Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – modern limnology, vegetation, and pollen deposition*

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Abstract

Twenty-four lakes on Svalbard were sampled for palaeolimnological studies and are described in terms of their geographical location, catchment characteristics, water chemistry, and flora. No sediment could be retrieved from one of the lakes. There is a close correlation, as detected by redundancy analysis, between lake-water chemistry and catchment variables, particularly bedrock geology and geographical location for 23 lakes. The flora of the lake catchments is statistically related, as shown by canonical correspondence analysis, to bedrock geology, climate (geographical location), and nutrient status (bird impact). Modern pollen assemblages from eleven lakes contain 2–25% far-distance extra-regional pollen. The modern local and regional pollen depositions are dominated by *Oxyria digyna,* Poaceae, *Saxifraga, Salix,* and Brassicaceae pollen.

Introduction

This paper presents the basic limnological, catchment, and floristic data for 24 lakes on Svalbard that were sampled for a range of palaeolimnological studies (Birks et al. 2004). These included the analysis of diatoms, chrysophyte cysts, chironomids, pollen, inorganic geochemistry, atmospheric contaminants, and persistent organic pollutants, and radiometric dating. This paper provides the documentation of all the sites sampled and studied in the project, which focused on recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments. It also attempts to explore statistically the relationships between lake-water chemistry and simple catchment variables, and between the vascular-plant flora of the catchments of the lakes and catchment characteristics. In addition, it presents modern pollen assemblages from surface lake-sediments from Svalbard. These are of particular interest because all modern pollen assemblages from Svalbard to date have been derived from moss polsters or surface peat rather than lake sediments. Although the paper is primarily descriptive, its main aim is to provide a background for the following six more analytical papers in this issue. Very few limnological or palaeolimnological surveys have been conducted in this region. Few of the lakes have been visited by scientists and it is thus important to document the results of this primary ‘baseline’ survey.

Methods

Field methods

Twenty-one lakes on a south-north transect (Figure 1) along the west coast of Svalbard from Bellsund (77º33'N) to Albert I Land (79º48'N) were visited and sampled between 28 July and 14 August 1995. During this period, the field crew lived and travelled aboard the boat *‘Farm’* from which an inflatable boat was used to carry equipment and people to the shore. The equipment was then carried on foot to the lakes and hence most of the lakes visited and sampled were within 1 km of the sea. The locations, altitude, approximate area, maximum depth, distance from sea, names (unofficial names are given in quotes), codes (A - U), and major vegetation zone of the 21 lakes are given in Table 1. The lakes were selected to be representative of the range of lakes in western Svalbard in terms of size, bedrock geology, and geographical position and to be accessible. Three additional lakes (Arresjøen, Birgervatnet, and ‘Scurvy Pond’) in the far north-west were visited and sampled by V.J. Jones and N.G. Cameron in 1993. These lakes are included in this study (see Table 1), giving a total of 24 lakes. The locations of all lakes are shown in Figure 1. No sediment could be recovered from Jensenvatnet (L).

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.

Table 1. Location, altitude, area, depth, and vegetation zone (Elvebakk 1997; Moen 1999) of the 24 lakes sampled on Svalbard (* M = middle arctic-tundra zone, N = northern arctic-tundra zone, P = arctic polar desert)

Lake code	Name	Latitude (N)	Longitude (E)	Altitude (m)	Area (ha)	Distance from sea (km)	Max depth (Zmax) (m)	Veg zone*
A	Veslekulpen	78°15'57"	12°55'26"	20.0	5.0	0.1	0.9	N
B	Hamnetangen	78°19'26"	12°50'47"	20.0	5.0	0.3	2.2	N
C	Ossian Sarsfjellet	78°57'04"	12°28'38"	60.0	13.0	1.2	26.0	M
D	McVitiepynten	78°52'25"	10°54'40"	20.0	9.0	0.4	1.3	N/P
E	'Murraybreen Pond'	78°45'13"	11°06'06"	30.0	2.0	1.0	1.4	N/P
F	Trongdalen	79°11'37"	11°39'25"	45.0	3.0	1.6	1.5	N
G	Signedalen	79°15'57"	11°32'30"	30.0	4.0	0.6	5.1	N
H	Hajeren	79°15'30"	11°33'30"	35.0	23.0	0.5	11.5	N
I	'Bjørnvatnet'	79°40'10"	10°48'30"	70.0	3.0	0.6	6.8	N/P
J	'Kobberfjorden Pond'	79°41'00"	10°48'42"	10.0	3.0	0.3	7.1	N
K	Kobberfjorden	79°41'00"	10°54'00"	50.0	5.0	1.7	12.5	P
L	Jensenvatnet	79°43'10"	10°50'50"	5.0	18.0	0.1	20.0	N
M	Hakluythovden	79°46'27"	10°45'10"	10.0	10.0	0.2	5.1	N
N	Salatberget	79°45'53"	10°43'00"	10.0	3.0	0.5	2.1	N
O	'Draba Pond'	79°48'20"	11°33'20"	20.0	4.0	0.4	2.0	N
P	'Ossian North'	78°57'25"	12°30'20"	50.0	5.0	1.0	6.7	N
Q	Ytertjørna	78°13'52"	12°56'30"	20.0	14.0	0.4	2.6	N
R	Spålen	78°13'12"	13°20'40"	20.0	8.0	1.0	1.2	N
S	Vassauga	77°45'30"	13°57'20"	15.0	3.7	1.9	1.3	N
T	Daltjørna	77°33'50"	14°13'55"	55.0	5.4	1.0	10.5	N
U	Tenndammen	78°06'00"	15°02'00"	5.0	15.0	1.0	2.5	M
Arsj	Arresjøen	79°40'30"	10°51'10"	15.0	34.0	0.3	29.0	N
Bir	Birgervatnet	79°48'35"	11°37'45"	10.0	12.0	0.5	15.0	P
Scur	'Scurvy Pond'	79°44'45"	12°18'15"	15.0	3.0	0.5	1.0	N

Table 2. Summary of surface sediments, cores, and core bottoms collected for different palaeolimnological analyses on Svalbard

Lake code & abbreviation	Name	Diatom ss	Diatom core	Cyst ss	Cyst bottom	Chironomid ss	Chironomid core	^{210}Pb dating	SCP core	SCP ss	POP analyses	Pb analyses	Geochemistry core	Pollen ss	
A	Veslekulpen	+	-	+	+	+	-	-	-	+	-	-	-	+	A
B	Hamnetangen	+	-	+	+	+	-	-	-	+	-	-	-	+	B
C	Ossian Sarsfjellet	+	(+)	(+)	(+)	+	+	+	+	+	+	+	+	+	C
D	McVitiepynten	+	-	+	(+)	+	-	-	-	+	-	-	-	(+)	D
E	‘Murraybreen Pond’	+	-	(+)	(+)	+	-	-	-	+	-	-	-	(+)	E
F	Trongdalen	+	-	(+)	(+)	+	-	-	-	+	-	-	-	(+)	F
G	Signedalen	+	-	+	+	+	-	-	-	+	-	-	-	+	G
H	Hajeren	+	-	+	(+)	+	-	-	-	+	-	-	-	+	H
I	’Bjørnvatnet’	+	-	+	+	+	-	-	-	+	+	-	-	+	I
J	’Kobberfjorden Pond’	+	-	+	+	+	-	-	-	+	-	-	-	(+)	J
K	Kobberfjorden	+	-	+	+	+	-	-	-	+	-	-	-	(+)	K
L	Jensenvatnet	*	*	*	*	*	*	*	*	*	*	*	*	*	L
M	Hakluythovden	+	-	+	+	+	-	-	-	+	-	-	-	+	M
N	Salatberget	+	-	+	+	+	-	-	-	+	-	-	-	+	N
O	‘Draba Pond’	+	-	+	+	+	-	-	-	+	-	-	-	(+)	O
P	‘Ossian North’	+	-	(+)	(+)	+	-	-	-	+	-	-	-	(+)	P
Q	Ytertjørna	+	+	+	(+)	+	+	+	+	+	+	+	+	+	Q
R	Spålen	+	-	(+)	(+)	+	(+)	-	-	+	-	-	-	(+)	R
S	Vassauga	+	+	+	(+)	+	(+)	+	+	+	-	+	+	+	S
T	Daltjørna	+	(+)	(+)	(+)	+	(+)	+	+	+	+	+	+	(+)	T
U	Tenndammen	+	(+)	(+)	(+)	+	+	+	+	+	+	+	+	+	U
Arsj	Arresjøen	+	+	-	-	+	-	+	+	+	-	+	+	-	Arsj
Bir	Birgervatnet	+	+	-	-	+	-	+	+	+	-	-	-	-	Bir
Scur	‘Scurvy Pond’	+	+	-	-	+	-	+	+	+	-	-	-	-	Scur

ss = surface sediment, SCP = spheroidal carbonaceous particles, POP = persistent organic pollutants,

+ = examined, (+) = examined but not enough fossils present and/or poor preservation, - = not available, * = no sediment

Table 3. Water chemistry and other limnological variables of the twenty four lakes sampled on Svalbard

