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Dominant Factors Controlling Variability in the Ionic Composition of West Greenland Lakes*

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Abstract

Over 80 lakes were sampled between the ice margin and the coast in West Greenland between 66 and 67°N and analyzed for their pH, alkalinity, conductivity, and major ions. Most of the lakes (67%) are dilute, circumneutral, and have conductivity values <150 $\mu\text{S cm}^{-1}$. There are, however, also saline lakes (2000–4000 $\mu\text{S cm}^{-1}$; $\text{NaHCO}_3/\text{CO}_3$, and $\text{Mg HCO}_3/\text{CO}_3$ -dominated), mainly around the head of the fjord. The main control on lake chemistry in this area is evaporation as indicated by the fossil shorelines surrounding the saline lakes. The high concentrations of Na indicate extensive inputs from either weathering or from eolian-transported silts (loess) derived from the sand outwash plains at the ice sheet margin. The pattern of cation dominance in the freshwater lakes is $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$. Variability in the water chemistry and the dominant controls on water chemistry were examined using PCA and RDA, respectively. There is a clear gradient in lake chemistry from west to east. This trend reflects the split between the dilute coastal lakes (with higher %Cl) and the saline lakes close to the head of the fjord. Altitude is also significant and probably reflects reduced weathering rates at upland sites (~500 m) with limited vegetation cover. A number of lakes had high SO_4 concentrations (maximum >10,000 $\mu\text{eq L}^{-1}$) and were clearly influenced by local geology.

Introduction

Arctic lakes are tightly linked to climate both directly and via catchment inputs, and these links should be easy to identify, as anthropogenic disturbances are comparatively small. As a result, Arctic lakes are ideally suited to climate-lake interaction studies and paleoclimate studies. However, relatively little is known about Arctic lakes although there is an on-going, long-term study of Toolik Lake, Alaska (O'Brien et al., 1997) and several studies in the Canadian High Arctic (e.g., Ludlam, 1996; Pienitz et al., 1997). Compared even to these limited studies, little is known about contemporary ecology or chemistry of Greenland lakes, despite their abundance.

There are thousands of lakes in West Greenland between 66 and 67°N, which, at 180 km, is the widest ice-free area in Greenland today (Fig. 1). The best known lakes in this area are the saline lakes at the head of Søndre Strømfjord, which have been known for about 100 yr (Williams, 1991). Much less is known about other lake types, apart from the fact that they are oligotrophic and dilute (Böcher, 1949; Røen, 1962). Many of the Greenlandic lakes are closed-basin lakes, and are ideally suited to paleoclimate research as they record changing effective precipitation over long periods of time (Fritz, 1996). Strongly evaporative periods with low precipitation can result in lower lake levels, lake isolation and eventually enhanced salt concentrations (Fritz et al., 1991). The area is particularly important for paleoclimate research because of its proximity to both the Greenland ice sheet to the east and the Davis Straits to the west, the latter

an important area for the North Atlantic climate-ocean system (Anderson et al., 2000). The main aims of the present study were to collect reliable contemporary data and establish the current limnological setting of this area as a baseline to such studies.

We sampled over 100 lakes between the ice-sheet edge and the coast south of Sisimiut (Fig. 1). This area covers a present-day climate gradient from low-arctic continental to low-arctic maritime, with associated changes in vegetation and limnology. Here we report results on the major ion chemistry from a largely unstudied group of lakes and use the data to infer controls on their chemistry.

Study Area

Søndre Strømfjord is a 170-km long glacial fjord located in south west Greenland between 66 and 67°N and 50 and 55°W. The area at the head of the fjord is characterized by a Low Arctic continental climate with mean annual temperatures ca. -6°C (annual temperature range = 30°C), continuous permafrost, and low precipitation (<150 mm yr^{-1}). The zone from here to about half way between the coast and the ice sheet margin is characterized by very low (negative) effective precipitation. The coast is more maritime, with a reduced annual temperature range (~ 25°C) and higher precipitation (300 mm yr^{-1}). The lower summer temperatures and the presence of coastal fog banks means that snow persists longer here and snow packs are present into mid- to late July.

Throughout the region, vegetation is dwarf-shrub tundra with *Betula nana*, *Salix glauca*, *Vaccinium* spp., *Empetrum nigrum*, and various herbs and grasses as codominants. There is a slight change in vegetation towards the coast, where *Empetrum* is more common. Bare or sparsely vegetated rock/soil/moraine

