# Lake-sediment records of recent environmental change on Svalbard: results of diatom analysis*

Vivienne J. Jones[1] and H.J.B. Birks[1,2]

[1]*Environmental Change Research Centre, University College London, 26 Bedford Way, London WC1H 0AP, U.K. (E-mail: v.jones@geog.ucl.ac.uk)*

[2]*Botanical Institute, University of Bergen, Allégaten 41, Bergen, N-5007 Norway. (E-mail: John.Birks@bot.uib.no)*

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## Abstract

Surface sediments from 23 lakes on Svalbard were analysed for diatoms. 182 taxa were found but samples generally have a low richness, with the majority of sites dominated by benthic genera such as *Fragilaria*, *Navicula,* and *Achnanthes*. Centric *Cyclotella* species occur at only three sites. Modern relationships between diatom abundance and water chemistry and other environmental variables were explored numerically and a preliminary transfer function for pH was developed. Lakes fell into three groups on the basis of their diatom assemblages: (1) high pH, high cation, high conductivity sites characterised by *Amphora libyca,* (2) shallow sites with relatively high nutrient values characterised by *Fragilaria* species, and (3) more acid and dilute sites with high amounts of snow cover in the catchments characterised by small *Achnanthes* species and *Navicula digitulus*. Five sediment cores representing the recent past were also analysed for diatoms. Three shallow sites were dominated by *Fragilaria* species throughout the period represented by the cores and no shifts in inferred pH were found. At two deeper sites (Arresjøen, Birgervatnet) major assemblage shifts are found which are unrelated to independent evidence for atmospheric contamination. Early (ca. 1200 AD) changes found at both sites are possibly related to the onset of the 'Little Ice Age'. Later changes are neither synchronous nor similar in nature and might be best explained as individual responses to the recovery from the 'Little Ice Age' and subsequent climatic warming.

## Introduction

The Arctic has undergone large climatic changes during the recent past with proxy data indicating warming since the mid-19th century, which appears to be unprecedented when compared to climate records extending back over the last 400 years (Overpeck et al. 1997). It has also become evident that inter-annual to century-scale climatic variability is the norm, and that ecosystem change is occurring in response to the evolving climate (Overpeck et al. 1997). There are few limnological data in the high Arctic, and this is becoming critical as this area is increasingly being recognised as being susceptible to impacts from atmospheric pollution and to amplified global warming (IPCC 1997). Arctic lake-sediment records can provide unique records of recent environmental change in inaccessible areas where expensive long-term monitoring programmes are not generally undertaken. In lakes where a chronology can be established by ^{210}Pb-dating, the analysis of the sedimentary record can address ecological themes such as species persistence and stability, and rates and directions of change in lake productivity and acidity (Anderson and Battarbee 1994), all of which can be influenced by both climate and pollution.

Freshwater algae are sensitive indicators of environmental change. Diatoms are particularly useful as they are often well-preserved in lake sediments and have been used for long-term environmental monitoring (Smol and Douglas 1996). The analysis of sediments from shallow ponds on Ellesmere Island suggested that warming since the mid-19th century has caused distinct shifts in the diatom flora (Douglas et al. 1994), and similar results have been found from lakes in the central Canadian Arctic (Rühland et al. 2003), in Finnish Lapland (Sorvari et al. 2002), and on Devon Island (Gajewski et al. 1997). However, it is unclear whether such dramatic changes are a circum-Arctic phenomenon.

On Svalbard there have been dramatic post-'Little Ice Age' glacial retreats in a region of the high Arctic where 20th century warming has been rapid (Birks et al. 2004c). Svalbard lakes and their biota should be sensitive to such changes. However, there are no ^{210}Pb-dated lake-sediment records that would allow us to assess the degree of recent change. This is in contrast to Holocene lake-sediment records from Svalbard, which are more numerous (e.g. Hyvärinen

1970; Birks 1991; Wohlfarth et al. 1995). In this paper, we assess the recent stability of diatom assemblages from lakes on Svalbard using diatom analysis from ^{210}Pb-dated short cores. The lakes on Svalbard selected in this study are not strictly pristine and contain spherical carbonaceous particle (SCP) and heavy metal records of atmospheric contamination (Rose et al. 2004; Boyle et al. 2004). We therefore also aim to use diatom analysis to assess whether there has been any effect of recent atmospheric contamination or pollution on these high Arctic lakes.

Diatom studies from the Arctic suggest that there appears to be a distinct arctic flora. However, many taxa are poorly described, and ecological data are limited (Douglas and Smol 1993). The freshwaters of Svalbard contain a relatively rich diatom flora, which has been described in earlier studies (e.g. Foged 1964; Picinska-Faltynowicz 1988; Metzeltin & Witkowski 1996; van de Vijver et al. 1999). These accounts do not, however, contain detailed environmental information. In this paper we attempt to establish the modern relationships between diatom abundance and water chemistry and other environmental variables, with the aim of creating appropriate local transfer functions.
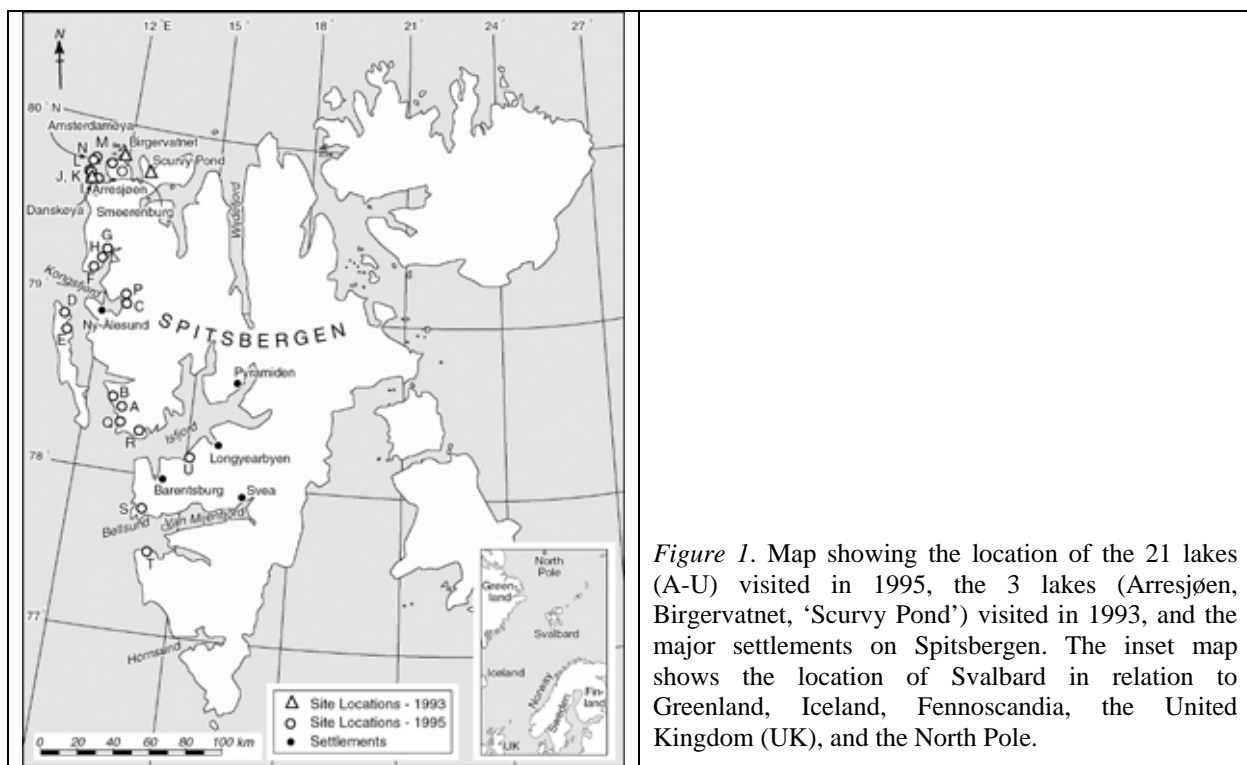


Figure 1. Map showing the location of the 21 lakes (A-U) visited in 1995, the 3 lakes (Arresjøen, Birgervatnet, 'Scurvy Pond') visited in 1993, and the major settlements on Spitsbergen. The inset map shows the location of Svalbard in relation to Greenland, Iceland, Fennoscandia, the United Kingdom (UK), and the North Pole.

