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Lake Diatoms as a Proxy for Holocene Environmental Change, West Greenland

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Abstract

There is great interest over the Greenland Ice Sheet in terms of future climate change, though there is a lack of understanding of climate change during the Holocene. Lakes can provide continuous and detailed records of paleoclimate; the distinct taxonomy and preservation potential of diatoms makes them a particularly useful proxy within paleoenvironmental reconstructions. Contemporary diatom assemblages and the environmental conditions of 25 lakes from a localized area in the Godthåbsfjord region, southwest Greenland, as well as a fossil core from one of the lakes, are studied. Multivariate analysis is undertaken to establish the relationships between the contemporary diatoms and environmental conditions, and the addition of another dataset from Søndre Strømfjord, west Greenland, provided an insight into lake and diatom variability. Transfer functions are then developed for several environmental variables, including pH, temperature and lake depth, and applied to the fossil diatom assemblages from the lake core. The fossil diatom assemblages and quantitative reconstructions indicate an acidification of the lake through the Holocene, and the quantitative reconstructions, along with additional proxy data of pollen, provide a record of several warming and cooling phases through the Holocene, including the Little Ice Age. There are however several issues, including multiple forcing variables acting on the contemporary diatoms, the provision of modern analogues for the fossil assemblages, as well as preservation problems, that raise several questions over the reliability of lake diatoms as a proxy for Holocene environmental change in southwest Greenland.

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Statement of Copyright

Acknowledgements

So many people have helped me get through this year, far too many to mention fully here so I shall try to be brief, but to anyone who knows me and is keen enough to read this, thank you for all the support.

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1 Aims and Previous Research

1.1 Introduction

There is a great deal of focus at present over the significance of the Greenland Ice Sheet (GIS) in terms of future climate change and global sea-level change, however there is a considerable lack of understanding of climate change during the current interglacial, the Holocene, particularly in western Greenland. This is a vital issue due to the complex responses of the ice sheet to periods of cooler and warmer conditions, particularly at ice margins (Jakobsson *et al.*, 2010). As such, there are increasing efforts to use proxy data from ice-free and ice marginal locations to determine paleoconditions.

Arctic lakes can provide continuous, datable and detailed sediment records of paleoclimate (Kaplan *et al.*, 2002; Sorvari *et al.*, 2002; Thomas *et al.,* 2011), and are more frequently being utilized in locations such as the Canadian High Arctic as well as Greenland. A range of proxies is often used, from biological to chemical. For biological proxies, such as chironomids and diatoms, it is important to identify and understand the mechanisms controlling abundance and distribution of species to allow for the production of suitable and accurate paleoenvironmental reconstructions (Velle *et al.*, 2010).

The distinct taxonomy and preservation potential of diatoms makes them a particularly useful proxy within paleoenvironmental reconstructions (Platt Bradbury, 1999). Diatoms are widely applied throughout Quaternary science in reconstructing environmental changes, including sea-level, acidity, precipitation and climatic changes. In terms of lake sediments, diatoms have proven themselves as vital indicators of ecological changes (Lowe & Walker, 1997); in higher latitude aquatic systems, diatoms are particularly important as they contribute significantly to the primary production (Sorvari *et al.*, 2002), and have been shown to be an indicator of lake trophic status and productivity (Lowe & Walker, 1997; Lotter *et al.*, 1998).

This thesis produces a training set of contemporary diatoms from 25 lakes across an elevation range from a study site located in south western Greenland, to establish the diatom flora present and the relationships to the lake environmental conditions. A Holocene fossil diatom record is also produced from a lake core, and is utilized to produce estimates of environmental changes for the lake and wider region. The record and inferred climatic signal is compared to other proxies and to previously published pollen and ice core temperature records from Greenland and elsewhere in the Arctic.

1.2 Research Aims

This thesis investigates Holocene environmental change using lake diatom assemblages near Nuuk, south-west Greenland. The main aims are:

- To understand the relationships between the contemporary environmental conditions and lake diatoms in south-west Greenland.
- To develop quantitative estimates of Holocene environmental change using a lake diatom fossil record.

Based on these aims, research questions have been developed. These have been produced based on the review of relevant literature, and are supported by clear objectives.

1. What is the distribution of contemporary diatoms at the sediment/water interface across an elevation gradient of lakes from a single location, and what is their relationship with the prevailing modern environmental conditions?
    - Establish the contemporary diatom assemblages and abundance using the sediment of 25 lakes covering a range of elevations (35-835m asl).
    - Determine the relationships between the assemblages and environmental variables using taxonomic and multivariate analysis.
2. How do fossil diatom assemblages and environmental conditions vary through the Holocene?

- Establish the fossil diatom assemblages of a lake core taken from close to the mid-point in the elevation range of the modern sampled lakes.
- Develop quantitative and qualitative estimates of environmental changes using the fossil diatoms, through the use of statistical approaches such as DCA and transfer functions.

3. How useful are lake diatoms as a proxy for environmental change in south-west Greenland?
   - Compare the estimates of change produced by the diatoms to those from other proxies and other studies in this region, south west Greenland, and elsewhere in the Arctic.

1.3 Diatoms

1.3.1 Introduction

The aim of this research is to utilize assemblages of diatoms from contemporary lake sediments to reconstruct Holocene paleoenvironmental conditions indicated by the fossil diatom assemblages within a lake core. Diatoms have been investigated for over two centuries, and as such there is a much greater understanding within paleoecology of their ecological preferences than with other members of the algal kingdom (Lowe & Walker, 1997). Within the algae community, diatoms are classified as Division Bacillariophyta. They are unicellular organisms that are ubiquitous within both marine and freshwater aquatic environments, forming approximately eighty percent of the World's primary producers (Battarbee *et al.*, 2001; Lowe & Walker, 1997; Stoermer & Smol, 1999). Siliceous cell walls are a key characteristic of diatoms, and the shape, size and features of these siliceous cell walls are indicative of their taxonomy.

1.3.2 Structure and Taxonomy

The structure of diatoms have undergone much detailed study, and the following section is based predominantly on the detailed descriptions of diatom structure provided by Battarbee *et al.* (2001) and Round *et al.* (1990).

Diatoms are unicellular algae. The contents of diatoms make them similar to other eukaryotic algae, however the silica present within diatoms is a factor of their uniqueness (Battarbee *et al.*, 2001; Round *et al.,* 1990). Silica has several roles in diatoms. It provides rigidity in cell walls, aids preservation of frustules as fossils, and intricately patterned silica walls are constructed that provide characteristics for taxonomy of living and fossil diatoms (Battarbee *et al.*, 2001; Round *et al.,* 1990).

Diatom cell walls are comprised of several siliceous components; the valve and cingulum are the two main components, both within the thecae (Batarbee *et al.*, 2001). The face of the valves of each theca contain the majority of taxonomic and determinable features; it is therefore necessary to have the valve view visible for microscope analysis, as these patterns allow for identification at the specific level for contemporary taxa, as well as for the majority of fossil taxa (Battarbee *et al.,* 2001; Round *et al.*, 1990). The cingulum is made up of bands formed during cell division that together form the girdle of the cell; these are not identical and are less patterned than the valves, and as such are often less straightforward to identify (Battarbee *et al.*, 2001; Round *et al.*, 1990).

Living diatom cells are able to maintain the position of rigid siliceous components through organic membranes, however some dead cells can become disarticulated in sediment; this can be an advantage for microscopic analysis as separated valves are likely to have their valve faces exposed for taxonomic classification (Battarbee *et al.*, 2001). In contrast, girdle bands can undergo dissolution or break up in sediments, though some species are more robust and therefore remain intact and can be counted independently from the valve e.g. *Tabellaria* (Battarbee *et al.*, 2001). Some diatom species form colonies; some are individual cells linked at their apices, whereas others form chains linked by spines, for which colonies of varying lengths can be discovered, though with some taxa colony structure can rarely survive in sediment (Battarbee *et al.*, 2001; Round *et al.*, 1990).

Within lake systems, planktonic taxa can be categorized into several different types. Euplankton or holoplankton taxa are those that spend their whole life cycle suspended in the water column; merplankton are those that spend some of it resting on the sediment; tychoplankton or pseudoplankton are those that spend it in the benthos but can be discovered re-suspended in the water column, and are highly common within both small and large lakes (Battarbee *et al.*, 2001). Benthic taxa are those that are found within the substrates around lake margins, and their extension into deeper areas of lakes is dependent on the penetration of light and the availability of suitable substrates (Battarbee *et al.*, 2001).

1.3.3 Paleoenvironmental Reconstruction

Due to their siliceous composition, diatoms have a high preservation potential in lake and fossil sediments, particularly fine-grained sediments that minimize damage (Anderson *et al.,* 1997; Gehrels, 2007; Lowe & Walker, 1997; Stoermer & Smol, 1999). The distinct taxonomy and preservation potential make diatoms a particularly useful proxy within paleoenvironmental reconstructions of long-term change, but their short lifespans and ability for rapid regeneration also allows for their application in investigating centennial scale climatic changes (LeBlanc *et al.*, 2004; Platt Bradbury, 1999). The application of diatoms for robust quantitative environmental reconstructions has been enhanced over the past several decades through improvements in dating, sediment sampling and coring, as well as the developments of numerical techniques (Batarbee *et al.*, 2001).

Diatoms are ubiquitous in almost all aquatic environments (Battarbee *et al.*, 2001; Stoermer & Smol, 1999). Aquatic environments provide valuable evidence for environmental fluctuations from centennial to millennial scales (Livingstone, 1984). Lacustrine sediments in particular accumulate gradually over time, containing details of the biological communities living within them, such as diatoms, as well as from the surrounding catchment, such as pollen

(Smol & Douglas, 2007). Sedimentary records within lakes therefore provide an archive of past environmental changes and events that can be reconstructed and interpreted through paleolimnology (Brodersen & Quinlan, 2006).

Within lakes, diatoms form the source communities for the sediment record due to existing in abundance in both benthic and planktonic habitats, reflecting the characteristics of where they inhabit (Battarbee *et al.*, 2001). As diatoms are generally autochthonous, they are sensitive limnological indicators that are suitable to infer past environmental conditions (Cremer *et al.*, 2001). They can be used to interpret a range of specific environmental conditions due to their distribution being controlled by multiple environmental variables (Gehrels, 2007; Platt Bradbury, 1999), and as such diatoms can be used to track shifts in various environmental conditions and how they relate to climate change (Douglas & Smol, 1999; Douglas *et al.*, 2004; Lim *et* al, 2007). These variables include, for example, water temperature and nutrient content, as well as water salinity and acidity; in the context of freshwater diatoms, trophic status, salinity and pH are the dominating controlling environmental variables (Lotter *et al.*, 1998; Lowe & Walker, 1997).

Several of the variables that have a role in forcing diatom assemblage composition are also closely related to other variables; this can pose difficulties in distinguishing the individual influence of certain variables on diatom assemblages. For example, the extent of light penetration and its intensity is dependent upon depth, seasonality, ice-cover, re-suspension of sediment as well as dissolved organic carbon; light is vital to the process of photosynthesis, which drives algal productivity in lakes and thus diatom species composition (Battarbee *et al.*, 2001). As diatoms have differing abilities to adapt to varying light, it is an important variable forcing assemblages with lakes, however it is not straightforward to quantitatively reconstruct (Battarbee *et al.*, 2001).

Within freshwater systems, pH is amongst the most important variables in controlling diatom assemblages; it has long been recognized, and there is a pH classification of diatom taxa that has been widely used to reconstruct past lake pH (Batarbee *et al.*, 2001). Similarly, the role of salinity as a forcing factor on diatom assemblages is also well recognized. Classification of diatoms in relation to salinity has been used to reconstruct sea-level changes in coastal and estuarine environments (e.g. Hamilton & Shennan, 2005; Woodroffe & Long 2009; 2010), and due to different taxa having defined optima along the salinity gradient, robust diatom-salinity transfer functions can be produced so the paleosalinity of salt lakes can also be reconstructed (e.g. Ryves *et al.*, 2002). This relationship to salinity and related variables has been used widely in paleolimnological reconstructions of salinity and indirectly climate; however highly saline and conductive lake systems are rare in Arctic regions, with the exception of some coastal sites and evaporative systems (Paul *et al.*, 2010).

Despite it being demonstrated that temperature has an influence on diatom life-cycles and potentially lake species composition, temperature also has a significant influence on catchment processes and other lake variables such as pH, nutrients and ice cover (Battarbee *et al.*, 2001). Due to the co-varying nature of these variables with temperature, it is very difficult to distinguish the individual specific influences of variables on diatom assemblages. In the context of alpine lakes however, relationships between temperature and variations within certain species of the *Cyclotella* genus have been demonstrated (Hausmann & Lotter, 2001; Wunsam *et al.*, 1995).

The role of nutrients is particularly significant to diatom assemblage composition. The dissolved silica available is important at regulating diatoms, due to their structure, as discussed in section 1.3.2. However the most significant nutrients in limiting algal and thus diatom growth is nitrogen (N) and phosphorus (P); P is generally the most important and is the variable most often used in diatom reconstructions of lake eutrophication (Batarbee *et al.*, 2001).

This relationship has also been highlighted in a reconstruction of recent total phosphorous for a lake in Sweden, with the quantitative reconstructions produced by a weighted averaging model being in good agreement with observed values (Bradshaw & Anderson, 2001). However, the role of total phosphorus on forcing diatom communities has both direct and indirect influences through other correlated variables, particularly in shallow (~<2m depth) lakes (Sayer *et al.*, 2010). It is vital to identify and understand the mechanisms controlling contemporary species abundance and distribution to allow for the production of suitable, accurate palaeoenvironmental reconstructions (Velle *et al.*, 2010), ultimately using a biotic communities response to an environmental variable as an indirect measure of the paleoenvironment (Smol & Douglas, 2007).

In terms of lake sediments, diatoms have proven themselves as vital indicators of local ecological changes (Lowe & Walker, 1997); in higher latitude aquatic systems, diatoms are particularly important as they contribute significantly to the primary production (Sorvari *et al.*, 2002). Diatoms have been utilized in several different ways in arctic environments, for instance lake diatoms have been applied to investigate recent climate changes (e.g. Jensen *et al.*, 2004; Michelutti *et al.,* 2003; Perren *et al.*, 2009; Sorvari *et al.,* 2002); for longer term Holocene palaeoenvironmental change through the use of lake and marine sediments (e.g. Kaplan *et al.,* 2002; Krawczyk *et al.*, 2010; LeBlanc *et al.,* 2004; Møller *et al.*, 2006; Olsen *et al.*, 2011; Platt Bradbury *et al.*, 1994; Ren *et al.*, 2009; Sha *et al.*, 2011), as well as to reconstruct sea-level change from isolation basins and salt marshes (e.g. Long *et al.*, 2008; Woodroffe & Long, 2009; 2010). This study will reconstruct some of the key forcing lake variables on diatoms, including pH, total phosphorus and water temperature, as well as other lake characteristics such as depth and elevation, which can be used to infer dry phases of the lake and air temperature.

1.4 Arctic Lakes and Paleoenvironments

1.4.1 Introduction

The arctic is an important region, as global warming appears to be amplified in higher latitudes (Bigler *et al.*, 2002). It is particularly important in terms of understanding spatial patterns and mechanisms of climatic variability, both natural and anthropogenic, due to the sensitivity of albedo to small alterations to ice and snow cover, and a variety of positive feed back mechanisms (Kaplan *et* *al.*, 2002; Smol & Douglas, 2007). It is also important in terms ice sheet mass, sea-level change, and the repercussions of this due to the potential contribution from ice-sheets in a warming climate; for example, the Greenland Ice Sheet has been losing mass at an accelerating rate over the past two decades (Rignot *et al.*, 2011).

Lakes within Arctic and sub-Arctic environments are maintained from the moisture provided by rain and snowmelt (Sorvari *et al.*, 2002; Thomas *et al.,* 2011). Such high latitude lakes are characterized by low species diversity and productivity, with simple food webs (Sorvari *et al.*, 2002). The water and biota of the lakes are therefore extremely sensitive to climate changes. In particular, it has been suggested that poorly buffered, low alkalinity Arctic lakes react more sensitively to climatic changes compared to those that have the ability to buffer climate-driven pH changes, such as Neoglacial cooling and recent (past ~100 years) warming, and this may be reflected by the diatom community within such lakes (Michelutti *et al.*, 2006).

Lakes often provide continuous and datable sediment records, offering potentially detailed records of paleoenvironments; despite this though, Arctic lake sediments are not frequently utilized (Kaplan *et al.*, 2002; Smol & Douglas, 2007; Sorvari *et al.*, 2002; Thomas *et al.,* 2011), and the processes acting on biological structures in the lakes, particularly at a millennial scale, are complex (Anderson *et al.*, 2008), and so the links between proxies and the environmental and climatic signals is not direct (Anderson *et al.*, 2012). Indeed, there can be significant difficulty in determining the role of climatic processes and in-lake processes on the communities of low arctic lakes, c.50-70^{o}N, making the determination of an unambiguous climatic signal complex to extract from lake records (Anderson *et al.*, 2008). Most paleolimnological studies within arctic regions therefore employ a diverse set of indicators when attempting to track an environmental variable (Lim *et al.*, 2007), and are often used indirectly to infer climate changes (Smol & Douglas, 2007).

1.4.2 Arctic Paleoenvironmental Reconstructions Using Diatoms

Lake Baikal, an inland sea in Siberia, has been subject to many paleolimnological and paleoclimatic studies over the past several decades, utilizing a range of biostratigraphic and geochemical indicators; diatoms however are the best-preserved and most dominant microfossils, with distinctive assemblages over centennial and millennial scales (Platt Bradbury *et al.*, 1994). The lake sediments and the indicators within them, particularly diatoms, have produced a record of paleoclimatic and limnological changes from the last glacial, ~15ka years and throughout the Holocene; the inferred productivity of the diatoms has been used to assess changing lake transparency, circulation and nutrient input (Platt Bradbury *et al.*, 1994). This demonstrates the usefulness of diatoms from inland lakes as a proxy for reconstructing past environmental and climatic changes. However, investigations of diatom assemblages in the sedimenting material and planktonic diatoms of the lake suggests that such paleoclimatic records can be refined through greater consideration of taphonomy (Ryves *et al.*, 2003), indicating that such methods are not as straightforward as they may seem, and there are multiple factors influencing diatom assemblages that require consideration.

Char Lake, located in the Canadian High Arctic, has also been subject to multiple limnological studies. A study of recent climatic changes of the region utilized physical, chemical and biological variables, including diatoms, from the lake (Michelutti *et al.*, 2003). The changes in the dominant diatom species in the assemblages found were consistent with recorded climatic changes, with an increased diversity in diatoms being consistent with longer ice-free periods; earlier in the record, the disappearance of fossil diatoms at a certain depth is speculated to represent a lack of diatom productivity due to cooler conditions and increased ice-cover (Michelutti *et al.*, 2003). This investigation particularly highlighted the significance of biological proxies in Arctic limnological studies, as the water chemistry variables did not reflect the measured climatic change that was evident within the diatom record (Michelutti *et al.*, 2003), again demonstrating the usefulness of diatoms as a proxy of Holocene climatic change. Diatoms have also been utilized to assess post nineteenth century

Arctic warming in Finnish Lapland (Sorvari *et al.*, 2002). The changes in assemblages were found to parallel the warming in the Arctic measured through other proxies, however the mechanism forcing this diatom response was unclear; this response was postulated to have been related to and complicated by the altered ice-cover duration and growing season (Sorvari *et al.*, 2002), though demonstrates the complexities of the relationships between diatoms and environmental conditions.

On the Holocene scale, a detailed diatom-based palaeoenvironmental record has been produced from a mid-Arctic lake on the Booth Peninsula, Canada (LeBlanc *et al.*, 2004). The diatom composition and concentration, along with sedimentology of the lake, provided a record of diversity and productivity, and was used to infer the temperature and climatic changes through the Holocene, including smaller scale fluctuations like the Little Ice Age and Medieval Warm Period (LeBlanc *et al.*, 2004). Similarly, Paul *et al.* (2010) have inferred changes through the Holocene using diatoms in the Canadian High Arctic, from a pond on Ellesmere Island. The diatom assemblages from two cores from the subsaline pond were used to infer climatic conditions through the Holocene; based upon the sedimentology of the core and on the ecological preferences of diatoms within the assemblages, the samples demonstrated an early- to mid-Holocene warm period and subsequent Neoglacial cooling (Paul *et al.*, 2010). Stable assemblages consisting of cold-water species demonstrated a colder climate; in contrast the presence of more complex diatoms and increased macrophytes indicate longer ice-free periods and a warmer climate (Paul *et al.*, 2010). Despite confidence in the preservation of this record of diatoms, there were some difficulties and uncertainties in the interpretation of some sections of the core due to the presence of ice interspersed with the sediment (Paul *et al.*, 2010), highlighting a potential source of difficulty in using such methods for paleoenvironmental reconstructions in arctic regions subject to continuous permafrost. However, the field site for the research in this thesis is in the low-arctic, south of the Arctic Circle, so should face minimal issues of ice within the core, and potentially produce a confident diatom record that may also demonstrate the Holocene thermal maximum and potentially the Neoglacial cooling shown in this Canada record.

Diatom assemblages from lake sediment have been used to quantify water pH, as well as July mean air temperature in conjunction with other indicators, throughout the Holocene from a lake in northern Sweden (Bigler *et al.*, 2002). This was achieved through the use of transfer functions, with the fossil assemblages from the lake sediment core and a contemporary training set of diatoms from 100 lakes distributed regionally in northern Sweden (Bigler *et al.*, 2002), demonstrating a successful application of lake diatoms to produce quantitative reconstructions. Quantitative reconstructions using transfer functions on lake diatoms have also been produced for a series of permafrost-affected lakes in Eastern Siberia (Prestryakova *et al.*, 2012). For this, the relationships between the present environmental conditions and the diatom characteristics were considered; magnesium, pH and water depth were amongst the most significant variables, the knowledge of which allowed for the development of a robust magnesium-transfer function, and provided a record of lake variability and stability of conditions during the Holocene through both the reconstructions and interpretation of the diatom assemblage (Prestryakova *et al.*, 2012). This study utilized many of the same methods that shall be undertaken in this thesis, including multivariate analysis, cluster analysis and transfer functions, and has demonstrated the applicability of such methods for establishing the relationships between diatoms and various environmental variables, and for producing quantitative reconstructions of these variables.

This section has highlighted multiple Holocene environmental and climatic studies that have utilized diatoms, showing the usefulness of diatoms for such studies but also demonstrating some of the issues and complexities that are associated with lake diatoms and their relationships to environmental conditions.

1.5 Greenland Paleoenvironments

1.5.1 Introduction

The Greenland Ice Sheet (GIS) is of significant interest in terms of future sea-level rise and climate change, however there is considerable uncertainty over the patterns of its behaviour (Jakobsson *et al.*, 2010), and relatively little understanding of how it has behaved during the present interglacial, the Holocene. This is an important area to increase knowledge on, as it will aid understanding and provide an improved context for changes to the GIS that are currently being observed, as well as providing data for mathematical ice sheet models utilized to predict both past and future change, and in the larger context, the implications it has for global climate change.

At present, the GIS is understood to have been smaller than present throughout most of the Holocene in southwest Greenland. Temperatures were several degrees higher than present during the Holocene thermal maximum (Kaufman *et al.*, 2004), and decreased as insolation fell during the neo-glacial, after 5000-4000 years BP (Wanner *et al.,* 2008); within these millennial scale temperature periods there were also several higher frequency fluctuations, including the 8200 years BP cold event, the Medieval Warm Period c.850-1300AD, and the following Little Ice Age c.1300-1800AD. The GIS is thought to have retreated behind the present day extent between 8-6000 years BP, reaching its minimum extent by 4000 years BP (Funder, 1989; Simpson *et al.*,2009), with a retreat of up to 40km in the southwest (Fleming and Lambeck, 2004), followed by readvance in the late Holocene to its present position over the last several millennia. The determination of former GIS dimensions and its response to climate change is therefore reliant on the use of proxy indicators, geomorphology and ice sheet models.

Ice sheet models, such as those by Huybrechts (2002), Tarasov & Peltier (2002) and Simpson *et al.* (2009) have been driven by temperature change that is derived from the oxygen isotope ($\delta^{18}O$) record produced from a Greenland ice core (GRIP; Dansgaard *et al.*, 1993). This core was collected at the summit from the interior of the ice sheet, and is representative of central Greenland conditions over the last two glacial cycles, with the record starting at 225kyr BP (Huybrechts, 2002). The location of the ice core can be seen in Figure 1.1. $\delta^{18}O$ is the difference between the ^{18}O:^{16}O ratio of a sample and of standard mean ocean water, normalized by the ratio of the standard, and is linked to site temperature (Alley *et al.*, 2010).

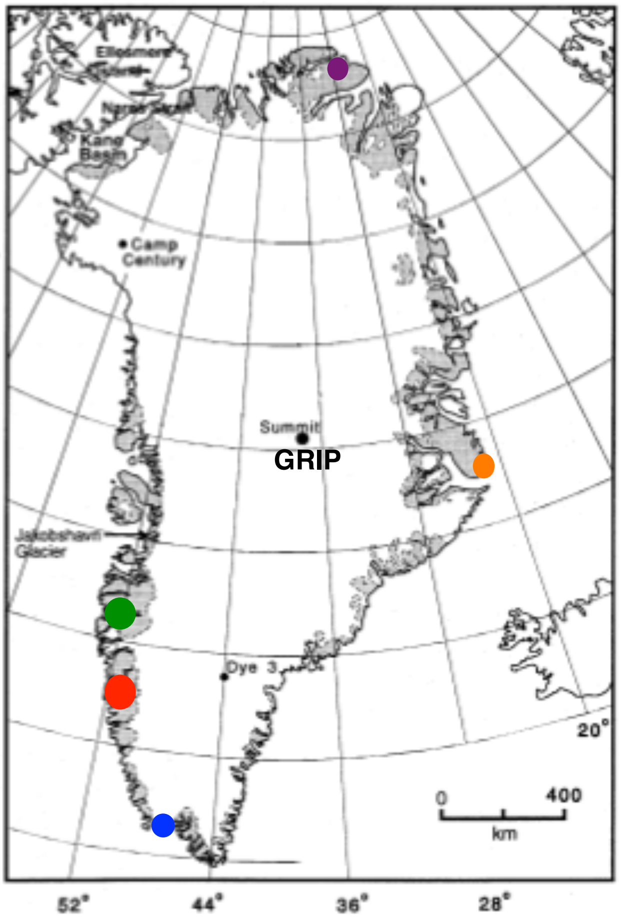


Figure 1.1 Map of Greenland indicating the locations of ice core records (GRIP and Dye) and some sites where lake diatoms have been utilized. Shading represents ice-free areas. Map modified from Huybrechts (2002).

Key:

Iverson (1952)
Fredskild (1983)
Kaplan *et al.* (2002)
Anderson *et al.* (2008)
Perren *et al.* (2009)
Cremer *et al.* (2001)
Olsen *et al.* (2011)

There are however multiple issues with the use of the $\delta^{18}O$ record. The $\delta^{18}O$ of ice is actually controlled by factors within the hydrological processes acting over various temporal scales, such as moisture source, precipitation seasonality, and air-surface temperature relationship (Alley *et al.*, 2010; Willemse & Törnqvist, 1999). It is therefore difficult to accurately correct for these additional factors when distinguishing the temperature record from the $\delta^{18}O$. Indeed, paleolimnological studies of west Greenland lakes revealed discrepancies in the ice-core time series (Willemse & Törnqvist, 1999). An additional, and perhaps more significant, issue is that $\delta^{18}O$ proxy records from ice cores best record the surface winter temperatures from the central part of the ice sheet, when the GIS surface mass balance and response is actually strongly controlled by summer temperatures in ablation zones, close to the margins and some distance from the ice core sites (Braithwaite, 1995; Vinther *et al.*, 2010). Despite this significance, there is a lack of robust Holocene summer temperature and environmental change records and proxies from the GIS periphery that are suitable to drive glaciological models.

Temperature records have been produced from the GIS ice cores (Figure 1.2). The ice core temperature record can be extrapolated to extend over the rest of the ice sheet as a function of elevation and latitude (e.g. Reeh, 1989), utilizing parameterizations based on direct observations of present day air temperatures at various stations across Greenland (Ohmura, 1987). These parameterizations though will be of limited accuracy when applied for paleoclimate, however they do provide a temperature model against which other proxy records can be compared.

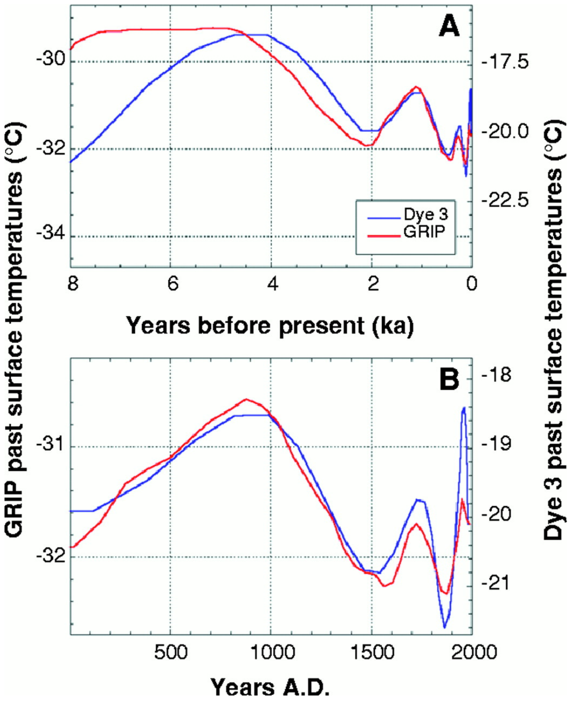


Figure 1.2 Reconstructed temperature histories of the GRIP (red) and Dye (blue) Greenland sites (Dahl-Jensen *et al.*, 1998)

In terms of other indicators of climatic and environmental change, there have been records produced from various locations around Greenland in the ice-free margins of the GIS. The changing productivity of lakes has been established at various locations through the use of proxies including diatoms and chironomids (e.g. Anderson *et al.*, 2008; Brodersen & Andrson, 2002; Cremer *et al.*, 2001);

productivity is a useful environmental variable to consider as it reflects the nutrient status of the lake, as well as climatic changes. Previous studies of lakes along Søndre Strømfjord have established various environmental conditions, such as isotopic composition and climatic gradients (Leng & Anderson, 2003), as well as analyzing diatoms to determine pH variations (Perren *et al.*, 2009; 2012) and stratigraphy to infer past lake-levels and paleohydrology (Aebly & Fritz, 2009), chironomids and alkenone unsaturation to infer lake-water temperature (Brodersen & Anderson, 2000; D'Andrea *et al.*, 2011) and also to produce Holocene reconstructions of lake conductivity to infer climatic and precipitation change (McGowan *et al.*, 2003; Ryves *et al.*, 2002).

1.5.2 Previous Studies

Greenland has been subject to multiple paleoenvironmental and paleoclimatic studies, with efforts at reconstructing various climatic and environmental features, from both terrestrial and marine sites; this section gives an overview of some of the relevant lake and diatom based studies.

Holocene climatic records derived from ice-free margins of Greenland have generally consisted the use of loss-on-ignition data, biogenic silica, and microfossils such as pollen and diatoms (e.g. Kaplan *et al*. 2002; Kaufman e*t al.*, 2004; Klug *et al*. 2009), though few of these are significantly well dated. Iversen (1952) initially provided an extensive overview of postglacial pollen in west Greenland, which was further expanded by Fredskild (1983) through the use of lake pollen records to determine paleoenvironments (Figure 1.1). An issue of pollen records though is that they are allochthonous, and it can therefore be difficult to determine the source, particularly in marine studies (de Vernal & Hillaire-Marcel, 2008). More recent studies of Greenland lakes have used multiple proxies to determine paleoenvironment and climate (e.g. Anderson *et al.* (2008), Cremer *et al.* (2001), D'Andrea *et al.* (2011), Eisner *et al.* (1995), Olsen *et al.* (2011)).

There have been multiple lake studies in western Greenland, particularly along Søndre Strømfjord, between Sisimiut and Kangerlussuaq and the ice margin. Modern lake studies along the fjord have included the analysis of stable-isotope composition over several years to establish the climatic gradient, particularly rainfall, of the fjord and how this is reflected in the isotopic composition of the lakes; within this seasonal trends are represented, including lower than average precipitation (Leng & Anderson, 2003). However, the composition is also forced by other variables such as snowmelt and evaporative loss (Leng & Anderson, 2003). This demonstrates the sensitivity of lakes to variations in climatic conditions on small, seasonal scales. However, it also revealed complexities based on the size of the lakes, with larger lakes demonstrating an ability to buffer the response to short term change, as well as a need to understand the hydrological setting to establish the sources of isotopic contribution (Leng & Anderson, 2003), and the usefulness of considering the water chemistry in conjunction with lake sediments when attempting paleoenvironmental reconstructions using lacustrine indicators. It is therefore necessary to consider that the records may demonstrate a varying strength of response to climatic and environmental change, and the source of the forcing, as individual lakes in west Greenland have demonstrated patterns of having largely individual histories, as well as spatial variability (Anderson *et al.*, 2012; Perren *et al.*, 2012).

The climatic history of lakes in western Greenland has been previously examined. In the Søndre Strømfjord region, the Holocene paleolimnological records consisting of diatoms, organic content and chlorophyll-*a* of three lakes have been used to establish the sequence of lake development and climatic change (Perren *et al.*, 2012). Based on the changes in species of the diatom assemblages and other proxies, the climatic shifts between the mid-Holocene warm periods are identified as well as changes in the effective moisture and eolian inputs, and again demonstrate the sensitivity of freshwater lakes within western Greenland, but also regional variability of the records within the lakes (Perren *et al.*, 2012). A similar eolian record was also produced from lakes in the same region along with respective pollen records; this also demonstrated the relationships between vegetation, eolian and limnological change (Eisner *et al.*, 1995), and lake stratigraphy has been used to establish Holocene lake-levels and the paleohydrology of Søndre Strømfjord (Aebly & Fritz, 2009).

Specific environmental variables have been reconstructed using proxies from lakes in western Greenland. Diatom-conductivity models have been developed and applied using a fossil diatom core and a series of lakes along Søndre Strømfjord, and produced a quantitiative conductivity record for the Holocene, allowing inferences in the variability of effective precipitation (McGowan *et al.*, 2003; Ryves *et al.*, 2002). In terms of temperature records from lake sediments in west Greenland, alkenone unsaturation measurements of lake sediments have revealed abrupt, centennial scale changes in temperature during the mid-late Holocene, consistent with changes also seen in the paleohydrology (Aebly & Fritz, 2009; D'Andrea *et al.*, 2011). Chironomids and lake environmental variables such as total nitrogen, total phosphorus and salinity have also been utilized (Brodersen & Anderson, 2002; Brodersen *et al.*, 2001). The relationship between the chironomids of the lakes and the trophic variables of total nitrogen and phosphorus, as well as temperature, was demonstrated to be strong; this indicates the potential for using quantitative reconstructions for climatic change and individual environmental variables from lakes in western Greenland (Brodersen & Anderson, 2002; Brodersen *et al.*, 2001).

An important issue to consider when using indicators from lakes is whether the community structure is being forced by climate or in-lake processes; Anderson *et al.* (2008) investigated this in the context of low-Arctic lakes using a multiple proxies from a site from south-west Greenland (Figure 1.1). Holocene climate change explained less of the variance than catchment or biotic relationships. However, vegetation succession is relatively limited and lakes have simpler trophic structures in the Arctic than in temperate systems, and west Greenland lakes also have limited or no anthropogenic disturbance (Anderson *et al.*, 2008). Though having an influence on the community structure of biological proxies, in-lake processes may not therefore completely overwhelm the signal that climate and environmental change may have caused, particularly in comparison to temperate lake records.

Within the Godthabsfjord region, the main study site of this thesis, there have been a number of lacustrine studies. Postglacial pollen and vegetational origin and development of the region and west Greenland were established through the study of multiple lake sediments from around the Godthabsfjord region (Iversen, 1952). The understanding of the development of the lakes and the environmental changes through the Holocene was expanded through the use of additional proxies including macrofossils and diatoms, as well as pollen (Fredskild, 1983; 1983a; Foged, 1977), demonstrating a sequence of stages of climatic change and lake development in the region, but also some regional variability of lakes, something that will be further investigated in this thesis. One of the lakes that has been repeatedly studied is 'Lake 100m s.m.' (Iversen, 1952; Foged, 1977; Fredskild 1983a; section 2.2). This lake is particularly close to the study site within this thesis, and has a dated chronology as well as pollen and diatom records that can be utilized and compared to the diatom record and reconstructions produced in this thesis. The diatom records from other west Greenland studies, both in the Godthabsfjord region and also along Søndre Strømfjord, provide comparative records for this thesis and to assess lake and diatom variability on a spatial and Holocene scale.