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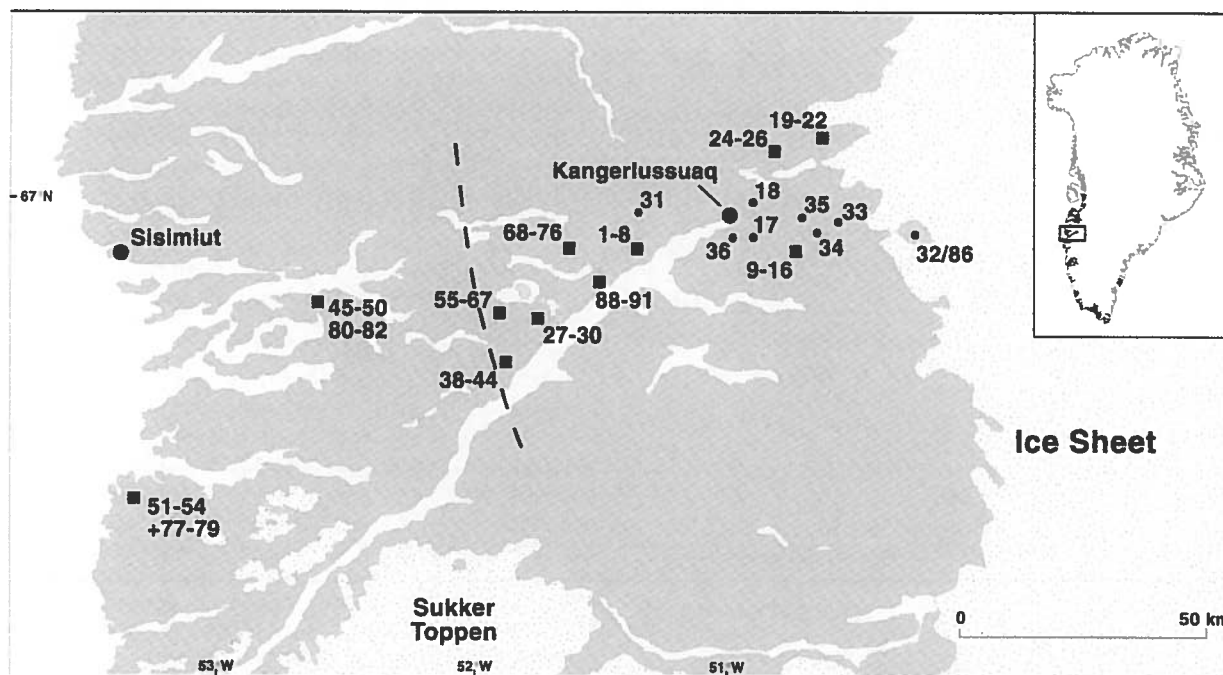


FIGURE 1. Location map showing an individual lake (●) or groups of lakes (■) in Western Greenland. The approximate position of the present-day limit of negative effective precipitation is indicated (- - -). Kangerlussuaq is the site of the airport and is also the name of the fjord in Greenlandic (Søndre Strømfjord in Danish).

areas are present throughout the region, and bare ground tends to increase with altitude. Due to the high evapotranspiration rates, many of the south-facing slopes have minimal vegetation cover, and there are abundant areas of bare soil and silt-loess deposits associated with eolian activity at the head of the fjord. More extensive vegetation cover is often associated with lake outflows and streams. The geology of the area is quite uniform and consists of granodioritic gneisses, with occasional outliers of marble. There is an increase in relief towards the coast, with a number of peaks >1200 m, which contrasts to the more "subdued" topography closer to the ice sheet.

STUDY LAKES

The study lakes are mainly small (most <50 ha), with depth ranging from ca. 2 to 67 m (Table 1). The sampled lakes cover an altitudinal gradient of around 550 m (Table 1). Shallow lakes (<2 m depth) were generally avoided as the ice thickness in this area (1.5–2 m) increases the possibility that they will freeze to the bottom. Many of the lakes stratify in the summer (N. J. Anderson, unpublished data), and a number are meromictic (Anderson et al., 1999). The lakes are frozen for nearly 9 months of the year: ice-out generally occurs in mid-June at the head of

the fjord (later at the coast) and the lakes refreeze around mid-to late September. Lake catchment areas are variable (but have not been quantified due to the poor map coverage), and not all the lakes are headwater lakes. Surface flow is limited in the summer throughout much of the study area, but particularly in the region from the ice-sheet margin up to ca. 80 km west. Many of the lakes have no direct surface inflow except for where one lake drains into another. Surface runoff tends to take place, if at all, during the spring melt period, when it percolates through the saturated zone as the soils thaw out. Likewise, for many other lakes, particularly close to the head of the fjord, outflows are seasonal, flowing in the early summer melt period but dry by the end of the summer. A number of the lakes are closed-basins, and the local topography precludes the presence of an outflow. None of the lakes have glacial melt water draining into them.

Methods

The sampled lakes mainly lie on the north side of the fjord and represent an east-west transect along the ice-free zone (Fig. 1). The two most easterly lakes (SS32 and SS86) are located on a nunatak, presently some ~5 km inside the present ice margin, and the most westerly are a few kilometers from the coast, about 35 km south of Sisimiut (Fig. 1). Between these two endpoints, the lakes are mainly clustered in groups, a sampling regime largely dictated by logistic constraints. Here we report results from 86 lakes sampled over five seasons between 1996 and the spring of 2000.