## Methods

### Sediment coring, diatom analysis

Surface sediment and core samples were obtained in 1995 from a series of 20 lakes (A - K and M - U) using a gravity corer (Glew 1989). Samples were also made available from three additional sites (Arresjøen, Birgervatnet, and 'Scurvy Pond') sampled in 1993 for the AL:PE project (Wathne et al. 1997). Sampling locations are shown in Figure 1. Samples were prepared for diatom analysis using standard methods (Battarbee 1986), approximately 500 valves per sample were counted at x1000 for the surface-sediment samples and approximately 350 valves per sample were counted for the core samples. Identification followed Foged (1964) and Krammer and Lange-Bertalot (1986-1991). In order to use SWAP and AL:PE data-sets for pH reconstruction, diatom nomenclature followed their guidelines (for SWAP Stevenson et al. 1991 and for AL:PE Cameron et al. 1999) and consequently, recent changes in nomenclature have not been made. The authorities are given in Appendix 1. Specimens of

*Fragilaria pinnata* were highly variable and although varieties were initially identified these were subsequently amalgamated as *F. pinnata* agg.

Water chemistry was obtained from the 23 sites and further details of field sampling and water chemistry methods, site locations, and lake descriptions are given in Birks et al. (2004) and Wathne et al. (1997).

Selected diatom images, raw diatom counts, and site details including water chemistry can be found on the European Diatom Database http://Craticula.ncl.ac.uk:8000/Eddi/jsp/index.jsp

*Numerical methods*

The modern diatom data-set is summarised in Table 1 in terms of number of samples, number of taxa, percentage number of non-zero values (= occurrences), the total inertia (= variance) of the data-set, and the minima, medians, means, and maxima of the effective number of taxa per sample. The effective numbers of occurrences per taxon, as estimated by Hill's (1973) N2 diversity measure (ter Braak 1990) are shown. The pH values are also summarised in terms of their range, mean, median, and standard deviation.

The 23 lakes were initially classified on the basis of their surface-sediment diatom assemblages using two-way indicator species analysis (TWINSPAN, Hill 1979) to detect major groupings of the lakes. This was implemented by the program TWINSPAN version 2.2a with pseudospecies cut values of 0, 2, 5, 10, and 20% and strict convergence criteria. The same data were ordinated by correspondence analysis (CA) to detect the major gradients in diatom composition. The unimodal-based CA was used because the diatom data have a gradient length, as estimated by detrended correspondence analysis (DCA) (Hill and Gauch 1980), of 3.64 standard deviations (Table 1), indicating that unimodal-based ordination methods such as CA or DCA are appropriate with these data. The CA results show no obvious arch-effect, so no detrending was required. CA was thus selected as an appropriate ordination method in this study. As the data-set is small (23 lakes) and there are many potential chemical (14) and catchment and limnological (17) 'predictor' variables, these variables were regressed onto the CA axes as an indirect gradient analysis (ter Braak and Prentice 1988) rather than incorporating these variables in a direct gradient analysis such as canonical correspondence analysis (CCA). However, CCA and its detrended equivalent were used to estimate how much variance in the modern diatom data is explained by particular environmental variables and to estimate the amount of compositional change along particular environmental gradients. Forward selection of predictor variables (ter Braak and Šmilauer 1998) was used to find the 'minimal adequate model' of statistically significant chemical and catchment variables. Statistical significance was established using Monte Carlo permutation tests (999 unrestricted permutations). The forward selection procedure was stopped when the additional effect of the selected variable was not significant at the $\alpha = \alpha/\nu$ level (where $\alpha = 0.05$, $\nu$ = number of multiple tests performed at each step in the forward selection, namely $1,2,\ldots,\nu$) according to the Bonferroni method of correcting for simultaneous multiple tests (Legendre and Legendre 1998).

As lake-water pH is the only statistically significant chemical predictor, as assessed by forward selection in CA and explaining 12.7% of the variance in the diatom data, a transfer function was developed for pH using weighted-averaging partial least squares (WA-PLS) regression (ter Braak and Juggins 1993). The final WA-PLS model was selected to have the smallest number of 'useful' components (*sensu* Birks 1998), and low RMSEP and maximum bias, as assessed by leave-one-out cross-validation (ter Braak and Juggins 1993; Birks 1995;

Cameron et al. 1999). The properties of the modern pH-diatom relationship were quantified (Table 1) by detrended canonical correspondence analysis (DCCA) (detrending by segments, non-linear rescaling; ter Braak and Juggins 1993) with pH as the only constraining variable. The amount of compositional change (gradient length) along the pH gradient is estimated by DCCA, along with the gradient length of the first unconstrained DCA axis. The relative strength of the pH-constrained DCCA axis, compared to the first unconstrained DCA axis, expressed as the ratio of their eigenvalues, is a useful measure of the strength of the pH relationship in the modern data (see Birks 1995; ter Braak and Juggins 1993 for details of these measures).

*Table 1. Descriptive statistics for the modern Svalbard diatom and pH data-set*

| | |
|---|---|
| Number of samples | 23 |
| Number of taxa | 182 |
| % number of positive values | 16.2 |
| Total inertia | 3.96 |
| **N2 for samples** | |
| Minimum | 2.88 |
| Median | 17.73 |
| Mean | 14.62 |
| Maximum | 33.35 |
| **N2 for taxa** | |
| Minimum | 1.0 |
| Median | 1.87 |
| Mean | 2.94 |
| Maximum | 13.17 |
| **pH** | |
| Minimum | 5.6 |
| Median | 6.9 |
| Mean | 7.1 |
| Maximum | 8.4 |
| Standard deviation | 0.87 |
| **DCA axis 1** | |
| $\lambda_1$ | 0.58 |
| Gradient length (SD) | 3.64 |
| % variance | 14.7 |
| **DCA axis 2** | |
| $\lambda_2$ | 0.35 |
| Gradient length (SD) | 2.55 |
| % variance | 8.9 |
| **DCCA/CCA axis 1 (constrained by pH)** | |
| $\lambda_1$ | 0.5 |
| Gradient length (SD) (DCCA) | 3.27 |
| % variance | 12.7 |
| **DCA axis 2 (unconstrained)** | |
| $\lambda_2$ | 0.29 |
| Gradient length (SD) (DCA) | 2.47 |
| % variance | 7.5 |
| $\lambda_1/\lambda_2$ | 1.71 |

In order that the modern pH optima of the commonest diatom taxa in our data-set could be compared with optima estimated from other data-sets (e.g. the AL:PE data-set of Cameron et al. 1999), pH optima were estimated for all taxa present in five or more samples by Gaussian logit regression using maximum likelihood (ter Braak and Looman 1986). These estimates are more reliable for comparative purposes than estimates of optima by weighted

averaging because the latter are very sensitive to the distribution of the environmental variable (in our case pH) in the modern data (ter Braak and Looman 1986).

The diatom assemblages from the five cores were fitted as passive or supplementary samples (ter Braak and Šmilauer 1998) on the basis of their diatom composition into the plane formed by CA axes 1 and 2 of the modern samples. The squared residual distance of each core sample to this plane was used as a measure of goodness of fit of the core samples. Plotting the core samples on the plane of the modern CA axes 1 and 2 provides a useful graphical summary of the similarities and changes in diatom composition of the core samples in relation to the modern samples and modern chemical variables.

In all the ordinations and regressions, the diatom percentages of all taxa were transformed to square-roots in an attempt to stabilise their variances. All ordinations were implemented by the program CANOCO version 3.12a (ter Braak 1990) with rare taxa downweighted and strict convergence criteria. WA-PLS was implemented by the program CALIBRATE version 0.81 (Juggins and ter Braak 1997) and Gaussian optima were estimated by the program GLR (S. Juggins, unpublished program).


## Results

*Surface-sediment diatom assemblages and their relationship with environmental variables*

Diatoms were enumerated from 23 surface-sediment samples, and a total of 182 taxa were found, of these 96 had greater than 1% abundance in any one sample, and ca. 15% could not be assigned to previously described forms. The majority of sites are dominated by benthic genera such as *Fragilaria*, *Navicula,* and *Achnanthes*; whilst centric planktonic *Cyclotella* species occur in three sites (Figure 2). Summary statistics of the taxa are given in Appendix 1 as the number of occurrences, the number of effective occurrences (N2; ter Braak 1990), the maximum percentage value attained, the lake identified with the maximum value, and the number of lakes where the taxon attains a value of 5% or more.

Although 182 taxa were found in the 23 surface-sediment samples, individual samples are generally poor in taxa with N2 values of 2.9 to 33.4, with a median of 17.7 and a mean of 14.6 (Table 1). In contrast the AL:PE surface-sediment samples from 118 high-altitude or high-latitude lakes have N2 values of 2.1 to 44.1 with a median of 20.8 and a mean of 21.1 (Cameron et al. 1999). The diatom taxa generally have a low number of effective occurrences in the Svalbard data, with a mean N2 of 2.9 and a median of 1.9 compared with a mean N2 of 6.8 and a median N2 of 3.3 in the AL:PE data-set (Cameron et al. 1999).

