

# Limnological and palaeolimnological studies of lakes in south-western Greenland

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The many lakes in south-western Greenland offer excellent opportunities for both limnological and palaeolimnological studies. The lack of any cultural disturbance means that these lakes are tightly and directly linked with their catchment areas and regional climate. As such, the development of the biological structure of these lakes over time should primarily reflect climate changes that have taken place since deglaciation. In turn, these changes in lake species composition and their productivity are preserved in the lake sediments. These lakes provide, therefore, excellent opportunities for studying the impact of past climatic changes on lake ecosystems. Similarly, the sediment records can also be used as proxies for palaeoclimatic changes. Clearly, however, to interpret sediment records in terms of fluctuating climate it is necessary to understand contemporary processes. The limnology of these lakes is not particularly well understood as only a few of the lakes

have been studied, and then only infrequently, over the last 50 years (Williams 1991).

Field work in 1997 and 1998 between Kangerlussuaq and Kap Farvel (Fig. 1A), had three main aims:

1. To generate limnological data on the functioning of the lakes in a transect along Søndre Strømfjord. The 'saline' lakes in the Kangerlussuaq area, at the head of Søndre Strømfjord, have been known for some time (Böcher 1949; Williams 1991), although their origin is not completely understood and their limnology has not been studied in detail (Böcher 1949; Hansen 1970).
2. To collect sediment cores from the saline lakes in the Kangerlussuaq area and from lakes at the outer coast adjacent to the Labrador Sea (Fig. 1), where laminated lake sediments have been identified previously (Anderson & Bennike 1997; Overpeck *et al.* 1998).

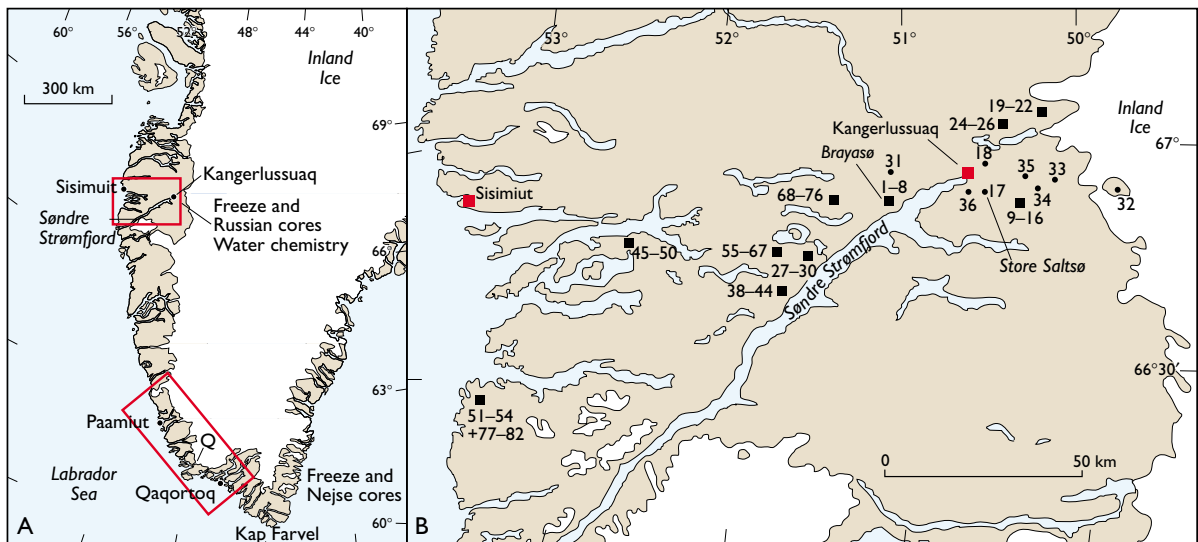


Fig. 1. **A:** The location of the study areas between Kangerlussuaq and Kap Farvel. Q: Nordre Qipisaqu Bræ. **B:** The location of the limnological survey around Kangerlussuaq and north of Søndre Strømfjord, and the sites of specific lakes (e.g. 32) mentioned in the text (■ = group of lakes; • = individual lake).

