Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994

Henrik Højmark Thomsen
and Niels Reeh (editors)

Open File Series 94/15

October 1994

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Ujarassiortut Kalaallit Nunaanni Misissuisoqarfiat
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Background

Oxygen 18 isotope studies ($\delta^{18}O$) from the large ice sheets of the Polar regions have given rich information about climate and environmental changes during the past c. 250 000 years (250 ka). This has been demonstrated by results from the deep ice-core drilling programmes on the central part of the Greenland ice sheet (e.g. Dansgaard *et al.*, 1982, 1993) and Antarctica (Lorius *et al.*, 1985; Jouzel *et al.*, 1987).

However, the old ice found at depth in the central regions of the ice sheets can also be retrieved at the ice sheet margin, where ice of different ages is found in a sequence with the oldest ice nearest to the ice edge (Lorius & Merlivat, 1977; Reeh *et al.*, 1987, 1991). Oxygen isotope climate research of this kind was undertaken in 1985, 1988 and 1992 at Paakitsoq north-east of Ilulissat/Jakobshavn, West Greenland (Fig. 1).

In 1985 surface ice were sampled with a spacing of 2-5 m along a profile on the ice sheet margin at Paakitsoq (Fig. 1),(Reeh & Thomsen, 1986). Analyses of the samples for $\delta^{18}O$ showed that Pleistocene ice, which was originally deposited in the Summit area of Central Greenland where two deep ice cores GRIP and GISP2 (Fig. 1) recently have been retrieved is distributed horizontally as a c. 600 m wide zone of ice parallel to the ice margin. To increase the details of the record ice samples were collected at the same location in 1988, but with sampling spacing reduced to between 0.5 and 1 m, and a 170 m section through the Pleistocene-Holocene transition was continuously sampled at 20-cm intervals (Reeh *et al.*, 1989). Comparison of this record with deep ice-core records from DYE 3 and Camp Century, Greenland (Fig. 1) and the Vostok deep ice core record from

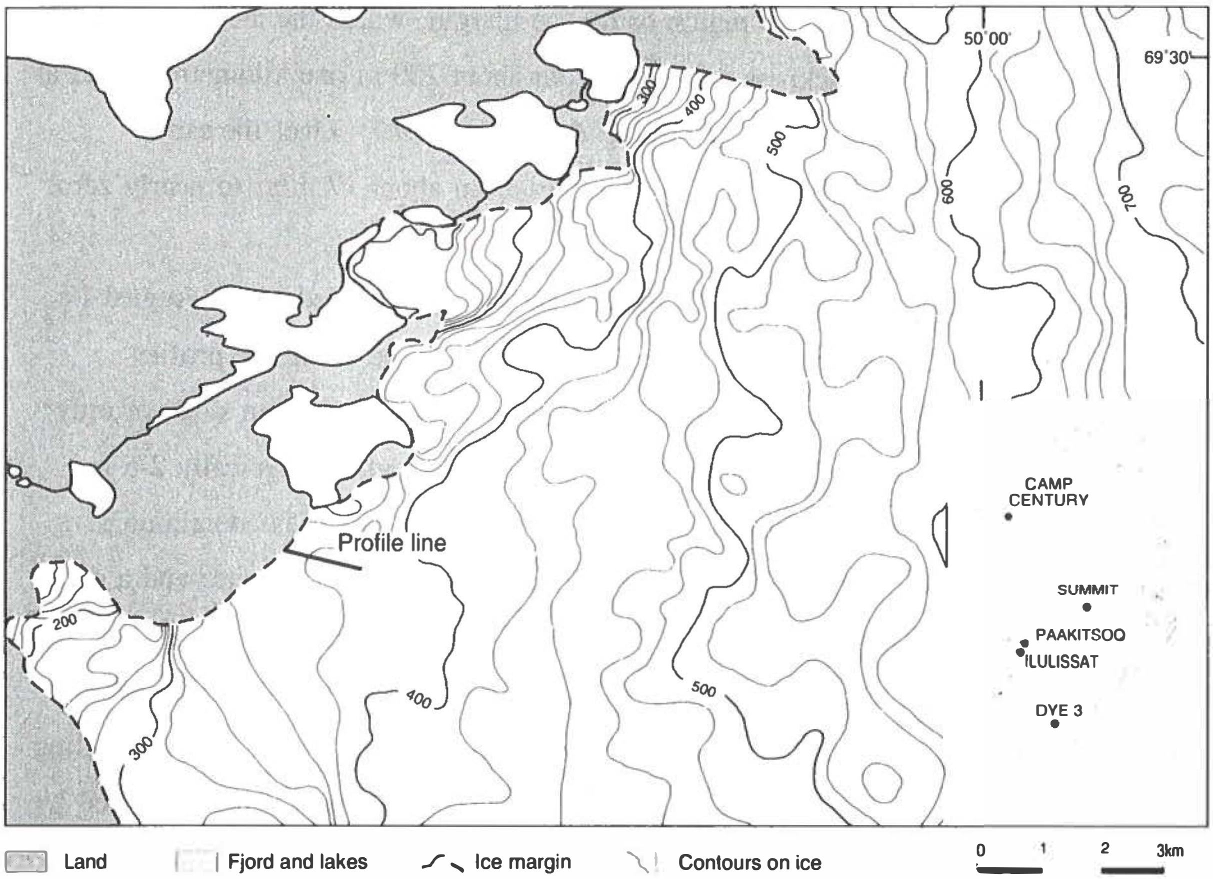

Fig. 1. Map of ice sampling location at Paakitsoq, West Greenland. Sampling profile is given. Insert map shows location of Paakitsoq and the three deep ice core drilling sites, Dye 3, Camp Century and Summit (GRIP and GISP2).

Antarctica, allowed an interpretation of the Paakitsoq record in terms of Emiliani isotopic stages (EIS) and a translation of the $\delta^{18}O$ record into a Greenland temperature record covering the past c. 150 000 years (Reeh *et al.*, 1991). This includes the early part of Holocene, Weichsel, Eem and also a part of Saale. In 1992 the Paakitsoq record was further enhanced when a 500 m section of the ice margin covering the Pleistocene period was continuous sampled at 20 cm intervals in order to optimise the comparison between the Paakitsoq and the Summit, GRIP and GISP2 records.

The Paakitsoq ice margin area and climate record

The Paakitsoq ice margin area is lying c. 40 km north-east of the town

Ilulissat/Jakobshavn in West Greenland. (Fig.1). The sampling profile is located in an elevation of c. 380 m in a cul-de-sac region of the ice margin, where the ice motion tends to stagnate (Fig. 1). The ice thickness decreases from about 200 m one kilometre inland to probably less than 10 m at the margin (Thorning & Hansen, 1987). Over the same distance, the ice-flow velocity at the surface decreases from about 17 m/yr to nearly zero. The annual ablation rate is 2-3 m/yr of ice.

The ice sampling programmes in 1985, 1988 and 1992 were carried out in August i.e. late in the ablation season. At this time of the year the ice surface along the profile consists of bubbly glacier ice. The surface is nearly horizontal with a mean slope of only 2° but local surface irregularities with wavelengths and waveheights of typically 2-5 m and 0,5 m respectively are common features. Numerous cryoconite holes containing dark material are present with diameters from a few millimetres to about one metre and a depth from 0.1-0.5 m.

The surface is characterised by a marked foliation approximately parallel with the ice margin and running with a c. 60° angle to the profile. The foliation is made by alternating zones of dark and light coloured ice as well as blue bands and dirt bands. As described by Reeh *et al.*, 1993 the light appearing surface ice is generally coarser than the dark appearing ice. Moreover the cryoconite holes are more abundant in the light coloured ice than in the dark ice where the dirt particles seem to be more uniformly distributed at the surface. Comparisons of the described foliation and the oxygen isotope values of surface ice samples show that light/dark coloured ice is associated with relatively high/low $\delta^{18}O$ values. Blue bands, 1-50 cm which can be followed over distances of several hundred metres are common features. They consists of clear coarse-grained ice with $\delta^{18}O$ values several ‰ higher than the surrounding ice. An explanation of this $\delta^{18}O$ anomaly is not yet known, but to judge from detailed sampling across the bands, they do not seem to break the continuity of the $\delta^{18}O$ record (Reeh et al., 1991). Dirt bands are also common and seems to be located in zones, and they can also be followed over distances of several hundred metres. A closer look at these bands shows that they consists of small pocket-like inclusions of fine debris. Both blue bands and dirt bands incline steeply to the south-east along the whole profile (Fig. 1).

A full interpretation of the 1992 detailed $\delta^{18}O$ record from Paakitsoq has not yet been accomplished. Publication on this matter will be made elsewhere. Preliminary correlation of the 1992 detailed ice margin record from Paakitsoq with the Summit, GRIP and GISP2 deep drilling record is in general agreement with the interpretation described above. An interpretation in terms of Emiliani isotopic stages (EIS) is shown in Fig. 2.

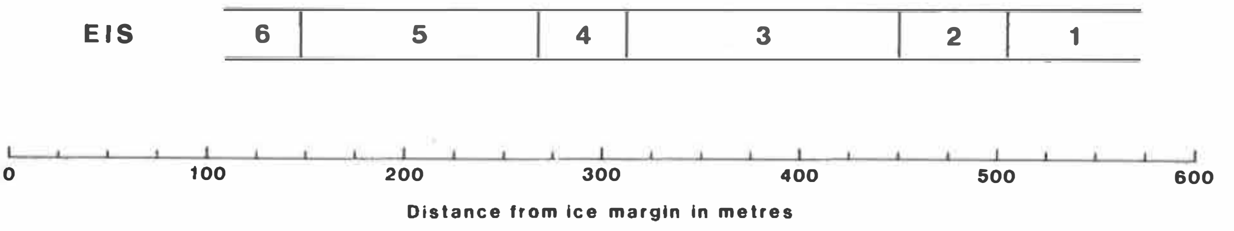

Fig. 2. Interpretation of the detailed 1992 Paakitsoq ice margin record in terms of Emiliani isotopic stages (EIS) plotted as a function of distance from the start of the profile at the ice margin.

Paakitsoq 1994 field programme and participation

The easily accessible ice at Paakitsoq offers a unique opportunity to study the major climatic events that occurred during the last glacial cycle, since large samples of ice with a limited age-range can be obtained. In this sense the ice margin record is an alternative to the deep ice-core records where the number of environmental parameters that can be studied is limited by the amount of ice available, each parameter requiring a certain amount of ice for its analysis (Reeh *et al.*, 1993). This possibility has attracted the attention of scientist working with environmental parameters requiring large ice samples. A joint project in Paakitsoq was therefore set up in the autumn 1993, and carried out in April 1994 with the aim of retrieving ice samples for studies of pollen, dust, chemistry, textures, fabric and visual stratigraphy. Furthermore measurements of mass balance, ice velocity and deformations were made in a stake network established on the ice margin during the 1992 field season. Besides giving the possibilities of studying the variation of the environmental parameters over a full glacial cycle, the project will also support the establishment of a better chronology along the Paakitsoq record.

The persons and institutions that took part in the field project and their working objects are listed below:

1) Danish Polarcenter Geological Survey of Greenland: (Niels Reeh, Henrik Højmark Thomsen)	$\delta^{18}O$ and ^{10}Be analysis. Measurements of ice velocity and deformation.
2) Alfred-Wegener-Institut für Polar- und Meeresforschung: (Thorsteinn Thorsteinsson)	Analysis of texture, fabric and visual stratigraphy. Measurements of ice velocity and deformation.
3) Geological Survey of Canada: (Jocelyne Bourgeois)	Pollen analysis.
4) Lamont-Doherty Earth Observatory Columbia University: (Pierre E. Biscaye)	Dust analysis.