Three major groups of assemblages are defined from the TWINSPAN classification (Figure 2). The results of a CA (Table 2) with the chemical variables regressed onto the CA axes (Figure 3) clearly illustrate the three groups of sites identified by TWINSPAN. pH (and associated variables such as alkalinity and the base cations) is strongly correlated (-0.90) with axis 1 which represents the major direction of floristic variation in the diatom data. Axis 2 may be a nutrient gradient with weak correlations with chlorophyll *a* (-0.16) and total dissolved phosphorus (-0.23). The correlation with manganese (0.24) is possibly a product of redox conditions at the more nutrient-rich sites. Results of forward selection indicate, however, that pH is the only statistically significant predictor variable (p = 0.001) and explains 12.7% of the inertia in the diatom data in a CCA with pH as the sole predictor variable. All 14 chemical variables account for 68.7% of the inertia in the diatom data (Table 2).
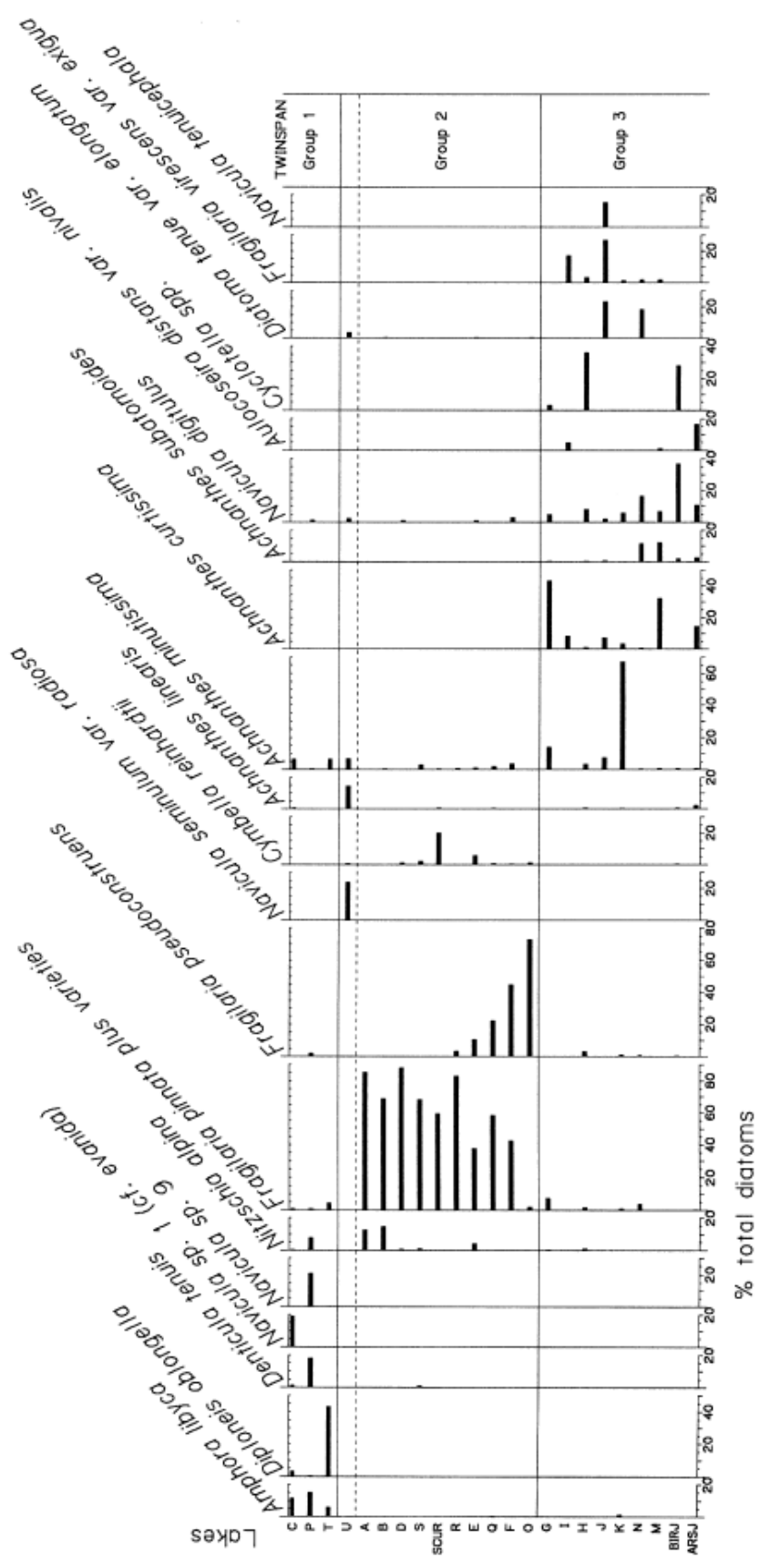
*Figure 2.* Summary of surface-sediment diatom assemblages from 23 lakes on Svalbard. Lakes are ordered according to their TWINSPAN classification, and diatoms are expressed as % total abundance with only the most common species shown.
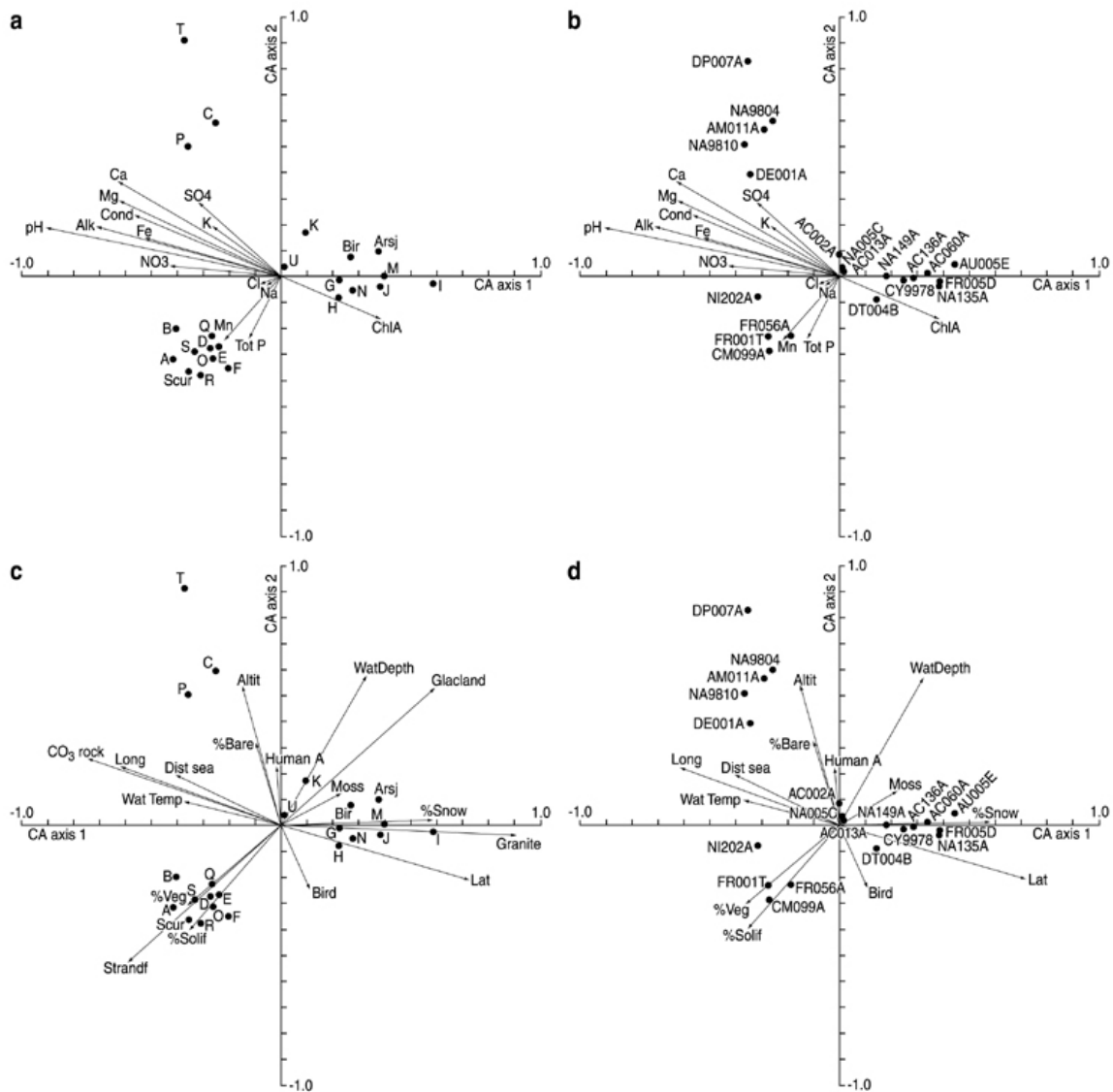
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*Figure 3. (a)* Results of Correspondence Analysis (CA) with 14 chemical variables regressed onto the CA axes, sites are indicated as codes (see Figure 2) *(b)* Results of Correspondence Analysis (CA) with 14 chemical variables regressed onto the CA axes, diatom species are indicated as codes (see Appendix 1) *(c)* Results of Correspondence Analysis (CA) with catchment and other limnological variables (17 variables) regressed onto the CA axes, sites are indicated as codes *(d)* Results of Correspondence Analysis (CA) with catchment and other limnological variables (17 variables) regressed onto the CA axes, diatom taxa are indicated as codes.