Spatial and temporal patterns of recent (last ~150 years) environmental change have been explored along a transect of lakes across the ice-free margin in west Greenland (Perren *et al.*, 2009). Diatom assemblages within sedimentary cores from 23 lakes were assessed to determine environmental changes; longitudinal and pH relationships were apparent across the transect of lakes (Perren *et al.*, 2009). The investigation concluded that west Greenland is one of the few Artic regions where lacustrine environments have not been impacted upon by anthropogenic activities (Perren *et al.*, 2009), and indicates the potential of Arctic lakes, particularly those in west Greenland, for providing natural climate records that have not been influenced by anthropogenic activities.

Biogenic silica is frequently interpreted as a direct proxy of paleoclimate; this assumes a strong link between the productivity of a lake and the air temperature (Kaplan *et al.*, 2002). Indeed, Kaplan *et al.* (2002) determined that lake sediments sampled in south Greenland lakes provide a record of climate history, due to the similarity of the lake biogenic silica record and borehole temperature records from a site 500km north (Figures 1.1 and 1.3). This is complicated however, as biogenic silica is a proxy of siliceous microfossils, particularly diatoms in this context, and is therefore ultimately a measure of paleoproductivity and the various variables that force diatom assemblages (Conley, 1988; Conley & Schelske, 2001; Kaplan *et al.*, 2002; Ragueneau *et al.*, 1996), which may in turn be used to assist in inferring paleoclimate.

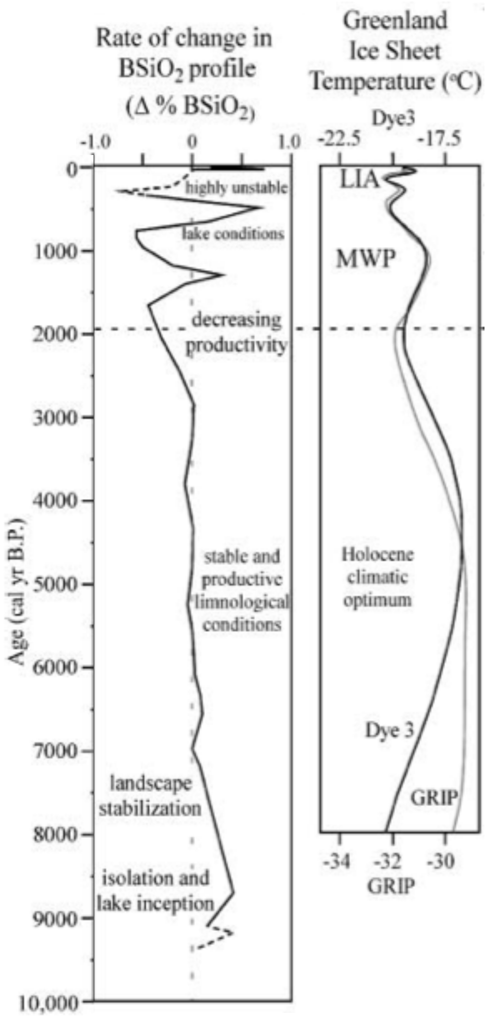


Figure 1.3 Rate of change in biogenic silica from a lake in south Greenland and the temperature record from ice cores in the Greenland Ice Sheet (Kaplan *et al.*, 2002).

In south Greenland, lake sediments from a coastal lowland have provided a continuous paleoenviornmental record of changes during the Holocene (Kaplan *et al.,* 2002)(Figure 1.1). Proxies used to interpret this record include the sediment stratigraphy, organic matter and biogenic silica; these were used to infer paleoproductivity of the lake, and decreases in the proxies c. 3000-2000 years BP indicate the lakes response to initial Neoglacial cooling. The sediment record of the lake is tightly coupled to lake production and Holocene climate, demonstrated by similarity to a borehole paleothermometry reconstruction from, and assists in validating the use of proxies, including biogenic silica, in paleoenvironmental reconstructions using arctic lake sediments (Kaplan *et al.*, 2002).

A diatom record from a lake on Raffles Sø, east Greenland (Figure 1.1), has been used to determine the postglacial environmental development of the area during the past 10,000 years (Cremer *et al.*, 2001). The diatom abundance and species composition of the lake was considered; the diatom record was characterized by low species number typical of extreme polar environments, and revealed there to be similar trends in diatoms and geochemical parameters, such as total nitrogen and total organic carbon, representing the changes in nutrient levels and lake productivity (Cremer *et al.*, 2001). This highlights the suitability of diatoms for such palaeolimnological applications in the Greenland context. The study of Holocene sediments from ice-covered Bliss Lake, northern Greenland, high arctic (Figure 1.1), utilized diatom analysis as well as other techniques, such as grain size, magnetic susceptibility and organic matter; the zones identified within the diatom assemblage coincided with those inferred from the lithology, physical and chemical proxies, and were used to determine the Holocene climatic history of warming and cooling of the lake and region, as well as the lake transition from marine conditions to isolation (Olsen *et al.*, 2011).

Diatoms from marine sources have also been used extensively around Greenland. Diatom assemblages from a marine core from Disko Bugt, west Greenland, have been used to infer late Holocene variations in the West Greenland Current (Krawczyk *et al.*, 20120). Sha *et al.* (2011) used diatoms from a marine core in Holsteinborg Dyb, west of Greenland, to reconstruct climatic changes over the last 1200 years. The diatoms displayed a high rate of consistency with the instrumental records for the last 70 years, demonstrating the reliability of diatoms for paleoceanographic and climatic studies (Sha *et al.*, 2011).

Fjords provide a record of the interaction of both terrestrial and marine processes, and can be used to explore the relationships between local and large-scale changes (Ren *et al.*, 2009). Fossil diatoms from a core from the Ameralik Fjord, part of the Godthabsfjord system in southwest Greenland, have been used to reconstruct mid-Holocene paleooceanographic and paleoclimatic changes, notably the progression of Holocene Thermal Maximum (Ren *et al.*, 2009). A similar study in the Ameralik Fjord analysed foraminifera, geochemical records and diatoms (Moller *et al.*, 2006). Shifts in the abundance of certain key species of diatoms determined hydrographic changes and ice conditions over the last 1500 years in the Igaliku Fjord, south Greenland (Jensen *et al.*, 2004).

1.5.3 Summary

Previous studies from southwest Greenland, and elsewhere in the Arctic, have demonstrated that diatoms are a good proxy to use to reconstruct climate and environmental changes through the Holocene. The relationship between the climate and diatoms in Arctic lakes is complex and requires further investigation. However, due to several factors, such as the basic food webs and little anthropogenic impacts on Arctic lakes, they may be utilized successfully to infer climatic and environmental changes. The southwest sector of the Greenland Ice Sheet is very climatically sensitive, and current ice models use ice core data from the centre of the ice sheet, which is not applicable at the margins. Southwest Greenland offers extensive potential for expanding our knowledge and understanding of Holocene environmental change through the use of lake sediments and diatoms. This study, from an ice margin location in southwest Greenland will investigate whether diatoms can be used to reconstruct Holocene climate changes with a view to further understanding ice margin temperatures and responses to climate events such as the Neoglacial, Medieval Warm Period and Little Ice Age in this location, and comparing this to other studies from the region and elsewhere in the Arctic.

2 Study Location

2.1 Introduction

The GIS covers an area of approximately 1.7million km^2, about 80% of the total area of Greenland (Alley *et al.*, 2012). The ice-free areas of Greenland are restricted to coastal margins, and are not evenly distributed around the coast; it is these ice-free zones that contain lacustrine environments that can offer sedimentary records to provide an insight of past environmental changes. Southwest Greenland in particular has a large corridor of ice-free land. This region lies to the west of the GIS, on the southeastern edge of Baffin Bay and to the north of the North Atlantic Ocean, and is therefore a key location in terms of GIS, climate and oceanographic changes (Figure 2.1).

The southwest Greenland ice-free region is characterized by the presence of thousands of lakes, providing an opportunity to study the diatoms and environmental conditions of the lakes and the region. The region is an important area of focus in understanding past conditions, but also present processes and predicting future changes.

The ice sheet surface in west Greenland is low elevation and gradient, and as such is sensitive to climate change, with a small variation in temperature resulting in large alterations to the size of the ablation zone. Models suggest the coastal corridor of west Greenland to have become free of ice during the early Holocene, with the ice sheet retreating inland of its present to its minimum extent 4000 years BP, before advancing during the neoglacial (Jakobsson *et al.*, 2010; Simpson *et al.*, 2009).

Studies suggest the lacustrine environments of west Greenland to be free from the impacts of anthropogenic activities (Perren *et al.*, 2009); Ryves *et al.*, 2002), and their biological structure is generally basic (Ryves *et al.*, 2002). The lakes from this region should therefore provide a sensitive and continuous record of climate and environmental changes throughout the Holocene.

2.2 Nuuk Field Site

The study area is a region northeast of Nuuk, southwest Greenland, in the low-Arctic, 64^{o}N, south of the Arctic Circle, in the west Greenland ice-free corridor (Figure 2.1). The geology of the study area consists predominantly of Archaean gneiss terrane, comprised of c. 3850-3300 Ma Færingehavn and the younger c. 2826-2750 Ma Tre Brødre terrance (GEUS, 1995; Hollis *et al.*, 2005; Næraa *et al.*, 2012). At the end of the last glacial maximum, 16000 years BP, the ice is modeled to have extended off the western coast of Greenland, on the continental shelf; between the 12000 and 10000 years BP, the ice had retreated to the Greenland coastline, and continuously inland to its minimum extent 4000 years BP, followed by readvance to its present position (Simpson *et al.*, 2009). The lakes in the region should therefore provide a record for the majority of the Holocene.

Lakes within the region have been previously utilized to provide pollen records for west Greenland (e.g. Fredskild, 1983; Iversen, 1952; section 3.3.2). Lakes along Godthåbsfjord have been used to establish the Holocene vegetative and climatic conditions (Fredskild, 1983; 1983a); one of these, 'Lake 100m s.m.', is labeled on Figure 2.2. The stages of the pollen identified from a core in this lake display an early eutrophic stage, followed by a mesotrophic and finally an oligotrophic stage, indicating a shift from climatic amelioration forcing the lake conditions to the role chemistry and vegetation of the catchment in the region (Fredskild, 1983a).

The paleovegetation of 'Lake 100m s.m.' has been established, beginning with a pioneer stage c. 9400 ^{14}C years BP, followed a *Salix-Cyperaceae* stage c. 8000-6300 ^{14}C years BP; *Salix* alone does not indicate climatic change, however the decline of open soil plants indicates less snow cover and an increase in temperature, and incorporates the inferred warmest and driest period in the record (Fredskild, 1983). This was followed by a *Betula nana-Juniperus* stage to 3500 ^{14}C years BP, and then an *Alnus crispa-Betula nana* stage to 1800 ^{14}C years BP suggestive a moist, warm climate, and finally a

Betula nana-Ericales stage to present indicating a change to cooler, more humid conditions (Fredskild, 1983). This indicates some interesting climatic and environmental changes to have occurred in the region during the Holocene, and are recorded within the lake sediments of the region.

The study site is located on the southern side of the Godthåbsfjord outlet, approximately 80km inland from the coast, approximately 40km from the ice-sheet margin, and approximately 35km northeast of Qoornoq (Figures 2.1 and 2.2). The site is towards the interior of Godthåbsfjord (Figures 2.1 and 2.2), and is characterized by a generally steep, mountainous, fell-field terrain with drawf-shrub heaths (Figures 2.2 and 2.3). The lakes sampled are located within N 64°36-40 and W 050°22-32, over an area of approximately 70km^2 (Table 2.1). Due to this positioning inland and close to the ice-margin, the lakes should strongly reflect terrestrial, ice-marginal environmental conditions and have greater synchronicity with climatic changes, rather than reflecting coastal, oceanographic conditions (Anderson *et al.*, 2012).

The steep relief of the area allowed the collection of samples from freshwater lakes covering an elevation range of 35-835m asl, but also from within relatively close proximity of one-another (Table 2.1; Figure 2.3). The extent of vegetation at the lake sites varied, and generally decreased with increasing elevation (Figure 2.4). Contemporary samples were collected from 25 lakes, and a fossil core collected from a lake at 608m asl (Figure 2.3). Collection of samples from a number of lakes in this area provides a more representative insight of variability of diatom flora and lake conditions within the region.

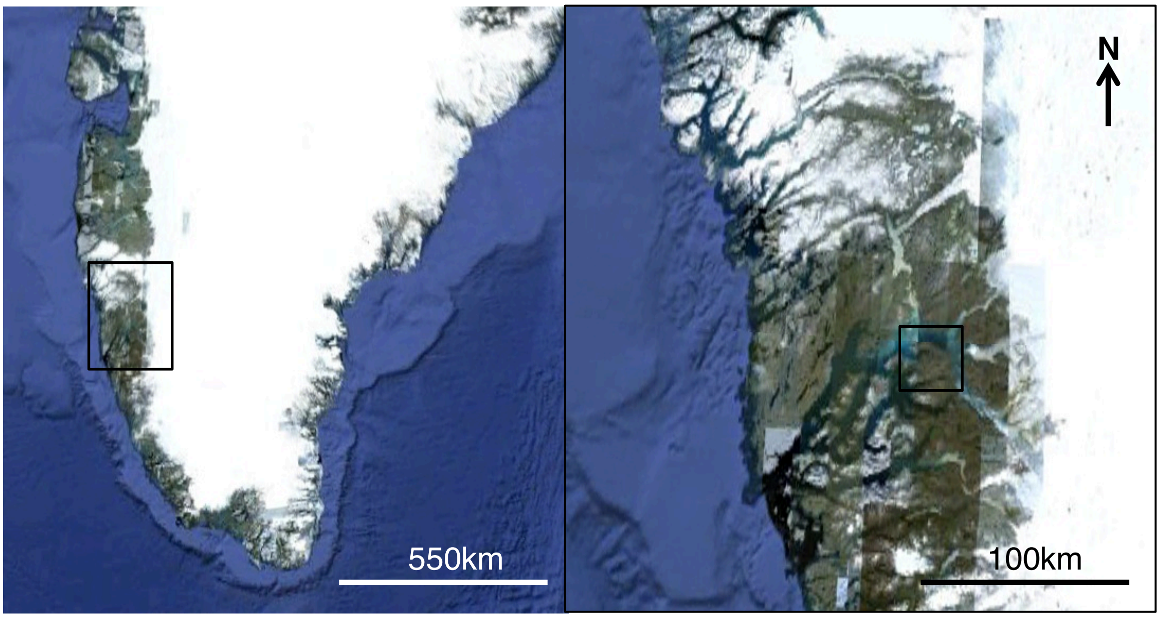


Figure 2.1 Position of the study location in south-west Greenland (left). Position of the study location on Godthåbsfjord (right). Images from Google Earth.

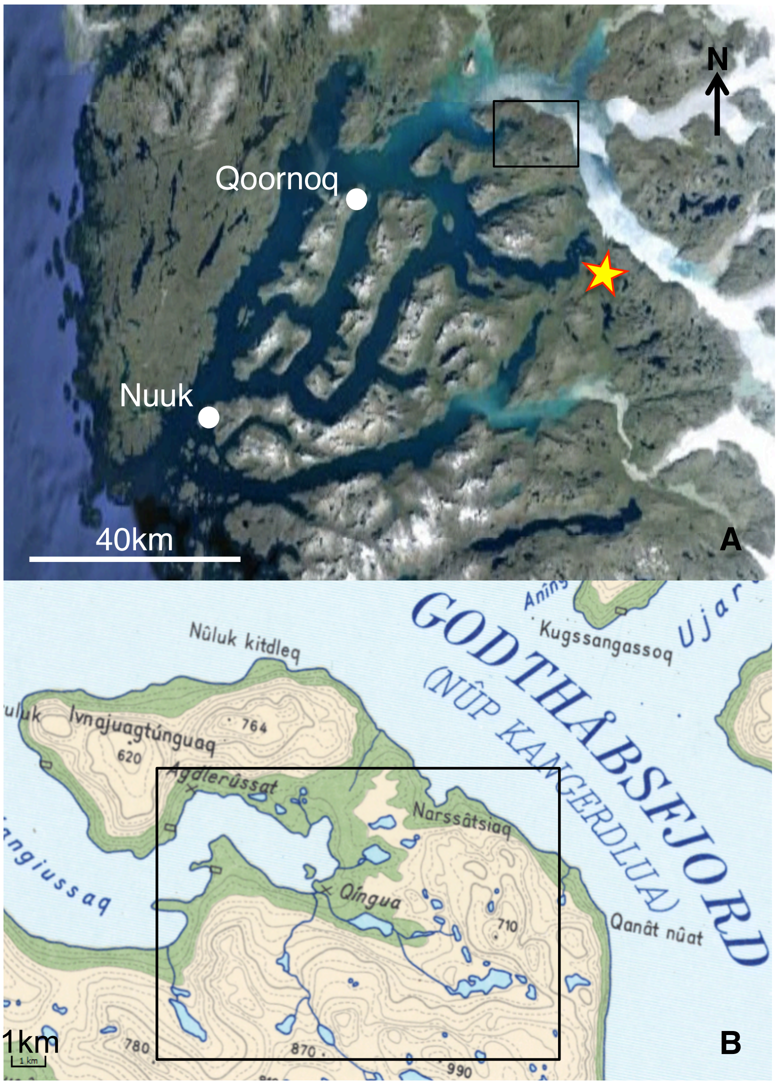


Figure 2.2 A shows the Godthåbsfjord region, with Nuuk, Qoornoq and the study location highlighted; position of 'Lake 100m s.m.' is indicated by the star. Image from Google Earth.

B is a topographic map of the study site in Godthåbsfjord, northeast of Qoornoq and Nuuk. Image from GEUS (1995).

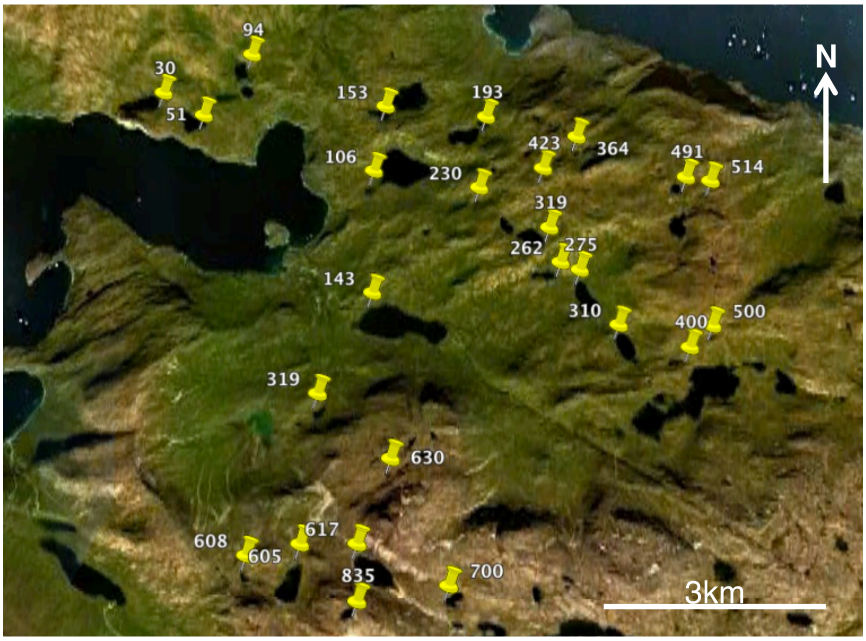


Figure 2.3 Positions of the 25 lakes sampled for contemporary sediment, environmental variables and water chemistry; labeled with elevation (m asl). 35-835m asl elevation range. Lake at 608m asl was sampled for a sediment core, studied in this thesis.

Elevation (m asl)	Latitude	Longitude	Elevation (m asl)	Latitude	Longitude
30	N 64°39.556	W050°31.787	364	N 64°39.202	W050°24.554
51	N 64°39.386	W050°31.078	400	N 64°37.646	W050°22.622
94	N 64° 39.830	W 50° 30.211	423	N 64°38.967	W050°25.133
106	N 64°38.967	W050°28.090	491	N 64°38.882	W050°22.696
143	N 64°38.056	W050°28.105	500	N 64°37.802	W050°22.249
153	N 64°39.438	W050°27.865	514	N 64°38.850	W050°22.287
193	N 64°39.369	W050°26.133	605	N 64°36.234	W050°29.194
230	N 64°38.829	W050°26.239	608	N 64°36.153	W050°30.095
262	N 64°38.271	W050°24.831	617	N 64°36.243	W050°28.217
275	N 64°38.214	W050°24.503	630	N 64°36.844	W050°27.686
310	N 64°37.811	W050°23.836	700	N 64°35.951	W050°26.685
319	N 64°38.524	W050°25.024	835	N 64°35.835	W050°28.214
319	N 64°37.310	W050°28.928			

Table 2.1 Elevation, latitude and longitude of the 25 lakes sampled.

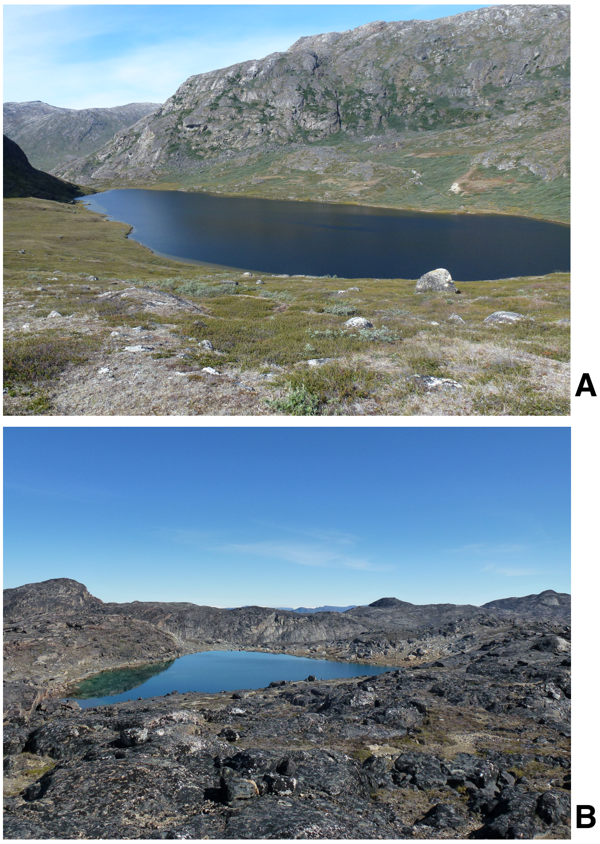


Figure 2.4 Images of two of the lakes studied in this thesis. A is the lowest elevation lake, at 30m asl; B is the highest elevation lake, at 835m asl.

2.3 Søndre Strømfjord Field Site

The contemporary data set was expanded through the inclusion of additional lakes from the Kangerlussaq region, along Søndre Strømfjord between Sisimiut and Kangerlussuaq, west Greenland (Figure 2.5). This data set was compiled and provided by Prof. John Anderson and Dr. David Ryves (Loughborough University), and comprises of 60 lakes. These lakes are positioned on the northern edge of the Kangerlussuaq Fjord (Søndre Strømfjord), along an east-west transect from the edge of the ice sheet near Kangerlussuaq to the coast, covering approximately 160km. This transect is approximately 260km north of the study location near Nuuk (Figure 2.5).

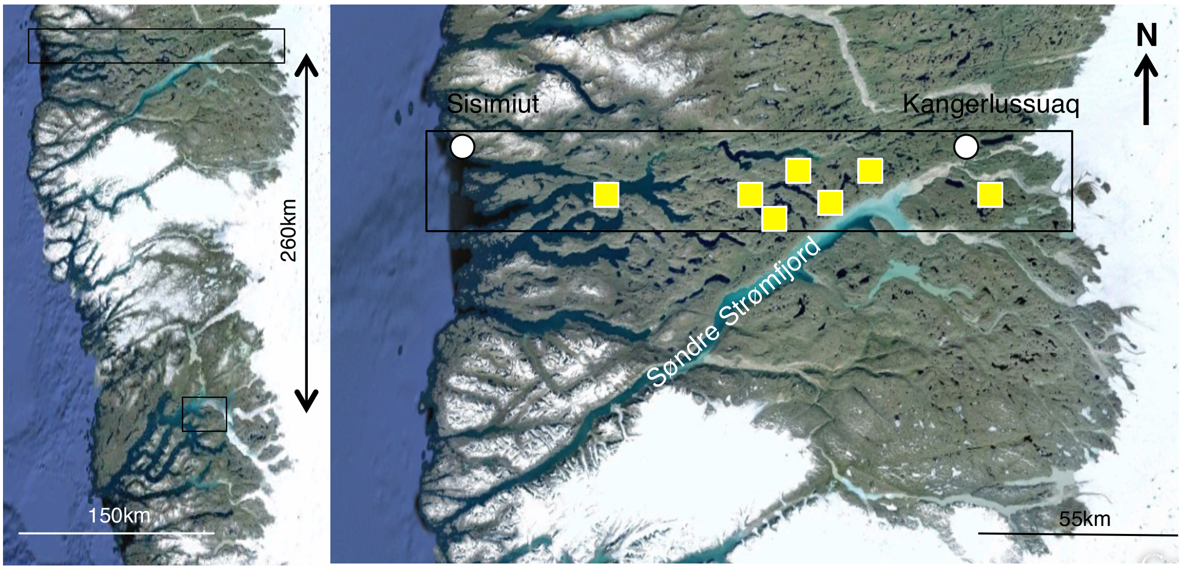


Figure 2.5 Position of the two dataset locations in south-west Greenland (left). Location of additional dataset lakes north of Kangerlussuaq Fjord (Søndre Strømfjord); 60 lakes were sampled along an east-west transect from Sisimiut to Kangerlussuaq: yellow squares indicate approximate positions of groups of some of these lakes (right; see appendix for individual lake altitude, latitude and longitude). Images from Google Earth.

Due to the positioning of this transect, the climatic conditions transition from low Arctic maritime at the coast, to low Arctic continental at the interior end at Kangerlussuaq (Anderson *et al.*, 2012; Ryves *et al.*, 2002). There are therefore significant differences in the lake environments, with those at the mouth of the fjord receiving much higher precipitation and with delays in periods of ice melt (Anderson *et al.*, 2012; Ryves *et al.*, 2002). This dataset also incorporates lakes ranging in salinity from coastal, dilute oligotrophic systems to subsaline (Anderson *et al.*, 2012; Ryves *et al.*, 2002), from an elevation range of 45-540m asl (see appendix). This dataset will provide a comparative set of data in terms of lake water chemistry and also diatoms, which may assist in attempting to understand the present lake conditions of the Nuuk lake set, but also in understanding the fossil diatoms and environmental changes preserved in the lake core.

3 Methodology

The methods used in this thesis have been categorized into three sections: field, laboratory and analytical methods.

3.1 Field Methods

3.1.1 Contemporary Samples: Nuuk Training Set

A total of 25 lakes were sampled during July and August 2011, covering an elevation range of 30 to 835m asl from the Nuuk area (section 2.2). Collection of surface sediment samples from each lake provides a spatial and environmental range of diatom communities. Surface sediment samples of 1cm thickness from the deepest part of each of the lakes were taken using a HTH corer (Renberg & Hansson, 2008) to provide the contemporary diatom data. Once returned to Durham, these sediment samples were placed into cold storage (~4^{o}C). Water samples were taken at a depth of 50cm in the lake centre for chemical analysis of alkalinity, pH, conductivity, anions and cations; water samples were also taken to provide measures of total carbon and total phosphorous. GPS co-ordinates were taken to record lake location, and other observations such as maximum lake depth, number of inflows and outflows, presence of fish, and catchment vegetation were recorded. The lake areas and lake profundal areas were calculated using maps. These variables will provide an insight into differences between the various present lake conditions, as well as variables that can be assessed in relation to the diatom assemblages.

3.1.2 Fossil Samples

2 sample cores were collected from pristine, shallow lakes with limited catchment drainage to reduce potential effects of catchment processes regulating the trophic status of the lake, and thus maximizing the role of in-lake processes. A core of approximately 2m in length was taken from a lake at 610m asl, from a depth of 3.9m. Once returned to Durham, the cores were placed into cold storage.

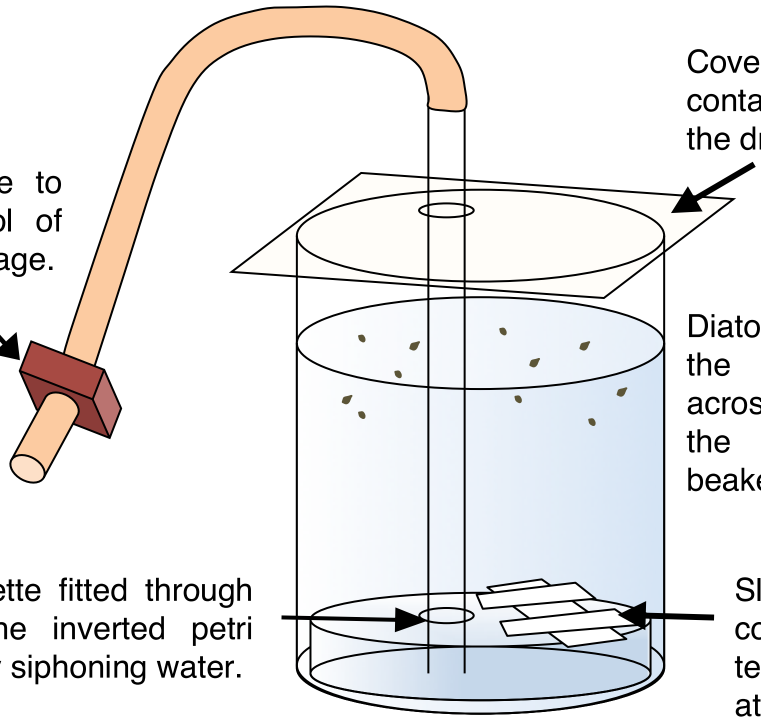
3.2 Laboratory Methods

3.2.1 Contemporary Diatoms

Slides were produced for the 25 contemporary lake samples. A small wet amount (0.2-0.23g) was taken and prepared using standard diatom preparation techniques (Palmer & Abbott, 1986).

To determine absolute abundance of diatoms (diatoms valves per gram of dry sediment), the settling technique outlined by Scherer (1994) was used. This method has been shown to be accurate when tested against known numbers, and provides an even distribution of diatom valves on slides (Scherer, 1994). Firstly, sediment samples were oven dried at 40°C. A small amount (0.02-0.03g) of dry sediment was taken, measured using a Sartorius CP225D balance, and placed into a half filled glass vial (15ml) of distilled water. To this a few drops of hydrochloric acid (10%) was added to remove carbonates, and 3ml of hydrogen peroxide (30%) to oxidize organics and disaggregate particles. The vials were then left for several hours on a warm plate (~40°C) to allow the oxidation reaction; after this, 1ml of dispersing agent (sodium hexametaphosphate, prepared from 40g of powder per liter of distilled water) was added and topped up with distilled water and left for a further hour. The sample vials were then placed in an ultrasonic bath for 1-3 seconds to disaggregate the sample. The vial contents were emptied into a flat-bottomed 1-liter beaker filled with de-ionized water. At the bottom of each beaker there was a glass petri dish that had a slide on top, with two cover slips attached; a pipette was fitted through a hole in the petri dish slowly drained the beaker from beneath the petri dish over approximately a 12-hour period (Figure 3.1 and 3.2). After the cover slips had air dried, permanent slides were made using Naphrax, as outlined with the standard method.

Water siphoned out through tubing.



Cover to prevent contamination during the draining period.

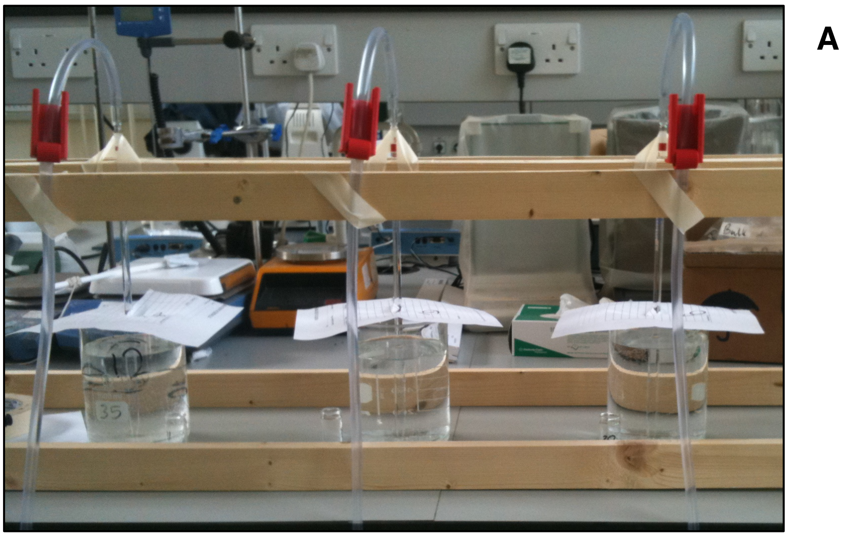
Plastic valve to allow control of rate of drainage.

Diatoms sink through the water to settle across the contents of the bottom of the beaker.

Glass pipette fitted through hole in the inverted petri dish slowly siphoning water.

Slide with two cover slips temporarily attached by a small amount of glue.

Figure 3.1 Apparatus arrangement for the production of diatom absolute abundance slides.



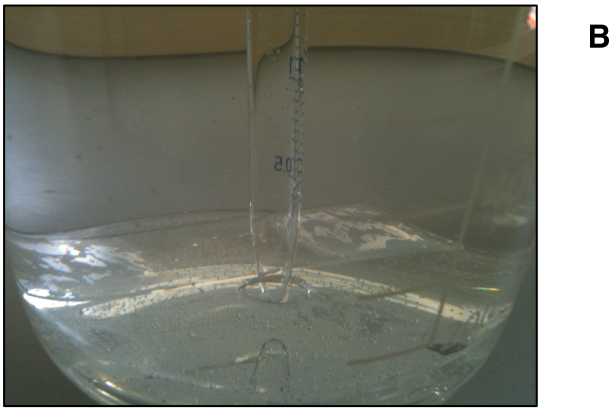


Figure 3.2 A) Image of several of diatom absolute abundance apparatus running simultaneously. B) Close-up image of coverslips at bottom of beaker, with the pipette through the central hole of an inverted petri dish.

3.2.2 Fossil Diatoms

The fossil core is approximately 2m in length and is assumed to represent the majority of the Holocene period, as lakes in the region formed 9500-8500 years BP as a result of relative sea-level fall due to glacio-isostatic adjustment following glacial unloading and retreat of the ice sheet inland (Long *et al.*, 2011). The core was scanned and split, and samples have been taken for chironomids and pollen as part of the Leverhulme funded ‘Tipping Points’ project, focusing on the neo-glacial transition. Samples for diatoms were also taken to correspond to these other proxies; as such, 23 samples were provided at 8cm intervals, providing a coarse overview of the conditions and trends in diatom assemblage at the lake during the Holocene. Following initial analysis, an additional 8 sub-samples were taken at 4cm resolution at particular areas of interest within the core. A small volume of sediment (approximately 0.5cm^3) was taken and prepared using the same standard technique as outlined for the contemporary diatom samples (3.2.1).

3.2.3 Biogenic Silica

Biogenic silica is widely applied in paleolimnological studies; it measures the amorphous silica content of sediment, and is often derived through chemical methods (Conley & Schelske, 2001). It is considered to be a good proxy for diatom abundance along with other siliceous microfossils, and when treated as a single proxy it provides an indicator of both diatom abundance as well as diatom productivity, depending on the environmental system (Conley, 1988; Conley & Schelske, 2001; Kaplan *et al.*, 2002; Ragueneau *et al.*, 1996). Biogenic silica is also better preserved in lake sediments than organic carbon (Berger *et al.*, 1989; Swann, 2010). It is therefore often strongly relied on as an indicator of paleoproduction at both marine and lacustrine sites, alongside other proxies such as diatoms and loss-on-ignition (Kaplan, *et al.*, 2002; Swann, 2010).

