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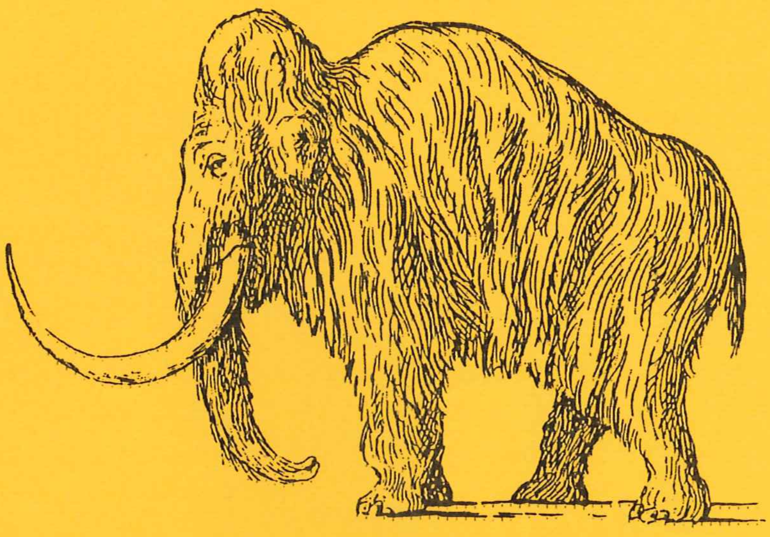
Kvartärgeologi



A paleoecological study of the Pleistocene-Holocene transition in the Kap Farvel area, South Greenland

Karl Ljung

Examensarbete, 20 p
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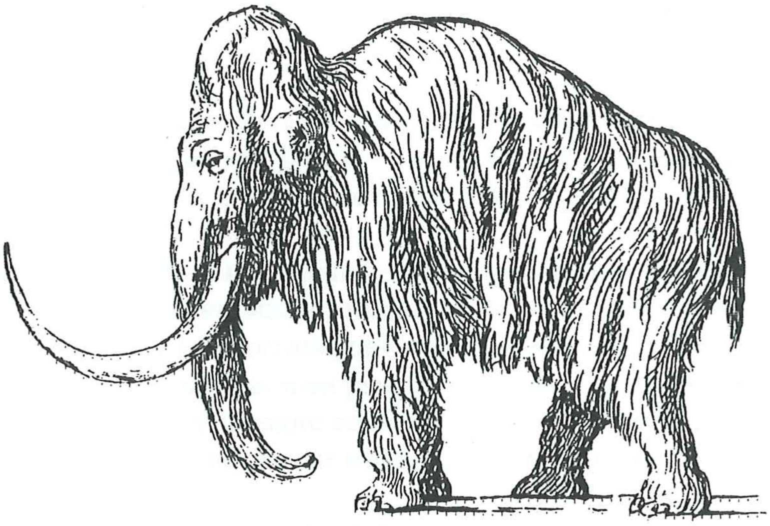

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A sedimentary sequence from a small lake situated on Taterakasik peninsula in the Kap Farvel area, South Greenland, was investigated with respect to pollen and other microfossil content, as well as loss-on-ignition and magnetic susceptibility values. The ^{14}C dates suggest that the sedimentation started shortly before 12 300 cal yrs. BP. and thus cover the transition from the supposedly cold Younger Dryas into the warmer Preboreal. The primary aim of the analysis was to interpret the climatic and vegetational shifts during this period.

The results show that Younger Dryas was cold and dry (continental climate). Immigration and establishment of terrestrial plants was very limited, due to the cold and dry environment. However, the production of the green algae *Pediastrum* was high, suggesting that the summers were fairly mild.

After the end of the Younger Dryas cooling the terrestrial vegetation expanded rapidly. The climate became warmer and more humid. The productivity in the lake increased due to warmer climate and higher influx of nutrients by increased run-off caused by higher precipitation and snowmelt.

The absence of marine dwelling dinoflagellate (Hystrix) during the Younger Dryas cooling indicates that the ocean was ice covered throughout the year. After the transition into the Preboreal, occurrence of marine organisms - most likely brought to the lake by sea-spray - indicate that the ocean was open for at least parts of the year. The ice-covered ocean during the Younger Dryas made the climate more continental and after the transition into the Preboreal the open waters made the climate milder and more humid.

Keywords: Lake sediments, South Greenland, Kap Farvel, Younger Dryas, Preboreal, pollen, plant succession, climate change.

Ljung, Karl, 2001: En paleoekologisk studie av övergången mellan Pleistocen och Holocen i Kap Farvel området, Sydgrönland. ***Examensarbete i Geologi vid Lunds universitet – Kvartärgeologi, nr 140.*** **24 pp.**

Sammanfattning.

En sedimentsekvens från Kap Farvel området på Sydgrönland undersöktes med avseende på polleninnehåll, magnetisk suseptibilitet och organisk halt. Sedimentens ålder bestämdes med ^{14}C-dateringar, vilka visade att sedimentationen i sjön började kort tid före 12 300 cal B.P. och därmed inkluderar övergången Yngre Dryas till Preboreal. Syftet med studien är att studera övergången från den förmodat kalla Yngre Dryas-perioden till det varmare klimatet under Preboreal, samt hur klimat- och vegetationsförändringarna under denna tid yttrar sig på Sydgrönland.

Resultatet av studien tyder på att klimatet under Yngre Dryas var kallt med lite nederbörd. Höga frekvenser av grönalgen *Pediastrum* i Yngre Dryas visar emellertid att sommartemperaturen inte var exceptionellt låg. En väldigt sparsam och köldtålig pionjärvegetation växte i området under denna tid.

Efter Yngre Dryas slut blev klimatet varmare och fuktigare. De växter som etablerats under Yngre Dryas drog nytta av klimatförbättringen och expanderade till ett kontinuerligt vegetationstäcke bestående av pionjärväxter. Produktionen i sjön ökade till följd av högre temperatur och ökad tillförsel av näringsämnen med smältvatten och regnvatten från omgivning.

Avsaknaden av marina Dinoflagellater *(Hystrix)* under Yngre Dryas tyder på att havet omkring Sydgrönland var fruset under hela året. Efter övergången till Preboreal visar förekomsten av *Hystrix* att havet öppnades upp. Det istäckta havet under Yngre Dryas medförde att klimatet fick en kontinental prägel medan det öppna havet i Preboreal ledde till ett fuktigare och varmare klimat vid kusten.

Ljung, Karl, 2001:En paleoekologisk studie av övergången från sen- till postglacial tid i Kap Farvel-området, Sydgrönland. *Examensarbete i Geologi vid Lunds universitet – Kvartärgeologi, nr 140.* 24 pp.

Populärvetenskaplig sammanfattning.

En sedimentsekvens från en sjö på Grönlands sydspets, Kap Farvel-området, undersöktes med avseende på polleninnehåll, magnetisk susceptibilitet och organisk halt. Sedimentens ålder bestämdes med ^{14}C-dateringar, vilka visade att sedimentationen i sjön började kort tid före 12 300 före nutid och inkluderar därmed övergången från senaste istidscykeln (Weichsel) till den nuvarande mellanistiden (Holocen).

Syftet med studien var att studera övergången från den sista kallfasen av den senaste glaciationen, Yngre Dryas, till det varmare klimatet under Preboreal, den inledande fasen av nuvarande mellanistid, och hur klimatförändringarna under denna tid yttrar sig på Sydgrönland.

Resultatet av studien tyder på att klimatet under Yngre Dryas var kallt och med låg nederbörd. Stora mängder av grönalgen *Pediastrum* under Yngre Dryas visar emellertid att sommartemperaturen inte var exceptionellt låg och att den provtagna sjön var isfri under sommaren. Endast en väldigt sparsam och köldtålig pionjärvegetation växte i området under denna tid. Polleninnehållet är extremt lågt i den undre delen av sedimentsekvensen, varför det är omöjligt att dra några slutsatser om vegetationens sammansättning. Man kan dock anta att de växter som först expanderade in i området efter övergången till Preboreal hade kommit in redan under Yngre Dryas. *Oxyria/rumex* är utpräglade pionjärväxter och det är möjligt att dessa fanns i området före övergången mellan Yngre Dryas och Preboreal.

Efter Yngre Dryas slut blev klimatet varmare och fuktigare. De växter som etablerats under Yngre Dryas drog nytta av klimatförbättringen och expanderade till ett växtsamhälle med typiska pionjärväxter som *Oxyria/Rumex*. Produktionen i sjön ökade dels till följd av högre temperatur, men också genom ökad tillförsel av näringsämnen med smältvatten och regnvatten från omgivning. Detta indikeras av ett högre innehåll av organiskt material i sedimenten.

Under Yngre Dryas var havet omkring Sydgrönland tillfruset under hela året. Det medförde att klimatet fick en mera kontinental prägel med kalla vintrar och låg nederbörd. De stora klimatförändringarna vid övergången från Yngre Dryas till Preboreal innebar emellertid att havsisen bröts upp under de varmare delarna av året. Det öppna havet kom därmed att fungera som ett värmemagasin men en ökad medeltemperatur som följd. Det skedde också en ökning av nederbörden, vilket troligen var en direkt effekt av det öppna havet.

Contents

1 Introduction

1.1 Background

When Johs. Iversen published his work *Origin of the flora of Western Greenland in the light of pollen analysis* in 1952-53 it was the first work dealing with the Late Quaternary palaeobotany of Greenland based on studies of pollen assemblages in lake sediments. Previously, the palaeoecology of Greenland solely relied on the present day distribution of plants. The new information from pollen analysis was a big step forward, and had great consequences for the understanding of the Late Quaternary history of Greenland.

Twenty years later, in 1973, Bent Fredskild published his massive doctoral dissertation, *Studies in the vegetational history of Greenland, palaeobotanical investigations of some Holocene lake and bog deposits*. This work is very important and an invaluable source of information for anyone studying the paleoecology of Greenland. He presented pollen diagrams from 18 lakes, from north, south and west Greenland.

The oldest sediments in Fredskilds (1973) study were dated to the early Holocene. Much of the discussion dealt with the vegetation history and possible causes for the vegetational changes, such as immigration patterns, climate and plant succession.

As none of Fredskilds (1973) sediment cores extended beyond the Preboreal, information about the climatically interesting period around the Pleistocene-Holocene transition was lacking.

In 1999 Svante Björck and Ole Bennike along with three students undertook a field trip to the Kap Farvel area. The aim was to retrieve sediments extending into the Glacial. They concentrated much of their efforts to core lakes on islands and peninsulas situated outside the main coast. These areas should have been deglaciated relatively early in relation to most other areas in Greenland, since they are situated fairly close to the Last Glacial Maximum (LGM). This proved to be correct and during the field trip they retrieved cores from islands and coastal peninsulas dated to app. 14 000 cal yrs. B.P. (Bennike & Björck 2000).

The present study is based on two sediment cores from a coastal locality where the bottom most dating yielded a ^{14}C age of 10 385 B.P., thus being of Younger Dryas age.