Lake code	Name	pH	Alkalinity ($\mu eq\ l^{-1}$)	Ca^{2+} ($\mu eq\ l^{-1}$)	Mg^{2+} ($\mu eq\ l^{-1}$)	Na^{+} ($\mu eq\ l^{-1}$)	K^{+} ($\mu eq\ l^{-1}$)	SO_4^{2-} ($\mu eq\ l^{-1}$)	Cl^{-} ($\mu eq\ l^{-1}$)	Total P ($\mu g\ l^{-1}$)	NO_3^{-} ($\mu eq\ l^{-1}$)	Mn^{2+} ($\mu eq\ l^{-1}$)	Fe^{3+} ($\mu eq\ l^{-1}$)	Chlor, *a* ($\mu g\ l^{-1}$)	Conductivity ($\mu S\ cm^{-1}$)	Water temp. (^oC)	Submerged bryophytes*	Secchi depth (m)
A	Veslekulpen	8.2	992	853.3	411.3	278.4	12.8	41.5	342.4	9.3	5.2	3.5	143.5	1.6	169	6.6	0	>0.9
B	Hamnetangen	8.4	832	863.3	466.4	356.7	15.4	41.5	227.1	16.9	0.6	4.3	101.9	1.0	189	6	0	>2.2
C	Ossian Sarsfjellet	8.0	608	1042.9	439.3	108.7	20.5	50.8	76.7	4.3	0.0	2.2	49.9	0.2	153	6.4	3	19.4
D	McVitiepynten	6.8	136	144.7	83.9	113.1	48.6	19.0	87.5	67.4	0.5	7.4	107.1	1.9	44	5.4	5	>1.6
E	‘Murraybreen Pond’	7.1	306	239.5	171.1	152.2	35.8	45.5	151	6.0	0.0	0.5	50.1	0.8	28	5.2	2	>1.9
F	Trongdalen	6.6	120	49.9	29.6	43.5	7.7	25.4	69.3	3.2	1.5	1.8	46.2	0.8	133	8	0	4.2
G	Signedalen	6.5	88	44.9	38.7	60.9	17.9	19.9	63.6	4.5	0.0	0.6	24.7	0.5	33	7.6	3	>5.1
H	Hajeren	6.6	104	49.9	38.7	60.9	10.2	22.3	66.3	5.1	0.6	3.0	28.1	1.2	26	8.3	+	4.8
I	’Bjørnvatnet’	5.6	72	20.0	36.2	121.8	15.4	16.7	90.2	3.5	0.6	0.5	23.6	0.3	22	7.5	5	>6.8
J	’Kobberfjorden Pond’	6.1	64	24.9	83.9	300.1	12.8	26.3	241	4.7	1.4	3.0	22.6	0.5	69	3.8	3	5.3
K	Kobberfjorden	6.4	80	49.9	22.0	56.6	7.7	7.3	35.9	2.7	0.5	5.6	26.2	0.1	76	2.7	+	>13
L	Jensenvatnet	6.6	96	568.9	2621.6	11253.4	276.2	30949	12551	22.6	64.2	21.5	196.5	2.9	2440	4.9	0	1.8
M	Hakluythovden	5.9	52	24.9	32.9	104.4	7.7	27.1	142.3	42.4	0.5	4.9	64.7	2.5	34	3.6	5	2.9
N	Salatberget	6.1	36	20.0	23.9	69.6	7.7	11.5	49.9	54.7	0.0	3.4	102.8	6.2	12	4	+	1.5
O	‘Draba Pond’	7.6	40	434.1	159.6	234.9	12.8	15.0	65.0	395.7	1.0	26.6	171.1	1.4	129	3.9	0	>2
P	‘Ossian North’	8.1	600	3004	930.4	178.3	74.2	1225.7	66.5	3.4	4.5	5.7	96.1	0.1	367	8.5	0	5.3
Q	Ytertjørna	7.9	664	648.7	348	204.4	5.1	73.8	190.4	7.5	2.1	15.0	214.5	0.4	153	8	+	>2.6
R	Spålen	7.7	432	853.3	183.4	191.4	2.6	143.5	228.4	14.6	0.5	17.4	334.2	1.1	120	7.6	1	>1.5
S	Vassauga	8.2	1311	1651.7	899.9	517.6	17.9	307.9	656.4	6.6	7.4	7.7	164.6	0.9	243	9.5	2	>1.3
T	Daltjørna	8.1	836	913.2	404.7	126.1	5.1	32.4	148.6	3.5	2.5	4.4	378.3	0.6	129	8.2	2	8
U	Tenndammen	7.1	220	339.3	562.7	2127.1	40.9	327.2	2342	4.4	0.0	23.6	341.0	0.5	323	8.6	0	>2.5
Arsj	Arresjøen	6.2	68	34.9	55.9	182.7	17.9	29.8	202.9	3.3	0.0	15.0	2.8	1.7	39	5	+	na
Bir	Birgervatnet	6.5	74	64.9	31.3	65.2	10.2	19.0	96.3	4.0	1.7	6.8	13.1	1.3	25	0.3	0	na
Scur	‘Scurvy Pond’	6.9	88	14.8	60.9	95.7	7.7	15.3	73.1	4.4	0.0	22.4	96.2	0.6	27	4.1	0	na

* 0 = absent, + = very rare, 1 = rare, 2 = occasional, 3 = frequent, 4 = abundant, 5 = very abundant

na = not available

Table 4. Catchment characteristics of the twenty four lakes sampled on Svalbard

Lake code	Name	% Snow (Aug 1995)	% Bare ground	% Veget-ation	% Solifluc-tion	Bird impact **	Human impact **	Granite	Carbon-ate rocks	Strand-flat lake	Glacial land-scape
A	Veslekulpen	0	15	85	0	3	0	0	1	1	0
B	Hamnetangen	0	0	100	0	4	0	0	1	1	0
C	Ossian Sarsfjellet	5	75	20	5	+	0	0	1	0	1
D	McVitiepynten	0	90	10	25	+	0	0	0	1	0
E	‘Murraybreen Pond’	0	90	10	20	+	0	0	0	1	0
F	Trongdalen	0	95	50	0	+	0	0	0	0	1
G	Signedalen	0	85	15	5	+	0	1	0	0	1
H	Hajeren	0	65	10	5	3	0	1	0	0	1
I	’Bjørnvatnet’	25	70	5	5	0	0	1	0	0	1
J	’Kobberfjorden Pond’	25	50	20	0	3	0	1	0	0	1
K	Kobberfjorden	30	70	0	10	0	0	1	0	0	1
L	Jensenvatnet	30	50	30	0	3	0	1	0	1	1
M	Hakluythovden	20	65	15	0	3	+	1	0	0	1
N	Salatberget	25	50	35	0	4	0	1	0	0	1
O	‘Draba Pond’	15	55	5	5	1	0	1	0	0	1
P	‘Ossian North’	40	99	1	0	+	0	0	1	0	1
Q	Ytertjørna	0	15	85	5	3	0	0	1	1	0
R	Spålen	0	45	55	15	3	0	0	1	1	0
S	Vassauga	0	50	50	5	+	0	0	1	1	0
T	Daltjørna	0	95	50	0	1	1	0	1	0	1
U	Tenndammen	0	20	80	0	3	3	0	1	1	0
Arsj	Arresjøen	50	50	+	0	+	0	1	0	0	1
Bir	Birgervatnet	95	5	+	0	+	0	1	0	1	1
Scur	‘Scurvy Pond’	20	75	5	20	+	0	0	0	0	0

***** 0 = no birds, + = very few birds, 1 = few birds, 2 = some birds, 3 = many birds, 4 = very many birds.

****** + = very low, 1 = some impact, 2 = medium impact, 3 = high impact.

Triplicate short sediment cores (ca. 20 cm) were taken from each site using a Glew (1989) gravity corer from the deepest part of each lake. At eight sites (Ossian Sarsfjellet (C), Ytertjørna (Q), Vassauga (S), Daltjørna (T), Tenndammen (U), Arresjøen (Arsj), Birgervatnet (Bir), and ‘Scurvy Pond’ (Scur)), a full sediment core was extruded vertically at every 0.25 cm for the top 5 cm and at every 0.5 cm from 5 cm depth to the core bottom. A second core was extruded at every 1 cm interval for chironomid analysis (Brooks and Birks 2004). The third core was extruded at 0.5 cm intervals and kept as a back-up. Surface sediments (0 - 0.25 cm) were collected at the 23 lakes for diatom (Jones and Birks 2004), pollen (lakes A - K, M - U only), chrysophyte cyst (lakes A - K, M - U only; Betts-Piper et al. 2004), and spheroidal carbonaceous particle (Rose et al. 2004) analyses and the top 0 - 1 cm was collected at the same 23 lakes for chironomid analysis (Brooks and Birks 2004). Core ‘bottom’ samples (1 cm thick) were collected from lakes A - K and M - U for chrysophyte cyst analysis (Betts-Piper et al. 2004). The mean depth of these ‘bottoms’ was 21 cm. For the analysis of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), the surface sediments (0 - 1 cm) of five cores at lakes C, I, Q, T, and U were amalgamated, homogenised, and stored cool in hexane-washed amber jars. ‘Bottom’ sediments 4 cm thick were also collected from these five lakes as pre-industrial sediments for PAH and PCB analyses. Sediment inorganic geochemistry (Boyle et al. 2004) was studied for six cores (lakes C, Q, S, T, U, Arsj). Not all the surface sediments, core 'bottoms', or cores contained countable fossils due to poor preservation or very low concentrations. Eight cores (lakes C, Q, S, T, U, Arsj, Bir, Scur) were dated by ^{210}Pb (Appleby 2004). Table 2 summarises the different samples and cores collected for a range of analyses and shows which samples were examined but found not to be suitable for palaeolimnological analysis.

Bulk water samples for chemical analysis were collected from the outflow of each lake in 0.5 l acid-cleaned polyethylene bottles. In addition, between 0.5 and 2.0 litres of water (depending on the ease of filtration) were filtered through 47 µm GFC filters, which in turn, were transferred to an ice-packed insulated container for subsequent chlorophyll *a* analysis. Chlorophyll *a* is a useful measure of total phytoplankton biomass. The filtrate was also stored cold in polyethylene tubes and kept cold for the later determination of total dissolved phosphorus concentration. On returning from Svalbard, the chlorophyll *a*, nitrate, and total phosphorus samples were preserved by freezing prior to analysis. Surface-water temperature was measured in the field, as was Secchi disc depth. The relative abundance of submerged bryophytes (mainly *Calliergon*, *Drepanocladus*, and *Scorpidium*) at each lake was estimated visually on a 7-point scale (Table 3).

A range of variables characterising the catchment of each lake was recorded in the field. The percentages of vegetated ground, bare ground, and snow-covered ground were estimated visually after surveying the catchment for plants. The percentage of the vegetated and bare ground that was being disturbed by solifluction or consisted of patterned ground (stone polygons, stone nets, frost boils, stripes, etc.) was also estimated. The approximate presence and impact of birds on each lake and its catchment were estimated from the numbers of birds present, the amount of guano and goose droppings around the shore, and the frequency of bird feathers, etc. and were recorded on a 6-point scale (Table 4). The main birds present were geese, ducks, terns, sandpipers, divers, skuas, kittiwakes, auks, guillemots, snowbuntings, and gulls. Almost all the lakes had no evidence of human impact in their catchment, except for lakes M (graves of whalers), T (waste and garbage), and U (derelict pump-house, much waste and debris). Human impact was recorded on a 4-point scale (Table 4). The catchment bedrock geology was determined from the 1:500,000 bedrock geological maps 3G and 1G for Svalbard. For numerical analysis, the catchment geology was simplified into acid 'granite' bedrock, carbonate-rich rocks, or neither. The geomorphological setting of each lake was recorded as strandflat landscape or glacial landscape, or a combination of both.