The most widely used method is wet-alkaline digestion due to the simplicity and robustness of the technique (Swann, 2010). This approach involves the digestion of non-biogenic silica alongside the biogenic silica sources; the silica is assumed to have originated from biogenic silica, and corrections can be made for digested non-biogenic silica (Swann, 2010). The aluminum concentration in the digested solution can be considered (Eggimann *et al.,* 1980; Swann, 2010); digested aluminium measurements can be used to account for the non-biogenic silica leached during digestion (Ohlendorf & Sturm, 2008; Swann, 2010). This silica/aluminium approach has been used on surface sediments (e.g. Koning *et al.,* 2002; Ragueneau *et al*., 2005) as well as in lake core sections (e.g. Swann, 2010). Comparison results show no significant discrepancies between the two approaches, indicating that the traditional approach is suitable in instances of low amounts of non-biogenic silica; however, as the amount of digested non-biogenic silica is not necessarily known in advance, the sequential silica/aluminium approach is recommended (Swann, 2010).

For this thesis, the silica/aluminium wet-alkaline digestion technique (Dobbie, 1988; Eggimann *et al*., 1980; Mackie, 2004; Swann, 2010) was adopted. Samples from the fossil core were taken to correspond to those taken for fossil diatoms. A small amount of sediment (<1g) from each sample was placed in polypropylene tubes and oven dried at 40°C. The dried sediment was milled and 50mg measured using a Satorius MC21S balance; this was then placed in a polypropylene tube with 20ml of 2M sodium carbonate solution, and digested in a water bath at 90-100°C for 4 hours. To help reduce loss of solution due to evaporation during this period, the tubes were covered with plastic watch glasses. Once cooled, to remove any undigested sample, the samples were filtered through Whatman 542 hardened ash less filter paper into a 100ml plastic volumetric flask; the filtrate was then made up to 100ml using de-ionized water. Throughout this process, the use of glass equipment was avoided to prevent potential contamination of silicate from the glass. To insure consistency of conditions experienced throughout this preparation process, all the fossil and contemporary samples were processed in their respective batches simultaneously.

The samples were analysed for Al and Si on a Mass Spectrometer in standard mode and a Perkin Elmer Elan 6100 DRC. Three standards were taken (100, 250 and 1000ppb Al and SiO_2) to form a linear calibration graph. A blank sample was also run and the Al and Si contents of this were subtracted from the sample values. To correct for non-amorphous silica derived from the sediments, twice the Al_2O_3 content of the solution was deducted from the values, assuming the SiO_2: Al_2O_3 ratio to be approximately two (Dobbie, 1988; Eggimann *et al.*, 1980; Mackie, 2004). Though a range of Al: Si ratios have been demonstrated to exist in lacustrine sediments, a ratio approximation of 1:2 is generally most appropriate (Ohlendorf & Sturm, 2008).

3.3 Analytical Methods

3.3.1 Contemporary and Fossil Diatom Identification

Counting of the contemporary lake and fossil diatoms within each slide was carried out in a systematic manner, using a Motic BA 300 microscope with x1000 magnification and immersion oil, with 250 being counted from each sample and identified following the taxonomy of Hartley *et al.* (1996). 250 diatoms is only a proportion of the assemblage present within a sample; various researchers often undertake larger counts of 300-400 specimens, which results in a lower counting error. However, the decrease in counting error from larger counts is relatively small given the additional time required to produce the larger counts. As such, 250 is an optimum amount to count given the time constraints on the research.

3.3.2 Diatom Assemblages

CONISS was performed on the contemporary lake diatom data. This is a form of incremental sum of squares cluster analysis, and was performed unconstrained through the use of the software *TIlia* v.2.0.2 and *TG View* v.2.0.2 (Grimm, 2004). CONISS was undertaken using the Euclidian distance method (no data transformation). This numerical approach divides the diatom data into assemblage zones based on the major taxa, and reduces the subjectivity introduced by attempting to do so by visual interpretation (Bennett, 1999). CONISS was also performed on the fossil diatom data, though will be constrained by the sample depth, thus dividing the fossil diatoms into zones down the core.

3.3.3 Contemporary Diatom Abundance

The slides created for determining the absolute abundance of the contemporary lake diatoms were counted using a Leica DM LB2 microscope with x1000 magnification and immersion oil. The method of counting followed that outlined by Scherer (1994). All whole diatoms within each field of view were counted and identified following the taxonomy of Hartley *et al.* (1996); the number of field of views counted was recorded, with care taken to ensure no overlap of the fields of view, and counting near the edge (~0.5mm) of the cover slip was avoided. Approximately 250 taxa were counted for each sample, so as to make the counts comparable to those from the other method. This data allows for the determination of diatoms in a known area, and consequently per gram of sediment. Assuming that the distribution of particles across the bottom of beaker is random, the amount of diatoms across the bottom of the beaker, and therefore in the original sample, can be determined (Scherer, 1994). This can be achieved through the following expression, formulated by Scherer (1994):

$T = (N\,B / A\,F) / M$

where,

T = number of diatoms per unit mass

N = total number of microfossils counted

B = area of bottom of beaker (mm^2)

A = area per field of view (mm^2)

F = number of fields of view

M = mass of sample (g).

3.3.4 Additional Lakes

Contemporary diatom assemblages and the respective lake environmental data was provided by Prof. J. Anderson and Dr. D. Ryves (Loughborough University) for an additional 60 lakes from a region further north in West Greenland (Section 2, Figure 2.4). To merge these with the contemporary diatom assemblages produced in this research, the diatom taxonomy was assessed and harmonized during a visit to Loughborough to ensure consistency between the two datasets. Comparisons between the two contemporary datasets in terms of assemblage similarities and species abundance was assessed in *C2* (Juggins, 2003), as was the similarities with the fossil assemblages; comparisons between the contemporary lake environmental conditions was also carried out between the two data sets.

3.3.5 Multivariate and Ordination Analysis

Ordination is a multivariate statistical approach within exploratory data analysis that is utilized to analyze the relationships between the contemporary diatom species assemblages and environmental lake variables. Ordination can simply be considered as arranging or ordering; in an ecological context, this involves arranging species/samples in relation to environmental gradients, or abstract axes that could represent such gradients (Austin, 1976), and using ordination axes produced to try to explain the species abundance (Lepš & Šmilauer, 2003). Unconstrained (indirect) ordination methods are those that seek gradients that represent the 'optimal' predictors/environmental variables for the species response (Lepš & Šmilauer, 2003); this is required when the environmental variables are unknown (Austin, 1976). Constrained (direct) ordination similarly finds gradients, however the gradients are linear combinations of given explanatory/environmental variables (Lepš & Šmilauer, 2003). This process allows the establishment of quantitative relationships between the present lake properties and the contemporary diatom assemblages, which can be used to inform the paleoenvironmental reconstructions (Lim *et al.*, 2007).

Principal component analysis (PCA) is a form of linear unconstrained (indirect) ordination (Lepš & Šmilauer, 2003); Goodall (1954) first utilized PCA in an ecological context. PCA is used to determine the major trends within the diatom assemblages, summarizing the variations (Lepš & Šmilauer, 2003). It is also used to consider all the measured environmental variables, and which may be the most significant (achieved through the use of *CANOCO 4.5*, with resultant data being plotted using *CanoDraw*). Following this, constrained ordination methods were utilized to consider the role of the lake environmental variables in the diatom species composition.

Canonical correspondence analysis (CCA) is a form of constrained (direct) ordination. CCA arranges the diatom species based on the values of the multiple lake environmental variables, expressing the relationships between species composition and environmental gradients (Austin, 1976), and as such the greater the dissimilarity between variables, the greater the distance between them. In simpler terms, it extracts the variation in the diatom assemblages that is explainable by the measured lake environmental variables (Lepš & Šmilauer, 2003). The resulting relationship can be displayed graphically, with other statistical values, such as the P-value, being produced for the variables.

Monte Carlo permutation tests were applied when running CCA. Permutation tests are a test of a null hypothesis. The null hypothesis is that the species composition is independent of the environmental variables; if this is correct, it does not matter to which species composition observations the explanatory values are assigned (Lepš & Šmilauer, 2003). Based on this, the environmental variable values are randomly assigned to individual samples of species composition and ordination analysis is conducted, and the test statistic is calculated; from this the significance level of the test can be calculated (Lepš & Šmilauer, 2003).

Once the ordination methods were completed, the results were displayed graphically on ordination diagrams, with the various aspects displayed by different symbols. In this thesis, bi-plots are used; these simultaneously plot the species and samples scores. For PCA, points represent species and are positioned to indicate their relation to the axes. In CCA, the arrows represent the environmental variables; the direction of the arrow indicates the direction of maximum correlation, and length the strength of this correlation. Point symbols represent the samples in both methods (Lepš & Šmilauer, 2003).

CCA was systematically repeated on the data, with those environmental variables that were discovered to be of little importance in the explanation of the variance of the diatom assemblages being excluded, so as to define those which are the most significant. As well as this though, individual lake samples with extreme environmental variables were considered, with some being excluded during the repeated CCAs to help prevent any skewing of the results in favour of a particularly extreme variable. This process was carried out on both the original training set of 25 contemporary lakes, and on the expanded training set with the additional 60 lakes.

3.4 Analytical Methods- Fossil Data Reconstructions

3.4.1 Detrended Correspondence Analysis

Detrended correspondence analysis (DCA) is a commonly used indirect ordination method that assists in overcoming the arch effect that can be produced by correspondence analysis (CA), whereby the positions of the samples on the second axis are strongly dependent on their positions on the first axis (Lepš & Šmilauer, 2003). Detrending by segments is an often-used approach for making the gradient straight (linear) (Lepš & Šmilauer, 2003), and in this case is used on the diatom assemblages alone to infer their relationships to the first axis. The purpose of using this is to determine the position of the contemporary lake samples, and also the fossil samples, in relation to the first DCA axis.

The axes produced by DCA are ranked in order so that the first axis explains the principal sources of variation in sample assemblages, and the progressively higher axes explain less of the data set variation (Holland, 2003). The sample scores produced within DCA represent the position of that sample on the axis, reflecting the value for that sample of the environmental variable that the axis represents (Holland, 2003). This allows for the use of DCA sample scores to estimate past environmental conditions of a particular variable, with axis 1 scores being taken as a direct measure of the principle forcing factor of environmental change (Holland, 2003).

This method has been used widely in a variety of environmental contexts, e.g. Holland (2003) to examine taxa and stratigraphic change, Shennan *et al.* (1995) to assess sea-level and vegetation change, and Kurek *et al.* (2009) to infer paleoclimatic and vegetation histories. The sample scores for the fossil assemblages were compared to those of the contemporary samples, and inferences made as to the changing environment, and in particular the variable that the DCA axis 1 appears to most strongly represent. The DCA axis 1 sample scores can plotted to produce an environmental curve for the fossil assemblages. This was done with the original Nuuk training set of 25 samples, and also with the expanded regional training set.

3.4.2 Transfer Functions

C2 (Juggins, 2003) is used to create and employ transfer functions to reconstruct environmental variables that have been demonstrated to be significant within the multivariate analysis. Transfer functions can be developed from the analysis of the quantitative contemporary biological data, in this case diatoms, to reconstruct particular environmental variables for the fossil diatom data (Imbrie & Kipp, 1971). This process essentially allows for the expression of an environmental variable as a function of biological data. Transfer functions achieve this by utilizing regression calculations to model the response of the contemporary diatom assemblages as a function of the environmental variable (Birks, 1995). Calibration then applies the response function to predict the past environmental variable based upon the fossil diatom assemblage (Birks, 1995).

The response function produced by the regression calculations can be either a linear response or a unimodal response model (Birks, 1995; Horton & Edwards, 2006). A unimodal response assumes a normalized clustering around the environmental variable, with the species optima for the environmental variable closest to the site will be the most abundant species; this is generally the case with species (Birks, 1995). A statistical approach that produces unimodal response is Weighted Averaging-Partial Least Squares (WA-PLS). The variance along the environmental gradient is considered, with each species assigned an ecological optimum, recording the range of the particular environmental variable it lies within, as well as its preferred position in the environmental variable and ecological tolerance (Horton and Edwards, 2006); it also takes into account residual correlations among the biological data (Birks, 1995).

Within *C2* (Juggins, 2003), each model that is run using WA-PLS produces a series of five different components. The first of these components maximizes the covariance between the vector of the weighted averages and the biological data, in this case the diatoms (Birks, 1995; Hamilton and Shennan, 2005); the further components maximize the same criteria but are uncorrelated to the previous components (Hamilton and Shennan, 2005; ter Braak *et al.*, 1993), and are therefore more distant from what is occurring in the environment. Due to this, only the first three components are generally considered for use for reconstruction, as components beyond this can be thought to be too far from the reality. Selection of the most suitable component is based upon the Root Mean Square Error of Prediction (RMSEP) and Coefficient of Determination (r^2). RMSEP gives the error of the predicted values, an assessment of the overall predictive ability and therefore precision, and r^2 the strength of relationship between the contemporary and inferred values (Birks, 1995; Leorri *et al.*, 2008). Bootstrapping provides cross validation; the bootstrapped r^2 value is considered as it is based upon pseudo-replicate datasets, 100 cycles, improving confidence. The components that are used for reconstruction are selected based upon a minimization of RMSEP and maximization of r^2 (Birks, 1995; Juggins, 2003).

Whilst the use of RMSEP and r^2 provide a measure of the performance, they only really reflect the internal consistency of the transfer function, and fail to offer a measure of the overall reliability of the estimates that the transfer functions produce (Horton and Edwards, 2006). It is important to consider whether the modern training set offers a fair representation of the fossil samples (Birks, 1995; Horton and Edwards, 2006); the greater the extent of dissimilarity between the fossil and training set data the more the transfer function is forced to extrapolate, producing a greater potential for error in the resultant estimates (Birks, 1995; Horton and Edwards, 2005; 2006). To identify fossil samples that lack good modern analogues, Modern Analogue Technique (MAT) can be applied (Birks, 1995; Horton and Edwards, 2005; 2006). This is done within *C2* (Juggins, 2003), for each of the developed transfer functions for the various environmental variables. The dissimilarity is calculated between the fossil samples and the ten most similar contemporary samples; those with coefficients below the tenth percentile can be considered as having good modern analogues, and those above as having poor modern analogues (Birks, 1995; Horton and Edwards, 2005; 2006).

Transfer functions were produced for several of the environmental variables using the Nuuk training set of 25 contemporary lakes, and are applied to the fossil assemblages to produce the respective reconstructions and errors for those variables. This was also done for two of the variables for which there was significant overlap between the datasets with the expanded training set. The results of these reconstructions were plotted and compared to those from the DCA axis 1 scores, as well as the fossil assemblages, to assess the environmental changes that have occurred through the Holocene.

3.5 Summary

This chapter has outlined the field, laboratory and analytical methods used throughout this thesis. The following chapters present the results of these methods for both the contemporary and fossil diatom data, and contribute to the main aims of understanding the contemporary relationships of the lakes diatoms, and also to developing a record of Holocene environmental change using a fossil lake diatom record.

4 Results

The results of this research have been split into three sections: the analysis of the local contemporary dataset, the expanded regional dataset, and also the analysis of the fossil core.

4.1 Local Analysis

4.1.1 Contemporary Diatom Assemblages

Contemporary diatom samples were collected from the surface 1cm of sediment of 25 separate lakes. All samples provided the minimum of 250 taxa; in total, 103 species were identified, though most samples contained c. 30-40 different species. Figure 4.1 shows the assemblages in respect to elevation. Several of the species are universal across all the lakes; *Tabellaria flocculosa* in particular has a significant presence in all of the lakes. *Fragilariforma virescens* and *Frustulia rhomboides* are also universal across the lakes, with varying abundance, as are *Fragilaria vaucheriae, Navicula cryptotenella* and *Pinnularia subcapitata var.* hilseana, with one or two exceptions. Interesting features include a decline of certain species, such as *Aulacoseira alpigena* and *Cyclotella spp*, with increased elevation. *Cyclotella spp* also have a distinct peak in the lake at 310 m; this lake is unique within the training set as it has an extreme sample depth of 20.1 m, whereas the majority of others are between 2-10 m deep.

The lowest elevation lake, at 30 m asl, is largely dominated by *Aulacoseira spp.*, with a high presence of *Cyclotella spp.*, with approximately 7% *Fragilariforma virescens* and 14% *Tabellaria flocculosa,* in the mid-ranges of abundance for those species found across the lakes; it has a relatively high abundance of diatoms (44.7 per g/10^{-5}). Lake 20, at 310 m asl, is the deepest lake in the set, and is unique with the high abundance of nearly 30% of *Cyclotella spp.* present. It has a low amount of *Frustulia rhomboides* and *Tabellaria flocculosa*, and 5% *Fragilaria vaucheriae* and *Fragilariforma virescens*, and an overall low abundance of diatoms (8.6 per g/10^{-5}). This lake also has the second lowest biogenic silica content and lowest loss-on-ignition compared to the rest of the lakes (Figure 4.1) Similarly, the shallowest lake, at 423 m asl, also has a low abundance of diatoms (6.8 per g/10^{-5}); it also has the third lowest biogenic silica content, and relatively low loss on ignition of 14.6%. It is characterized by a higher than average amount of *Achnanthes spp.*, and an increase in the presence of *Cyclotella rossii* and *Eunotia exigua*, with average values of *Fragilaria vaucheriae, Fragilariforma virescens, Frustulia rhombiodes* and *Tabellaria flocculosa.*

The lake in the middle of the elevation range, at 400 m asl, is characterized by a large spike in the amount of *Eunotia arcus* and *Navicula crytotenella*, and average amounts of the common species *Fragilaria vaucheriae, Fragilariforma virescens, Frustulia rhombiodes* and *Tabellaria flocculosa*; it has a diatom abundance of 15 per g/10^{-5}. The highest elevation lake, at 835 m asl, is dominated by a large abundance of *Frustulia rhomboides,* and has a large number of *Eunotia spp.*, with a distinct peak in the amount of *Eunotia veneris* and *Eunotia vanheurckii* compared to the other lakes. It has the lowest amount (2%) of *Fragilariforma virescens* of all the lakes, as well as a low amount (5%) of *Tabellaria flocculosa*, and a low abundance of diatoms (6.7 per g/10^{-5}).

Unconstrained cluster analysis, CONISS, was performed on the contemporary lake diatom data using TGView v1.7.14. (Grimm, 2004) to define separate zones within the assemblages (section 3.3.2). This split the sample assemblages into four major zones (Figure 4.2). There appears to be no trend in terms of elevation influencing the assemblage zones. In general, zone 1, comprised of seven samples, is characterized by the presence of *Fragilaria vaucheriae,* and *Fragilariforma virescens*; zone 2 is the largest, comprised of ten samples, and characterized by *Eunotia arcus, Frustulia rhomboides* and *Tabellaria flocculosa*; zone 3 by *Cyclotella rossii* and *Cyclotella stelligera*, and zone 4 has seven samples, characterized by *Aulacoseira alpigena*. Zone 3 consists of just one lake; this is the lake at 310m asl, the deepest lake that has a uniquely high abundance of *Cyclotella stelligera* and *Cyclotella rossii*.

The lake sampled for a fossil core has the lowest biogenic silica abundance of the lakes, and a relatively average loss-on-ignition content of 18.54%; it also has the lowest diatom abundance (0.65 per g/10^{-5}). In terms of diatom assemblages, there are reasonable similarities between the contemporary sample from the fossil core lake, at 608m asl, and the sample from the top (0cm) in the fossil core. The contemporary sample had 31 diatom species, and the top of the lake core 28 species; of these, both shared the same most abundant species (>5% abundance): *Cymbella hebridica, Fragilariforma virescens, Navicula cryptotenella, Pinnularia subcapitata var. hilseana, Pinnulaira viridis* and *Tabellaria flocculosa.* This similarity between the contemporary assemblage of the lake and that in the top of the fossil core indicates that the record in the core is a relatively fair reflection of the conditions of the lake

4.1.2 Biogenic Silica and Loss-on-Ignition

The percentage of biogenic silica and diatom abundance generally shows some similarity though there is no distinct relationship apparent between the two. In some instances, such as the lake at 310m asl, the diatom abundance, biogenic silica and loss-on-ignition all display a decrease in value; however, with the lake at 605m asl, there is an increase in the diatom abundance, but a decrease in the amount of biogenic silica and also loss-on-ignition (Figure 4.1), indicating there to be complex relationships. There is a decrease of these values at the highest elevations, implying a reduction in the productivity within these higher elevation lakes, though all the values fluctuate significantly across the elevation range.

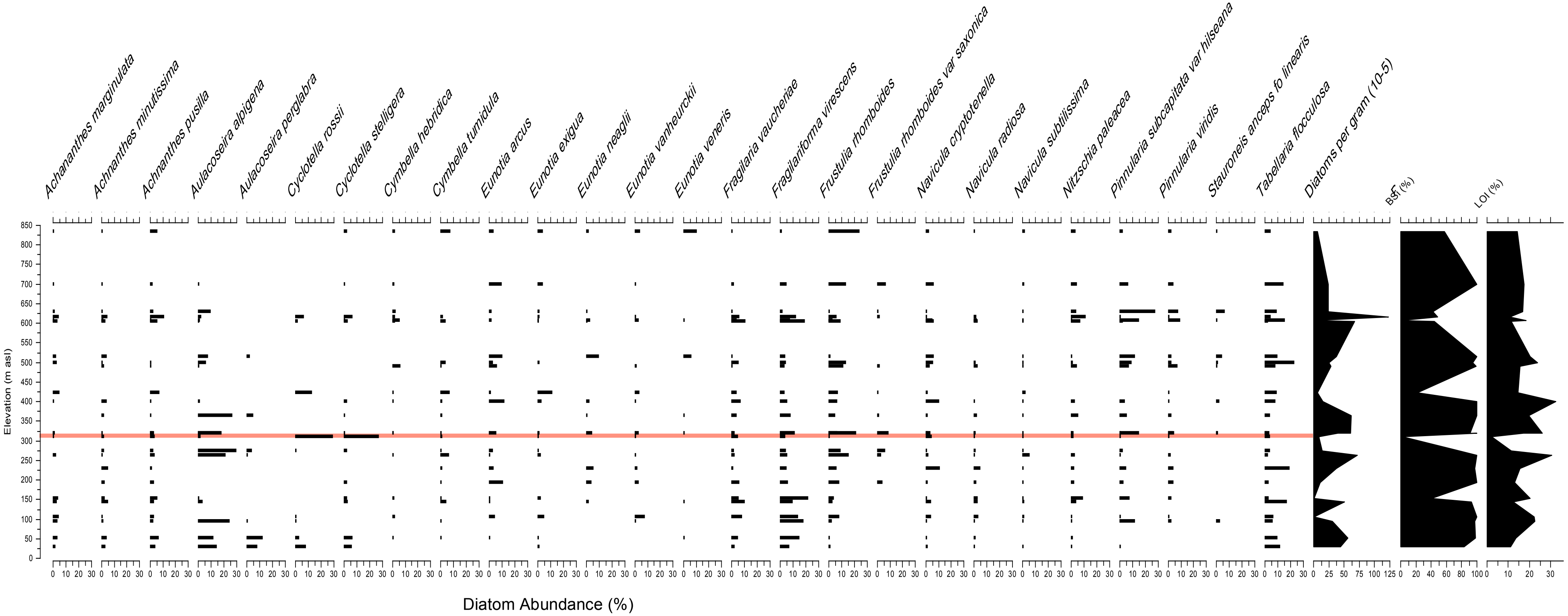


Figure 4.1 Percentage contemporary diatom assemblages of the 25 lakes sampled in the Nuuk region, plotted against their respective elevation (m asl). Only species with an abundance of over 5% and occurring in at least three lakes are displayed. Abundance of diatoms and biogenic silica content is displayed on the far right. Highlighted in red is the lake at 310m asl.

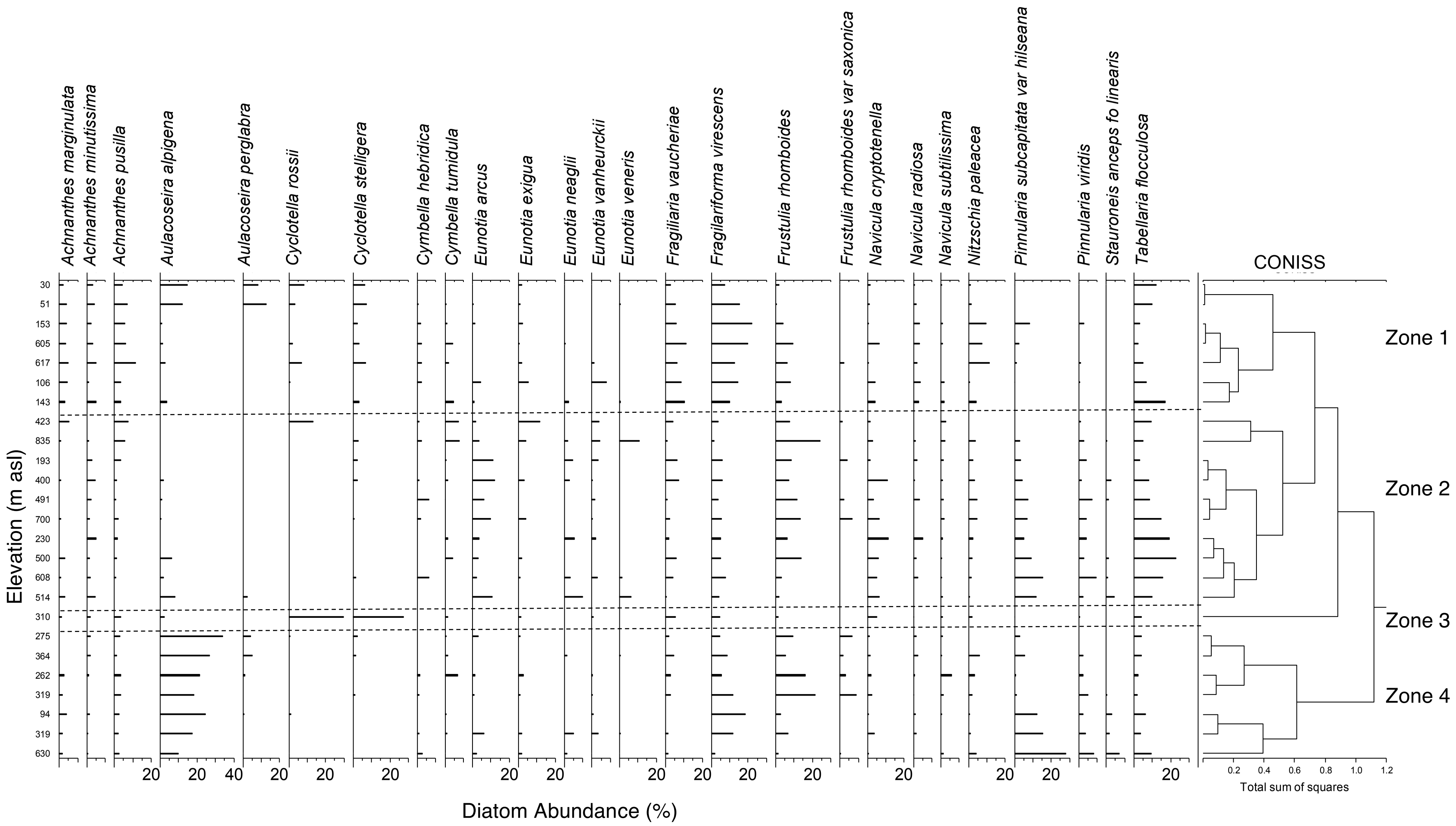


Figure 4.2 Result of unconstrained cluster analysis (CONISS) on the contemporary lake assemblages against elevation (m asl); dashed lines represent the boundaries between the most prominent zones identified. Only the most abundant (>5%) species of diatoms are shown.

4.1.3 Principal Component Analysis

Initial analysis was conducted using all the contemporary lake diatom data. Unconstrained linear analysis was first performed through principle component analysis (PCA); this provides an overview of any major trends within the contemporary lake diatom assemblages (section 3.3.5).

Figure 4.3 shows the results of the PCA performed using only the contemporary lake diatom assemblages. As can be seen, there is not an even distribution of diatom species around the PCA axes. There appears to be three groupings around the axes: to the top of the vertical axis, to the right of the horizontal axis, and in the lower left quadrant. Within these, there appears to be further clustering of species. Some species in particular, such as *Cyclotella spp.* are heavily correlated to different axes. As well as this, there are several of the diatom species that appear to be negatively correlated to one another, such as *Fragilariforma virescens* and *Tabellaria flocculosa*.

The PCA results in terms of the lakes can be seen in Figure 4.4. Again there appears to be a random distribution of the lakes around the axes, with several lying close to different axes, and some being strongly negatively correlated to one another. Based on this unconstrained linear PCA analysis of the contemporary lake diatom assemblages, there appears to no distinct single trend present within the assemblages. Due to the apparent scattered distribution and alignments with different axes, it suggests there to be multiple factors forcing the assemblages. This relationship of the contemporary lake diatom assemblages in relation to various measured lake environmental variables is investigated through the use of Canonical Correspondence Analysis.

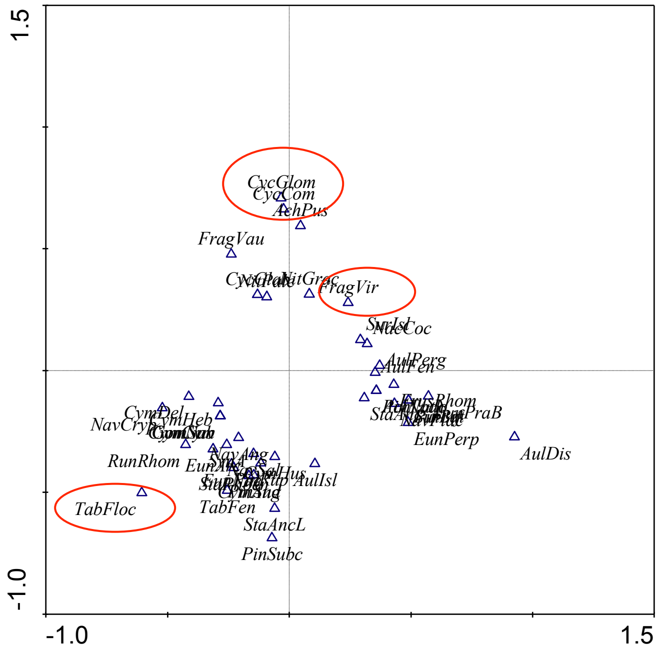


Figure 4.3 PCA results of diatom species (only those with over 12% occurrence displayed). Some of the apparent trends are that the *Cyclotella spp.* are correlated to the vertical axis, and *Fragilaria virescens* and *Tabellaria flocculosa* are negatively correlated (circled).

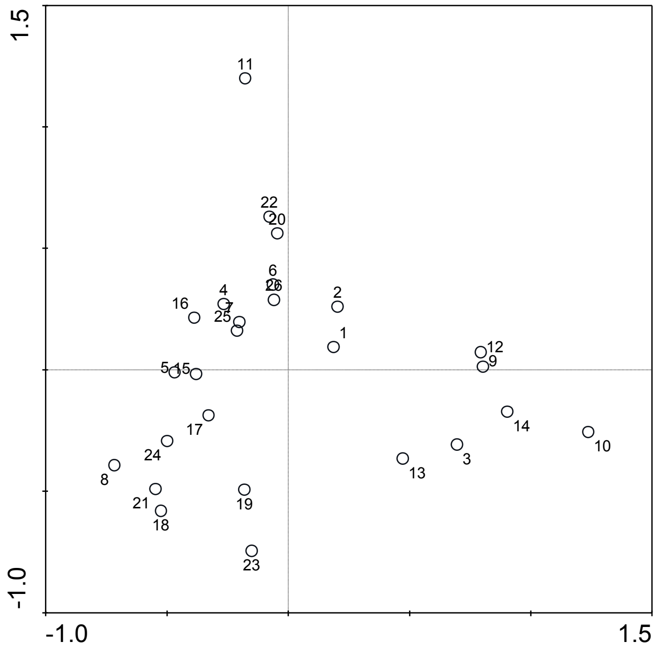


Figure 4.4 PCA results of the 25 contemporary lake samples from Nuuk; sample numbers represent the lakes in altitudinal order (1= lowest, 25= highest).

4.1.4 Environmental Variables

For each of 25 lakes in the contemporary dataset, a series of 34 environmental variables were measured, including water chemistry and physical characteristics. These lakes were sampled over a small spatial area, but large elevation gradient (section 2.2) to examine the relationship between lake elevation and lake environmental setting in western Greenland. The other variables were collected to provide a thorough record of the present lake conditions, chemical and physical, and to allow for examination of the relationship of environmental setting and diatom community, as well as for the examination of variability that exists between the lakes. Those classed as bottom values were collected 0.5m above the lake bed, and surface values from 0.5m below the water surface. There is considerable variability for a number of these variables between the lakes, though some, such as salinity, has minimal variability (Figure 4.5). These environmental variables are used to examine the relationships and forcing variables of the diatoms, through the use of PCA and Canonical Correspondence Analysis.

The results of the unconstrained PCA for the 34 measured environmental variables can be seen in Figure 4.6. This helps to narrow down those that are likely most significant in relation to the diatom assemblages in the lake samples. There is some clustering of variables, particularly to the right of the horizontal axis, suggesting there may be difficulty in distinguishing the individual influence of each of these variables; there are also some variables that are negatively correlated, such as bottom temperature and sample depth, which would be expected as depth increases, the bottom temperature would decrease. Using this distribution of variables around the axes, it is possible to interpret which environmental variables relate to particular species. For instance, species in the upper right quadrant, such as *Fragilariforma virescens* (Figure 4.3), appear to be strongly influenced by the depths; those around the top of the vertical such as the *Cyclotella spp.* correlate with total phosphorus (TP), and just to the left *Fragilaria vaucherie* correlates to area; in the lower left quadrant, *Tabellaria flocculosa* appears to strongly relate to bottom temperature.