Figure 3 shows the catchment and other limnological variables regressed onto the CA axes. These variables explain 81.8% of the inertia of the diatom data (Table 2). The variables most strongly correlated with axis 1 are granite bedrock (0.88), latitude (0.71), carbonate bedrock (-0.73), and longitude (-0.60). Latitude and longitude are negatively correlated in this data-set as the lakes lie on a north-west to south-east gradient (Birks et al. 2004a). Many catchment variables also have high correlations with axis 1, such as % snow in the catchment (0.57), glaciated landscape (0.58), and strandflat landscape (-0.58). Axis 2 has high positive correlations with altitude (0.52) and water depth (0.56) and high negative correlations with strandflat landscape (-0.52), percent vegetation cover (-0.30), and percentage solifluction (-0.39). Forward selection indicates that only two of these variables, granite bedrock (p = 0.001) and strandflat landscape (p = 0.005) are statistically significant (p < 0.05) and together they explain 20.3% of the inertia in the diatom data in a CCA when they are the only predictor variables.

*Table 2*. Results of correspondence analysis of the modern diatom data. The eigenvalues, the % of the total inertia of the diatom data, the % of the total inertia of the diatom-chemistry data and of the diatom-catchment data, and the correlations are given for axes 1-4.

| | Axis1 | Axis2 | Axis3 | Axis4 |
|---|---|---|---|---|
| Eigenvalue | 0.58 | 0.40 | 0.32 | 0.27 |
| % inertia of diatom data | 14.7 | 10.1 | 8.2 | 6.8 |
| % inertia of diatom-chemistry data | 19.2 | 8.7 | 8.9 | 8.5 |
| Diatom-chemistry correlations | 0.95 | 0.77 | 0.87 | 0.93 |
| % inertia of diatom-catchment data | 17.2 | 11.7 | 8.5 | 7.0 |
| Diatom-catchment correlations | 0.97 | 0.97 | 0.93 | 0.89 |

Total inertia = 3.96; total inertia 'explained' by all 14 chemical variables = 2.72; total inertia 'explained' by all 17 catchment and limnological variables = 3.21

*Table 3*. Performance statistics for the pH-diatom WA-PLS regression model based on 'leave-one-out' cross-validation RMSEP = root-mean-square-error of prediction, $r^2$ = correlation of determination. The final model is shown in bold.

| Component | RMSEP | $r^2$ | Maximum bias |
|---|---|---|---|
| 1 | 0.42 | 0.77 | 0.76 |
| **2** | **0.39** | **0.80** | **0.68** |
| 3 | 0.38 | 0.80 | 0.67 |
| 4 | 0.38 | 0.80 | 0.61 |

Three lakes (C, P, T) form a very distinct group (TWINSPAN Group 1). The most important common species in Group 1 is *Amphora libyca*, which occurs at about 10% abundance at the three sites (Figure 2). *Diploneis oblongella* is abundant at Daltjørna (T) whilst an unknown *Navicula* species and *Denticula tenuis* are common at 'Ossian North' (P), and *Navicula cf. evanida* achieves ca. 20% abundance at Ossian Sarsfjellet (C). Group 1 sites have high positive CA axis 2 scores and low negative CA axis 1 scores and are associated with high pH, calcium, magnesium, and conductivity values (Figure 3). These sites are the highest altitude sites with a high percentage of bare rock in their catchments (Figure 3). *Amphora libyca* and *Diploneis oblongella* are cosmopolitan alkaliphilous diatoms typical of relatively high conductivity waters. These three lakes all belong to group 1 defined by Birks et al (2004a) on the basis of water chemistry alone.

Ten lakes (A, B, D, E, F, O, R, Q, S, 'Scurvy Pond') form a distinct cluster in the CA and are also classified into TWINSPAN Group 2. These sites have low negative axis 1 and low negative axis 2 scores (Figure 3) and consist of shallow, strandflat sites with relatively well developed catchment vegetation and which are visited and presumably influenced by birds (Figure 3). These sites also have relatively high nutrient values. In terms of the classification of the lakes on the basis of water chemistry (Birks et al. 2004a), this diatom-defined group contains lakes of all three chemistry groups (five Group 1 lakes, four Group 2 lakes, two Group 3 lakes). The diatom assemblages of the sites in diatom Group 2 are mostly dominated by *Fragilaria* species such as *F. pinnata*, *F. construens* var. *venter*, and *F. pseudoconstruens* together with *Nitzschia* species such as *N. frustulum* and *N. alpina*, and *Cymbella reinhardtii* (Figure 2). *Fragilaria*-dominated assemblages are common in physically disturbed, unstable environments often characteristic of the early Holocene and recently deglaciated sites (Haworth 1975; Denys 1990; Bradshaw et al. 2000) and in basins isolated from the sea (Stabell 1985; Douglas et al. 1996). *Fragilaria* species may also be most competitive on sand or silty habitats (Kingston 1984) such as those found in these strandflat lakes on Svalbard where aquatic macrophytes are rare.

Tendammen (U) is not dominated by *Fragilaria* species and has relatively high abundances of *Navicula seminulum*, *Achnanthes linearis,* and *A. minutissima*. This sites lies in the middle of the CA axes. The diatom flora at this site is unique and the lake is not readily classified into any of the groups identified by TWINSPAN, lying in either Group 1 or 2. This

site has the most marked anthropogenic influence of any of the lakes sampled and was used as a water supply to a mine until 1967. It is also the only site where there is clear trace metal evidence for anthropogenic enrichment (Boyle et al. 2004). In terms of lake-water chemistry, it belongs to Group 3, along with 'Draba Pond' (O) (Birks et al. 2004).

Nine lakes (G, H, I, J, K, M, N, Arresjøen, Birgervatnet) are classified into TWINSPAN Group 3, which also forms a distinct cluster in the CA analyses. These sites have positive axis 1 scores and low positive or negative axis 2 scores. In contrast with Group 1 these are sites with low calcium, conductivity and pH values (Figure 3). They all belong to Group 2 defined by Birks et al (2004a) on the basis of water chemistry alone. The lakes tend to be at high latitude and on granite catchments with a high snow cover (Figure 3). The assemblages are dominated by a range of taxa including *Fragilaria virescens* var. *exigua*, *Achnanthes curtissima*, *A. marginulata*, and *Tabellaria flocculosa*. This is the only group containing centric diatoms, with *Cyclotella* species being present at Signedalen (G), Hajeren (H), and Birgervatnet (Bir), and *Aulocoseira* species present at sites 'Bjørnvatnet' (I), Hakluythovden (M), and Arresjøen (Arsj). Water depth does not seem to be a good predictor of the presence of planktonic *Cyclotella* species since they are currently absent from some deep lakes (e.g. Arresjøen and Ossian Sarsfjellet (C) both of which have maximum depths greater than 20 m). The species characteristic of Group 3 are common in the AL:PE and SWAP data-sets from predominately soft-waters (Cameron et al. 1999). Wolfe (1996) reported similar *Achnanthes* assemblages from an oligotrophic and acid-sensitive lake on Baffin Island.

*Development of a pH-diatom transfer function*

At present there is no modern surface-sediment diatom-water quality training set available from Svalbard. Since the diatom flora is sufficiently unique, the construction of a local training set is required as species ecologies cannot be reliably used from elsewhere. A transfer function for pH reconstruction was constructed using WA-PLS. The diatom data have a statistically significant relationship to pH (p = 0.001) as assessed by a Monte Carlo permutation test of CCA axis 1 constrained by pH. There is also an important secondary gradient (Table 1) but the ratio of the pH-constrained eigenvalue to the first unconstrained eigenvalue is 1.71, compared with 1.09 in the AL:PE data-set, suggesting that there is a very strong pH relationship in the Svalbard data-set.