Moreover, Lise Rangvid worked as cook, and assisted with collection and preparation of samples.

Logistics and general conditions

The fieldwork at Paakitsoq took place from April 10 to May 1 1994. The group was transported to and from the working location at the ice margin with helicopter from Ilulissat/Jakobshavn. A tent camp was set up on the ice margin at the end of the sampling profile (Fig. 1). Two weatherport tents served as a canteen and a laboratory tent respectively.

After setting up of camp facilities, the sampling profile line from 1992 was re-established by surveying and marked with poles for every 50 m. Much of the profile was snow free as it had also been during previous years spring-time fieldwork, Blue bands and dirt bands were clearly visible.

April was chosen as the field period, as there is more than 12 hours daylight and the mean temperature in Ilulissat/Jakobshavn is below zero ($-3.5°$ - $-12.5°C$) which should prevent samples from being contaminated by meltwater and exclude problems with ice-core drilling.

However the weather conditions in April 1994 turned out to be quite abnormal. After a few days with clear sky and temperatures around $-20°C$, the weather turned bad, first with snow storm and later increasing temperature and rain from April 13 to April 17. The temperature stayed above zero from April 18 to April 26 in daytime hours and went again below zero during the last days of the field period.

These abnormal weather conditions affected the field programme in two ways. Firstly, a large part of the sampling profile was covered with deep new-fallen snow, making it more difficult to study the surface features. Secondly, the high temperature made drilling difficult and caused a high risk of getting the drill stuck in the ice, which actually happened several times under the work. The different drills available from the individual participating groups were therefore tested for advantages and disadvantages under these circumstances and were shared in the work according to their benefits. Some of the original field plans therefore had to be changed and a closer coordination of the different drilling programmes were made to achieve maximum efficiency.

However, the programme was accomplished with only a few modifications. Reports on the separate programmes are given in the following articles (Biscaye, 1994; Bourgeois, 1994; Reeh & Thomsen, 1994; Reeh *et al.*, 1994; Thorsteinsson & Oerter, 1994).

References

Biscaye, P.E. 1994: Sampling of ice for dust studies on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 10-15 (this volume).

Reeh, N., Oerter, H. & Miller, H. 1993: Correlation of Greenland ice-core and ice-margin $\delta(^{18}O)$ records. In Peltier, W.R. (ed.) Ice in the Climate System. *NATO ASI Series*, **Vol. I 12**, 481-497. Springer-Verlag Berlin Heidelberg.

Reeh, N., Thomsen, H.H., Oerter, H. & Bøggild, C.E. 1994: Ice deformation and velocities along the Paakitsoq profile sampling line, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 20-29 (this volume).

Reeh, N., Oerter, H., Letréguilly, A., Miller, H. & Hubberten, H.W. 1991: A new, detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global planet. Change Sect.)* **90**, 373-383.

Thorning, L. & Hansen, E. 1987: Electromagnetic reflection survey 1986 at the Inland Ice margin of the Pakitsoq basin, central West Greenland. *Rapp. Grønlands geol. Unders.* **135**, 87-95.

Thorsteinsson, T. & Oerter, H. 1994: Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 35-40 (this volume).

Reeh, N., Oerter, H. & Miller, H. 1993: Correlation of Greenland ice-core and ice-margin δ(^{18}O) records. In Peltier, W.R. (ed.) Ice in the Climate System. *NATO ASI Series*, **Vol. I 12**, 481-497. Springer-Verlag Berlin Heidelberg.

Reeh, N., Thomsen, H.H., Oerter, H. & Bøggild, C.E. 1994: Ice deformation and velocities along the Paakitsoq profile sampling line, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 20-29 (this volume).

Reeh, N., Oerter, H., Letréguilly, A., Miller, H. & Hubberten, H.W. 1991: A new, detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global planet. Change Sect.)* **90**, 373-383.

Thorning, L. & Hansen, E. 1987: Electromagnetic reflection survey 1986 at the Inland Ice margin of the Pakitsoq basin, central West Greenland. *Rapp. Grønlands geol. Unders.* **135**, 87-95.

Thorsteinsson, T. & Oerter, H. 1994: Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 35-40 (this volume).

Sampling of ice for dust studies on the ice margin at Paakitsoq, West Greenland

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Objectives

The primary objective of the Lamont-Doherty Earth Observatory (LDEO) participation in the Paakitsoq-94 Expedition was to obtain samples of ice for atmospheric dust analysis; that is, samples larger than can be obtained by conventional deep drilling. Work has been done at LDEO to determine the provenance of atmospheric dust in ice cores using mineralogical and Sr- and Nd-isotope composition analysis. To develop and implement analytical techniques to go beyond these methods, we need larger samples of dust, and the Paakitsoq-94 Expedition offered the opportunity to obtain such samples. A corollary, or secondary, objective was to do high temporal resolution (closely spaced) sampling of ice across abrupt stratigraphic (paleoclimatic) boundaries.

Sampling strategy

In order to do high-resolution (or any other kind of non-random) sampling, it is necessary to get the exact locations on the sampling profile of the climatic events under study. In the Paakitsoq area, the 1994 re-establishment of the 1992 $\delta^{18}O$ profile involves some uncertainties due to the ice flow, so the exact spatial relationship between the 1992 and 1994 profiles could not be determined in the field. The planned method to resolve this uncertainty was based on the proportional relationship between dust quantity and the concentration of dissolved major ions, and the fact that glacial era and stadial ice is dustier than is interglacial, interstadial ice. These relationships have recently been reported in a number of studies on Greenland and Antarctic ice cores. Dusty, high-ionic-concentration ice, when melted, should have a higher electric conductivity than should less dusty ice, so, by taking a series of small, near-surface samples, one should be able to determine the boundaries between glacial and interglacial ice, and perhaps even stadial and interstadial ice along the re-established 1994 Paakitsoq profile and, hence, its spatial relationship to the 1992 $\delta^{18}O$ profile.

It was planned to obtain three kinds of samples of ice, and hence the dust particles it contains:

1) as agreed during the preparation of the Paakitsoq field programme, LDEO would analyze the particles in large-volume samples of ice taken for pollen analysis by Jocelyne Bourgeois (Bourgeois, 1994). This technique, developed and previously used by Bourgeois and her colleagues in the Glaciology Section of the Geological Survey of Canada, involves melting ice in situ using an immersion heater in a core hole drilled into the ice at the desired stratigraphic level. After melting up to 50 litres of ice, the meltwater and the particles it contains is pumped out of the hole into clean containers, brought back to the camp and filtered through Millepore filters of 8 μm pore size, which is the lower size limit of pollen (Bourgeois, 1994). To obtain samples of the particles associated with the pollen, the water that passes the 8 μm filter is then re-filtered through a 0.45 μm pore size Millepore filter. Because 8 μm filter would also retain a significant proportion of the <8 μm particles in the sample, it was agreed to analyze at least one sample both by the sequential 8-then-0.45 μm filtration, and a replicate sample filtered entirely onto a 0.45 μm filter. This was designed to observe any effects of mineralogical and isotopic fractionation resulting from selective retention of the larger size range of particles on the 8 μm filter vs. those eventually retained by the 0.45 μm filter.

2) To drill ice cores to return to LDEO as ice, to undergo lyophilization (freeze-drying) for the extraction of particles.

3) Because of the limitation on the amount of ice that I could return to the U.S.A. as ice, it was also planned to take ice-core samples which would be melted and filtered at Paakitsoq during the field work.

Bourgeois (Bourgeois, 1994) planned to take samples from selected horizons throughout the entire profile, from Holocene to previous-glacial (Saalean) ice. Because LDEO would obtain the particles from those samples (<8 - >0.45 μm), the remaining sampling was concentrated on what appeared to be several abrupt climate change boundaries as defined by the 1992 Paakitsoq oxygen isotope profile, viz. the transition from Last Glacial to Holocene that included the ice representing the Bølling, Allerød and Younger Dryas intervals.

Accomplishments during Paakitsoq 1994 field period

1) Bedding angle. To obtain ice cores representing the shortest stratigraphic interval (maximum temporal resolution), one should drill parallel to the bedding of the ice. No exact information exists about the inclination of the bedding at Paakitsoq. However the inclination of blue bands in the ice was determined at three locations along the entire profile to be 70° toward the southeast, together with Thorsteinsson (Thorsteinsson & Oerter, 1994). The bedding in the ice was then determined to be 70°, assuming that it is parallel with the angle of the blue bands. Some confirmation of this was given in the measurement of the angle of inclination of dust bands that had melted on the surface and sides of ice hummocks along the profile; these too were found to be dipping 70° toward the southeast.

2) Electrical Conductivity. A number of days was used to take short cores from various locations in the profile. The ice was melted, and conductivity measurements on the meltwater were made. The results were very inconsistent and disappointing. The range of conductivities expected for very clean to very dusty ice was from c. 5 to c. 60-80 $\mu S\ cm^{-1}$, but the range encountered in the samples at Paakitsoq was only 4-23 $\mu S\ cm^{-1}$, which was very much toward the low end of the range of the conductivity meter available. Because of inconsistencies between samples from the same core (same bed, drilled at the 70° bedding angle) and even from subsamples from the same portion of the core, a lot of checking of the calibration of the meter was done using a range of standards brought to the field, and checking of stability of the measurements with time. The only thing that was even somewhat consistent was that the conductivity of bands of blue ice was higher than that of the "normal" ice on either side of it, (Reeh et al. 1991, report that the blue ice is consistently "warmer" in terms of $\delta^{18}O$, than the "normal" ice on either side of it.). Also pH paper was tried to see whether or not glacial ice was
significantly different from interglacial ice, but this too proved to be uninformative. After a

few days, the conductivity measurements were given up, as they were too time consuming, and drilling large-volume ice cores was begun.

Because the scheme to use conductivity to locate position in the profile did not work, the idea of obtaining large-volume, closely-spaced samples across stratigraphic boundaries that reflected abrupt climate changes had to be abandoned. Most cores were therefore drilled parallel to the 70° bedding angle at locations thought to be within the ice representing the several Glacial-to-Holocene periods (Glacial, Bølling, Allerød, Younger Dryas and Pre-Boreal). Some attempt was also made to sample the ice at the transitions across some of these boundaries by drilling normal to the 70° (southeast-dipping) bedding plane, i.e., drilling at a 20-degree angle towards the northwest.

3) Filtered particles from pollen samples melted in situ. This work is more thoroughly documented in Bourgeois (1994) but a total of 18 samples was taken, and the water that passed the 8 µm filters was filtered onto 0.45 µm filters for the LDEO particle analysis. The water melted in situ for these samples totalled c. 680 litres, or an average of c. 38 litres per sample (range: 35 to 40 litres.). The last sample taken, at 387.5 m on the profile, was filtered in duplicate by Bourgeois: once in the normal, sequential 8 µm then 0.45 µm way, and once all onto a 0.45 µm filter.

4) Filtered particles from ice cores taken in Last Glacial-to-Holocene ice. A total of 11 cores (27.8 m of ice) drilled in ice from Last Glacial to earliest Holocene age were melted and filtered onto 0.45 µm filters at Paakitsoq. Part way through the field period, the cuttings were saved from the drilling, along with the cores, in order to increase the volume of ice sampled and therefore of particles to be filtered. For the drill used (9 cm ID; 12.5 cm OD), the addition of cuttings increased the size of the sample taken by c. 90%.

5) Ice cores returned to LDEO. Thanks to Thorsteinn Thorsteinsson who lent me two of his insulated boxes for shipping ice, I was able to return four boxes containing 6 cores (17.24 m of ice) from Paakitsoq. These boxes of ice are in the freezer at PICO in Kangerdlussuaq/Søndre Strømfjord and will be flown back to the U.S.A. by military aircraft in August.