3. To consolidate the surface sediment sampling programme started in 1996, particularly with a view to establishing a transfer function for lake-water conductivity for West Greenland (Anderson & Bennike 1997).

### Laminated sediments in ‘saline lakes’ in the Kangerlussuaq area

During the course of taking surface sediment samples in 1996 a number of lakes with laminated surface sediments were identified. As it is very difficult to retain the laminated structure of surface sediments using normal gravity, piston or Russian corers due to the high water content, it is necessary to freeze the sediment *in situ* using a freeze corer. With this coring method, solid CO<sub>2</sub> mixed with ethanol is used to freeze sediment in a flat-sided metal container (Fig. 2A). As it is easier to take the full (Holocene) sediment sequence when working from the ice surface of a frozen lake, a number of lakes were re-visited in April 1997 to take freeze cores of the unconsolidated surface sediments and Russian cores (Fig. 2C) of the deeper sediments. We cored four lakes, three ‘saline’ lakes (Brayasø, lake 6 and Store Saltsø (Fig. 1; conductivities *c.* 3000  $\mu\text{S cm}^{-1}$ )) and a sin-

gle fresh-water lake as a reference site (lake 2; conductivity 450  $\mu\text{S cm}^{-1}$ ). The sediment records of the three saline lakes are all clearly laminated throughout (Fig. 2B, C).

Laminations are formed by the preservation of distinct inputs to the sediment surface; annual laminations or varves result when there are distinct seasonal inputs each year. Such distinct seasonal inputs occur in most lakes as the result of annual peaks in phytoplankton productivity, meltwater inputs etc. Their preservation, however, requires more optimal conditions: reduced energy inputs to the lakes, deep water, and often an anoxic hypolimnion with low benthic invertebrate populations. Arctic lakes in general have extended periods of ice cover, around Kangerlussuaq the ice-free period is around three to four months. Ice cover reduces the amount of physical wind mixing of the water column and hence disturbance of the sediments. The long period of ice cover may account for the coarsely laminated structure observed in many West Greenland lake sediments. However, the very fine laminations (< 1 mm) preserved in Brayasø and lake 6, for example, require something more than extensive ice cover; this is probably the combination of meromixis and anoxia.

In closed-basin lakes, the concentration of salts in the lake water primarily reflects changing precipita-

