, as reflected in total diatom concentrations, also shows a slight increase (Figure 6).

In their review of available data on the Medieval Warm Period, Hughes and Diaz (1994) and Crowley and Lowery (2000) use, among other records, ice core and pollen data but not, diatom records. The possibility of recording the MWP in high-resolution diatom records should be considered. For instance, diatom records other than from this present study may also have recorded the Medieval Warm Period in lakes from the Canadian Arctic (Joynt III & Wolfe 2001;

Wolfe 2000). In a paleotemperature reconstruction of the Fog Lake gravity core from Baffin Island, the Medieval Warm Period may be present. Diatom-inferred summer water temperatures reveal an increase of approximately 1.5°C between ca. 1125 and 900 yr. B.P. (Joynt III & Wolfe 2001). In addition, a 6500-yr diatom record on Solstice Lake, Ellesmere Island, may indicate a more diverse flora at approximately 1400 yr. B.P. (Wolfe 2000). The diatom floristic composition, which appears to be more diverse during this time, at least show that a warming occurred sometime before the LIA and sometime during the last 1500 years B.P. of the Neoglacial cooling. Evidently, studies at higher resolutions may better show this centennial scale climatic shift. In any case, it would appear that paleolimnological diatom records are able to record the same centennial-scale climate shifts interpreted in ice and ocean cores (see Overpeck et al. 1997).

6.3.2 Zone 3B - Little Ice Age (ca. 660 to 150 yrs. B.P.; ca. 1210 to 1830 yrs. A.D.)

Despite the ambiguous temporal delimitations (Gajewski 1993) within sedimentary records, it is generally agreed that the Little Ice Age, between approximately 1450 and 1850 AD, is a global-scale climatic fluctuation (Bradbury 1988; Grove 1988; Overpeck et al. 1997). Crowley and Lowery (2000) also suggested that Little Ice Age temperatures from the Northern Hemisphere records (e.g. tree-ring, ice core, historical, oxygen isotope, and pollen data) were about 0.45-0.50°C colder than the mid-20th century warm period (Crowley & Lowery 2000).

In general, a cooling trend can be inferred in the diatom flora of the JR01 core between approximately 660 and 150 yr. B.P. (1210 and 1830 yr. A.D.) (Figures 10, 11). This is evident by the change in flora from the previous zone (Zone 3A). From 660 yr. B. P. to 150 yr. B. P. (1210 and 1830 yr. A.D.), there is a decrease in floristic composition. As it is always the case, *Fragilaria* increases in abundance at this time (Figure 4). The percent relative abundance values for *Fragilaria* spp. are high from 660 to 150 yr. B. P. (1210 to 1830 yr. A.D.) (above 98%) and they dominate the entire diatom composition. Between 445 and 180 yr. B.P. (1475 and 1790 yr. A.D.), the percent relative abundance values of the *Fragilaria* spp. do not fall below 99%. Its predominance between 660 and 150 yr. B.P. (1210 and 1830 yr. A.D.) likely reflects a more severe climate, as recorded in other Arctic records. A high abundance of *Fragilaria* species during the Little Ice Age is observed in a sediment core from Hagelsewli lake in the Swiss Alps (Lotter & Bigler 2000), and from Col pond and Elison lake at Cape Herschel in east-central Ellesmere (Douglas et al. 1994, 2000).

However, the more diverse taxa assemblages within this cool interval, between 530 and and 260 yr. B.P. (1360 and 1700 yr. A.D.) reveals smaller-scale fluctuations, especially noticeable in the diatom concentration diagram (Figure 11). From 530 to 260 yr. B.P. (1360 and 1700 yr. A.D.) several taxa appear: *Achnanthes* spp., *Amphora pediculus*, *Brachysira vitrea*, *Cymbella* spp., *Denticula* spp., *Navicula hustedtii* f. *obtusa*, *Nitzschia perminuta*, *Nitzschia frustulum*, *Psammothidium abundans* f. *rosenstockii*, *Staurosira construens* and araphid frustules. Subtle changes in the diatom flora within this period follow a succession similar to other high-resolution paleoclimate records from the Arctic. In a compilation of paleoclimate records from arctic lake sediments, tree rings, glaciers and marine sediments (Overpeck et al. 1997), several records showed generally colder conditions in the arctic in the 17th-century and an increase in temperatures during the 18th century, although the timing and duration varied between regions. A varved sediment record from northern Ellesmere Island also showed a 17th century cooling (Lamoureux & Bradley 1996). However, a distinct climate cooling from the 17th to the first half of the 19th century was found in an isotopic and chemical analysis of four ice cores in northern Greenland (Fischer et al. 1998). Given the imprecision of the dating and the results of other paleoclimate records, it is not unreasonable that the JR01 diatom record may be reflecting this climate variability at a decadal scale. Additional high-resolution diatom diagrams are needed in order to verify the spatial and temporal extent of these changes.

6.3.3 Zone 3C – Climatic Warming (150 yrs. B.P. to present)

A gradual shift to a more diverse and productive flora in the last 150 years B.P. (1830 years A.D.) suggests a response to the recent warming trend. At approximately 150 years B.P.

(1830 years A.D.), the diatom flora shift to an assemblage closely resembling the Zone 1 assemblage (Figures 10, 11). After ca. 100 yr. B.P. (1890 yr. A.D.), the present day diatom composition is established. A few raphid diatoms appear at ca. 180 yr. B.P. (!790 yr. A.D.) (*N. vulpina*, *Neidium* spp., *Nitzschia* spp.), although *N. vulpina* and *Neidium* spp., in particular, no longer appear in the diatom record after 150 yr. B.P. (1830 yr. A.D.).

All the taxa present in the last 180 years B.P. (1790 years A.D.) can be found in the previous Zone 1 flora, however the Zone 3 assemblage is not as extensive in terms of floristic composition as in Zone 1. For instance, the following taxa are present in Zone 1 but not present in Zone 3: *Achnanthes laevis*, *Amphora inariensis*, *Amphora pediculus*, *Brachysira* spp, *Caloneis* spp., *Cymbella designata*, *Cymbella diluviana*, *Cymbella incerta*, *Cymbella subaequalis*, *Gomphonema* spp., *Melosira* spp., *Navicula leptostriata*, *Psammothidium* cf. *bioretii* and *Sellaphora pupula*. Along with the establishment of diverse taxa after 100 yr. B.P. (1890 yr. A.D.), total diatom concentrations (Figure 6) generally increase (Average 9.5 x 10^8 valves/cc). Several taxa other than *Fragilaria*, such as, *Navicula hustedtii* f. *obtusa*, *Cymbella* spp. and *Nitzschia* species, increase in concentration over the last 50 years B.P. (1940 years A.D.) Similarly, after 150 yr. B.P. (1830 yr. A.D.), percentages of *Fragilaria* spp. fall below 98% and gradually decrease to present-day values at 85%.

This shift to a more diverse and productive flora is not unlike many other paleolimnological studies which interpret a recent warming throughout the Arctic and the Subarctic regions in both North America and Europe (e.g. Douglas et al. 1994; Gajewski et al. 1997; Hughen et al. 2000; Overpeck et al. 1997). On Ellesmere Island, for example, an increased diversity and a shift to a more complex periphytic and epiphytic assemblage was observed in Ellison lake, Col pond and Camp pond cores and dated to early nineteenth century (Douglas et al. 1994, 2000). Diatom records from other lakes on Ellesmere (e.g. Bunting, Connell, Stewart) also reflect the recent warming in climate (Doubleday et al. 1995; Hamilton et al. 2000; Smith 2002; Wolfe 2000). Climate-related changes in the diatom and sedimentary record have also been observed in paleolimnological investigations on Devon (Gajewski et al. 1997), Bathurst (Lim et al. 2001), Baffin (Wolfe 1991; Joynt III & Wolfe 2001) and in northwestern Finnish Lapland (Sorvari & Korhola 1998). Although an increase in Arctic lake productivity in the last two centuries has been widely recognized in paleolimnological studies (Douglas et al. 2000; Gajewski et al. 1997; Overpeck et al. 1997), many questions remain with respect to the timing of its inception, its geographic extent and its degree of severity.