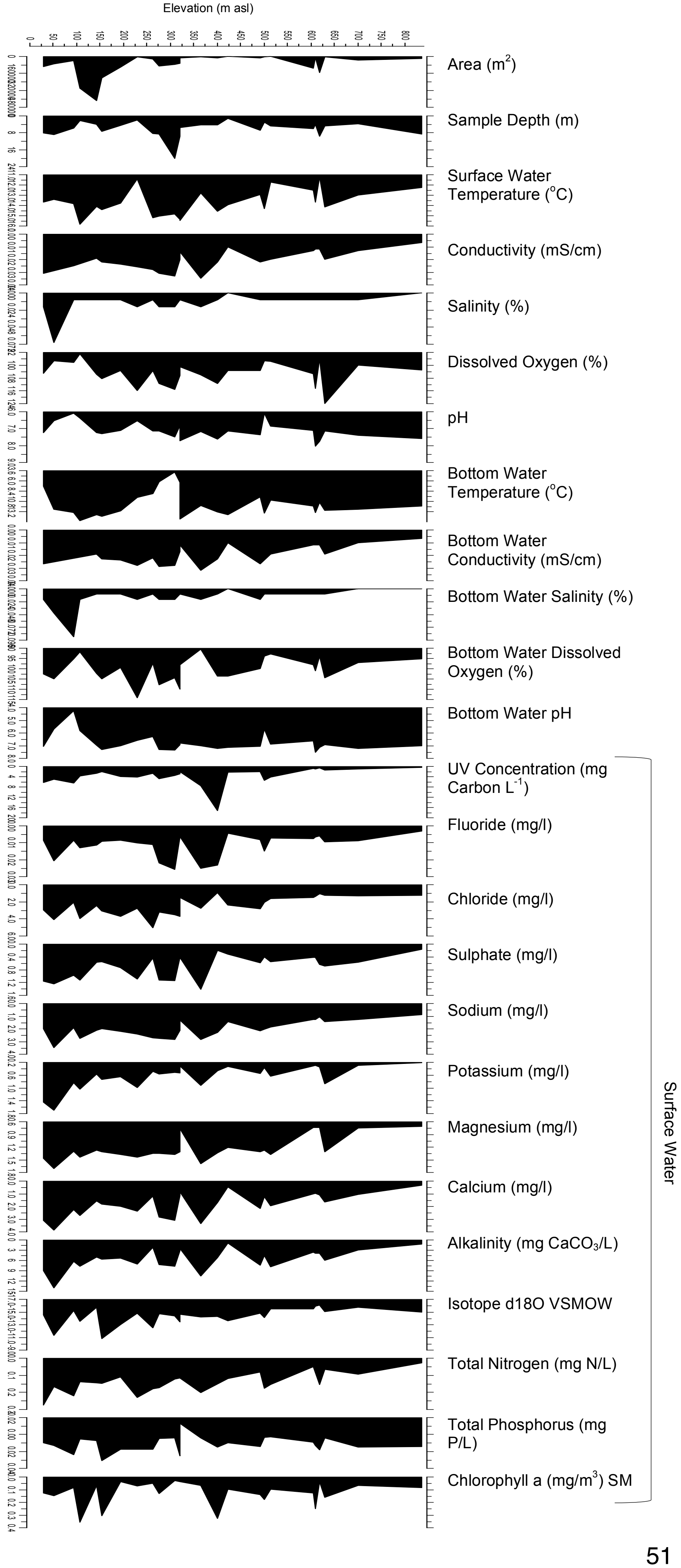
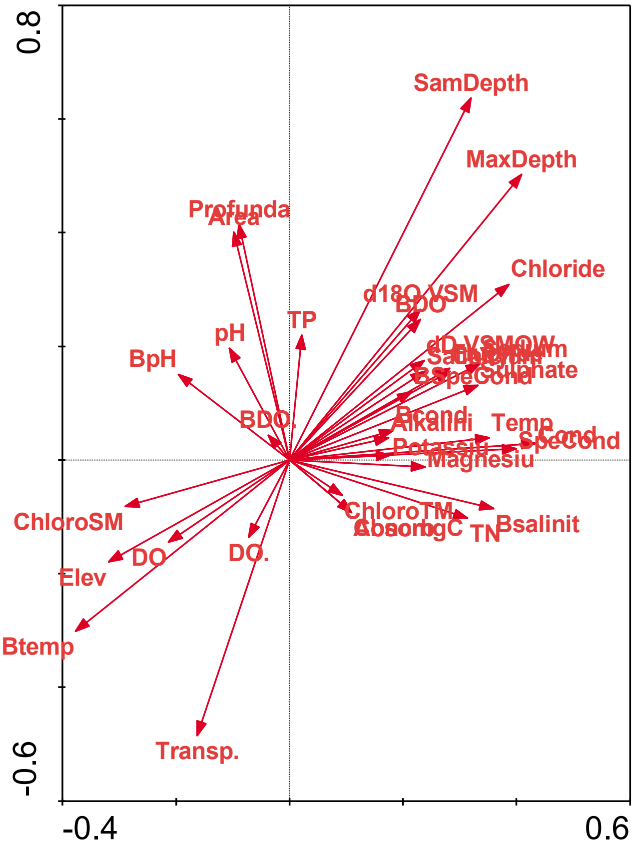


Figure 4.5 Environmental variables of the 25 contemporary lakes against their respective elevation; a total of 34 variables were measured for each lake, including elevation, 25 of which are shown in this figure (those excluded done so on the basis of similarity to other variables e.g. specific conductivity shows same variance between lakes as conductivity).



Elev: Elevation
SamDepth: Sample Depth
MaxDepth: Maximum Lake Depth
Area: Lake Area
Profunda: Lake Profundal Area
Temp: Surface Water Temperature
SpeCond: Surface Water Specific Conductivity
Cond: Surface Water Conductivity
Salinity: Surface Water Salinity
DO.: Surface Water Percentage Dissolved Oxygen
DO: Surface Water Dissolved Oxygen
pH: Surface Water pH
BTemp: Bottom Water Temperature
BSpeCond: Bottom Water Specific Conductivity
BCond: Bottom Water Conductivity
Bsalinit: Bottom Water Salinity
BDO.: Bottom Water Percentage Dissolved Oxygen
BDO: Bottom Water Dissolved Oxygen
BpH: Bottom Water pH
Transp.: Water Transparency Percentage
ConcmgC: UV Concentration
Absorb: UV Absorbance
D18O VSM: Isotope d18O VSMOW
dD VSMOW: Isotope dD VSMOW
Chloride: Chloride
Floride: Floride
Sulphate: Sulphate
Sodium: Sodium
Potassiu: Potassium
Magnesiu : Magnesium
Calcium: Calcium
Alkalini: Alkalinity
TN: Total Nitrogen
TP: Total Phosphorus
ChloroSM: Chlorophyll a (Standard Method)
CHloroTM: Chlorophyll a (Trichromatic Method)

Figure 4.6 PCA results for the 34 measured environmental variables.

4.1.5 Canonical Correspondence Analysis

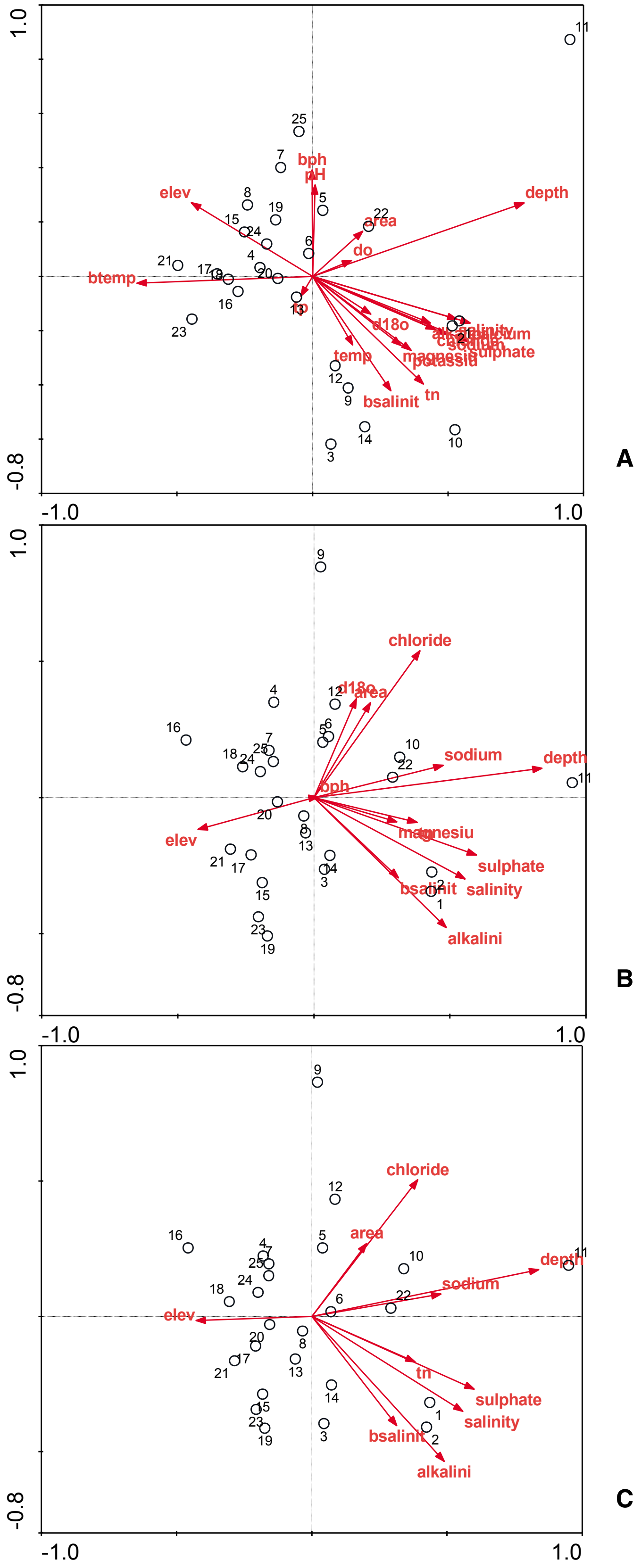
The initial 34 environmental lake variables used in the unconstrained PCA were cut down to just 20 to include in the CCA due to their potential role in influencing lake diatom assemblages. These variables are: lake elevation, area, sample depth, water temperature, salinity and pH; bottom temperature, dissolved oxygen, alkalinity, δ18O, total nitrogen and total phosphorous; the anions chloride and sulphate, and the cations sodium, potassium, magnesium and calcium. Those excluded were done so on the basis of being a crude measure (e.g. transparency, max depth), a similar variable (e.g. profundal area is extremely similar to lake area), or due to having an apparent lack of significance (e.g bottom dissolved oxygen, UV absorbance). The 20 selected were compared to the diatom assemblages in constrained, Canonical Correspondence Analysis (CCA).

CCA was carried out with forward selection; this helped to establish those environmental variables with the most significant role in explaining the diatom assemblages of the lakes, allowing the assessment of the usefulness of each variable, and the amount of variability they explain (Lepš & Šmilauer, 2003). The CCA was repeatedly run following this, with environmental variables that contributed little to the explanation of the lake diatom assemblages being removed. The initial CCA including the 20 environmental variables explained 85.16% of the variance in diatom assemblages observed. Within this, sample depth and total nitrogen were the most statistically significant variables, with P-values of 0.004 and 0.008 respectively, and explaining 19.68% of the variance in the diatoms explained by the 20 environmental variables (Figure 4.7A). 7 of the environmental variables that explained little of the variance were then eliminated (temperature, bottom temperature, dissolved oxygen, pH, total phosphorous, potassium and calcium) (Figure 4.7B) and again a further 3 were excluded following this (bottom pH, δ18O and magnesium) (Figure 4.7C). These 10 remaining environmental variables explain 48.68% of the variance observed in the diatom assemblages (Table 4.1).

CCA	Number of Variables	Total Variance Explained (%)	Significant Variables	P-Values
All Lakes	20	85.16	Depth	0.004
	13	57.2	Total Nitrogen	0.008
	10	48.68		
2 Lakes Excluded (310 & 423m asl)	20	93.2	Depth	0.004
	8	48.31	Sulphate	0.002
			Area	0.038

Table 4.1 CCA performance, including the total variance explained by the variables included, and the p-values of the most significant variables (those with a p-value <0.05).

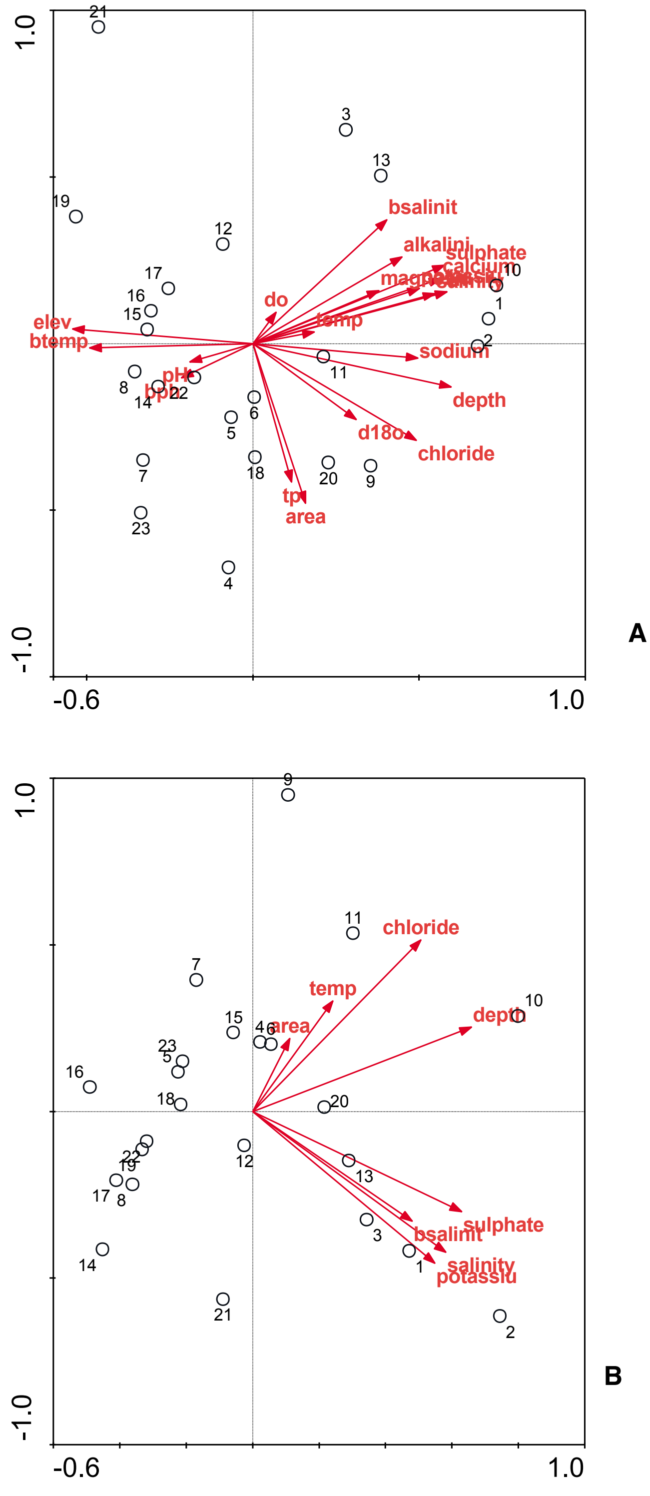
As can be seen in the biplots, there does not appear to be a clear arrangement of the lake samples in an altitudinal order, with no apparent trend in the distribution around the CCA axes. However, there are a couple of samples that do appear to be outliers, such as sample 11, which is positioned on the far right of the CCA bi-plots (Figures 4.7A, B and C). Such lakes may have an extreme environmental variable that may be affecting the assemblage, and therefore the performance of the sample within the CCA.



Figures 4.7A, B and C CCA biplots of lake samples and environmental variables. 4.7a has all 20 environmental variables included for CCA; 4.7b has 7 excluded, and 4.7c 10 excluded. Sample 11 is distinct in its position to the far right of the axes in all three analyses. This is lake 20, which is the deepest lake in the dataset, and one that is excluded from further analysis; there is clearly a strong correlation between this lake and sample depth within CCA.

The first of the lakes to be excluded from the CCA model were those with extreme depths. The majority of the lakes have depths ranging from 2-10 m (Figure 4.5). However, sample 11 in Figures 4.7A, B and C represents Lake 20, a lake at 310 m asl with a sampling depth of 20.1 m, and resultantly has a significantly lower bottom temperature than other lakes of 4.04°C and different diatom assemblage compared to the other lakes (Figures 4.1 and 4.5); this is therefore not representative of the rest of the samples in the model and not suitable for inclusion. Similarly, sample 16 represents Lake 12, a lake at 423 m asl with a shallow depth of 1.2 m was excluded (Figures 4.1 and 4.5). CCA was then run again with the initial 20 environmental variables. The exclusion of these two samples resulted in distinct changes compared to the initial CCA model (Figure 4.7 and 4.8); the variables explained 93.2% of the variance, with depth, sulphate and area being statistically significant, with P-values of 0.004, 0.002 and 0.038 respectively, and responsible for 24.86% of the explained variance (Table 4.1). The CCA was then repeated including only variables responsible for explaining more than 5% of the variance, a total of 8 of the original 20 variables (Figure 4.8). These explained 48.31% of the variance (Table 4.1).

There are some interesting features to note in the CCA biplots. One of these is the lack of correlation between salinity and chloride; one would expect these to correlate, as they are essentially a measure of the same environmental condition. This could be due however to the salinity levels that were measured being very small, with little range (values of 0, 0.01 or 0.02 with only two exceptions) between the lakes, and therefore no distinct relationships to the much more varied chloride values are apparent. The reason for this differentiation is likely due to the different detection methods used; salinity was measured in the lake using a probe, whereas chloride was quantified in the laboratory. The salinity values were therefore excluded on the basis of lack of variability over the dataset, and not considered as a variable for reconstruction. As well as this, some of the variables that have been demonstrated to have a significant contribution in explaining the diatom assemblages, such as area, are of little interest to reconstruct. However some, such as depth and pH, can provide insights into the changing environment, including drying and acidification trends.



Figures 4.8A and B CCA biplots following the exclusion of two lake samples. 4.8A has all 20 environmental variables included, and 4.8B has 12 variables excluded.

4.2 Regional Analysis

The following sections discuss the contemporary diatom assemblages of the expanded, regional set of lakes, and the results of multivariate analysis the samples have undergone. This regional dataset incorporates the 25 lakes from the Nuuk fieldsite (section 2.2), and the additional 60 lakes from along Søndre Strømfjord, between Sisimiut and Kangerlussuaq (section 2.3).

4.2.1 Contemporary Diatom Assemblages

The contemporary dataset of lakes was expanded through the inclusion of 60 additional lakes from a transect further north, in the Kangerlussuaq region (section 2.2). These lakes assemblages contained a total of 234 species. Once merged with the local Nuuk data set, there were a total of 85 samples and 297 species of diatoms; however, there is a lack in overlap of species between the two datasets in terms of diatom species, with only 47% of the species present in the Nuuk set occurring in the additional Kangerlussuaq set. To simplify the complexity of a larger data set, the samples and diatoms were assigned codes, and taxonomic harmonization was carried out through a collaboration to ensure accurate taxonomy of the diatoms.

4.2.2 Principal Component Analysis

PCA was conducted on the species data. Once again, there are some distinct areas of clustering of species, with varying distribution around the axis (Figure 4.9). There are three particular clear areas of clustering; in the upper right positive quadrant, close to the horizontal axis; in the lower left negative quadrant, close to the vertical axis, and in the upper left quadrant, close to the vertical axis. The *Cyclotella spp.* are also distinct in their position towards the upper left (CYSTELL, CYOCELL, CYO22B). A factor in causing the various clustering of species will be due to the discrepancies in species between the two merged datasets (discussed in section 4.4).

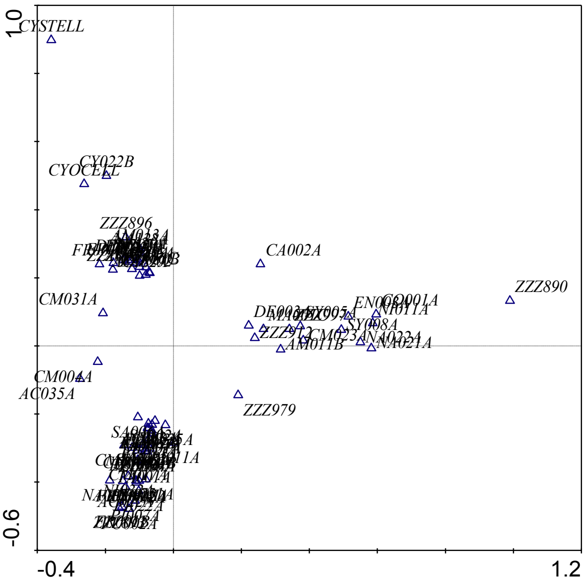


Figure 4.9 PCA results of diatom species from the expanded dataset (only those with over 10% occurrence displayed).

4.2.3 Canonical Correspondence Analysis

The environmental variables and their significance on the lake diatom samples were considered through the use of CCA, as with the previous section 4.1.5. The expanded data set incorporated a total of 13 environmental variables that were present in both the original separate data sets. The biplot of this CCA is shown in Figure 4.10A; there is some clustering of lakes, notably those from the Nuuk area are clustered in the upper left quadrant, and also a clustering of some of the lakes from Søndre Strømfjord around the low end of the vertical axis. In terms of the environmental variables, the lake diatom assemblages from the Nuuk site appear to be related to pH, and are within the range of elevation. Those from the Søndre Strømfjord data set appear to be significantly related to a variety of different variables, and displaying opposite trends to those in the Nuuk region. The most significant variables at explaining the variance of the diatom assemblages from the expanded data set were potassium, sodium, depth, calcium, alkalinity, total phosphorus, total nitrogen and chloride, all with p-values lower than 0.05 (Table 4.2).

Some of the lakes from the Søndre Strømfjord region were highly saline, with extreme conductivity values in comparison to the rest of the dataset, particularly those from the Nuuk region. The CCA was repeated with 11 of the lakes removed. This resulted in a reduced clustering to the right of the axis, and a correlation in the total phosphorus (TP) and total nitrogen (TN) on the vertical axis with a large clustering of the Søndre Strømfjord lakes; the pH has also changed and no longer explains the Nuuk data very well (Figure 4.10B). There is also an increased significance in several of the environmental variables, notably pH, depth and area.

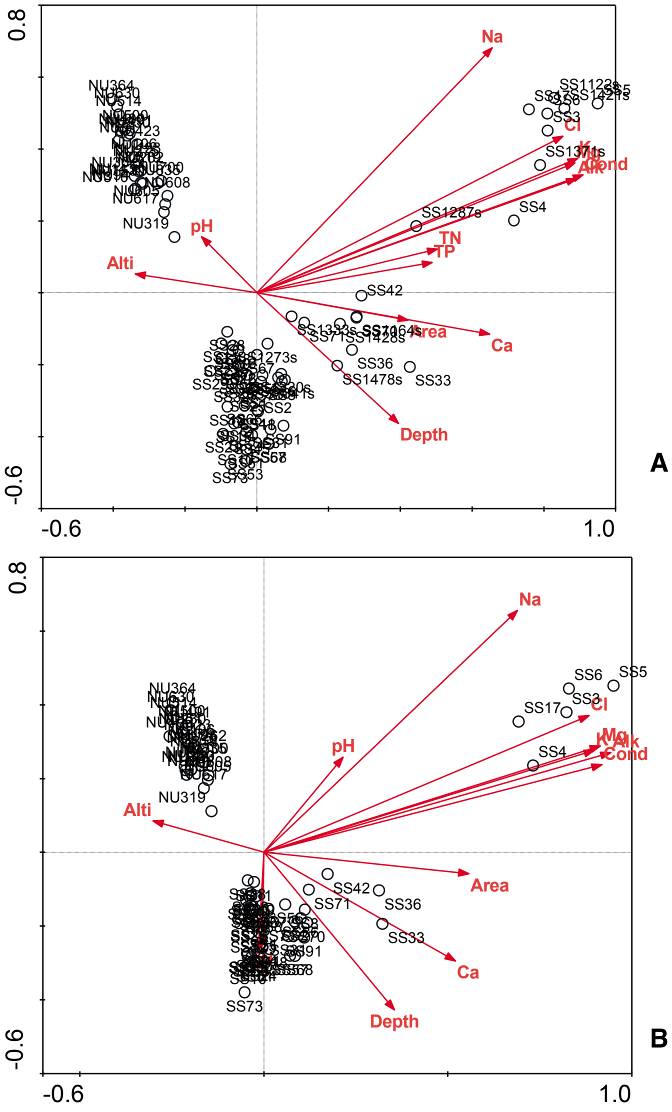
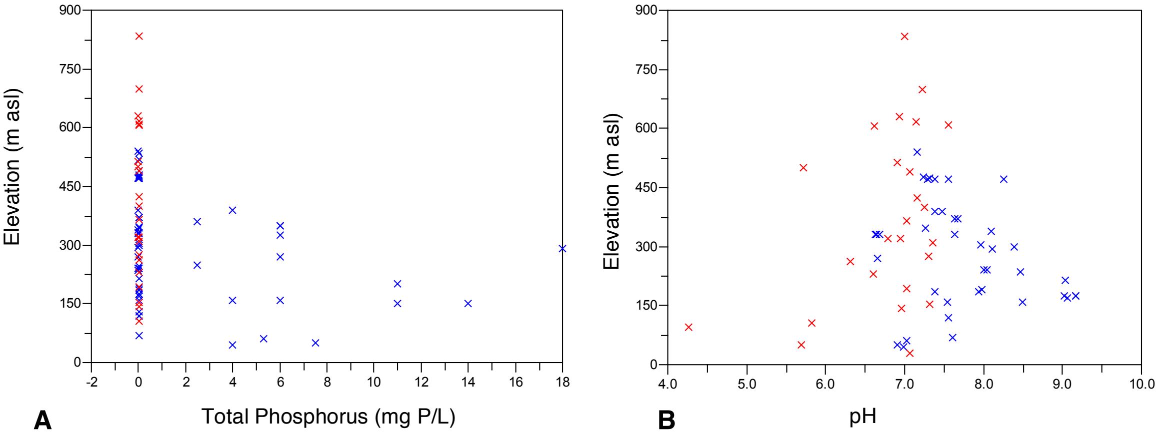


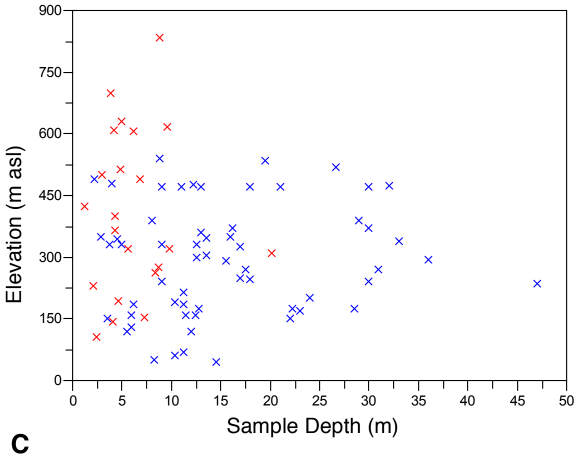
Figure 4.10A and B. CCA biplots of the lake samples and the 13 environmental variables. 'NU' indicates samples from the Nuuk fieldsite, and 'SS' those from the Søndre Strømfjord site. A has all 85 lake samples, and B has 11 of the saline lakes from the Søndre Strømfjord set excluded.

Table 4.2 Significant variables in the regional CCA (those with a p-value <0.05). 8 out of the 13 variables are significant. In total, all the variables in the CCA explained 38.55% of the variance.

Significant Variables	P-Values
Alkalinity	0.002
Sodium	0.002
Total Phosphorus	0.002
Sample Depth	0.002
Potassium	0.002
Total Nitrogen	0.006
Chloride	0.006
Calcium	0.026

The reason for these distinct, unrelated relationships between the samples and the environmental variables becomes apparent when the environmental variables of the datasets are compared. The environmental conditions of the lakes from the two data sets are distinctly different for a number of the variables, creating a lack of overlap between the data sets. For example, all the values for total phosphorus, total nitrogen and conductivity from the Nuuk lake set are at the low end of the range of values from the Søndre Strømfjord lakes, which has values several orders of magnitude larger (Figure 4.11A, B and C). However, those variables that are comparable include elevation and pH. The lakes from the Søndre Strømfjord region are generally more alkaline than those from the Nuuk region, though there is considerable overlap that may be suitably applied for reconstruction of the fossil data set (Figure 4.11B).





Figures 4.11A, B and C Plots of environmental variable values from the Nuuk dataset (red) and Søndre Strømfjord (blue), plotted against the respective lake elevations.

Due to the fundamental differences in the environmental conditions of the lakes, and the differences in the diatom assemblages of the contemporary data sets and the fossil core (section 4.4), it would only be suitable to attempt to reconstruct the environmental variables that are comparable between the two data sets. Those that are comparable are pH, for which there is overlap in the contemporary data, and also lake elevation; the reconstruction of elevation can be used as an inference of temperature, as temperature decreases with increasing elevation.

4.3 Nuuk Fossil Core

The following sub-sections discuss the diatom assemblages from the fossil core, as well as reconstructions of environmental conditions using the fossil assemblages and the contemporary datasets.

4.3.1. Stratigraphy

The stratigraphy of the core consists predominantly of brown gyttjas and grey clays (Figure 4.12). The lower section of the core consists of clays from 184-140cm; this gets progressively darker up core, and is homogenous with the exception of a small (~1cm) group of fine black laminations at 154cm (Figure 4.12). From ~140-120cm there is a gradual colour change into the gyttjas in the upper section of the core. Gyttja comprises the majority of the core, from approximately 120cm to 0cm; within this though there is some variability in the colour, with the gyttja getting lighter up the core. There are also several small (1-~3cm) bands present throughout the gyttja sections, some of a grey-brown gyttja, but also some potential moss bands (Figure 4.12).

4.3.2 Fossil Diatom Assemblages

Samples from the fossil core were taken at regular 8cm intervals, totaling 23 samples, however 6 of these samples proved to be barren. In total 66 species were identified, with most samples having c. 20 species, however one sample had only 10 species. This decrease in the diversity of species compared to contemporary lake diatom species can be attributed to several factors.

Fragmentation of diatoms was evident in the fossil samples, with many becoming unidentifiable; dissolution was also evident in many samples, again making many of the diatoms unidentifiable. As such, the diatom assemblages may be skewed in favour of those with greater preservation potential and resilience. Overall, the amount of dissolution increased up the core, with exception of the top 10cm (Figure 4.13).

The fossil core was split into zones using constrained cluster analysis, CONISS, with no transformation, using TGView v1.7.14. (Grimm, 2004)(3.3.2). With the barren samples excluded, the remaining samples have been divided into five separate zones; the division of two of these zones corresponds with the sections of core for which the samples were barren (Figure 4.13).

Zone 1 is comprised of two samples, within the paler clays at the base of the core, and is characterized by the presence of alkaline species *Staurosirella lapponica*, a relatively high amount of *Fragilariforma* virescens, and a low amount of *Tabellaria flocculosa*. Zone 2 contains four samples, and is within the transition to darker clays. It is characterized by a large amount of *Tabellaria flocculosa*, and decline and absence of *Staurosirella lapponica*, and a fluctuating amount of *Fragilaria vaucheriae* and *Fragilariforma virescens.* Zone 3, the middle zone, is made up of five samples that cover the transition from dark clays into gyttas. It is characterized by relatively low amounts of *Tabellaria flocculosa,* and lower amounts of *Fragilaria vaucheriae* and *Fragilariforma virescens* than in the previous zones. This zone also has the arrival of the acidic-circumneutral *Eunotia arcus* species in more significant quantities, as well as *Aulacoseira valida*. Also of interest are the spikes in *Staurosirella lapponica* at the boundaries of this zone, particularly at 1.04m, as this sample is surrounded by barren samples. This zone may reflect large fluctuations in the condition of the lake due to the diverse nature of the assemblages that are within it.

Zone 4 is the largest zone, comprising six samples, and incorporates a barren phase, and the transition from zone 3 to 4 is also a barren phase. The zone is characterized by the presence of *Stauroneis phoenicenteron* and *Stauroneis anceps fo. linearis*, which are otherwise almost absent in all other zones. It also has a marked increase in *Tabellaria flocculosa* and *Eunotia arcus*, suggesting a productive period and acidification of the lake. Zone 5, the most recent zone, is comprised of three samples. It is characterized again by a large amount of *Eunotia arcus*, and a relative decline in *Tabellaria flocculosa*, with an absence of the *Stauroneis spp.*, and an increase in *Pinnularia spp.*

Aulacoseira valida is present in most of the samples in the fossil core, excluding those from the lower section of the core; the presence of this species can be used to infer changes in diatom productivity, with high abundances being associated with phases of high productivity (Stefanova *et al.*, 2003). The increase in acidic *Eunotia arcus* up the fossil core suggests an acidification trend up the core; this is also suggested by the decline of the alkaline species *Staurosirella lapponica* (Owen *et al.*, 2008) up the core.

4.3.3 Biogenic Silica and Loss-on-Ignition

The amount of biogenic silica generally decreases up the fossil core (Figure 4.13), corresponding with the transition from clays at the base gradually into the gyttja layers (Figure 4.12). The exception of this trend is a spike ~0.64m; this sample was taken from a band of grey-brown gyttja, in close proximity to a potential moss band, and corresponds to a decrease in the diatom dissolution (Figure 4.12). As would be expected, the loss-on-ignition has an inverse relationship to the biogenic silica, displaying a general increase up the core (Figure 4.13).

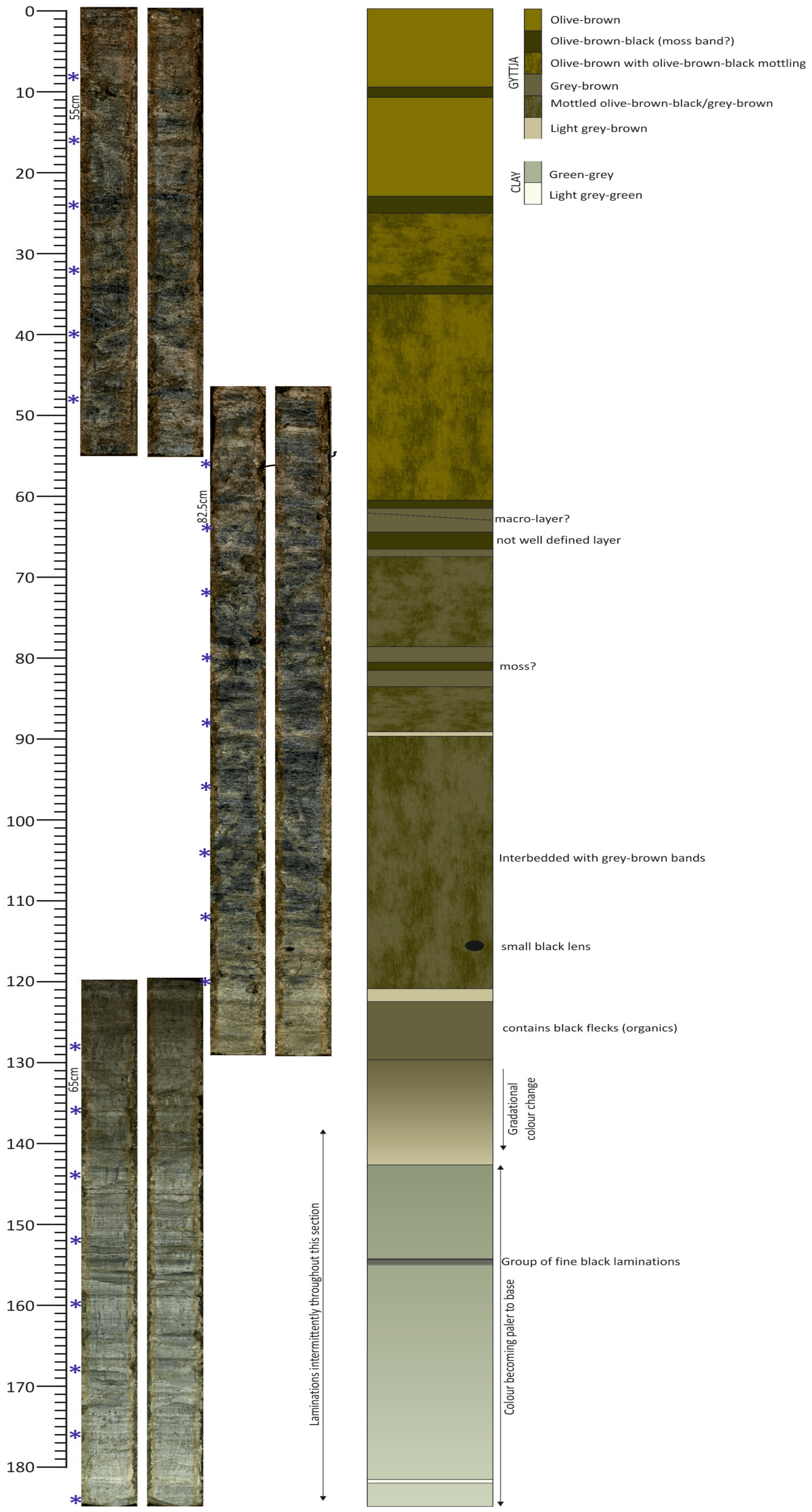


Figure 4.12 Images and detailed stratigraphy of the Nuuk fossil core. Asterix indicate positions of initial samples at 8cm intervals.