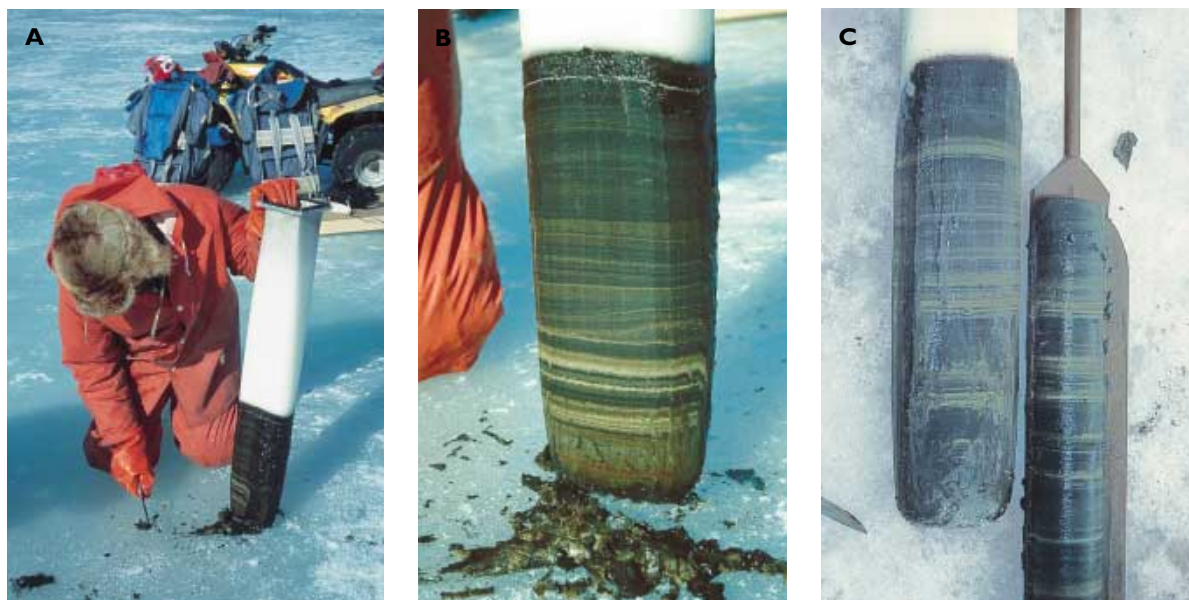


Fig. 2. **A:** The freeze corer immediately after retrieval showing the frozen sediment and the frozen overlying water. **B:** Close-up of a freeze core from Store Saltsø immediately after retrieval, showing the clear laminated structure of the sediment. **C:** Comparison of a freeze core of the surface sediments and Russian core (from Brayasø) demonstrating the ease with which the two core types can be correlated. The diameter of the Russian core, to the right, is 10 cm.



Fig. 3. **A:** Field camp near one of the lakes in April, 1998. **B:** The Nesje corer is lifted out of the sediment using a hi-lift jack.

tion/evaporation ratios and groundwater inputs. The latter are probably minimal in the Kangerlussuaq area due to the influence of permafrost. In this area, therefore, the record of changing lake water conductivity during the Holocene should reflect changes in local patterns of precipitation and evaporation, i.e. a record of regional climate change. As conductivity is a major influence on the diatom community composition of lakes, transfer functions are being developed using weighted averaging methodology. This transfer function will permit a quantitative reconstruction to be made of historical lake water conductivity and hence changing precipitation/evaporation ratios over time.

### **Coring in south-western Greenland adjacent to the Labrador Sea and implications for glaciation history**

During March and April 1998, sediment cores were collected from two of the basins in southern Greenland where laminated sediments had previously been located, and two additional basins were cored. We camped at the lakes, and used a chartered Sikorsky S-61 to move the coring and camping equipment (Fig. 3).

Freeze cores were collected from the two basins with laminated sediments, one 25 km north-west of Qaqortoq ( $60^{\circ}51.4'N$ ,  $46^{\circ}27.8'W$ ) and one 10 km north of Paamiut ( $62^{\circ}5'N$ ,  $49^{\circ}36.7'W$ ) (Fig. 1A). From each lake six cores were taken, so that local differences from core to core could be eliminated. Both lake basins showed laminated sediments for the whole sampled interval, with a few turbidites present. The freeze cores were shipped frozen to Boulder, Colorado, USA where work is now in progress to establish whether the laminae represent

annual layers (varves). The thickness of the laminae are being measured using a microscope, since the mean thickness of the laminations is only around 0.2 mm. From the same two lakes, and from two additional lakes, longer cores were collected using a Nesje corer (Nesje 1992). This is a percussion-piston coring system which can penetrate stiff sediments at water depths of up to c. 100 m. The corer is hammered down into the sediment using a weight with static ropes. Cores up to 4.5 m in length (8 cm diameter) were collected. Magnetic susceptibility was measured along each core using a Bartington loop prior to cutting the cores for shipping to Boulder.

Some radiocarbon dates based on humic acid extracts are now available from the Nesje cores. One is from an isolation basin near Paamiut, South-West Greenland (Fig. 1A) with a threshold at 17 m above sea level. A sample from the transition between the marine and lacustrine sediments yielded an age of 8.8 ka BP (uncalibrated radiocarbon years before present). This date is surprisingly old when compared with dates from other isolation basins in the area (Kelly & Funder 1974), but the sample may come from brackish water sediments rather than lacustrine sediments. At the coring site, at a water depth of more than 40 m, less than 90 cm of Holocene gyttja was recovered, which indicates a low sedimentation rate in this basin.