6) Miscellaneous samples. I also took a number of surface samples of dust by chipping ice and/or snow in which dust was concentrated by solar melting. I took two samples of sediment from the portion of the shore of a recently emptied ice-dammed lake near the ice margin just north of the profile.

Locations if ice-cores drilled along the profile are listed in the appendix to this report.

Planned analyses of samples

All samples of dust taken at Paakitsoq will be initially analyzed for mineralogy using the new Philips X-Ray Diffractometer that was delivered to LDEO during the field period. Based on those results, a significant number (but not necessarily all) will be analyzed for Sr and Nd isotope composition to obtain, along with mineralogy, tracer characteristics that hopefully will identify (or at least place boundary conditions on) the provenance of the dust, and therefore on the transport pathways of different air masses traversing Greenland during the several climatic conditions that occurred during at least the past 100 000 years. The techniques used are similar to those being used at LDEO to study smaller samples of the GISP2 ice core from Summit in Central Greenland, and to those used to determine the origin of dust from last glacial maximum (LGM) ice in East Antarctica (Grousset *et al.*, 1992).

Collaborators

Two Lamont-Doherty colleagues, Dorothy Peteet (also of Goddard Institute for Space Studies, NY, NY) and Francis Grousset (also of the University of Bordeaux, France) will be collaborating with me in the analysis of the Paakitsoq samples. They are also Co-Investigators on a National Science Foundation (NSF) grant that was funded just days before my leaving for Paakitsoq.

Dorothy Peteet will examine the samples taken by me in the Latest Glacial-to-Earliest Holocene for pollen. We will attempt to separate the mineral- from the pollen-grains before analysis so as to avoid the kind of potential for mineral fractionation by size that is inherent in the samples filtered sequentially for pollen at 8 μm and for particles at 0.45 μm. The separation of samples for this limited stratigraphic effort vs. that of Bourgeois (1994) who is surveying pollen across the entire profile was worked out before the Expedition and will be confirmed between Bourgeois and Peteet.

Francis Grousset will aid in the Sr and Nd isotope composition analyses. In addition, a third Lamont colleague, Todd Sowers, will participate in the analysis of Paakitsoq samples, particularly for Sr and Nd isotope composition analysis. Sowers will also analyze certain of the cores returned as ice from the interval around the Younger Dryas for methane, along with colleagues at the University of Rhode Island.

References

Bourgeois, J.E. 1994: Sampling for pollen on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 16-19 (this volume).

Grousset, F.E., Biscaye, P.E., Revel, M. Petit, J.R., Pye, K., Joussaume, S. & Jouzel, J. 1992: Antarctic (Dome C) ice core dust at 18 k.y. B.P.: Isotopic constraints on origins. *Earth & Planet. Sci. Letters* **111**, 175.182.

Reeh, N., Oerter, H., Letréguilly, A., Miller, H. & Hubberten, H.W. 1991: A new,detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global planet. Change Sect.)* **90**, 373-383.

Thorsteinsson, T. & Oerter, H. 1994: Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 35-40 (this volume).

Sampling for pollen on the ice margin at Paakitsoq, West Greenland

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Objectives

Pollen analysis studies in polar ice caps require large volume of ice normally not available through ice core drilling, unless several core segments are combined. This is sometimes possible in Holocene period ice, where the resolution is high. However in Pleistocene ice one risks combining a large time increment and thereby obliterate some climatic signals. One way to overcome this problem is by melting a large volume of ice, in situ, from an previously drilled borehole and pumping the water to the surface. This method was first tried in two shallow boreholes (approx. 130 m deep) on the Agassiz Ice Cap in the Canadian Arctic (Koerner *et al.*,1988; Bourgeois, unpublished results) where about ten levels were sampled from the Pleistocene and early Holocene ice. Results from this study allowed us to establish the age of the bottom ice as interglacial. Other pollen fluctuations seen in the ice age and late glacial were more difficult to interpret because of a lack of chronological control, due mainly to the small amount of Pleistocene ice available (only 10 metres) at the bottom of the ice cap.

The Paakitsoq ice margin site offers by comparison nearly 600 m of old ice from which a detailed $\delta^{18}O$ record has already been produced (Reeh *et al.*, 1991). Furthermore, this ice, which emerges at the surface, is easily accessible by comparison to ice from a deep borehole. Consequently, it should be an ideal site for undertaking a pollen study of the Pleistocene ice. In the spring of 1994, the main objective of the study was to sample where major shifts occur along the 600 m long isotopic record. We hoped to determine if these shifts corresponded to changes in vegetation (seen as changes in pollen spectrum and in concentration) or possibly be related to changes in atmospheric circulation.

Sampling procedures

The choice of the sampling sites were based on the 1992 $\delta^{18}O$ record. Only "events" extending a few metres along the section were chosen because the movement of the ice, since the summer of 1992, could not be precisely determined in the field.

At the site, we drilled to one metre depth to avoid possible contamination from previous summers' melt. The core fragments were used for studies by other members of the field party (Reeh & Thomsen, 1994; Thorsteinsson & Oerter, 1994). Between 1.5 and 2.5 litres of filtered water (to .45µm) was set in the hole. This allowed us to first test the impermeability of the borehole (see later) and secondly to form a priming medium for the melting device. This device consisted of two immersion heaters encased in a ribbed metal block, 32 cm in total length and 10 cm in diameter. The immersion heaters were wired in parallel to produce a 3.0 Kw heater. The device, hanging from a rope attached to a metal bar at the surface, had to be covered with water at all time. It was powered by a 5kW generator, although 3kW would have been sufficient, and left to melt the ice for 2.5 to 3.5 hours. It was then pulled from the hole and a small bilge pump connected to a plastic tubing was used to retrieve the water from the hole. The water was pumped into large plastic bags and brought to the laboratory tent to be filtered. Approximately 40 litres of water was pumped out of the hole after 2.5 hours of heating. Towards the end of the field season this amount was for unknown reasons reduced to 35 litres for the same hours of heating.

On a few occasions, specially in the oldest ice, the water drained out of the hole; sometimes at the very beginning of the procedure but also after a few hours of melting. No cracks could be seen from the surface. In some cases, part of the sample was saved, but in others another hole had to be drilled. After the water was pumped out, the depth and thickness of the cavity was measured. The sample varied between 38 cm and 53 cm in length with the cavity having more or less the shape of an inverted pear.

The annual snow layer was sampled for pollen near the camp to establish modern deposition at the site for comparison with the older samples. As well, an annual snow sample or a shallow core, representing the last few years of accumulation, was to be sampled during the summer at the GISP2 deep-drilling site to obtain a modern analog for the old ice originating near the Summit area, in Central Greenland.

In the laboratory tent, each sample bag was weighed and the water poured into a 19-litre pressure vessel. It was then pressure filtered through an 8μm pore-size, 50 mm diameter cellulose filter. The filtered water was collected in a plastic bag and re-filtered through a .45 μm pore-size cellulose filter for dust analysis (Biscaye, 1994). One set of samples usually consisted of four 10 l bags. Each bag was filtered separately but sometimes it was necessary to change filters after a few litres because of the heavy dust content. The filtration system was flushed with filtered water between each set of samples to avoid contamination.

Results

One snow sample and eighteen ice samples were collected at the ice margin for pollen analyses studies (see appendix). The first ice sample was taken closest to the margin, in ice tentatively dated as being from the end of the previous glacial period (Emiliani's isotopic stage 6). Several samples were then collected in the following isotopically warm period to see, if it is possible from the pollen content of the ice to determine which part is the Eemian and also see if large pollen changes are associated with the isotopic variations seen within that time period. In ice that is undoubtedly from the last glacial period, samples were not as closely spaced but ice with very cold and warm isotopic values were sampled. Because of a lack of time and problems with the ice drills (Reeh & Thomsen, 1994; Thorsteinsson & Oerter, 1994), the late glacial could not be sampled. Part of that section is covered by Pierre Biscaye (Biscaye, 1994). One sample from the early-Holocene was also sampled for this study. At each sample site, a series of $\delta^{18}O$ samples were collected in order to precisely locate the site on the 1992 $\delta^{18}O$ profile (Reeh & Thomsen, 1994).

Throughout the filtering procedure, changes in dust concentration and colour were noticed. Filtering time for a 10 l sample on an 8μm pore-size filter varied between three and ninety minutes. With the .45μm pore-size filter it usually took at least twice as long to filter. As a general rule, samples from the last interglacial and Holocene were "cleaner" than the ice age samples but within the ice age, some apparent warm peaks contained more dust than the cold periods. Samples also changed from different shades of brown and grey throughout the profile. The early Holocene sample was noticeably different from the others by it's colour (grey) and time of filtration (<3 minutes on 8μm and >60 minutes for

.45µm). Photographs of the 8µm pore-size filters, which contain most of the dust, were taken for future reference, as they will be destroyed as a result of the pollen laboratory procedure used. The dust from the .45µm filters will be studied by Pierre Biscaye (Biscaye, 1994).

Pollen analysis of the samples will start in the summer of 1994. One filter will first be analyzed from each set of samples to obtain an estimate of the pollen concentration. Analysis of the samples will hopefully be completed by early spring of 1995.

References

Biscaye, P.E. 1994: Sampling of ice for dust studies on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 10-15 (this volume).

Koerner, R.M., Bourgeois, J.C. & Fisher, D.A. 1988: Pollen analysis and discussion of time-scales in Canadian ice cores. *Ann. Glaciol.* **10**, 85-91.

Reeh, N. & Thomsen, H.H. 1994: Ice sampling for ^{10}Be and $\delta^{18}O$ analysis on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 30-34 (this volume).

Reeh, N., Oerter, H., Letréguilly, A., Miller, H. & Hubberten, H.W. 1991: A new, detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global planet. Change Sect.)* **90**, 373-383.

Thorsteinsson, T. & Oerter, H. 1994: Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 35-40 (this volume).

Surface topography, ice ablation, ice deformation and velocity along the Paakitsoq profile sampling line

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Pole network and sampling line

To help interprete the environmental records obtained from the ice-sampling profile at the Inland Ice margin at Paakitsoq, West Greenland, studies of surface topography, mass balance and ice dynamics were initiated in the 1988 field season. During this season two poles for ablation- and velocity measurements were drilled into the ice to about 5 metre depth at distances of about 500m and 1000m from the ice margin. The poles were positioned by distance and angle measurements from a reference point established at the mountain slope west of the profile line. The reference point was connected to the local surveying network established by GTO (The Greenland Technical Organisation, now GFU, Greenland Field Investigations) and the coordinates of the measuring points were referred to the local GTO coordinate system (GTO,1983). The two poles were re-surveyed in May 1989, and in August 1989 two replacement poles were drilled into the ice close to the 1988 poles. All four poles were positioned in May 1990.

At the beginning of the next field season in August 1992, it appeared that all poles had melted out and were lying on the ice surface. Since the former foot-points of the poles could still be located, the horizontal motion of the poles since May 1990 could be determined. However, ablation and vertical velocities could not be obtained for this period.

In the 1992 field season, an attempt was also made to re-establish the 1988 profile line. Over most of the profile (50 m - 450 m) the 1992 profile line is within one metre from the 1988-line. At the end of the 1992 line (550 m) the distance between the profile lines increased to 2.5 m. Moreover, the stationing along the 1992 profile line is shifted 2.5 m towards the margin in respect to the stationing along the 1988 profile line.