Water samples for chemical analysis were taken either from the center of the lake from a boat or from the littoral zone using waders. Samples were also taken through the ice (in April–May 1999 and May 2000), and in June 1999 and June 2000, lakes were visited prior to ice-out. In these situations samples were

TABLE 1
Summary of physical characteristics of 86 lakes

	Altitude (m)	Area (ha)	Maximum depth (m)	Area:Maximum depth
Mean	300.7	32.7	16.5	2.0
Maximum	595.0	184.0	67.0	10.4
Minimum	40.0	1.3	2.2	0.2

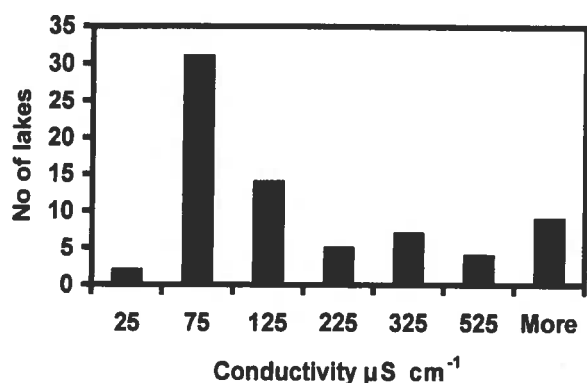


FIGURE 2. Frequency distribution of conductivity values in the sampled lakes.

taken from the ice-free moat that was present on most lakes. In general, the time of sampling varied between May and September. The sampling frequency was not constant for all lakes and therefore we present only mean data here. For some lakes there are only individual samples due to logistic constraints. The sampling density, therefore, was insufficient to address seasonality effects, and we do not consider it further here. However, given the conservative nature of major-ion chemistry in dilute lakes, it is not probably a significant problem.

Samples were kept cool while in the field (in the dark) and refrigerated prior to analysis. The first samples taken in August 1996 were frozen prior to analysis. These samples were analyzed at the Geological Survey of Denmark and Greenland (GEUS) laboratory and show good agreement with analyses from the Freshwater Fisheries Laboratory (Pitlochry) with the exception of pH. For those samples (analyzed at Pitlochry) where we have both alkalinity and pH, $\log(\text{alkalinity})$ is a very good predictor of pH ($n = 73$, $r^2 = 0.97$). $\log(\text{Alk})$ is used as a proxy for pH in further analyses, as not all sites have reliable pH measurements. All samples taken after 1998 were analyzed at Pitlochry. Water chemical analyses followed standard methods (see Harriman et al., 1990), with the exception that the major cations and anions were analysed using on a DIONEX DX 100 ion chromatography system. Conductivity values are calibrated to 20°C.

Results of the water chemistry analyses are presented as the

mean of all available sampling dates, and for the multivariate analyses (below) all data were log transformed after adjustment for zero or negative values where necessary. To identify major trends in the data and possible environmental controls, Principal Components Analysis (PCA) and Redundancy Analysis (RDA) analyses were performed using CANOCO 4 (ter Braak and Smlauer 1998), based on 86 sites with full major ion chemistry and 79 with full environmental data. For the RDA, where major trends in the species (chemistry) data are constrained by imposed environmental variables, the six variables used were: altitude (m), latitude, longitude (as a measure of distance along the sampled gradient), lake area (ha), maximum depth (m), and area: maximum depth. Transformations to reduce the effect of extreme values were applied to area and area:depth (log), and depth (square root). As vegetation and climate/weather primarily vary along the sampled gradient in an east-west direction, site location should account for most of the variability explained by these variables at the regional scale. This does not, of course, preclude the influence of vegetation variability at a more local, catchment scale (for which we have insufficient data). Significance of RDA ordinations was assessed using a Monte Carlo test with 499 permutations in all cases. Significance of explanatory variables was tested using Bonferroni-adjusted forward selection, regression coefficient t -values and the significance of the first axis 1 of single-variable RDAs.

Results

The majority of the lakes are dilute: approximately half of the lakes have conductivity $<100 \mu\text{S cm}^{-1}$, and $\sim 88\%$ of the lakes have conductivity $<500 \mu\text{S cm}^{-1}$ (Fig. 2). Ten lakes have conductivity values above $800 \mu\text{S cm}^{-1}$, and these are referred to as the "saline lakes" (Fig. 2; Table 2). Only two lakes, with $\text{pH} < 5.0$, have negative alkalinity. The water chemistry results are summarized in Table 2 and Figure 3. In general, cation dominance in the saline group was $\text{Na} > \text{Mg} > \text{K} > \text{Ca}$ (Fig. 3) and in dilute lakes, $\text{Ca} > \text{Mg} > \text{Na} > \text{K}$ (Fig. 3). Alkali metals ($\text{Na} + \text{K}$) and Mg are important in both fresh and saline lakes, accounting for 20 to 60% of the cation sum (Fig. 3). Saline lakes are most clearly separated from freshwaters by the relative importance of Ca, which in the saline group decreases from about 20% to $<5\%$ as conductivity increases.

TABLE 2

Summary of pH, conductivity, and major ion concentrations in saline and nonsaline lakes. The nonsaline means are also given excluding the high SO_4 groups of lakes (SS70-76)

	pH	Conductivity (S cm^{-1})	Alkalinity (eq L^{-1})	Cl (eq L^{-1})	SO_4 (eq L^{-1})	Ca (eq L^{-1})	K (eq L^{-1})	Mg (eq L^{-1})	Na (eq L^{-1})
All lakes									
Mean	7.45	388	1966	1478	548	669	433	1805	1778
Maximum	9.17	4072	19060	20279	10431	3676	4899	20906	25671
Minimum	4.91	20	-10	22	4	89	6	36	39
Saline means									
Mean	8.76	2387	11302	10827	3344	1697	3075	12296	13206
Nonsaline means									
Mean	7.28	160	774	304	278	587	108	506	335
Mean of freshwater lakes (excluding SS70-76)									
Mean	7.36	136	783	242	60	517	82	399	263
Mean of lakes SS70-76									
	6.90	756	1598	2285	3721	1932	787	3071	2707
Means of the nunatak lakes									
SS32	7.28	51	365	57	24	209	34	229	81
SS86	8.26	334	3061	498	3.5	1257	277	1956	619