The vascular plant flora in the catchments of lakes A - O, Q, R, Birgervatnet, and 'Scurvy Pond' were recorded and the relative abundance of each species was estimated on a 4-point scale (Table 5). Plant lists (presence/absence only) were made for the remaining five catchments. Plant taxonomy and nomenclature follow Rønning (1996).

Laboratory analyses

The water samples were analysed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) for Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Mn^{2+}, and Fe^{3+}, SO_4^{2-} and Cl^{-} were determined by ion chromatography (IC) and alkalinity by gran titration. pH was measured using a Beckmann Φ10pH meter and electrode, and conductivity with a PHOX 52E conductivity meter. Chlorophyll *a* was extracted using cold methanol digestion and its concentration determined by spectrophotometry (Talling and Driver 1961). Samples for total phosphorus were digested by sulphuric acid-potassium persulphate and the resulting concentration of orthophosphate determined by the addition of ammonium molybdate and ascorbic acid (Standard Methods 1975).

Table 5. The flora in the catchments of the twenty-four lakes sampled on Svalbard. Lake codes follow Table 1. Species found in only one catchment are listed at the bottom of the table

Lake code	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	Arsj	Bir	Scur
Species																								
Cardamine bellidifolia					3			1	1						1			1				+		1
C. nymanii				2													1			+				
Carex rupestris			3												2		1	1						
Cassiope tetragona			3														1							
Cerastium arcticum	2		2	3	3				1			1	1	1		+	2	3	+	+	+		2	3
C. regelii			1	2	3		1	1							2		1					+		3
Cochlearia groenlandica				2	2				1	2			3	3			1			+				1
Draba alpina															1				+				1	1
D. micropetala			1		1										1									
D. subcapitata				1	1																			
Dryas octopetala			3												2	+		1		+				1
Dupontia pelligera		3			2													1	2					
Festuca brachyphylla																1		3	3					
F. hyperborea	3	2													3									
Koenigia islandica			2	1						1					1		1		+	+				1
Luzula arctica	3	2	3	2				1																
L. arcuata			3					1	1			1												
L. confusa	3	2	3	4	4	4	4	4	3	2	3	2		1	4		4						4	4
Minuartia rubella				1																+	+			
Oxyria digyna	2		2	2	1	3	1	1	1						1		2							1
Papaver dahlianum				1	2				1		1				1			1	+			+		1
Pedicularis hirsuta				1															2					
Phippsia algida			1	3	4			1	3	3	2	1	3	2	4							+	3	3
P. concinna	3	2			3	1	3	3	1															
Poa alpina			1		1	1			1						2			2					1	2
P. arctica	3	2	2		1				1			2			1							+		1
Polygonum viviparum			2													+	1	2	+	+	+			
Potentilla spp.	1																	1						
Ranunculus hyperboreus						2						1							3	1	+			
R. lapponicus				2														1						
R. pygmaeus	1			1					1	1			1	1			2	1	+		+		2	1
Sagina cespitosa						1			1						1							+		
S. nivalis									1						1									
Salix polaris	2	4	4	1	3	2	4	3	1		1	1			3	+	4	4	+	+	+	+	2	2
Saxifraga aizoides				2														1	1	+				
S. cespitosa	3	4	2	3	3	1	2	3	1			1			3	+	3	3	+	+		+	2	3
S. cernua	1		2	1	3		1	1	1		1				3		1	1	+	+	+	+		1
S. foliolosa	1			2	1	1	1	2	1	1			1	1	2									2
S. hieracifola					1												1	1						
S. hirculus	1																2	2	+					
S. hyperborea				1	1		1		1	1	1	1	1		2							+		
S. nivalis	1	1	1		1		1	1	1			1			1			1	+	+				1
S. oppositifolia	4	4	4	3	3	1			1	1	1				3	+	4	4	+	+				3
S. rivularis				2	1				2	1	1	1	1	1	3							+		1
S. svalbardensis						1			1									1						
S. tenuis			2	1	2	3	1	2	1		1				1		1	1	+				1	1
Silene acaulis		2	2													+								
Stellaria crassipes				1						1														
S. humifusa		2												1			1							
Total no. of taxa	15	8	41	23	23	12	12	14	25	10	9	10	8	7	26	7	24	33	21	13	6	11	9	22

1 = very rare, 2 = rare, 3 = occasional, 4 = frequent.   For lakes P, S-U, Ars: + = present, otherwise absent

Additional species: **Lake A** *Chrysosplenium tetrandrum* 2; **Lake C** *Salix reticulata* 1, *Carex nardina* 3, *C. misandra* 1, *Cystopteris dickeana* 1, *Hyperzia selago* 1, *Potentilla chamissonis* 1, *Trisetum spicatum* 2, *Draba norvegica* 1, *Arnica alpina* 1, *Taraxacum arcticum* 1, *Poa abbreviata* 1, *Tofieldia pusilla* 1, *Empetrum nigrum* 1, *Poa glauca* 1; **Lake M** *Ranunculus sulphureus* 1; **Lake Q** *Festuca rubra* 1, *F. vivipara* 3; **Lake R** *Silene uralensis* 1, *Deschampsia alpina* 3, *Eriophorum triste* 1, *Draba corymbosa* 1, *Juncus biglumis* 1, *Equisetum arvense* 1, *E. variegatum* 1; **Lake S** *Saxifraga platysepala* +, *Draba nivalis* +, *D. fladnizensis* +, *Ranunculus nivalis* +; **Lake U** *Eriophorum scheuchzeri*.

Arsj = Arresjøen, Bir = Birgervatnet, Scur = 'Scurvy Pond'

Surface-sediment samples were prepared for pollen analysis using method B of Berglund and Ralska-Jasiewiczowa (1986), and the residues suspended in 2000 centistokes silicone oil. Whole slides were counted at equally spaced traverses at a magnification of x400 (bright field) until a total of at least 150 land pollen and spores was recorded. Critical determinations were made at x1000 using an oil-immersion objective. Identifications were made to the lowest possible taxonomic level using modern reference material and standard pollen and spore keys. Other microfossils such as algae, fungal spores, and fungal hyphae which were encountered on the pollen slides were also noted.

The loss-on-ignition at 550ºC was determined for all core sediment samples by ignition for 2 hours of oven-dried (105ºC) sediment and expressed as a percentage of weight loss after ignition compared to the dry sediment weight at 105ºC (Heiri et al. 2001).

Details of the other analytical techniques used in this study are given in the subsequent papers of this special issue (Appleby 2004; Betts-Piper et al. 2004; Boyle et al. 2004; Brooks and Birks 2004; Jones and Birks 2004; Rose et al. 2004).

Numerical analyses

Patterns in the lake chemistry of the 23 lakes with sediment (we were unable to obtain sediment from lake L, and as its water chemistry shows a strong marine influence, it was deleted) were explored by means of principal components analysis (PCA) (Legendre and Legendre 1998) of a correlation matrix between 14 chemical variables (pH, alkalinity, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, total dissolved P, NO_3^{-}, Mn^{2+}, Fe^{3+}, chlorophyll *a*, conductivity).

The statistical relationships between lake chemistry and the lakes' catchment, geographical, and geological variables were assessed by redundancy analysis (RDA) (ter Braak 1994), the constrained or canonical equivalent of PCA in which the ordination axes based on the chemical variables ('response variables') are constrained to be linear combinations of the catchment and other variables ('predictor variables') that maximise the total regression sum of squares between the responses and the predictor variables. The RDA was based on a correlation matrix between chemical variables. The statistical significance of RDA axes 1 - 3 was established by unrestricted Monte Carlo permutation tests (199 permutations). To explore further the relationships between lake chemistry and the predictor variables, a forward selection procedure (ter Braak and Šmilauer 1998) was used but in this case 999 permutations were used to allow the application of a Bonferroni correction for multiple simultaneous tests (Legendre and Legendre 1998). Partial RDA (ter Braak 1994) was also used to assess the role of predictor variables after the effects of site location have been allowed for statistically.

The patterns and statistical relationships between the vascular-plant flora (76 taxa) recorded on a relative abundance scale in the catchments of 19 of the lakes sampled (Table 5) and 15 potential predictors of floristic composition (latitude, longitude, altitude, bird impact, distance from sea, % snow, % bare ground, % vegetated ground, % solifluction, presence of carbonate-rich or granite bedrock, strandflat landscape, glacial landscape, and lake-water pH and conductivity as surrogate measures for the base-status of the catchments) were studied by canonical correspondence analysis (CCA) (ter Braak 1986). The CCA results were compared with results from an unconstrained correspondence analysis (CA) to evaluate if the predictor variables used in the CCA capture the major floristic gradients as detected by CA (ter Braak 1986). The statistical significance of CCA axes 1 - 3 was established by unrestricted Monte Carlo permutation tests (199 permutations). In the CA and CCA rare taxa were downweighted. A forward selection procedure (ter Braak and Šmilauer 1998) was applied to find the minimal number of predictor variables required to characterise the major floristic gradients. In this case 999 permutations were used to permit a Bonferroni correction to the Monte Carlo p-values in multiple simultaneous tests (Legendre and Legendre 1998).

All PCA, RDA, CA, and CCA were implemented using the console version of CANOCO 4.0 (ter Braak and Šmilauer 1998).