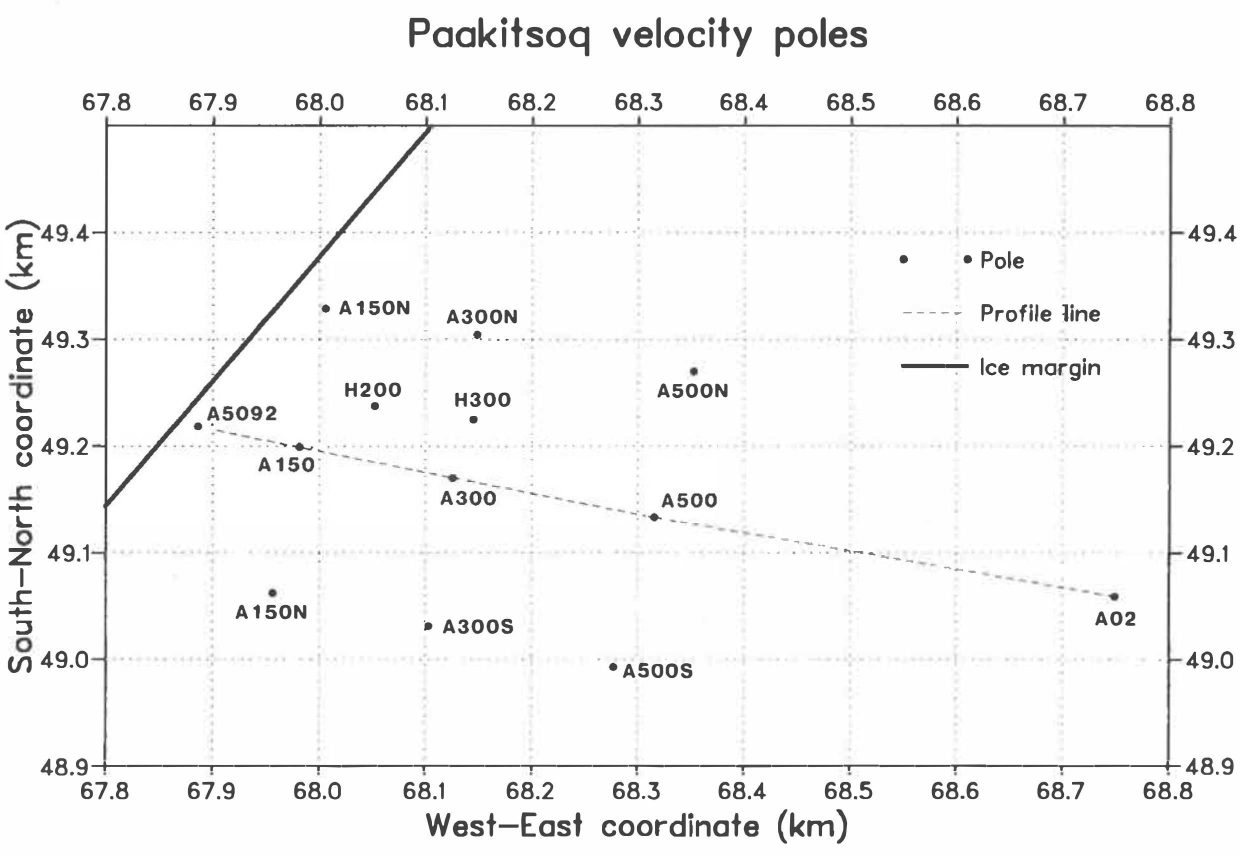

Fig. 3. Network of poles for ablation and velocity measurement.

In 1992 a new network consisting of 10 poles was established, see Fig. 3. The poles were re-measured in April 1994 for determination of ablation, and velocity- and strain-rate distributions around the sampling line. Table 1 gives an outline of the ablation and velocity poles.

In the 1994 field season, an attempt was also made to re-establish the 1992 sampling profile line. This was done rather successfully, the positions of all 50 metre marks in the 1994 profile being less than half a metre displaced from the corresponding points in the 1992 profile.

Table 1. Paakitsoq. Coordinates of ablation and velocity poles

Point	Date	Time	Decimal time (days since 31.12.87)	y (m)	x (m)	z_{top} (m)	z_{ice} (m)	z_{t-i} (m)
A0188	31.07.88	12:00	212.50	68353.46	49123.60	377.95	377.77	0.18
-	08.08.88	12:00	220.50					0.45
-	04.05.89	12:00	489.75	68348.13	49122.80	380.89	379.78	1.11
-	09.08.89	12:00	590.75					2.67
-	07.05.90	11:30	857.30	68339.81	49121.61	382.75	379.75	3.00
A0190	09.08.89	12:00	590.75					0.90
-	07.05.90	11:30	857.30	68339.32	49121.20	380.99	379.66	1.33
-	16.08.92	03:37	1689.15	68317.04	49117.98		377.00	
A0288	31.07.88	12:00	212.50	68837.46	49049.18	391.87	391.71	0.16
-	08.08.88	12:00	220.50					0.44
-	04.05.89	12:00	489.75	68828.32	49050.06	393.99	392.94	1.05
-	09.08.89	12:00	590.75					2.59
-	07.05.90	11:30	857.30	68813.58	49051.83	394.76	391.99	2.77
-	16.08.92	03:37	1689.15	68778.19	49056.55		388.42	
A0290	09.08.89	12:00	590.75					1.01
-	07.05.90	11:30	857.30	68812.59	49051.37	393.20	391.86	1.34
-	15.08.92	13:00	1688.54	68777.55	49055.46		388.36	
-	23.04.94	20:00	2305.33	68749.51	49059.83		388.83	
H200	31.07.88	12:00	212.50	68067.09	49238.62		374.96	
-	15.08.92	13:00	1688.54	68052.59	49237.55		375.18	
H300	31.07.88	12:00	212.50	68163.43	49228.14		375.78	
-	15.08.92	13:00	1688.54	68146.06	49225.34		375.11	
Lake point	16.08.92	04:08	1689.17	69071.54	49043.18	396.19	393.90	2.29
-	29.04.94	22:00	2311.41	69041.67	49045.78	399.30	394.21	4.78
A500	16.08.92	04:08	1689.17	68330.64	49135.71	377.82	376.59	1.23
-	21.04.94	18:00	2303.25	68315.99	49133.88	381.54	377.30	4.24
A300	16.08.92	04:08	1689.17	68134.55	49173.11	376.31	375.28	1.03
-	21.04.94	18:00	2303.25	68126.29	49170.95	380.11	375.76	4.35
A150	16.08.92	04:08	1689.17	67987.45	49201.18	375.95	374.88	1.07
-	21.04.94	18:00	2303.25	67981.63	49199.59	379.20	375.38	3.82
A50	16.08.92	18:00	1689.75	67890.08	49219.82	375.41	373.82	1.59
-	21.04.94	18:00	2303.25	67886.56	49218.86	377.54	374.02	3.53

Point	Date	Time	Decimal time (days since 31.12.87)	y (m)	x (m)	z_{top} (m)	z_{ice} (m)	z_{t-i} (m)
A500N	16.08.92	04:08	1689.17	68364.70	49269.67	376.00	374.92	1.08
-	21.04.94	18:00	2303.25	68352.64	49270.07	379.69	374.76	4.93
A300N	16.08.92	18:00	1689.75	68155.60	49304.68	374.82	373.72	1.10
-	21.04.94	18:00	2303.25	68148.93	49304.51	378.75	373.92	4.83
A150N	16.08.92	18:00	1689.75	68009.75	49329.22	374.82	373.66	1.16
-	19.04.94	16:00	2301.17	68006.20	49328.97	377.83	373.26	4.57
A500S	16.08.92	04:08	1689.17	68295.29	48997.65	378.68	377.72	0.96
-	19.04.94	16:00	2301.17	68277.76	48993.33	382.21	376.26	3.95
A300S	16.08.92	18:00	1689.75	68114.41	49034.41	376.58	375.66	0.92
-	19.04.94	16:00	2301.17	68103.48	49031.81	379.83	375.47	4.36
A150S	16.08.92	18:00	1689.75	67964.66	49065.46	375.02	373.82	1.20
-	19.04.94	16:00	2301.17	67956.70	49062.69	378.03	374.23	3.80

z_{top} is elevation of top of pole, z_{ice} is elevation to ice surface, z_{t-i} is height of pole top above ice surface.

Surface elevation and horizontal ice velocity

Surface elevations along the profile line have been determined in four different years (Table 2 and Fig. 4). There is a tendency for the spring (April, May) observations to be higher than the late summer observations. This simply reflects the fact that a vertical upward movement of the ice with roughly uniform speed takes place all year round, whereas the ablation causing surface lowering is concentrated in a few summer months. Apart from this seasonal variation of surface elevation, there is no indication of surface elevation change in the period from August 1988 to May 1994.

Based on the 1994 surface elevations along the sampling profile line and the pole network, a local surface elevation map has been drawn (Fig. 5). The map indicates that the profile line runs close to the local topographical divide, the ice surface to the north and south of the line sloping towards the northwest and southwest, respectively. However, as shown in Fig. 6 displaying the horizontal ice velocity distribution over the area, the "dynamic" divide is displaced at least 150 metre to the north in respect to the topographical divide. Even the flow lines trough the three northernmost points seem to

Table 2. Paakitsoq. Coordinates of profile points

Point	Date	Time	Decimal time (days since 31.12.87)	y (m)	x (m)	z_{top} (m)	z_{ice} (m)	z_{t-i} (m)
A0-88	31.07.88			67842.57	49228.20		372.76	
Ice margin	31.07.88			67866.03	49223.64		371.6	
A750-88	31.07.88			68580.93	49098.09		379.7	
A600-94	26.04.94	21:00	2308.37	68428.54	49116.87		377.91	
A550-88	31.07.88			68382.84	49128.14		377.6	
A550-92	15.08.92	14:00	1688.58	68379.75	49126.32		377.33	
A550-94	26.04.94	21:00	2308.37	68379.52	49126.15		377.48	
A500-88	31.07.88			86333.69	49136.52		375.8	
A500-92	16.08.92	04:08	1689.17	68330.64	49135.71	377.82	376.59	1.23
A500-94	26.04.94	21:00	2308.37	68330.45	49135.43		377.76	
A450-92	15.08.92	14:00	1688.58	68281.68	49145.16		375.81	
A450-94	26.04.94	21:00	2308.37	68281.54	49144.72		376.39	
A400-88	31.07.88			68235.03	49153.85		375.15	
A400-92	15.08.92	14:00	1688.58	68232.63	49154.61		375.32	
A400-94	26.04.94	21:00	2308.37	68232.48	49153.96		376.01	
A350-92	15.08.92	14:00	1688.58	68183.62	49163.95		375.13	
A350-94	26.04.94	21:00	2308.37	68183.61	49163.91		377.13	
A300-88	31.07.88			68136.91	49172.42		376.06	
A300-92	16.08.92	04:08	1689.17	68134.55	49173.11	376.31	375.28	1.03
A300-94	26.04.94	21:00	2308.37	68134.41	49173.19		376.09	
A250-92	15.08.92	14:00	1688.58	68085.59	49182.44		374.95	
A250-94	26.04.94	21:00	2308.37	68085.43	49182.63		375.23	
A200-88	31.07.88			68038.71	49191.28		373.95	
A200-92	15.08.92	14:00	1688.58	68036.38	49191.80		374.74	
A200-94	26.04.94	21:00	2308.37	68036.47	49192.23		375.14	
A150-92	16.08.92	04:08	1689.17	67987.45	49201.18	375.95	374.88	1.07
A150-94	26.04.94	21:00	2308.37	67987.48	49201.45		375.57	
A100-88	31.07.88			67940.81	49209.79		373.16	
A100-92	15.08.92	14:00	1688.58	67938.43	49210.55		374.28	
A100-94	26.04.94	21:00	2308.37	67938.34	49210.98		374.59	
EB0189	07.05.89			68351.85	49137.87		378.88	
EB0289	07.05.89			68305.55	49148.49		377.58	
EB0389	07.05.89			68466.81	49104.96		379.76	
EB0489	07.05.89			68354.01	49074.93		379.32	
EBO689	07.05.89			68467.69	49050.31		380.88	
EB0789	07.05.89			68114.88	49171.78		377.89	
EB0889	07.05.89			67930.47	49218.50		376.06	