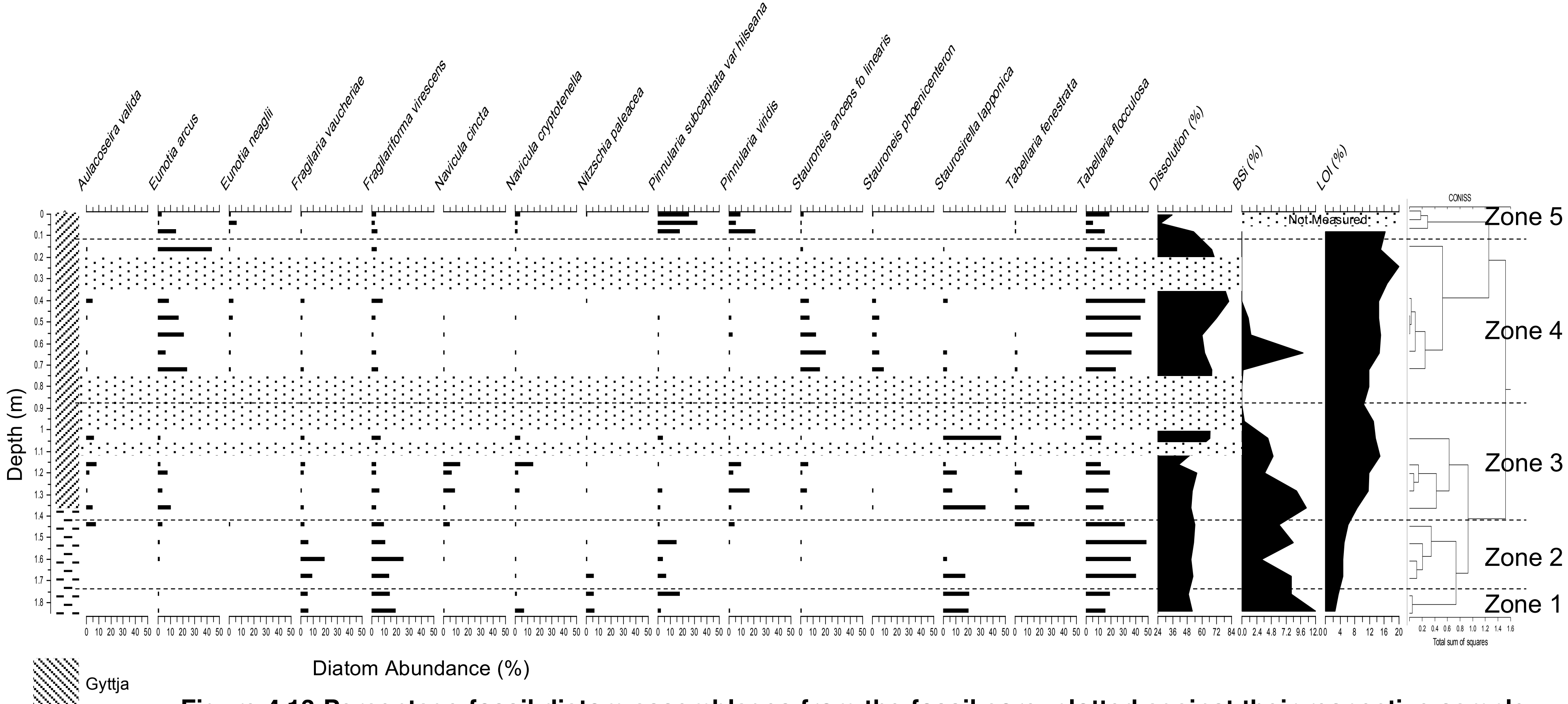


Figure 4.13 Percentage fossil diatom assemblages from the fossil core, plotted against their respective sample depth. Only species with an abundance over 5% and occurring in at least three of the samples are displayed. Shaded sections indicate barren samples. Included is a simplified stratigraphy of the core (Figure 4.12 displays the detailed stratigraphy). Percentage dissolution, loss-on-ignition, biogenic silica and the results of cluster analysis are shown on the far right; dashed lines represent the zones identified by the cluster analysis.

4.3.4 Age

The core is assumed to represent the majority of the Holocene period. Lakes in the Godthåbsfjord region formed 9500-8500 cal years BP as a result of relative sea-level fall due to glacio-isostatic adjustment following glacial unloading and retreat of the ice sheet inland (Long *et al.*, 2011). The basal date of a lake near the fossil core site is from the early Holocene. Iverson's (1953) 'Lake 100m s.m.' basal date is 8640±130 C^{14} years BP (Fredskild, 1983a); this lake is located within the interior of Godthåbsfjord, approximately 30km south of the lakes sampled in this study (Figure 2.2). This core is therefore anticipated to represent approximately 9000-8500 C^{14} years BP to present, equivalent of approximately the last 9500 cal years.

4.4 Modern and Fossil Diatom Assemblages

In terms of the fossil assemblage relationship with the two contemporary datasets, there is generally poor representation of the fossil species. 51 of the fossil assemblage species appear in the local Nuuk dataset (77% of the fossil set), but the top ten most abundant species in the Nuuk data set have little or no abundance in the fossil data (Table 4.3). The Søndre Strømfjord lake species also have little similarity to the fossil data, and also the contemporary Nuuk data (Table 4.3). The result of this similarity is that the regional dataset, despite it's vastly increased number of species, shares only 55 of them with the fossil assemblage (83% of the fossil set), and the most abundant species are found in low numbers or not at all in the fossil set (Table 4.3). Therefore, by adding the data from Søndre Strømfjord, only an additional 4 species are found in the fossil dataset. This significant lack in similarity between the individual contemporary and fossil datasets has significant implications on attempting to understand the changes and environmental conditions the diatoms represent, and also has implications on the suitability of using quantitative methods to reconstruct change due to the lack of modern analogues.

Top 10 Local	Local	Fossil	Top 10 Søndre Strømfjord	Søndre Strømfjord	Fossil	Top 10 Regional	Regional	Fossil
Aulacoseira alpigena	34.1	3.2	Diatoma tenuis + D. moniliformis	88.1	0	Diatoma tenius + D. moniliformis	88.1	0
Cyclotella rossii	29.6	0.5	Achnanthes conspicua	56.8	0	Achnanthes conspicua	56.8	0
Pinnularia subcapitata var hilseana	27.9	18.2	Cyclotella stelligera	51.7	0.4	Cyclotella stelligera	51.7	0.4
Cyclotella stelligera	27.5	0.4	Navicula kuelbsii	41.5	0	Navicula kuelbsii	41.5	0
Frustulia rhomboides	24.3	1.3	Cyclotella radiosa	39.7	0	Cyclotella radiosa	39.7	0
Tabellaria flocculosa	23.1	49	Nitzschia perminuta	32.8	0	Aulacoseira alpigena	34.1	3.2
Fragilariforma virescens	22.2	25.6	Amphora pediculus	32	0	Nitzschia perminuta	32.8	0
Aulacoseira perglabra	12.5	0	Cyclotella rossii	30.7	0.5	Amphora pediculus	32	0
Eunotia arcus	12	44.2	Fragilaria pinnata	30.3	0.4	Cyclotella rossii	30.7	0.5

Table 4.3 Ten most abundant diatom species in the Local (Nuuk), Søndre Strømfjord, and Regional (Nuuk & Søndre Strømfjord) datasets, and the corresponding abundance in the fossil dataset (%).

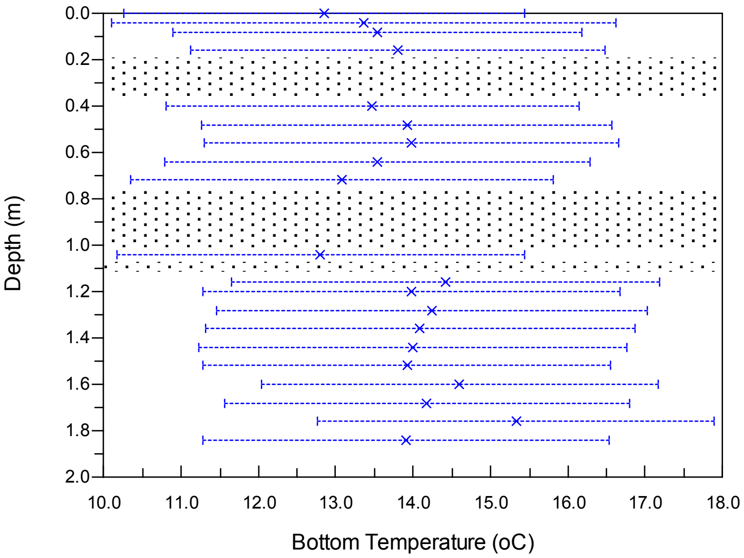
4.5 Environmental Reconstructions

Transfer functions, and the corresponding modern analogues, were developed and applied to the fossil core using the local Nuuk contemporary dataset (25 lakes), and also the expanded regional dataset (85 lakes), for several environmental variables: pH, bottom temperature, total phosphorus, elevation and depth. These variables were selected due to their comparability between the two datasets (elevation, pH; section 4.2.3), their significance in the CCA analyses (total phosphorus, sample depth; Table 4.2), and due to the inferred relationship to changing environment and climate (bottom temperature, depth and elevation). Detrended correspondence analysis was also performed using both the datasets.

4.5.1 Bottom Temperature

Only the local dataset had bottom temperature data for the lakes; the transfer functions were produced using all 25 lakes, and repeated with Lake 12 and Lake 20 samples excluded due their extreme depths, as discussed in the previously (section 4.1.5). The reconstructed bottom water temperature values fluctuate between 12-15°C, with errors ±2-3°C; there is a distinct spike to a high temperature of ~15.3 °C at a 1.76m depth, followed by a decline to fluctuating lower temperatures, ~12.8-14.4°C, with the lowest temperature of 12.8°C at 1.04m (Figure 4.14). The temperature for the top of the core, 0cm, is 12.86°C; this is lower than the measured contemporary bottom temperature of the lake, which is 13.41°C, though this is well within the errors of the model.

Figure 4.14 Reconstructed bottom temperature using the local model of 25 lakes. The reconstructed values fluctuate up core, however there is considerable overlap in the errors.



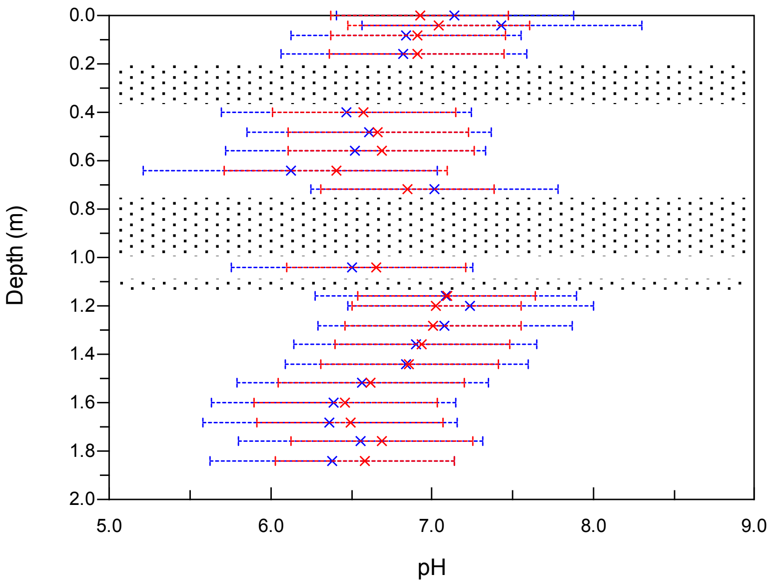
4.5.2 pH

Initially, a transfer function for pH was produced using all of the samples and diatom species in the local contemporary training set; it was also repeated with two of the lakes excluded (section 4.1.5) With the local models, the bottom pH values fluctuate between 6-7 up the core, with a maximum value of ~7.4

reached at 0.04m depth (Figure 4.15). The value at the top of the core, 0cm, is 7.15; the measured value of the contemporary bottom pH from lake is 7.55, indicating an underestimate of the pH from the 0cm sample.

A transfer function using the regional dataset was also produced; however, only 64 of the possible 85 lakes were incorporated in this due to 21 lakes lacking pH data. The reconstructions of the fossil core produced show an acidic-neutral status of the lake, with values fluctuating in a pH range of 6-7, and with error ranges of ~0.5 (Figure 4.15). There is an apparent acidification in the mid-section of the core that corresponds to the inferred changes suggested by the diatom assemblages, with increases in species such as *Eunotia arcus*, and a decline in species such as *Staurosirella lapponica* (section 4.3.2). The maximum value reached is again at 0.04m, with a value of 7.04, and the value at 0cm is 6.93, again lower than the contemporary lake value of 7.55. The errors produced by the regional model are considerably smaller than those of the local models (Figure 4.15).

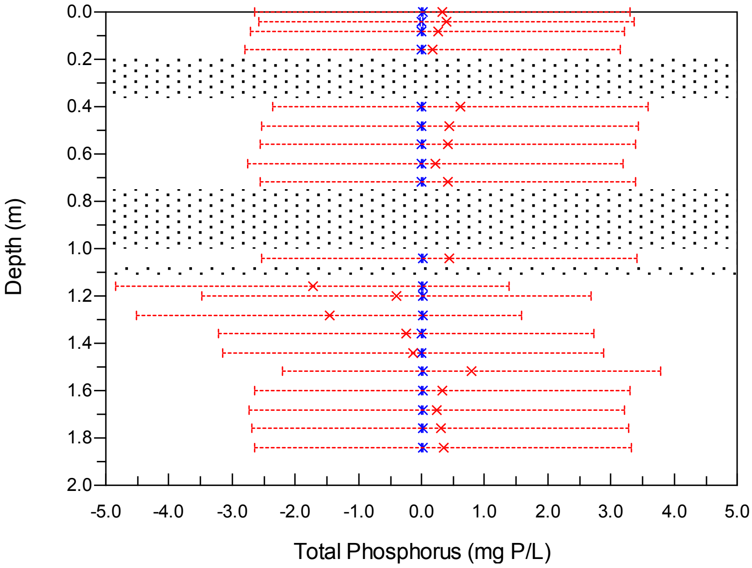
Figure 4.15 Reconstructed pH of the lakes using the local set of 25 lakes (blue), and the regional set of 64 lakes (red).



4.5.3 Total Phosphorus

Two local models were produced as with the previous variables. Within both models, the total phosphorous values fluctuate up the core, with sharp declines at 1.44m and 0.72m, and a maximum value at 1.2m. The sample at 1.2m is unique in being the only sample from the core containing *Navicula placentula*, and the highest abundance of *Gomphonema angustum*. The sample from the top of the core, 0cm, had a reconstructed value of 0.0013 mg P/L; this is lower than the measured contemporary total phosphorus value of 0.015 mg P/L. A model was developed using the regional dataset; 11 lakes from the Søndre Strømfjord set were excluded due to having extreme total phosphorus values (Figure 4.11A). Despite this, the reconstructed values are considerably more extreme than those produced by the local models, with much greater errors (Figure 4.16).

Figure 4.16 Reconstructed total phosphorus of the lakes using the local set of 25 lakes (blue), and the regional set of 74 lakes (red).

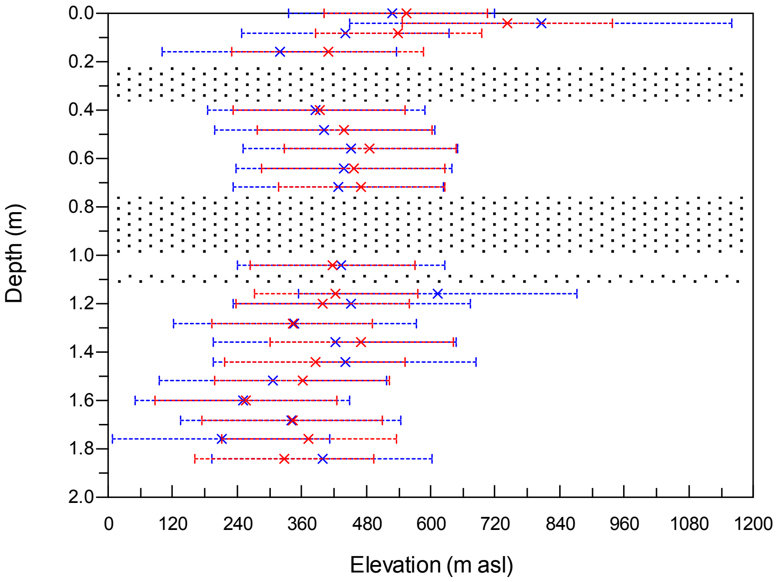


4.5.4 Elevation

Lake elevation is a useful feature to reconstruct as it can be used as an inference of air temperature, because as altitude increases, the air temperature declines. The local model was developed using all 25 lakes. The values fluctuate up the core, between 210-805m asl; the lowest elevation of 210m asl is at 1.76m depth, and the highest of 805.4m asl at 0.04m (Figure 4.17). The sample from the top of the core, at 0cm, has a reconstructed elevation of 538m asl; this is 80m lower than the actual lake elevation of 608m asl, but within the error ranges. The regional model incorporated all 85 lakes. The reconstructed elevations varied from 257-743m asl, with the lowest elevation occurring at 1.6m, and maximum at 0.04m, as with the local model; the value for the sample at 0cm is 554.26m asl, which is again lower than the actual elevation of the lake, but is well within the errors of the model (Figure 4.17). The sample at

0.04m has the highest elevation, colder than the rest of the dataset, and has an increase in *Pinnularia subcapitata var. hilseana*, and decreases in *Eunotia* arcus, *Pinnularia viridis* and Tabellaria *flocculosa* in comparison to the samples immediately prior in the core. The regional model has lower errors of 150-200m compared to the 180-280m errors of the local models. Overall, the reconstructed elevations suggest a lack of a continuous steady temperature at the site, and indicate a number of temperature fluctuations. In general, all models indicate an increase in elevation, implying cooling up the core; however, due to the overlap in errors, it is possible that it remained constant (Figure 4.17).

Figure 4.17 Reconstructed elevation of the lakes using the local set of 25 lakes (blue), and the regional set of 85 lakes (red).

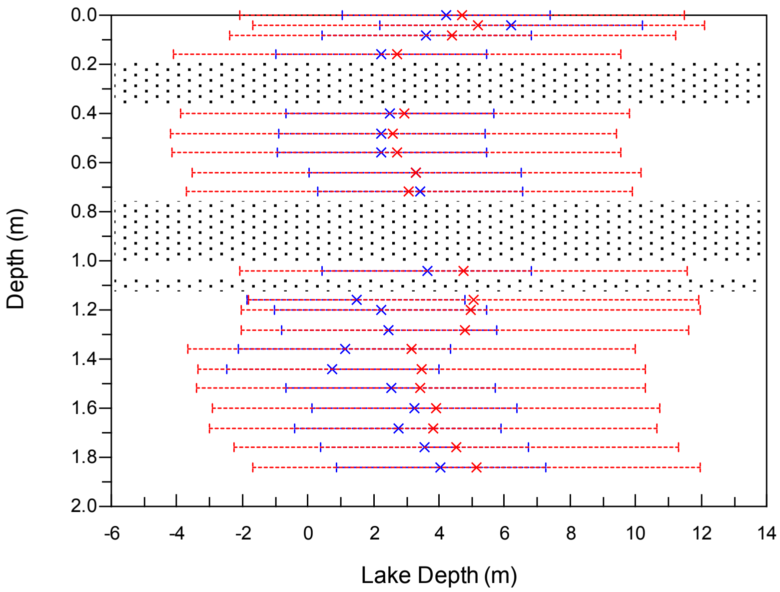


4.5.5 Depth

Lake depth can be reconstructed to provide an insight into potential drying out episodes. Two local models were produced, one with all 25 lakes, and the other using 23, the deep and shallow lake being excluded as discussed previously (sections 4.1.5 and 4.5.1). The two models produce similar trends, with slightly differing values of up to 0.5m; however, the model with the two extreme lakes excluded has considerably smaller errors than the model with all 25 lakes. Overall, the reconstructed depths fluctuate from between 0.7-6.5m. In both, the sample at 1.44m has the shallowest depth, and the sample at 0.04 m the deepest (Figure 4.18). The sample at the top of the core, 0cm, has reconstructed values of 4.21 and 4.96 respectively; this is well within the errors and quite close to the actual contemporary lake sample depth of 4.2m. The sample at 1.16m is prior to a barren phase in the core, and has a relatively shallow reconstructed depth of 1.47m, potentially suggesting a drying episode; similarly, the sample at 0.16m follows a barren phase and has a reconstructed depth of 2.23m (Figure 4.18).

The regional model of 85 lakes was also run to reconstruct lake depth. This produced less extreme fluctuations in depth than the local models, with values between 2.61 and 5.2m. The sample at 0.48m has the shallowest reconstructed depth of 2.61m, and again the sample at 0.04m the deepest at 5.2m (Figure 4.18). This deep value at 0.04m corresponds to an increase in *Pinnularia subcapitata var. hilseana*, and decreases in *Pinnularia viridis* and Tabellaria *flocculosa.* Again the sample at 0.16m follows a barren phase and has a reconstructed relatively low reconstructed depth of 2.72m; similarly the sample prior to this phase at 0.4m has a reconstructed depth of 2.96m (Figure 4.18). The errors for this regional model are 6.8-7m, which is considerably higher than those from the local models, which range from 1.9-4m, suggesting that for this variable the local training set may provide a more suitable model.

Figure 4.18 Reconstructed lake depth of the lakes using the local set of 25 lakes (blue), and the regional set of 85 lakes (red).



4.5.6 Performance and Modern Analogues

In terms of the performance of the various transfer functions, there is some variation as to whether the local or regional models performed better for the different environmental variables (Table 4.4). For pH, the regional model that was applied has a higher bootstrapped r^2 and a lower root mean square error of prediction (RMSEP) than both of the local models, offering a more robust transfer function (section 3.3.6). In contrast, with total phosphorus and depth, the regional models have a higher bootstrapped r^2 value than the local models, but also higher RMSEP values; with the elevation transfer functions, the regional model has a lower RMSEP than both the local models, but it also has lower bootstrapped r^2 values. Therefore based on the performance of the transfer functions alone, there is no clear indication as to whether the local or regional training set is better to use; it is dependent on the environmental variable that is being reconstructed.

Transfer function model		Bottom Temperature (°C)	pH	Total Phosphorus (mg P/L)	Elevation (m)	Sample Depth (m)
Local (25 lakes)	r^2	0.273	0.069	0.025	0.358	0.354
	RMSEP	2.694	0.759	0.011	201.544	3.228
Local (23 lakes)	r^2	0.318	0.041	0.004	0.376	0.405
	RMSEP	2.258	0.784	0.012	195.375	1.950
Regional	r^2	-	0.664	0.577	0.280	0.474
	RMSEP	-	0.532	1.042	155.371	7.218

Table 4.4 Bootstrapped r^2 (r^2) and root mean square error of prediction (RMSEP) for the transfer functions. Displayed are the component 2 scores for the two local models, and the scores for the regional models produced with the varying number of lakes for the respective environmental variables.

Modern analogue technique (MAT) was run on the local training sets (25 lakes and 23 lakes), to assess the dissimilarity between the contemporary and fossil assemblages, and thus which fossil samples have good modern analogues

within the contemporary samples (section 3.3.6). The results of this can be seen in Table 4.5. All of the fossil core samples have Min. DC values that exceed the 10th percentile and therefore lack modern analogues, reducing the reliability in the reconstructed environmental values for the local models. With the regional models (85, 74 and 64 lakes), the set with 85 lakes has 9 fossil samples and the other two sets have 8 with Min. DC values below the 10th percentile and therefore have good modern analogues, improving confidence in
the quantitative reconstructed values produced for these samples.

Depth in Core (m)	Local Training Set	Regional Training Set	Depth in Core (m)	Local Training Set	Regional Training Set
0	88.10	27.11	0.96	-	-
0.04	108.64	56.70	1.0	-	-
0.08	105.15	50.89	1.04	118.21	103.56
0.16	104.58	105.98	1.08	-	-
0.2	-	-	1.12	-	-
0.24	-	-	1.16	97.46	93.24
0.32	-	-	1.2	105.10	101.65
0.36	-	-	1.28	109.50	78.85
0.4	89.96	92.95	1.36	118.71	109.31
0.48	92.79	91.50	1.44	102.43	88.70
0.56	100.72	100.09	1.52	88.84	76.56
0.64	98.59	98.66	1.6	73.74	80.53
0.72	98.07	96.07	1.68	83.90	84.21
0.76	-	-	1.76	92.79	85.94
0.8	-	-	1.84	91.60	90.77
0.88	-	-			

Table 4.5 Min. DC scores for the fossil samples and the local and regional training sets. The local training set lacked any good modern analogues for the fossil samples. The regional training set of 85 lakes had a 10th percentile of 89.16, so 9 samples have good modern analogues; the regional set of 74 and 64 lakes had 10th percentile of 86.05 and 86.93 respectively, so 8 samples have good modern analogues. Shading indicates good modern analogues.

4.5.7 DCA Axis 1

Detrended correspondence analysis (DCA) was performed to provide a passive reconstruction of environmental change from the fossil sample using the DCA axis 1 sample scores, as explained in the methodology (section 3.3.5). This was initially done with the local, Nuuk contemporary dataset, and then also the expanded, regional dataset.

The local analysis was run using all the 25 contemporary lake samples and also the fossil samples that provided a diatom record. The fossil samples all consistently scored higher on the axis than the contemporary samples alone (Figure 4.19). Based on the distribution of the contemporary samples along the first axis (horizontal), the pH value seems to be the main forcing factor, with the lakes with lower pH values appearing higher on the axis; that is not to say that other environmental variables are not involved in the forcing of the assemblages, however other variables such as salinity/conductivity are of such small values and ranges in the dataset that they would not be suitable to attempt to infer variations.

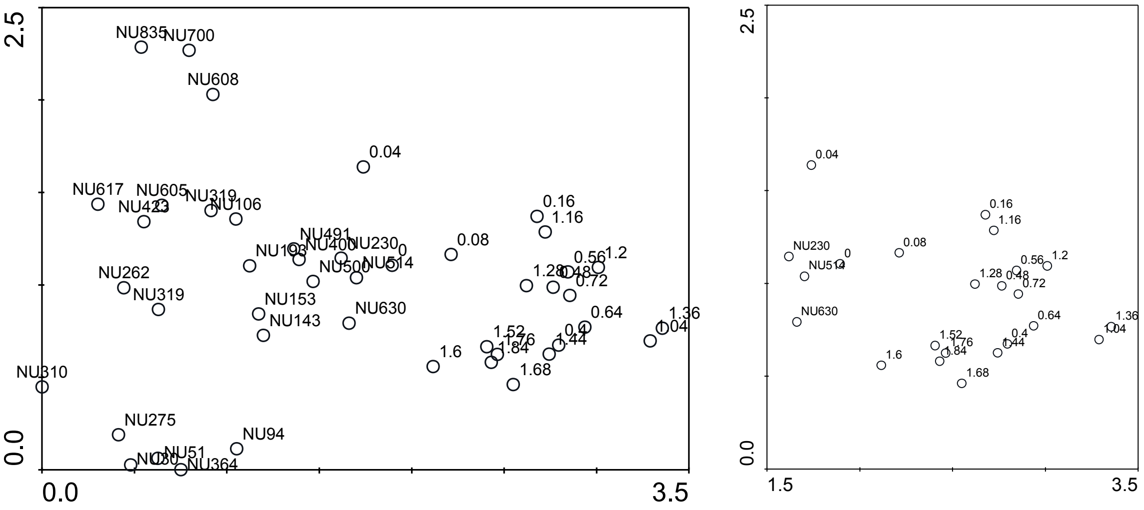


Figure 4.19 DCA scores of Nuuk training set of 25 lakes and the fossil samples from the Nuuk lake core. Contemporary samples are labeled 'NU' and their respective lake elevation, and the fossil samples by their depth in the core. Image on the left shows the full axis and the samples, and on the right is the higher section of the axis showing the fossil samples and some of the overlap with the contemporary samples.

Generally the DCA axis 1 scores for the fossil samples from the mid-section of the core are higher than those from the base and top of the core. In terms of pH, this suggests a general acidification through the middle of the core, with some sharp fluctuations at certain points. To assess whether the DCA scores are actually reflecting the pH conditions, they were compared to the reconstructions of pH produced by the local transfer function (Figure 4.20); there is not a clear linear relationship apparent, suggesting that pH is not a lone forcing factor, and that the reconstructions are not exclusively representing the same environmental variable. These inferences should therefore be treated with caution.

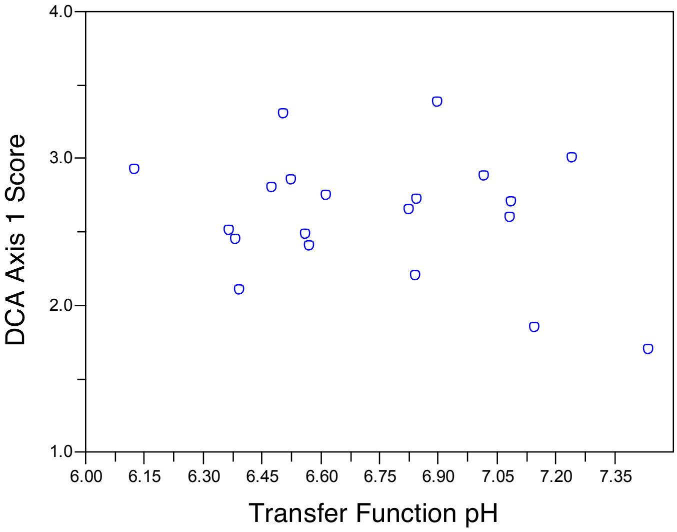


Figure 4.20 DCA axis 1 scores and reconstructed pH values produced by the transfer function using the local, Nuuk, training set.

The regional analysis was repeated using the complete expanded data set of 85 contemporary lake samples along with the 17 fossil samples. The DCA axis results again demonstrate there to be significant differences in the assemblages from the different regions, and that the fossil samples relate most closely to those from the Nuuk region. However, this data set included the lakes that were highly saline/conductive and are significantly different to those from the site of interest. Though the conductivity of the lake is a factor on the diatom assemblages, the lakes from the Nuuk region have conductivity values multiple magnitudes smaller than those from the Søndre Strømfjord region, so it is unreasonable to attempt comparisons of this variable between the data sets and to attempt to reconstruct it. DCA was repeated with these 11 highly conductive lakes excluded (Figure 4.21), aiming to provide a more representative relationship between the fossil and contemporary samples.

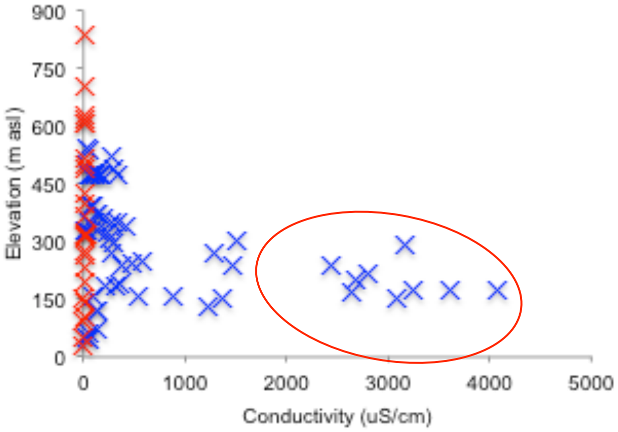


Figure 4.21 Conductivity of the Nuuk dataset lakes (red), and Søndre Strømfjord (blue), against respective lake elevations. The 11 lakes excluded are highlighted.

Once again, the two regional data sets are in separate clusters, and the fossil samples are most closely related to the higher ranges of the Nuuk samples (Figure 4.22). The first axis had by far the largest gradient of all the axes and explained the greatest amount of variance. Based on the arrangement of the samples along the first axis (horizontal), and with regards to one another, the axis appears to loosely represent the differences between the lake pH values, with the lower values relating to higher pH (Figure 4.22). However, when the DCA scores are compared to the transfer function reconstructions (Figure 4.23), there appears to be a poorer, less linear relationship than that produced by the local dataset (Figure 4.20). Therefore the DCA axis 1 scores cannot be taken to represent this variable alone, however it can be considered along with the other reconstructions as a potential non-quantitative indication of environmental changes in the fossil core. Overall there is a general increase in the DCA scores progressively up the core, with some distinct fluctuations, such as at 1.6m (Figure 4.22).

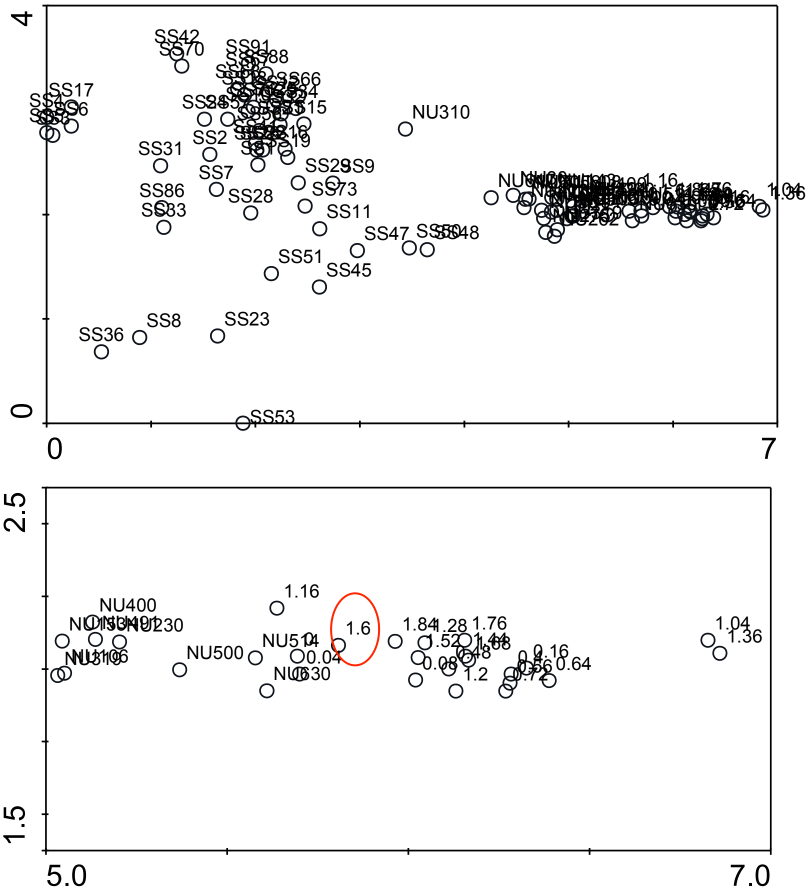


Figure 4.22 DCA scores of regional set of 74 lakes and the fossil samples from the Nuuk lake core. Contemporary samples are labeled 'NU' (Nuuk) and 'SS' (Søndre Strømfjord), and the fossil samples by their depth in the core. The sample at 1.6m is highlighted.

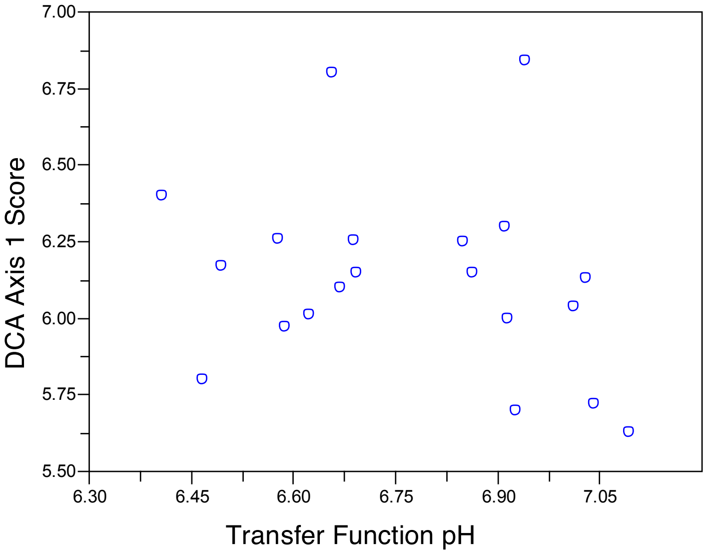


Figure 4.23 DCA axis 1 scores and reconstructed pH values produced by the transfer function using the regional training set.

4.5.8 Proxy Data and Quantitative Reconstructions

The environmental variable reconstructions shall now be considered with respect to the additional proxies produced from the Nuuk fossil core, including biogenic silica and loss-on-ignition.

The reconstructed pH in the bottom of the core are relatively constant, before beginning to rise from approximately 1.44m upwards; this coincides with the transition from clays to gyttja. The pH values indicate an acidification in the mid-section of the core, ~0.7m-0.4m. This corresponds to the inferred changes suggested by the diatom assemblages, with increases in species such as *Eunotia arcus* and *Tabellaria flocculosa*, and a decline in species such as *Staurosirella lapponica* (section 4.3.2, Figures 5.2 and 5.5). Throughout this period, there is an increase in the loss-on-ignition, with fluctuating dissolution, and a spike in the biogenic silica content consistent with the presence of diatoms following a barren phase (Figure 5.2). During this phase, there is also a shift in the bottom water temperature from warming to cooling, and also a decline in the elevation also representing cooling (Figure 5.5).