Another basin near Paamiut, and well above the marine limit, also contained less than 1 m of Holocene gyttja, the oldest part of which was dated to 9.6 ka BP. A lake basin 25 km north-west of Qaqortoq, contained c. 1.8 m of Holocene gyttja with a basal age of 9.1 ka BP, underlain by glacio-lacustrine sediment with clasts of gyttja. These clasts were dated to 9.6 ka BP, and the dates indicate deglaciation of the basin followed shortly

afterwards by an early Holocene glacial re-advance and recession. The 9.6 ka BP date is the oldest date on Holocene sediments from this part of Greenland, and provides a minimum date for the deglaciation of this region.

The most impressive Nesje core sequence was obtained from a lake basin (61°0.7'N, 47°45'W) situated below the marine limit, close to Nordre Qipisaqqu Bræ, which is an outlet glacier from the Greenland Inland Ice (Fig. 1A). The thick sequence comprises glacio-marine sediments, marine sediments, lacustrine gyttja, clay gyttja, glacio-lacustrine sediments and 5 cm of gyttja. The lake was isolated from the sea around 8.4 ka BP, and the transition from gyttja to clay gyttja, which marks the onset of the neoglaciation, is dated to 4.0 ka BP. This, together with a similar date from eastern North Greenland (Bennike & Weidick 1999, this volume), is one of the best dates for the start of the neoglaciation in Greenland. The base of the glacio-lacustrine sediments is dated to 0.5 ka BP, which dates the beginning of the Little Ice Age.

### Surface sediment sampling of lakes along a climatic gradient

The area from the margin of the Inland Ice at the head of Søndre Strømfjord westwards to the coast south of Sisimiut (Fig. 1B) represents a major climatic gradient, from more continental conditions close to the ice sheet to the more maritime influenced coastal zone. Mean summer air temperatures are higher at the head of the fjord, rainfall lower and there is greater evapotranspiration. Summers at the coast are generally cooler and damper with greater influence of local fog, with snowbanks remaining to late in the summer. It is a reasonable assumption that both lake community structure and productivity should reflect these climatic differences. Recently, attempts have been made to develop transfer functions that relate both diatoms and chironomids to climate variables, for example air or water temperature (e.g. Lotter *et al.* 1997). It is hoped to develop similar models for West Greenland. However, to develop similar models successfully requires a range of lakes covering the gradient to be modelled. Single measurements of lake-water temperature have limited usefulness. In 1998, thermistors to measure surface water temperature were put out in 20 lakes along a gradient from the Inland Ice margin to the coast (Fig. 1B). The thermistors were set to record lake water temperature every 30 minutes from 6 June until 10 September. The data

obtained provide a reliable method of estimating mean surface water temperature, and are currently being related to data from the meteorological stations at Sisimiut and Kangerlussuaq.

The first lakes sampled in 1996 were limited to a lake (32) on a nunatak at the edge of the Inland Ice and other lakes up to c. 40 km to the west. The aim of the lake surface sediment sampling undertaken in 1997 and 1998 was, therefore, to complete the sampling of lakes along the climatic gradient between the Inland Ice margin and the outer coast. In 1997 a further 17 lakes were sampled in three separate groups: an intermediate group 60 km west of the airport at Kangerlussuaq, a group at around 400 m altitude, 40 km south-west of Sisimiut and a third group at the coast. The lakes in the last two groups had low conductivities (c. 40  $\mu\text{S cm}^{-1}$ ) whereas the first group included a lake (42; Fig. 1B) with higher than average conductivity (1600  $\mu\text{S cm}^{-1}$ ). Another 22 lakes were sampled in 1998, 30 km to the north-east of lake 42, and these included several lakes with higher than average conductivities. Such lakes (with conductivities of 1200 to 2000  $\mu\text{S cm}^{-1}$ ) are intermediate between the dilute outer coastal lakes and the area close to the



Fig. 4. Fossil shorelines at lake 70. The present-day conductivity of this lake is 2500  $\mu\text{S cm}^{-1}$ .

airport at Kangerlussuaq, where the 'saline' lakes (Williams 1991) are found (conductivities around  $3000 \mu\text{S cm}^{-1}$ ). The latter probably only occur in those areas close to the head of the fjord with low precipitation/evaporation ratios. Lake 42 may represent an approximate outer (westerly) limit for the occurrence of the West Greenland type of saline lakes (Williams 1991). The palaeoclimatic significance of these lakes is indicated by the evidence of higher shorelines (Fig. 4). The implication is that the conductivity of the lakes has increased due to evaporation (see below).