The final 2-component WA-PLS model (Table 3, Figure 4a) was selected using the criteria discussed by Birks (1998) and has a RMSEP of 0.39 pH units and a maximum bias of 0.68 pH units. There is a good relationship between predicted and observed pH values ($r^2$ = 0.8) but there is a systematic bias, with pH values being over-predicted at the lower pH values and under-estimated at the higher end of the pH gradient (Figure 4b). This bias is a feature of WA-PLS and results from its implicit inverse deshrinking regression (ter Braak and Juggins 1993; Birks 1998; Cameron et al. 1999).

The species pH optima as estimated by Gaussian logit regression (Appendix 1) can be compared to those obtained from other data-sets. For species that are rare (less than 5 occurrences) optima cannot be reliably estimated. Some taxa, e.g. *Achnanthes marginulata,* have fitted curves with a minimum (Gaussian regression coefficient $b_2 > 0$) instead of a maximum. Optima could not be estimated for these taxa and these are marked by asterisks in Appendix 1.

When the pH optima are compared with those obtained for the AL:PE and SWAP calibration sets it is apparent that whilst some species have similar optima e.g. *Navicula*

*pseudoscutiformis* and *Achnanthes austriaca* v. *helvetica*, most species exhibit quite different optima. Some, e.g. *Fragilaria* species, have lower optima, whilst others have higher optima, e.g. *Pinnularia microstauron* and *Tabellaria flocculosa*. These differences are probably due to the limited nature of the Svalbard calibration set which, because of its small size, does not cover sufficiently large environmental gradients to give a reliable picture of species optima. Therefore we used the AL:PE data in addition to the local transfer function for all down-core pH reconstructions.
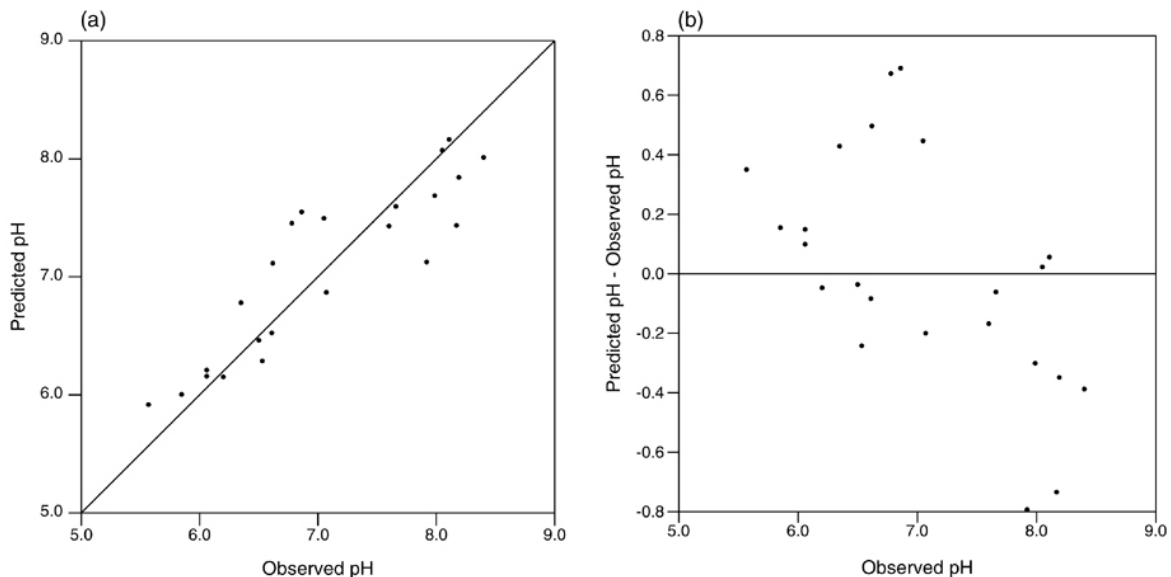


*Figure 4a*. Predicted pH from a 2-component WA-PLS model plotted against measured pH at 23 sites on Svalbard ($r^2 = 0.8$).

*Figure 4b*. Plot of residuals (predicted – observed pH) against measured pH.

## *Diatom analysis of sediment cores*

Eight cores were examined for diatoms. Of these five were suitable for counting with severe dissolution problems encountered at lakes Ossian Sarsfjellet (C), Dajtjørna (T), and Tenndammen (U). At Vassauga (S) no diatoms were found below a depth of 8 cm. Dissolution problems may be due to sulphate formation at these sites (Österholm 1990) and lakes C and T have relatively high sulphate concentrations in their surface waters (Figure 3).

## *Ytertjørna*

At Ytertjørna (Q) 14 levels were analysed for diatoms (Figure 5). The profile is relatively stable and is dominated by *Fragilaria pinnata* and its varieties throughout. The upper part of the profile, above 8 cm (ca. 1900 AD) has higher percentages of *Achnanthes lacus-vulcani* and *A. minutissima*. Below 6 cm (ca. 1930 AD) *Cymbella reinhardtii* and *Caloneis bacillum* are more common, whilst below 20 cm (ca. 1500 AD) *Fragilaria construens* var. *venter* is more abundant. Diatom-inferred pH shows relatively stable values using both the AL:PE and Svalbard calibration data-sets, with an inferred pH of ca. 7.5 for most of the core. Both models give a good agreement to the modern measured pH (7.9).

Nutrients were found to have a weak signal in the modern data-set and no useful transfer functions could therefore be made. However, it is still important to examine evidence for changing nutrient concentrations, since in the absence of anthropogenic enrichment, variations in nutrient status might be a consequence of changes in climate (Battarbee 2000)

and/or atmospheric nutrient deposition. Diatom samples were therefore fitted passively onto the CA (Figure 6). All the core samples from Ytertjørna have good fits to the CA with low squared residual distances. There is a clear trend of decreasing axis 2 scores from the bottom of the core to the surface. This may indicate a decrease in total dissolved phosphorus over time or alternatively decreasing manganese.

*Vassuaga*

At Vassuaga (S) no diatoms are preserved below 8 cm (ca. 1810 AD) (Figure 8), which can probably be explained by dissolution as there is a large increase in calcium carbonate below 8 cm (Boyle et al. 2004). Above 8 cm the assemblages are dominated by *Fragilaria pinnata*, commonly making up over 50% of the assemblage. *F. construens* var. *venter* is the only other abundant diatom in the core, with other species only making up a very minor component of the assemblage. There is no trend in inferred pH shown by either inference model. The local data-set gives a higher reconstructed pH (ca. 8) than that obtained from the AL:PE training set (ca. 7 - 7.5). Present-day pH is 8.2.

*Birgervatnet*

At Birgervatnet (Bir) 25 levels were analysed for diatoms (Figure 9). The base of the core (below ca. 16 cm) is dominated by the aerophilic species *Orthoseira dendroteres*, which achieves over 90% abundance at 18 cm. This may represent a period of intense erosion. Above 16 cm this species is only present at low (<10%) abundance and *Navicula digitulus* is the most common species, with *Achnanthes suchlandtii* common from 16 - 6 cm. In the uppermost levels (after ca. 1950 AD) the centric forms *Cyclotella* cf. *planetophora* and an unidentified *Cyclotella* species increase in abundance along with several small *Achnanthes* and *Navicula* species. The local (Svalbard) pH model gives consistently lower values (ca. 6 - 6.5) than the AL:PE model (ca. 6.5 - 7) although both suggest a stable pH throughout the profile with no consistent trend. The present-day pH is 6.5.

