Palaeo-environmental studies on the Greenland ice sheet margin

Niels Reeh, Henrik Højmark Thomsen and Carl Egede Bøggild

Oxygen 18 isotope studies ($\delta^{18}O$) of ice from the large ice sheets of the Polar regions have given rich information about climate and environmental changes during the past *c.* 150 000 years (150 ka), and probably much longer. This has been demonstrated by results from the deep ice-core drilling programmes on the central part of the Greenland Inland Ice (e.g. Dansgaard *et al.*, 1982; Johnsen *et al.*, 1992) and Antarctica (Lorius *et al.*, 1985; Kouzel *et al.*, 1987). However, the old ice found at depth in the central regions of the ice sheets can also be sampled and studied at the surface of the ice sheet margins, where ice of different ages is found in a sequence with the oldest ice nearest to the ice edge (Loirus & Merlivat, 1977; Reeh *et al.*, 1987, 1991). Oxygen isotope climate research of this kind was undertaken in 1985 and 1988 at Paakitsoq near Ilulissat/Jakobshavn, West Greenland. These studies were continued and elaborated in 1992.

Flow pattern in an ice sheet

The background of the ice margin isotopic study is the following: an ice sheet can be considered a sedimentary deposit consisting of sequences of layers deposited annually in the accumulation zone as snow. The annual snow layers are buried beneath subsequent snow layers and, as they sink into the ice sheet, undergo continuous thinning. This is initially a result of densification, by which the snow layers are transformed into ice. Later the layers are stretched, mainly due to flow-induced vertical compressive strain, until they are transported by the ice motion into the ablation zone where the ice is removed by melting or calving of icebergs. In areas where ablation by melting is predominant, the layers move upwards relative to the surface where they eventually melt away. The ice flow pattern, illustrated in Fig. 1, shows particle paths in a cross-section of an ice sheet. From this figure it can be seen that the higher the ice was originally deposited in the accumulation area, the deeper into the ice sheet it will sink, and the nearer to the ice sheet margin it will reappear at the surface in the ablation zone. Consequently the oldest ice is found near the base and along the margins of the ice sheet. In principle, a complete sequence of all the deposited layers can be obtained either by deep drilling from the surface to the base in the accumulation zone, or by surface sampling from the equilibrium line (the line separating the accumulation and ablation zones) to the ice margin. In the latter case the layers become progressively younger with distance from the margin of the ice sheet.

Ice margin $\delta^{18}O$ record

In 1985 samples of surface ice were collected along a profile on the ice margin at Paakitsoq (Fig. 2), northeast of Ilulissat/Jakobshavn, West Greenland (Reeh & Thomsen, 1986). Analyses of the samples for $\delta^{18}O$ show that a *c.* 600 m wide zone of ice parallel to the ice margin is of Pleistocene origin (Reeh *et al.*, 1987). How-

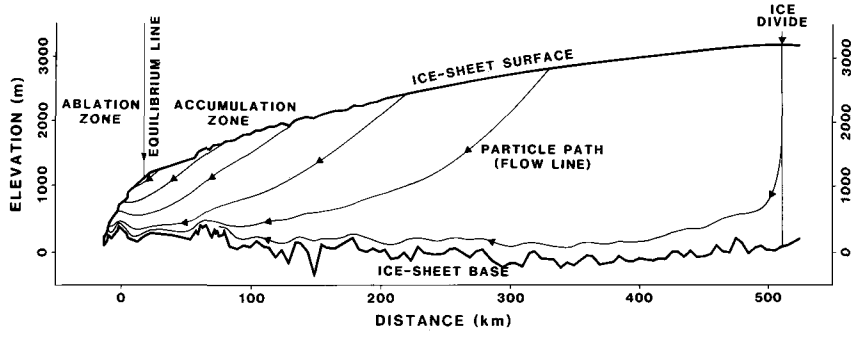

Fig. 1. Ice flow pattern showing particle paths in a cross-section of an ice sheet (after Reeh *et al.*, 1991).