### Limnology of lakes in the Kangerlussuaq area

In 1996, the lake sediment sampling concentrated on obtaining surface sediment samples to be used for developing transfer functions for lake water conductivity and total phosphorus using diatom, zooplankton and chironomids remains in the surficial sediments (Anderson & Bennike 1997). Development of transfer functions requires some understanding of the contemporary lake communities and the way they function. Unfortunately, relatively little is known about the present day status of the lakes. Therefore, in an attempt to characterise the limnology of the lakes in the Kangerlussuaq area, a synoptic survey was started in 1997. The objectives were to collect physical, chemical and biological data for as many lakes as possible around Kangerlussuaq where sediment samples previously had been collected. In August 1997, a total of 19 lakes were sampled, including five saline lakes. The sampling programme included profiles of temperature, oxygen, pH, conductivity and light. Water samples for chemistry, phytoplankton, micro- and mesozooplankton were also collected at two depths (one if the water column was fully mixed). Samples of epiphytic algae were also collected and the macrovegetation was recorded and collected along a transect in each lake. In four lakes the light measurements were expanded to include measurements of spectral light attenuation and light absorption by particles.

As laminated sediments were found in a number of lakes it was important to know if the saline lakes were permanently stratified, as meromixis is a common cause of laminated sediments in both arctic and temperate lakes (Hardy *et al.* 1996). Figure 5 shows profiles of conductivity, temperature and oxygen for Brayasø, one of the five saline lakes sampled in 1997. Conductivity and temperature were uniform to a depth of 5.3 m where there was a sharp pycnocline where the conductivity

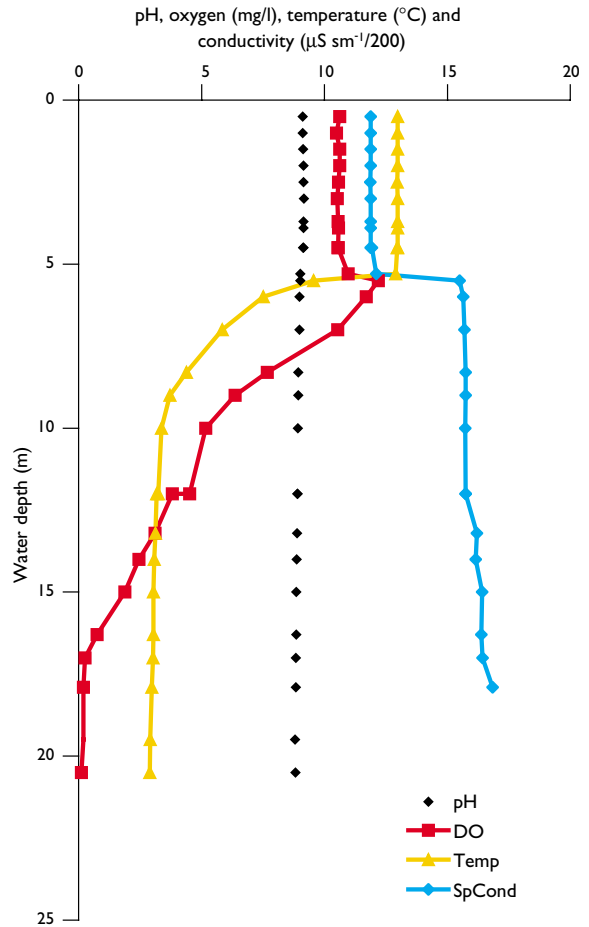


Fig. 5. Profiles of dissolved oxygen (DO), conductivity ( $\mu\text{S cm}^{-1}$ ; spCond), pH and temperature (temp  $^{\circ}\text{C}$ ) for Brayasø in August 1997 plotted against depth in the lake.

increased by 30% ( $> 600 \mu\text{S cm}^{-1}$ ) in just over 0.2 m water depth (Fig. 5). Below the pycnocline there was a gradual decline in temperature, reflecting the attenuation of light with depth, and thereby decline in the accumulation of solar energy. An interesting aspect was that the difference in salinity between the less saline surface layer and the dense hypolimnion was large enough to maintain a stratification when the surface layer cools in the autumn. The lake is, therefore, permanently stratified and must be classified as a meromictic lake.