In terms of the reconstructed temperatures, both bottom water temperature and that inferred from the elevation, there is significant variability in the bottom section of the core, from 1.84 to 1m depth (Figure 5.5). This incorporates the transition from clays at the bottom of the core into darker clays and gyttja. This is reflected by the variability in the diatom assemblages across those depths; the amount of dissolution of diatoms over this period remains relatively constant, however the biogenic silica fluctuates considerably, and the loss-on-ignition increases through the period (Figure 5.2). This suggests a highly variable period of climatic and environmental conditions in the lower section of the core, variability that is not evident in the temperature records from the Greenland ice cores (Figure 5.4); this demonstrates the ice-free corridor and lakes in western Greenland to have been sensitive to climatic changes.

4.5.8 Summary of Reconstructions

The 1.84m long lake fossil core from a lake at 608m asl near Nuuk has a relatively consistent stratigraphy. The stratigraphy consists of light clays at the base of the core, that get progressively darker, with a transitional phase ~140-120cm into brown gyttjas ~120-0cm (section 4.3.2). Within the gyttja sections there are several bands of darker gyttja and potential moss bands. Based on the age of other lake cores from the region, this lake core is anticipated to represent 9000-8500 years BP to present (section 4.3.4). The loss-on-ignition generally increases up the core; in contrast, the biogenic silica decreases, with the exception of a spike at ~0.64m, corresponding with a potential moss band (section 4.3.3, Figures 4.12 and 4.13).

The amount of dissolution of the fossil diatoms in the core also generally increased up the core, with the exception of the shallowest, most recent samples from 0.08-0m (Figure 4.12). In terms of the diatom assemblages, the lake core did not provide a complete record; there are several barren sections ranging in size, from 8cm to 24cm in the core (Figure 4.13). Constrained cluster analysis identified five zones within the core based upon the dominant diatom species (Figure 4.13). There are several species universal through the core, such as *Tabellaria flocculosa*, and an increase in acidic species, such as *Eunoita arcus*, up the core, particularly in the mid- and upper sections of the core (Figure 4.13).

The quantitative reconstructed values produced by the local and regional transfer functions and DCA axis 1 scores have been plotted against the respective sample depths (Figure 4.24). The DCA axis scores of the local and regional datasets show similar trends, though the regional set was higher on the axis and generally has more extreme fluctuations (Figure 4.24). With the various transfer functions developed for the different environmental variables, the variables generally demonstrate changes at the same time, and the local and regional models generally show the same trend. The exception of this is the total phosphorus reconstructions and also those of lake depth; this is likely due to the discrepancies in the contemporary diatom species (section 4.4), and also the broader ranges in the environmental values of the regional dataset (Figure 4.11).

The reconstructed bottom temperature demonstrates a lack of stability and several fluctuations throughout the core (Figure 4.24); these changes shall be considered in the discussion in relation to other temperature records, such as those from the ice cores, and also pollen records from the core. This variability in temperature throughout the core is also reflected in the elevation reconstructions, which contains many of the same features as the bottom temperature reconstructions (Figure 4.24). The pH reconstructions vary up the core, with some minor fluctuations and a general acidification ~0.7-0.4m. The reconstructed lake sample depths produced variability that is consistent with the trends shown by the other variables. Overall, the reconstructions of pH, elevation and sample depth have produced the more reliable reconstructions, though all shall be considered within the discussion (section 5.2.3).

The local transfer function reconstructions lack modern analogues; in contrast, the regional dataset provides a number of good modern analogues for the fossil samples, improving confidence in the quantitative values produced for these particular samples. As well as this, the regional models generally produced smaller errors (Figure 4.24). However, the errors are still considerable for all the reconstructions with considerable overlap between the samples such that no change may have actually occurred. However, the stratigraphy and changing diatom assemblages indicate there to have been changing environmental conditions up core (sections 4.3.1 and 4.3.2).

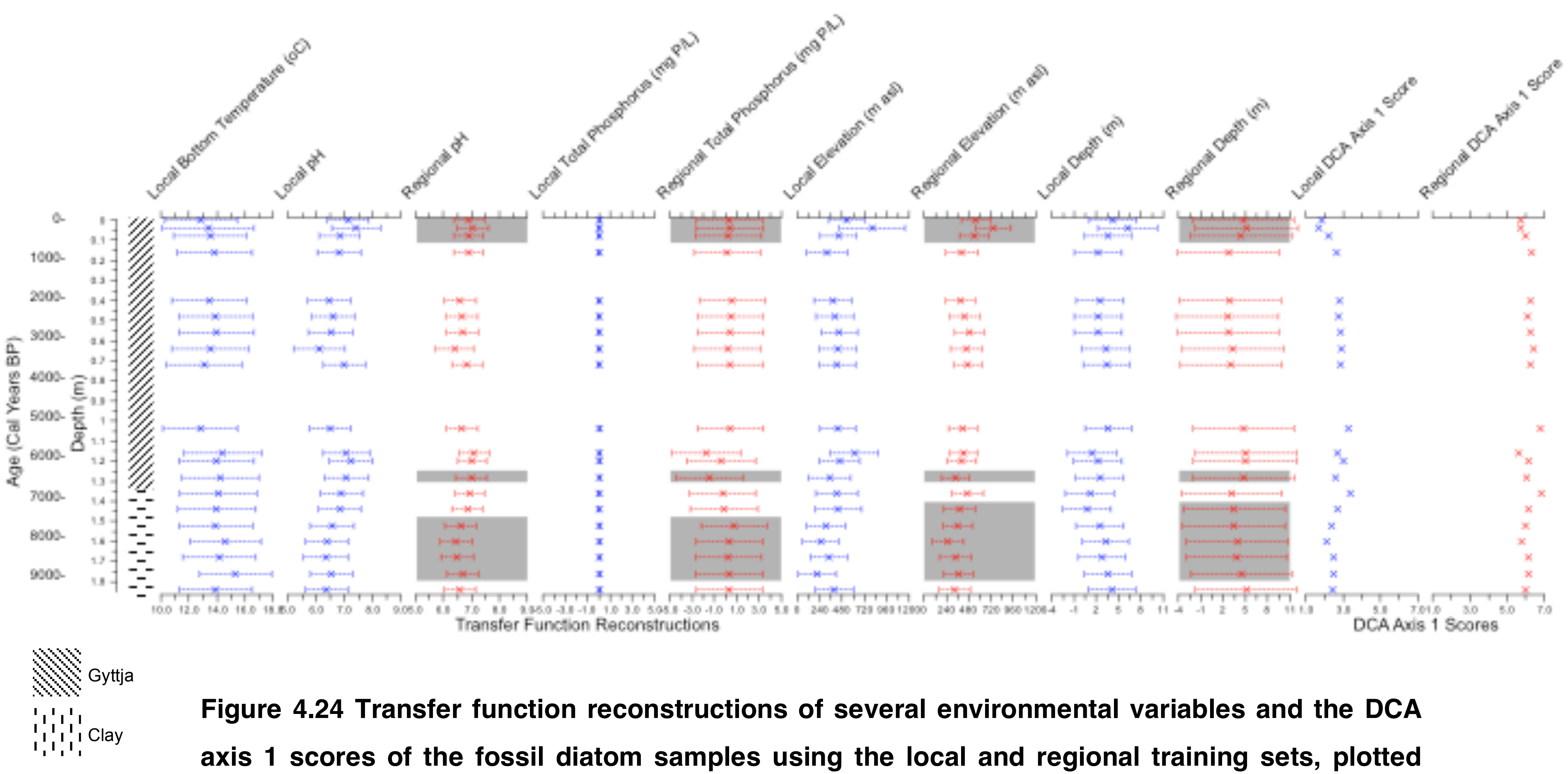


Figure 4.24 Transfer function reconstructions of several environmental variables and the DCA axis 1 scores of the fossil diatom samples using the local and regional training sets, plotted against their respective sample depth and interpolated age. Shaded sections indicate that the samples have good modern analogues (Table 4.5 displays details of the modern analogues). Included is a simplified stratigraphy of the core (Figure 4.12 displays the detailed stratigraphy).

5 Discussion

This chapter discusses the inferred and quantitative reconstructions of Holocene environmental change from the proxy data. Also discussed is the contemporary lake diatom data from the local dataset, and also the expanded regional dataset, and explores the differences between the two and the problems encountered. Finally, the problems of the environmental reconstructions and the general usefulness of lake diatoms as a proxy for environmental change in west Greenland are considered, as well as the limitations of the project as a whole.

5.1 Reconstructing Environmental Change from Greenlandic Lakes

Holocene lake sediments from Greenland have been used for a variety of paleoecological and environmental studies. Early studies in west Greenland, particularly around the Godthåbsfjord region, include those by Iversen (1953), Foged (1977) and Fredskild (1983). Iversen (1952) initially provided an extensive overview of postglacial pollen in west Greenland in an effort to establish the origin of flora and development of the vegetation. Fredskild (1983) further expanded upon this through the use of lake pollen records to determine development of the lakes and the paleoenvironments through the Holocene; this identified stages of lake development, with shifts between climate and the catchment vegetation and chemistry forcing the conditions in the lake. Over the past few decades there have been a variety of studies of Greenlandic lakes, using a wider range of proxies, including pollen, diatoms, chironomids and biogenic silica, to assess particular environmental variables and climatic changes (section 1.5.2); this section considers the reconstructions that have been produced in this thesis, and how they relate to other studies.

5.1.1 Diatom Assemblages & Other West Greenland Studies

The fossil diatom assemblage from the Nuuk lake fossil core is not as diverse as the contemporary assemblages that are applied in this thesis, and the diversity generally decreases down the core (section 4.3.2), and is also not fully represented by the training sets (section 4.4). However, there is some overlap in species, and some similarities to other Greenland lake fossil assemblages. A fossil core from Bliss Lake, north Greenland, ~2000km north of the Nuuk field site (Olsen *et al.*, 2012; Figure 1.1) shares a number of the same common lake genera as the Nuuk fossil core, such as *Eunotia spp., Fragilaria spp.* and *Nedium spp.*, and also shares the common feature of having *Tabellaria flocculosa* present throughout the majority of the core (Figure 5.1).

In terms of other west Greenland lakes, there are several comparative fossil lake diatom assemblages. Braya Sø is a subsaline lake at approximately 170m asl, located just east of Kangerlussuaq, on the northern side of Søndre Strømfjord, ~250km north of the Nuuk fieldsite; the core length is 2m, and the diatom assemblage is largely dominated by species with high conductivity optima, as expected for a subsaline lake (Ryves *et al.*, 2002). However, there is also a low (<10%) presence of certain species with low conductivity optima, some of which are common with the Nuuk fossil core, such as *Achnanthes minutissima*, *Pinnularia microstauron* and *Fragilaria spp.* (Ryves *et al.* 2002; Figure 5.1). *Achnanthes minutissima* is present throughout most of the Braya Sø core, though is only in a few samples of the Nuuk core. *Pinnularia microstauron* has a fluctuating presence in the Braya Sø core, though declines in the upper 40cm of the core; similarly, *Pinnularia microstauron* has a higher presence in the lower sections of the Nuuk core, occurring between 1.76 and 1.16m. A nearby lake to Braya Sø also produced a fossil diatom record, starting approximately 8000 years BP (Anderson *et al.*, 2008); this also produced some similar species such as *Achnanthes minutissima* and *Fragilaria spp.*

The study by Perren *et al.* (2009) of lakes in the Kangerlussuaq region, discussed in section 4.2.2, produced short cores of just 20cm depth for a series of lakes, from coastal to inland environments. These records all contain *Cyclotella rossii* and *Cyclotella stelligera*, species almost completely absent within the Nuuk fossil core. However, lakes located in the western side of the transect, inland and closer to the ice sheet, share a number of common species with the Nuuk fossil core. These lakes contain *Achnanthes spp.* and *Fragilaria* *spp.*, both of which are present within the upper sequences of the Nuuk fossil core. *Aulacoseira alpigena* is also present within one of the lake sequences, which is located on a nunatak, and is also most abundant in the top 20cm of the Nuuk fossil core (Figure 5.1).

The most relevant fossil diatom assemblage to this Nuuk fossil core is that from 'Lake 100m s.m.' (Foged, 1977), approximately 30km south of the study site (Figure 2.2). The fossil diatom species in 'Lake 100m s.m.' display a number of similar trends to that evident in the Nuuk fossil assemblage, such as the presence of *Eunotia arcus*, *Pinnularia viridis*, *Stauroneis anceps fo. linearis* and *Stauroneis pheonicenteron* in the middle and upper sections of the core, and *Navicula cincta* in the lower section (Figure 5.1). A feature of the 'Lake 100m s.m.' record is the consistent presence of *Tabellaria flocculosa* from the lower middle through to the top of the core, a similar dominance that is a major feature of the Nuuk fossil core (Figure 5.1). These similarities between the fossil assemblages suggest a shared history of lake development and climatic forcing for these lakes close to the ice margin within the Godthåbsfjord region.

The general similarity in some of the species within the various fossil assemblages of diatoms from lakes within Greenland, and particularly west Greenland, indicates some common Greenlandic lake species. The similarity of certain species between the lakes also indicates that the lakes may be indicating similar responses to environmental forcing and lake development, suggesting the potential of local and regional signals being represented within the fossil diatom assemblages of the lakes in western Greenland.

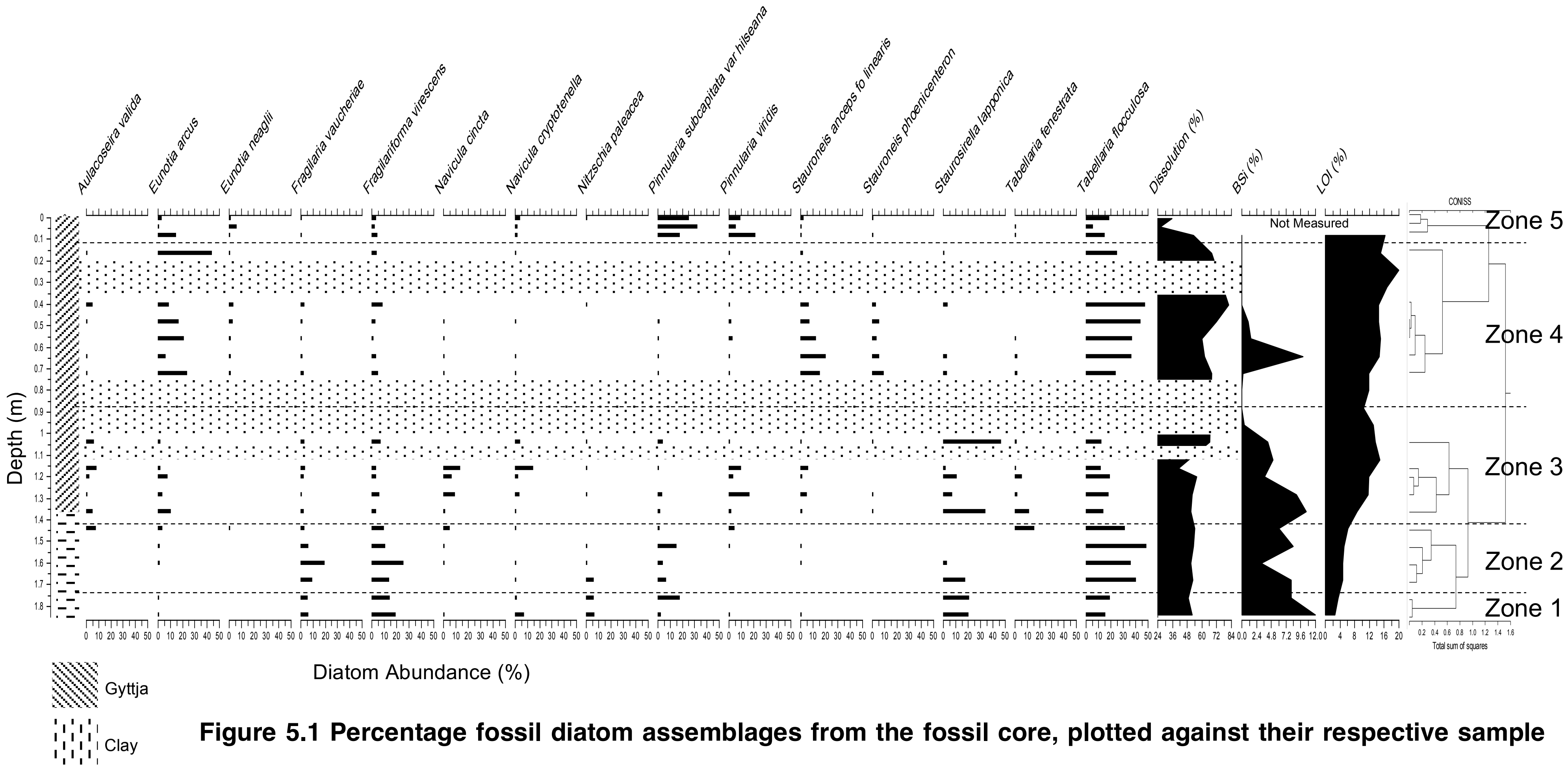
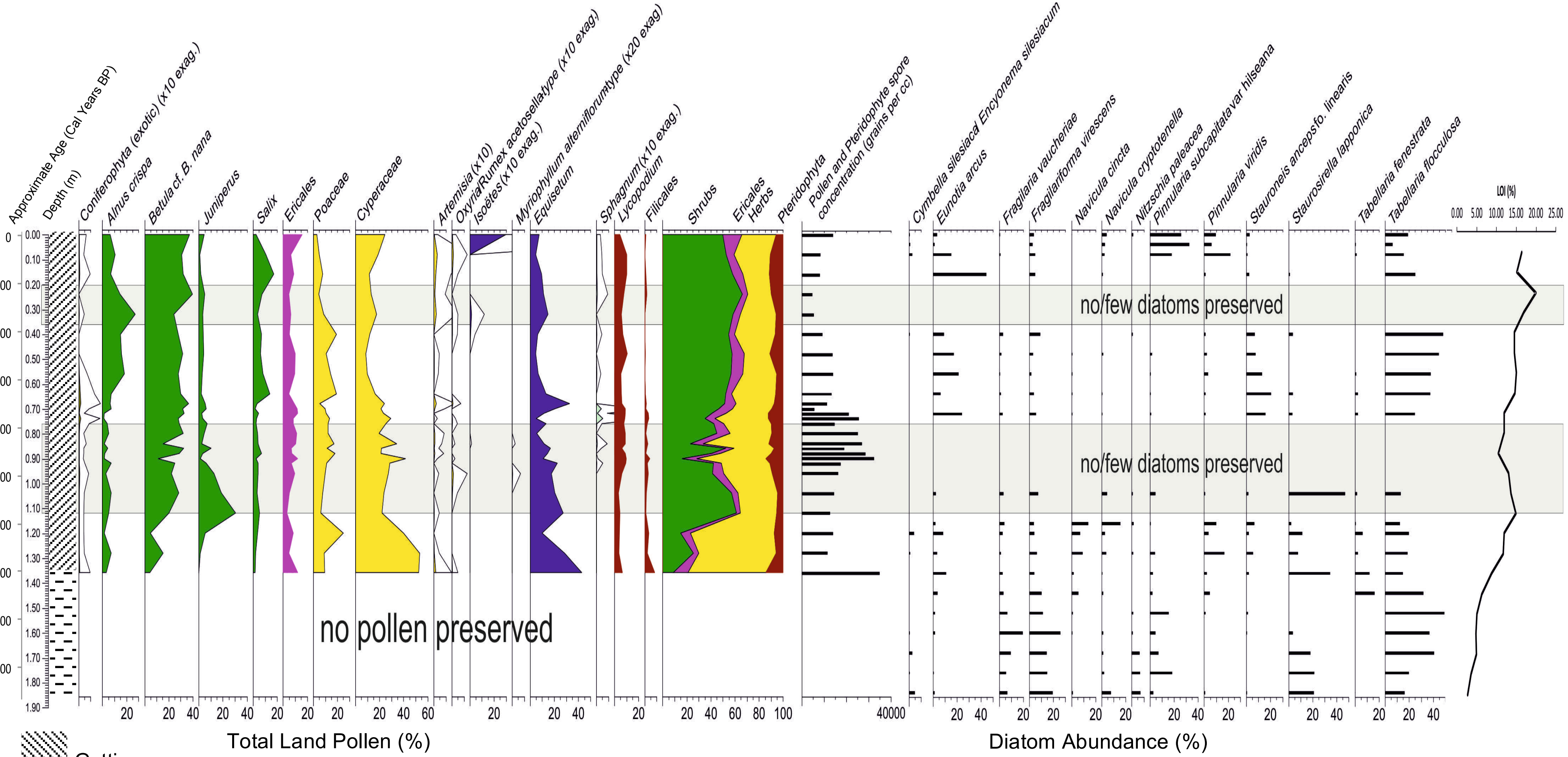


Figure 5.1 Percentage fossil diatom assemblages from the fossil core, plotted against their respective sample depth. Only species with an abundance over 5% and occurring in at least three of the samples are displayed. Shaded sections indicate barren samples. Included is a simplified stratigraphy of the core (Figure 4.12 displays the detailed stratigraphy). Percentage dissolution, loss-on-ignition, biogenic silica and the results of cluster analysis are shown on the far right; dashed lines represent the zones identified by the cluster analysis.

5.1.2 Lake Pollen Data

Pollen records provide an insight into past climatic conditions. Pollen was also sampled within the Nuuk lake fossil core by Dr Helen Ranner (Durham University). The lower section of the core consists of herbaceous and grass pollen, declining in presence between ~1.5-1.2m depth, as the presence of tree and shrubs increases (Figure 5.2). There is a sharp rise in the presence of *Juniperus* at 1.12m, corresponding to a barren diatom sample (Figure 5.2), just prior to an increase in the deciduous *Betula* genera at 1.04m, a none barren diatom sample. Following 1.12m, the amount of *Juniperus* declines, whilst the amount of *Betula* remains relatively constant. Between 0.65 and 0.55m there is an increase in *Alnus crispa*, corresponding to a phase of an increase in the amount of *Eunotia* arcus (Figures 5.1 and 5.2); the *Alnus* remains fairly constant up the rest of the core, before declining during the last ~0.3m. The increase in the tree species suggests a general cooling up the core from ~1.10m, and the rise in *Alnus* in particular indicates a decline in temperatures, a potential signal of the neoglacial.

The total pollen sum is low at the bottom of the core, with a rise from 1.36m onwards, before a decline from 0.48m (Figure 5.2). This differs with some features of the fossil diatom assemblages, as there are several barren phases within the core (Figures 5.1 and 5.2). However, the barren diatom sample at 1.12m corresponds to an increase in the amount of *Juniperus*, indicating a potential warm phase and perhaps a shallowing of the lake that led to a halt in diatom productivity. The barren diatom phase from 1 to 0.76m corresponds to the initial increase in *Betula* and decline in sedges, and the barren phase between 0.36 and 0.2m corresponds to inverse fluctuations in the amounts of *Alnus* and *Betula*, and a decrease in total pollen sum (Figures 5.1 and 5.2).



5.2 Relative pollen and diatom assemblage with loss-on-ignition data from the Nuuk fossil core. Only pollen and diatoms reaching 10% of the total sum are included, with additional pollen species shown where they are important in determining the local environment during the phases that are barren of diatoms. Produced in collaboration with Dr Helen Ranner (Durham University).

5.1.3 Chronology

An approximate chronostratigraphy for the Nuuk fossil core is established through the association of similar features that have been quantitatively dated from nearby sites, primarily through changes in the pollen assemblage. Ideally quantitative dates for the core itself would be used via radiocarbon dating, however this is not possible in the time frame of this research.

‘Lake 100m s.m.’ in the Godthåbsfjord region is within close proximity (~30km) to the Nuuk fossil core site (Figure 2.2), and has a basal date of 8640±130 C14 years (9652-9592 cal years BP; Fredskild, 1983); the Nuuk fossil core is therefore assumed to represent most of the Holocene and have a basal date of approximately 9500 cal years BP (section 4.3.4). The clay-gyttja transition in the ‘Lake 100m s.m.’ record has an age of 7770±130 C14 years (c. 8639- 8594 cal years BP; Fredskild, 1983), and this age is loosely associated with the clay-gyttja transition in the lower section of the Nuuk fossil core.

A core from Lake Igaliku in southern Greenland has a dated Holocene pollen record. This record displays a spike and decline in *Juniperus* c. 5000 years BP, prior to rise in *Betula* c. 4000 years BP (Massa *et al.*, 2012) that is also evident in the Nuuk record, and is used as a tie point to offer an approximate chronology for the Nuuk lake pollen record (Figure 5.2). Fredskild’s (1983) lake pollen records from ‘Lake 100m s.m.’ also provides a paleovegetation record for the inner Godthåbsfjord region. The influx of *Betula* and *Juniperus* is dated as having occurred c. 6000 14C years (c. 6934-6846 cal years BP), and *Alnus* c. 4000 14C years (c. 4522-4476 cal years BP), offering a comparative chronology to that from Massa *et al.* (2012) from southern Greenland. These dates from the ‘Lake 100m s.m.’ and of the dated pollen assemblage shifts are associated with the similar features seen in the Nuuk fossil record, and ages have been interpolated assuming a constant rate of sedimentation (due to the generally homogenous nature of the stratigraphy (section 4.3.1)) to provide an approximate chronology for the core. These approximate ages for the record are used from here on.

5.1.4 Environmental Variable Reconstructions

Within this thesis, several environmental variables have been reconstructed using the contemporary lake diatoms and those from the fossil lake core; these include lake bottom temperature, pH, total phosphorus, elevation and lake depth (section 4.5). The quantitative reconstructed values from the transfer functions show there to have been fluctuations in all of the variables up the core, however, these reconstructions are not necessarily completely reliable due to the associated errors, and also due to the complexity of the lake fossil core itself. Each shall be discussed, and considered in relation to other studies.

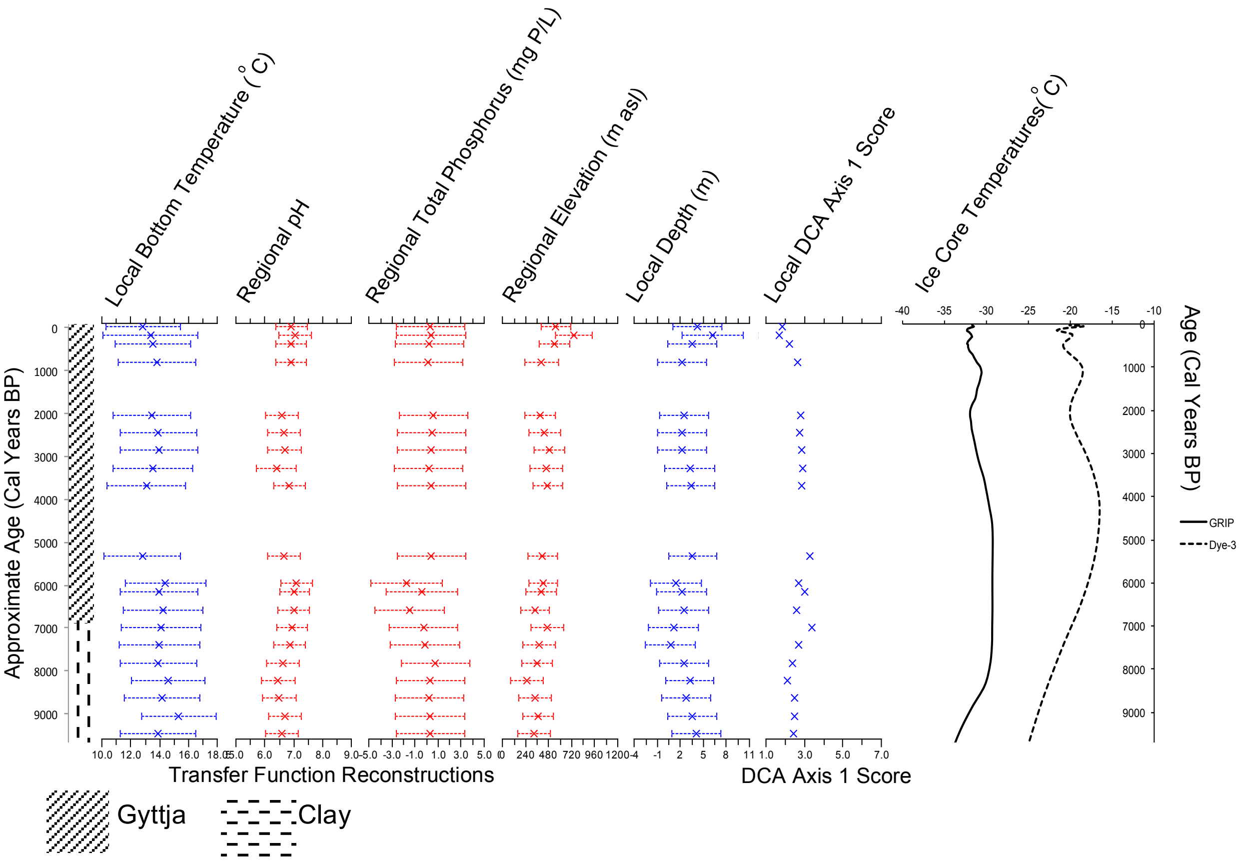


Figure 5.3 Transfer function reconstructions of several environmental variables and the DCA axis 1 score of the fossil diatom samples using the local training sets, plotted against the approximate age inferred from dated events in 'Lake 100m s.m.'. Details of the performance of the reconstructions are provided in section 4.5.6. Included is a simplified stratigraphy of the core (Figure 4.12 displays the detailed stratigraphy), and the GRIP and Dye-3 ice core temperature records.

The quantitative reconstruction of bottom temperature produced in this thesis fluctuates up the core (section 4.5.1), with an overall decline in temperature up core. When compared to the borehole temperature values produced from the GRIP and Dye-3 ice cores, there appears to be some similarities (Figure 5.3). For example, there is a rise and decline in the reconstructed bottom temperature between 4000-2000 cal years BP, which could represent a delayed response to the shift from rising to declining temperatures seen in Dye-3 record at approximately 4000 years BP; this shift also corresponds to the increase in *Alnus* crispa seen within the pollen, and is consistent with the chronology that has been applied to the fossil core (section 5.1.2; Figure 5.2). This indicates some agreement between the pollen and diatom data and quantitative reconstructions. Similarly, the apparent temperature rise that has occurred by ~1000 cal years BP, and the fall following this, could relate to the rise and fall seen in the GRIP and Dye records from 1500 years BP to present.

The reconstructed pH values from the fossil core initially remain fairly constant, before rising between 8000-6000 cal years BP (section 4.5.2). There is a fall in pH at ~5300 cal years BP, a sample within the barren phase that did contain diatoms; these lower values continue into the uppersection of the core, from ~3300-2000 cal years BP, corresponding to the transition in temperature (Figures 5.3), and also an apparent acidification up core indicated by the increase in species, such as *Eunotia arcus* (Figure 5.1), a trend also seen in the 'Lake 100m s.m.' record (Figure 5.4). This is consistent with the trend of lakes in glaciated northern temperate latitudes of becoming more acidic over time, including in western Greenland, due to long term cooling following the Holocene Thermal Maximum and catchment soil development (Bigler *et al.*, 2002; Foged, 1977; Perren *et al.*, 2012; Figure 5.4). The reconstructed core surface value (7.15 and 6.93, local and regional models respectively; section 4.5.2) is an underestimate of the measured bottom water pH for the lake (7.55), demonstrating issues relating to the accuracy of the quantitative values that are produced by transfer functions.

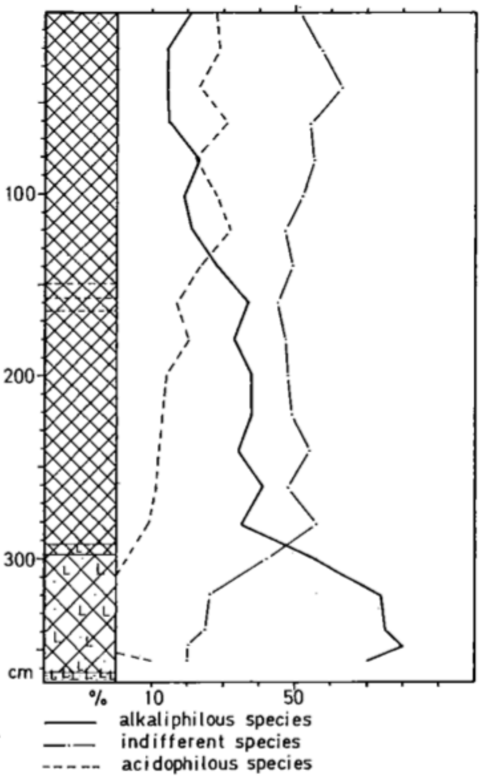


Figure 5.4 Change in amount of diatom species within pH-groups from the 'Lake 100m s.m.' fossil core. Foged (1977).

Other studies have used the same transfer function approach to reconstruct pH. Correspondence Analysis revealed pH to be the most significant forcing variable of lake diatoms from a series of 23 lakes in Svalbard (Jones & Birks, 2004). From this a pH transfer function was developed to quantify recent (last millennia) changes, and identified similar issues of different transfer function models producing differing results for the various lake fossil records, and also a differing record of recent pH changes between the lakes, attributed to differing fossil diatom diversity but also the environmental conditions of the lake (i.e. depth, acidity) (Jones & Birks, 2004), issues discussed later in this chapter. Diatom assemblages from lake sediment have also been used to quantify water pH, as well as July mean air temperature in conjunction with other indicators, throughout the Holocene from a lake in northern Sweden (Bigler *et al.*, 2002). This was achieved through the use of transfer functions, as with this study, with the fossil assemblages from the lake sediment core and a contemporary training set of diatoms from 100 lakes distributed regionally in northern Sweden (Bigler *et al.*, 2002). However, this study encountered some of the same issues as in this thesis, which shall be discussed towards the end of this section.

The reconstructed values for total phosphorus up the core vary significantly dependent upon the transfer function model that was used (section 4.5.3). Those from the regional model are much more extreme, and exceed the contemporary total phosphorus values of the local set of Nuuk lakes (Figure 4.5), and have very large error terms; these reconstructions from the model are therefore not considered as reliable or accurate. The reconstructions from the local model however indicate there to have been minimal change in the total phosphorus of the lake, with a slight increase in the uppermost, most recent sample (Figure 5.3). This suggests that there was little change in the total phosphorus of the lake, contrasting to the shift in total phosphorus displayed by lakes in the Kangerlussuaq region, west Greenland, as they become more oligotrophic through the Holocene (Perren *et al.*, 2012). It could also suggest that in the southwest Greenland context, diatoms do not provide a strong record of total phosphorus, as was also suggested by the lack of significance of total phosphorus in explaining the diatom assemblages during CCA of the local dataset (section 4.1.4), despite there generally being considered, and also demonstrated, strong relationships between total phosphorus and modern lake diatoms in other regions, though not in Greenland (e.g. Battarbee *et al.*, 2001; Lotter *et al.*, 1998).

The reconstructed elevation of the fossil samples can be considered as a representation of the air temperature, with increasing elevations indicating decreasing temperature. These reconstructions indicate there to have been a lack of continuous steady temperatures up the core (section 4.5.4). However, overall there is an apparent cooling trend, though there is significant overlap in errors (Figure 5.3). The fluctuating nature of the record and overall decline in temperature bears some similarities to that of the reconstructed bottom water temperatures of the lake, providing confidence in the use of elevation as a proxy for temperature. An interesting feature of this record is the highest reconstructed elevation is for the sample ~300 cal years BP, which has a value in excess of 800m asl, and far colder than the rest of the dataset; as this is a relatively recent and rapid decline in temperature, it could be a record of the Little Ice Age event, c.1300-1800AD, which is also evident within the GRIP and Dye-3 records, which the core chronology is consistent with (Figure 5.3).

The reconstructed lake sample depth provides an insight into the changing depth of the lake, and therefore potentially a record of drying-events; this is a particularly interesting variable to consider due to the barren phases within the core, where sedimentation continued and diatom productivity ceased. This shall be fully discussed later, within section 5.1.4. With this variable, the local model provides a more suitable reconstruction (section 4.5.5). The reconstructed sample depth varied more in the lower section of the core, ~9500-7700 cal years BP (Figure 5.3), and remained fairly constant ~3500-2000 cal years BP; again the sample ~300 cal years BP demonstrates a rapid increase, producing the largest value for the reconstructed sample depth, indicating there to be a relationship between lake depth and temperature. Prior to the barren phases within the core, there do appear to be slight falls in the reconstructed lake sample depths (e.g. ~6000 (1.16m) and ~800 (0.16m) cal years BP; Figures 5.2 and 5.3), suggesting a potential drying out of the lake, causing a decrease in depth and reducing the diatom productivity, or increasing dissolution. Indeed, a reconstruction of lake depths for lakes in the Kangerlussuaq region indicate a low-stand prior to 6070 cal years BP, though this is then followed by a rise in lake levels which is not seen in the Nuuk fossil reconstructions (Aebly & Fritz, 2009). However, the sample at ~5300 cal years BP does not completely fit with this. As well as this, the decline in reconstructed sample depth is not reflected by a rise in the temperatures, both the bottom water temperature and that inferred by the lake elevation. Models of lake levels in western Greenland were more sensitive to precipitation changes than temperature (Aebly & Fritz, 2009), suggesting more complex factors have been acting on the lake and the diatoms, and is an area for future study.