The recent changes in climatic conditions are due to anthropogenic factors, such as the increase in greenhouse gas concentrations especially after 1920, and partially due to non-anthropogenic factors, such as increased solar irradiance and decreased volcanic activity beginning in the mid-19th century (Overpeck et al. 1997). In order to determine the degree of influence of either factor, it is critical to determine the timing of the warming (Overpeck et al. 1997; Wolfe 2000).

Studies completed in different regions of the Arctic Archipelago provide various approximate chronologies for its inception (e.g. early 19thC, Douglas et al. 1994; last 125 yrs. B.P., Wolfe 2000; last 100 yrs, Bradley 1990; last 70 years, Gajewski et al. 1997). Wolfe & Perren (2001) and Gajewski et al. (1997) suggest that the changes initiated in the previous century have clearly intensified in the recent decades, which may contribute to this ambiguous time range. For example, from a study of annually-laminated sediments on Devon Island, Gajewski et al. (1997) suggest that a longer ice-free period or warmer summer temperatures occurred in the last 70 years as compared to the entire last century. These results coincide well with the reappearance of the Zone 1 diatom flora at ca. 150 years B.P. (ca. 1830 years. A.D.) in the JR01 diatom record and the firm establishment of all Zone 3C flora by ca. 100 years B.P. (ca. 1890 years A.D.) (Figure 10, 11). The increase in taxa other than *Fragilaria* within the last 50 years B.P. (1940 years A.D.) also appears to be in agreement with the annually-laminated sediments on Devon Island (Gajewski et al. 1997).

Certain studies (Douglas et al. 1994, 2000) have remarked on the unprecedented nature, both in terms of magnitude and abruptness, of the recent change in the arctic lake sediments on Ellesmere Island. However, diversity within the recent sediments (Zone 3C) of the JR01 core was surpassed earlier in the Holocene (Zone 1) (Figures 5, 11). For instance, there are at least 14 taxa that are present in Zone 1 but not in Zone 3C. In terms of degree of change, the abruptness from Zone 3B to Zone 3C appears to be comparable to the shift in the diatom record between Zone 1 and 2. It took approximately half of a century for a complete shift in composition to occur between Zone 3B and Zone 3C. Conversely, the shift to the Neoglacial cooling between Zone 1 and Zone 2 of the JR01 diatom record occurred within a span of approximately 90 years. This value might even have been smaller if the sampling resolution had been higher in this section of the core. Other Holocene diatom stratigraphies have also recorded three distinct diatom zones with a similar abrupt shift in climate (B.B. Wolfe et al. 1996; Pienitz et al. 1999; Wolfe 2000).

The less diverse floristic composition in Zone 3C as compared to Zone 1 of the JR01 core (Figures 5, 11) may be due to either one of two reasons. On the one hand, water quality, such as the differences in carbonate input between the two zones, may account for the differences found between the assemblages. On the other hand, the two zones may not be at the same phase with respect to responding to warmer temperatures. The diatom assemblage in Zone 1 may be a result of thousands of years of climate amelioration that had occurred earlier in the Holocene, whereas the current assemblage in the JR01 lake core may not be fully established. Global climate models predict a twenty-first century warming that is expected to exceed the thermal maximums reached in the mid-Holocene (Schindler 2001). It remains to be seen whether or not species diversity and production in the next centuries will indeed exceed those found earlier in the Holocene in the JR01 record (Zone 1).

The JR01 record from Boothia Peninsula and other records from across the Canadian arctic region contribute to our understanding of the recent climate warming. Many sites from the

Arctic Islands seem to show a widespread ecological response to global warming. However, some studies from Northern Quebec and Labrador apparently do not show a change in aquatic communities in the recent past. Chironomid (Fallu 2001) and diatom (Ponader et al. 2002) records appear to indicate a stable climate in recent history. However, studies of the vegetation also record this warming (Gajewski 2000). Tree-ring reconstructions from this region have identified ecological responses to the recent changes in climate (Payette & Delwaide 2000; Lescop-Sinclair & Payette 1995; Morin & Payette 1984), by an increase in the density of tree populations (Morin & Payette 1984; Payette & Filion 1985) or in the advancement in treeline along the coast of Hudson Bay (Lescop-Sinclair and Payette 1995).

Given these conflicting results, it is possible that the aquatic organisms within the lacustrine environment in Northern Québec may somehow not be responding to the recent change in climate. It should be noted that a Holocene diatom stratigraphy from Amarok Lake on Baffin Island had also not showed any evidence of climatic amelioration following the Little Ice Age (Wolfe 1994).

6.4 Suggestions for future research

The diverse taxa and the high number of species in the JR01 lake core, especially in Zone 1 and in the most recent diatom assemblage (Zone 3C), make it difficult to decipher which chemical or physical variable from the existing arctic and subarctic inference models (e.g. Wilson et al. 1996; Joynt III & Wolfe 2000; Lim et al. 2001) best represents the lake ecosystem through time. A modern analogue study is required within the central arctic region.

In addition, it is regrettable that the early Holocene period in the JR01 record was not retrieved. Despite the relatively unambiguous interpretations of early to mid Holocene warming in arctic studies, there appears to be some discrepancy regarding its inception and the timing of the maximum (Gajewski 1995; Gajewski et al. 2000; Hyvarinen 1985). A study of this period from other well-dated cores might serve to clarify this debate.

Fragilaria is prevalent within lakes throughout continental North America, the Arctic Archipelago and Europe (Douglas et al. 1994; Lotter & Bigler 2000; Smol 1988; Wolfe 1991). It especially dominates in cooler environments such as high latitude and high altitude lakes, which is also reflected in the lacustrine sediments down core. However, it is difficult to infer decisive environmental conditions based on the ecological knowledge from this taxon alone. They are also difficult to identify (Morales 2001; Wolfe 2000). Future research could focus on morphological variation within the genus, relating the varying morphology to environmental stress, on inter-species competition, and refining our present knowledge with respect to its ecology.

CHAPTER SEVEN

7.0 Summary

A 485 cm core from a lake unofficial called JR01, from Boothia Peninsula, central mid Arctic, Nunavut, Canada, yielded a high-resolution diatom record, which reflect the oscillations in climate from the early/mid Holocene to the present. One hundred and sixty-three species in 36 genera were identified, most of which have been documented in the Canadian Arctic Archipelago (Hamilton et al., 1994). Five radiocarbon dates provided the chronology.

Three distinct zones are reflected in the relative percentage abundance and diatom concentration diagrams for the core (5800 yrs. B.P.). A more diverse and productive flora implies warmer temperatures in the middle Holocene (ca. 5800 - 4360 yrs. B.P.), and the presence of epiphytic, epipelic, epilithic and tychoplanktonic species at this time suggests a complex community with a well-developed littoral habitat (Douglas & Smol 1994; Ludlam et al.1996; Smol & Cumming 2000). The presence of circumneutral taxa during this period is in agreement with the low carbonate content of the sediment. High magnetic susceptibility values and sharp fluctuations in total diatom concentrations indicate rapid inputs of allochtonous sediment from the surrounding catchment during this period. Shifts in magnetic susceptibility, organic and carbonate content during this period may also indicate shifts in either vegetation or hydrology from the surrounding catchment.

A complete shift in diatom composition to a predominantly *Fragilaria* flora and the reduction in diversity and production suggest a cooler climate in this region after approximately 4360 years B.P.. A climatic deterioration, between 4000 and 1000 yr. B.P. has also been recognized in several sediment and ice core studies from North America (Douglas et al. 1994; Gajewski 1995; O'Brien et al. 1995; Smith 2002; Viau et al. 2002; Wolfe 2000). The presence of alkaliphilous taxa, such as *Cocconeis* and *Fragilaria*, may also reflect the rapid increases in carbonate content. However, the assemblage shifted after approximately 450 years of increasing carbonate input. The oligotrophic environment as indicated by the presence of *Fragilaria*, *Psammothidium abundans* f. *rosenstockii* and *Amphora inariensis* may not only have been due to the colder water temperatures. Carbonate may also have hindered the cycling of nutrients by adsorbing organic and inorganic nutrients from the water and removing them from the trophogenic zone.

