

ANALYSES OF TWO ICE CORES DRILLED AT THE ICE-SHEET MARGIN IN WEST GREENLAND

by

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ABSTRACT

In 1978 two ice cores were drilled to depths of 46 and 92 m respectively at Camp 3, at the west margin of the Greenland ice sheet. Both core drillings reached bedrock. In addition, surface samples were collected in the marginal area along an estimated flow line.

The $\delta^{18}\text{O}$ profiles of the two ice cores and of the surface samples show similar features. All three $\delta^{18}\text{O}$ records reveal the characteristic shift (of 5–6 per mil for the Pleistocene–Holocene transition 11 000 years ago) observed in Greenland deep ice cores from Camp Century and Dye 3.

The $\delta^{18}\text{O}$ results, as well as the measured temperature profiles in the bore holes, are used to provide more insight into the rheology of the ice sheet. The analyses of marginal ice samples is an important supplement to deep ice-core analyses.

INTRODUCTION

An ice sheet is an archive of precipitation from the past. In the central part of the polar ice sheets, the deposited snow is covered by subsequent snow layers and compacted into ice. The ice becomes more deeply buried as it moves towards the edge of the ice sheet, where it melts or calves, in the form of icebergs, into the ocean. According to flow models, the oldest ice (which originates from the ice divide) reaches the surface at the margin. Farther inland, younger ice (which originates from locations between the ice divide and the coast) will be found at the surface. The youngest ice will be at the equilibrium line (which separates the ablation area from the accumulation area). Surface samples taken along a flow line in the ablation area are therefore expected to show characteristics similar to those of an ice core from the interior of the ice sheet. Stable-isotope investigations on surface-ice samples from marginal zones in Greenland have confirmed this expectation (Raynaud 1977, Reeh and others 1987).

Ice cores to bedrock in the ablation area are expected to show the same record as surface samples along the flow line between bore hole and ice margin. We have drilled two ice cores to bedrock along an estimated flow line in the ablation area at Camp 3 (69.7°N, 50.1°W) on the EGIG track in West Greenland (Fig.1). In this region the flow line, which starts at Crête (a possible location for a new deep drilling), reaches the ice margin. Results from the two ice cores are compared with results from surface samples collected along the estimated flow line between the bore holes and the ice margin.

FIELD WORK

Field work was done in the summers of 1977 and 1978. In 1977 about 20 ice cores, each to a depth of 1 m,