1.2 Aim of the study

The Pleistocene-Holocene transition from the Younger Dryas cooling into the Preboreal was a time of large climatic changes around the North Atlantic. The change was very rapid and effected Europe and the east coast of North America (Björck *et al.* 1996, Björck *et al.* 1997). Often this climatic change is very well defined in sediment sequences throughout the region.

On Greenland the change is recorded in the GRIP ice-core and termed GS-1 (Björck *et al.* 1998). The GRIP ice core also shows that the change from the Younger Dryas into Preboreal was very rapid.

The main object of the present study was to investigate the microfossil content, mainly pollen, algae, spores and insect remains, combined with measurements of magnetic susceptibility, organic content, and ^{14}C datings from a lake in southernmost Greenland, during this climatically interesting period. The aim of the study was to interpret and discuss the vegetational, lacustrine and climatic development of the area 12 300-10 000 cal yr B.P.

The most important questions that are raised in this work are: (1) How fast and in which order did the re-establishment of terrestrial and aquatic plants take place and can the vegetation development be related to previous paleoecological work in the region? (2) What climatic changes can be inferred from the different proxy records and can local ocean related changes be related to climatic changes?

2 The study area

2.1 Description of the study site

Lake N23 is situated on the Taterakasik peninsula, 47 m a.s.l., 60°04'57''N, 45°97'75''W, which forms the eastern shore of Tasermiut fjord inlet (Fig. 1). The peninsula is about 4 km long and 2 km wide. The highest point reaches 244 meter above sea level. The lake is situated between two small summits in a valley. The lake is approximately 200 m long and 100 m wide and drains to the north through the valley.

The two cores were taken from the middle of the lake at 2.2 m water depth where the sediment thickness was expected to be greatest.

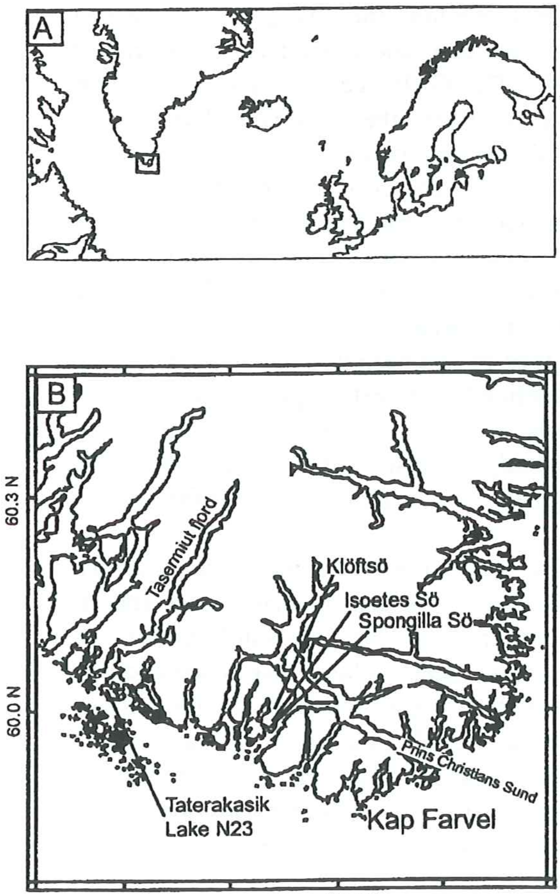

Fig 1. (A) Map of the North Atlantic region. The area covered by the map in B is indicated. (B) Map of the Kap Farvel area showing the localities mentioned in text.

2.2 Topography

South Greenland is a mountainous area with high, rocky peaks reaching above 2000 m.a.sl., separated by fjords that cut deep into the land. The fjords can be very large and often reach all the way to the inland ice. The mountainsides lining the fjords are often very steep and rocky.

The outer coastline is abundant in large and small islands, which in many places form true archipelagos. In the Kap Farvel area much of the ice-free land consits of islands.

The inland-ice only reaches the outer coast in few places on Greenland; generally the glacier fronts are found at the fjord heads, a long distance from the coast. Most of Greenland's coast is therefore ice-free. Melville Bugt in northeastern Greenland, between Upernavik and Thule, is the largest area on Greenland where the ice-front forms the coastline. In Kap Farvel area all glaciers end at the fjord heads.

Outside the Greenland Ice Cap numerous small alpine glaciers are present on the mainland, as well as on the islands. In the Kap Farvel area the glaciation limit is situated at 600-800 m.a.sl at the coast and rises to around 1600 m.a.sl. at the margin of the ice-sheet (Weidick 1981). The low glaciation limit at the coast is due to lower summer temperatures and higher precipitation.

The ice-sheets consist of two large domes, one in the southern part and one in the middle part. Both domes are situated closer to the east coast. The easterly situation of the southern dome is partly due to the higher precipitation that the east coast receives (Weidick 1981).

2.3 Geology

The bedrock of the Kap Farvel area consists of granite, gneiss and metamorphosed sediments and volcanics belonging to the Ketilidian complex that was formed between 1800 Ma to 1500 Ma (Bondesen 1981). North of this lies the oldest bedrock on Greenland, the archaic basement with an age of 3750-2500 Ma. North of the archaic zone there are again younger bedrock.

The Ketilidian complex has been extensively folded, but not much metamorphosis has taken place after the complex was formed (Bondesen 1981).

During the Last Glacial Maximum (LGM) the inland ice expanded past the present day shoreline and onto the shelf. In north Greenland ice filled the fjords and basins, but did not form a large ice cover reaching the shelf break. Further south the ice sheet expanded all the way to the shelf break and formed a continuos ice cover, which is the case around Kap Farvel (Funder & Hansen 1996).

At around 15 000 ^{14}C yrs. B.P. break up of the ice sheet started (Funder & Hansen 1996). The deglaciation continued in two steps with different driving mechanisms. The first step, 15 000-10 000 ^{14}C yrs. B.P., was mainly driven by rising sea level and increased calving of the ice front, and the second step was due to increased melting during the Preboreal warming (Funder & Hansen 1996). There are no clear evidence of glacial advances during the Younger Dryas cooling in south Greenland. The reason for this is probably that the climate was too cold and dry to allow any glacial growth (Funder & Hansen 1996).

The marine limit in south Greenland is situated between 20 and 80 m.a.sl (Funder & Hansen 1996). The lowest marine limit is found on the Southeast coast, between Kap Farvel and Kangerlussuaq, where the marine limit is situated around 20 m.a.sl. On the Taterakasik peninsula the marine limit has been determined to 40 m.a.sl. by extrapolating the marine limit from the outer islands (Björck 2001; pers. comm).

The low marine limit indicates that the ice cover over land has not changed much since LGM, or that there has been a build up of ice during the Holocene (Funder & Hansen 1996). The marine limit is believed to have formed immediately after the deglaciation, and is dated to around 10 000 ^{14}C yrs. B.P. in most areas.

2.4 Climate

Although the distance between north and south Greenland is very large (2700 km), the whole island is situated within the same climate zone, the Arctic climate zone, which is defined as areas where the mean temperature of the warmest month is below 10°C (Fristrup 1981). The steepest climate gradients on Greenland are found from the coast to the inland, due to the maritime influence at the outer coast.

Close to the coast the climate is characterised by mild winters and cold summers, with large amounts of precipitation throughout the year. Further inland the temperature is cooler during winter and warmer during summer, and the precipitation is lower.

A similar difference exists between the northern and southern parts. The largest temperature difference between north and south is found during winter. Because of the polar night above the Arctic Circle the winter temperatures become extremely low, whereas the polar summer has 24 hours of sunlight resulting in relatively high summer temperatures (Fristrup 1981).

Prins Christian Sund in the Kap Farvel area has an annual precipitation of 3 000 mm and a mean annual temperature of 1°C (Fristrup 1981). Further inland the precipitation is considerably lower and the summer temperature is higher.

A precipitation gradient also exists between the east and west coast in South Greenland, and the east coast receives the largest amount of precipitation (Reeh 1989). The higher precipitation in the southeast is partly responsible for the easterly situation of the ice dome of the inland-ice.

The temperature gradient along the fjords, from a marine setting at the coast to continental conditions at the fjord heads, is the most important climatological gradient on Greenland, and results in more or less coast parallel boundaries between different climate zones.

2.5 Present vegetation

Since Greenland is situated within the same climate zone the vegetation in the northern and southern part shows considerable similarities. The boundaries between different vegetation types follow the climatic gradients and are more or less parallel to the coast. The change between north and south are only minor compared to the difference between the outer coast and the inland.

At the coast, the low summer temperature due to the cooling effect of the ocean and the foggy weather only permits more tolerant species to grow. Further inland the climate is more favourable, but even in the inland in southern Greenland the harshness of the climate is reflected in the vegetation, where trees and shrubs only rise up from prostrate scrubs in sheltered valleys.

At the outer coast the dominating vegetation type is the dwarf-shrub heath, dominated by low woody species, often growing on a carpet of moss. Grass-like species occurs along with herbs. On the outer coast *Empetrum hermaphroditum* is the dominant shrub with some *Vaccinium uliginosum.* Further inland *Vaccinium* can take over and dominate the shrub-heath and herbs are becoming more important (Feilberg *et al.* 1984).

Further inland where the growing season is longer and warmer, copse vegetation become the dominant vegetation type. The most common shrub is *Salix glauca,* which can form shrubs up to 3 meters high under favourable conditions as far north as the interior of Scoresby Sound. The ground vegetation of the willow copse is dense and often mossy. Common species are *Deschampsia flexuosa, Calamagrostis langsdorff, Angelica archangelia, Campanula geiseckiana* and *Lycopodium annontium.*

In south Greenland "forests" of tree forming birch *(Betula pubecens)* can be found at the fjord heads where the climate is most favourable. It usually reaches about 3 m in height, but occasionally it can grow to 8 m. It grows at altitudes up to about 100 m.a.sl. The ground vegetation in these areas is dominated by *Deschampsia flexuosa,* with scattered *Campanula geiseckiana* and *Heiracium alpinum* (Feilberg 1984).

On south facing slopes, with sufficient water supply, rich herb vegetation can develop. The slopes become snow free early in spring and therefore the growing season starts early. Typical species for the herb-slope are *Salix glauca, Angelica archangelica, Planthera hyperborea, Leucorchis albeida, Chamaenerion angustifolium, Heiracium alpinum*, several species of Club-mosses and ferns.

In areas where snow accumulates and persists until mid- or late summer snow patch vegetation develops. The snow cover protects the plants from frost and wear during winter and give a constant water supply during melting, but the late melting of the snow cover shortens the growing season and in cold summers the plants may not have time to flower or ripen the fruits. Typical species of the snow-patch vegetation are *Salix herbacea, Harimanella hypnoides, Carex microglochin.* On snow-patches that become snow free later the vegetation is sparser. In the latest snow-patches on north slopes only mosses can grow. In the interior of south Greenland, in places where summers are warm, snow-patches are only present at higher altitude (Feilberg *et al.* 1984).