Smaller-scale climatic trends, such as the Little Ice Age (ca. 550-150 yr. B.P.) and the Medieval Warm Period (ca. 1000-700 yr. B.P.), appear to be reflected in the shifts of the JR01 diatom flora and production. As with the other paleoclimatic records (Crowley & Lowery 2000), the increase in floristic composition and diatom production is subtle. Nonetheless, the results of the JR01 lake core indicate that high-resolution paleolimnological diatom records may be able to record the same centennial-scale and decadal-scale climate shifts (e.g. MWP) that have been interpreted in ice and ocean cores, as well as from lake sediments (Gajewski 2000; Overpeck et al. 1997). However, these shifts must considered with caution on account of inherent errors in radiocarbon dating and extrapolations, as well as the subtle supporting diatom evidence.

Finally, a gradual shift to a more diverse and productive flora in the last 150 years B.P. (1830 years A.D.) suggests a response to the recent warming trend. Although an increase in Arctic lake productivity in the last two centuries has been widely recognized in paleolimnological studies (Douglas et al. 2000; Gajewski et al. 1997; Overpeck et al. 1997), many questions remain with respect to the timing of its inception, its geographic extent and its degree of severity. The results in the JR01 diatom stratigraphy coincide well with the hypothesis that changes have intensified from the previous century (Gajewski et al. 1997; Wolfe & Perren 2001). The absence of known circumneutral flora previously recorded in Zone 1 is an agreement with the increase in carbonate content. Within the JR01 diatom record, the floristic composition and total number of diatom concentrations are not as extensive as what is found in the early/mid Holocene (Zone1) of the JR01 core. Therefore within the JR01 diatom record, the recent change in climate appears have had a precedent in the early/mid Holocene warm period, although the current assemblage in the JR01 core may not, as of yet, be fully established. The JR01 sediment record is one of many records from the Arctic Islands that seem to be recording the global warming. However, conflicting results in Northern Québec between past vegetation records and aquatic organisms from lake sediments cast doubt on the sensitivity of aquatic organisms within this region to the recent change in climate. Suggestions for further research are to acquire a diatom inference model from the central arctic region, to obtain high-resolution lake cores for the entire Holocene and to clarify the morphological and ecological variations in *Fragilaria*.

References

Anderson, N.J. 1990. Variability of sediment diatom assemblages in an upland, wind-stressed lake (Loch Fleet, Galloway, SW Scotland) *Journal of Paleolimnology* 4:43-59.

Andreev, A.A. & Klimanov, V.A. 2000. Quantitative Holocene climatic reconstruction from Arctic Russia. *Journal of Paleolimnolog.* 24:81-91.

Atkinson, D.E. 2000. *Topoclimatic modeling of summer surface air temperature in the Canadian Arctic Archipelago.* Department of Geography. Theses (Ph.D). Ottawa: University of Ottawa.

Bachman, J., Karlén, W., Källén, E., and Rodhe, H. 1999. Man-made versus natural climate change. *Ambio*. 28:376-377.

Battarbee, R.W. 1986a. Diatom analysis. *In* Berglund, B.E. [Ed.] *Handbook of Holocene Palaeoecology and Palaeeohydrolog.* Wiley: Chichester:527-570.

Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., Juggins, S. 2001. Diatoms. *In* Smol, J.P., Birks, H.J.B., Last, W.M. [Eds.] *Tracking Envrionmental Change Using Lake Sediments : Terrestrial, Algal and Siliceous Indicators*. Kluwer Academic Publishers : Maine, pp.155-202.

Birks, H.J.B, & Birks, H.H. 1980. *Quaternary palaeoecology* London: E. Arnold Publications.

Blake, W. Jr. 1989. Inferences concerning climatic change from a deeply frozen lake on Rundfjeld, Ellesmere Island, Arctic Canada. *Journal of Paleolimnology* 2:41-54.

Blake, W., Boucherle, M.M., Fredskild, B., Janssens, J.A., & Smol, J.P. 1992. The geomorphological setting, glacial history and Holocene development of Kap Inglefield Soslah;, Inglefield Land, north-west Greenland. *Meddel. Grønl. Geosci.* 27:1-42.

Blom, T., Korrhola, A., Weckström, J., Laing, T., Snyder, J., MacDonald, G., & Smol, J. 2000. Physical and chemical characterization of small subarctic headwater lakes in Finnish Lapland and the Kola Peninsula.*Verh. Internat. Verein. Limnol.* 27 :316-320.

Borchardt, M.A. 1996. Nutrients. *In* Stevenson, J.R., Bothwell, M.L., Lowe, R.L. [Eds.] *Algal Ecology: freshwater benthic ecosystems.* Academic Press, San Diego, pp. 183-221.

Bourgeois, J.C., Koerner, R., Gajewski, K. & Fisher, D. 2000. A Holocene ice core pollen record from Ellesmere Island, Nunavut, Canada. *Quaternary Research* 54:275-283.

Bradbury, J.P. 1986. Late Pleistocene and Holocene paleolimnology of two mountain lakes in western Tasmania. *Palaios* 1:381-8.

Bradbury, J.P. 1988. A climatic-limnologic model of diatom succession for paleolimnological interpretation of varved sediments at Elk Lake, Minnesota. *Journal of Paleolimnology* 1:115-131.

Bradley, R. 1990. Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian High Arctic. *Quaternary Science Reviews* 9:365-384.

Brown, K.M., Douglas, M.S.V. & Smol, J.P. 1994. Siliceous microfossils in a Holocene, high arctic peat deposit (Nordwestö, northwestern Greenland). *Canadian Journal of Botany* 72:208-16.

Burgis, M.J. & Morris, P. 1987. *The Natural History of Lakes*. New York: Cambridge University Press.

Campeau, S., Pienitz, R., & Héquette, A. 1999. *Diatoms from the Beaufort Sea coast, southern Arctic Ocean (Canada).* Bibliotheca Diamotologica, Band 42. Stuttgart: J. Cramer.

Cremer, H., Melles, M. & Wagner, B. 2001. Holocene climate changes reflected in a diatom succession from Basaltsø, East Greenland. *Canadian Journal of Botany.* 79: 649-656.

Crowley, T.J., & Lowery, T.S. 2000. How warm was the Medieval Warm Period? *Ambio* 29(1):51-54.

Cumming, B.F., Wilson, S.E., Hall, R.I. & Smol, J.P. 1995. *Diatoms from Lakes in British Columbia (Canada) and Their Relationship to Lakewater Salinity, Nutrients and Other Limnological Variables.* Bibliotheca Diatomologica. Vol. 31. Stuttgart: J. Cramer.

Dearing, J. 1994. *Environmental Magnetic Susceptibility: Using the Bartington MS2 System.* Kentworth: Chi Publishing.

Denicola, D.M. 1996. Periphyton responses to temperature at different ecological levels. *In* Stevenson, J.R., Bothwell, M.L., Lowe, R.L. [Eds.] *Algal Ecology: freshwater benthic ecosystems.* San Diego: Academic Press. pp.149-181.

Dixit, S.S., Smol, J.P., Kingston, J.C. & Charles, D.F. 1992. Diatoms: powerful indicators of environmental change. *Environmental Science and Technology* 26:22-33.

Doubleday, N.C., Douglas, M.S.V. & Smol, J.P. 1995. Paleoenvironmental perspectives on black carbon deposition in the high Arctic. *Sci. Total Environ.* 160/161:661-8.

Douglas, M.S.V., & Smol, J.P. 1993. Freshwater diatoms from high arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.). *Nova Hedwigia* 57(3-4):511-552.

Douglas, M.S.V. & Smol, J.P. 1995. Paleolimnological significance of observed distribution patterns of chrysophyte cysts in arctic pond environments. *Journal of Paleolimnology* 13:79-83.

Douglas, M.S.V. & Smol, J.P. 1995b. Periphytic diatom assemblages from high Arctic ponds. *Journal of Phycology* 31:60-69.

Douglas, M.S.V. & Smol, J. P. 1999. Freshwater diatoms as indicators of environmental change in the High Arctic. *In* Stoermer, E.F. & Smol, J. P. [Eds.] *The Diatoms: Applications for the Environmental and Earth Sciences.* Cambridge University Press, Cambridge, pp. 227-44.

Douglas, M.S.V. & Smol, J. P. 2000. Eutrophication and recovery in the High Arctic: Meretta Lake (Cornwallis Island, Nunavut, Canada) revisited. *Hydrobiologia* 431:193-204.

Douglas, M.S.V., Smol, J.P., & Blake, W. Jr. 1994. Marked post-18th century environmental change in high-arctic ecosystems. *Science* 266: 416-419.