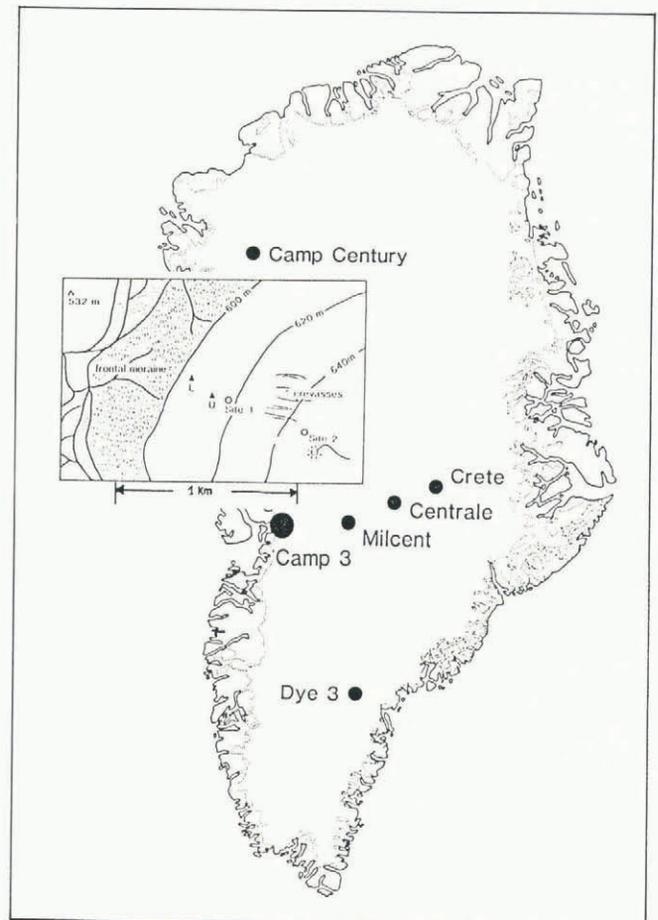


Fig.1. Map of Greenland, with the locations of Camp 3, Milcent, Station Centrale, Crête, Camp Century and Dye 3. The enlarged map of the Camp 3 region shows the position of the drill sites, "Upper" (U) and "Lower" (L) poles.

were recovered. The drilling sites were distributed along an estimated flow line from the edge of the moraine to about 400 m farther inland. The samples for stable-isotope measurements were prepared in the field.

In 1978 two ice cores to a depth of 46 m (drill site I) and to 92 m (drill site II) were drilled with an electro-mechanical auger developed and constructed at the University of Bern. The ice-core diameter is 7.5 cm.

Continuous cores were recovered, but they broke into disks a few centimeters thick. Drill site I was located 300 m inland from the edge of the moraine. Several small stones and some "pockets" of dirt were observed in the lower part of the ice core. At 46 m depth, drilling stopped due to a large boulder or to bedrock.

Drill site II was located 410 m farther inland. At 91 m depth the ice core became wet and all the ice chips in the core barrel were washed out. We assume that this was due to flowing water. The last meter of the ice core contained very few visible dirt particles. We stopped drilling, because we did not want to incur the risk of losing the drill.

The recovered ice cores were packed in plastic tubes, stored in freezers at a temperature below -10°C and transported frozen to the laboratories in Copenhagen and Bern for stable-isotope ($\delta^{18}\text{O}$) studies.

Temperature profiles were measured in the bore holes (Stauffer and Oeschger 1979). The temperature decreased from the melting point at the surface to about -5°C at 6 m depth. Below this depth, the temperature increased and again reached the melting point at 30 m depth. The ablation and the horizontal velocity were measured at two selected locations. The thickness of the ice sheet was measured with a 60 MHz radar system from the Electromagnetic Institute at the Technical University of Denmark (TUD).

RESULTS

1. $\delta^{18}\text{O}$

The $\delta^{18}\text{O}$ values from the ice cores are shown on a depth scale in Figures 2 and 3. There are detailed $\delta^{18}\text{O}$ records, based on 10 cm samples, for the bottom part of the two cores, 29 and 24 m respectively. As these records do not provide any extra information, they are not shown here.