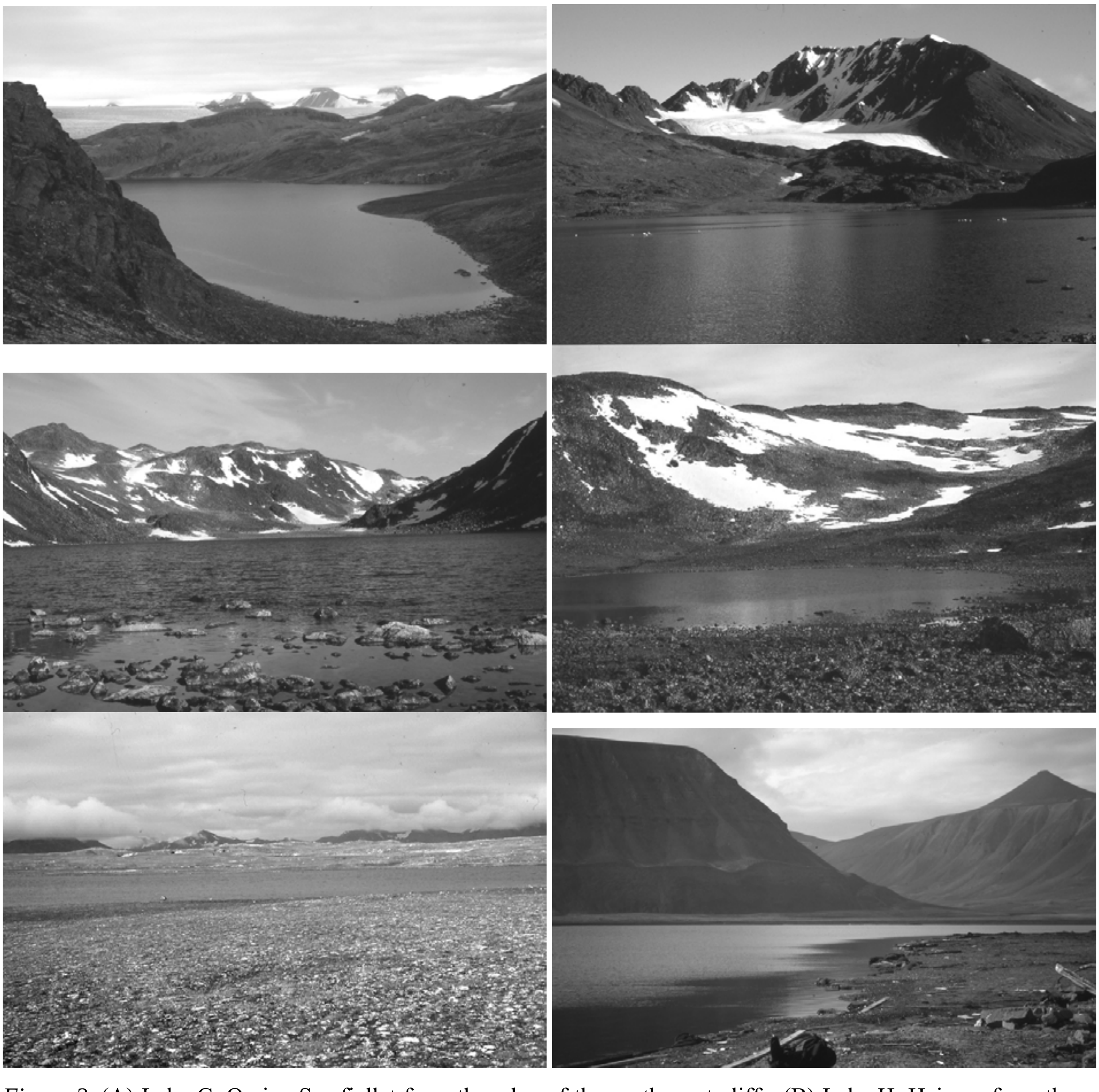

Figure 2. (A) Lake C, Ossian Sarsfjellet from the edge of the north-west cliffs. (B) Lake H, Hajeren from the western side looking to the Nilsfjell glacier. (C) Lake I, showing its very barren catchment. (D) Lake Q, Ytertjørna, a representative lake in the strandflat on the north side of Isfjorden. (E) Lake U, Tenndammen showing the building and pumping debris on the eastern shore. (F) Arresjøen from near the southern shallow area. All photos taken by H.J.B. Birks except for (E) which is by D.T. Monteith.

Results and discussion

The basic geographical, physical, chemical, and botanical data for the 24 lakes sampled and their catchments are given in Tables 1 - 5. Before analysing and discussing these data, notes on additional features are given to supplement these basic data.

Lake A, Veslekupen, Oscar II Land, Spitsbergen

The bedrock geology is mapped as the Wedel Jarlsberg complex of conglomerate, carbonate rocks, and phyllite. This shallow strandflat lake lies within moss-dominated outer-fjord tundra, with some lichen-rich areas on wind-exposed ridges and areas of degraded moss-tundra. This tundra belongs to the northern arctic-tundra zone (NATZ) (Elvebakk 1997; Moen 1999). There was extensive filamentous algal growth along the wind-swept shores. Reindeer had recently visited the lake.

Lake B, Hannetangen, Oscar II Land, Spitsbergen

This strandflat lake overlies Gipsdalen (Middle Carboniferous) carbonate rocks. It lies within open outer-fjord tundra with much extensive open 'fjell-field' and some moss- and lichen-dominated tundra. The vegetation belongs to the NATZ.

Lake C, Ossian Sarsfjellet, Oscar II Land, Spitsbergen

This large deep lake lies on Pre-Cambrian gneiss/migmatite and is bounded by cliffs on the northern and eastern sides of the shore (Figure 2A). On the southern less-steep side, there is a series of fresh glacial moraine ridges and at the head of the valley there are extensive snow patches. An indistinct outflow flows out of the west side of the lake and drains to Kongsfjorden. There is a very rich flora on the cliffs around the lake including *Salix reticulata, Empetrum nigrum, Carex nardina,* and *Cassiope tetragona*. The vegetation belongs to the middle arctic-tundra zone (MATZ) (Elvebakk 1997; Moen 1999).

Lake D, McVitiepynten, Prins Karls Forland

This shallow lake occurs in very open rock desert with extensive patterned ground (polygons, stone nets, frost boils, etc.) The underlying bedrock is Tertiary sandstone. The vegetation is mapped as part of the NATZ, but it resembles (Moen 1999; Elvebakk 1997) arctic polar desert with much *Papaver dahlianum* (see Elvebakk 1997).

Lake E, 'Murraybreen Pond' (unofficial name), Prins Karls Forland

This site is very similar to Lake D.

Lake F, Trongdalen, Albert I Land, Spitsbergen

This lake lies within bare rocky moraines with extensive stone polygons and stripes by the lake. It appears to be a kettle-hole within the 'Little Ice Age' moraines of the Blåshaugbreen glacier at the head of Trongdalen. Bedrock geology is Pre-Cambrian gneiss/migmatite. The vegetation belongs to the NATZ. Sediment accumulation within the lake is very restricted and confined to areas between boulders.

Lake G, Signedalen, Albert I Land, Spitsbergen

This lake overlies Pre-Cambrian gneiss/migmatite, and is surrounded by extensive open areas and small areas of lichen- and moss-dominated tundra, belonging to the NATZ. Arctic char were seen in the lake.

Lake H, Hajeren, Albert I Land, Spitsbergen

This lake has an extensive delta fan and glacial moraines on its east side, leading up to a small glacier on Nilsfjellet about 0.8 km from the lake's shore (Figure 2B). Bedrock geology is Pre-Cambrian gneiss/migmatite and the vegetation is mapped as the NATZ.

Lake I, 'Bjørnvatnet' (unofficial name), Danskøya

This small but deep lake (Figure 2E) to the south of Arresjøen lies in a barren landscape of boulder-fields, screes, patterned ground, and snowbeds overlying Pre-Cambrian gneiss/migmatite. What vegetation is present is considered to be arctic polar desert or extremely open stands within the NATZ.

Lake J, 'Kobberfjorden Pond' (unofficial name), Danskøya

This small but deep lake is bounded by a glacial moraine and beach ridge on its north shore. The bulk of the catchment is boulder fields and scree and snowbeds, with some 'bird-cliffs' supporting luxuriant moss-dominated vegetation with abundant *Cochlearia groenlandica* (Eurola and Hakala 1977). The uppermost sediment was a bright purple colour, presumably caused by bacterial pigments. The bedrock geology is Pre-Cambrian gneiss/migmatite and the vegetation is mapped as the NATZ.

Lake K, Kobberfjorden, Danskøya

When this small but deep lake was sampled (4 August 1995) there was still about 30 cm of ice covering about 80% of the lake surface. The bedrock geology is Pre-Cambrian gneiss/migmatite and the very sparse vegetation is mapped as arctic polar desert. The bulk of the catchment is bare rock, scree, and snow.

Lake L, Jensenvatnet, Danskøya

This large deep cirque lake is held in by a moraine and beach-ridge complex. The catchment is mainly bare rock (Pre-Cambrian gneiss/migmatite), scree, snow, and 'bird-cliffs' (Rønning 1996). What vegetation of vascular plants is present is confined to the south-facing bird-cliffs and is mapped as NATZ. Despite many attempts, no sediment samples could be obtained. Judging by the water chemistry (Table 3), this lake is strongly influenced by seawater.

Lake M, Hakluythovden, Amsterdamøya

This large lake lies within a glacial cirque with massive back-wall cliffs. It is held in by moraine and storm beach-gravels. Bedrock geology is Pre-Cambrian gneiss/migmatite and the catchment is predominantly cliffs with abundant birds, snowbeds, and rock desert and scree. 'Bird cliff' vegetation with abundant *Cochlearia groenlandica* (Eurola and Hakala 1977) is locally prominent.

The limited vegetation away from the cliffs is mapped as the NATZ. Seven graves of whalers were found on the moraine and reindeer droppings were frequent. Filamentous algae were frequent in the outflow and there was extensive submerged moss growth even at 5 m water depth.

Lake N, Salatberget, Amsterdamøya

This small lake is surrounded by large bird cliffs consisting of Pre-Cambrian gneiss/migmatite on its north, east, and southern sides with abundant *Cochlearia groenlandica*. The catchment vegetation is mapped as the NATZ. Reindeer droppings were abundant and there was extensive filamentous algal growth in the outflow stream.

Lake O, 'Draba Pond' (unofficial name), Albert I Land, Spitsbergen

This is a small moraine-bounded pond surrounded by large cliffs of gneiss and limestone. The catchment is predominantly cliff, scree, and snow. There are many solifluction terraces running into the lake. The limited vegetation, containing three species of *Draba* (hence its informal name), is mapped as the NATZ. Small springs enter the lake below the extensive snow fields.

Lake P, 'Ossian North' (unofficial name), Oscar II Land, Spitsbergen

This lake is a deep kettle hole lying within a very young moraine system just above the Conwaybreen glacier. The underlying bedrock geology is Pre-Cambrian gneiss/migmatite. The catchment is almost entirely boulder fields and scree. The very sparse vegetation belongs to the NATZ. Sediments within the lake are restricted to small pockets between boulders.

Lake Q, Ytertjørna, Oscar II Land, Spitsbergen

This shallow lake (Figure 2F) lies in a bedrock depression within the extensive strandflat on the northern side of Isfjorden. The bedrock geology is mapped as crystalline late Proterozoic basement complex. The catchment is well vegetated and belongs to the NATZ zone with extensive moss-dominated areas by the lake.