Apart from dwarf-shrub heaths, fens and marshes dominate the lowlands of Greenland. The wetlands can cover vast areas, up to several square kilometres. Most of the wetlands are found along streams and lakes. The plant composition depends on the amount of available nutrients, stability of the ground and the snow-cover. Common species on poor fens are *Eriophorum angustifolium, Scirpus caespitousus, Ranunculus lapponicus, Vaccinium* spp. On richer fens *Kobresia* ssp, *Carex microglochin* and *Equisetum* grow.

No flowering plants are present in large, deep lakes due to the abrading effect of ice and waves, whereas small lakes and ponds can have a very rich flora (Feilberg *et al.*1984). Common plants in the shallow water close to the shore in south Greenland are *Hippuris vulgaris, Menyanthes trifoliata* and *Carex saxatilis.* In the deeper parts further out *Potamogeton alpinus* and *Sparganium hyperboreum* float on the surface. Rich ponds may be completely filled in by the surface living species, whereas ponds poor in nutrients can be nearly lifeless, having waters as pure as distilled water (Feilberg *et al.* 1984).

In south Greenland the most important factor controlling the geographical distribution of vegetation types is the climatic gradient between the outer coast and the inland. In general it can be said that the inland has a more favourable climate with longer and warmer growing season giving rise to higher and denser vegetation, whereas the coast has colder summers that only permit more tolerant species to grow.

3 Methods

3.1 Field work

The fieldwork was performed by Svante Björck and Ole Bennike along with three students in April 1999. Coring was carried out with a 75-mm-diameter Russian corer with a 1-m-long chamber from lake ice. The cores were stored in refrigerator wrapped in plastic until examination.

The two cores (N23-560, N23-575) were taken in the middle of the lake where the sediment thickness was expected to be greatest. The water depth at the coring point was 2.2 meters and the retrieved sediment sequence reached 5.75 m. All measurements were made from the ice surface of the lake.

3.2 Laboratory work

3.2.1 Core description

The two cores (N23-560 and N23 575) were described in the laboratory with respect to colour, grain size, organic content, and amount of coarse organic matter. The upper boundary between units in the stratigraphy was described as sharp, fairly sharp, rather gradual or gradual.

The description of the lithology is based on minerogenic and organic content, sediment structures and colours, occurance of macrofossils and characteristics of upper boundaries.

3.2.2 Loss-on-ignition

Samples of 2-3 g wet sediment for determination of organic matter content were taken every 5 cm along the core. The organic matter was measured by loss-on-ignition. First the samples were dried at 105°C over night and after that ignited at 550°C for 3 hours.

On ignition the organic matter of the samples combusts and the organic matter is calculated as percentage combusted material of dry weight.

Loss-on-ignition is mainly a measurement of organic carbon and related to the productivity in the lake and the influx of organic matter from the surroundings.

3.2.3 Magnetic susceptibility

Magnetic susceptibility was measured with the long-core apparatus at the laboratory at the Department of Quaternary Geology, Lund University. The magnetic susceptibility was continuously measured over the core with 2 mm increments, and calibrated to the air between every reading.

Simplified the magnetic susceptibility can be described as a measurement of the ability of the material to be magnetised. Ferri-, antiferri-, para- and diamagnetic minerals/materials contributes to the magnetic susceptibility (Walden *et al* 1999).

The magnetic susceptibility value of the sediment is related to the amount of minerogenic minerals brought into the lake. Variations in magnetic susceptibility value are reflecting changes in minerogenic influx by streams and precipitation.

3.2.4 Dating

The chronology of the sequence was established by means of radiocarbon dating. Samples of selected macrofossils were taken out at four depths along with one bulk sample. All samples were taken from the same core: N23-575.

The samples were dated with the Accelerator Mass Spectrometry (AMS) method at the ^{14}C laboratory at the Department of Quaternary Geology, Lund University (LuA) and the Department of Quaternary Geology, Uppsala University (Ua).

3.2.5 Pollen analysis

Where possible samples for pollen analysis were taken with a 2 ml syringe. Where the content of coarse organic material, mainly water mosses, was too high the use of syringe was not applicable and a sharp blade was used to cut out the samples. For most samples 2 cm^3 were taken, but where the minerogenic content was very high about 4 cm^3 was regarded appropriate.

The pollen samples were prepared in agreement with the conventional acetolysis method with added *Lycopodium*-spores (Berglund & Ralska-Jasiewiczowa 1986). The samples were coloured with neutral-red and mounted in glycerine on slides.

All samples have very low pollen contents and sufficient pollen sums as proposed in different handbooks, for example Berglund & Ralska-Jasiewiczowa 1986 and Moore *et al.* 1991, could not be reached without an enormous effort. Total pollen sums on one slide varies between 50 in the top of the section to as low as 0 in the bottommost part. It was only possible to reach pollen sums exceeding 100 in the uppermost part.

For determination of pollen taxa the reference samples at the Department of Quaternary Geology, Lund University, has been used along with literature, for example Moore & Webb (1991) and Faegri & Iversen (1989).

As Rundgren (1995) points out there is a good correlation between local pollen spectra and local vegetation in arctic tundra environment, in spite of the low pollen production. The main characteristics of the tundra pollen spectra are (1) high proportion of nonarboreal pollen, particularly Gramineae and Cyperaceae, (2) significant proportion of tree pollen of long distance origin, and (3) a generally low pollen influx (5-2500 grains $cm^2 yr^{-1}$). The good correlation between local vegetation and deposition of nonarboreal pollens is due to the inefficient dispersal of pollen grains. Herbs, prostrate shrubs and forbs, which generate a pollen rain close to the ground, that only are wind transported for a short distance before settling, dominate the vegetation.

Therefore the pollen diagrams from arctic tundra regions can be taken as a good representation of the local vegetation. The mosaic character of the vegetation must, however, be considered and the pollen spectra gives a mixed picture of an environment with plants growing in different communities within a restricted area.

The zonation is based on the percentage diagram. The pollen concentration for the important taxa are also presented for comparison.

3.2.6 Taxonomic determination

The following types of pollen and spores are distinguished. Many pollen grains are very difficult to determine to species level and were grouped in genera. Below follows a description of the different species included in each group.

Betulaceae

Birch has only been determined to genus and includes both dwarf birch *(Betula nana)* and tree/shrub birch *(Betula pubescens, B. glanduosa)*. According to previous works birch did not reach Greenland until 8 000 ^{14}C years B.P. in the Scorseby Sound area in west Greenland (Fredskild 1991). In the Kap Farvel area it did not appear until around 3 800 ^{14}C years B.P. (Fredskild 1973).

As the birch is a late immigrant to Kap Farvel no efforts were made to determine its pollen to species level. It is assumed that all Betulaceae pollen grains are of long transported or redeposited origin. Most of the determined pollens are most likely tree birch.

Ericales

The tetrad pollen grains are often easy to distinguish to types and sometimes to specific species. However the state of preservation is not always sufficient and pollen grains appear crumbled and disintegrated. All badly preserved pollen grains along with obscured pollen grains are grouped together in *Ericales* sp. This means that the values of the determined Ericaceae, *Empetrum, Vaccinium,* are minimum values.

The most common Ericales pollen grains are *Empetrum* and *Vaccinium.* No distinction has been made between *Empetrum hermaphroditum* and *E. nigrum,* but the pollen grains are most likely *Empetrum hermaphroditum.* The *Vaccinium* group includes both *V. uliginosum* and *V. vitis-idaea.* Efforts have also been made to determine *Cassipoe hypnoides, Loiseleueria procumbus* and *Pyrola* spp. These taxa are easily distinguishable from *Empetrum* and *Vaccinium* but can be hard to distinguish from one another.

Gramineae

The Gramineae group contains around 60 genera, and the different species are very difficult to determine further, and no effort was made to do so.

Rosaceae
Many Rosaceae pollen grains are hard to determine to species. The only types that have been distinguished are *Potentilla* and *Filipendula.* Within these two groups no further separation was made.

Rumex* and *Oxyria
Rumex acetosella and *Rumex acetosa* pollen were not separated, as this is very difficult (Fredskild 1973). Distinguishing *Rumex acetosella* from *Oxyria digynia* is also very troublesome and therefore these pollen types are grouped together as *Oxyria/Rumex* in the pollen diagram.

Salix
Determination of different *Salix* pollen is possible but very difficult and no separation has been made between the different types. *Salix* is a late immigrant to Greenland. Fredskild uses the term emerge for the rise in *Salix*-curves that takes place around 7 500 ^{14}C years B.P., meaning that it may have immigrated around 8 000 ^{14}C years B.P. but did not expand and become established until later.

Here the *Salix*-pollen grains are considered long transported or redeposited.

Pinus
Pinus is not a part of the present Greenlandic flora and in the sediments it appears as exotic long transported pollen (Fredskild 1973).

Alnus
Alnus is growing today in restricted areas in West Greenland. The immigration of *Alnus* probably took place after 3 500 cal B.P. (Fredskild 1984).

Exotic pollen
Wind transported exotic pollen make up an important part of all Greenlandic pollen diagrams (Fredskild 1973, Fredskild 1984). Apart from the above-mentioned taxa, *Chenopodiaceae, Artemisia, Ulmus* are considered to be wind-transported to Greenland (Fredskild 1973, Fredskild 1984).

Aesculus have never been shown in any pollen diagrams from Greenland before, and are most likely due to contamination in the laboratory.

Pediastrum
Colonies of the green algae *Pediastrum* have only been determined to generas, even though it is clear that several different species appear in the samples.

Botryoccocus
Colonies of the algae *Botryoccocus* have been counted without respect to different types.

Flatworm cocoons
Flatworm cocoons have been distinguished and described by van Geel *et al.* (1981). In the group two types are included, type 353A and 353B. These two types are representatives of the non-parasitic flatworm order Rhabdocella (Class Turbellaria) (van Geel *et al.* 1981).

cf Geoglossum sphangnophilum
This taxon has been determined according to van Geels description (1976). This fungus only grow on *Sphagnum* and would be a strong indicator of *Sphagnum* growing in the area. However, there are several different species of Geolgossaceae and the determination to species migth be questionable.

3.6 Numerical methods

Principal component analysis (PCA) is a statistical technique for describing the variations of large data sets with many variables in a more perceptible way. The samples are ordinated in a multidimensional "space". The first principal component axis is the vector that describes most data points, the second axis the vector that describes second most data points etc. The result for every horizon is presented with one vector for each axis.

The mathematics of the method can be found in ter Braak & Šmilauer 1998. The program CANOCO for Windows was used to perform the analysis (ter Braak & Šmilauer 1998).

By applying principal component analysis it might be possible to detect subtle changes within large data sets.