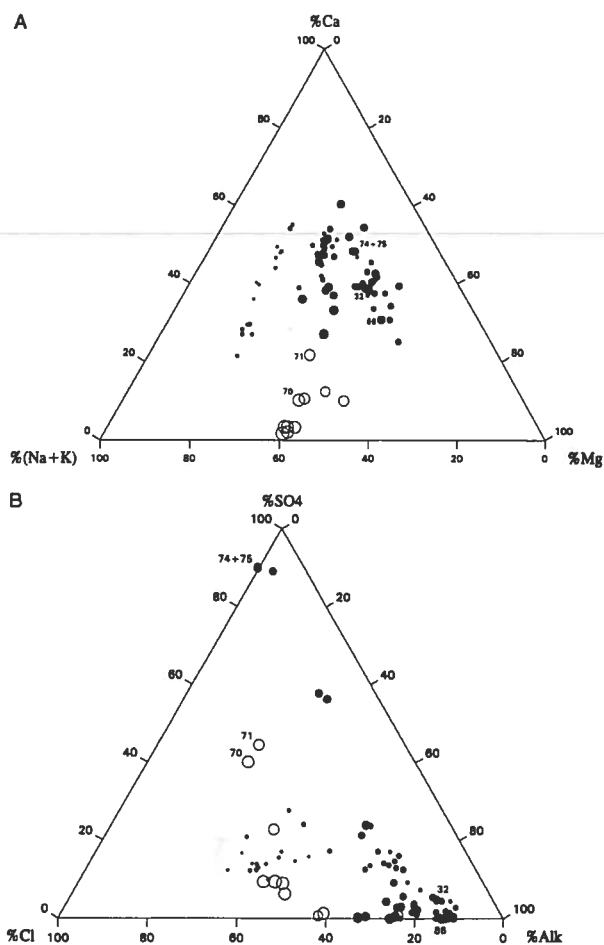


FIGURE 3. Major cations (A) and anions (B) expressed as a percentage of the cation or anion sum for 86 lakes, with symbols scaled according to lake conductivity. Saline lakes are shown as empty circles. Sites referred to in the text are labelled.

Alkalinity (mainly bicarbonate with some carbonate) is the dominant anion (up to 90%) in most freshwater lakes, with Cl and then SO_4 . Two of the saline lakes (SS70, SS71), some 80 km west of the ice sheet (Fig. 1) were different in that the dominant anion was SO_4 (ca. 10,000 $\mu\text{eq L}^{-1}$) and Na-Mg were of approximately equal dominance (ca. 12,000 $\mu\text{eq L}^{-1}$; 30–40% of cations). In the dilute lakes, anion abundance followed the pattern: $\text{HCO}_3 > \text{Cl} > \text{SO}_4$ (Fig. 3).

MULTIVARIATE ANALYSES: PCA AND RDA

The first two components of the 86-site PCA (Fig. 4a) explain nearly 90% of the variance in the major ion data and pH (1st eigenvalue: 0.788; 2nd = 0.106). Conductivity and the main cations (Ca, Na, K) and Cl are highly correlated with the first axis, as is alkalinity (Fig. 4a). SO_4 is weakly correlated with both axes. The PCA analysis reflects the major conductivity gradient in the sampled lakes: the saline lakes plot to the far right of the ordination. The PCA confirms this splitting of the lakes into three groups: a saline group (10 lakes), a large group of dilute lakes and a small but significant group of five lakes, high in SO_4 (Fig. 4a), two of which (lakes 74 and 75) are acid (pH < 5) and form a subset.

Even with the 10 saline lakes removed, the PCA results are

similar, with conductivity and most ions highly correlated on axis 1 (accounting for 63.4% of the variance, with axis 2 a further 19.2%). To explore more subtle variations in the dataset, further analyses were carried out on datasets with ions expressed as percent of cation or anion sum (log transformed for SO_4), but including conductivity (representing the dominant axis of concentration data PCAs) and alkalinity (for pH) (Fig. 4b). Axis 1 (explaining 36.9%) contrasts sites, plotting to the right, with high conductivity, alkalinity (pH), and cations dominated by K and Mg against sites with high percent of Ca and SO_4 on the left. Axis 2 (explaining 29.9%) separates sites where Na and Cl are important against those whose anions are dominated by bicarbonate alkalinity.

Constrained analysis (RDA) was carried out on the 69-lake %dataset (i.e., with saline sites removed) to explore relationships with broader-scale environmental parameters without the influence of the saline lakes (Fig. 4c). Six environmental variables account for 51.7% of the variation in chemistry data. The ordination as a whole and axes 1 and 2 individually are significant ($P < 0.01$). Axis 1 (explaining 36.7%) is highly correlated with increasing longitude (distance from ice sheet) and, less strongly, inversely with altitude and latitude, while axis 2 (explaining 8%) is highly correlated with lake depth. %Mg, %K, %Alk, and to a lesser extent conductivity increase with distance from the ice sheet, while %Na and %Cl increase towards the coast. The deepest lakes appear to have high % SO_4 (e.g., SS70, SS71).