Lake R, Spålen, Oscar II Land, Spitsbergen

This lake is similar to lake Q in its geology and vegetation. It is shallower and lies within a series of beach-ridges within the strandflat.

Lake S, Vassauga, Nordenskiöld Land, Spitsbergen

This shallow strandflat lake lies within a series of beach-ridges. The bedrock geology is the Bellsund Group late Pre-Cambrian basement rock and the Billefjorden Group of the early Carboniferous. The catchment is very flat and consists of extensive tundra belonging to the NATZ with a large number of species. Reindeer were observed grazing around the lake.

Lake T, Daltjørna, Wedel Jarlsberg Land, Spitsbergen

This deep lake is surrounded by steep bird cliffs on its western and southern sides and by glacial moraines on the eastern side. The catchment is predominantly bare ground, mainly boulder fields and screes. The bedrock geology is late Pre-Cambrian basement and diamictite. The limited catchment vegetation belongs to the NATZ. There is evidence of local human presence with tin cans and other waste near the seepage out-flow on the northern side. Reindeer were present.

Lake U, Tenndammen, Nordenskiöld Land, Spitsbergen

This shallow lake was selected because of its proximity to the former mining areas in Colesdalen and the settlement at Colesbukta. The bedrock geology is Palaeocene – Eocene sandstone, shale, and coal seams. The catchment has a subdued topography and the lake is surrounded by mires with abundant *Eriophorum scheuchzeri* around the northern and western shores, through which the outflow drains to the sea. There is extensive evidence for former human impact around the lake in the form of a former water pumphouse that provided water to Colesbukta, and large amounts of associated buildings and piping debris (Figure 2C). The catchment is well vegetated with tundra belonging to the MATZ.

Arresjøen, Danskøya

This large deep lake is bounded by cliffs on its northern, eastern, and southern sides and the catchment is almost totally barren rock or snow (Figure 2D). The bedrock geology is Pre-Cambrian gneiss/migmatite. The vegetation is mapped as the NATZ, but it is in reality arctic polar desert. Arctic char occur in the lake.

Birgervatnet, Albert I Land, Spitsbergen

This deep lake receives glacial melt-water from Birgerbreen on the south-eastern and southern shores of the lake. Besides glacial ice, the rest of the catchment is bare rock and snow. The bedrock geology is mapped as Pre-Cambrian gneiss/migmatite. At the time of water sampling (6 August 1995) about 98% of the lake was still covered by ice and snow. Reindeer were abundant. The vegetation is arctic polar desert.

'Scurvy Pond' (unofficial name), Haakon VII Land, Spitsbergen

This small shallow pond lies in a rock bar in the outflow plain of the massive Richardvatnet on the east side of Raudfjorden. The bedrock geology is Devonian sandstone. The catchment is very open, consisting mainly of rock desert and screes. There are extensive areas of patterned ground around the lake. The vegetation is mapped as the NATZ.

Water chemistry

Lake L was deleted because it was not possible to obtain any surface sediments from the lake (Table 2) and because its water chemistry (Table 3) is totally different from the rest of the lakes sampled, with extremely high concentrations of Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, and Cl^{-}. It is likely that there is trapped seawater in the basin. The remaining 23 lakes (Tables 2 and 3) are generally circum-neutral or base-rich with high Ca^{2+} (range = 20 - 3004 μeq l^{-1}, median = 145 μeq l^{-1}) and Mg^{2+} (22.2 - 930.4 μeq l^{-1}, 83,9 μeq l^{-1}) concentrations, and high pH (5.6 - 8.4, 6.86) and alkalinity (36 - 1311 μeq l^{-1}, 120 μeq l^{-1}). The concentrations of Na^{+} (43.5 - 2127 μeq l^{-1}, 126 μeq l^{-1}, Cl^{-} (35.9 - 2342 μeq l^{-1}, 96.3 μeq l^{-1}), and SO_4^{2-} (7.3 - 1226 μeq l^{-1}, 27.1 μeq l^{-1}) are very variable and depend, in part, on proximity to the sea, exposure, geology, and landscape type with higher values generally occurring in strandflat lakes near the sea. The nutrient-related variables suggest that the lakes are generally nutrient-poor with low chlorophyll *a* (0.0001 - 1.4 µg l^{-1}, 0.0009 µg l^{-1}), nitrate (0 - 7.4 µeq l^{-1}, 0.6 µeq l^{-1}), and total dissolved P (2.7 – 395.7 µg l^{-1}, 4.7 µg l^{-1} values). Principal components analysis (PCA) of the water chemistry data (14 variables) from the 23 lakes (Figure 3) shows a strong co-variance with variables such as conductivity, pH, Mg^{2+}, SO_4^{2-}, Ca^{2+}, alkalinity, NO_3^-, and K^+. These variables dominate PCA axis 1 (42.4% of the total variance) and contrast base-rich lakes (A, B, C, P, Q, R, S, T) with base-poor lakes. PCA axis 2 (19.7 % of the total variance) has high loadings for total dissolved P, chlorophyll *a*, Mn^{2+}, Na^+, Cl^-, and Fe^{3+} and separates lakes O and U from the rest. The PCA results suggest that three broad groups of lakes can be defined on the basis of their water chemistry – Group 1 (lakes A, B, C, P, Q, R, S, T) with high alkalinity, conductivity, Ca^{2+}, Mg^{2+}, and pH; Group 2 (lakes D, E, F, G, H, I, J, K, M, N, Arresjøen, Birgervatnet, 'Scurvy Pond') with low pH, Mg^{2+}, Ca^{2+}, alkalinity, and conductivity; and Group 3 (lakes O and U) with high total dissolved P, Mn^{2+}, and chlorophyll *a* concentrations (Figure 3).

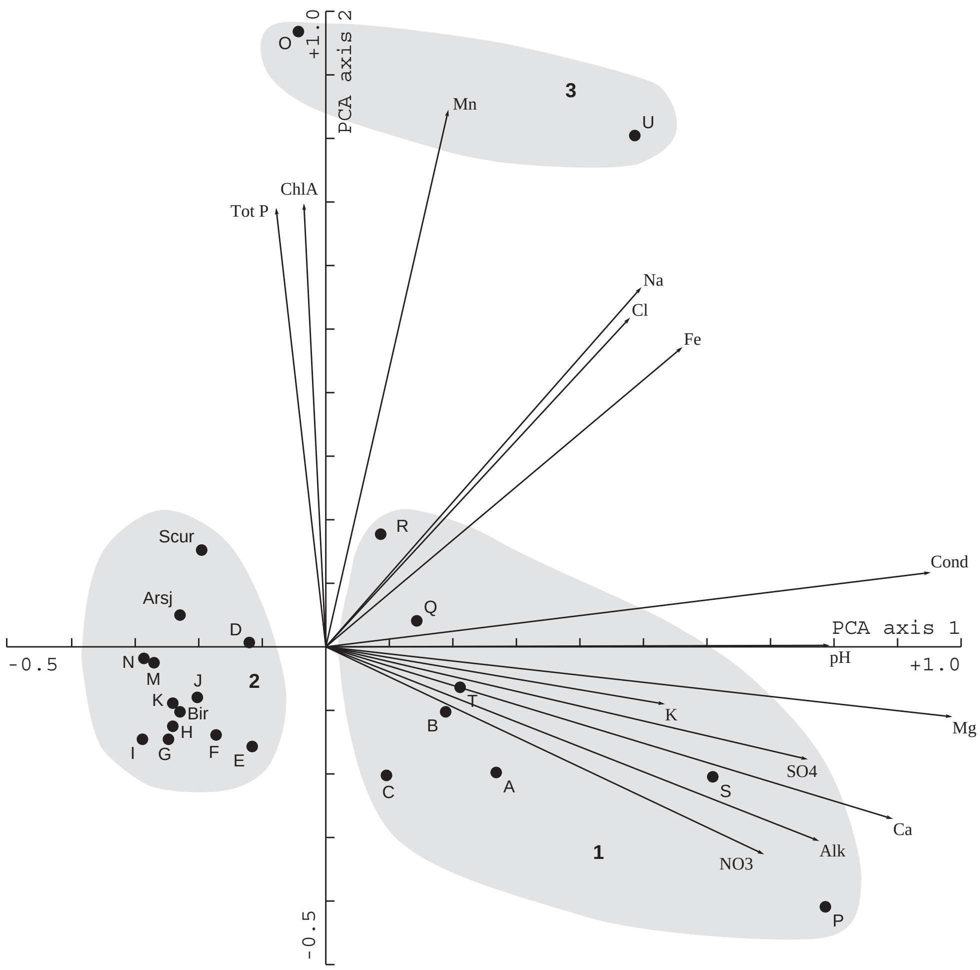

Figure 3. Plot of the 23 Svalbard lakes on PCA axes 1 and 2. The 14 chemical variables are shown as biplot arrows and the scaling used is correlation biplot scaling. The three lake groups (Groups 1, 2, 3) are shaded. Abbreviations: Cond. = conductivity, Alk = alkalinity, N03 = NO_3^-, SO4 =SO_4^{2-}, ChlA = chlorophyll *a*, Tot P = total dissolved P, Scur = 'Scurvy Pond', Arsj = Arresjøen, Bir = Birgervatnet.

Redundancy analysis (RDA) with the 14 lake-water chemistry variables as 'responses' and the 17 catchment, geographical, and other limnological variables (Tables 1, 3, and 4) as 'predictors' shows that 59% of the variance in the chemistry data can be explained by the catchment and related variables on RDA axes 1 and 2 (Table 6). Both axes are statistically significant (p = 0.005), as assessed by 199 unrestricted Monte Carlo permutations. The close correspondence between the eigenvalues of the PCA and RDA of the water chemistry data (Table 6) indicates that the major patterns of variation in the chemical variables are captured by the catchment and related variables. Group 1 lakes (high alkalinity, pH, etc.) are associated in the RDA with strandflat landscape, high vegetational cover in the catchment, and the occurrence of carbonate-rich bedrock in the catchment (Figure 4). Group 2 lakes (low pH, etc.) are deep, occur on granitic bedrock, had much snow in their catchments at the time of sampling, low bird presence and little or no evidence for human activity, and generally occur at high latitudes. The two Group 3 lakes (high total dissolved P, etc.) occur at very low altitude, and have high bird impact and evidence for human activity in the catchment. In an attempt to develop a 'minimal adequate model' with as few predictor variables as possible, forward selection of predictors in RDA was done, with the statistical significance of each predictor assessed by 999 unrestricted Monte Carlo permutation tests and the significance level adjusted by a Bonferroni correction for simultaneous tests (Legendre and Legendre 1998). Only two predictor variables are statistically significant ($P < 0.05$), longitude (explaining 29% of the variance in the chemical data) followed by the presence or absence of carbonate bedrock (15%) (Table 6). Longitude is highly correlated in the full RDA (Figure 4) with variables such as high vegetation cover and strandflat, and is acting as a composite variable for the complex of high vegetation cover, strandflat landscape, low snow cover, and low water depth. If the geographical variables of latitude and longitude are treated as covariables and their explanatory power is partialled out in a partial RDA, the only statistically significant predictor is carbonate bedrock, explaining 20.1% of the residual variance (0.62).