Douglas, M.S.V., Smol, J.P., & Blake, W. Jr. 2000. Summary of paleolimnological investigations of High Arctic ponds at Cape Herschel, east-central Ellesmere Island, Nunavut *In*: M. Garneau and B.T. Alt [Eds.] *Environmental Response to Climate Change in the Canadian High Arctic Geological Survey of Canada. Bulletin 529.* pp.257-269.

Dyke, A.S. 1984. *Quaternary Geology of Boothia Peninsula and Northern District of Keewatin, Central Canadian Arctic Memoir 407.*Ottawa: Geological Survey of Canada.

Edlund, S.A. & Alt, B.T. 1989. Regional Congruence of Vegetation and Summer Climate Patterns in the Queen Elizabeth Islands, Northwest Territories, Canada. *Arctic* 42:3-23.

Fallu, M.-A..2001.Fossils from lake sediments in Northern Québec and Labrador: A window into past climate changes. InfoNorth. *Arctic* 54(4):468-476.

Fallu, M.-A., & Pienitz, R.. Diatomées lacustres de Jamésie-Hudsonie (Québec) et modèle de reconstitution des concentrations de carbone organique dissous. 1999. *Écoscience* 6(4):603-620.

Fallu, M.-A., Allair, N., & Pienitz, R. 2000. *Freshwater diatoms from northern Québec and Labrador (Canada): Species-environment relationships in lakes of boreal forest, forest-tundra and tundra regions*. Bibliotheca Diatomologica, Band 45. Stuttgart: J. Cramer.

Fisher, D., Koerner, R. & Reeh, N. 1995. Holocene climate records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada. *The Holocene* 5:19-24.

Fischer, H., Werner, M., Wagenbach, D., Schwager, M., Thorsteinnson, T., Wilhelms, F. & Kipfstuhl, J. 1998. Little ice age clearly recorded in northern Greenland ice cores. *Geophysical Research Letters* 25:1749-1752.

Flower, R.J., Ozornina, S.P., Kuzmina, A., Round, F.E. 1998. *Pliocaenicus* taxa in modern and fossil material mainly from eastern Russia. *Diatom Research* 13:39-62.

Fritz, S. 1996. Paleolimnological records of climatic change in North America. *Limnology and Oceanography* 42(5):882-9.

Gajewski, K. 1993. *The role of paleoecology in the study of global climate change.* Review of Paleobotany and Palynology. 79:141-151.

Gajewski, K. 1995. Modern and Holocene pollen assemblages from some small Arctic lakes on Somerset Island, NWT, Canada. *Quaternary Research* 44:228-236.

Gajewski, K. 2000. Climate of the last millennium in eastern North America and impacts on the vegetation. *PRACE GEOGRAFICZNE* 107:101-105.

Gajewski, K. & Frappier, M. 2001. A Holocene lacustrine record of environmental change in northeastern Prince of Wales Island, Nunavut, Canada. *Boreas* 30:285-289.

Gajewski, K., Hamilton, P.B. & McNeely, R. 1997. A high resolution proxy-climate record from an Arctic lake with annually-laminated sediments on Devon Island. *Journal of Paleolimnology* 17:215-225.

Gajewski, K., Mott, R.J., Ritchie, J.C., Hadden, K. 2000. Holocene vegetation history of Banks Island, Northwest Territories, Canada. *Canadian Journal of Botany* 78:430-436.

Gajewski, K., Payette, S. & Ritchie, J. C. 1993. Holocene vegetation history at the boreal-forest – shrub-tundra transition in north-western Québec. *Journal of Ecology* 81:433-443.

Gajewski, K., Vance, R., Sawada, M., Fung, I., Gignac, L.D., Halsey, L., Jasmin, J., Maisongrande, P., Mandell, P., Mudie, P.J., Richards, P.J.H., Sherin A.G., Soroko, J., & Vitt, D.H. 2000. The climate of North America and adjacent ocean water. *Canadian Journal of Earth Sciences* 37:661-681

Germain, H. 1981. *Flore des Diatomées*. Paris : Société Nouvelle des Éditions Boubée.

Goldsborough, L.G., & Robinson, G.G.C. 1996. Pattern in wetlands. *In* R.J. Stevenson, M.G. Bothwell, and R.L. Lowe [Eds.] *Algal Ecology: Freshwater Benthic Ecosystems* San Diego: Academic Press, pp. 77-117.

Grove, J.M. 1988. *The Little Ice Age*. London: Routledge.

Hamilton, P. B., Douglas, M.S.V., Fritz, S.C., Pienitz, R., Smol, J. P. & Wolfe, A. P. 1994. A compiled freshwater diatom taxa list for the arctic and subarctic regions of North America. In: P.B. Hamilton (ed.) Proceedings of the fourth Arctic-Antarctic Diatom Symposium. *Canadian Technical Report of Fisheries and Aquatic Sciences, Ottawa* 1957:85-102.

Hamilton, P.B., Gajewski, K., Atkinson, D.E., & Lean, D.R.S. 2001. Physical and chemical limnology of 204 lakes from the Canadian Arctic Archipelago. *Hydrobiologia* 457:133-148.

Hay, M.B., Michelutti, N., & Smol, J. P. 2000. Ecological patterns of diatom assemblages from Mackenzie Delta lakes, Northwest Territories, Canada. *Canadian Journal of Botany* 78:19-33.

Heiri, O., Lotter, A.F., & Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproductibility and comparability of results. *Journal of Paleolimnology* 25: 101-110.

Houghton, J.T., Jenkins, G. J. & Ephraums, J.J. [Eds.]. 1990. *Climate Change: the IPCC Scientific Assessment*. Cambridge University Press, Cambridge.

Hudon, C., Duthie, H.C., Smith, S.M. & Ditner, S.A. 1986. Relationships between lakewater pH and sedimentary diatoms in the Matamek Watershed, Northeastern Quebec, Canada. *Hydrobiologia* 140:49-65.

Hughes, M.K. & Diaz, H.F. 1994. Was there a 'Medieval Warm Period', and if so, where and when? *Climatic Change* 26:109-142.

Hughen, K.A., Overpeck, J.T., & Anderson, R.F.. 2000. Recent Warming in a 500-year paleotemperature record from varved sediments, Upper Soper lake, Baffin Island, Canada. *The Holocene* 10:9-19.

Hyvärinen, H. 1985. Holocene pollen stratigraphy of Baird Inlet, east-central Ellesmere Island, arctic Canada. *Boreas* 14:19-32.

Integrated Taxonomic Information System (ITIS) on-line database. Retrieved (08/15/02). http://www.it is.usda.gov.

Joynt, E.H. III. 1999. *Calibration and Application of Lake Diatoms as Proxies for Climate Change on Baffin Island, Nunavut, Canada.* M.S. thesis, University of Colorado, Dept. of Geological Sciences, Boulder, Colorado, 98 pp.

Joynt, E.H. III, & Wolfe, A. P. 2001. Paleoenvironmental inference models from sediment diatom assemblages in Baffin Island lakes (Nunavut, Canada) and reconstruction of summer water temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 58:1222-1243.

King, R.H. 1991. Paleolimnology of a polar oasis, Truelove Lowland, Devon Island, N.W.T., Canada. *Hydrobiologia* 214:317-325.

Kingston, J.C., & Birks, H.J.B. 1990. Dissolved organic carbon reconstructions from diatom assemblages in PIRLA project lakes, North America. Phil. Trans. r. Soc., London, B 327:279-288.

Krammer, K., & Lange-Bertalot, H. 1991a. *Bacillariophyceae*. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. *In* Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. [Eds], *Süsswasserflora von Mitteleuropa.* Band 2/3. Stuttgart: Gustav Fischer Verlag.

Krammer, K., & Lange-Bertalot, H. 1991b. *Bacillariophyceae*. 4. Teil: Achnanthaceae. *In* Ettl, H., Gärtner, G., Gerloff, J., Heynig, H., Mollenhauer, D. [Eds], *Süsswasserflora von Mitteleuropa.* Band 2/4. Stuttgart: Gustav Fischer Verlag.

Krammer, K., & Lange-Bertalot, H. 1997a. *Bacillariophyceae*. 1. Teil: Naviculaceae. *In* Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. [Eds], *Süsswasserflora von Mitteleuropa.* Band 2/1. Stuttgart: Gustav Fischer Verlag.