Three variables (longitude, altitude, and depth) were found to be significant and together explain 46.3% of the data. Variance partitioning was performed to analyze the contributions of each component (unique effects, interactions of 2 or all 3 variables, and unexplained variance) (Table 3). While longitude is the most important variable (accounting for 28.8% of variance independent of altitude and depth), the interaction between altitude and longitude is significant (7.1%). Depth (uniquely 5.8%) is largely independent of the other variables. Very little variation (0.1%) is common to all three variables. A *t*-value biplot (not shown) can be used to infer which environmental variables contribute significant explanation for each chemical parameter (ter Braak and Smilauer, 1998). Results suggest that longitude explains significant variance for all chemical variables except % SO_4 and %Ca, altitude is correlated to conductivity, and depth is related to conductivity, %alkalinity, and % SO_4 . Thus of the 10 chemical parameters, only %Ca seems unrelated to any variables examined.

Both saline and nonsaline lakes at the head of the fjord have Cl concentrations above the regional mean (Fig. 5) although Cl (as % of total anions) shows a clear decrease away from the coast (Fig 5).

Discussion

CHEMICAL CHARACTERISTICS OF THE SALINE LAKES AND SOURCES OF SALINITY

The majority of the lakes in West Greenland are dilute (Fig. 2) and oligotrophic (Røen 1962, Ryves et al., 2001). The saline lakes have, however, received the most attention in the limited limnological studies that have been undertaken in this area. Technically, the West Greenland saline lakes are subsaline, falling in the range 0.5–3 g L^{-1} TDS (Williams 1991). In this study, we have included all lakes with conductivity above 800 $\mu\text{S cm}^{-1}$ as saline, as they share a similar ion chemistry, which is distinct from the dilute lakes (Table 2, Fig. 4a, b).

The Greenland saline lakes are interesting for a number of

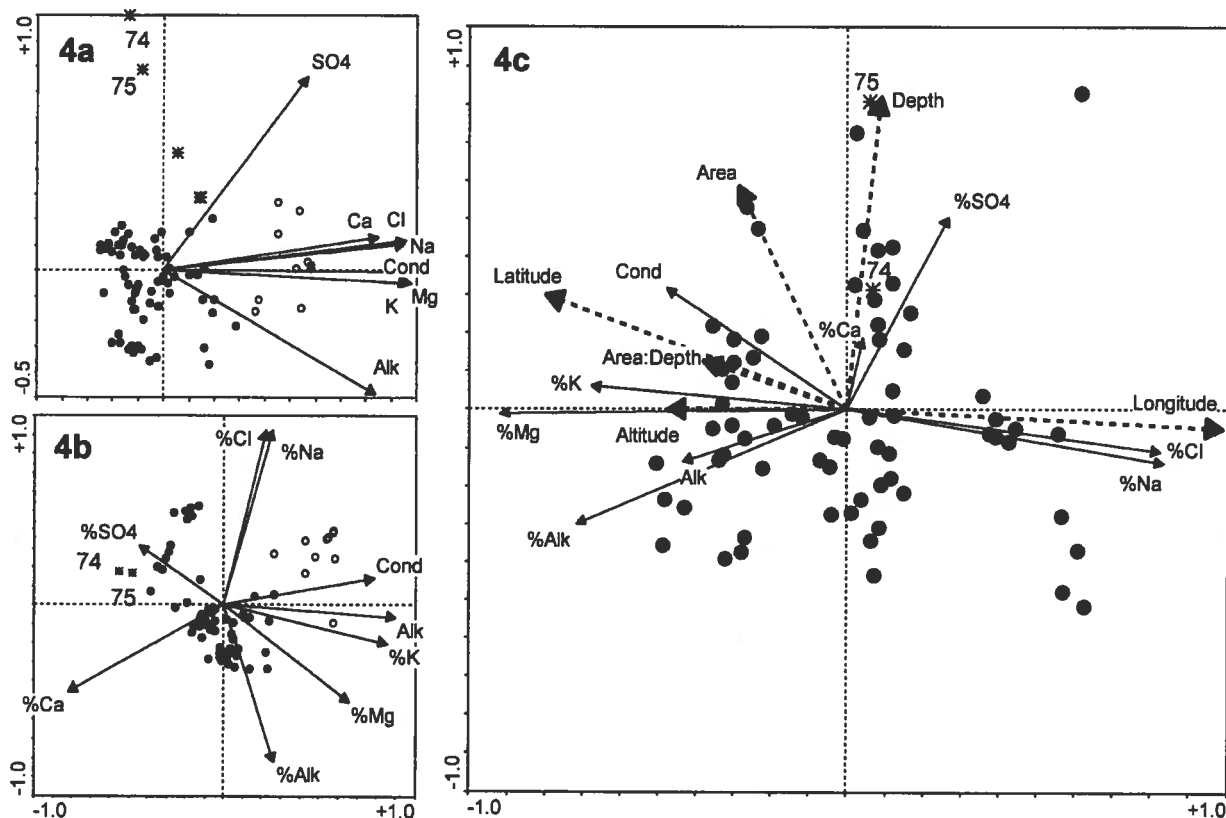


FIGURE 4. PCA and RDA ordinations of water chemistry data. Saline lakes are shown as empty circles (a, b). Sites 74 and 75 referred to in the text are labelled (*). Solid arrows (vectors) are chemical parameters. Values increase along vectors and parameter importance is proportional to vector length. Correlations between variables can be estimated by the cosine of their vectors. (a) 86 lake PCA of major ions and conductivity expressed as concentrations suggests 3 groupings of lakes (saline, dilute and high sulfate: *) (b) 79 lake PCA (excluding lakes 79–84, 87, 93) of major ions expressed as % data, with conductivity and alkalinity (for pH). (c) 69 lake RDA (excluding saline lakes) of % data as (b). Environmental variables constraining the chemistry data are drawn as dotted vectors.