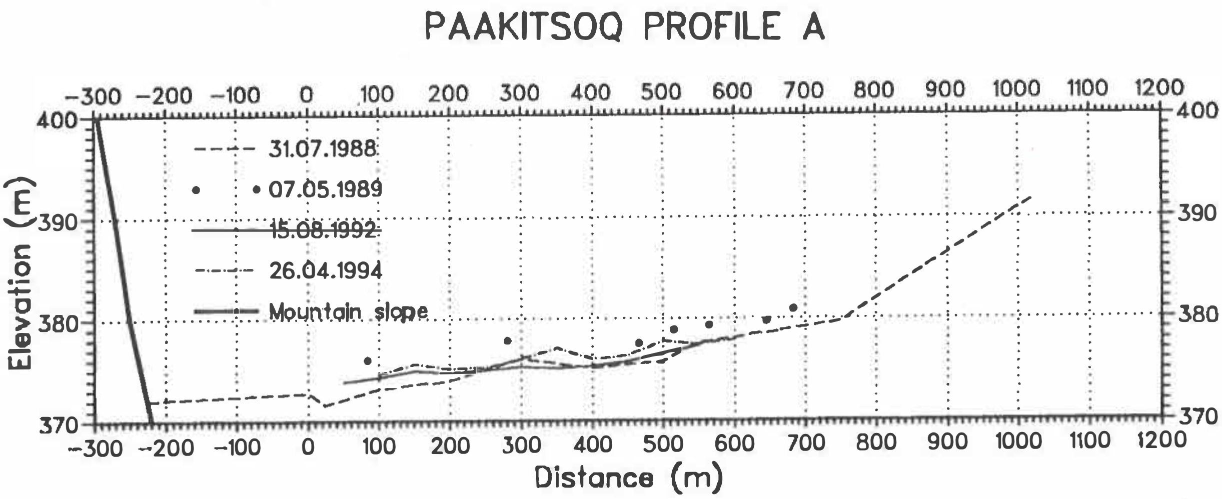

Fig. 4. Surface elevation profiles along the sampling line.

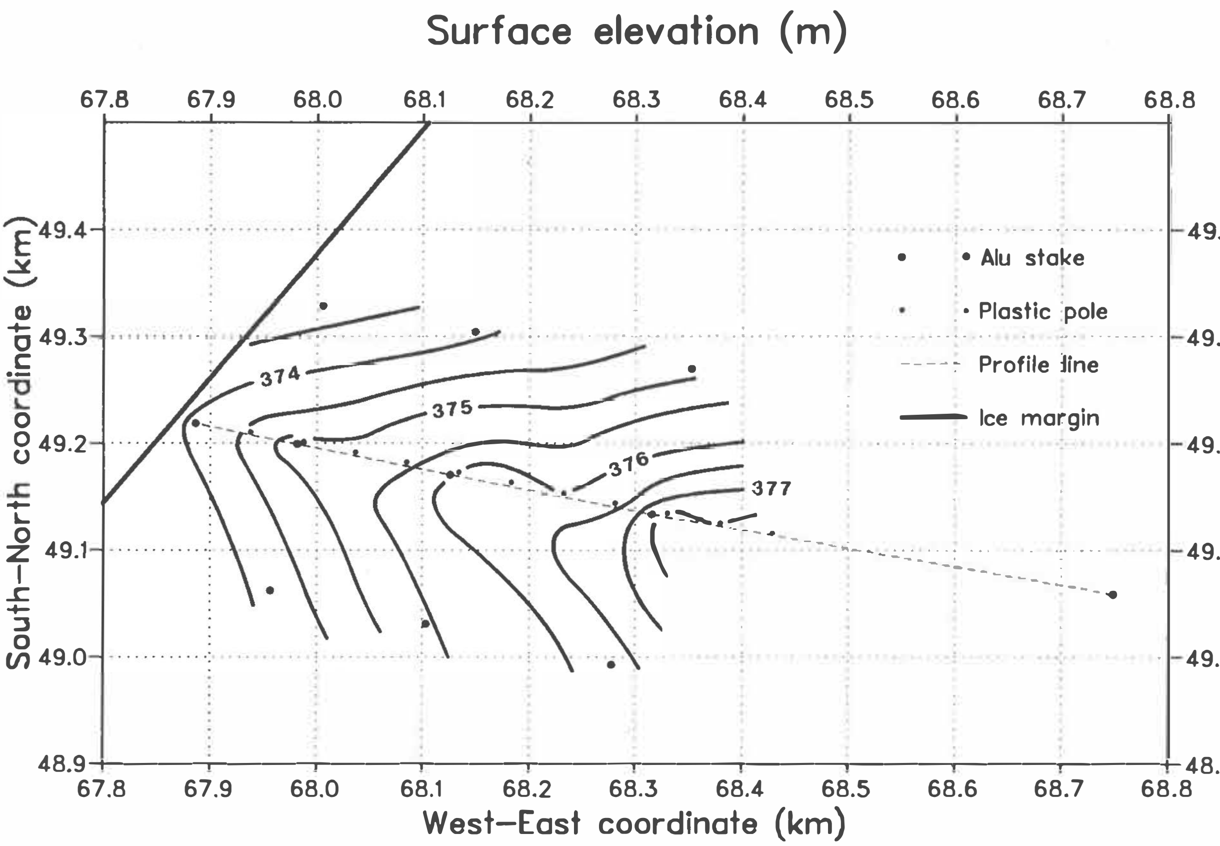

Fig. 5. Map showing surface elevations in metre above sea level along the Paakitsoq sampling line.

turn towards the south when approaching the margin. Evidently, the ice-flow direction at the ice margin is not perpendicular to the surface elevation contours, as is the case for ice sheet flow farther away from the margin. Presumably, bed slope and pressure from upstream ice play an important role for the dynamics of the margin-near ice.

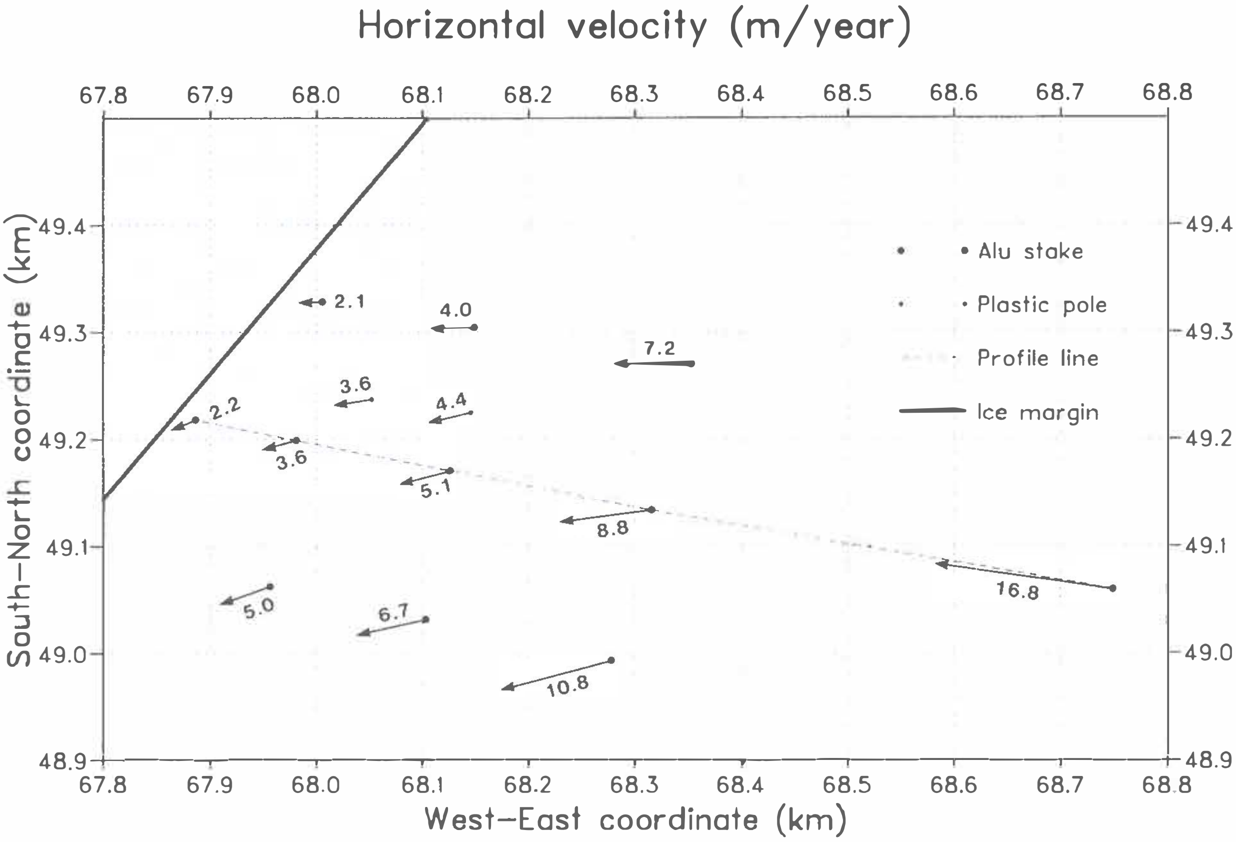

Fig. 6. Horizontal velocity field around the Paakitsoq sampling line.

Vertical ice motion and strain rate

Fig. 7. illustrates the vertical ice motion, displaying the angle of inclination with the horizontal of the velocity vectors. The closer to the margin and the farther to the north, the steeper the velocity vector. Since, for the case of steady state flow, stratification tends to be aligned with the direction of motion near the margin (Paterson, 1981, p. 222), Fig. 7 indicates a much smaller inclination of the stratification (10° - 40°) than that inferred from the blue band and dirt band inclination of about 70°. However, a comparison of distinct features in the $\delta^{18}O$ profiles obtained along the profile line in 1988 and 1992 indicates that flow conditions at the profile site are far from steady state. Hence, stratification and ice motion need not be aligned. A detailed study of the flow conditions at the profile and the implications for the stratification (bedding) is in progress and will be published elsewhere.

The increase of the inclination of the velocity vector towards the north might reflect a steeper upward sloping bed in the direction of motion to the north than further south. This supports the idea, that the displacement to the north of the "dynamical" divide in respect to the topographical divide is caused by the bed having a downward slope towards the south.