Krammer, K., & Lange-Bertalot, H. 1997b. *Bacillariophyceae*. 2. Teil: Bacillariaceae, Epithemiaceae, Suriellaceae. *In* Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. [Eds], *Süsswasserflora von Mitteleuropa.* Band 2/2. Stuttgart: Gustav Fischer Verlag.

Lafarge-England, C., Vitt, D.H., England, J. 1991. Holocene soligenous fens on a High Arctic fault block, northern Ellesmere Island (82°N), N.W.T., Canada. *Arctic and Alpine Research* 23:80-98.

Laing, T. E., & Smol, J. P. 2000. Factors influencing diatom distributions in circumpolar treeline lakes of Northern Russia. *Journal of Phycology* 36:1035-1048.

Laird, K.R., Fritz, S.C., Massch, K.A., & Cumming, B.F. 1996b. Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature* 384:552-4.

Laird, K.R., Fritz, S.C., & Cumming, B.F. 1998b. A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: A sub-decadal record of the last 2300 years. *Journal of Paleolimnology* 19:161-79.

Lamoureux, S.F., & Bradley, R.S. 1996. A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *Journal of Paleolimnology* 16:239-255.

Lange-Bertalot, H., & Genkal, S.I. 1999.*Diatoms from Siberia I: Islands in the arctic ocean (Yugorsky-Shar Strait)*. Iconographia Diatomologica. Vol. 6. Vaduz: A.R.G. Gantner Verlag K.G.

Lange-Bertalot, H. 2001. *Diatoms of Europe: Diatoms of the European inland waters and comparable habitats. Navicula* sensu stricto. 10 Genera Separated from *Navicula* sensu lato. *Frustulia*. Vol. 2. Ruggell: A.R.G. Gantner Verlag K.G..

Lavoie, C., & Payette, S. 1996. The long term-stability of the boreal forest limit in subarctic Québec. *Ecology* 77:1226-1233.

Lescop-Sinclair, K. & Payette, S. 1995. Recent advance of the arctic treeline along the eastern coast of Hudson Bay. *Journal of Ecology* 83:929-936.

Lim, D.S.S., Douglas, M.S.V., & Smol, J.P. 2001. Diatoms and their relationship to environmental variables from lakes and ponds on Bathurst Island, Nunavut, Canadian High Arctic. *Hydrobiologia* 450: 215-230.

Lim, D.S.S., Douglas, M.S.V., Smol, J. P. and Lean, D. R. S. 2001. Physical and chemical limnological characteristics of 38 lakes and ponds on Bathurst Island, Nunavut, Canadian High Arctic. *Internat. Rev. Hydrobiol.* 86(1):1-22.

Lotter, A.F., Pienitz, R. & Schmidt, R. 1999. Diatoms as indicators of environmental change near arctic and alpine treeline. *In* Stoermer, E.F. & Smol, J. P. [Eds.] *The Diatoms: Applications for the Environmental and Earth Sciences.* Cambridge University Press, Cambridge, pp. 205-26.

Lotter, A.F. & Bigler, C. 2000. Do diatoms in the Swiss Alps reflect the length of ice-cover? *Aquatic Sciences* 62:125-141.

Ludlam, S., Feeney, S. & Douglas, M.S.V. 1996. Changes in the importance of lotic and littoral diatoms in a high arctic lake over the last 191 years. *Journal of Paleolimnology* 16:184-204.

MacDonald, G., Felzer, B., Finney, B., & Forman, S. 2000. Holocene lake sediment records of Arctic hydrology *Journal of Paleolimnology*. 24: 1-13.

Maxwell, J.B. 1980. *The climate of the Canadian Arctic Islands and adjacent waters.* Atmospheric Environment Services. Downsview, Ontario: Environment Canada.

Miller, G.T., Jr. 1995.*Environmental Science : Working with the Earth*. 5th Ed. Belmont: Wadsworth Publishing Company.

Morales, Eduardo A. Morphological studies in selected fragilarioid diatoms (Bacillariphyceae) from Connecticut waters (U.S.A.). 2001. *Proceedings of the Academy of Natural Sciences of Philadelphia* 151:105-120.

Morin, A., & Payette, S. 1984. Expansion récente du mélèze à la limite des forêts (Québec nordique). *Canadian Journal of Botany* 62 :1404-1408.

Moser, K.A., Smol, J.P., Lean, D.R.S., & MacDonald, G.M. 1998. Physical and chemical limnology of northern boreal lakes, Wood Buffalo National Park, northern Alberta and the Northwest Territories, Canada. *Hydrobiologia* 377:25-43.

O'Brien, S.R., Mayewski, A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.I. 1995. Complexity of Holocen climate as reconstructed from a Greenland ice core. *Science* 270:1962-1964.

Overpeck, J.T., Hughen, K.A., Hardy, D., Bradley, R.S., Case, R., Douglas, M.S.V., Finney, B., Gajewski, K. Jacoby, G., Jennings, A.E., Lamoureux, S., Lasca, A., MacDonald, G.M., Moore, J.J., Retelle, M., Wolfe, A.P. & Zielinski, G.A. 1997. Arctic environmental change of the last four centuries. *Science* 278:1251-6.

Patrick, R., & Reimer, C.W. 1975. The diatoms of the United States II. Part I. The Academy of Natural Sciences of Philadelphia. Monograph 13.

Payette, S. & Delwaide, A. 2000. Recent permafrost dynamics in a subarctic floodplain associated with changing water levels, Québec, Canada. *Arctic, Antartic, and Alpine Research* 32(3):316-323.

Payette, S. & Filion, L. 1985. White spruce expansion at the tree line and recent climatic change. *Canadian Journal of Forest Research* 15:241-251.

Pienitz, R. & Smol, J. P. 1993. Diatom assemblages and their relationship to environmental variables in lakes from the boreal forest-tundra ecotone near Yellowknife, Northwest Territories, Canada. *Hydrobiologia* 269/270: 391-404.

Pienitz, R., Smol, J.P. & Birks, H.J.B. 1995. Assessment of freshwater diatoms as quantitative indicators of past climatic change in the Yukon and Northwest Territories, Canada. *Journal of Paleolimnology* 13:21-49.

Pienitz, R., Smol, J.P. & Lean, D.R.S. 1997a. Physical and chemical limnology of 59 lakes located between the Southern Yukon and the Tuktoyaktuk Peninsula, Northwest Territories (Canada). *Canadian Journal of Fisheries and Aquatic Sciences* 54:330-346.

Pienitz, R., Smol, J. P. & Lean, D.R.S. 1997b. Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada). *Canadian Journal of Fisheries and Aquatic Sciences* 54:357-358.

Pienitz, R., Smol, J.P., & MacDonald, G.M.. 1999. Paleolimnological reconstruction of Holocene climatic trends from two boreal treeline lakes, Northwest Territories, Canada. *Arctic, Antarctic, and Alpine Research* 31:82-93.

Ponader, K., Pienitz, R., Vincent, W., & Gajewski, K. 2002. Limnological conditions in a subarctic lake (northern Québec, Canada) during the late Holocene: analyses based on fossil diatoms. *Journal of Paleolimnology* 27:353-366.

Prather, C. & Hickman, M. 2000. History of a presently slightly acidic lake in northeastern Alberta, Canada as determined through analysis of the diatom record. *Journal of Paleolimnology* 24:183-198.

Reavie, E.D., & Smol, J.P. *Freshwater diatoms from the St. Lawrence River*. Bibliotheca Diatomologica. Band 41. Stuttgart: J. Cramer.

Rühland, K., & Smol, J.P. 1998. Limnological characteristics of 70 lakes spanning arctic treeline from Coronation Gulf to Great Slave Lake in the Central Northwest Territories, Canada. *Int. Rev. Hydrobiol.* 83:183-203.

Rühland, K.M., & Smol, J.P. 2002. Freshwater diatoms from the Canadian arctic treeline and development of paleolimnological inference models. *Journal of Phycology* 38:249-264.

Sai, L. Ng., & King, R.H. 1999. Development of a diatom-based specific conductivity model for the glacio-isostatic lakes of Truelove Lowland: implications for paleoconductivity and paleoenvironmental reconstructions in Devon Island lakes, N.W.T., Canada. *Journal of Paleolimnology* 22:367-382.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millenium. *Canadian Journal of Fisheries and Aquatic Sciences* 58:18-29.