TABLE 3

RDA Variance partitioning - 69 sites, 10 chemical parameters (%data)^a

Parameter	Components				
	Unique	Joint	Covariable		
Longitude (36%)	28.8	Longitude	Altitude	Depth	7.1
Altitude (11.6%)	4.4	Altitude	Depth	Longitude	0.0
Depth (6.0%)	5.8	Depth	Longitude	Altitude	0.1
				Common	0.1
Total	46.3				
Unexplained	53.7				

^a Variance (percentage) of chemistry dataset explained by three significant parameters (longitude, altitude, and depth). Value in parentheses is that explained in single-variable RDA. The total variance explained by all three parameters together can be split into several parts (components): that unique to each parameter, variance shared between two parameters (joint variance) with the third as covariable, and variance common to all parameters. All unique effects are significant at $P < 0.01$.

reasons including their chemical composition and the factors resulting in their formation. Saline lakes in both the Arctic and Antarctic are relatively common but are often formed by trapping marine water in isolation basins as the result of isostatic uplift (Burton, 1981; Ouellet et al., 1989). These tend to be considerably more saline than those occurring in West Greenland. All the saline lakes referred to here are at an altitude above the marine limit, which at the head of the fjord is about 60 m (half way out to the coast it is approximately 90 m). Therefore, there has to be an alternative explanation. Although our study confirms the results of earlier studies regarding the chemistry of saline lakes in the Søndre Strømfjord area (Hansen, 1969; Williams, 1991) (see below), we have identified a number of previously unknown saline lakes, including some farther to the west. Lakes with conductivity above the regional average (i.e. over $1000 \mu\text{S cm}^{-1}$) occur up to 80 km west of the ice margin. Our results suggest that they are moderately common.

The primary cause of the enhanced salinity observed in some of the closed-basin lakes is evaporation. The negative P-E balance at the head of the fjord is well known (see below). Further, albeit negative evidence, is the absence of saline lakes at the coast, where precipitation is higher. Although there are no available data, groundwater inputs/outputs are assumed to be small, because of the presence of permafrost.

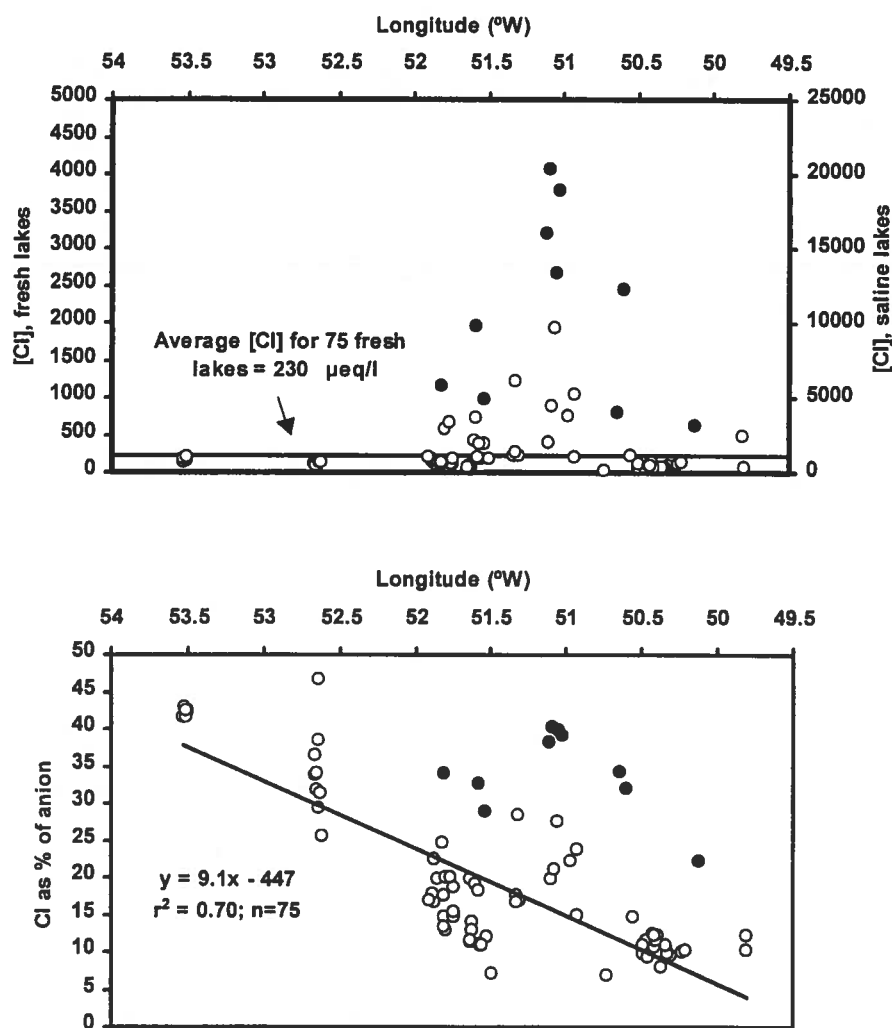


FIGURE 5. Distribution of chloride as a function of longitude in 85 West Greenland lakes as (upper) concentrations in $\mu\text{eq L}^{-1}$ and (lower) % of anion sum. Note that longitude increases from ice sheet to coast. Saline lakes are shown as empty circles. Sites referred to in the text are labeled. Saline lakes are plotted against the right y-axis in 5(upper). The regression in 5(lower) excludes the saline lakes.