4 Results

4.1 Lithology

The lithostatigraphy of the cores have been described in detail in the laboratory, Table 2. All depths in core N23-575 are measured from the ice surface of the lake. The cores are correlated by the very sharp and well-defined boundary between Unit 1 and 2 at 558 cm. All depths in core N23-560 are measured from this level. Using this boundary as a synchronous time marker was considered a reliable correlation horizon, as it is sharp and well defined in both cores. The correlations made, showed that the initial field measurements were remarkably exact. The difference in the depth measurements between the cores were less than one centimetre.

4.2 Magnetic susceptibility and loss-on-ignition

The results of the magnetic susceptibility and loss-on-ignition measurements are presented in Fig. 2 and 3.The bottom most unit consists of silt and clay, and there are no traces of organic matter according to the loss-on-ignition. The magnetic susceptibility curve reaches very high

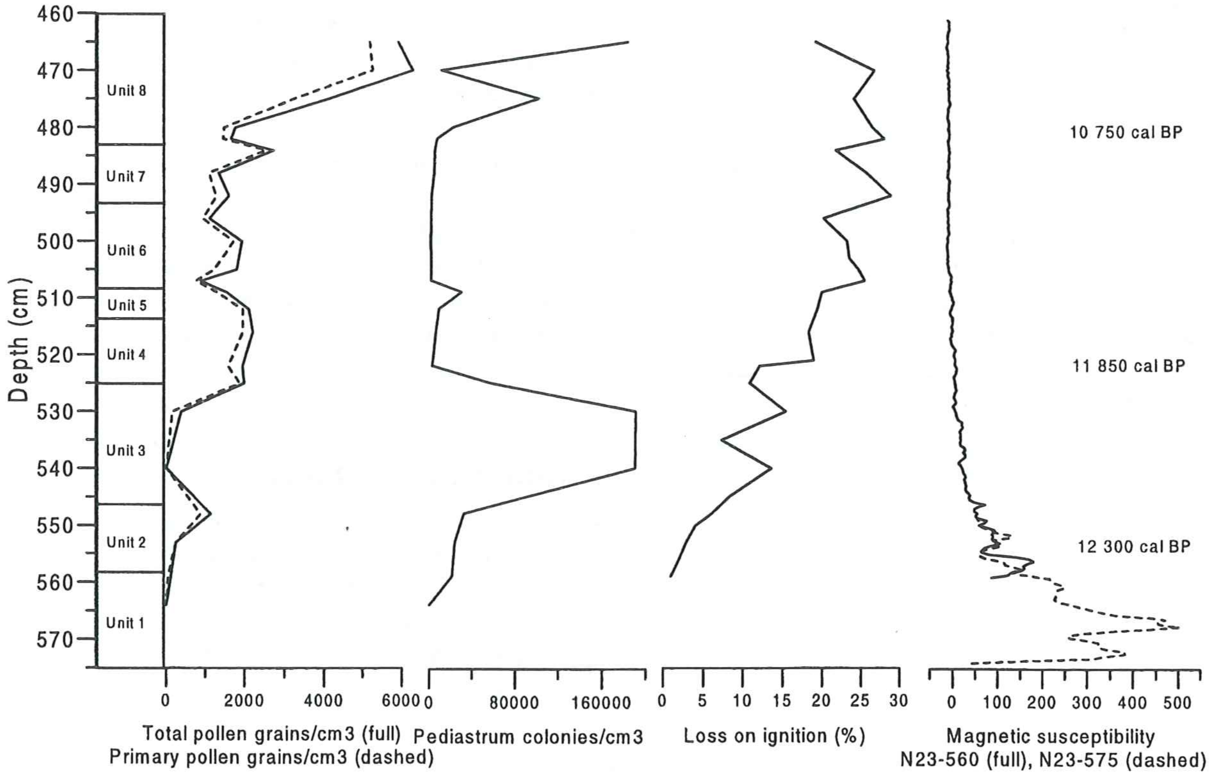

Fig. 2. Pollen concentration, Pediastrum concentration, loss-on-ignition and magnetic susceptibility. The values extending beyond 560 cm in pollen- and Pediastrum concentration are from core N23-575.

Table 1. Radiocarbon datings from core N23-575. The samples LuA-5029 and LuA-5030 have not been used in chronology.

Depth (cm)	Sample Nr	Material	Obtained ^{14}Cage BP	Calibrated ^{14}C age BP, two sigma probability	Cal. age BP used in chronology
482.5-483.5	LuA-5031	bulk	8980±120	10240-9910	10 750
503-505	LuA-5029	terrestr. moss	6510±160	7570-7260	7415
516-517	Ua-15422	terrestr. moss	10 180±115	12 300-11 400	11 850
534-535	LuA-5030	terrestr. moss	11 270±110	13 430-13 130	13 280
557-558	Ua-15421	terrestr. moss	10 385±115	12 650-11 950	12 300

Table 2. Litostratigraphic description of core N23-575 and N23-560

Core: N23-560

Unit	Depth (cm)	Description
8	483-460	Brown faintly laminated silty algae-rich gyttja.
7	493-483	Light brown faintly laminated silty clayey algae-rich gyttja. Upper boundary is fairly sharp.
6	508-493	Dark brown laminated silty clayey algae-rich gyttja. Laminae consist of thin dark layers. The lamination is inclined between 506 and 499 cm. Upper boundary is rather gradual.
5	513.5-508	Light brown laminated silty clay gyttja Upper boundary is rather sharp.
4	525-513.5	Greenish brown grey silty clay gyttja. Lamination between 525 and 521 cm. Laminae consist of variations in content of coarse organic matter. 520-515.5 is dark brown, very rich in water mosses. Lighter layer of silty clay gyttja at 513 cm. Upper boundary is rather sharp.
3	546,5-525	Brown grey - dark brown silty clay gyttja. Increasing content of water mosses towards the top. Thin layers of silty clay gyttja, low content of water mosses at 541 and 534.5 cm.Very high content of water mosses from 531 to 525.Upper boundary is sharp and inclined.
2	558-546.5	Grey silty clay, very rich in water mosses. 558-552 is laminated. The lamination consists of grey silty clay with no coarse organic matter and grey silty clay high in coarse organic matter (water mosses). At 552-54,6 the lamination disappears and the content of water mosses increases.Upper boundary is rather sharp.
1	560-558	Grey faintly laminated silty clay. The lamination consists of thin silt layers. There are no coarse organic matter visible to the naked eye. Upper boundary is sharp. Further penetration was not possible.

Core: N23-575

Unit	Depth (cm)	Description
8	484-475	Brown faintly laminated silty algae-rich gyttja.
7	494-484	Light brown faintly laminated silty algae-rich gyttja.Upper boundary is fairly sharp.
6	506-494	Dark brown laminated silty algae rich gyttja. Lamination consists of thin (1 mm) darkish-black laminae. The upper boundary is rather gradual.
5	513-506	Grey brown laminated silty clay gyttja. The unit has a low content of coarse organic matter. The upper boundary is rather gradual.
4	522-513	Greenish brown-grey silty clay gyttja. Rich in water mosses between 519-516 cm. Thin, 1 mm, darker layer at the upper boundary. Upper boundary is rather sharp.
3	547-522	Brown grey – dark brown silty clay gyttja. The unit is rich in water mosses. Differences in the content of water mosses forms several layers in the unit. A layer of grey silty clay gyttja 3 mm thick is present at 533 cm. A clast of grey silty clay gyttja is present at 539 cm. At 543-534 cm dark brown with very high content of water mosses. Between 534 and 531.5 cm the content of water mosses is lower. 531.5-522 cm dark brown with high content of water mosses. Upper boundary is rather sharp.
2	558-547	Light grey brown grey silty clay. The unit is laminated between 556-551 cm. The lamination consist of 1-3 mm thick layers with higher content of coarse organic matter (water mosses). The content of coarse organic matter increases upwards in the unit. Higher content of coarse organic matter occurs between 557 and 555. The upper boundary is rather gradual.
1	575-558	Laminated silty clay. Lamination consists of thin coarser laminae and is inclined between 564-562.5 cm. Between 562-558 cm the lamination is planar. At 560 there is a thin, 1 mm thick, silt-fine sand layer. The thickness of the laminae varies between 0.5–2 mm. There is no coarse organic matter visible to the naked eye in the unit. The upper boundary is rather sharp. It was not possible to penetrate further.

values and the amplitude is large.

After the transition into Unit 2 the organic content increases to c. 5%, while the magnetic susceptibility values decrease, but show some large fluctuations In Unit 3 the organic content fluctuates between 5 and 15%. The magnetic susceptibility decreases in this unit and the amplitude of the fluctuations gradually become smaller.

In Unit 4 the amount of organic matter reaches 18%, and is fairly constant up throughout Unit 5. The magnetic susceptibility continues to decrease and the fluctuations become less pronounced. Loss-on-ignition reaches its highest values, (25%), after which it decreases. However, this decrease is mostly due to the uppermost sample, and might therefore not represent a significant trend. After the transition into Unit 6, the magnetic susceptibility reaches low and stable values.

4.3 ^{14}C-datings and calibration

Five samples have been ^{14}C dated by accelerator mass spectrometry measurements (Table 1). The obtained radiocarbon dates have been calibrated with OxCal v 2.18 (Ramsey 1995; Stuvier *et al.* 1998). Two of the datings are situated on the radiocarbon plateaux at around 10 000 B.P. and 10 400 B.P., which results in large uncertainties for the calibrated ages (Table 1).

Two datings are considered to give erroneous ages (LuA-5029 and LuA-5030). The reason for this is not certain, but is most likely due to various types of contamination.

The remaining three dates have been used to establish an age-depth curve (Fig. ?). With this curve it is possible to estimate the sedimentation rate and the approximate age for any level along the core. The curve, which will be further discussed in chapter 6.1, shows a dramatic change in sedimentation rate at the sample Lu-15422.

4.4 Pollen analysis

The pollen diagram was zoned into five *local pollen assemblage zones* (Tat: A-E p.a.z), Plate 1. The zones are determined by the relationship in percentage between the different taxa. The percentages are based on the total pollen sum including all local taxa. Excluded from the total pollen sum are exotic and unidentified pollen taxa and other microfossils, i.e. algae, moss spores, fungal spores and insect remains.

No numerical method for zonation of the diagram was applied, as the pollen sums were considered too low for such methods.

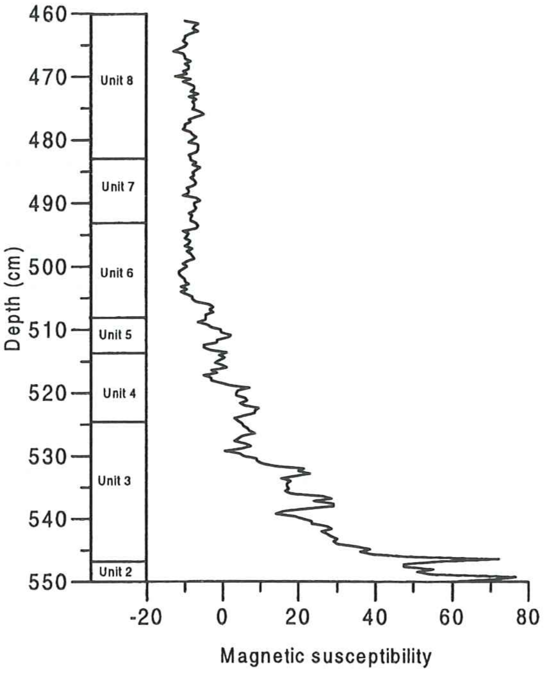

Fig. 3. Detailed magnetic susceptibility curve for core N23-560. The diferrences in amplitude are clearly visible.