Schönfelder, I., Gelbrecht, J., Schönfelder, J., & Steinberg, C.E.W. 2002. Relationships between littoral diatoms and their chemical environment in northeastern German lakes and rivers. *Journal of Phycology* 38:66-82.

Schwoerbel, J. 1987. *Handbook of limnology*. New York: Halsted Press.

Sheath, R.G. 1986. Seasonality of phytoplankton in northern tundra ponds. *Hydrobiologia* 138:75-83.

Smith, I.R. 2002. Diatom-based Holocene paleoenvironmental records from continental sites on northeastern Ellesmere Island, high Arctic, Canada. *Journal of Paleolimnology* 27:9-28.

Smol, J.P. 1983.Paleophycology of a high arctic lake near Cape Herschel, Ellesmere Island. *Canadian Journal of Botany* 61:2195-204.

Smol, J.P. 1988. Paleoclimate proxy data from freshwater arctic diatoms. *Verhandlungen. Internationale Vereinigung fur theoretische und angewandte Limnologie/Proceedings. International Association of Theoretical and Applied Limnology/Travaux. Association internationale de Limnologie theorique et appliquee.* 23:837-44.

Smol, J.P. 1990. Are we building enough bridges between paleolimnology and aquatic ecology? *Hydrobiologia* 214:201-206.

Smol, J.P., Walker, I.R. & Leavitt, P.R. 1991. Paleolimnology and hindcasting climatic trends. *Verh. Internat. Verein. Limnol.* 24:1240-6.

Smol, J.P., Cumming, B.F., Douglas, M.S.V., Pienitz, R. 1995. Climatic changes in Canada using paleolimnological techniques. *Geoscience Canada* 21:112-7.

Smol, J.P., & Cumming, B. F. 2000. Tracking long-term changes in climate using algal indicators in lake sediments. *Journal of Phycology.* 36:986-1011.

Sorvari, S., & Korhola, A. 1998. Recent diatom assemblage changes in subarctic Lake Saanajärvi, NW Finnish Lapland, and their paleoenvironmental implications. *Journal of Paleolimnology* 20:205-215.

Verschuren, D., Laird, K.R., & Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* 403:410-4.

Veres, A.J., Pienitz, R., & Smol, J.P. 1995. Lake Water Salinity and Periphytic Diatom Succession in Three Subarctic Lakes, Yukon Territory, Canada. Arctic 48(1):63-70.

Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E. & Sawada, M.C. 2002. Widespread evidence of 1500 yr climate variability in North America during the past 14 000 yr. *Geology* 30:455-458.

Walsh, J.E., & Crane, R.G. 1992. A comparison of GCM simulations of Arctic climate. *Geophyical Research. Letters* 19:29-32.

Weckström, J., Korhola, A. & Blom, T. 1997. The relationship between diatoms and water temperature in thirty Subarctic Fennoscandian lakes. *Arctic, Antarctic, and Alpine Research* 29:75-92.

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*. 3rd ed. New York: Academic Press.

Williams, K.M. 1990a. Paleolimnology of three Jackman Sound lakes, southern Baffin Island, based on down-core diatom analyses. *Journal of Paleolimnology* 4:203-17.

Wilson, S.E., Cumming, B.F., Smol, J.P. 1996. Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219-lake data from western North America. *Canadian Journal of Fisheries and Aquatic Sciences* 53:1580-1594.

Wolfe, A.P. 1991. Mid and late Holocene diatoms from 'Water Supply Lake', Baffin Island, N.W.T., Canada. *Journal of Paleolimnology* 6: 199-204.

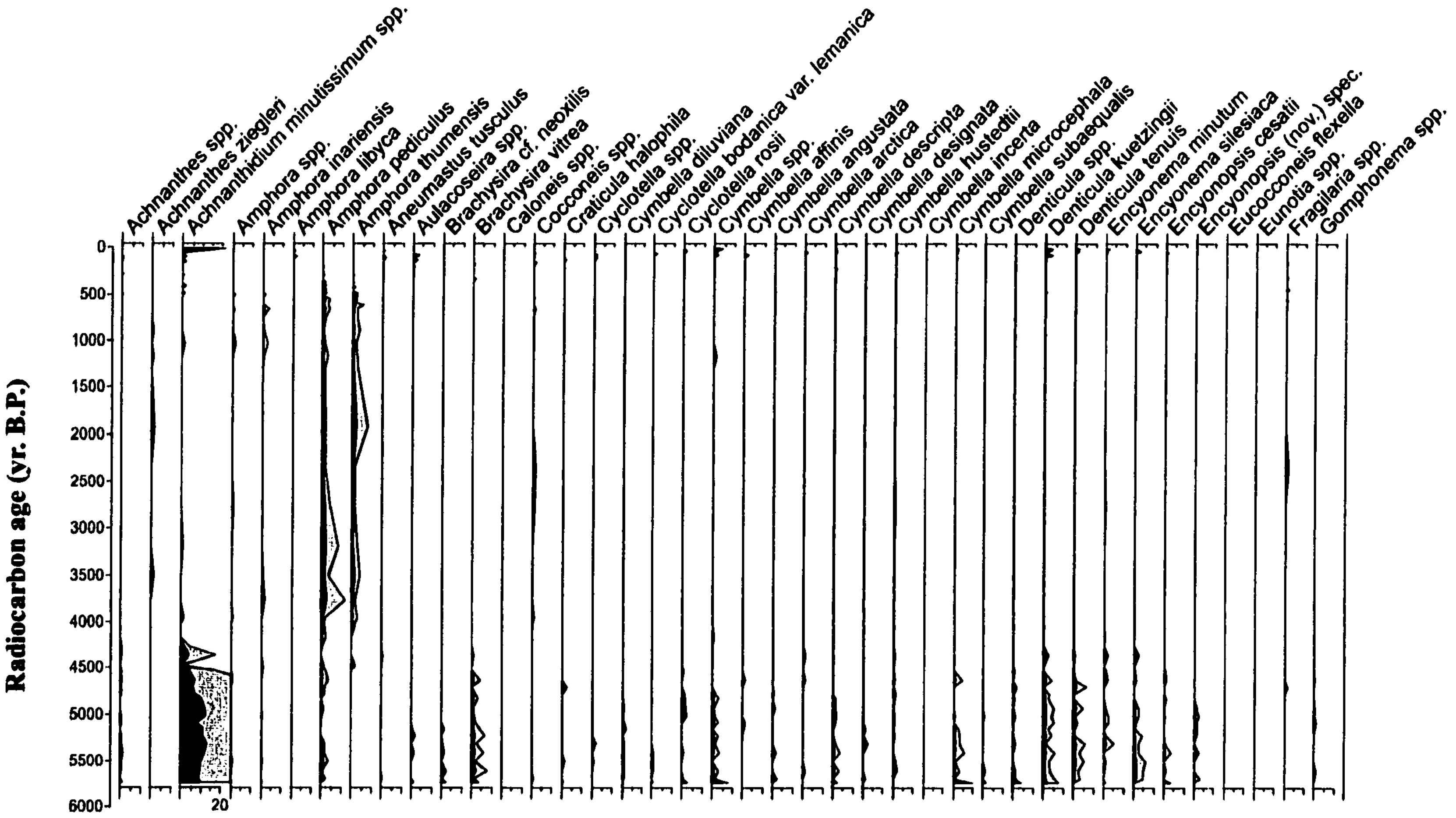
Wolfe, A. P. 1994. Late Wisconsinan and Holocene diatom stratigraphy from Amarok Lake, Baffin Island, N.W.T., Canada. *Journal of Paleolimnology* 10:129-139.

Wolfe, A. P. 2000. A 6500-year diatom record from southwestern Fosheim Peninsula, Ellesmere Island, Canadian High Arctic. In: M. Garneau and B.T. Alt (ed.) in *Environmental Response to Climate Change in the Canadian High Arctic Geological Survey of Canada. Bulletin 529.* pp.249-256.