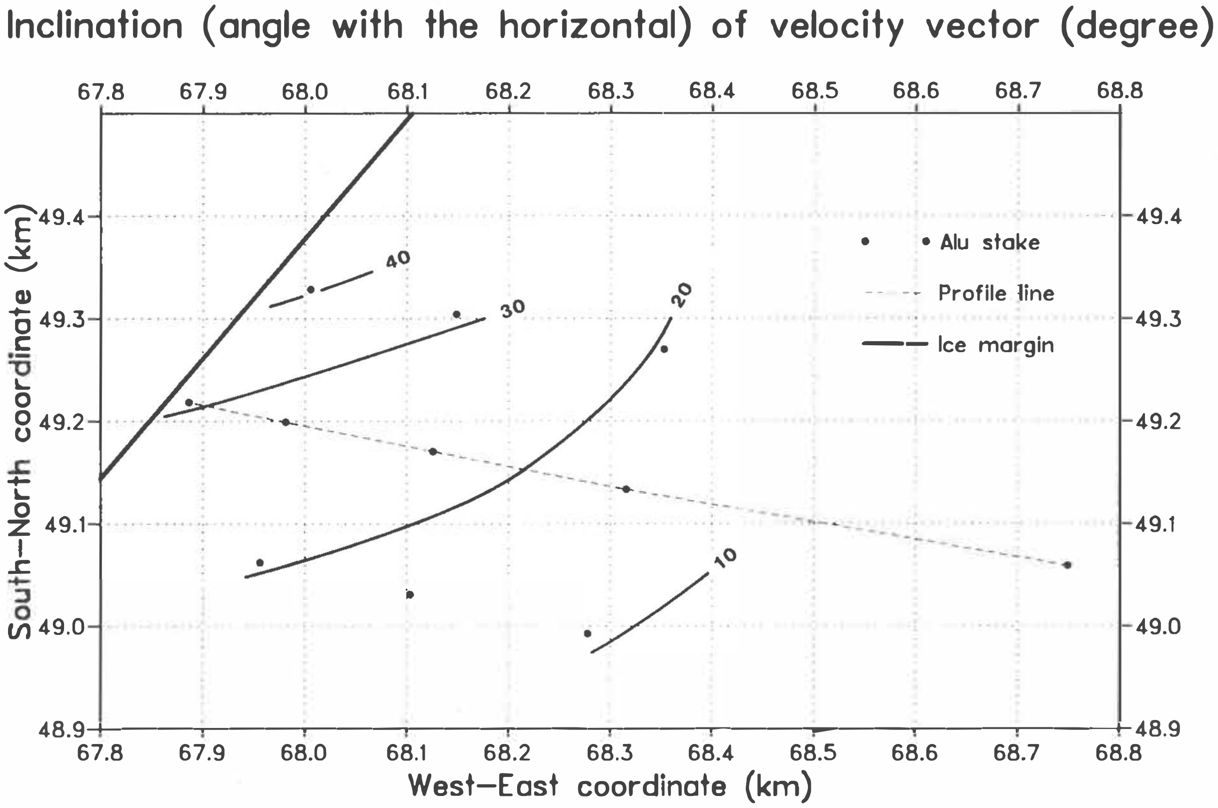

Fig.7 Inclination of velocity vector at the Paakitsoq sampling line

Fig. 8 shows the strain-rate distribution along the profile line. The principal compressive and tensile stresses are directed approximately along and transverse to the profile line. The thin dashed lines shows one of two perpendicular directions that keeps the direction unchanged during the local deformation. Close to the margin, this direction becomes parallel to the margin, but even at 500 m distance from the margin, the direction is only slightly different from that of the ice margin. This means that the strike of the foliation, which is approximately parallel to the ice margin will not change very much from one year to another.

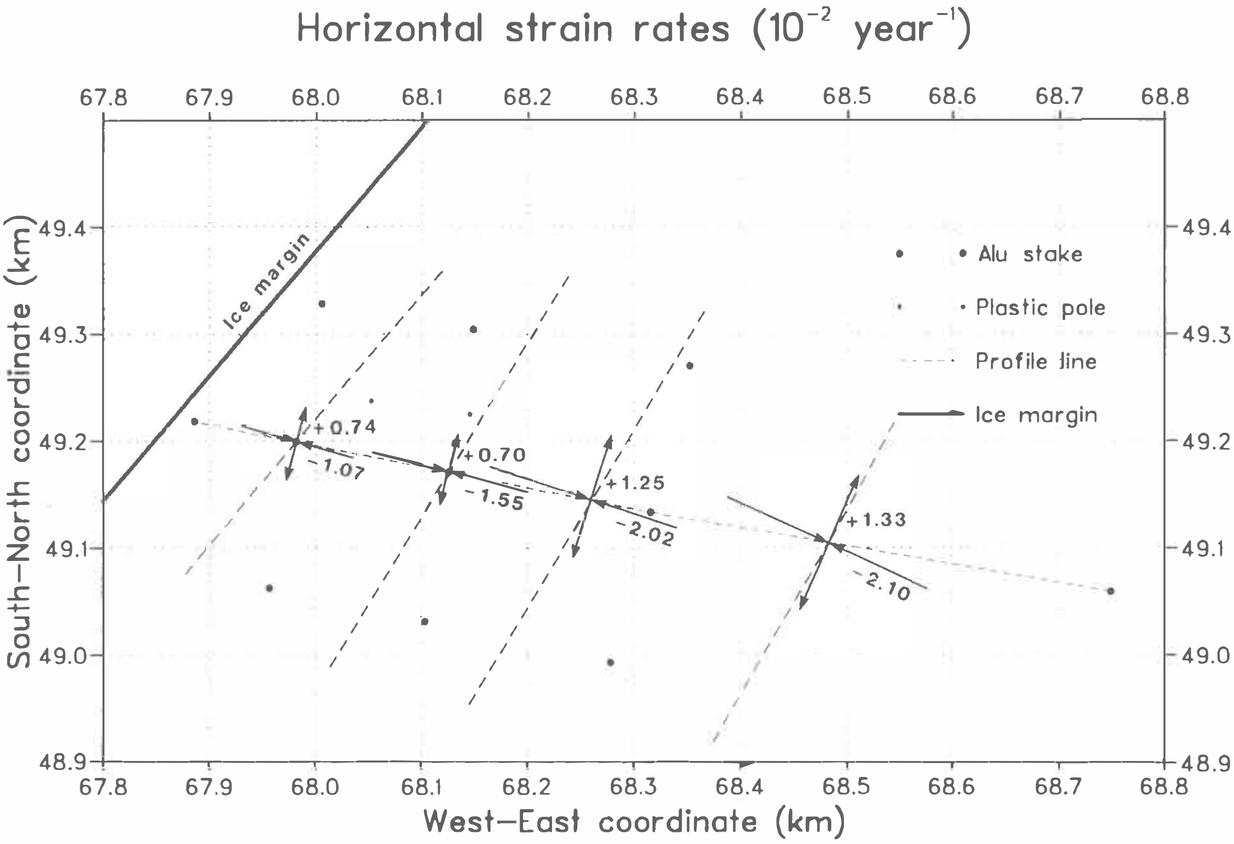

Fig.8. Strain-rate distribution along the Paakitsoq sampling line.

Ablation

The ice ablation at the profile line is illustrated in Fig. 9. There is a general decrease of ice ablation towards the ice margin caused by increased winter snow accumulation near the margin which delays the start of the ice melt. However, there is also a clear increase of ice ablation from south to north across the profile line. This is likely to be due to higher wind speeds to the north due to a channelling effect of the depression containing Lake 326, see map in Fig. 1. High wind speeds will remove the winter snow resulting in a - relatively speaking - early start of the ice melt, and furthermore increase ice ablation during the melt season.

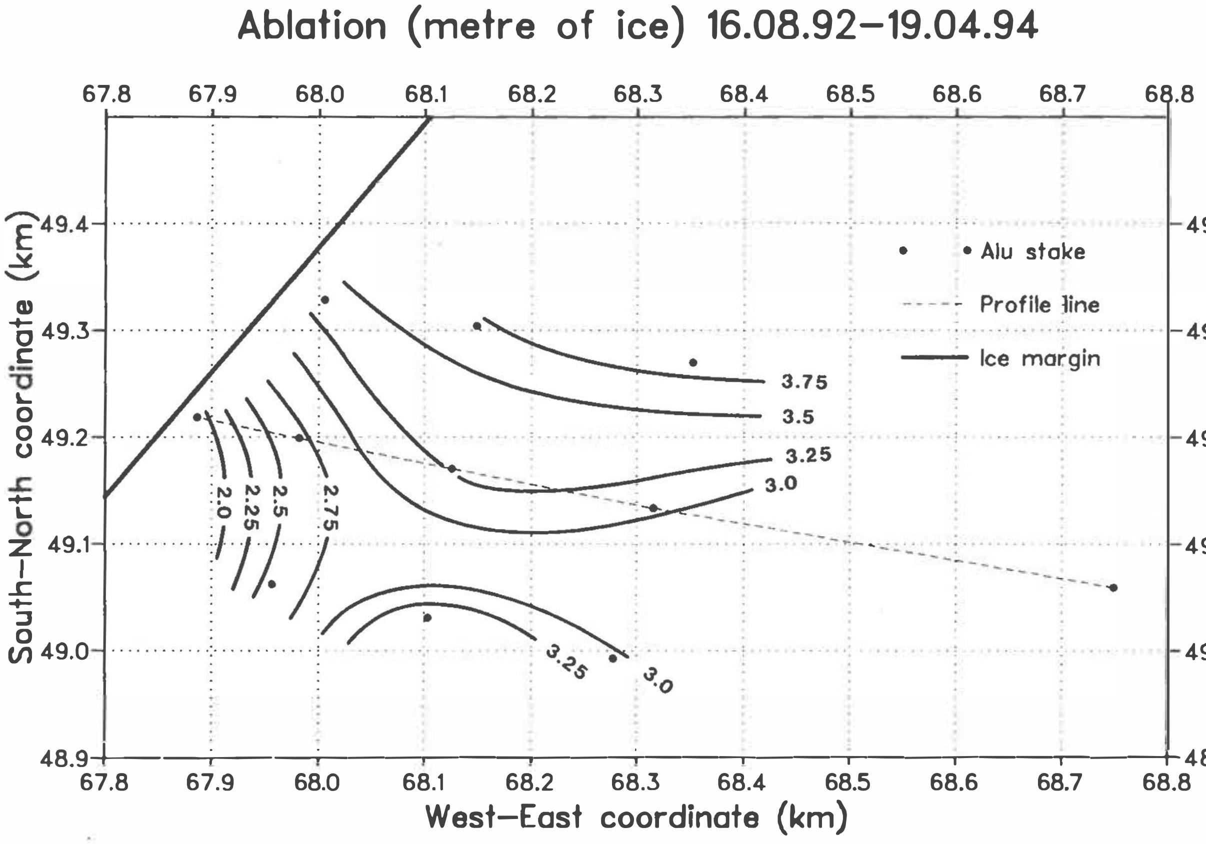

Fig. 9. Distribution of ice ablation near the Paakitsoq sampling line

References

GTO, 1983: Forundersøgelse Vandkraft 1982, Anlægsteknik - Hydrologi Paakitsup Akuliarusersua, Ilulissat/Jakobshavn. *Grønlands Tekniske Organisation, Direktoratet FBA/FVK, februar 1983.*

Paterson, W.S.B. 1981: *The Physics of Glaciers*. Second Edition, Pergamon Press Ltd.

Ice sampling for ^{10}Be and $\delta^{18}O$ analysis on the ice margin at Paakitsoq, West Greenland

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Objectives

One of the major problems for interpretation of climatic and environmental records from ice sheets is the establishment of reliable time scales (Budd *et al.*, 1989; Hammer, 1989; Reeh, 1989). Well established absolute dating methods are only valid for dating a few tens of thousands of years back in time (Hammer, 1989). For ice older than that one is depending on ages calculated by ice flow models (eg. Lorius *et al.*, 1985) based on assumptions about eg. climate history and ice temperature. These calculations therefore get more uncertain the further back in time the dating is extended. However different records can be correlated by matching well-defined stratigraphic features and marked patterns in the recorded parameters.

The Paakitsoq ice margin record has been correlated with the Greenland deep drilling records from Dye 3 and Camp Century, and the Vostok deep ice-core from Antarctica. The correlation is based on marked events in the $\delta^{18}O$ record and a time scale is established using ^{10}Be peaks in the Camp Century and Vostok cores as time markers (Reeh *et al.*, 1991). Raisbeck *et al.* (1987) concluded that the two distinct peaks at c. 35 ka and 60 ka in the Vostok ^{10}Be record are most likely due to production-rate changes in the atmosphere caused by extraterrestrial disturbances and should therefore also be detectable in Greenland ^{10}Be records. Two distinct ^{10}Be peaks are in fact found in the Camp Century ^{10}Be record (Reeh *et al.*, 1991). Beer *et al.* (1992) question the existence of the 60 ka ^{10}Be peak in the Camp Century record, as only the 35 ka peak was found in their study.