Tat A: Gramineae p.a.z., 565-527.5 cm

In the oldest zone, pollen sums are very low, between 0-10 pollen grains/horizon. The only taxon that appears throughout most of the zone is Gramineae. Because of the very low pollen sums the values of Gramineae fluctuate greatly, from 0 to 100%. Exotic pollen grains of *Pinus* and *Betula* are present in the zone and reach 15% and 20%, respectively. *Alnus* and *Oxyria/Rumex* occur with one pollen grain each.

The most striking features of the zone are the high values of Pediastrum, 90-100 %, and Cladocera, 90-95 %, values.

Tat B: Oxyria/Rumex-Gramineae p.a.z., 527.5-513.5 cm

In this zone *Oxyria/Rumex* pollen grains occur for the first time, with the exception of one pollen grain in zone Tat A. *Oxyra/Rumex* immediately reaches its highest values (75%) in the sequence, and never drops below 60% within the zone. Gramineae attains values around 15%, and Cyperaceae pollen occur for the first time and become more abundant within the zone, reaching around 10% at the top. *Ranunculus* pollen grains also occur for the fist time in the middle of the zone and reach values around 10%.

Pediastrum along with Cladocera decrease shortly after the beginning of the zone. From around 100% Pediastrum rapidly drops down to 40%, and Cladocera shows a similar pattern declining from nearly 100% to 10%. Rhabdoicella cocoons appear for the first time, and rapidly increase to 60%. Moss spores appear for the first time and increase in one step to 95%. Ang 4 follows the development of moss spores and reach 90%.

Tat C: Ericaceae-Oxyria/Rumex p.a.z., 513.5-493.5 cm

The appearance of ericaceous pollen grains along with a rapid decrease in *Oxyria/Rumex* mark the beginning of this zone. *Oxyria/Rumex* pollen grains drop to around 20% in the lower part of the zone and then rise to 25% in the upper part, followed by a decrease at the boundary to Tat D. Pollen grains of *Empetrum, Vaccinium* and Ericaceae sp. become more common between 515 and 505 cm. *Empetrum* reaches its highest values of about 20%. Gramineae and Cyperaceae show fluctuating values around 20 %. Pollen grains of Rosaceae are also new to the zone, except for one pollen grain in Tat B.

Alnus pollen are new among the exotic pollens, except for one pollen grain in zone Tat A, and reach over 20%.

Pediastrum colonies drop to their lowest values (30%) during this zone. In the uppermost part the *Pediastrum* curve starts to rise, reaching 40% at the boundary to Tat D. Findings of *Botryococcus* is new to this zone and reaches around 12%.

Tat D: Cyperaceae-Ericaceae p.a.z., 493.5-470m

The beginning of the zone is marked by a rapid increase in Cyperaceae, from around 10% in Tat C to 35%, along with a decrease in *Oxyria/Rumex* down to 10%. Towards the end of the zone Rosaceae values start to increase.

Throughout the zone *Pediastrum* frequencies increase, reaching over 90%. Flatworm cocoons reach maximum values (65%) in the beginning of the zone, and decrease thereafter. Moss spores are also abundant during this zone, reaching 90%.

Tat E: Gramineae-Rosaceae-Ericaceae p.a.z., 470-465

The uppermost zone is dominated by rising Gramineae, Ericaceae sp. and Rosaceae values. Cyperaceae frequencies drop from 40 to 20% during the zone. Rosaceae reaches maximum values (27%) in this zone, and *Pediastrum* and *Cladocera* increase dramatically. Moss spores, Hystrix, flatworm cocoons, Geoglossaceae spores and Ang 4.

4.5 Multivariate analysis

In the PCA analysis the 1st axis represents 59% of the variation, the 2nd 20% and the 3rd 10%.

The sample values for the first PCA axis is presented in Fig 4, along with the strength of the variables. From the plot it is obvious that the sequence can be divided in three zones.

The first zone, sample levels 559-530 yield highly positive values. The variables with the highest positive value are *Pediastrum* and magnetic susceptibility and in the first zone these parameters reach high values (Fig. 4).

The next PCA zone starts between 530 and 525 cm depth, when the 1st axis scores shift from positive to negative values. The samples remain negative until the uppermost sample at 465 cm depth, after which the values

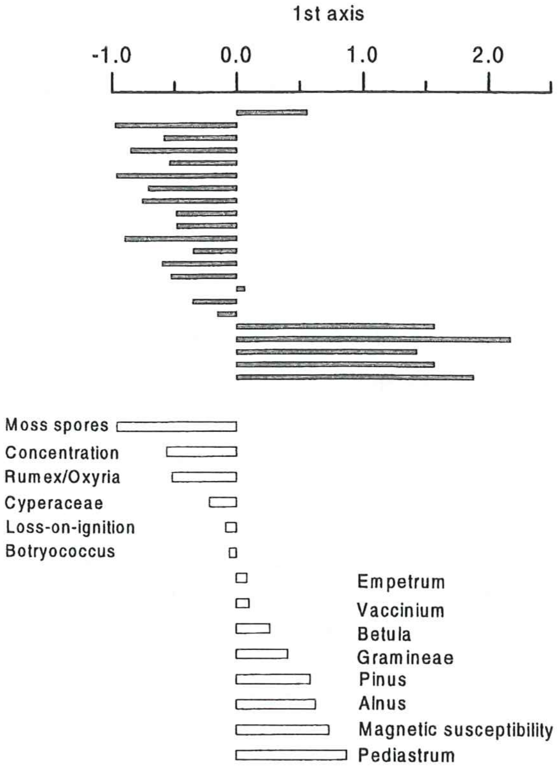

Fig. 4. Stratigraphic plot of sample scores on first axis (59 %) and variable strength.

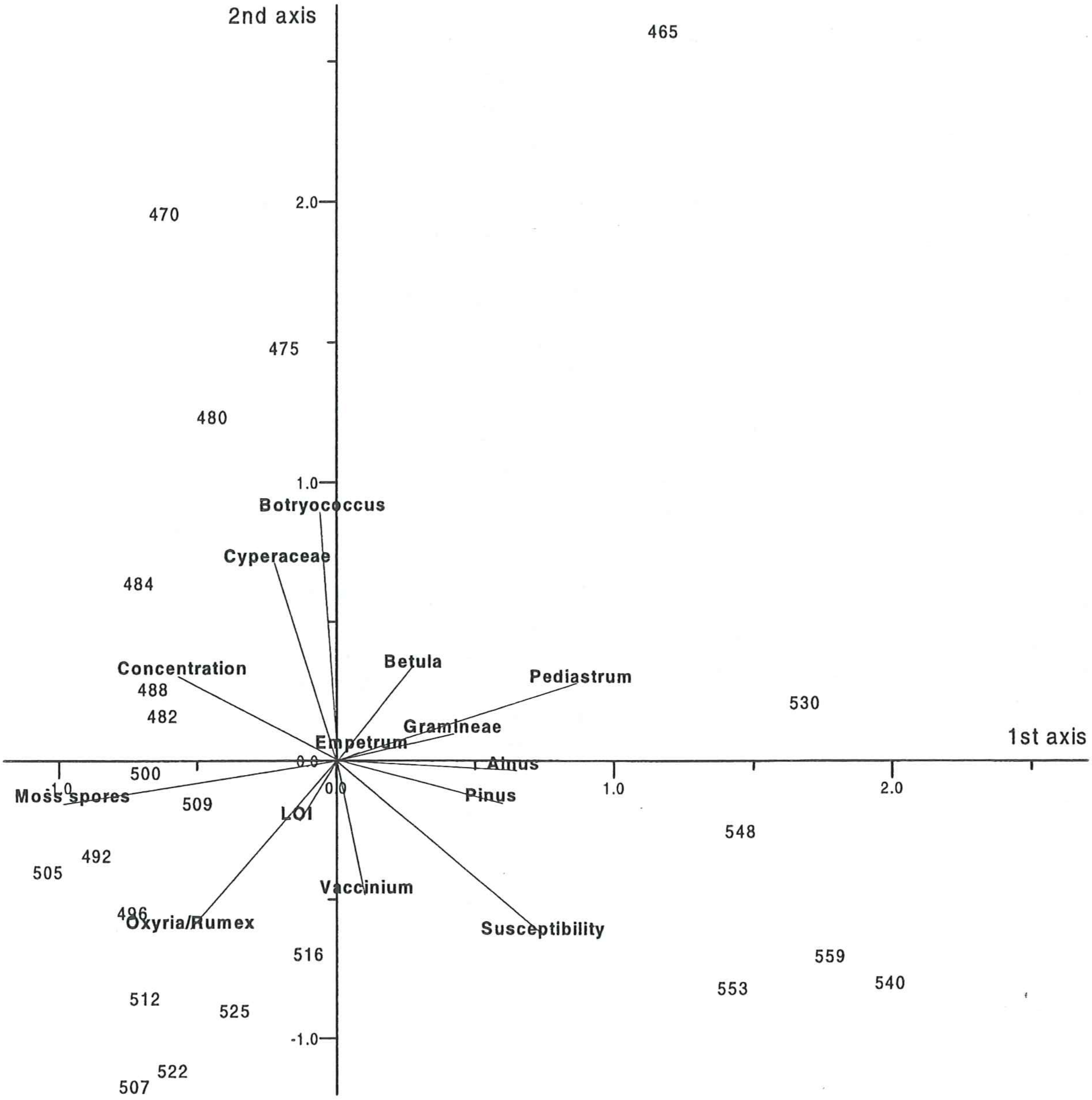

Fig. 5. Biplot for 1st and 2nd PCA axis.

become positive again.

The most important factor for driving the values in a negative direction are high pollen concentrations, moss spore values and *Oxyria/Rumex* percentages, and the negative values during this second phase is mainly due to increasing importance of these parameters.

The change to positive values for the uppermost sample is largely associated with a large increase in *Pediastrum* along with declining frequencies of moss spores, and *Oxyria/Rumex* and Cyperaceae pollen grains.

The results from the PCA analysis are also presented as biplots for the 1st and 2nd axes (Fig. 5) and the 1st and 3rd axes (Fig. 6). In the plot for the 1st and 2nd axis the three zones are also clearly distinguishable. Furthermore, the samples follow a clockwise development from the lower right corner of the plot to the upper right corner. Based only on the biplot it is hard to distinguish any zonation within the second zone, but with the aid of the pollen diagram the local pollen assemblages Tat B-D can be distinguished. The uppermost pollen zone is, however, only represented by one sample at 465 in the PCA, while it consists of two samples in the pollen diagram.