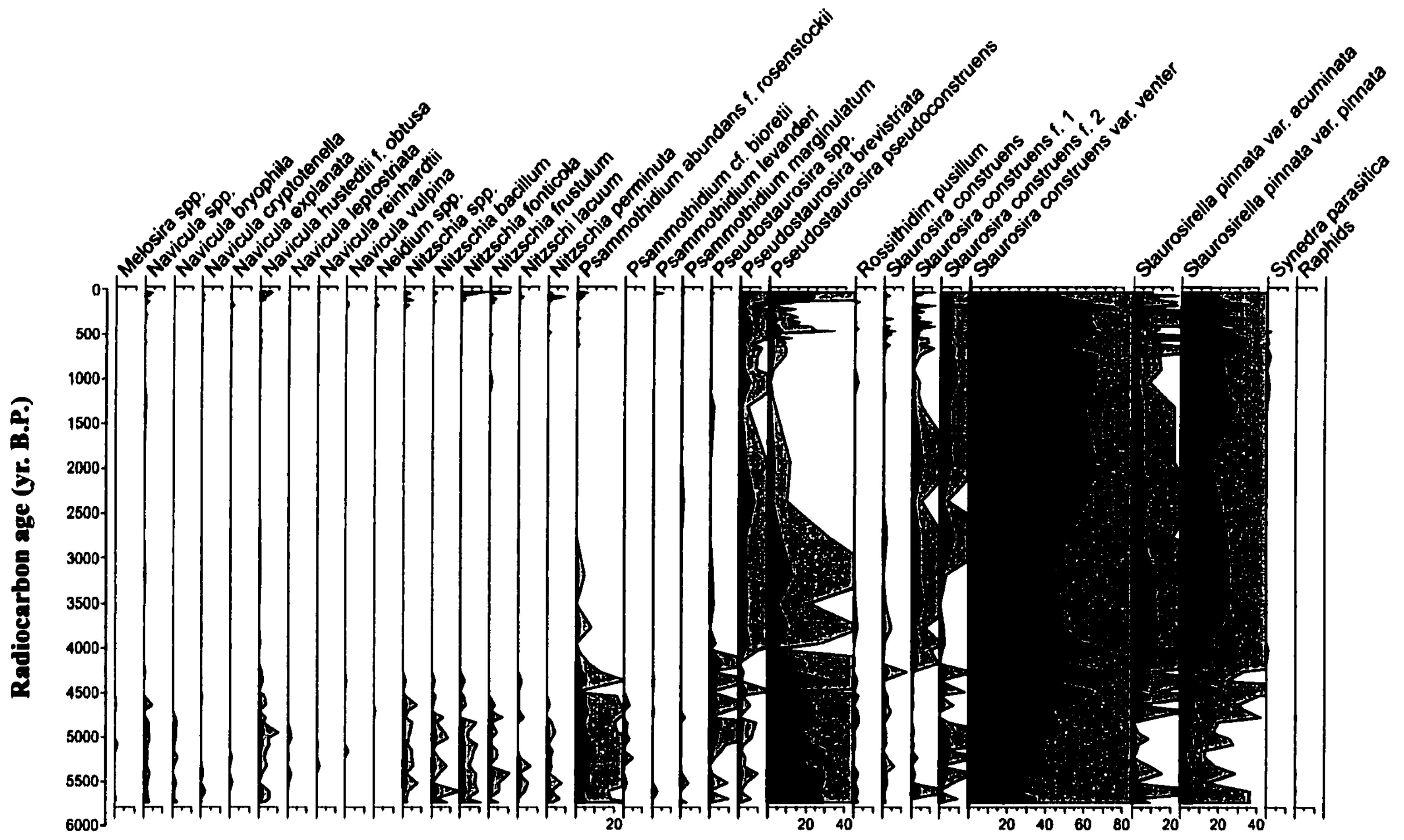
Wolfe, A.P., & Perren, B.B. 2001. Chrysophyte microfossils record marked responses to recent environmental changes in high- and mid-arctic lakes. *Canadian Journal of Botany* 79:747-752.

Wolfe, B.B., Edwards, T., Aravena, R., & MacDonald, G. 1996. Rapid Holocene hydrologic change along boreal treeline revealed by ^{13}C and ^{18}O in organic lake sediments, Northwest Territories, Canada. *Journal of Paleolimnology* 15:171-181.

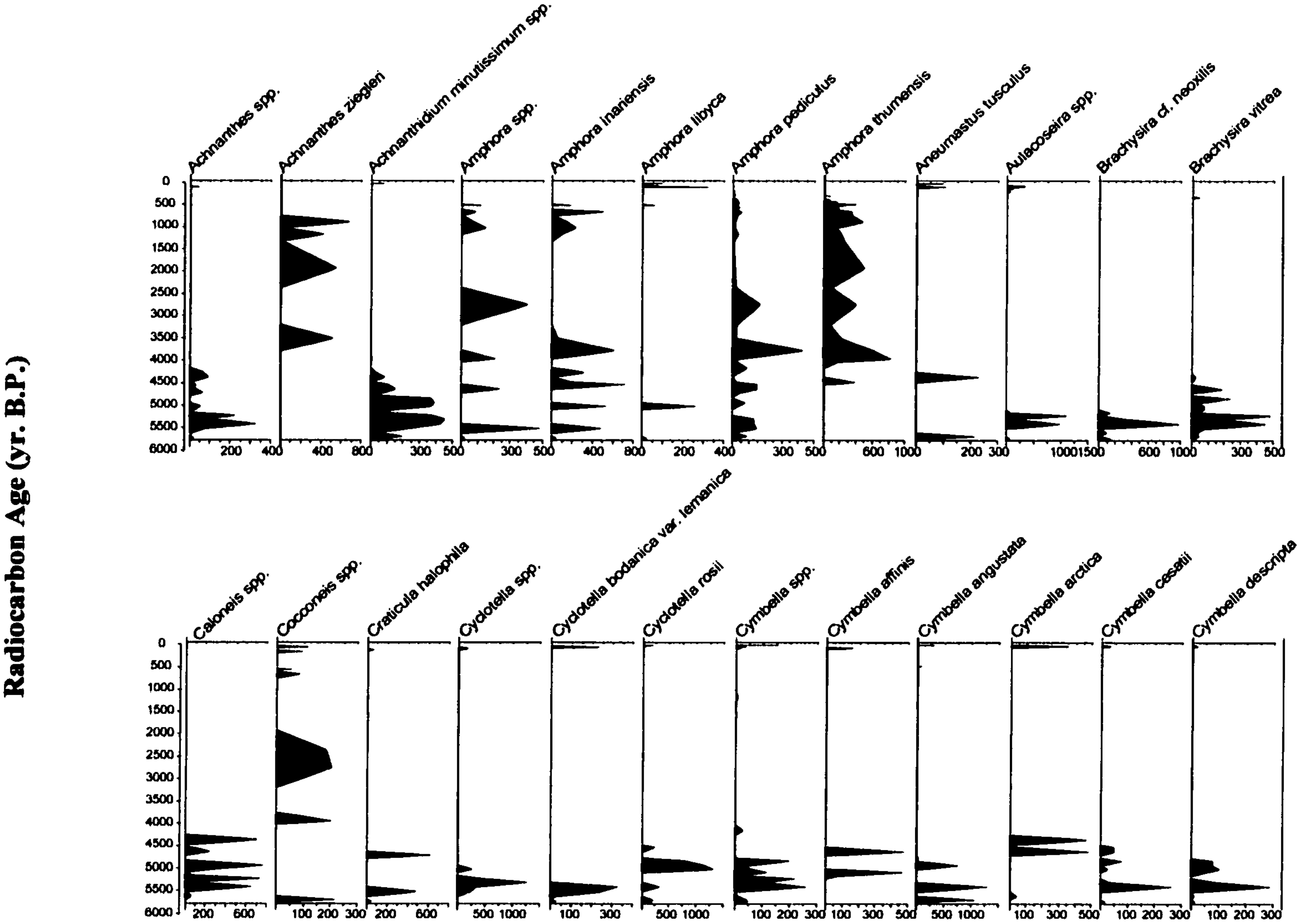
Wolin, J.A. & Duthie, H.C. 1999. Diatoms as indicators of water level change in freshwater lakes. *In* Stoermer, E.F. & Smol, J. P. [Eds.] *The Diatoms: Applications for the Environmental and Earth Sciences.* Cambridge University Press, Cambridge, pp. 183-204.