However the 60 ka ^{10}Be peak can not be excluded as the used sampling interval in their work was not selected for a search for this peak.

To obtain further time markers in the Paakitsoq ice margin record an ice sampling programme for locating possible ^{10}Be peaks were set up. Several drillings down to 4 m were planned to obtain a continuous sampling of ice around the locations on the profile where the ^{10}Be peaks were expected to be present.

Sampling of ice for ^{10}Be analysis

It was planned to drill cores down to 4 m of depth and exclude the upper 1 m to be sure to avoid possible surface contamination from refreezing of meltwater. To get a continuous sampling record around the locations on the profile, where the ^{10}Be peaks were expected to be present, one 4-metre core should be drilled for each meter, assuming that the internal layering in the ice dips with the same 70° angle as the blue bands (Thorsteinsson & Oerter, 1994).

However the drilling programme did not turn out as expected, mainly due to the high air temperatures during most of the field period, but also because the drills available were insufficient to cope with the difficult drilling conditions (see also Thorsteinsson & Oerter, 1994). The used motor-driven drill, originally designed for drilling in snow and firn, was repeatedly stuck in the ice and had to be chipped free with ice axes. During these hardships the drill was damaged, but could still be used for hand coring down to about 1.2 m. Similar problems with the drilling was also experienced by Thorsteinsson (Thorsteinsson & Oerter, 1994) using another drill. The drill equipment available was therefore shared and the programmes coordinated to get maximum efficiency in the work (Thorsteinsson & Oerter, 1994).

Because of these problems, cores was only drilled to about 0.5 - 0.8 m of depth, and the top c. 0,3 m was avoided in the samples. Furthermore the search for the ^{10}Be peaks was concentrated about the 35 ka peak, which had been found in the Camp Century record from North Greenland (Beer *et al.*, 1992). Samples were drilled symmetrically around the expected location of the 35 ka ^{10}Be peak with a sampling spacing of 2,5 m. After retrieving, the ice cores were cleaned and packed in plastic bags. Places, where dust was visible on the surface, were avoided, since dust contains far larger amount of ^{10}Be than ice (Beer, pers. communication). A total of 51 samples were taken each with a melted volume larger than one litre.

Furthermore one sample for ^{10}Be analysis was taken from the Holocene part of the Paakitsoq profile to check if the ^{10}Be concentration in this ice is lower than in the ice age ice, which is the case in the ice core records (Beer *et al.*, 1988). Moreover, three samples were taken from the Saalean part of the profile. All samples are listed in the appendix to this report.

The samples was brought back to the camp and melted. The sample volume was determined with a measuring glass to an accuracy of better than 1 %. The samples were stored in plastic bottles, and 1 ml carrier (containing 0.3 ml ^{9}Be and 2.0 mg Cl) was added with a calibrated pipette.

Sampling of ice for $\delta^{18}O$ analysis

The location of the 1992 Pakitsoq $\delta^{18}O$ profile was re-established on the ice surface by surveying. A check revealed that the position of all 50 metre markings in the 1994 profile was displaced less than half a metre from the corresponding positions in 1992. In order to further check the accuracy of the location, several ice samples for $\delta^{18}O$ analysis were collected at different locations along the entire profile. The samples were collected in the same way as in 1992. The upper about 10 cm of ice was cut away by means of an ice axe and the ice was then collected continuously as 20-cm samples with a chisel and filled into plastic bottles closed with tight covers. The ice samples eventually melted to fill more than half the bottle, thus limiting isotopic fractionation due to evaporation to an insignificant amount.

A total of 301 ice samples were taken. At four locations samples were taken from longer sections of the profile. Measured from the start of the profile these sections cover 137.0 - 152.8 m, 387.0 - 397.8 m, 500.0 - 506.8 m and 514.0 - 519.8 m. Furthermore ice samples were taken from 16 other locations along the profile, where samples for the analysis of other environmental parameters under the Paakitsoq 1994 programme, were drilled (Biscaye, 1994; Bourgeois, 1994; Thorsteinsson & Oerter, 1994). At each of these locations six ice samples were collected symmetrically around the drill holes. The locations are listed in the appendix to this report.

Collaborators

The ^{10}Be analyses will be made by J. Beer at Environmental Physics, Institute for Aquatic Sciences and Water Pollution Control, ETH-Zürich, Switzerland and the $\delta^{18}O$ analyses will be made by H. Oerter at Alfred-Wegener-Institut für Polar- und Meeresforschung, Germany.

References

Beer, J., Siegenthaler, U., Bonani, G., Finkel, R.C., Oeschger, H., Suter, M. & Wölfli, W. 1988: Information on past solar activity and geomagnetism from ^{10}Be in the Camp Century ice core. *Nature* **331**, 675-679.

Beer, J., Johnsen, S.J., Bonani, G., Finkel, R.C., Langway, C.C., Oeschger, H., Stauffer, B., Suter, M. & Woelfli, W. 1992: ^{10}Be peaks as time markers in polar ice cores. *In* Bard, E. & Broecker, W.S. (ed.) *The last deglaciation: Absolute and radiocarbon chronologies*, 141-153. Springer, Berlin Heidelberg.

Biscaye, P.E. 1994: Sampling of ice for dust studies on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 10-15 (this volume).

Bourgeois, J.E. 1994: Sampling for pollen on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 16-19 (this volume).

Budd, W.F., Andrews, J.T., Finkel, R.C., Fireman, E.L., Graf, W., Hammer, C.U., Jouzel, J., Raynaud, D.P., Reeh, N., Shoji, H., Stauffer, B.R. & Weertman, J. 1989: How can ice chronology be established ? Group report. *In* Oeschger, H. & Langway, C.C. Jr (ed.) *The environmental Record in Glaciers and Ice Sheets,* 177-192. Wiley, New York.

Hammer, C.U. 1989: Dating by physical and chemical seasonal variations and reference horizons. *In* Oeschger, H. & Langway, C.C. Jr (ed.) *The environmental Record in Glaciers and Ice Sheets,* 99-121. Wiley, New York.

Lorius, C., Jouzel, J., Ritz, C., Merlivat, L., Barkov, N.I., Korotkevich, Y.S. & Kotlyakov, V.M. 1985: A 150,000-year climatic record from Antarctica ice. *Nature Lond.* **316**, 591-596.

Raisbeck, G.M., Yiou, F., Bourles, D., Lorius, C., Jouzel, J. & Barkov, N.I. 1987: Evidence for two intervals of enhanced ^{10}Be deposition in Antarctic ice during the last glacial period. *Nature* **326**, 273-277.

Reeh, N. 1989: Dynamic and climatic history of the Greenland Ice Sheet. *In* Fulton, R.J.(ed.) Quaternary Geology of Canada and Greenland. *Geological Survey of Canada,Geology of Canada* **1**, 795-821.

Reeh, N., Oerter, H., Letréguilly, A., Miller, H. & Hubberten, H.W. 1991: A new, detailed ice-age oxygen-18 record from the ice-sheet margin in central West Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global planet. Change Sect.)* 90, 373-383.

Thorsteinsson, T. & Oerter, H. 1994: Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 35-40 (this volume).

Ice core drilling for studies of texture, fabric and visual stratigraphy on the ice margin at Paakitsoq, West Greenland.

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Objectives

The main purpose of the Alfred-Wegener-Institut (AWI) programme was to drill ice cores for the study of textures, fabrics and visual stratigraphy in the ice at Paakitsoq. In addition, samples to be used as standard water for isotope measurements were to be collected.

The ice crystals in polar ice sheets are constantly undergoing growth, rotation and recrystallization to accommodate changing stress systems, strains and temperatures. Thin section studies on existing deep ice cores from the Greenland Ice Sheet, drilled at Camp Century in North Greenland, Dye 3 in South Greenland and Summit (GRIP and GISP2, deep-drillings) in Central Greenland, have revealed that:

- grain growth occurs in the uppermost 6-700 m of the ice sheet but is below that inhibited by increasing strain of the ice and the presence of impurities.

- c-axes rotate towards the vertical axis of compression and thus a pattern of preferred orientation is found in the lower part of the ice sheet (Herron *et al.*, 1985).

- crystal size variations observed in the GRIP core are found to be strongly correlated with variations in climatic parameters, such as $\delta^{18}O$ and dust.

- dynamic recrystallization leading to the growth of large crystals appears to occur in the lowest part of the Central Greenland ice sheet.

The flow properties of the ice sheet are significantly affected by the change in fabric pattern. If shear stresses are present, a crystal oriented with its basal planes parallel to the direction of shear will deform 10-100 times more readily than a crystal oriented with the basal planes perpendicular to shearing. Several authors believe this to be the cause of enhanced flow of Wisconsin ice at Camp Century and Dye 3, compared to Holocene ice above, since the Wisconsin ice has developed a strong preferred fabric and shear stresses are active in this part of the ice sheet (Paterson, 1991).

Since ice cores have previously not been retrieved from the ice margin regions, no information is available on the fabric development during flow from the inner regions of the ice sheet to the margin. The Pakitsoq study thus represents the first study of this kind.

The stress condition at Pakitsoq is one of vertical compression towards the margin, where a mountain blocks further flow outwards, accompanied by extension parallel to the margin due to divergent flow (Reeh *et al.*, 1994). In addition, each summers ablation requires ice to flow upwards from below to keep the profile in steady state (which it is believed to be in). This upward flow probably is in a direction of 20° to the vertical, since dirt bands and blue ice bands observed throughout the profile are inclined around 70°. C-axis measurements on thin sections cut from the cores should reveal whether this complex ice flow situation is reflected in the crystal fabric. It will particularly be studied whether there is an indication of preferred orientation perpendicular to the 70° banding; this would indicate shearing parallel to this direction. Also, thin section studies should reveal whether the compression of the ice towards the margin is reflected in the shape of the individual grains; this is observed in the GRIP ice core from Summit in Central Greenland, where grains become flattened due to the vertical compression.

The grain-size dependence on climatic conditions, which is very marked in the GRIP core, will also be studied on the Pakitsoq samples. If the grain-size variations turn out to be similar to those observed in the GRIP core; i.e. small crystals in Wisconsin and Saalean ice and large in Eemian (plus a strong correlation between grain size and $\delta^{18}O$), then this would constitute important support of the Pakitsoq climatic record. In addition, this would show that ice flow from the inner ice sheet regions to the margin does not lead to disappearance of original texture due to recrystallization.

The blue-ice bands crossing the profile raise several questions. It has already been found (H. Oerter, pers. communication) that the ice grains are much larger in the bands than in the surrounding ice, and they also show higher $\delta^{18}O$ values than adjacent ice. The crystal size and orientation studies could yield important clues to whether these bands are inherent in the ice layering or whether they are a secondary phenomenon.

One of the problems with the Pakitsoq profile is that the distance proportions of the Wisconsin ice and the proposed Eemian ice (300 m to 100 m, i.e. 3:1), do not match the corresponding proportions in the GRIP core (1200 m to 80 m, i.e. 15:1) (Dansgaard *et al.*, 1993). This could be due to the "softness" of the Wisconsin ice, which is not expected to be marked at the ice divide but should lead to preferential thinning of the Wisconsin ice as the ice margin is approached. Results from c-axis measurements can hopefully cast a light on this problem.