Detrended Correspondence Analysis (DCA) axis 1 scores provide a general environmental change curve. As with the quantitative reconstructions, there was considerable variability in the lower section of the core, and also a fluctuation in the uppermost section of the core. The overall trend shows the environmental conditions in this southwest Greenland lake to have varied throughout the Holocene, consistent with the variations seen by the quantitative reconstructions produced by the transfer functions (Figure 5.3)

Some of the issues that have been confronted in this thesis in relation to the quantitative environmental reconstructions are similar to those met by Bigler *et al.* (2002). For example, a predominant problem in both the studies in terms of the reconstructions is that the diatom samples have a ‘poor’ fit with the contemporary training set. In the Bigler *et al.* (2002) study this was particularly an issue for the early Holocene, whereas with the core in this thesis, it is an issue throughout large sections of the core (sections 4.5.6, 5.1.4 and 5.3.1). Other indicators including pollen and chironomids also produced the same problem, whereby the fossil assemblages were not well represented by the contemporary assemblages (Bigler *et al.*, 2002); it is likely therefore that the Nuuk core may have the same problems for these other proxies. It is vital that the environmental reconstructions are evaluated for the fit of the assemblages, as despite transfer functions always providing a quantitative reconstruction, it may not necessarily be a fair or accurate value, as has been discussed. Indeed, values produced from models could be over- or underestimates, particularly for more extreme values, as encountered with total phosphorus values in Sweden (Bradshaw & Anderson, 2001), an issue that cannot be thoroughly assessed without other data to validate the values.

5.1.5 Identification of Barren Periods

Along with the physical preservation issues of dissolution and fragmentation within the core, discussed in section 5.3.1, there were several barren periods that were also identified (Figure 5.1). These barren periods varied in size from just 6cm to 24cm sections of the core. These were identified based upon the lack of diatoms within the samples; some slides proved to be completely absent of diatoms, though some provided several diatoms over the entire slide (section 3.3.1), however too few (<10) to provide a suitable assemblage for that sample. Some confidence in the identification of these barren periods is given through the corresponding decline in biogenic silica for the larger barren periods in the mid- and upper sections of the core, as this implies a decline in the productivity in diatoms that is reflected in their absence.

In terms of an explanation for the cause of these barren periods, the quantitative reconstructions of certain environmental variables provide some insight. In particular, the reconstructed lake sample depth using the local model demonstrates a decline in depths prior to some of the barren periods, and there is also a decline in elevations shown by the regional models, indicative of warming (sections 4.5 and 5.1.3; Figure 5.3). This could demonstrate a drying out of the lake; this would account for a continuation of sedimentation and a halt in the diatom productivity, as discussed previously in section 4.5.5. Pollen is preserved through these periods (Figure 5.2); prior to the first barren section there is a peak in *Juniperus*, indicative of warm, dry conditions, and following the second barren period an increase in *Salix*, suggestive of a wetter climate. These shifts in pollen along with the barren diatom periods suggest a more complicated relationship between these proxies and the lake record of climatic change.

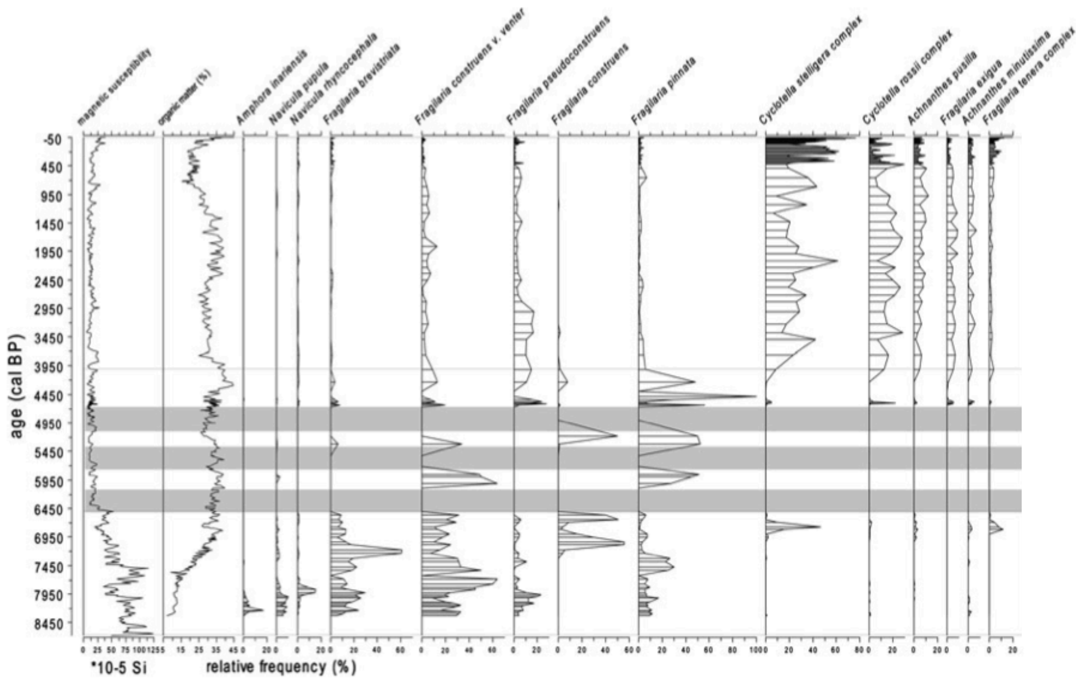


Figure 5.5 Most significant diatom taxa, magnetic susceptibility and organic matter content from a lake core 250km north of the Nuuk core site; grey bands indicate diatom barren periods.

The identification of barren periods with a lack of diatoms in a lake core is not unique to this study; others have also encountered sections without diatoms that have been associated with climatic changes, such as cooler conditions causing increased ice cover (e.g. Michelutti *et al.*, 2003), so climatic changes are a possible explanation for the barren phases within this core. Indeed, a study by Perren *et al.* (2012) of a core from a lake ~250km directly north from the lake core studied in this thesis also contained several barren diatom phases. The barren phases identified in the Perren *et al.* (2012) study are dated between ~6500 and 4500 cal years BP (Figure 5.5). This roughly corresponds to the approximate age associated with the largest and also single sample barren period identified in the Nuuk fossil core (Figure 5.1); higher resolution sampling within the barren phase of the Nuuk fossil core may reveal this large barren period to be a series of smaller barren phases similar to those within the Perren *et al.* (2012) record. The specific reason for the lack of diatoms is unknown, though it is postulated that diatom production and preservation was prevented due to lowering lake levels during mid-Holocene aridity, indicated by other lake studies in western Greenland (Aebly & Fritz, 2009; Anderson and Leng, 2004; Perren *et al.*, 2012), and also seen in the quantitative reconstruction of sample lake depth for the Nuuk fossil record (Figure 5.3). A second barren diatom period is not seen in the Perren *et al.* (2012), however lake lowering is observed in the Kangerlussuaq region 3880-2560 cal years BP (Aebly & Fritz, 2009); the second barren period recorded in the Nuuk core could therefore represent aridity during neoglacial cooling.

5.1.6 Holocene Environmental Change from Lake Diatoms in Greenland

The reconstructions produced in this thesis (section 4.5) provide additional insight into the environmental change of southwest Greenland, and also the role of diatoms as the basis for such reconstructions. The reconstructions undertaken demonstrate there to have been considerable environmental variability, with a number of changes occurring in terms of pH and temperature, as well as lake sample depth. Previous studies using lake diatoms in Greenland have used them in conjunction with other proxy indicators to produce an overview of environmental and climatic change; some have used lake diatoms to quantitatively reconstruct specific variables. This study contributes quantitative reconstructions of several variables, giving an overview of Holocene environmental change, which is supported by several other proxies, such as pollen. It has also produced a general environmental change curve through the use of DCA (secion 4.5.7) supporting the changes in environment shown by the diatom assemblages and the quantitative reconstructions.

Previous studies of lake sediments and pollen within the Godthåbsfjord region have identified a general trend of climate amelioration and warmer temperatures through the early and mid-Holocene, with declining temperatures the last couple of millennia (Fredskild, 1983). This general pattern is supported by three major periods of climatic conditions in western Greenland that have been identified via the influence that temperature, moisture and eolian activity have on the development of lakes (Perren *et al.*, 2012). These zones include an early warm and dry period through until ~5600 cal years BP, followed by a transition into cooler and wetter conditions of the Neoglacial from ~4500 cal years BP, and an increase in eolian deposition, aridity and windiness in the last ~500 years. These periods are supported by reconstructions of lake depth and paleohydrolgy in western Greenland, that display a warmer moister climate through the mid-late Holocene, with the most recent 700 years being drier than the previous 6000 years (Aebly & Fritz, 2009).

The environmental change demonstrated by the proxies and quantitative reconstructions in the Nuuk fossil core are generally consistent with these previous reconstructions of environmental and climatic change. The pollen record of the core appears consistent with a warming climate through the early and mid-Holocene, with cooling following 4000 cal years BP, and a shift in the most abundant pollen species over the last ~800 years, trends which are also apparent in the lake bottom temperature reconstructions (Sections 5.1.2 and 5.1.3; Figures 5.2 and 5.3). The diatom species present within the core and the quantitative pH reconstructions also represent an acidification trend through the

Holocene, consistent with previous studies of lake development within western Greenland and elsewhere (e.g. Foged, 1977; Perren *et al.*, 2012; section 5.1.3).

In terms of the temperature changes, the reconstructions of bottom water temperature and elevation suggest long-term changes in temperature, with recent (within the last 1000 years) fluctuations that may represent the Little Ice Age (Figure 5.3). In the early Holocene, the bottom water temperature reconstructions display some warming, followed by a period of stable temperatures to ~6000 cal years BP, prior to a barren phase; this is largely consistent with the GRIP temperature record, and also the climatic warming and amelioration identified in the other lake studies (e.g. Fredskild, 1983). Evident in the bottom temperature and GRIP record is a transition to cooling ~4000-3000 cal years BP (Figure 5.3). Reconstructed lake depth from the Nuuk fossil core varies throughout the Holocene (Figure 5.3), potentially indicating changes in temperature and also the amount of precipitation (Aebly & Fritz, 2009), which is also indicated by barren diatom periods (section 5.1.4), complicating the inferences of the direct relationship to the climate and the physical history of changes that occurred in the lake.

The use of the lake diatoms for these quantitative reconstructions of environmental change have however also highlighted several issues relating to their application in the Greenlandic lake context. This includes the variability in the diatom assemblages between the lakes, the preservation of the diatoms, and also distinguishing the forcing variables of the diatoms.

5.2 Modern Lake Diatom Assemblages

Modern lake diatom assemblages were produced for 25 lakes from a localized area in the interior of the Godthåbsfjord; one of these lakes also produced the fossil core analyzed in this thesis (section 2.2). An additional dataset of contemporary lake diatoms from the Kangerlussuaq region, approximately 260km north, was combined with the local dataset to produce a regional scale training set. This section discusses the diatom assemblages within the local lake set, and also of the expanded regional set, as well as the implications of producing training sets covering a large area.

5.2.1 In-Lake Similarity

The lake at 608m asl within the 25 lakes sampled to form the contemporary dataset of diatoms from the Nuuk field site was also sampled for the fossil core. The contemporary sample for the lake dataset was taken form the top 0.5cm of surface sediment in the lake; from the fossil core, a separate sample was taken from the top of the core, at 0cm. The contemporary surface sediment sample was taken at a depth of 4.2m, and the core from a depth of 5m. These samples were taken to assess the similarity of the contemporary diatoms within the lake.

There are reasonable similarities between the two samples (section 4.4); both share the same most abundant species, and almost the same number of total species. This suggests some homogony in the contemporary diatom assemblages within the lake sampled. However, as a number of variables force the diatom composition of lakes, as discussed in section 1.3.3, the assemblages from different depths of the lake, particularly among the shallows, will likely differ significantly from these samples due to differing light penetration and other associated variables such as temperature. The similarity demonstrated by the surface sediment and fossil core assemblages demonstrates that for samples taken from similar depths, such as within 1m, and localities in a lake, the composition is generally the same and therefore representing the same settings. This should however in future be repeated within closer depths, and compared with other lakes to consider the homogeny of contemporary diatom assemblages within lake environments.

5.2.2 Similarity Between Local Lakes

25 lakes were sampled for diatoms, and covered an elevation range of 30-835m asl (section 2.2). These lakes were sampled over a small area and a large elevation range to assess whether elevation is the major forcing variable on lake and diatom characteristics in western Greenland.

The diatom flora of the lakes varied considerably, though there are several species that were universal across most, if not all, of the lakes. These universal species include the largely dominant *Tabellaria flocculosa*; also highly abundant are the fragilarophyceae species *Fragilaria vaucheriae* and *Fragilariforma virescens*; *Frustulia rhomboides, Navicula cryptotenella* and *Pinnularia subcapitata var. hilseana* also have a significant presence across the lakes (Figure 5.6). There are some spikes in particular species in certain lakes, such as the *Aulacoseira spp.*. *Aulacoseira perglabra* is present in some of the lower elevation lakes, disappearing in lakes above 550m asl; *Aulacoseira alpigena* is also present in the lower elevation lakes, disappearing above 700m asl, with particularly large abundances occurring between 250-350m asl. *Cyclotella spp.* have a similarly scattered presence, with a distinct dominance in abundance of both *Cyclotella rossii* and *stelligera* in the lake at 310m asl, the deepest lake of the dataset (Figure 5.6). Overall, there does not appear to be a trend in the diatom assemblages in relation to lake elevation, which was confirmed by the results of unconstrained cluster analysis (Figure 4.2).

Multivariate analysis reveals that lake sample depth, lake area, and lake water sulphate to be the most significant environmental variables at explaining the contemporary diatom assemblages of the lakes. Elevation was not a significant variable, and unconstrained cluster analysis also revealed that the lakes assemblages to not to be exclusively associated with elevation. Lake depth reflects a number of other environmental variables, including temperature and light penetration, which also influences the ability of diatoms to photosynthesize (section 1.3.3), so it is therefore difficult to distinguish specifically what exactly the forcing variable acting on the diatoms is that is being represented. Similarly, area can be linked to complex issues of circulation and sedimentation patterns, and sulphate is not the nutrient that would be expected to be most significant, as phosphorus and nitrogen are most often associated as having a forcing role on diatom productivity (section 1.3.3, Batarbee *et al.*, 2001). These uncertainties over the individual forcing factors on the contemporary diatoms

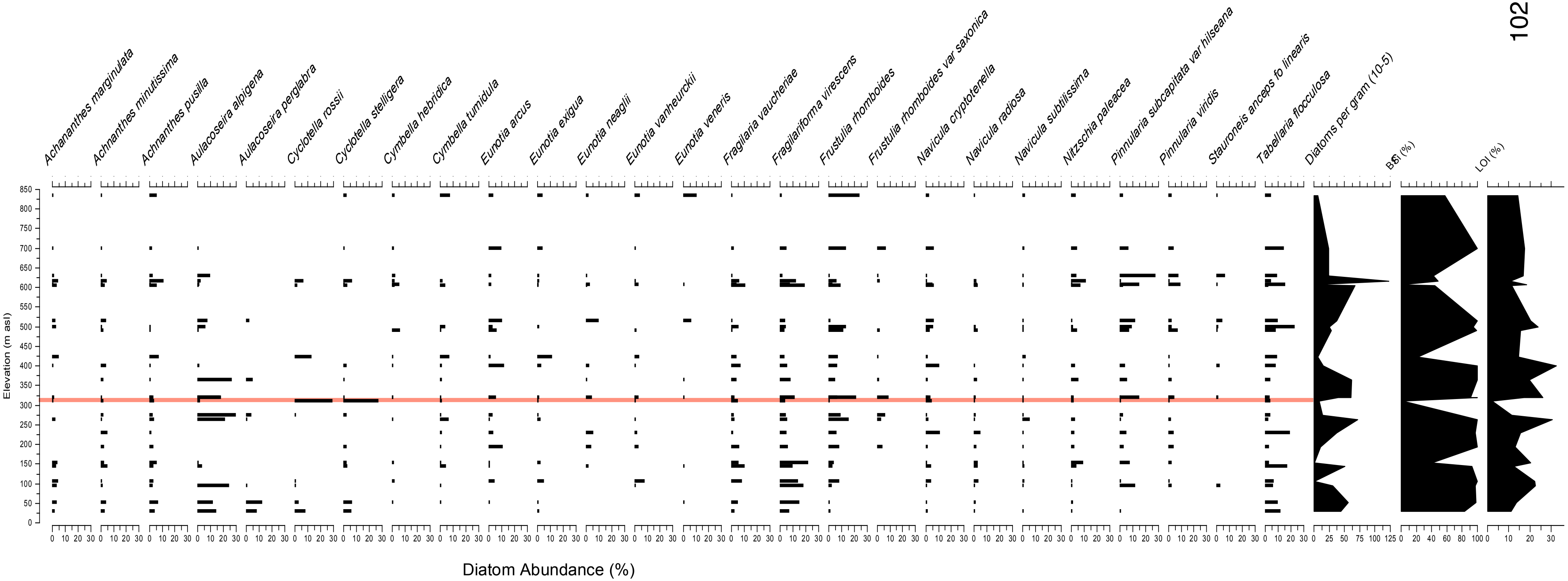


Figure 5.6 Percentage contemporary diatom assemblages of the 25 lakes sampled in the Nuuk region, plotted against their respective elevation (m asl). Only species with an abundance of over 5% and occurring in at least three lakes are displayed. Abundance of diatoms and biogenic silica content is displayed on the far right. Highlighted in red is the lake at 310m asl.

within the lakes creates ambiguity over what environmental factors are being reconstructed from the fossil core, and displays the complexities of the relationships between the diatoms and lake conditions.

A study by Perren *et al.* (2009) sampled a series of 23 lakes over an east-west transect in the Kangerlussuaq region. As with this study, the lakes featured particular species that were dominant across most of the lakes (dependent on their location in relation to the coast). Some of the dominant species present are the same as those identified in the local Nuuk dataset. For example, *Achnanthes minutissima, Cymbella microcephala, Cyclotella stelligera, Cyclotella rossii, Navicula subtilissima* and *Frustulia rhomboides* (Figures 5.6 and 5.7)*.* The study by Perren *et al.* (2009) focused on the spatial differences along a transect from coastal lakes to those in-land at the ice margin, incorporating significantly different environmental settings of lakes; this is reflected in the transition from more acidophilous diatoms within the coastal lakes, to more planktonic taxa in the lakes closer to the ice-margin. The diatom assemblages from the local Nuuk dataset are from relatively close to the ice margin (section 2.2), and as such the contemporary diatom assemblages from that set of lakes bare a closer resemblance to those further inland in the Perren *et al.* (2009) set, including species such as *Cymbella microcephala, Achnanthes* genera and *Fragilaria* genera.

The study by Perren *et al.* (2009) discuses that lakes are forced by individual lake sensitivity, which in turn changes to the diatom composition, even when within the same geological and climatic region. This study is consistent with this finding. However, the study also concluded that west Greenland lakes demonstrate spatial trends (Perren *et al.*, 2009); this is accurate on the broad scale of lakes covering an area of several hundred kilometers, however, this study of local lakes in Nuuk, covering a small area but a large elevation range, indicates there to be distinct variability between lake diatom assemblages dependent upon the individual lakes. This suggests such groupings of lakes over large areas can be very coarse and overlook subtle but important differences between lakes and their respective diatom composition; when compiling such datasets, issues of significant lake differences can be overcome by keeping certain lake factors constant, as discussed later in this chapter (section 5.2.4).

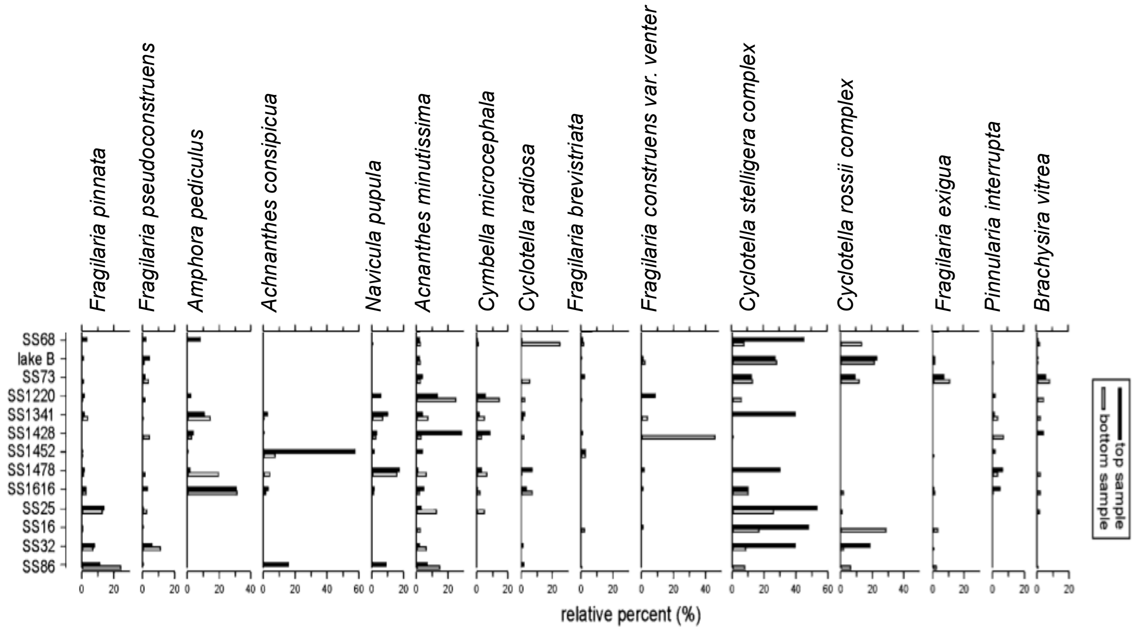


Figure 5.7 Diatom stratigraphies of selected taxa from lakes within the eastern side of the Kangerlussuaq transect, western Greenland. 'Top samples' from 0cm and 'bottom samples' from 15cm depth in the lake sediment. Diagram adapted from Perren *et al.* (2009).

Climatic conditions have a primary role on the environmental change processes that force lake ecosystems (Anderson *et al.*, 2012). As the lakes in this thesis are taken from within a relatively small area, the climatic conditions should remain relatively constant for all of the lakes, though due to the elevation range that is covered by these lakes there will be some climatic differences in terms of air temperature. Other than climatic forcing, lake catchment processes have a significant role on lake variability (Anderson *et al.*, 2012). The role of climatic conditions and the influence of catchment-lake interactions are more evident in coastal lake systems than in those from inland areas, as inland catchments have greater similarity (Anderson *et al.*, 2012). However, as is evident within the series of lakes near Nuuk discussed in this thesis, despite being from a localized, inland area, there are significant differences in the diatom compositions and environmental conditions of the lakes; in total, 103 diatom species were identified, though most lake samples contained c. 30-40 species (Figure 5.6; section 4.1.3). Previous studies of alpine lakes in northern Sweden have also demonstrated that similar neighbouring lakes to have significantly different sediment sequences and minerogenic influx despite the similar environmental settings (Rubensdotter and Rosqvist, 2003), highlighting the role of local lake catchment and geomorphological processes. There is therefore a need for a greater consideration of the individual lake-catchment relationships, as this will help to enable the establishment of the specific local catchment and lake record, and the links to the broader, regional scale signal with other lakes (Anderson *et al.*, 2012; Rubensdotter and Rosqvist, 2003).

5.2.3 Regional Scale Training Set

Within this thesis, a regional scale dataset was compiled. This involved combining the local dataset near Nuuk, with an additional set of lakes over a larger area near Sisimiut, approximately 260km north (section 2.3).

As discussed in the previous section, 5.2.2, there is variability in the environmental conditions and diatom assemblages of the lakes from the localized area; this dissimilarity in environmental conditions and diatom assemblages from different lakes was further emphasized through the inclusion of lakes from a wider area. The 60 lakes within the Søndre Strømfjord dataset cover a wider geographical area than those from the Nuuk site, as well as a significant climatic gradient (section 2.3). This provides a broader set of diatom assemblages representative of the present lake conditions in west Greenland, both for comparison to the other present day lake conditions, but also for comparison to the fossil assemblages from within lake cores.

The variation in the composition of diatoms between the Nuuk and the Søndre Strømfjord training sets that have been combined to form the regional dataset are quite significant. Though a number of species are present in both, there are large discrepancies in the abundances. The Nuuk training set contained 103 species, 49 of which are also within the 234 species in the Søndre Strømfjord dataset, and only two diatom species occur in both the top ten species of the local Nuuk and Sisimiut training sets (Table 4.3). This indicates there to be large differences in the settings of the lakes; this may be of benefit when reconstructing a fossil assemblage (section 5.2.4), and provides an insight into the differences in diatom flora across the lakes in southwest Greenland. The lakes further inland (closer to the ice sheet than the coast) in the Søndre Strømfjord training set shared more similar diatom assemblages to those in the Nuuk dataset, however there were some significant genera, such as *Cyclotella spp.*, that were in most of the Søndre Strømfjord lakes but almost completely absent in the Nuuk lakes. Both training sets display changes in diatom assemblages that do not appear to be associated with changes in elevation, despite the inland lakes of the Søndre Strømfjord training set cover a much smaller elevation range (70-530m asl) than those within the Nuuk training set (30-835m asl).

In contrast to the local set of lakes (section 5.2.2), multivariate analysis revealed eight environmental variables to be significant in explaining the diatom assemblages of the Søndre Strømfjord training set, as opposed to only three in the Nuuk training set, only one of which, depth, being significant for both of the training sets (Tables 4.1 and 4.2). The differences in the explanatory variables for the diatom assemblages of the datasets demonstrates the broader environmental conditions that have been incorporated into the dataset through the additional lakes. Søndre Strømfjord covers the climatic gradient from low Arctic maritime at the coast, to low Arctic continental at the interior end at Kangerlussuaq, with differences in environment including salinity and precipitation (Anderson *et al.*, 2012; Ryves *et al.*, 2002; section 2.3), in contrast to the freshwater lakes from a localized area in Godthåbsfjord (section 2.2). This highlights the need to consider the repercussions of compiling a training set of lake diatoms and environmental variables that covers a much larger area.

The issues encountered in this study of lakes suggests that the forming of training sets over large, regional areas is not necessarily always a suitable or beneficial approach.

5.2.4 Lessons when Constructing Training Sets

The collection of the local training set for this thesis, and the expansion into a regional scale dataset, have produced a number of lessons that can be taken and considered for future studies.

One of the main issues of the construction of the regional training set, and also to a slightly lesser extent the local training set, in this thesis was that some of the environmental variables from the Søndre Strømfjord dataset are several order of magnitudes larger than those in the Nuuk training set, with more extreme ranges in values, providing little overlap with present conditions with the local dataset, including the lake sampled for the fossil core (Figure 4.11). Though this provides a wider range of conditions and modern analogues for the transfer function to use, it also results in greater disparity in the diatoms and environmental conditions, and is reflected in some of the reconstructions from the regional models having much larger errors. As well as this, though the regional training set offers more good modern analogues for the fossil samples, despite the inclusion of the additional 60 lakes, there was little similarity between the fossil and the regional diatom assemblages, with the ten most abundant species in the regional training set having a minimal presence in the fossil assemblages (Table 4.3).

There are several steps that can potentially be taken in future studies when compiling a training set to overcome some of the issues that have been encountered in this thesis. These recommendations largely relate to the need for consistency between the lakes that are used. The lake sampling for the training set in this thesis assumed that elevation would be the most important variable on the diatom assemblages, which has been revealed not to be the case, and therefore the need for consistency in other variables was overlooked.

Firstly, constant lake depth sampling will help alleviate the issues of co-linear variables; with a larger depth, there is reduced temperature and light penetration, which influences the process of photosynthesis and ultimately algal productivity and composition (section 1.3.3). The influence of this is particularly evident in the local Nuuk dataset with the lake at 310m asl, which has a sample depth of 20.1m, the deepest within the local training set, and a uniquely different diatom composition from the rest of the local training set (section 4.1.1). Another potential physical lake variable to consider keeping constant is lake area, as this appeared as one of the more significant variables during multivariate analysis, particularly in with the local training set (section 4.1.4). The number of inflows could also be limited to help restrict the influx of catchment sediments, allowing a better understanding of the processes and environment of the lake, external of the influence of complex catchment processes, as discussed in the previous section. Finally, particularly in the context of this study, saline lakes should not be included, as this had a strong influence on the other environmental variables and diatom assemblages (section 4.2).

Of course, these recommendations are very much dependent on the context of the study, what feature is aiming to be reconstructed, and how much it is likely to have changed over time, as well as the attributes the lake the fossil core is from. The main aim of this thesis is to reconstruct environmental change through the Holocene; to do this, individual variables such as lake depth are considered. The training sets that are being utilized can be manipulated to provide the most suitable set of contemporary data; this has been done within this thesis through the exclusion of deep and shallow lakes and also saline lakes in the regional training set (sections 4.1.4, 4.2.3 and 4.5). This is a fairly common practice. For example, a dataset of lakes and their diatoms from the Kangerlussuaq region has been produced focusing on saline lakes, which involved the exclusion of other lakes to produce a suitable subset for the reconstruction of conductivity (Ryves *et al.*, 2002); certain lakes can therefore be excluded within a training set to give a particular variable a dominant role. To construct suitable training sets, an idea of the context of the lake setting and the changes it has undergone is required, as well as considerations of the variable that is to be reconstructed and its relationships to other variables and lake diatoms.

5.2.5 Additional Proxy Data

As well as utilizing diatoms to examine the differences in the lakes, additional proxy data, including biogenic silica, loss-on-ignition and diatom abundance was considered. This additional data was acquired for each of the 25 lakes in the local dataset. The biogenic silica and loss-on-ignition content of the lakes generally appear to show loosely similar trends, though the percentage values for the loss-on-ignition are considerably lower than those of the biogenic silica (Figure 5.6). The biogenic silica content can be considered as a measure of the productivity of the lake, and ultimately the diatom productivity and abundance, as discussed in section 3.2.3.

The inclusion of the abundance data of diatoms is useful as it provides a quantitative value for each of the lakes, and one that can be compared directly to the inferred measure from biogenic silica. The abundance of diatoms varied greatly between the different lakes, with no distinct trend. Some of the trends demonstrated in the diatom abundance are reflected in the biogenic silica, such as at 640m asl, as would be expected as the two proxies can be taken to indicate the same variable of lake productivity, though this relationship is not seen with all the lakes.

The diatom abundance and biogenic silica of the lakes do not generally have a distinct relationship, indicating that the use of biogenic silica as a proxy for diatom abundance in southwest Greenland is not necessarily appropriate, as content other than diatoms appears to be forcing the biogenic silica in the sediments of the lakes. This could also be a result of errors in the measures and calculations of biogenic silica within the lake sediments; this could be assessed in future through the repeating of the method. This however is only in contemporary context; biogenic silica has been widely used successfully in the reconstruction of paleoclimates from lake fossil cores in south Greenland (e.g. Kaplan *et al.*, 2002).

These variations in the values of the additional proxy data demonstrate the distinct differences in diatom productivity, organic content and variability that exists between the lakes from a localized area, but also some of the discrepancies that can exist between the different proxies used.

5.3 Problems with Environmental Reconstructions

Though this thesis has produced both inferred and quantitative environmental reconstructions, there are several problems relating to them. These problems include issues due to the differences in the contemporary diatom assemblages and environmental variables at the different lakes, and general dissimilarities, as well as fossil diatom preservation problems and extent of barren phases.

5.3.1 Preservation Issues of Modern and Fossil Diatoms

Within the Nuuk lake core, there was evidence of significant preservation issues throughout. Diatoms within the core had undergone valve fragmentation and dissolution; dissolution generally increased up the core, with the exception of the uppermost samples in the core (Figure 5.1). Some similar issues were observed within the contemporary diatom samples also, however, on a much less severe scale. Such preservation issues of diatoms do occur in freshwater systems, and are associated with both the water chemistry and physical lake conditions, with variables such as temperature, pH, salinity and ionic strength being demonstrated to force diatom dissolution (Ryves *et al.*, 2006).

The resultant effects of such preservation issues are differential between species (Ryves *et al.*, 2006). It is therefore likely that less robust species, particular finer forms such as *Nitzschia* spp., of diatoms that were within the core have not been preserved, and a bias assemblage record is produced composed of the diatom species that are more robust to the effects of fragmentation and dissolution, particularly the more silicified taxa such as *Aulacoseira* spp. and larger *Cyclotella* spp. (Ryves *et al.*, 2006). Salinity has been demonstrated to be the most significant variable affecting diatom dissolution in west Greenland, and also high pH can increase dissolution; conversely, increasing water depth may reduce dissolution and improve preservation through the reduced mixing (Ryves *et al.*, 2006).

With the lake cored in this thesis, it is not clear what has caused the dissolution, as the lake itself and those within the same area have very low salinity levels and relatively low pH values, and the reconstructed water depths do not correspond to distinct changes in the dissolution (Figures 5.1 and 5.3). The inferences and quantitative reconstructions of the changing environmental conditions from this lake core should therefore be treated with caution, as these preservation issues can result in unpredictable errors associated with the quantitative reconstructions, and the diatom dissolution has not been fully parameterized (Barker *et al.*, 1992; Ryves *et al.*, 2006). It also suggests that despite the good preservation potential of diatoms within freshwater lakes (section 1.3.3), a complete record cannot always be guaranteed, and that diatoms are not wholly reliable as a proxy for environmental reconstructions in southwest Greenland.

5.3.2 Lake Dissimilarity through Space and Time

This study has revealed there to be extensive dissimilarity in lakes in southwest Greenland, in terms of both the contemporary and fossil diatom assemblages and also the environmental conditions. Spatially, there can be major differences in the conditions and assemblages of the lakes between sites; this can be related to the proximity to coast and ice sheet, as discussed with relation to the Søndre Strømfjord training set, and also variances between inland lakes at different sites but also from within a localized area (sections 5.2.2 and 5.2.3). This dissimilarity produces complexities in the compiling of a suitable training set for environmental reconstructions, but also for determining the relationships of lakes to in-lake processes, local lake catchments and also regional scale changes. The dissimilarity of the lakes in southwestern Greenland is also reflected in the changing diatom assemblages within the fossil core from the lake in the Godthåbsfjord region, showing how the lake conditions vary both spatially and temporally. It is therefore difficult to fully identify and distinguish contemporary lake conditions and diatom assemblages that can confidently be associated and related to the fossil core for accurate and reliable environmental reconstructions.

5.3.3 Summary

In summary, the use of lake diatoms to reconstruct environmental changes in southwest Greenland have demonstrated there to be several problems that in future require greater consideration. These problems include the range of diatoms and environmental conditions of lakes, and how this dissimilarity exists over space and time, as well as preservation issues of fossil diatoms and the presence of barren periods that produce a fragmented record (section 5.1.4). The use of lake diatoms for environmental reconstructions is therefore not necessarily always appropriate, particularly in the southwest Greenland context, and raises concerns of their application in other lake studies and environmental reconstructions.

6 Conclusions

6.1 Research Aims

The main aim of this thesis was to understand the relationships between contemporary environmental conditions and lake diatoms in southwest Greenland, and to develop quantitative estimates of Holocene environmental change using a lake diatom fossil record. To achieve the aim, three research questions were developed; these shall now be revisited and answered, and the conclusions summarized.

1. What is the distribution of contemporary diatoms at the sediment/water interface across an elevation gradient of lakes from a single location, and what is their relationship with the prevailing modern environmental conditions?

The contemporary diatom assemblages from 25 freshwater lakes covering an 800m elevation range at a site 35km northeast of Qoornoq in the Godthåbsfjord region has been established. There are several diatom species that were common and highly abundant across almost all the lakes, incuding *Tabellaria flocculosa, Frustulia rhomboides, Fragilaria vaucheriae, Navicula cryptotenella* and *Pinnularia subcapitata var.* hilseana. However, there was also variability in the diatom species of particular lakes, such as *Cyclotella spp,* as well as in the environmental conditions of the lakes.