*Arresjøen*

At Arresjøen (Arsj) 19 levels were analysed for diatoms (Figure 10). A number of clear changes in the diatom assemblages occur, the most marked of which is at 4 cm (ca. 1750 AD). Below this level the centric planktonic species *Cyclotella tripartita* is relatively important making up more than 10% of the assemblage, but this species disappears above 4 cm and diatoms such as *Achnanthes lacus-vulcani* and *Navicula* species 1 become more common. Below 16 cm *Navicula schmassmanni*, *F. pinnata,* and *P.* cf. *balfouriana* are more important. Above 10 cm (ca. 1220 AD), *Aulocoseira distans* var. *nivalis* increases in abundance whilst *A. lirata* var. *alpigena* becomes less dominant. pH reconstructions using the local and AL:PE models give almost identical results, pH is stable at the base of the core, and there is a very slight acidification trend from about 16 - 10 cm, above which pH values appear to stabilise. The present-day pH is 6.2. Diatom samples fitted passively onto the CA show a poor fit at 6, 8, 12, and 14 cm, but the trend of increasing axis 1 and axis 2 scores suggests a decreasing trend of nutrients as well as a slight decrease in pH (Figure 6).
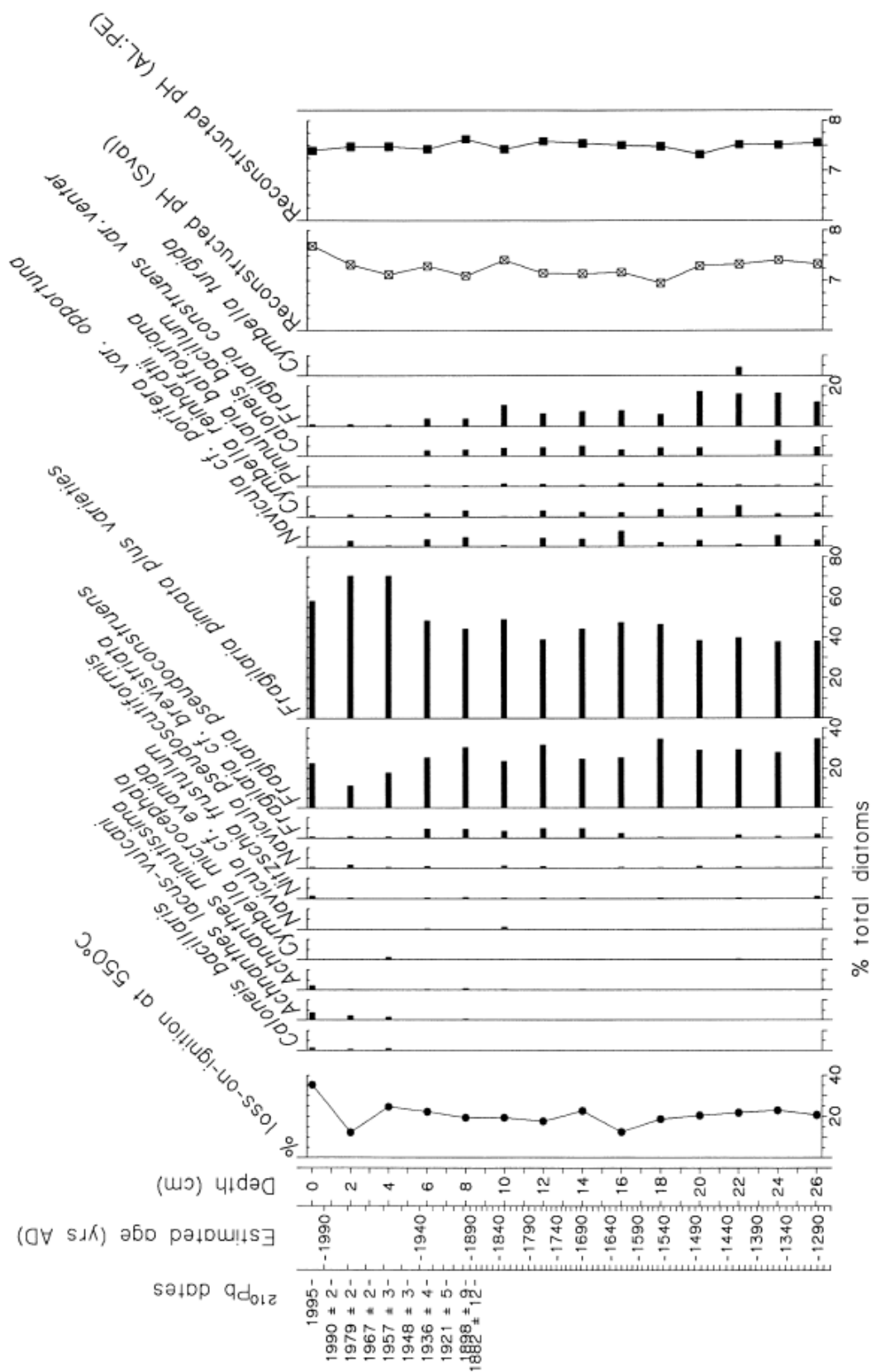
*Figure 5.* Recent changes in diatom assemblages at Ytertjørna (Q), expressed as % total diatoms. Inferred pH estimated from AL:PE (Cameron et al. 1999) and Svalbard (this study) calibration data-sets. $^{210}$Pb dates and associated errors are shown on the left-hand side of the diagram, along with an estimated age scale.
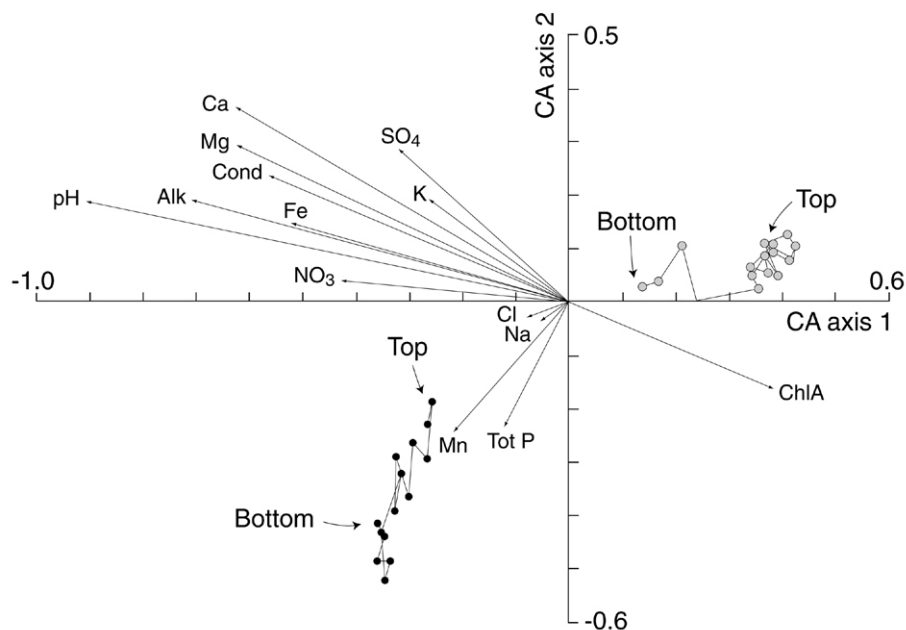
13

*Figure 6.* Results of Correspondence Analysis (CA) with diatom samples from Ytertjørna and Arresjøen fitted passively as closed circles and shaded circles, respectively. The other sites had poor fits and are therefore not shown.
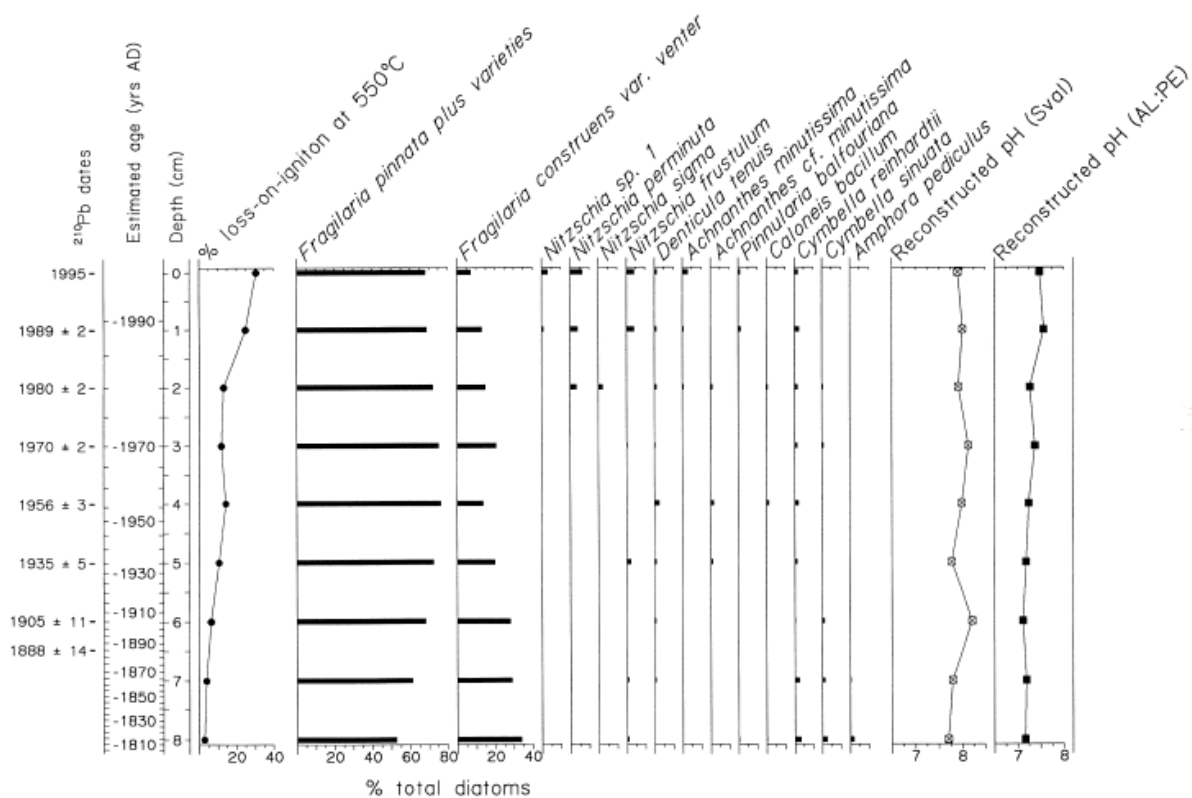