EVAPORATIVE CONCENTRATION IN CLOSED BASINS

Within the zone of negative P-E balance, the role of the presence or absence of an outflow in controlling lakewater chemistry is exemplified by neighboring lakes on the nunatak (lakes SS32 and SS86; Figs. 3, 4). These small lakes are less than a km apart and have the same local climate and geology, but the more concentrated SS86 is slightly smaller (5 ha) and shallower (maximum depth: 13 m) than SS32 (15 ha, 21 m max. depth). However, the most important difference is the absence of an outflow from lake SS86. The chemistry of the two lakes is significantly different (Table 2, Figs. 3, 4), presumably due to the evaporative concentration of salts at the closed-basin lake. The outflow from SS32 is seasonal—it was dry in September 1999, for example, but the through flow of the spring meltwater is presumably sufficient to remove excess salts. SS86 is not a saline lake at present, but its chemistry relative to SS32 is indicative of the effect of the lack of an outflow, although the negative P-E balance over this area is at present only small. Elevated salinity may also result from local geological sources of salts.

Although evaporation is the primary cause of enhanced salinity, the chemistry indicates that they are not merely evaporated rainwater—there has to be another external input of salts, either from soils (local weathering products of unusual geological deposits) or from the atmosphere. Anionic dominance by chloride rather than sulfate might be expected in the absence of

a bedrock source of sulfur but Hansen (1969) argued that the low sulfate concentrations in the lakes were due to the formation of iron sulfides in the catchment soils. This mechanism, while possibly occurring locally, is unlikely given the dryness of area. One of the lakes that Hansen (1969) focussed on was Store Salt Sø (SS17), which compared to the other saline lakes, has relatively low SO_4 concentrations (ca. $400 \mu\text{eq L}^{-1}$).

Moreover, Hansen (1969) seriously underestimated the high rates of evaporation in the area around the head of the fjord and dismissed evaporation as a causal mechanism. In a study undertaken in 1977, Hasholt and Søggaard (1978) estimated the potential evapotranspiration to be ca. 300 mm for the period 25 May to 7 September 1977. They estimated that on a transect from Sisimiut to Kangerlussuaq (see Fig. 1), negative effective precipitation would start at approximately 80 km from Sisimiut and increase towards the ice sheet. The most westerly saline lakes found to date (SS42 and SS70), are some 80 and 90 km from the outer coast. SS42 has a conductivity of $1500 \mu\text{S cm}^{-1}$ and probably represents the westerly limit of saline lake occurrence. Further evidence for high rates of evaporation are the salt encrustations that occur on some of the clay and loess deposits around some of the saline lakes (e.g., SS4, SS71). Lake location (as longitude) was the most important explanatory variable in the RDA analyses (Fig. 4c; Table 2) and supports the conclusion that directly or indirectly the climate gradient has an effect on lake chemistry in this region.

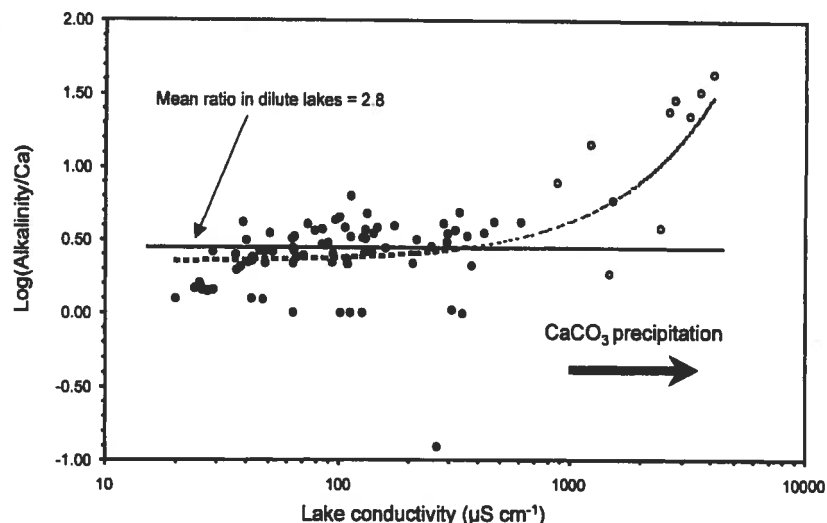


FIGURE 6. Ratio of carbonate alkalinity ($\mu\text{eq L}^{-1}$, predominantly HCO_3^-) to $\mu\text{M Ca}^{2+}$ for 84 West Greenland lakes (excluding acid lakes SS74 and 75). Average alkalinity:Ca ratio for 74 dilute lakes (filled circles) is 2.8. As lakes become more concentrated (increasing conductivity) by evaporation, calcite solubility threshold is reached in saline lakes (empty circles), resulting in CaCO_3 precipitation and sharp increase in alkalinity/calcium trend (dotted line).