Canonical Correspondence Analysis was undertaken to determine the relationships between the sediment surface lake diatom assemblages and the environmental conditions. With the full dataset of 25 lakes and the inclusion of 20 environmental variables, 85% of the variance in diatoms was explained; this declined to 48% when 10 of the less significant variables were excluded. Within this, total nitrogen and sample depth were the most significant variables. This was repeated with two of the lakes with extreme environmental variables of sample depth (20.1 and 1.2m) excluded; the 20 environmental variables explained 93% of the variance, and 10 variables 48%, with depth, sulphate and area being the most significant variables. The variance explained by the number of environmental variables demonstrates the sensitivity of diatoms to multiple factors, and the role of depth is complex as it can reflect a number of variables simultaneously, such as temperature and light penetration, which in turn effects diatom productivity. Elevation did not appear significant in forcing the diatom assemblages.

Overall, there was variability in the diatom species present across the lakes with some common, universal species. Multiple environmental variables contribute to explaining the variance, with sample depth consistently appearing the most significant.

2. How do fossil diatom assemblages and environmental conditions vary through the Holocene?

The fossil diatom assemblage from a lake within the Nuuk dataset, at an elevation of 608m asl, has a variation in species through the Holocene. The changes of species within the core appear to indicate a slight acidification of the lake through the Holocene, and the absence of diatoms during periods between c. 6000-4000 and c. 2000-1000 cal years BP suggests a lack of productivity and potential dry phases of the lake. The Detrended Correspondence Analysis Axis 1 Scores of the diatoms indicates there to have been shifts in the climatic conditions during the Holocene. The diatom based quantitative reconstructions, along with the lake pollen data, indicate climatic warming during the early Holocene, cooling from c. 4000 years BP, and increased climatic variability during the last 1000 years. Within these fluctuations during the last millennia, there is a decline in temperature inferred from large increases in elevation and sample depth that is associated with the Little Ice Age event.

3. How useful are lake diatoms as a proxy for environmental change in south-west Greenland?

The diatom record produced from the lake core has allowed for an inference of changing lake conditions and climatic change during the Holocene. However, the reliability of the specific variable reconstructions that have been produced is ambiguous. This is largely due to the high variability in the lake conditions and contemporary diatom assemblages within both the local and regional training sets that are used, as well as the issues of fossil preservation within the lake fossil core. The equivocal relationships between the diatoms and the environmental variables of the lakes, established by the first research question, also reveals the complexities of distinguishing variable specific reconstructions. Overall, diatoms are useful for inferring general changing lake and therefore climatic conditions, however, their application for quantitative reconstructions of individual environmental variables, though useful, may not necessarily produce reliable records.

6.2 Research Summary

This thesis has provided an insight into the use of lake diatoms as a proxy for Holocene environmental change in southwest Greenland. The diatoms, along with other proxies from the lake, and the quantitative reconstructions produced demonstrate environmental changes throughout the Holocene. However, the analysis of the contemporary diatoms in relation to the present environmental lake conditions revealed complexities and uncertainties over the variables forcing the diatom assemblages, as well as issues of lake fossil diatom preservation in southwest Greenland. These are matters to be considered in future research.

6.3 Study Limitations

This thesis has highlighted multiple limitations and issues of using lake diatoms as environmental proxies in west Greenland. Firstly is the lack of clear, distinct relationships between the contemporary lake diatoms and the forcing environmental variables, or a single overriding environmental variable. Multivariate analysis demonstrated there to be substantial collinear relationships between several of the variables, and no singularly significant variable. This creates uncertainty in distinguishing what environmental features the contemporary diatom assemblages are responding to and what the species reflect in terms of environmental conditions. This is fundamental to the study, as understanding the contemporary species response to environmental conditions is what enables the interpretation of the fossil diatom assemblage, and inferences of what past environmental conditions and changes they represent. This is an area for future research, and in this context could be further examined through the expansion of the dataset by studying more lakes from the Godthåbsfjord region.

A second issue is the poor preservation of the fossil diatoms within the lake core. Large amounts of fragmentation and dissolution of diatoms was apparent throughout the core; in several instances this resulted in barren samples, and is likely to have significantly skewed the species occurrences in favour of those with greater resilience and preservation potential. Also a major issue of the fossil assemblage was its dissimilarity to the contemporary assemblages; this again generated uncertainty in trying to establish what environmental changes the assemblages represent, and also for the transfer functions meant a significant absence of good modern analogues for the majority of the fossil samples. As such, the relationship between the contemporary and fossil diatom assemblages is disjointed, and requires further research to allow for a confident and reliable reconstruction of the paleoconditions of the lake.

Despite these issues and limitations, this research offers an important contribution to Holocene paleoenvironmental studies in west Greenland, and an additional insight into the behaviour and relationships of lake diatoms and the environment, and issues of fossil preservation. The use of diatoms and various proxies indicate that they can be applied to reconstruct Holocene environmental change in west Greenland, however, to improve confidence and reliability it requires much further research. Future research could expand and improve the dataset and understanding of the relationships of diatoms and environmental variables, and thus allow more informed reconstructions, whether through simple species inferences, or quantitative methods such as transfer functions. This will contribute to a better understanding of Holocene climatic and environmental changes in west and southwest Greenland, and provide an improved context for understanding present conditions and predicting future changes that may occur.

Appendix

Elevation, latitude and longitude of the 60 lakes comprising the Søndre Strømfjord dataset.

Elevation (m asl)	Latitude	Longitude	Elevation (m asl)	Latitude	Longitude
45	66.49483333	53.50783333	300	66.73833333	51.81083333
50	66.49383333	53.52966667	305	66.84633333	51.79866667
60	66.84683333	52.61866667	325	67.05763804	51.21754469
70	67.04	50.555	330	66.89545	51.30483333
118	66.95333333	50.21333333	330	66.85966667	52.64216667
120	66.98667	50.92833333	330	66.85716667	52.65116667
130	66.96	50.125	330	66.85683333	52.65316667
150	67.03995869	51.1724296	340	66.8954	51.32216667
150	67.06248964	51.12766017	345	67.11833	50.46666667
160	66.9823077	51.05805091	348	67.12	50.49666667
160	66.747	51.80383333	350	67.00085614	51.1458916
160	66.98833333	50.64333333	350	66.99117089	51.14273854
170	66.98833	51.04666667	360	67.06201592	51.18143864
175	66.99833	51.02833333	370	67.11167	50.47166667
175	66.99	51.08833333	370	67.10667	50.49333333
175	66.99667	51.11	390	66.85783333	51.90383333
185	66.99667	50.97	390	66.85266667	51.87466667
185	67.00333	51.105	470	66.96133333	49.80615
190	67.01333	51.08166667	470	66.935	50.40166667
200	67.02090777	51.09489276	470	67.14667	50.305
215	66.99	50.59833333	470	67.15833	50.34
235	66.95433333	51.5825	470	67.16667	50.33166667
240	66.9455	51.5845	470	66.965	49.80166667
240	66.96	51.5325	475	66.92	50.43666667
245	67.02666667	50.92833333	477	66.91333	50.455
250	67.07142244	51.09085792	480	66.93833	50.415
270	67.04728573	51.24851994	490	66.92667	50.41666667
270	66.96533333	51.49683333	520	66.93167	50.43
290	67.05022409	51.26757918	535	66.83833333	51.63333333
295	66.84883333	51.76483333	540	66.83	51.62833333

Contemporary raw diatom counts for the 25 lakes samples.

Lake Elevation (m asl)	30	51	94	106	143	153	193	230	262	275	310	319	319	364	400	423	491	500	514	605	608	617	630	700	835
Achnanthes flexella/ Eucocconeis flexella	0	0	0	7	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	1	0	0	0
Achnanthes gibberula	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Achnanthes laevis	4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Achnanthes levanderi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Achanthes lutheri	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Achananthes marginulata	5	9	9	11	7	10	0	0	7	0	3	4	4	0	2	13	0	7	7	9	2	12	4	2	2
Achnanthes minutissima	8	10	4	3	12	6	7	12	2	5	5	0	1	5	11	0	6	3	11	8	4	12	1	3	3
Achnanthes nodosa	2	0	0	0	5	4	3	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	1	0
Achnanthes perfida	0	7	0	0	0	0	4	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Achnanthes pusilla	11	17	6	8	8	14	8	4	9	7	9	9	5	3	3	19	2	3	0	15	2	28	6	5	14
Amphora normanii	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	4	0	0	0	0	0	0	0	0
Amphora veneta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Aulacoseira alpigena	36	29	59	0	8	2	0	0	54	85	5	48	43	66	4	0	2	14	19	3	4	6	24	1	0
Aulacoseira fennoscandica	13	2	0	0	0	0	0	0	0	13	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Aulacoseira perglabra	20	30	1	0	0	0	0	0	2	10	0	0	0	13	0	0	0	0	6	0	0	0	0	0	0
Caloneis crassa	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Cyclotella rossii	20	8	3	1	0	0	0	0	0	1	73	0	0	0	0	33	0	0	0	5	0	17	0	0	0
Cyclotella stelligera	15	17	0	0	7	6	6	0	0	6	68	3	0	3	6	0	0	0	0	8	3	17	0	1	7
Cymbella angustata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	10	0	0
Cymbella cesatii	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cymbella cymbiformis	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cymbella delicatula	1	0	0	2	2	2	2	5	0	0	0	0	3	1	1	3	6	3	1	5	0	0	2	0	5
Cymbella hebridica/ Encyonema hebridicum	0	1	0	5	0	4	0	0	3	0	0	2	2	0	2	2	16	0	0	5	14	5	6	4	5
Cymbella helvetica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Cymbella hustedtii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Cymbella microcephala	10	2	1	4	4	4	8	3	4	3	7	10	0	5	6	12	8	2	3	3	4	1	2	0	1
Cymbella naviculiformis	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cymbella pusilla	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Cymbella silesiaca/ Encyonema silesiacum	2	0	4	4	2	1	5	0	0	0	0	0	0	3	0	0	0	3	1	7	1	3	0	0	0
Cymbella tumidula	0	2	1	0	11	3	1	4	17	2	4	0	3	4	4	18	1	9	0	11	0	5	0	0	19
Denticula subtilis	0	0	0	0	3	0	0	0	1	1	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0
Diploneis petersenii	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Epithemia sorex	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Eunotia arcus	0	1	0	11	2	3	27	8	3	8	0	2	15	0	29	4	16	7	26	0	5	0	5	23	9
Eunotia bigibba	0	1	3	0	1	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eunotia exigua	4	2	0	13	0	6	0	0	7	2	3	2	4	0	8	29	0	4	0	1	2	4	4	10	10
Eunotia flexuosa	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eunotia glacialis	0	0	0	0	0	0	0	0	0	0	0	0	5	0	4	0	0	0	2	0	3	0	0	0	0
Eunotia neaglii	0	0	0	0	5	0	11	13	0	0	0	0	12	3	7	0	0	0	24	1	7	0	3	0	5
Eunotia pectinalis var. minor	0	0	0	7	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eunotia pectinalis var. minor fo. impressa	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0
Eunotia perpusilla	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Eunotia praerupta var. bidens	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Eunotia rhomboidea	0	0	0	2	0	0	0	6	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	2	0
Eunotia septentrionalis	0	0	0	0	6	8	0	3	2	1	0	3	0	0	0	0	6	0	1	0	0	0	0	0	0
Eunotia serra	0	0	0	5	0	1	8	4	1	3	0	2	0	0	0	0	5	0	1	0	0	0	0	1	0
Eunotia serra var. diadema	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	2	0	0	0	0	0
Eunotia tenella	0	1	5	1	1	5	3	0	0	0	0	0	0	0	4	0	0	0	0	1	0	0	6	9	0
Eunotia triodon	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0
Eunotia vanheurckii	0	0	2	19	0	0	8	5	1	0	2	1	8	0	1	10	4	0	0	0	7	3	0	1	11
Eunotia veneris	0	1	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	15	0	3	0	0	0	27
Fragilaria constricta	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fragilaria crotonensis	0	0	0	0	0	0	4	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fragilaria islandica	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fragilaria vaucheriae	7	13	0	21	24	15	16	4	7	5	13	7	4	11	18	10	3	13	1	28	10	16	3	5	2
Fragilariforma virescens	18	37	44	35	23	55	15	12	14	12	11	30	29	21	14	9	10	11	10	49	18	31	5	13	4
Frustulia rhomboides	4	1	6	20	7	10	21	15	40	23	3	56	17	13	17	19	30	31	4	24	7	15	3	32	60
Frustulia rhomboides var. saxonica	0	0	0	0	0	0	10	0	8	16	0	23	0	4	0	3	6	0	0	0	0	5	1	16	0
Gomphonema acuminatum var. coronatum	0	0	2	0	0	0	0	3	0	0	0	2	0	0	3	0	6	0	0	0	0	1	0	0	0
Gomphonema angustum	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	2	0	0	0
Gomphonema apicatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	9
Gomphonema pseudoaugur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Gomphonema subtile	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gomphonema truncatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0
Mediocare circulare	0	0	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0
Navicula angusta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
Navicula cincta	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0
Navicula cocconeiformis/ Cavinula cocconeiformis	8	0	0	0	2	0	0	0	0	5	1	8	0	0	2	0	5	0	0	1	0	3	0	0	1

Navicula cryptotenella	4	2	1	10	10	1	4	26	5	2	12	6	9	4	26	4	8	13	15	16	12	1	1	15	7
Navicula gregaria	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navicula joubaudii	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navicula medioconvexa	4	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navicula mediocris	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Navicula placentula	0	1	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navicula pelliculosa	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navicula radiosa	2	4	3	9	7	8	5	12	2	4	1	1	4	6	2	0	8	3	0	8	6	5	0	0	3
Navicula rhynchocephala	0	0	0	0	4	0	0	0	0	0	2	1	0	8	4	0	6	0	0	0	0	1	0	0	0
Navicula salinarum	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	6	0	2	0	0	0	5	0	0
Navicula subtilissima	1	0	1	4	4	2	3	2	14	2	2	3	0	1	2	7	3	1	2	2	1	0	3	4	5
Nitzschia acicularis	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	4	0	0	0	0	0	0
Nitzschia archibaldii	0	0	0	0	12	0	5	0	0	1	3	0	0	0	1	0	0	0	0	0	0	5	2	0	0
Nitzschia gracilis	2	2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nitzschia paleacea	3	4	1	2	10	24	6	6	8	0	5	5	3	15	8	0	12	4	1	18	3	28	10	11	9
Pinnularia biceps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Pinnularia laticeps	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinnularia mesolepta	0	0	1	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Pinnularia microstauron	0	0	0	1	2	6	4	0	0	0	0	0	4	0	0	0	0	0	2	1	3	0	1	0	0
Pinnularia nodosa	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Pinnularia subcapitata var hilseana	1	0	29	1	0	20	8	12	2	7	1	3	38	14	10	0	19	21	29	6	36	3	68	16	7
Pinnularia viridis	0	0	6	1	0	7	10	10	6	0	1	13	9	6	3	2	19	6	6	0	22	2	20	10	7
Semiorbis hemicyclus	0	0	2	8	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stauroneis anceps	0	0	0	0	0	0	0	2	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
Stauroneis anceps fo. gracilis	4	2	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stauroneis anceps fo. linearis	0	0	7	0	0	0	0	0	0	0	0	1	4	0	6	0	3	3	11	0	2	0	17	0	1
Stauroneis phoenicenteron	0	0	0	0	0	2	0	2	0	0	0	0	3	0	0	0	2	0	0	0	4	1	3	0	0
Stauroneis producta	0	0	0	3	0	3	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0
Stauroneis tackeii	2	0	0	0	0	0	3	0	0	0	0	0	0	1	0	3	0	0	0	0	0	0	0	0	0
Surirella bifrons	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Surirella islandica	1	1	0	0	1	0	0	0	1	5	0	1	0	0	3	0	1	0	0	5	0	1	1	0	2
Surirella linearis var. constricta	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Synedra acus	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Tabellaria fenestrata	0	1	0	1	2	0	0	6	0	0	1	0	4	5	0	0	0	3	10	1	5	0	1	7	0
Tabellaria flocculosa	30	24	15	17	40	8	8	45	6	10	10	5	9	10	20	24	22	52	24	6	37	12	23	35	12

Contemporary raw environmental and chemical data.

Elevation (m asl)	30	51	94	106	143	153	193	230	262	275	310	319	319	364	400	423	491	500	514	605	608	617	630	700	835
Area (m2)	94636.93	70462.98	40070.79	302436.01	417590.38	205332.44	103739.21	2721.19	26055.53	90456.83	77704.12	67817.3	16483.9	4315.05	13177.51	993.74	16963.31	3636.81	2273.69	114709.51	8358.75	153281.68	2844.75	33316.73	19944.57
Sample depth (m)	8.1	9	5.75	2.38	4.1	7.3	4.6	2.1	8.4	8.7	20.1	9.8	5.6	4.3	4.25	1.2	6.8	3	4.9	6.2	4.2	9.6	4.95	3.9	8.8
Temperature (^{o}C)	13.71	13.43	13.84	15.85	14.11	14.41	13.8	11.4	15.23	15.06	14.83	15.38	15.48	12.8	14.56	13.95	12.95	14.31	11.72	12.55	13.69	11.23	14.15	12.98	12.26
Specific Conductivity (mS/cm^{o})	0.039	-	0.032	-	0.023	0.027	0.03	0.037	0.034	0.037	0.041	0.025	0.017	0.046	0.028	0.013	0.028	-	0.027	0.017	0.015	0.017	0.025	0.016	0.009
Conductivity (mS/cm)	0.031	-	0.025	-	0.019	0.022	0.024	0.026	0.028	0.031	0.033	0.02	0.014	0.035	0.022	0.01	0.022	-	0.02	0.013	0.012	0.012	0.02	0.013	0.007
Salinity	0.02	0.04-0.10	0.01	-	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0	0.01	-	0.01	0.01	0.01	0.01	0.01	0.01	0
Dissolved Oxygen (%)	105.1	97.5	98.5	93	105.9	108.4	103.3	115.9	103.4	111.5	115.1	106.5	101	106	111.6	103.6	103.4	97.4	97.8	105.5	114.7	96.2	124	100.1	103
Dissolved Oxygen (mg/L)	10.88	10.18	10.21	9.19	10.89	11.06	10.69	12.82	10.38	11.21	11.68	10.63	10.05	11.24	11.31	10.7	10.91	9.96	10.56	11.08	11.9	10.53	12.52	10.53	10.9
pH	7.23	6.54	6.09	6.37	7.26	7.32	7.11	6.53	7.31/	7.15	7.51	6.82	7.73	7.18	7.63	7.16	7.36	6.08	6.86	7.13	8.04	7.75	7.15	7.41	7.6
Temperature (^{o}C) (Bottom)	7.2	12.74	13.42	15.35	13.92	14.3	13.13	9.94	9.08	6.23	4.04	6.4	14.97	11.75	13.34	13.94	9.81	13.58	10.55	11.94	13.41	11.06	12.92	12.67	11.9
Specific Conductivity (mS/cm^{o}) (Bottom)	0.04	-	-	-	0.024	0.029	0.031	0.039	0.031	0.044	0.047	0.025	0.015	0.043	0.029	0.013	0.039	-	0.027	0.017	0.015	0.017	0.024	0.013	0.008
Conductivity (mS/cm) (Bottom)	0.027	-	-	-	0.019	0.023	0.024	0.028	0.022	0.029	0.028	0.017	0.012	0.032	0.023	0.01	0.027	-	0.019	0.012	0.012	0.012	0.019	0.01	0.007
Salinity (Bottom)	0.02	0.02	0.09	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0	0
Dissolved Oxygen (%) (Bottom)	102.5	105.1	95.3	91.9	102.4	105.1	99.5	114.3	99.3	107.8	104.5	110	98.1	90.5	103.6	103.6	100	94	92.9	98.1	101.1	94	104.5	97.2	95.3
Dissolved Oxygen (mg/L) (Bottom)	12.34	11.14	9.92	9.25	10.59	11.06	10.46	12.89	11.39/10.93	13.4	13.65	13.46	9.9	9.76	10.83	10.7	11.32	9.77	10.34	10.6	10.56	10.33	11.04	10.3	10.29
pH (Bottom)	7.06	5.69	4.26	5.82	6.96	7.32	7.02	6.6	6.39	7.3	7.36	6.95	6.79	7.03	7.25	7.16	7.06	5.72	6.91	6.62	7.55	7.15	6.94	7.23	7
Transparency (% of lake depth)	71.60	65.56	81.74	100	100	100	100	180.95	100	100	100	100	100	100	241.18	100	100	100	100	100	100	100	100	100	100
UV concentration (as mg Carbon L-1)	6.27	5.06	6.59	2.14	3.85	4.03	2.33	7.53	2.16	4.21	3.02	2.82	4.79	3.67	3.56	17.18	5.395	2.79	1.55	0.67	0.4	0.87	1.125	1	2.09
UV absorbance @ 254.0 nm	0.1092	0.0881	0.1147	0.0373	0.0669	0.0701	0.0406	0.131	0.0376	0.0733	0.0525	0.0491	0.0833	0.06385	0.0619	0.2989	0.09385	0.0485	0.027	0.0116	0.007	0.0152	0.01965	0.0175	0.0363
Fluoride (as F)	0.0085	0.0208	0.0085	0.0094	0.0131	0.0086	0.0044	0.0251	0.0084	0.0072	0.0066	0.0112	0.0219	0.0249	0.0258	0.0234	0.0151	0.0114	0.0096	0.0062	0.0033	0.0078	0.0068	0.0088	0.0065
Chloride (as Cl)	2.9447	4.1265	2.0648	3.0935	3.9896	3.7216	2.4223	2.7784	2.8484	1.643	3.7063	5.0247	3.209	3.4921	3.5244	0.9573	2.0651	2.4733	1.2812	1.0859	1.2911	1.485	1.3662	1.3369	1.5391

Sulphate (as S)	Sodium	Potassium	Magnesium	Calcium	Alkalinity	d18O VSMOW	dD VSMOW	Total Nitrogen (mg N/L)	Total Phosphorus (mg P/L)	Chlorophyll-a (standard method)	Chlorophyll-a (trichromatic method)	%BSi	Diatom Abundance (diatoms per gram 10^{-5})
1.1546	1.9791	1.4462	1.4686	3.1147	8.955	-14.55	-112.15	0.276289939	0.01003009	0.13	0.89	83.44	44.74
1.2452	3.4738	1.6913	1.7058	3.8694	14.0295	-11.29	-96.026	0.165856685	0.013039117	0.15	0.72	98.61	56.70
0.9816	1.9001	0.8423	1.2968	2.253	6.368	-15.22	-113.78	0.220866508	0.024072217	0.09	0.88	97.22	30.58
0.5609	1.9855	0.7409	1.3169	1.845	5.6715	-10.82	-95.094	0.147451143	0.03109328	0.31	1.01	100.00	1.46
1.1312	2.7521	1.0502	1.4428	2.7444	7.761	-13.48	-107.53	0.140213008	0.00551655	0.36	0.94	92.74	51.06
0.7418	2.2137	0.6556	1.3784	1.9953	5.373	-12.97	-106.33	0.108985627	0.017552658	0.04	0.67	40.59	1.39
0.3119	1.4647	0.3297	1.2099	0.4849	0.995	-13.63	-106.91	0.119739427	0.01003009	0.10	0.64	100.00	10.93
1.4202	2.8705	0.919	1.5996	3.3636	10.547	-14.19	-110.78	0.203288181	0.004513541	0.07	0.80	97.42	37.72
0.5953	2.1702	0.5587	1.3193	2.1782	7.363	-14.75	-114.74	0.081273912	0.014543631	0.14	0.71	99.92	71.90
0.5548	1.8587	0.6363	1.373	1.9678	7.8605	-15.49	-116.94	0.156136904	0.003009027	0.10	0.84	76.59	14.57
0.4158	2.1412	0.5367	1.3113	1.1672	3.0845	-13.39	-108.19	0.116450603	0.025075226	0.04	0.71	2.75	8.56
0.4408	2.7041	0.4826	1.3527	1.1752	2.2885	-12.51	-104.07	0.180375503	0.017552658	0.05	0.76	100.00	40
1.1256	2.7625	0.5758	1.3554	2.8572	7.2635	-14.70	-114.29	0.175234689	0.005015045	0.13	1.09	90.97	60.49
1.1216	2.8324	0.5219	1.3703	3.0646	7.6615	-14.52	-113.47	0.120026822	0.007522568	0.04	0.57	100.00	62.08
1.1434	2.8365	0.5214	1.3832	3.0969	7.6615	-14.37	-113.34	0.122485472	0.004513541	0.03	0.56	100.00	15.03
0.1939	2.3073	0.4742	1.3437	1.7162	5.2735	-14.31	-113.15	0.152883326	0.015045135	0.33	0.79	21.69	6.81
0.4107	2.0287	0.3659	1.2708	1.247	4.577	-14.13	-111.33	0.175681717	0.003510532	0.18	0.74	99.22	28.72
0.5778	2.1189	0.5658	1.2801	1.5731	4.975	-15.70	-118.53	0.146177917	0.007522568	0.07	0.85	94.51	25.41
0.6967	1.4377	0.8783	1.3126	1.6443	6.0695	-15.04	-114.08	0.065936522	0.004012036	0.16	0.70	100.00	37.88
0.6328	1.0716	0.3464	0.741	1.1271	3.8805	-16.09	-123.36	0.15377738	0.018555667	0.04	0.65	44.43	66.99
0.16	0.877	0.2162	0.7204	0.3546	1.194	-14.91	-117.01	0.02704515	0.014543631	0.08	0.59	0.72	0.65
0.4184	1.2689	0.3149	0.7411	1.0309	3.582	-15.46	-118.34	0.049396513	0.009528586	0.13	0.65	48.53	123.23
0.4162	1.2809	0.2941	0.7445	0.984	3.8805	-15.90	-117.35	0.08426464	0.013039117	0.25	0.99	42.25	24.62
0.5755	1.2906	0.3001	0.7566	1.0556	2.985	-15.73	-121.09	0.093652213	0.015045135	0.07	0.69	100.00	24.44
0.416	1.3192	0.316	0.7691	0.8708	2.587	-14.63	-113.38	0.116450603	-0.013039117	-	-	57.76	6.65

Fossil core raw diatom count.

Sample Depth (m)	0	0.04	0.08	0.16	0.2	0.24	0.32	0.36	0.4	0.48	0.56	0.64	0.72	0.76	0.8	0.88	0.96	1	1.04	1.08	1.12	1.16	1.2	1.28	1.36	1.44	1.52	1.6	1.68	1.76
Achnanthes flexella/ Eucocconeis flexella	1	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Achanathes marginulata	3	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	1	0	0	0	0	0	0	0	0
Achnanthes minutissima	5	3	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	5	0	0	0	0	0	0	0	0
Achnanthes nodosa	2	0	0	1	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	3	3	0	2
Achananthes pusilla	1	1	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Aulacoseira alpigena	6	1	6	2	-	-	-	-	3	0	0	2	1	-	-	-	-	-	1	-	-	0	0	0	0	7	0	0	0	0
Aulacoseira valida	0	0	0	2	-	-	-	-	11	1	0	1	1	-	-	-	-	-	15	-	-	21	6	2	13	18	0	0	0	0
Caloneis crassa	0	0	0	0	-	-	-	-	0	0	0	1	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Cyclotella rossii	0	0	0	0	-	-	-	-	0	0	0	1	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Cyclotella stelligera	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	1	-	-	0	0	0	0	0	0	0	0	0
Cymbella angustata	2	3	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	2	-	-	0	0	0	0	0	0	0	1	0
Cymbella cistula var. maculata	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	2	0	0	0	0	0	0
Cymbella delicatula	1	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	2	0	0
Cymbella hebridica/ Encyonema hebridicum	22	13	1	0	-	-	-	-	0	4	4	0	0	-	-	-	-	-	0	-	-	1	0	0	0	0	0	0	0	0
Cymbella helvetica	0	4	0	0	-	-	-	-	0	0	3	0	2	-	-	-	-	-	1	-	-	8	18	0	2	0	0	0	0	0
Cymbella microcephala	2	0	0	1	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Cymbella silesiaca/ Encyonema silesiacum	1	2	6	0	-	-	-	-	1	0	0	0	0	-	-	-	-	-	0	-	-	0	9	2	0	0	0	1	6	1
Cymbella tumidula	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	1	0	0
Eunotia arcus	8	3	35	99	-	-	-	-	18	35	46	14	54	-	-	-	-	-	5	-	-	5	19	8	25	8	3	3	0	1
Eunotia bigibba	0	0	1	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Eunotia exigua	6	4	2	0	-	-	-	-	0	0	0	1	3	-	-	-	-	-	0	-	-	0	0	2	0	0	0	0	0	0
Eunotia neaglii	4	16	2	1	-	-	-	-	7	6	3	4	3	-	-	-	-	-	0	-	-	0	0	0	0	1	0	0	0	0
Eunotia pectinalis var. minor fo. impressa	0	0	4	8	-	-	-	-	1	4	6	14	0	-	-	-	-	-	3	-	-	5	3	0	0	0	0	0	0	0
Eunotia praerupta var. bidens	0	0	0	0	-	-	-	-	0	0	0	0	3	-	-	-	-	-	0	-	-	0	0	0	0	1	0	0	0	0
Eunotia septentrionalis	1	0	3	11	-	-	-	-	0	0	0	5	7	-	-	-	-	-	0	-	-	0	13	0	1	1	0	0	0	0
Eunotia serra var. diadema	0	0	2	2	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Eunotia tenella	0	2	0	4	-	-	-	-	1	8	5	0	0	-	-	-	-	-	0	-	-	17	11	0	2	1	1	0	0	1
Eunotia triodon	0	1	0	6	-	-	-	-	1	0	5	1	0	-	-	-	-	-	0	-	-	0	0	1	0	0	0	0	0	0
Eunotia vanheurckii	1	22	0	4	-	-	-	-	0	6	4	0	0	-	-	-	-	-	0	-	-	7	0	0	0	0	0	0	0	0

Eunotia veneris	2	42	7	1	-	-	-	-	0	0	2	6	0	-	-	-	-	-	0	-	-	0	4	0	0	0	0	0	0	0
Fragilaria vaucheriae	1	0	2	0	-	-	-	-	6	3	1	3	6	-	-	-	-	-	8	-	-	10	6	3	6	7	13	41	21	13
Fragilariforma constricta	0	1	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Fragilariforma virescens	9	6	11	10	-	-	-	-	18	6	3	8	12	-	-	-	-	-	17	-	-	9	9	14	9	22	22	54	31	34
Frustulia rhomboides	2	6	3	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	3	-	-	0	0	1	0	0	0	0	0	0
Gomphonema acuminatum var. brebissonii	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	1	1	0	0	0	0	0
Gomphonema acuminatum var. coronatum	0	0	0	0	-	-	-	-	1	1	1	0	0	-	-	-	-	-	1	-	-	3	2	5	3	1	2	1	0	0
Gomphonema angustatum	0	0	0	4	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Gomphonema angustum	5	2	4	0	-	-	-	-	5	0	3	2	0	-	-	-	-	-	3	-	-	5	8	6	1	1	5	1	0	0
Gomphonema gracile	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	1	0	0	0	0	0
Gomphonema truncatum	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	2	-	-	0	0	0	0	0	1	0	0	0
Navicula angusta	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	1	-	-	0	0	0	0	0	0	0	0	0
Navicula cincta	0	0	0	0	-	-	-	-	0	1	1	1	1	-	-	-	-	-	0	-	-	34	16	21	4	12	2	1	0	0
Navicula cryptotenella	10	6	5	2	-	-	-	-	0	2	0	1	1	-	-	-	-	-	10	-	-	38	6	8	1	2	0	2	2	4
Navicula placentula	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	1	0	0	0	0	0	0	0
Navicula radiosa	6	0	1	0	-	-	-	-	0	0	0	0	1	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Navicula salinarum	1	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	2	-	-	0	0	0	0	0	0	0	0	2
Navicula subtilissima	0	0	0	0	-	-	-	-	0	0	1	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Nedium affine	2	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Nitzschia amphibia	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	3
Nitzschia archibaldii	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	1	0	0	0	0	0	4
Nitzschia bremensis	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	1	0	1	2	0
Nitzschia gracilis	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	1	0	0
Nitzschia palea	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	2	0	0	0	0
Nitzschia paleacea	2	0	0	0	-	-	-	-	1	0	0	0	0	-	-	-	-	-	1	-	-	3	0	2	0	0	2	1	14	15
Pinnularia borealis	0	0	0	0	-	-	-	-	3	3	2	1	3	-	-	-	-	-	0	-	-	0	0	0	0	4	6	2	0	0
Pinnularia divergens var. parallela	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	1	0	1	0	0	0
Pinnularia krasskei	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	1	-	-	0	0	0	0	0	0	0	0	0
Pinnularia major	0	0	0	1	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	0	0	0	0	0
Pinnularia mesolepta	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	4	3	0	0	0	6
Pinnularia microstauron	0	0	4	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	1	3	8	4	5	7	2	0	9
Pinnularia subcapitata var hilseana	64	81	42	0	-	-	-	-	0	3	1	1	2	-	-	-	-	-	10	-	-	1	0	9	5	4	31	9	15	42
Pinnularia viridis	24	15	50	2	-	-	-	-	2	4	7	2	2	-	-	-	-	-	1	-	-	25	8	38	5	10	2	0	0	0
Stauroneis acuta	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	0	0	4	0	0	0	0
Stauroneis anceps fo. gracilis	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	15	0	0	0	0	0	0

Stauroneis anceps fo. linearis	6	1	2	5	-	-	-	-	14	15	28	45	35	-	-	-	-	-	3	-	-	16	4	12	4	0	2	1	0	0
Stauroneis phoenicenteron	3	0	2	0	-	-	-	-	6	12	8	13	21	-	-	-	-	-	1	-	-	0	0	1	1	0	0	0	0	0
Stauroneis producta	0	0	0	0	-	-	-	-	0	0	0	0	0	-	-	-	-	-	0	-	-	0	0	2	0	0	0	0	0	0
Staurosirella lapponica	0	0	0	2	-	-	-	-	7	0	0	7	7	-	-	-	-	-	110	-	-	5	26	17	80	0	0	7	39	49
Tabellaria fenestrata	0	1	3	0	-	-	-	-	0	0	2	5	5	-	-	-	-	-	4	-	-	1	14	5	28	35	0	0	0	0
Tabellaria flocculosa	47	15	36	56	-	-	-	-	97	91	82	82	55	-	-	-	-	-	30	-	-	30	45	42	34	69	99	77	89	45

Fossil core raw chemical data.

Sample Depth (m)	Moisture (%)	LOI (%)	Carbonate (%)	Inorganic (%)	BSi (%)	Dissolution (%)
0						35.46
0.04						26.32
0.08	77.61	16.32	2.30	81.38	0.00	52.94
0.16	76.49	15.12	2.07	82.81	0.00	68
0.24	85.86	19.94	2.38	77.68	0.00	
0.32	83.56	16.84	2.87	80.28	0.00	
0.40	81.90	14.45	1.84	83.71	0.00	82
0.48	80.07	14.57	1.10	84.33	1.03	72
0.56	80.78	15.02	1.54	83.44	1.50	60
0.64	79.47	14.63	1.92	83.45	10.00	62
0.72	75.80	11.88	1.53	86.59	0.24	68
0.80	75.80	11.94	1.24	86.82	0.00	
0.88	73.94	10.40	1.49	88.11	0.00	
0.96	78.03	13.07	1.21	85.72	0.38	
1.04	79.00	13.64	2.40	83.95	4.27	66.67
1.12	81.43	14.92	2.88	82.20	5.14	
1.16						41.18
1.20	72.29	11.93	1.80	86.27	3.75	56
1.28	70.97	11.74	1.85	86.41	8.94	52
1.36	65.74	8.76	1.37	89.87	10.56	50.94
1.44	63.23	6.26	1.66	92.08	6.06	54
1.52	57.70	5.05	1.33	93.62	8.38	52.94
1.60	53.54	4.76	1.13	94.11	3.16	50.98
1.68	54.69	4.87	1.45	93.68	8.05	52.83
1.76	49.48	3.62	0.94	95.44	8.12	49.02
1.84	42.04	2.66	0.95	96.39	11.98	52

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