*Figure 7.* Recent changes in diatom assemblages at 'Scurvy Pond', expressed as % total diatoms. Inferred pH estimated from AL:PE (Cameron et al. 1999) and Svalbard (this study) calibration data-sets. [210]Pb dates and associated errors are shown on the left-hand side of the diagram, along with an estimated age scale.
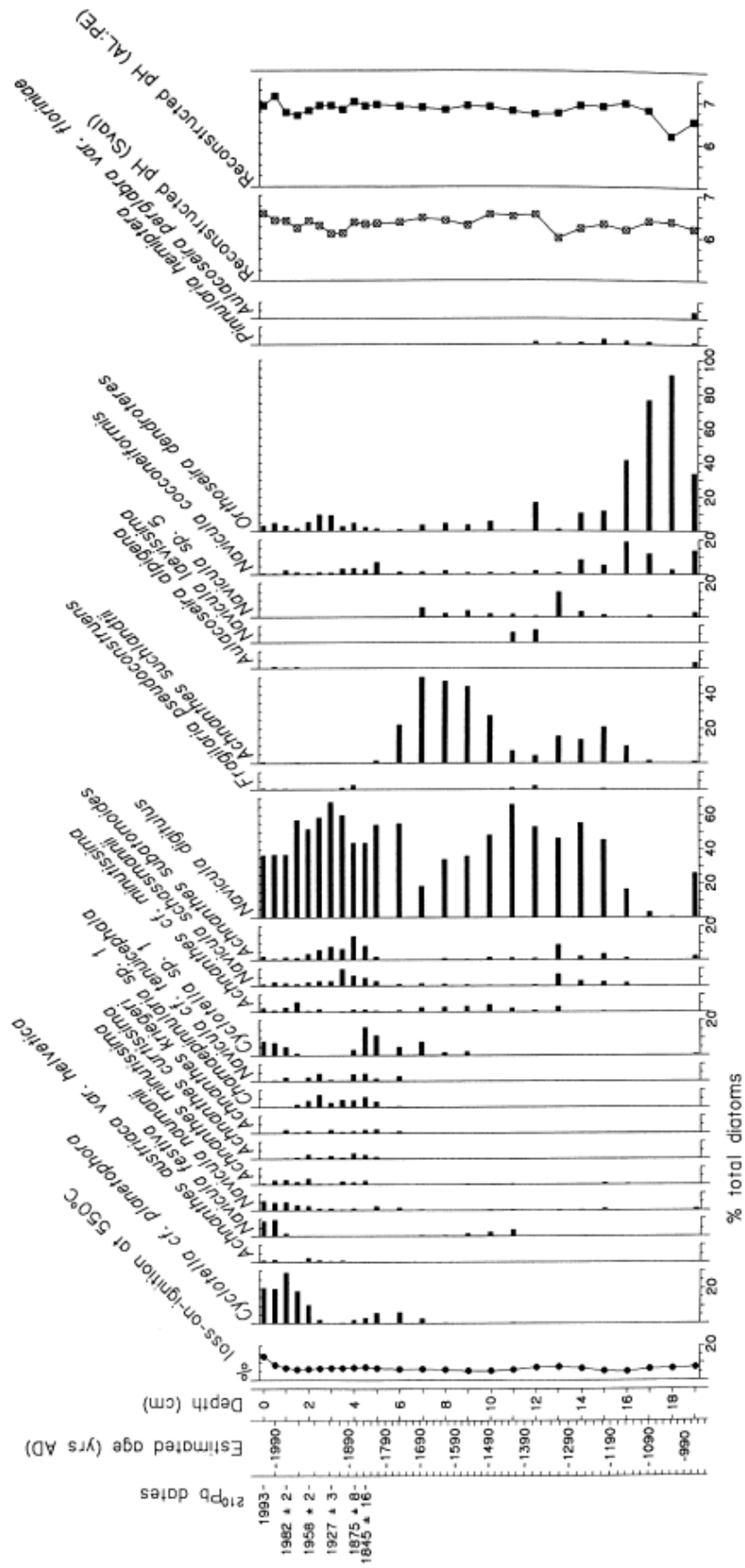
14

*Figure 8.* Recent changes in diatom assemblages at Birgervatnet, expressed as % total diatoms. Inferred pH estimated from AL:PE (Cameron et al. 1999) and Svalbard (this study) calibration data-sets. ²¹⁰Pb dates and associated errors are shown on the left-hand side of the diagram, along with an estimated age scale.

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*'Scurvy Pond'*

At 'Scurvy Pond' (Scur) 20 levels were analysed for diatoms (Figure 7). The assemblage at this site is dominated (usually > 50%) by *F. pinnata* and its varieties throughout, with smaller amounts of *Cymbella reinhardtii* and *Nitzschia* species. *Pinnularia* cf. *balfouriana* is more common between 14 - 4 cm (ca. 1350 - 1890 AD) and *C. reinhardtii* also increases towards the top of the core. Overall species diversity is extremely low. The consistent dominance of *Fragilaria* species, together with the low diversity, suggests the persistence of turbid and unproductive conditions throughout the period represented by the core. Neither the local (Svalbard) nor the AL:PE pH models suggest any substantial trend in diatom-inferred pH over time. The Svalbard model reconstructs consistently lower pH values (between ca. 6 - 6.5) than those obtained by AL:PE (ca. 7.5). This is due to the higher optimum for *F. pinnata* in the AL:PE data-set. The present-day pH is 6.9.

**Discussion**

*Modern diatom assemblages*

Over 180 diatom taxa were found in fossil material and modern surface sediments from 23 lakes on Svalbard. This compares well with other studies reviewed by Picinska-Faltynowicz (1988) and van de Vijver et al. (1999). For example, van de Vijver et al. (1999) found 131 taxa from shallow alkaline streams and pools in the Brøgger Peninsula. *Navicula*, *Cymbella*, *Achnanthes*, *Nitzschia,* and *Fragilaria* were found to be the most abundant genera with *Achnanthes petersenii* the most common taxon. These species are different from those encountered in this study probably because the samples of van de Vijver et al. (1999) were obtained from very shallow pools prone to dessication.

Douglas and Smol (1993, 1994, 1995) examined 35 shallow ponds on Ellesmere Island, and found over 130 taxa. Variance partitioning showed 15.8% of the variance could be explained by water chemistry, specifically alkalinity. They also noted an abundance of benthic forms and an absence of plankton. The dominant species were *Nitzschia frustulum* var. *perpusilla*, *Cymbella microcephala*, *Caloneis* sp. 1, *N. denticulate,* and *Navicula schoenfeldtii*, whereas small *Fragilaria* species were almost absent. Their sites are shallow ponds that freeze to the bottom, and which also have more aquatic vegetation, and this may explain some of the differences in the diatom flora.

*Recent environmental changes on Svalbard; evidence from the sediment record*

The diatom assemblages were examined in five cores, and these fall into two distinct groups. The first group of lakes (Ytertjørna (Q), Vassauga (S), and 'Scurvy Pond') are shallow, strandflat lakes with relatively high nutrient values (Figure 3) presently dominated by *Fragilaria* species (Figure 2). These lakes show a low diversity of fossil assemblages through time, being dominated by *Fragilaria* species, especially *F. pinnata,* throughout, with no trend in inferred pH values. However, they show a marked increase in the rate of biotic compositional change in the last 50 – 100 years (Birks et al. 2004b). Boyle et al. (2004) suggest that four sites on Svalbard (Ytertjørna (Q), Vassauga (S), Daltjørna (T), and Tenndammen (U)) show significant geochemical and sedimentary changes at ca. 1970 AD which may be a response to a regional climatic shift (see Birks et al. 2004b).

*Figure 9.* Recent changes in diatom assemblages at Arresjøen, expressed as % total diatoms. Inferred pH estimated from AL:PE (Cameron et al. 1999) and Svalbard (this study) calibration data-sets. $^{210}Pb$ dates and associated errors are shown on the left-hand side of the diagram, along with an estimated age scale.