The relatively high concentrations of chloride in lakes close to the head of the fjord (Fig. 5, upper) may be derived from the deflation of late-glacial marine deposits exposed as terraces along the side of the fjord. Even the nonsaline lakes in this area have enhanced Cl concentrations (relative to the mean [Fig 5, lower]). There is a clear indication of increased Cl concentrations in lakes close to the coast when Cl is expressed as a percentage of total anions, as has been observed elsewhere (Pienitz et al., 1997) (Fig. 5, lower). Similarly, correcting for marine influence on Mg concentrations (using Cl), it is clear that there are important catchment-derived sources of Mg.

The Na:Cl ratio in the lakes (1.18 molar) is considerably greater than that of seawater (0.858), suggesting a local source of Na. Excess sodium in the lakes is probably derived from the loess—which in turn is derived from the glacial deposits in the large outwash plains in Sandflugtdalen and Ørkendalen. There is considerable eolian activity at the head of Søndre Strømfjord today and has been since ca. 6000 yr BP (Dijkmans and Törnqvist, 1991). Eolian-derived loess deposits can be found throughout the area. In the late winter/early Spring, vegetation is covered in a fine "dust" (Anderson, unpublished field observations). Böcher (1949) postulated that these silt deposits might be a source of salts.

The saline lakes in the study area are $\text{NaCO}_3\text{-NaHCO}_3$ and MgHCO_3 -dominated and characteristically have low Ca, in contrast to the fresh lakes where Ca is dominant. In lakes with molar ratios of $\text{HCO}_3^-:\text{Ca} \gg 1$, precipitation of CaCO_3 is predicted under evaporative concentration models (Type I lakes: Eugster and Jones, 1979). Dilute Greenlandic lakes are carbonate and bicarbonate enriched compared to calcium (Fig. 6) and become progressively more so as concentrations increase beyond the point of CaCO_3 solubility, as expected from the solute pathway model (Eugster and Jones, 1979). Evidence of progressive, long-term calcite precipitation is found in many saline lake sediment cores in the region, although even in the most saline lakes in West Greenland the process has not removed epilimnetic Ca completely.

EFFECT OF LOCAL GEOLOGY

Although geology is generally quite uniform in the study area, the effect of local catchment anomalies can not be discounted. The clearest example of this is the SS70–76 lake group (Fig. 1), where all of the lakes have higher than average SO_4 concentrations (Table 2; the concentration in SS70 is $> 10,000 \mu\text{S cm}^{-1}$). The PCA analysis indicates that these lakes form a distinct subgroup (Fig. 4a; see also Fig. 3). These lakes are located around an outcrop of marble which is exposed extensively on a number of the hillslopes, particularly around SS74 and SS76. These unvegetated outcrops have weathered into a distinctive orange-reddish color and are very friable. The exact cause of the increased sulfate is not known, but these deposits may contain impurities such as gypsum or there may be sulfide-rich ores associated with the contact that leads to the enhanced SO_4 in surface runoff and lakewater.

EFFECT OF ALTITUDE

In the RDA, altitude was a significant variable influencing lake water chemistry (Fig. 4c, Table 3). There is presumably reduced weathering at higher altitudes, more bare rock, limited vegetation cover and soil development. It is clear that the group of lakes 50 km west of the airport (SS27–30) are quite distinctive. Located at an altitude of 550 m in boulder-strewn catchments, these lakes have consistently low conductivity values ($40 \mu\text{S cm}^{-1}$). The group of lakes (SS88–91) immediately (ca. 15 km) east of SS27–30 have slightly higher conductivity values ($120 \mu\text{S cm}^{-1}$) but are at a lower altitude (300 m). The lakes 15 km south east of the airport (SS9–16) (Fig. 1) cover a range of altitudes (470–550 m) but have mean conductivity values above $100 \mu\text{S cm}^{-1}$. These lakes are close to Ørkendalen (Desert Valley), which is one of the main sources of loess, and presumably it is this proximity to these eolian silt inputs that offsets the reduced weathering rates that occur at this altitude.

Conclusion

The saline lakes at the head of Søndre Strømfjord are a small but chemically interesting group of lakes that are atypical in that their salinity is not marine derived. The main influence on the saline lakes is evaporation (the most likely explanation of the fossil shorelines) followed by inputs of salts from terrestrial sources, mainly silts deflated from glaciofluvial deposits at the edge of the ice sheet (possibly together with long-range atmospheric inputs). The chemistry of the saline lakes is the result of local weathering processes together with the eolian inputs from glacial deposits close to the head of the fjord. These inputs contribute differently to alkalinity generation in the lakes (NaCO_3 ; Ca and $\text{MgHCO}_3/\text{CO}_3$) while evaporative concentration has resulted in long-term removal of Ca by precipitation. We have located more saline lakes than previously known, but they are still a minority (ca. 10%) as they are effectively limited to a zone within 80 km of the ice sheet margin (see Fig. 1). Given the large number of lakes in the area (ca. 20,000), the significance of the saline lakes needs to be seen in a wider perspective. The saline lakes are, however, worthy of more study, both in terms of their contemporary ecology and functioning (Anderson et al., 1999) and because of their importance as palaeoclimate records, as they reflect changing effective precipitation in this area.

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