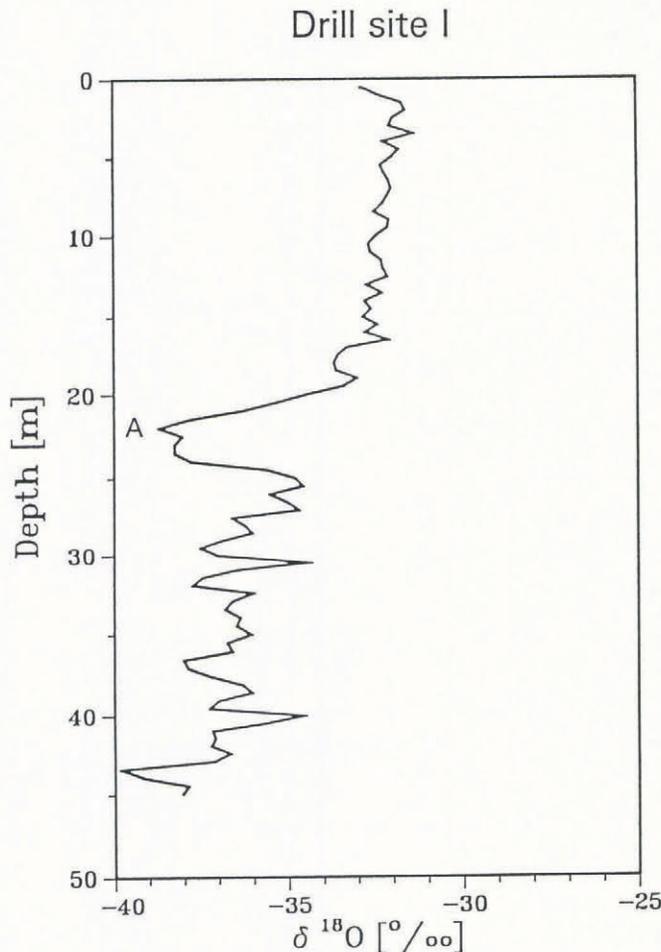


Fig.2. The continuous $\delta^{18}\text{O}$ record of the ice core from drill site I, on a vertical depth scale. The $\delta^{18}\text{O}$ sample length is 50 cm. The minimum "A", at the depth of 22 m, corresponds to the Younger Dryas, just before the Pleistocene-Holocene shift 11 000 years ago. The record reveals a $\delta^{18}\text{O}$ shift of 6‰ in the depth interval 18–22 m.

The surface $\delta^{18}\text{O}$ profile in Figure 4 is shown versus distance from the moraine. This profile comprises 44 points spaced 5–10 m apart, starting at the stagnant moraine and ending 100 m above drill site I. Each point represents the mean of 10 cm samples from a 1 m hand-augered ice core.

2. Ablation, horizontal velocity and surface slope

Two poles were erected in 1977 on the ice surface, 150 and 300 m from the moraine. Based on measurements made in 1977 and 1978, we estimate the annual ablation and horizontal velocity shown in Table I.

TABLE I. GLACIOLOGICAL CHARACTERISTICS

	Ablation m of ice/year	Horizontal velocity m/year
"Lower pole"	2.4	10
"Upper pole"	2.6	15
Range	Measured mean surface slope Degree	
Moraine – drill site I	5	
Drill site I – drill site II	3	
Drill site II – Camp 3bis	1.5	

3. Radar-sounding

In 1971, a TUD airborne-radar survey (60 MHz), close to the EGIG track, showed that the ice thickness increases some 600 m in the distance interval 4–5 km from the edge