The biplot for the 1st and 3rd axis displays a more scattered pattern, but there is a clear zonation between negative and positive sample values along the x-axis. The samples from 559 to 530 cm and the uppermost sample at 465 cm show positive values, while the "negative" group of samples is displayed as two zones, one consisting of the samples 525 to 512 cm and 500 cm, and the other group between 509 to 470 cm.

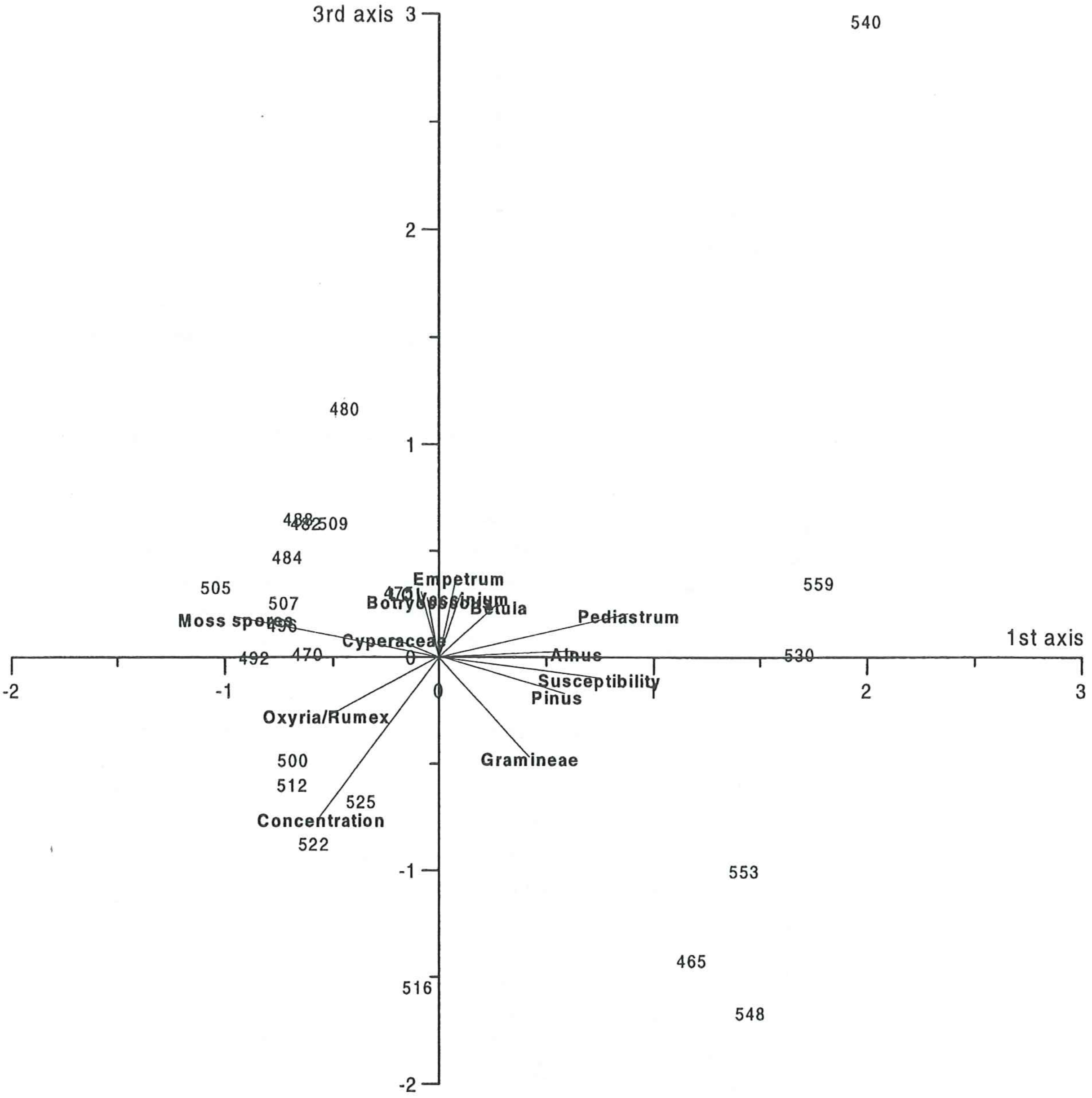

Fig. 6. Biplot for 1st and 3rd PCA axis

5 Interpretations

5.1 Datings and correlations

The age depth curve shows a great change in the sedimentation rate with the sample Ua-15422 (Fig. 7). This change is interpreted as the transition from Younger Dryas to Preboreal, and is probably related to environmental changes around the lake at that time. As the calibrated age spans are so great for the two lower samples it is not possible to only base the timing of the Younger Dryas-Preboreal transition solely on the age depth curve, but other parameters also have to be considered.

It is likely that changes in sedimentation, lake production and pollen spectra also take place at the YD-PB climatic transition, since it is considered to be a more or less synchronous event in the North Atlantic region (Björck *et al.* 1996). Hypothetically it can therefore be used to determine the exact position of this important boundary. Changes associated with a climatic shift are registered in the pollen diagram, pollen concentrations, loss-on-ignition curve and in the zonation of the principal component analysis between Unit 3 and Unit 4 at a depth of 530-525 cm (Fig. 2 and 4). Taken together all these parameters strongly indicate that the boundary between units 3 and 4 represents the YD-PB transition, and has an age of 11 550 cal ^{14}C years BP (Björck *et al.* 1997). However, this is not a definitive evidence for the age of the lithological change, as it can be delayed due to other factors such as soil properties, plant succession patterns etc. It is, however, the possibly best age estimate and it is unlikely that the changes in the different parameters during the Pleistocene/Holocene transition would be of significantly different age.

5.2 Vegetation history

Before 11 525 cal BP, 575-527.5 cm

A short time after deglaciation the first plants immigrated into the barren land areas. The first vegetation to become established was that of a very sparse pioneer vegetation with low pollen production. The vegetation was discontinuous with much bare soil open to erosion. As very few pollen grains are found in this zone it is difficult to make any certain conclusion about the actual plant composition. But the low pollen concentration indicates a very sparse flora with limited vegetation cover. According to the classification system of Walker (2000) for the tundra biome this vegetation type was most likely a *cushion forb, lichen and moss tundra* or *graminoid and forb tundra.* Characteristic for the first of these vegetation types is a discontinuous cover of rosette plants or cushion forbs with lichen and true mosses. The second vegetation type is more continuos, predominantly herbaceous, and dominated by forbs, true mosses and lichens. Both types have a very low pollen production, and the low pollen sums do not permit any distinction to be made.

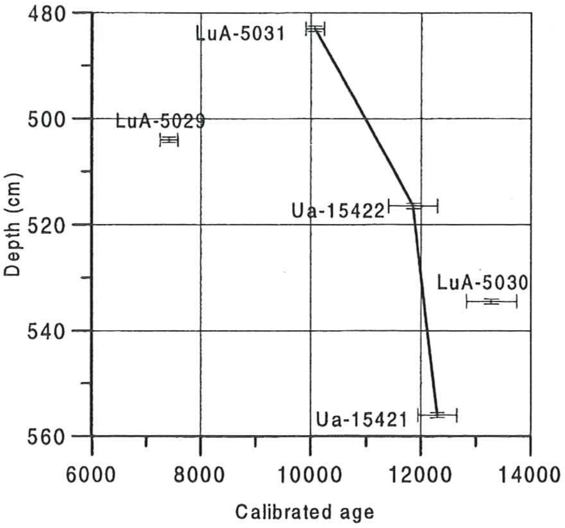

Fig. 7. Calibrated radiocarbon datings as function of depth.

The findings of Gramineae and *Oxyria/Rumex* are most likely of local origin. These species are known from the earliest phase in the vegetation development in harsh environments (Vorren *et al.* 1978, Mathewes 1992).

11 550-11 250, 527.5-513.5 cm

The transition into Tat: B shows great changes in the pollen diagram. Suddenly *Oxyria/Rumex,* and Cyperaceae appear in the pollen diagram. There is also a rise in the total concentration of pollen grains, Fig??. Above all *Oxyria/Rumex* dominates the pollen diagram and most likely dominated the vegetation as well. *Oxyria* is a typical pioneer species that was very important during the early Preboreal stages of the vegetation history in many Greenland lakes (Fredskild 1973).

During this phase the very restricted pioneer tundra expanded into a more continuos vegetation cover. The immigration of most species that are present during this phase probably took place during the preceding phase. After 11 550 cal BP (527 cm) they expanded rapidly and formed a vegetation dominated by pioneer species.

11 250- 10 250 cal BP, 513.5-470 cm

Emergence of ericaceous plants marks the end of Tat:B, and the start of a new phase in the vegetation history. From a pioneer vegetation during Tat:A and B the vegetation changed into a dwarf-shrub heath very rapidly. *Oxyria/Rumex* still makes up for a substantial part of the pollen diagram but the dwarf-shrubs replaced the *Oxyria/Rumex* dominated pioneer vegetation. The still relatively large amount of *Oxyria/Rumex* pollen indicates that some areas still were characterized by pioneer vegetation.

The importance of *Oxyria/Rumex* is further reduced after the beginning of Tat: D p.a.z. indicating that the later immigrants, mainly ericaceous plants, gradually replaced the pioneer vegetation.

A distinct rise in Cyperacea pollen grains at the unit C/D transition might indicate wetter conditions.

10 250-10 100 cal BP, 470-465 cm

The uppermost zone consists of only two samples, but is still clearly distinguishable. The most striking feature of the zone is a dramatic rise in Rosaceae pollen. There is also a decline in Cyperaceae pollen grains.

Still the dwarf-shrub heath is the dominating vegetation type, but the Rosaceae pollen might be an indicator for a more varied environment, with more species and individuals. There is also a dramatic rise in total pollen concentration, Fig. 2, indicating a more dense vegetation cover.

The decline in Cyperaceae along with the rise in Gramineae might indicate a change towards vegetation favoured by drier conditions.

6 Discussion

6.1 Lacustrine environment and climate change

The lowermost Unit 1 consists of silt and clay without any organic matter (Table. 1) and probably represents the onset of sedimentation in the basin. These sediments may be of glacial origin and deposited very close to the active ice-margin.

After some time the organic production began, indicated by increasing loss-on-ignition values within Unit 2 (Fig. 2). *Pediastrum* and water-mosses started to grow in the lake. The existence of *Pediastrum* implies that the lake was ice-free during the summer, that the waters were relative clear and that the temperature in the water was warm enough for algae growth.

During this time the soils around the lake were fresh and rather unstable. There was much bare soil with high content of glacially derived silt and clay subject to erosion. The decreasing input of minerogenic matter indicated by the falling magnetic susceptibility curve (Fig. 3) is due to two factors. After deglaciation there is a general decline in the amount of silt and clay in the ground due to out-wash by precipitation and melt water (Matthews 1992). The out-wash of fine minerogenic matter is very large shortly after deglaciation and then declines gradually. The soil stability is also increased due to establishment of plants further decreasing the out-wash of fine materials. During Unit 2 the high and fluctuating magnetic susceptibility values indicate that the soil was unstable and with only a very limited vegetation cover.