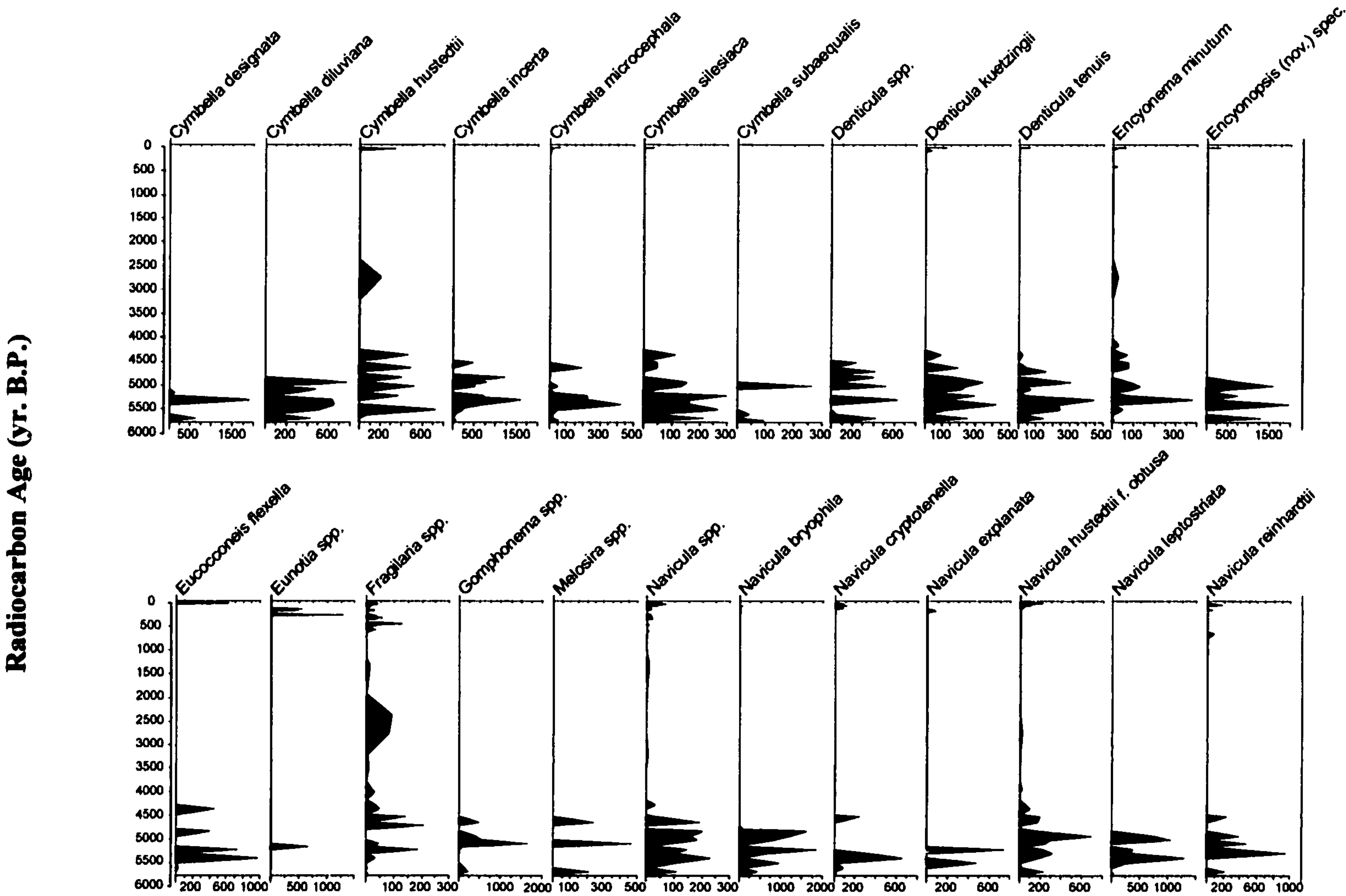
Appendix A
JR01 lake, Boothia Peninsula
Percent relative abundance (*Achnanthes* spp. - *Gomphonema* spp.)



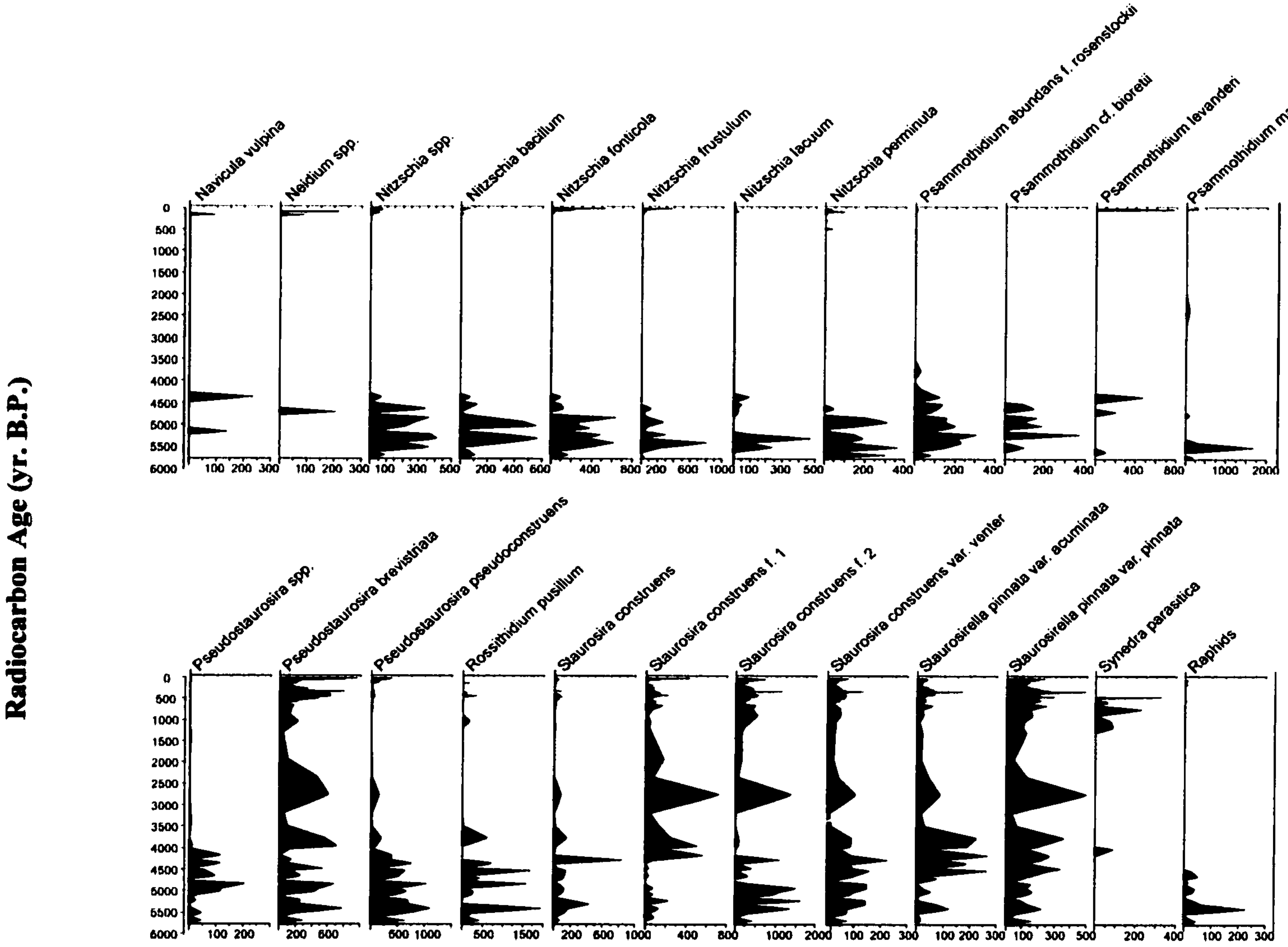
Appendix A
JR01 lake, Boothia Peninsula
Percent relative abundance (*Melosira* spp. - raphids)



Appendix B
JR01 lake, Boothia Peninsula
Diatom concentrations (*Achnanthes* spp. - *Cymbella descripta*)



Appendix B
JR01 lake, Boothia Peninsula
Diatom concentrations (*Cymbella designata - Navicula reinhardtii*)



Appendix B
JR01 lake, Boothia Peninsula
Diatom concentrations (*Navicula vulpina* - Raphids)