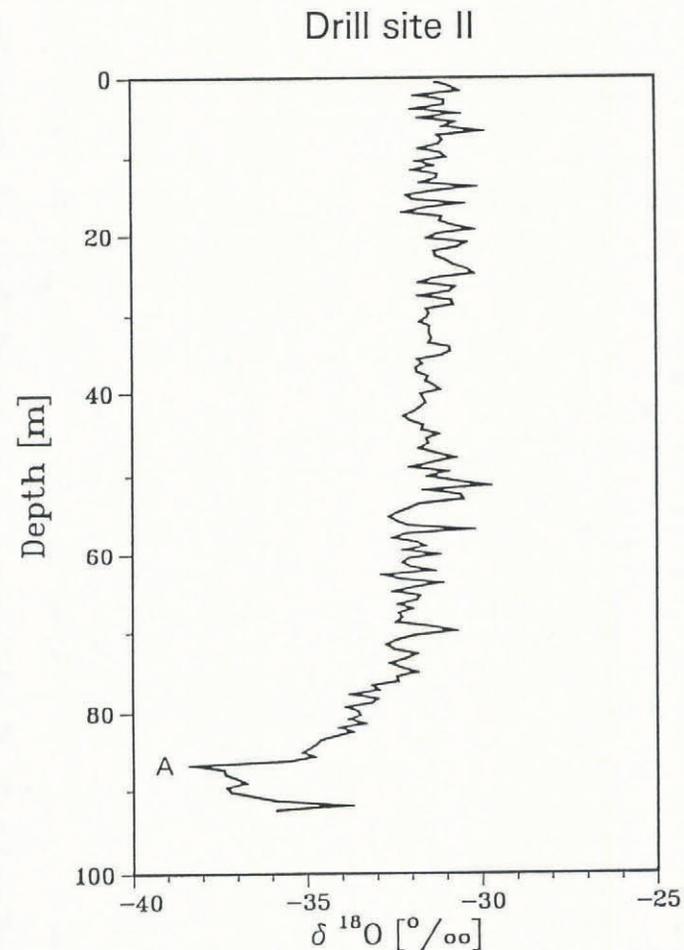


Fig.3. The continuous $\delta^{18}\text{O}$ record of the ice core from drill site II on a vertical depth scale. The $\delta^{18}\text{O}$ sample length is 55 cm. The minimum "A" is found at 86 m and the 6‰ $\delta^{18}\text{O}$ shift is found in the depth interval 75–86 m.

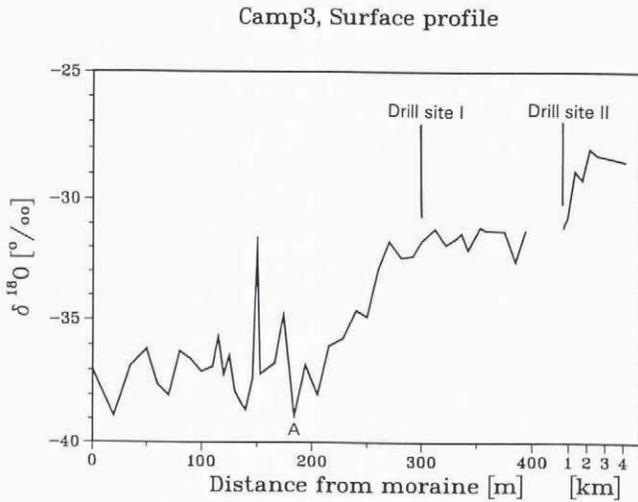


Fig.4. The $\delta^{18}\text{O}$ record based on surface samples collected from 1 m ice cores spaced 5–10 m apart on an estimated flow line through drill sites I and II. The horizontal scale represents distance from the stagnant main moraine. Note the different units on this scale. The minimum "A" is found 184 m from the moraine, and the 6‰ $\delta^{18}\text{O}$ shift spans the distance 184–270 m.

(Gudmandsen 1973). As we hoped to be able to measure the ice thickness at the terminus itself, the 60 MHz-radar was hauled on the surface from drill site I to the former EGIG site, Camp 3bis, 4 km up-stream. Single-shot measurements were made for every 200 m between the moraine and a point 2.6 km from the moraine, and again at the site, 4 km from the moraine. Two depth measurements, recorded on an instant film, were performed at each site, with the antenna oriented along and across the expected flow line. The results are ambiguous, except for Camp 3bis, where a clear bottom signal shows an ice depth of 170 m. The bedrock at this site is 540 m a.s.l. The results from the other sites (the bottom 2.6 km of the profile) are difficult to interpret, but indicate depths in the range 100–200 m. The difficulty is probably due to the high content of free water (3%) in the ice from the lower part, compared to the low content (0%) at Camp 3bis (Stauffer and Oeschger 1979).

4. Analyses of gases extracted from ice samples

A few gas analyses have been performed on samples from the drill site I ice core. The results are given in Table II and are compared with a mean value of nine ice samples from the thermally drilled Crête ice core (Stauffer 1981). The air has been extracted by a melt-extraction method, which leads to excessive CO_2 values, due to chemical reaction with impurities in the melt water. Therefore no CO_2 results are presented here.

DISCUSSION OF RESULTS

The surface profile and the lower part of both ice cores show more negative $\delta^{18}\text{O}$ values than any surface values found in central Greenland today. All three records show a characteristic shift of between 5 and 6‰ in $\delta^{18}\text{O}$ values. This shift is similar to that observed in Greenland deep ice cores for the Pleistocene–Holocene transition (Dansgaard and others 1982). Therefore we conclude that this shift in the three records represents ice from the same period, i.e. the final transition from the last glaciation to the Holocene, dated at 10 750 years B.P. (Hammer and others 1986). The minimum, marked "A" in the three records, is thus part of the Younger Dryas. The feature represented by the 6‰ change in all three records is the only isochrone we place with confidence on all the records, even though it looks as if all the records show the termination of the warmer Allerød period, and the records from drill site I and the surface show the entire Allerød period, which occurred before the Younger Dryas period.