To our knowledge this is the first time that a meromictic lake type has been recorded in the Arctic for a lake not formed due to isostatic uplift of a fjord (e.g. Quillet *et al.* 1989; Overpeck *et al.* 1998). Brayasø is located about 200 m above sea level. There is no outflow from

the lake and the salinity must come from salts that are washed out of the soil (atmospheric inputs are low) and accumulate in the lake over time. This means that the salinity in the lake and the associated meromixis are of arid origin, whereas most other saline lakes in the Arctic are saline because of their proximity to the sea (e.g. Quillet *et al.* 1989; Ludlam 1996; Overpeck *et al.* 1998). Similar profiles of conductivity and temperature were measured in the other four saline lakes, while the 14 freshwater lakes had a normal circulation pattern. Most of the latter are dimictic with a period of summer stratification, where the surface temperature reaches *c.* 13°C.

Another aspect of the limnological survey was the relationship between circulation pattern within a lake, its macrovegetation and the oxygen concentrations in the hypolimnion. Figure 5 shows that the oxygen concentration was uniform in the well-mixed epilimnion, while an oxygen maximum occurred at the pycnocline due to an accumulation of phytoplankton at this depth. Below the pycnocline there was a gradual decline in oxygen with depth, with anoxic conditions at the bottom. This profile (Fig. 5) is in contrast to the other saline lakes where oxygen is found all the way to the bottom. The reason for this difference is that macrovegetation was absent in Brayasø below 4 m, whereas the other saline lakes had macrovegetation below the pycnocline, which prevented oxygen depletion in the hypolimnion.

Finally, by sampling 19 different lakes we aimed to characterise the biological structure of the plankton community and the macrovegetation, in particular mosses which form dense mats in many lakes. The lakes covered a broad range of salinity and dissolved organic carbon concentrations, and some support fish populations (stickleback and Arctic char). The sampling programme included measurements of the standing stock of bacteria, protozoa, phytoplankton, rotifers and zooplankton in the water column. The samples are still being processed, but it is already clear that the lakes show distinct biological differences, especially regarding the phytoplankton and zooplankton abundance and biomass. The substantial differences in biological structure among the lakes probably reflects the influence of both the fish populations (on the lower trophic levels) and the ionic content of the water. The limnological survey was continued in 1998 at the two coastal lake groups. The investigation was similar to that carried out at the head of the fjord (above), but with the inclusion of gill netting to determine the abundance and size structure of fish.

It is expected to be able to describe in reasonable detail the biological structure of the lake types found along the gradient from the Inland Ice to the coast. This will provide the opportunity to relate the occurrence of microfossils (diatoms, zooplankton, chironomids) in the surface sediment to the biological and physical structure, particularly salinity and nutrients of the lakes, and allow an evaluation of past and present climate and trophic changes.

## Conclusions

High temporal resolution records of climate proxies (such as lake water conductivity) are very important for determining time scales of former climatic variability. The best temporal resolution obtainable from lake sediments is from varves, where inter-annual resolution can be combined with an absolute chronology (by counting the number of varves). This combination of laminated sediments and the possibility of the application of a quantitative climate proxy (diatom-inferred conductivity) is very promising. Although it is not yet known whether the laminated sediments from the south-western Greenland lakes are varves, the detailed and variable structure of laminations at Store Saltsø, Brayasø and other lakes (Fig. 2B, C) should contain climatic and environmental information. To extract this information it is important to understand both the ecological and physical limnological processes that result in these laminations and how they reflect local climate and catchment processes. In addition, the sediment records from lakes in Greenland also hold a large potential for studies of glaciation history and sea-level changes.

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