The transition from Unit 2 to Unit 3 is associated with changes in production and sedimentation. The very high concentration of *Pediastrum* in the sediment shows that the conditions for algal growth were very favourable and the lake was blooming. The rising loss-on-ignition values are mainly due to the rapid algal growth. The magnetic susceptibility decreases and the fluctuations are less pronounced (Fig. 3).

Blooming of *Pediastrum* early in the lake development is a common feature for recently deglaciated lakes and has been shown in many Greenlandic lakes (Fredskild 1973, Funder 1978, Björck & Persson 1981) as well as in other parts of the world (Vorren *et al.* 1988). *Pediastrum* is one of the first organisms to invade lakes and take advantage of the lack of competition as well as the high amount of nutrients. As soon as the influx of fine minerogenic matter is reduced and the lake water clears, sunlight is able to penetrate and algae start to grow. Even in relatively cold climates small lakes and ponds are warmed up enough during the summer to allow rapid algal growth. The algal growth in lake N23 is most likely triggered by the reduction of clay and silt in suspension allowing sunlight to penetrate. Already established algae in the lake took advantage of the improved light conditions and expanded rapidly.

After the end of the Younger Dryas the climate underwent large changes around the North Atlantic region, which had great effects on the environment on South Greenland. The production of *Pediastrum* dropped dramatically and almost simultaneously the organic production increased, Fig 2. On land the vegetation expanded rapidly forming a more continuous vegetation cover.

The rise in the loss-on-ignition curve shortly after the transition into the Preboreal is caused by increased production in the lake and increased out-wash of organic litter from the surroundings.

Part of the increased organic content in the sediment could be explained by higher precipitation and raised lake level. A higher water level would submerge the land areas close to the shore and wash out organic litter from the ground. More precipitation would also have increased the out-wash of organic litter. The increased out-wash of nutrients favoured the production in the lake as can been seen by the rapid rise of flat worms (Turbellaria) and after some time *Botryococcus*. In contrast to the other lake dwelling organisms, *Pediastrum* declines rapidly and nearly disappear after the end of the Younger Dryas (Fig. 2), probably due to increased competition by other organisms and deteriorating light conditions as a consequence of the increased content of organic matter in the water.

The loss-on-ignition and magnetic susceptibility values are fairly stable through Unit 4 and 5. At the transition between Unit 5 and 6 the LOI rises (Fig. 2) and the magnetic susceptibility drops to a low and stable level (Fig. 3). The lithology also changes to a algae rich gyttja. This change is associated with emergence of ericaceous plants and formation of dwarf shrub heaths. The woody plants increase the soil stability reducing the amount of minerogenic material brought into the lake, as shown by the change in magnetic susceptibility.

The alga *Botryococcus* immigrates into the lake in Unit 6 (Fig. 4). The emergence of these algae might be due to the lower input of fine minerogenic material after the development of dwarf-shrub heaths, which might have improved the light conditions. The increased input of organic material shown by the rising LOI curve brought more nutrients into the lake and was most likely favoured the algae growth as well.

During Unit 6 the LOI curve is rising and at the boundary to Unit 7 it reaches a maximum value. After the maximum there is a downward trend in Unit 8. The maximum in organic content correlates to a maximum in flatworm cocoons (Turbellaria). The great abundance of organisms living in the lake indicates high productivity and a good supply of nutrients.

There is also a rapid increase of Cyperaceae during Unit 7 and it dominates the pollen diagram up to the end of Unit 8. Cyperaceae is favoured by wet conditions and might be taken as an indication of generally high amounts of precipitation. High precipitation also cause increased run-off with more out-wash of organic matter from the ground litter. The increased input of organic matter from the surroundings increased the amount of nutrients in the lake which favoured productivity. The growth of *Botryococcus* and *Pediastrum* is favoured by a high input of organic material via inflow, which indicates increased precipitation (Fredskild 1995).

The decline in loss-on-ignition in the uppermost sample correlates to the decline in Cyperaceae and flat worm cocoons and might be due to less precipitation and less out-wash of organic resulting in lowered lake productivity.

The more humid conditions during the early Holocene was most likely caused by the rapid break up of sea ice (see discussions below) following the Younger Dryas cooling. The open ocean suplied the air with moisture which increased precipitation. The open ocean also warmed the air during the autumn and spring. If the ocean was open during the winter the effect would have been considerable on the winter climate.

6.3 Plant succession and climate change

On recently deglaciated terrain the re-establishment of vegetation takes place in a successive way, giving rise to a progressively more widespread and varied vegetation. The pathway of the succession is dependant on several factors relating to the physical properties of the surroundings, local and regional climate, immigration pattern and the ecosystem as a whole (Mathewes 1992).

The plant succession can often be divided into well-defined zones with different plant composition. However, some of the succession is merely changes within the plant community itself, e.g. transition from prostrate dwarf-shrub heaths to erect dwarf-shrub heaths, and is hard to detect in a pollen diagram. In areas with similar physical properties and climate the plant succession could be expected to be more or less similar, at least on a broader scale. Large regional climate changes, e.g. the Younger Dryas cold spell, are likely to affect the succession and with sufficient information such changes are possible to detect in palaeoecological data.

However, the effect of regional climate changes during the first phases of succession can be difficult to distinguish from general plant succession, e.g. replacement of pioneer species by later immigrants, or immigration events. By comparing several pollen diagrams from progressively older sites within a geographically restricted area a chronosequence can be established. From the chronosequence it is possible to separate similarities and discrepancies in the vegetation development and separate changes due to regional climate changes from those of immigration and general plant succession.

Here data from three lakes situated in South Greenland, Isoetes Sø, Spongilla Sø and Kløftsø, investigated by Fredskild (1973) are used as comparison material in a chronosequence. The three lakes are situated close to the Taterakasik peninsula in an area of similar topography and climate (Fig. 1). It can be assumed that on a regional scale the conditions are similar at the different sites. On a local scale, however, there are most likely differences in terms of oceanity, exposure etc.

The vegetation successions displayed by the pollen diagrams show considerable similarities during the early stages.

In the first phase of the vegetation history in lake N23 (Tat: A p.a.z) all parameters indicate very cold tolerant tundra vegetation with extremely low pollen production. This phase is dated and correlated to the Younger Dryas cold spell, se chapter 5.1. Indicating that the first immigration of plants took place under very severe conditions. In the harsh environment only restricted pioneer vegetation consisting of Gramineae and herbs could grow.

As can be seen when comparing the datings of the first local pollen assemblages zones this vegetation type only formed in lake N23 during the Younger Dryas (Fig. 8). In the lakes that became deglaciated in the early Preboreal the first pollen assemblage zones are dominated by *Oxyria* and resembles the second phase (Tat:B) in lake N23 (Fig. 8). The difference in the plant composition of the first local pollen assemblage is due to the different climatic conditions during the deglaciation and immigration of the first plants.

After the transition into the Preboreal the climate shift triggered a rapid expansion of the vegetation. The plants that had immigrated during the Younger Dryas cold phase took advantage of the climatic amelioration and expanded rapidly. During the Younger Dryas the very restricted pioneer vegetation expanded and formed a vegetation community dominated by the species that had arrived earlier: *Oxyria/Rumex*, Gramineae and Cyperaceae. The transition from the first cold tolerant pioneer vegetation into the more continuous vegetation after 11 525 cal yrs. B.P. (527 cm) is clearly visible in the principal component analysis plot (Fig. 6). After this dramatic change the plot indicates a more successive change.

Oxyria/Rumex is a common feature of the first pioneer vegetation in all lakes that became ice free in the early Preboreal in South Greenland (Fredskild 1973). It is also an important taxon in other parts of Greenland, e.g. West Greenland and Scoresby Sund, during the first phase of plant succession (Fredskild 1973, Funder 1978, Björck & Persson 1981).

The *Oxyria*-phase (Tat:B p.a.z) came to an end when Ericaceous plants emerged. The *Oxyria/Rumex* dominated vegetation was replaced by dwarf-shrubs that eventually formed dwarf-shrub heaths.

The sudden emergence of Ericaceous plants is most likely a matter of succession. When comparing the timing of the transition into an Ericaceous dominated plant community it is clear that it is not an immigration event, but a phase in the general plant succession (Fig. 8). *Empetrum* and *Vaccinium* have been found in a lake in the archipelago outside Taterakasik peninsula dated to 11 500 yr. B.P. showing that the immigration to the Kap Farvel area took place very early (Björck *et al.* submitted 2001).

The succession from pioneer vegetation with *Oxyria/Rumex* to expansion of dwarf-shrub heaths has been recorded in many areas

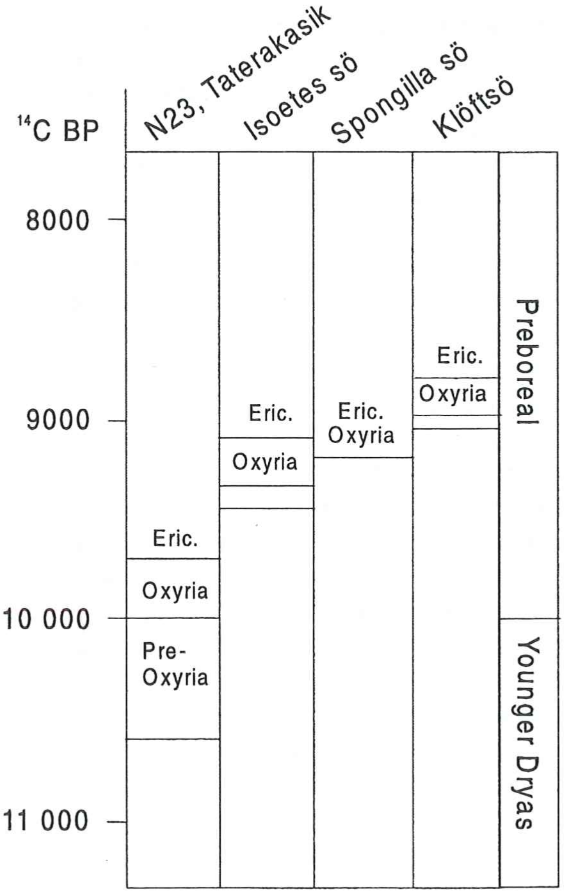

Fig. 8 Timing of the start of the Oxyria dominated zone and the emmergence of Ericaceous plants in some lakes situated in Kap Farvel area. The lowest line in the columns mark the approximate onset of sedimentation. The data from Isoetes Sø, Spongilla Sø and Kløftsø can be found in Fredskild 1973.

and is part of the general succession of plants in recently deglaciated areas (Matthewes 1992). The emergence of dwarf-shrubs is depending on such parameters as soil formation, competition and growth rate.