In all three records the $\delta^{18}\text{O}$ values of the oldest Holocene ice are -32‰ , corresponding at present to a mean annual temperature of -26.3°C at the site of formation (Dansgaard 1961). This value suggests that the ice originates from a location between Station Centrale and Milcent some 350 km from the terminus of the ice. In addition, flow characteristics lead us to expect that the ice at Camp 3 originates from a region between Station Centrale and Milcent (Reeh 1984). The relatively short travel distance for the ice at Camp 3 is not surprising, as Camp 3 is located between the ice streams to Equip Sermia at the north and Jakobshavn ice stream to the south, and is thus in a region where divergent flow can be expected.

Data for the two ice cores are shown in Table III.

The 150 m of the surface profile closest to the moraine consist of "black ice", i.e. clear ice with very few air bubbles and inclusions of fine dust particles, concentrated in "pockets". The low $\delta^{18}\text{O}$ values of this ice (-37‰) are also found in the bottom part of the ice from drill site I, whereas it is missing in the ice core from drill site II. The

TABLE II. AIR CONTENT AND AIR COMPOSITION IN ICE SAMPLES FROM CAMP 3 AND CRÊTE

Location	Depth below surface m	Total gas content ml/kg	N_2 %	O_2 %	Ar %
Camp 3	1.93	73.6	83.7	15.9	0.83
	2.13	69.6	82.2	17.0	0.83
	3.55	71.2	80.5	18.6	0.82
	4.6	79.1	78.4	20.2	0.72
	8.5	64.1	78.8	20.2	0.95
	8.5	74.8	78.4	20.7	0.82
	11.0	68.0	79.7	19.4	0.86
	11.0	77.1	81.6	17.5	0.82
	21.0	40.3	81.6	17.5	0.83
	21.0	41.2	82.5	16.7	0.78
	Camp 3 mean		65.9 ± 13.2	80.7 ± 1.8	18.4 ± 1.6
Crête mean		71.6 ± 2.7	78.1 ± 1.0	20.8 ± 1.0	0.97 ± 0.03

TABLE III. ICE CORE CHARACTERISTICS

Ice cores from	Drill site I	Drill site II
Distance from the moraine	300 m	710 m
Length of ice core	46 m	92 m
Length of $\delta^{18}\text{O}$ samples in Figures 1 and 2	0.50 m	0.55 m
Depth of Pleistocene–Holocene transition	22 m	86 m
$\delta^{18}\text{O}$ value of Younger Dryas	-38.5‰	-38.5‰
$\delta^{18}\text{O}$ value at the surface	-31.8‰	-31.2‰

thickness of this "black ice" (which represents ice older than 11 ka) can be calculated, assuming that equilibrium and no divergent flow exist on a plain bedrock in the terminus region which has been investigated here. Bauer (1968) reports that the end moraine has been stagnant since at least 1912. For this region Renaud (1969) gives a rate of ablation of 2.10 m of ice per year and Bauer (1968) gives a horizontal velocity (determined during the years 1948–59) of 18 m per year. Our measurements, which are based on the single year 1977–78, are not inconsistent with these values. The assumption of no divergent flow makes the point A (a Younger Dryas isochrone), in Figures 2, 3 and 4, part of the same flow line. In Figure 5 the flow line is shown as the regression line, based on the three points A. Using a simple continuity calculation and assuming that our measured horizontal velocity of 15 m per year and the annual ablation of 2.5 m per year are typical for the region under investigation, we recorded a 30 m thick layer of "black" ice at the bottom in the marginal zone at Camp 3 (see Fig.5).