Table 6. Summary of the PCA and RDA results of the lake-water chemistry data (23 lakes).

	Axes 1	Axes 2	Axes 3
PCA 14 chemical values			
Eigenvalue	0.42	0.20	0.15
% variance explained	42.2	19.7	15.0
RDA 14 chemical variables & 17 predictor variables			
Eigenvalue	0.41	0.19	0.14
% variance explained	40.6	18.8	14.4
Response-predictor correlation	0.98	0.98	0.98
Monte Carlo permutation p-value	0.005	0.005	0.01
RDA 14 chemical variables & 2 predictor variables selected in forward selection			
Eigenvalues	0.32	0.12	0.22
% variance explained	32.4	11.7	-
Response-predictor correlation	0.90	0.87	-
Monte Carlo permutation p-value (Bonferroni corrected)	0.0001	0.005	-

The PCA and RDA results suggest that there are three major groups of lakes based on their water chemistry and that these groups result from the geographical positions and geomorphological and geological settings of the lakes and their catchments.

Modern flora and vegetation

A preliminary correspondence analysis (CA) of the floristic data (Table 7, plots not presented) indicates that the major compositional gradient is between the flora of the catchments of lakes A, B, Q, and R with high cover, frequent grasses, and abundant *Saxifraga hirculus* and the flora of the catchments of the other lakes (except lake C) with low plant cover and low amounts of species such as *Saxifraga rivularis, S. hyperborea, Cochlearia groenlandica, Phippsia algida,* and *Sagina nivalis*. The rich flora in the catchment of lake C is very different, with species such as *Carex rupestris, C. nardina, Cassiope tetragona, Dryas octopetala, Luzula arcuata,* and *L. arctica*. There is a group of species that occur in almost all catchments (Table 5) (e.g. *Salix polaris, Oxyria digyna, Poa alpina, Saxifraga oppositifolia, Cerastium arcticum, Luzula confusa*). The first two CA axes represent 34% of the total variance (Table 7).

Table 7. Summary of the CA and CCA results of the lake-catchment floristic data (19 catchments)

	Axes		
	1	2	3
CA 76 species			
Eigenvalues	0.34	0.23	0.22
% variance ('inertia') explained	20.4	13.6	13.4
CCA 76 species and 15 predictor variables			
Eigenvalues	0.33	0.22	0.20
% variance ('inertia') explained	19.9	13.3	11.8
Species-predictor correlation	0.99	0.99	0.95
Monte Carlo permutation p-value	0.005	0.005	0.005
CCA 76 species and 3 predictor values selected in forward selection			
Eigenvalue	0.29	0.18	0.09
% variance ('inertia') explained	17.6	10.9	5.5
Species-predictor correlation	0.95	0.93	0.84
Monte Carlo permutation p-value (Bonferroni corrected)	0.0001	0.005	0.03

The similarity of the CA and the canonical correspondence analysis (CCA) results (Table 7) suggests that the predictor variables used in the CCA explain well, in a statistical sense, the major gradients in floristic composition represented by the first few CA axes. The major floristic gradient (Figure 5) reflects the environmental difference between some strandflat lakes (A, B, Q, R) with high vegetation cover, high pH, high bird impact, and carbonate-rich bedrock in their catchment (see Figure 2D) and lakes with low vegetation cover, high snow cover and bare ground, and low lake-water pH on granite bedrock, and at relatively high latitudes (lakes D, E, F, G, H, I, J, K, L, M, N, O, Birgervatnet, 'Scurvy Pond') (see Figures 2B, 2C). The group of four strandflat lakes has frequent *Saxifraga hirculus,* a range of grasses such as *Festuca rubra, F. vivipara, F. hyperborea, F. brachyphylla*, and *Dupontia pelligera*, localised occurrences of *Saxifraga hieracifolia* and *Chrysosplenium tetrandrum*, and an abundance of common plants such as *Salix polaris, Saxifraga oppositifolia,* and *Luzula confusa.* These lakes all lie within the northern arctic-tundra zone (NATZ) (Elvebakk 1997). In contrast the group of 14 lakes has a very limited flora of *Saxifraga rivularis, S. hyperborea, S. foliolosa, Phippsia algida, Draba alpina, Papaver dahlianum, Stellaria humifusa, Cochlearia groenlandica,* and *Koenigia islandica.* These lakes have catchment vegetation of either arctic polar desert (lakes D, E, I, K, Birgervatnet) or the NATZ (lakes F, G, H, J, L, M, N, O, 'Scurvy Pond'). The middle arctic-tundra zone (MATZ) lake C (Figure 2A) with its rich flora including *Dryas octopetala, Carex rupestris, C. nardina, Empetrum nigrum,* and *Cassiope tetragona* is positioned by itself in Figure 5 and is characterised by its relatively higher altitude (60 m) and distance from sea, high lake-water pH, and carbonate-rich bedrock.

Forward selection of the predictor variables within CCA (ter Braak and Šmilauer 1998) shows that only three variables are statistically significant (Table 7); lake-water pH (explaining 15% of the total floristic variance), altitude (10.8%), and latitude (7.8%). These three variables characterise the three main types of catchment floras, namely fertile strandflat catchments (see Figure 2D) resulting in high lake-water pH, polar desert or sparse NATZ catchments (see Figures 2B, 2C) generally in the far north and with low lake-water pH and the rich MATZ flora of lake C (Ossian Sarsefjellet) at an altitude of 60 m (see Figure 2A).

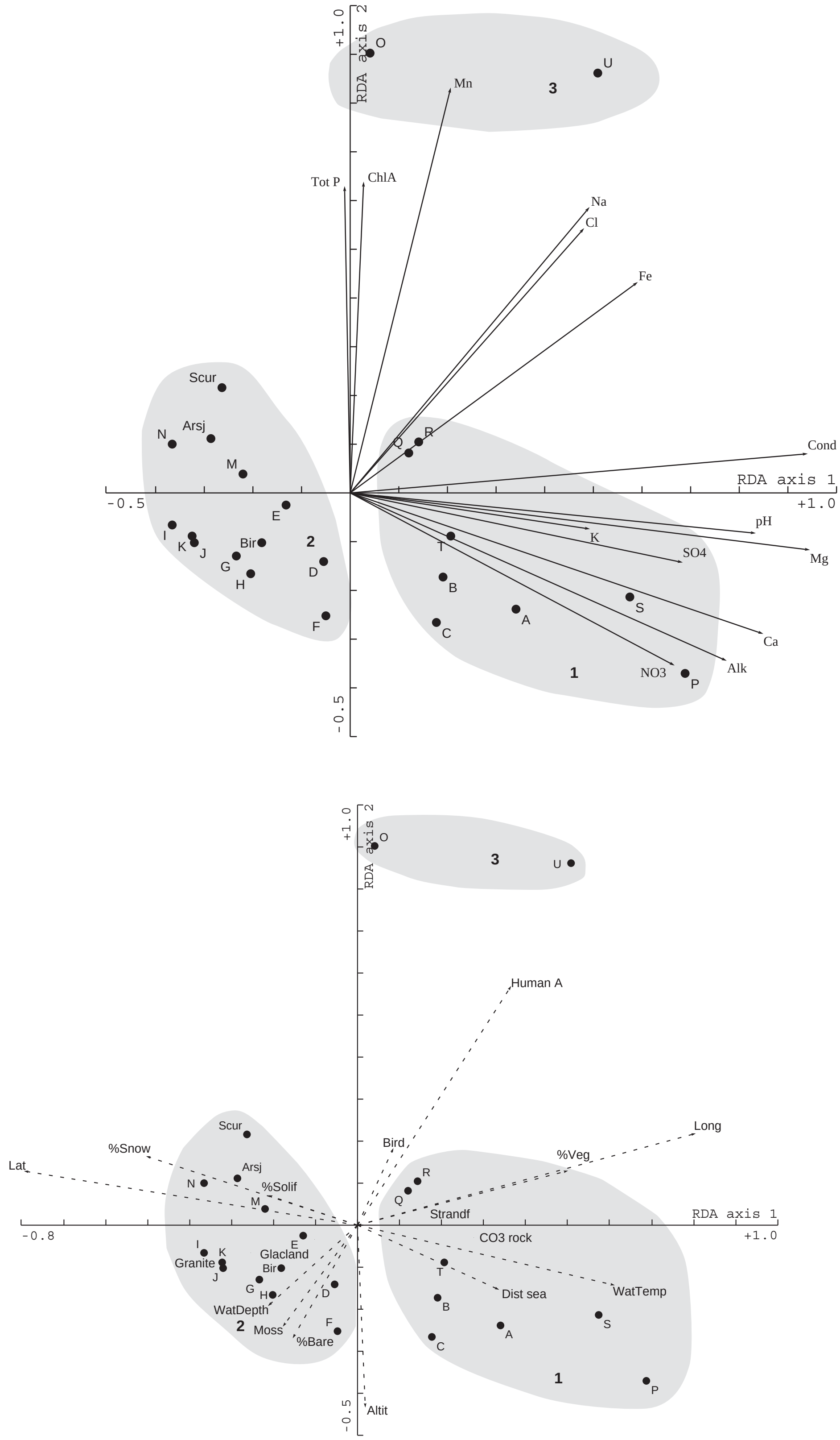

Figure 4. Plot of the 23 Svalbard lakes on RDA axes 1 and 2. The 14 chemical variables are shown as biplot arrows (upper plot). The 17 catchment, and geographical variables (lower plot) are shown as biplot arrows (quantitative variables) or as centroids (nominal variables). The three lake groups defined on the basis of the PCA of the chemistry data are shaded. The scaling is correlation biplot scaling. Abbreviations as in Figure 3, with the addition of Lat = latitude, % Solif = % solifluction, Glacland = glaciated landscape, WatDepth = water depth, Altit = altitude, Human A = human activity, Bird = bird presence, Long = longitude, % Veg = % vegetation, Strandf = strandflat landscape, dist sea = distance from sea, WatTemp = water temperature, CO3 rock = carbonate bedrock.