The plant community is also determined by the immigration of species, for example is the absence of *Salix* and *Betula* due to their late immigration and not to succession.

After the emergence of Ericaceous plants they are important throughout the pollen diagram and dwarf-shrub heaths seem to be a stable vegetation type during the early Preboreal (Fig 4).

The uppermost local pollen assemblage zone in lake N23 (Tat:E) displays a new phase in the plant succession that is not directly comparable to the other lakes mentioned. Ericaceous plants are still important but *Oxyria/Rumex* are nearly absent and Rosaceae shows a dramatic rise. There is also a very rapid increase in total pollen concentration (Fig. 2), indicating a more wide spread and varied flora where pioneer species are replaced by later immigrants.

6.4 Marine influence on the lake in relation to sea-ice extent and climate

The presence of dinoflagellate cysts, "Hystrix", is strong evidence for marine influence on the lake. Findings of marine dinoflagellates have previously been made by Fredskild in lake Spongilla Sø, in South Greenland (1973). In contrast to lake N23 it was a truly marine environment until the isolation at approximately 9200 ^{14}C yr. BP (Fredskild 1973). But Hystrix was also found after the isolation and Fredskild concluded that the dinoflagellates were transported to the lake by overflow of seawater during high tide or by wind driven sea-spray.

Lake N23 was never a truly marine environment, as shown by the presence of the fresh water algae *Pediastrum* in the lowermost part. Hystrix first appears in Tat:B after the end of the Younger Dryas cooling. The only possible way that Hystrix could have entered the lake is by sea-spray. Because of the distance to the marine limit and the elevation of lake N23 overflow is unlikely as explanation for the presence of marine organisms.

During the first stage of the lake development (Tat:A) the absence of Hystrix indicates that the sea-spray was non-existent (Plate 1). Considering that the distance between the ocean and the lake was shorter early after the deglaciation, due to the isostatically down-pressed land, it could be expected that the sea-spray was greater during those times. As there is no sign of influence of marine waters in Tat:A it can therefore be concluded that the sea-spray was prevented until the start of Tat:B.

If the ocean was completely ice covered throughout the year it is unlikely that wind transported sea-spray would take place. The sudden appearance of Hystrix would in this case be a direct result of break up of sea ice after the Younger Dryas cooling.

The Younger Dryas cooling had great effects on the ocean circulation patterns and sea-surface temperatures (SST) and sea-ice cover. During the Younger Dryas cooling the polar front moved south to the latitude of northern Portugal (Ruddiman & McIntyre 1981). In the Norwegian Sea sea-surface temperature dropped more than 5°C (Bard *et al.* 1987), and reconstruction of the winter sea-ice indicates a position at 52°N (Renssen & Isarian 1998). This would mean that the ocean around South Greenland was covered by sea-ice throughout the year during the Younger Dryas cold phase.

The end of the Younger Dryas cooling was a dramatic event that affected ocean circulation patterns in the North Atlantic and sea surface temperatures. In the Greenland-Iceland-Norwegian Seas an abrupt rise of 9°C in SST in half a century have been inferred (Koç *et al.* 1993). The break up of sea-ice was probably as rapid as the change in SST and, as indicated by the sudden emergence of Hystrix, the sea-ice conditions in the waters around Kap Farvel shifted from ice cover throughout the year to open waters in a very short period of time.

This theory is further supported by the investigations of a lake in the archipelago outside the inlet of Tasermiut fjord where sedimentation started app. 14 000 ^{14}C yr. BP. A drop in the amount of sulphur indicates less marine influence during the Younger Dryas cold phase (Björck *et al.* submitted).

From its first appearance, Hystrix is present throughout the core except in the uppermost sample and at 509 cm. The absence of Hystrix in the uppermost sample could be interpreted as a climatic change and increased sea-ice. Other data, e.g. the decrease in loss-on-ignition, the disappearance of flat worms, and the result from the multivariate analysis (Fig. 6), might be taken as support for this explanation, but the change is only seen in the uppermost sample and a more plausible explanation for the absence of Hystrix could be that the land uplift increased the distance to the ocean with a consequent decrease in sea-spray.

7 Conclusions

1 Sedimentation in lake N23 commenced shortly before 12 300 cal B.P.
2 Organic sedimentation started around 12 300 cal B.P.
3 Cold and dry climate characterised the Younger Dryas cooling in the Kap Farvel area. This was most likely due to the presence of sea-ice that persisted throughout the year. However, the presence of Pediasrum indicate that the lake was ice free during parts of the summer and the temperatures not extremly cold.
4 As indicated by the precence of marine living organisms (Hystrix) the end of the Younger Dryas cooling was associated with break-up of the sea-ice around Kap Farvel. When the ocean opened up, the climate became more maritime with warmer winters and more precipitation. This change appears to have been very rapid.
5 The first immigration of plants took places during the Younger Dryas cooling, but only formed a very sparse vegetation cover. After the transtition into Preboreal the plants that already had immigrated took advantage of the improving conditions and expanded rapidly into a pioneer vegetation of herbs, grasses and sedges. After the end of the Younger Dryas the vegetation succession around lake N23 shows conciderablbe similarities with other sites in South Greenland.
6 The end of the Younger Dryas climate state was associated with increasing amounts of precipitation. The precipitiation seems to increase even more after app. 11 000 cal. BP. After app. 10 250 cal. BP there is indications of decreasing amount of precipitation.

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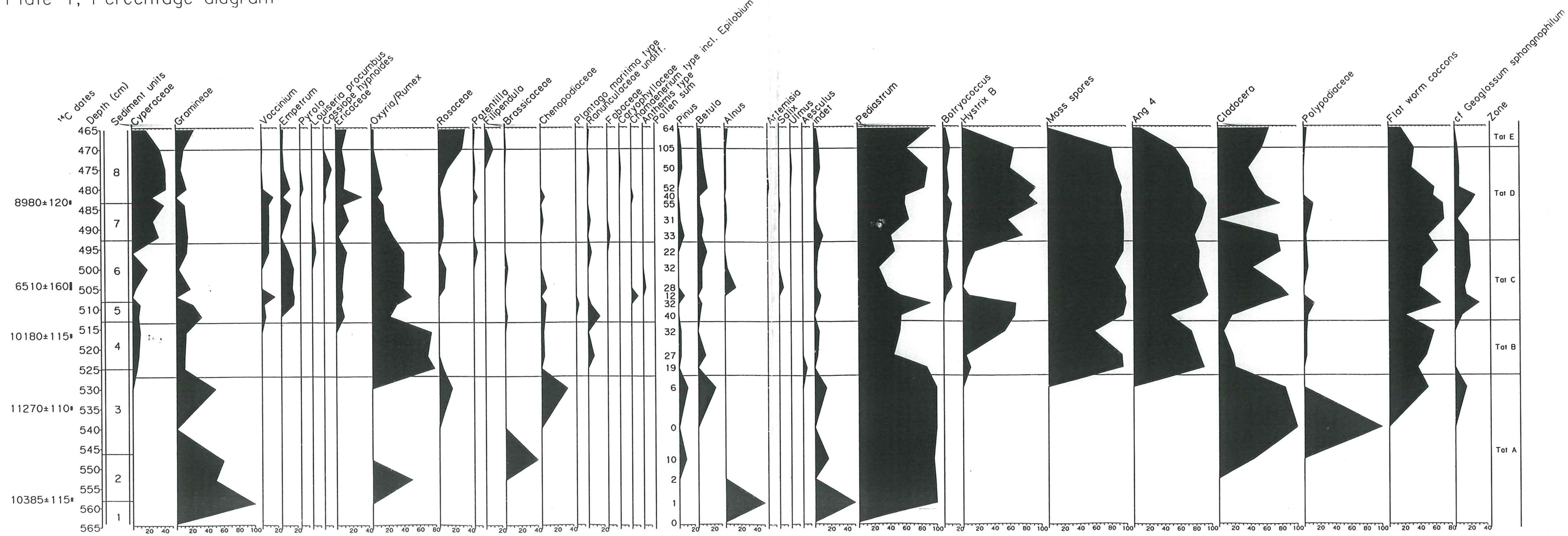
Lake N23, Taterakasik
Plate 1, Percentage diagram



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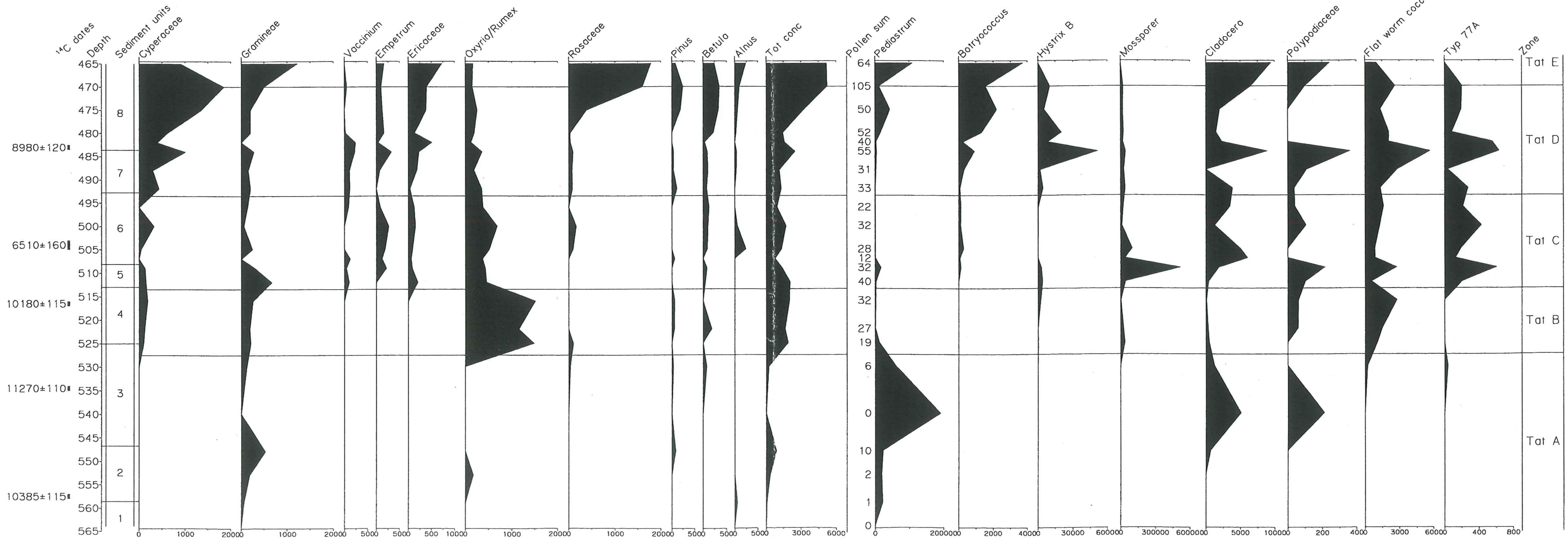
Lake N23, Taterakasik

Plate 2. Concentration diagram.



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