The results of the total gas content, and especially of the gas composition, for Camp 3 deviate from the mean value of samples from Crête. The lower gas content and the depletion of more soluble air components (like O_2 and Ar) can be explained by assuming that internally produced melt water has left the ice after achieving equilibrium with the

air in the bubbles at the corresponding pressure (Stauffer 1981). If we exclude the values from 21 m depth, the mean total gas content for Camp 3 does not deviate significantly from the Crête value; however, a significant depletion of the more soluble components exists in Camp 3, relative to Crête, and the large scatter in total gas content could be due to non-uniform wash-out processes.

CONCLUSIONS

The three $\delta^{18}\text{O}$ profiles clearly exhibit the Pleistocene–Holocene transition 11 000 years ago. As in other Greenland deep ice cores, this transition is represented by a $\delta^{18}\text{O}$ shift of 6 per mil (from -38 to -32‰) in all three records.

The ice at the margin is temperate but covered by a layer of cold ice, which prevents the surface melt water from percolating the temperate ice. This protective layer explains why the $\delta^{18}\text{O}$ records give no indication of any fractionation due to melt-water percolation (Arnason 1969). The preservation of $\delta^{18}\text{O}$ oscillations in this temperate ice is understandable too when we consider the minor loss of mass in the form of melt water (of the order of only 1%), as calculated from the measurements of the gas content and composition (Stauffer 1981).

In the marginal zones it is relatively easy to recover large ice samples which originate from the last glaciation. However, the dating of the ice is less accurate than in deep ice cores from the central part of the ice sheet. The scientific value of the ice at Camp 3 is limited, because this ice is temperate. We know that the gas content and composition are affected substantially by the influence of melt water and we conclude that the concentration of soluble impurities is affected as well.

There is a strong indication from our results that the stratigraphy is still preserved in the marginal zone. The transition from Pleistocene to Holocene ice was found, both at the surface and in the two ice cores, at the depth predicted by a simple flow model. Therefore the "Younger Dryas isochrone" seems to form a continuous plane in the ice. There is no indication of large-scale folding or of discontinuities.

Investigations in the ablation area of an ice sheet can never replace deep drilling in the interior of an ice sheet. Deep-drilling operations should, however, be supplemented by investigations in the corresponding marginal areas. Investigations in the future should include core drillings farther inland in the ablation zone. If the ice temperature farther inland is below the freezing point, results from measurements of the gas composition and the concentration of chemical impurities can be compared with the results from deep cores.

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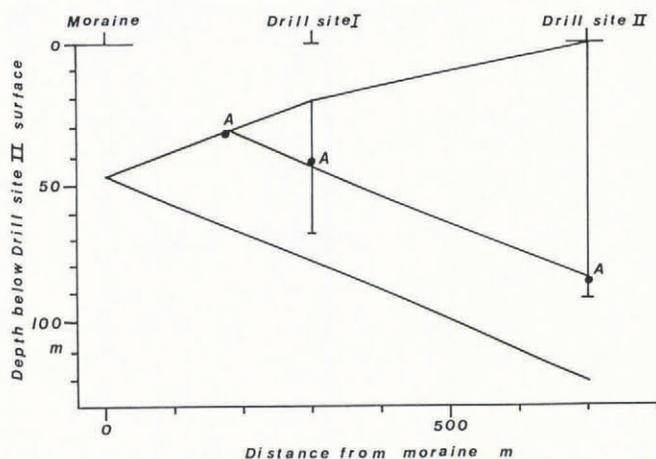


Fig.5. A sketch of the marginal zone at Camp 3, with the locations of the two drill sites. The vertical scale represents distance in meters below the surface at drill site II. The horizontal scale represents distance in meters from the stagnant main moraine. The surface slope is plotted from measured values and a plain bottom is assumed in this region. "A" indicates the position of the Younger Dryas minimum in the three $\delta^{18}\text{O}$ records. The regression line through the points "A" ((185,-32) (300,-43) and (710,-86)) determines a flow line and a 30 m thick layer of "black ice" at the bottom of the ice (see text).

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