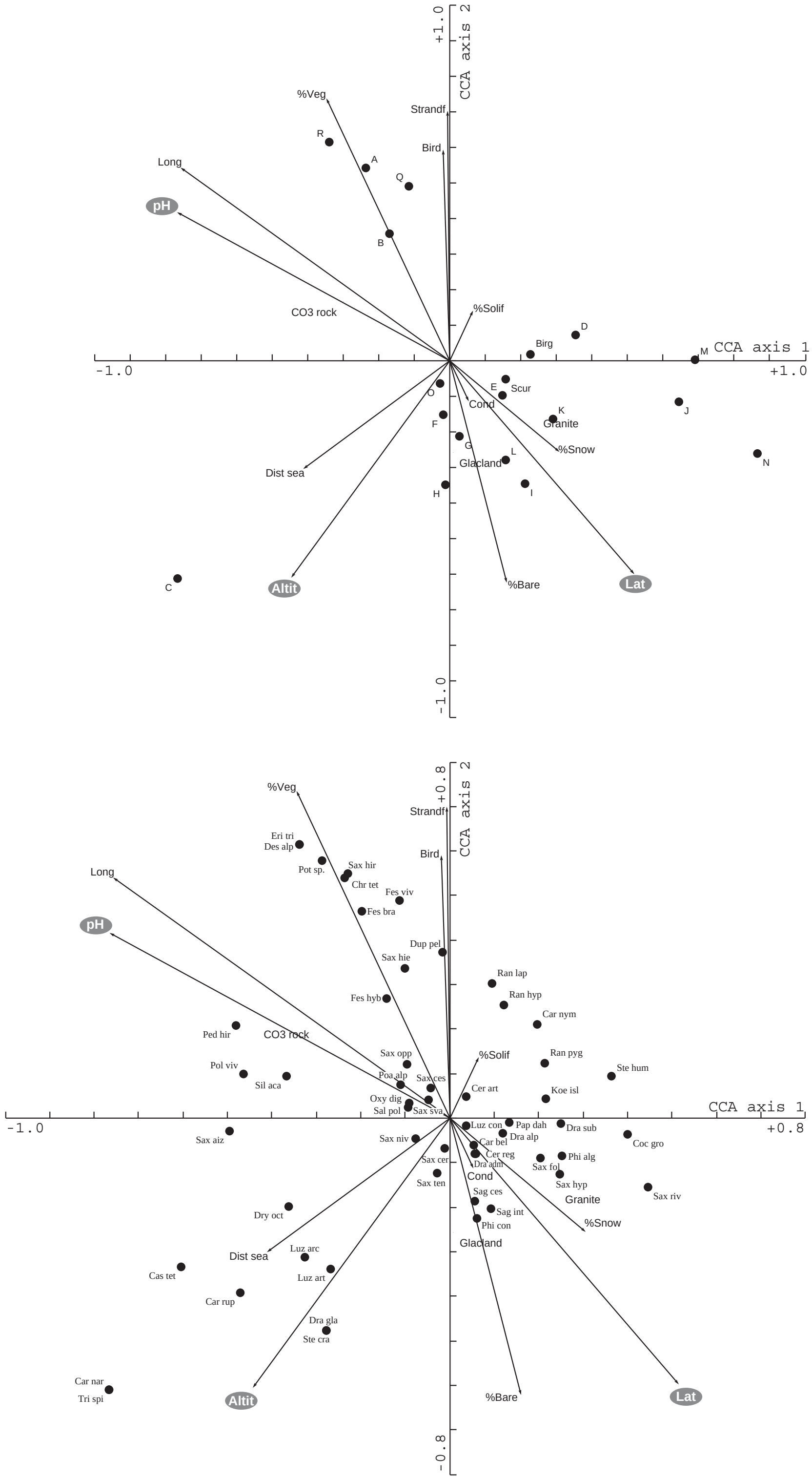

Figure 5. Plot of 19 lake catchments on CCA axes 1 and 2 based on the floristic composition of the catchments (76 taxa) and 15 catchment 'predictor' variables. Selected plant species (those with an effective number of occurrences (N2) of 2 or more) are shown in the lower plot in relation to the 15 catchment variables, whereas the 19 catchments are shown in the upper plot in relation to the catchment variables. The catchment variables are shown as biplot arrows (quantitative variables) or as centroids (nominal variables). The scaling is correlation biplot scaling, the lake scores plotted are linear combinations of the predictor variables, and the species scores are scaled to be weighted mean lake scores. Abbreviations are as in Figures 3 and 4 for the lake names and predictor variables. Taxon abbreviations are the first three letters of the genus name and the species name as given in Table 5. The three catchment variables (Latitude (Lat), altitude (Altit), and pH) chosen in forward selection are highlighted.

The scale of sampling in this study, namely the flora and vegetation of lake catchments, lies between the broad scale of the major vegetation zones such as the northern arctic-tundra and arctic polar desert zones (Elvebakk 1997) and the fine scale of individual quadrats used in the delimitation and definition of plant associations and alliances (Elvebakk 1994) or in the study of local-scale diversity (Jónsdóttir 2002; Eide et al. 2002). Several plant associations may be present within a catchment and their distribution within a catchment is often primarily determined by topography. This, in turn, can influence hydrology, local temperatures, wind exposure, snow-lie, availability of cliffs for birds, surface slope stability, and the extent of frost-heaving and solifluction, all of which can result in different vegetation types (e.g. Virtanen and Eurola 1997; Virtanen et al. 1997; Rønning 1969; Nimis 1985). In contrast, the broad-scale vegetation zones are primarily determined by climate, in particular aspects of growing-season temperatures (Elvebakk 1997). The patterns of variation in the floristic composition at the catchment scale appear to be determined by a combination of regional climate (represented indirectly in Figure 5 by latitude and altitude) and bedrock geology (granite or carbonate-rich rocks on Figure 5). Elvebakk (1982) discusses the importance of bedrock geology in determining the occurrence and abundance of many species on Svalbard. Of the 28 species of vascular plant considered by Elvebakk (1982), three are clearly basiphilous, ten are circumneutral, nine are indifferent, and six are acidophilous in their soil preferences. In addition to soil base-status, which is primarily a function of bedrock geology, nutrients, such as nitrogen and phosphorus, have a marked effect on arctic vegetation. This is shown most dramatically by the spectacular and luxuriant vegetation on and just below 'bird cliffs' on Svalbard (e.g. Elvebakk 1997; Rønning 1996; Eurola and Hakala 1977; Odasz 1994) with an abundance of *Cochlearia groenlandica, Oxyria digyna, Poa alpigena,* and *Phippsia algida*, and a great dominance of mosses and lichens. As nitrogen and phosphorus are generally in short supply in arctic ecosystems, it is not surprising that there is a strong correlation between % vegetation cover, bird impact, carbonate-rich bedrock, lake-water pH, and the occurrence of several grasses and herbs (Figure 5). The major patterns of floristic composition at the catchment scale are thus determined by climate, base-status, and nutrient levels.

Modern pollen assemblages

The twenty surface sediments (lakes A - K, M - U) examined for pollen and spores generally have a very low pollen concentration. Only eleven of the samples contained pollen and spores in sufficient quantity to allow pollen counts of 150 - 225 grains. A total of 45 pollen types, three pteridophyte spore types, and one bryophyte (*Sphagnum*) spore type were found, along with some indeterminable (mainly degraded and corroded types) and a few unknown types. Of the 49 identified microfossil taxa, only twelve are from plant taxa that do not grow on Svalbard today (*Alnus, Betula, Corylus, Pinus, Quercus, Lotus*-type, *Thalictrum,* Umbelliferae*, Urtica*-type, *Lycopodium* (reticulate), *Artemisia,* Chenopodiaceae). These are almost certainly far-distance transported from areas further south, probably Fennoscandia (Johansen and Hafsten 1988), and represent the extra-regional component (sensu Janssen 1984) of pollen deposition on Svalbard. This extra-regional component ranges from 2% to 25% of the total pollen assemblage. Some pre-Quaternary microspores were found in three of the surface sediments (lakes C, Q, U), presumably derived from glacial till or pre-Quaternary sedimentary rocks in the lake catchments.

A two-way indicator species analysis (TWINSPAN; Hill 1979) of the modern pollen data using default pseudospecies cut levels, strict convergence criteria, and other default settings suggests that three groups of modern pollen assemblages can be distinguished. The modern pollen spectra are arranged in Figure 6 on the basis of the TWINSPAN classification and ordering. Group 1 is characterised by abundant Brassicaceae and Poaceae pollen, presumably derived from *Cochlearia groenlandica* and grasses such as *Phippsia algida* and *Poa* spp. that dominate the vascular plant growth in the 'bird cliff' vegetation around lakes M and N. Group 2 consists of modern pollen spectra from seven lakes, four of which are strandflat sites (lakes A, B, Q, and S) with well-vegetated catchments (50 - 100%) (see Figure 2D). The modern pollen assemblages in this group are dominated by *Oxyria digyna* pollen, a locally frequent wind-pollinated plant in a range of habitats on Svalbard, along with 5 - 25% *Salix* pollen, presumably derived from the almost ubiquitous and abundant dwarf-willow *S. polaris*. Poaceae, *Cerastium alpinum*-type, and *Saxifraga* (mainly *S. oppositifolia/S. aizoides*) pollen are also frequent and attain values up to 5 - 20%. A range of other dwarf-shrub and herb pollen types (not shown on Figure 6) also occur but always in very low amounts and with only one or two occurrences, including *Empetrum nigrum,* Ericaceae-type, *Arenaria*-type, *Chrysosplenium, Pedicularis, Polygonum viviparum, Potentilla*-type, Juncaceae, *Sagina*, *Saxifraga* cf. *S. foliolosa*, and *Taraxacum*-type. The four strandflat lakes (A, B, Q, S) have higher percentages of *Oxyria digyna, Saxifraga oppositifolia/S. aizoides* and *Cerastium alpinum*-type pollen than the other three lakes in this group. It is surprising that the surface sediment from lake I contained pollen in countable concentrations as its catchment is almost barren of vegetation (Figure 2C). The catchments of lakes G and H (Figure 2B) have slightly more vegetation than the catchment of lake I. In contrast, surface sediments from some of the lakes with well-vegetated catchments (e.g. F, R, T) have such low pollen concentrations that they are effectively uncountable. The two pollen spectra in Group 3 (Figure 6) are characterised by high percentages of Poaceae, *Carex*-type, and *Salix* pollen. The two lakes in this group are totally different lake types, lake C (Figure 2A) and lake U (Figure 2E) but they are the only two lakes in the middle arctic-tundra zone (Table 1). The high Poaceae, *Carex*-type, Cyperaceae undiff., and *Salix* pollen values at U presumably reflect the abundance of mires with abundant grasses and sedges, and some dwarf willow in low-lying areas around the lake. The high Poaceae and *Carex*-type values at lake C are more surprising. Although grasses and sedges are locally frequent in the catchment of C (see Table 5), they are all low-growing dwarf plants (e.g. *Carex rupestris, C. nardina, Poa arctica, Trisetum spicatum*) and are not expected to produce or disperse much pollen. Interestingly, pollen catches in a Burkard trap during 1986 at Ny-Ålesund (Johansen and Hafsten 1988) closely resemble the modern pollen assemblages in Groups 1 and 2, with much local and regional *Salix, Oxyria digyna,* and *Saxifraga* pollen and about 10% extra-regional pollen of *Betula, Pinus, Alnus*, and *Juniperus*.