Drilling programme

During the April 1994 field campaign, a total of 81 cores of lengths 0.4-1.2 m were retrieved from 71 different locations along the entire profile and a total of about 42 m of cores was obtained. Cores were drilled in the Holocene, Younger Dryas, Wisconsin, Eemian and Saalean parts of the profile (see appendix). In addition, about 20 cores reaching 1-4 m depth have been retrieved from selected parts during previous expeditions.

Furthermore ice for the isotope standard water was collected and melted while chipping free with ice axes a drill, which was stuck in the ice at 2 m depth in Saalean ice. The AWI programme was centered around drilling ice cores with a motor-driven drill, which has been successfully used to retrieve firn cores down to 15 m depth during the North Greenland Traverse, but has to this authors knowledge not been tried out in ice before. The original plan was to drill some 10 cores down to 3-4 meter depth and concentrate on the Eemian part of the profile. This plan had to be abandoned for the following reasons:

- Temperatures were above zero for almost half of the days in the field period. This always makes drilling difficult, and in the initial phase the drill became stuck in the ice several times. Chipping it free with ice axes was difficult and time consuming and we judged that drilling to 3-4 m would not be feasible because of the risk of loosing a drill. Coring was therefore done during evening and early night when the temperatures were lower, but when temperatures fell at the end of the field period drilling was also possible during daytime. However other problems with the drilling were encountered.

- The engine is turning the AWI drill quite fast and often this results in sudden packing of chips in front of the cutters, and freezing onto them, after which the drill was either stuck in the ice or was skating on the packed chips and penetrating no deeper. Often the drill would not penetrate more than 3-5 cm in each run, making the drilling process extremely cumbersome.

- The core catchers on this drill do not work in ice. They are in the form of hooks, which slide in from the side, when the drill is turned slightly backwards. But these hardly ever managed to grab the core which thus was left in the hole when the drill was pulled up. The core then had to be reached and pulled up by hand, but obviously this method only worked down to a depth of 70 cm, meaning that cores drilled with the AWI drill did not reach deeper than 1 m.

- We devised a way of circumventing this problem: Having drilled a core too deep to be reached by hand and pulled up the drill, one could break the core off the hole bottom with a metal rod, so that it was sitting loose. Water was then poured on a cloth tied to the front end of a rod, which was put down into the hole until the cloth touched the core. The wet cloth then froze onto the core, which then could be pulled up. This method worked, but was of little use, since we decided not to go deeper than about 1 m.

- A serious problem was, that the metal rods (1 cm thick) intended for turning the drill by hand when the engine had been dismantled, were not strong enough. They worked fine in firn, but here they easily got bent, when force had to be used on them. This made drilling by hand practically impossible and nothing was found in the expedition gear which could replace these rods.

- We found out that it made an incredible difference for drilling whether the ice was covered with snow or not. Probably this was due to temperature differences; the temperature at 1 m depth in snow-free ice was about $-10°$– $-12°C$, but 3-4 degrees colder in snow-covered ice. In fact drilling normally went smoothly in the latter ice and the drill penetrated up to 60 cm in one run.

- Using antifreeze in the hole made drilling much easier, in any kind of weather. We had limited supplies but these made the difference during the last, hectic days of drilling.

Because of the above mentioned general problems with drilling (see also Reeh & Thomsen, 1994), the drilling was coordinated with the pollen (Bourgeois, 1994) and ^{10}Be (Reeh & Thomsen, 1994) sampling programmes to achieve maximum efficiency.

Observation of ice-surface features

Heavy snowfall during the expedition limited the originally planned studies of the blue bands and dirt bands crossing the profile, but some of these layers were studied and samples collected. The inclination of these bands was found to be about 70° along the profile. An important question is whether these are inherent in the layer sequence, in which case their origin could be traced to the central regions of the ice sheet. Some of the observed dirt bands could be layers of volcanic ash and by direct comparison with dated ash layers in the Central Greenland deep ice cores, a study of these dirt (ash?) layers would give dated reference horizons in the Paakitsoq profile. - It is rather surprising how straight and regular most of the dirt bands appeared and one would expect them to have a more irregular appearance if they were bottom-derived; i.e. scraped or frozen into the ice from the bottom. The same applies to the blue bands, which simultaneously seem to demand and defy explanation! They appear to belong to the layering and stretch over distances of hundreds of metres in both directions from the profile. They show abnormally high $\delta^{18}O$ - values and grain sizes, but do not seem to be related to melting-refreezing processes, since their co-isotope values lie on the meteoric water line. This seems to exclude the possibility that they represent regelation ice formed at the bottom or ice formed when surface meltwater/rainwater filled open cracks and froze. Crystal analysis of the samples could give important clues to whether these bands are inherent in the ice layering or whether they are a secondary phenomenon.

References

Bourgeois, J.E. 1994: Sampling for pollen on the ice margin at Paakitsoq, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 16-19 (this volume).

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J. & Bond, G. 1993: Evidence for general instability of past climate from a 250-kyr ice- core record. *Nature* **364**, 218-220.

Herron, S.L., Langway, C.C. & Brugger, K.A. 1985: Ultrasonic velocities and crystalline anisotropy in the ice core from Dye 3, Greenland. *In* Langway, C.C., Oeschger, H. & Dansgaard, W. (ed.) Greenland ice core: Geophysics, geochemistry and the environment. *Geophysical Monograph, Am. Geophysical Union* **33**, 23-31.

Paterson, W.S.B. 1991: Why ice age ice is sometimes "soft". *Cold Reg. Sci. Technol.* **20**, 74-98.

Reeh, N. & Thomsen, H.H. 1994: Introduction to the Paakitsoq 1994 field programme. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 2-9 (this volume).

Reeh, N., Thomsen, H.H., Oerter, H. & Bøggild, C.E. 1994: Ice deformation and velocities along the Paakitsoq profile sampling line, West Greenland. *In* Thomsen, H.H. & Reeh, N. (ed.) Field report on palaeo-environmental studies at the Greenland ice sheet margin, Paakitsoq, West Greenland, 1994. *Open File Ser. Grønlands geol. Unders.* **94/15**, 20-29 (this volume).

Appendix (page 41-44). List of ice-cores and samples collected at the ice margin of Paakitsoq, West Greenland, April 1994. Analysis parameters are given.

Position from start of profile [m]	Dust (LDEO) core length [m]	Pollen (GSC) sample depth [m]	^{10}Be (DPC/GGU) volume [ml]	$\delta^{18}O$ (DPC/GGU) number of samples	Fabric (AWI) core length [m]
136.00 I			1580		
136.00 II			1500		
136.45			1980		
137.00 I				6	0.40
137.00 II					0.32
137.00 III					0.61
137.50	1.10*	1,10		6	
146.00				6	c.1.0
146.50	1.08*	1.08		6	
150.60				6	1.10
153.50	1.18*	1.18		6	0.87
161.00	1.20*	1.20		6	1.09
175.95	1.06*	1.06		6	1.15
189.85	1.13*	1.13		6	1.08
207.30 I	1.00*	1.00		6	0.96
207.30 II	1.12*	1.12			0.72
221.55 I	1.00*	1.00		6	0.91
221.55 II					0.92
227.95	1.03*	1.03		6	0.55
245.00	0.98*	0.98		6	0.35
261.00 I	1.08*	1.08		6	0.50
261.00 II					0.38
270.00 I					0.35
270.00 II					0.35
270.00 III					0.37
270.00 IV					0.37
277.00	1.07*	1.07		6	0.38
286.40					0.59
286.80					0.46
300.40					0.55
301.60					0.44
306.30					0.71
313.10 I	1.08*	1.08		6	0.43
313.10 II					0.28
329.90			930		0.56
332.50			980		0.54

* Depth of filtered sample (<8 - >0.45 µm). ** Depth of filtered sample (> 0.45 and >8 µm).
Abbreviations: AWI: Alfred-Wegener-Institut für Polar- und Meeresforschung, DPC: Danish Polar Center, GGU: Geological Survey of Greenland, GSC: Geological Survey of Canada, LDEO: Lamont-Doherty Earth Observatory of Columbia University.

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335.25			1045		0.79
337.45			960		0.60
340.00			1000		0.59
342.35			950		0.70
345.20			860		0.62
347.50			960		0.58
350.00		-	1580	6	0.53
350.60					0.28
352.50			885		0.44
355.00			1240		
357.50	1.01*	1.01	1260	6	
360.00			1160		
362.50			1200		
365.00	1.06*	1.06	1265	6	
367.50			1165		
370.00			1225		
372.50			1185		
375.00			1180		
377.50			1220		
380.00 I			1260		
380.00 II			-		
380.00 III			1120		
380.00 IV			1190		
382.50 I			1195		
382.50 II			1445		
385.00 I			1260		
385.00 II			1600		
387.50 I	1.14*	1.14	1230	6	0.19
387.50 II	1.02**	1.02	985		0.69
387.50 III			1600		
390.00 I			1255	6	
390.00 II			1595		
392.50 I			1200	6	
392.50 II			1320		
395.00 I			1245	6	
395.00 II			1585		

* Depth of filtered sample (<8 - >0.45 μm). ** Depth of filtered sample (> 0.45 and >8 μm).
Abbreviations: AWI: Alfred-Wegener-Institut für Polar- und Meeresforschung, DPC: Danish Polar Center, GGU: Geological Survey of Greenland, GSC: Geological Survey of Canada, LDEO: Lamont-Doherty Earth Observatory of Columbia University.

Appendix (page 41-44). List of ice-cores and samples collected at the ice margin of Paakitsoq, West Greenland, April 1994. Analysis parameters are given.

Position from start of profile [m]	Dust (LDEO) core length [m]	Pollen (GSC) sample depth [m]	^{10}Be (DPC/GGU) volume [ml]	$\delta^{18}O$ (DPC/GGU) number of samples	Fabric (AWI) core length [m]
397.50 I			1180	6	
397.50 II			1440		
400.00 I			1250		
400.00 II			695		
402.50			1000		0.58
404.80			1020		0.54
407.70			1140		0.55
410.00			1035		0.58
412.45			1100		0.61
414.95			1040		0.57
417.40			1125		0.62
420.00			1040		0.61
422.35			1220		0.61
424.95			1185		0.55
450.00					0.65
475.00					0.67
491.55	2.75			6	
495.00	3.03				
502.65	0.90			6	
505.75	4.20			6	
506.00	1.85			6	
506.90	2.75				
507.00					0.70
510.18	0.80				
511.00					0.41
513.05	3.70				
514.00					0.58
514.47	3.21			6	
515.60	3.20			6	
516.73	2.97			6	
516.92	3.18			6	
517.00				6	0.64
518.40	3.70			6	
518.45	3.15			6	
519.13	3.15			6	
521.58	3.83				

* Depth of filtered sample (<8 - >0.45 µm). ** Depth of filtered sample (> 0.45 µm).
Abbreviations: AWI: Alfred-Wegener-Institut für Polar- und Meeresforschung, DPC: Danish Polar Center, GGU: Geological Survey of Greenland, GSC: Geological Survey of Canada, LDEO: Lamont-Doherty Earth Observatory of Columbia University.

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Position from start of profile [m]	Dust (LDEO) core length [m]	Pollen (GSC) sample depth [m]	^{10}Be (DPC/GGU) volume [ml]	$\delta^{18}O$ (DPC/GGU) number of samples	Fabric (AWI) core length [m]
533.60	0.95				
536.00					0.31
550.30					0.51
600.00					0.46
679.80					0.41
680.00	1.17*	1.17	1980	6	0.87

* Depth of filtered sample (<8 - >0.45 µm). ** Depth of filtered sample (> 0.45 µm).
Abbreviations: AWI: Alfred-Wegener-Institut für Polar- und Meeresforschung, DPC: Danish Polar Center, GGU: Geological Survey of Greenland, GSC: Geological Survey of Canada, LDEO: Lamont-Doherty Earth Observatory of Columbia University.

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