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The second group of cores are from Arresjøen and Birgervatnet, both of which are deeper, more acid lakes with a higher percentage of snow in their catchments than the strandflat lakes. Because they are deeper and larger than the strandflat lakes there are more habitats available for diatom colonisation and growth and consequently the assemblages are more diverse, and include centric, presumably planktonic forms. Planktonic diatoms are found in Holocene sequences elsewhere in the Arctic (Lemmen et al. 1988; Douglas et al. 1996; Wolfe 1996). These two lakes have much more 'dynamic' diatom assemblages than the first group, exhibiting very dramatic changes through time. At Arresjøen there is a major change at ca. 4 cm (extrapolated ^{210}Pb date ca. 1750 AD) with the loss of a *Cyclotella* species, and also earlier changes at 12 cm (extrapolated age ca. 1300 AD) and at 16 cm (extrapolated age ca. 800 AD). At Birgervatnet there is a major change at the bottom of the core (before ca. 1200 AD) and other changes above 5 cm (ca. 1810 AD) and above ca. 2.5 cm (ca. 1940 AD) characterised by the decline of *Achnanthes suchlandtii* and increasing percentages of *Cyclotella*. Both lakes show a marked increase in the rate of biotic compositional changes in the last 50 years (Birks et al. 2004b)

Rose et al. (2004) demonstrate that lakes on Svalbard receive atmospheric contaminants and therefore may be susceptible to the effects of acid precipitation. At Birgervatnet increased numbers of SCPs are observed above 2.5 cm (ca. 1940 AD) but this is not coincident with any change in diatom-inferred pH. Similarly, at Arresjøen the loss of the *Cyclotella* flora does not appear to be related to atmospheric contamination since it occurs well before the increases in SCPs from fossil fuel combustion. There is no evidence of any impact of atmospheric pollution at any of the sites. Although low levels of contamination are evident (see Rose et al. 2004), these do not appear to be sufficient to cause acidification and the critical loads for these sites have not been exceeded (cf. Lien et al. 1995).
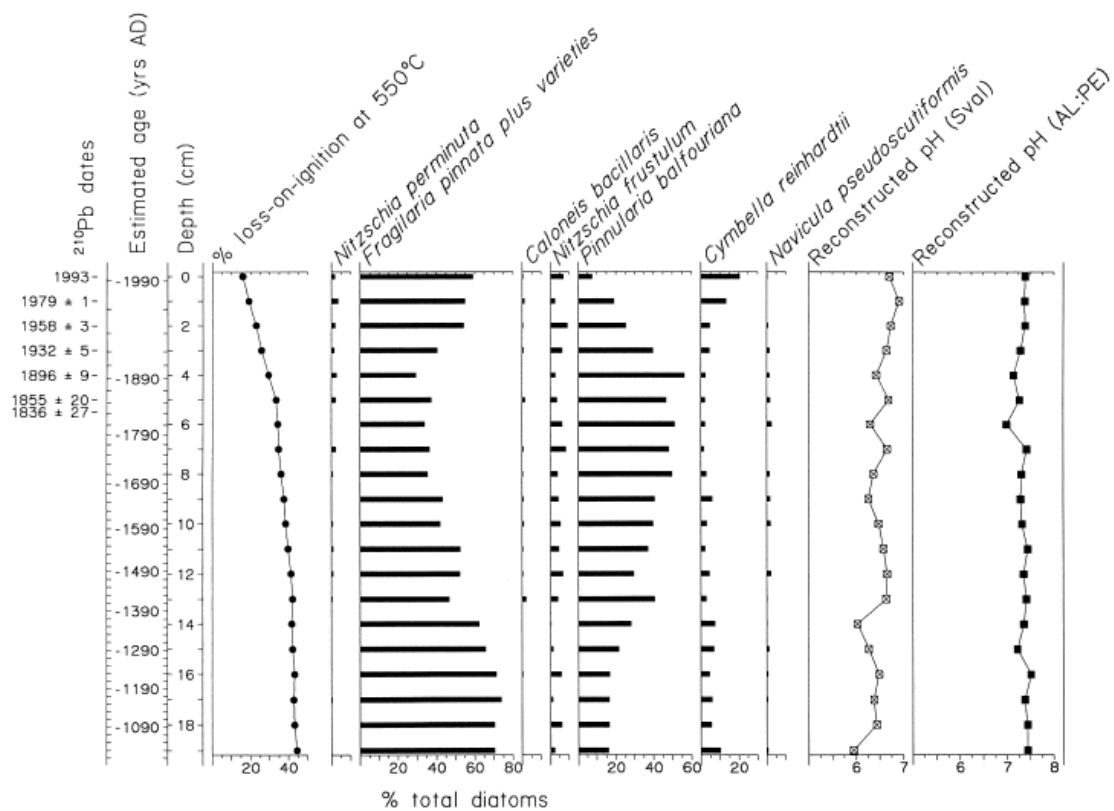


*Figure 10*. Recent changes in diatom assemblages at Arresjøen, expressed as % total diatoms. Inferred pH estimated from AL:PE (Cameron et al.1999) and Svalbard (this study) calibration data-sets. [210]Pb dates and associated errors are shown on the left-hand side of the diagram, along with an estimated age scale.

It is likely that changes at Arresjøen and Birgervatnet are related to either specific catchment changes or to regional climate change. Changes in the light and/or the ice climate of the lake may be responsible for the shifts observed in the planktonic diatom communities. At Arresjøen the timing of the loss of *C. tripartita* is coincident with a small increase in organic matter, which Boyle et al. (2004) suggest is best explained in terms of increased allochthonous supply. The loss of the diatom plankton might be partly explained by a change in the light regime associated with an increase in turbidity caused by enhanced catchment erosion and the inwash of soil. At Birgervatnet changes in the planktonic component do not appear to be associated with any changes in organic matter. At 'Scurvy Pond' and Ytertjørna (Q) floristic change is not associated with trends in % LOI, whilst at Vassauga (S) an increase in LOI is associated with a decline in *Fragilaria construens* var. *venter.*

**Conclusions**

In some parts of the Arctic, palaeolimnological evidence suggests that 20th century shifts in lake ecosystems have occurred; in some cases these have been linked to the impact of global warming. For example, studies of the palaeolimnology of Ellesmere Island ponds document only subtle species changes before 1850 AD with recent diatom assemblages showing marked shifts which may be related to recent climate warming (Douglas et al. 1994; Overpeck et al. 1997). At these sites changes are so marked that no analogues for pre-1800 assemblages can be found. In addition, the diatom changes pre-date the deposition of atmospheric contaminants, and UV changes are thought to be too recent to explain the changes.

At two sites situated in north-west Svalbard (Arresjøen and Birgervatnet) less than 25 km apart there are major shifts in diatom assemblages over the past millennium which are statistically significant in the last 50 - 100 years (Birks et al. 2004b) but which cannot be explained by the impact of atmospheric pollution. At three other sites, major assemblage shifts are not evident but a marked increase in the rate of biotic change occurs in the last 50 - 100 years (Birks et al. 2004b).

Changes observed in recent lake sediments on Svalbard can possibly be related to recent climatic events, namely the 'Little Ice Age' and documented changes from the 20th century onwards (Birks et al. 2004c). Most glaciers on Spitsbergen advanced during the 'Little Ice Age' forming extensive and well-preserved moraines reaching their maximum Holocene position during the last century (Svendsen and Mangerud 1992). The glaciers retreated with subsequent 20th century warming (Werner 1993) with temperatures being warmer than any other time in the last ca. 500 years (Tarussov 1992). Ice-core data from Svalbard suggest a duration of the 'Little Ice Age' from 1550 - 1920 AD (Tarussov 1992). Other ice-core records suggest a two-phase development with cold periods between 1200 - 1500 AD and 1700 - 1900 AD (Gordiyenko cited in Svendsen and Mangerud 1997). The earlier events evident at Birgervatnet and Arresjøen may possibly be related to the climatic events of the 'Little Ice Age', especially the earlier changes seen around 1200 AD. However, the dating for this period at our sites is not adequate to make close comparisons. Meteorological observations from Spitsbergen document an increase in annual temperature from 1912 to the late 1930s, a decrease from the 1930s to the 1960s, and an increase from the 1960s to the present. Annual rainfall has increased by 25% since 1912. These climate changes may be related to the very recent diatom changes observed at all sites of the last 50 years. This is discussed further by Birks et al. (2004b).

Overall the results confirm the observation that the Arctic biosphere is not at a steady state, and that inter-annual to century scale climate variability may be the norm (Overpeck et

al. 1997). As climate continues to change, the limnology of Arctic lakes will also continue to respond.


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