The frequency and values of *Huperzia selago* and *Dryopteris*-type spores in the modern assemblages (Figure 6) are surprising, in light of how infrequently the relevant spore-producing plants were found in the vegetation of the lake catchments. It is possible that some of these spores may be far-distance transported (cf. van der Knaap 1987a, 1988a). The comparatively low (2 - 25%) percentages of the presumed extra-regional component (Figure 6) contrast with values of up to 80% extra-regional pollen in Holocene lake sediments from northern Svalbard (Hyvärinen 1970) and on Bjørnøya (Hyvärinen 1968). The low diversity (12 taxa) of the extra-regional component in the eleven lakes studied here contrasts with the high diversity (63) of taxa resulting from far-distance transport found in peats and surface mosses on Spitsbergen and Jan Mayen Island reported by van der Knaap (1987a, 1987b, 1988a, 1988b, 1991).

The most important palynological feature of the modern pollen samples is the absence of countable pollen in nine of the twenty samples. For the eleven countable samples, the major features are the low percentages of extra-regional pollen, the high values of local and extra-local pollen (Janssen 1984) such as Brassicaceae, *Oxyria digyna*, *Saxifraga,* and *Salix*, and the occasional occurrence of pollen types from low-growing arctic herbs and dwarf-shrubs such as *Chrysosplenium, Arenaria*-type, *Sagina, Empetrum nigrum,* and *Ranunculus hyperboreus*-type (cf. van der Knaap 1990). It is possible that some of these pollen types are transported into lakes by melt water and run-off rather than by wind dispersal (van der Knaap 1990). The absence of pollen in 45% of the samples and the generally low pollen concentrations in the remaining 55% highlight the difficulties of pollen analysis on Svalbard as a tool for reconstructing past vegetational and environmental history (Birks 1991).

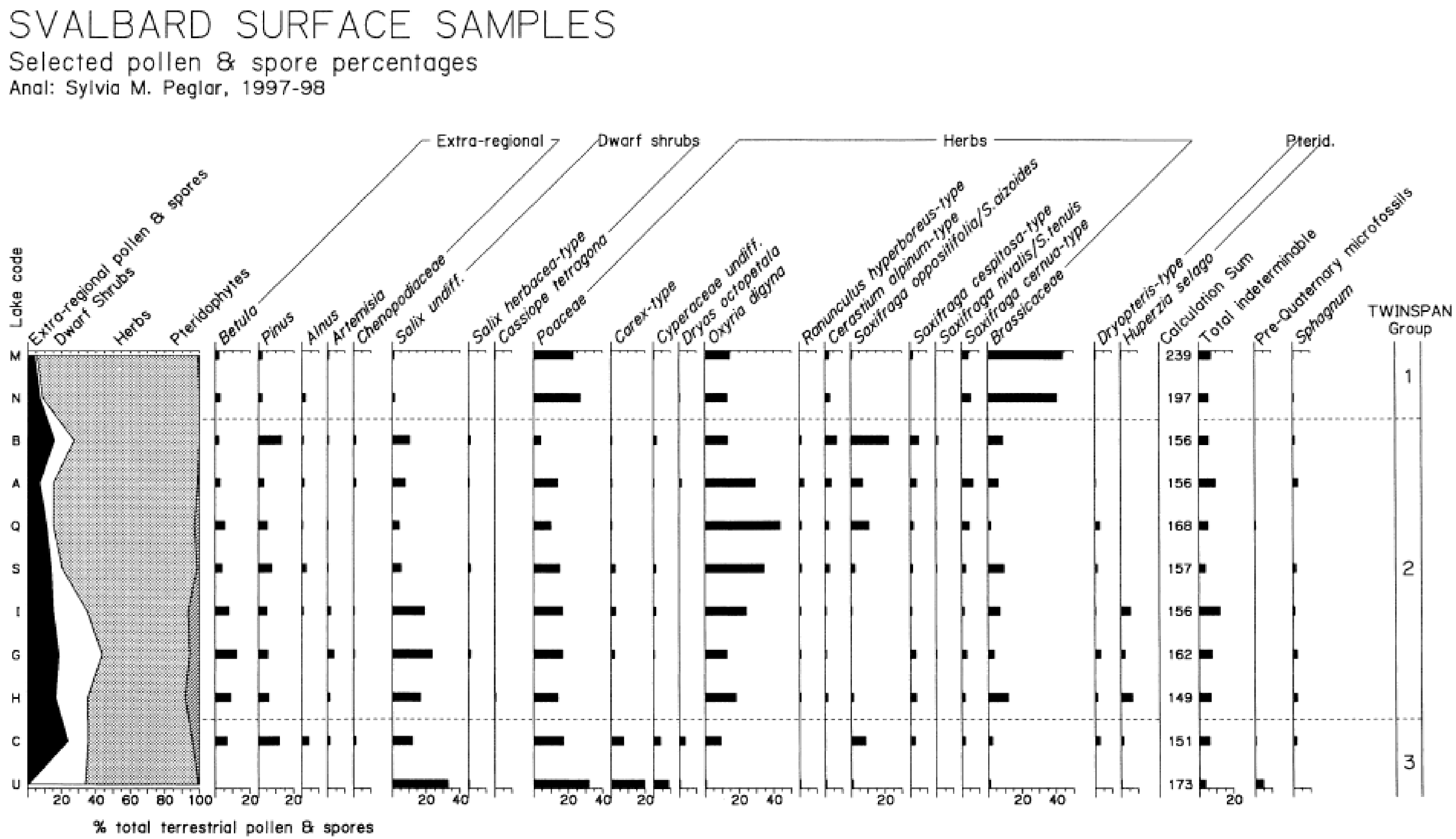

Figure 6. Modern pollen assemblages from eleven lakes on Svalbard. The lakes are arranged in the order suggested by a TWINSPAN of the pollen data. Only selected pollen and spore taxa are shown. All taxa are expressed as percentages of total terrestrial pollen and spores (Calculation sum).

Conclusions

The conclusions from this primarily descriptive account are as follows.

(1) Three distinctive groups of lakes on Svalbard can be distinguished on the basis of their water chemistry. Group 1 lakes have relatively high conductivity, alkalinity, Ca^{2+}, Mg^{2+}, and pH values and occur on the strandflat, have high vegetation cover in the catchment, and carbonate-rich bedrock in their catchments. Group 2 lakes have low pH, conductivity, alkalinity, Ca^{2+}, and Mg^{2+} values and occur on granitic bedrock, had much snow in their catchments in August 1995, and generally occur in northern Svalbard. Group 3 lakes have high total dissolved P, Mn^{2+}, and chlorophyll *a* concentrations and experience high bird impact or human disturbance. Of the simple catchment variables recorded, longitude and the presence (and absence) of carbonate bedrock provide a statistically significant explanation of the observed patterns in lake-water chemistry.

(2) Because of poor preservation or very low concentrations of fossils, not all the cores or core tops and bottoms collected were suitable for all palaeolimnological analyses (Table 2). The chironomid stratigraphies are from lakes C, Q, and U (Brooks and Birks 2004) that belong to lake chemistry Group 1 (C, Q) and Group 3 (U). The diatom stratigraphies (Jones and Birks 2004) are from lakes in Group 1 (Q, S), and Group 2 (Arresjøen, Birgervatnet, 'Scurvy Pond'). The chrysophyte cyst 'tops and bottoms' (Betts-Piper et al. 2004) are from lakes in all three groups, namely Group 1 (A, B), Group 2 (G, I, J, K, M, N), and Group 3 (O). Spheroidal carbonaceous particle stratigraphies (Rose et al. 2004) are from lakes in all three chemistry groups (Group 1 (C, Q, S, T), Group 2 (Arresjøen, Birgervatnet, 'Scurvy Pond'), Group 3 (U)). Sediment geochemical analyses (Boyle et al. 2004) similarly cover all three lake chemistry groups (Group 1 (C, Q, S, T), Group 2 (Arresjøen), and Group 3 (U).

(3) The major floristic gradients in the vascular-plant flora of the catchments of the lakes similarly reflect the distinction between sites on granite bedrock in northern Svalbard with high snow cover and bare ground in the catchment and sites with carbonate-rich bedrock, high vegetation cover, high bird impact, and high lake-water pH. One site, Ossian Sarsefjellet, has a different flora and this is probably a result of the lake catchment being in an inner-fjord setting and hence having warmer growing-season temperatures than in the outer-fjord coastal sites.

(4) Modern pollen assemblages from surface lake-sediments on Svalbard contain between 2 - 25% far-distance extra-regional pollen (mainly *Betula* and *Pinus*). The regional and local pollen deposition consists primarily of Poaceae, *Salix, Oxyria digyna*, and *Saxifraga* pollen. Local and extra-local deposition includes Brassicaceae and *Carex*-type pollen. The modern pollen assemblages primarily reflect catchment features such as the presence of 'bird cliffs' with their characteristic flora and vegetation, the presence of mires around the lakes, and the abundance of vegetation within the catchments.

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