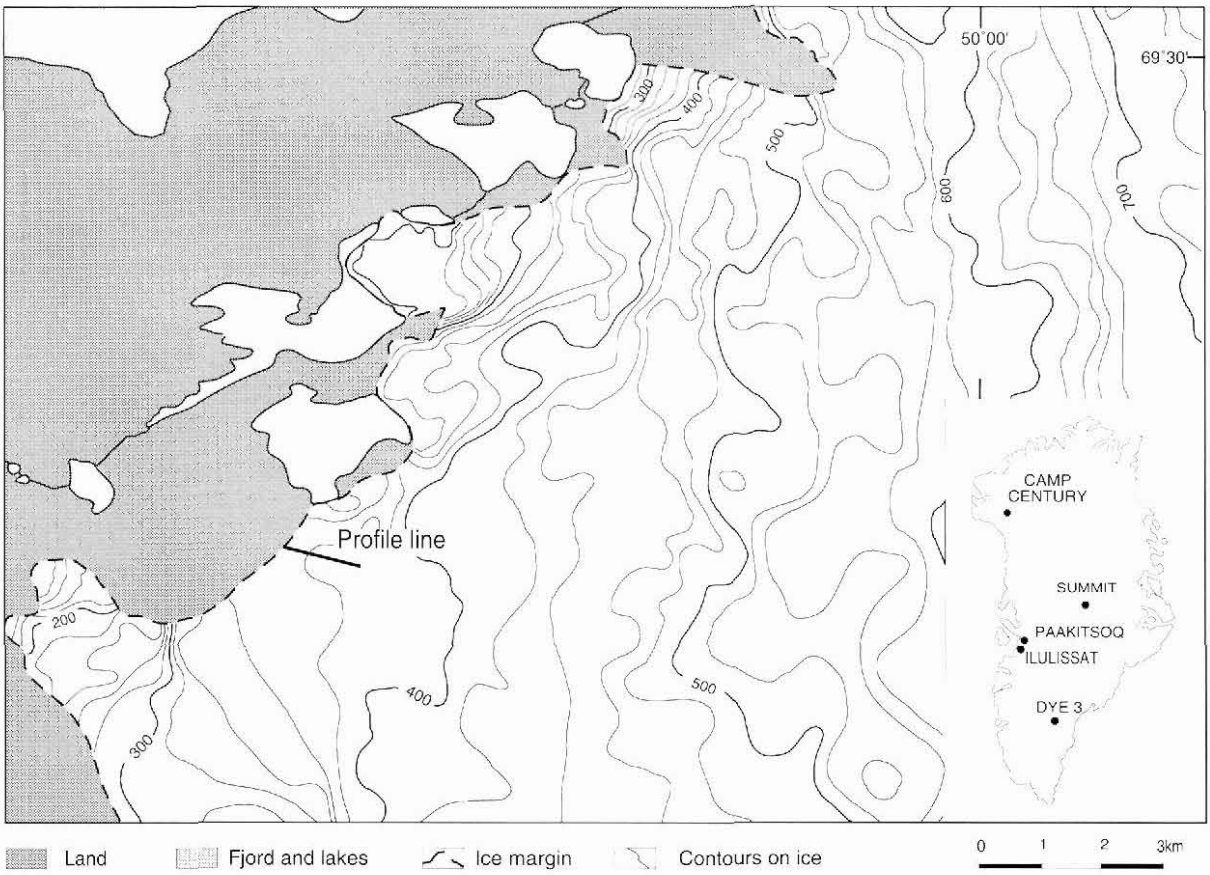

Fig. 2. Map of ice sampling location at Paakitsoq, West Greenland. Sampling profile is given. Insert map shows location of Paakitsoq and the three deep ice core drilling sites, Dye 3, Camp Century and Summit.

ever, the sample spacing of 2–5 m used in 1985 was not close enough to convincingly resolve the details of the Pleistocene $\delta^{18}O$ record.

Ice samples were collected at the same location in 1988, but with sample 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 and the Vostok deep ice core record from Antarctica, shows that important climatic information can be extracted from the ice margin record for a period of at least 150 ka (Reeh *et al.*, 1991). This period includes the early part of the present interglacial (the Holocene), the last glacial epoch, the preceding interglacial, and also a part of the previous glacial.

A tentative interpretation of the Pleistocene $\delta^{18}O$ variations in terms of Emiliani isotopic stages is shown in Fig. 3. The Allerød/Younger Dryas oscillation at the Pleistocene–Holocene transition is also indicated on the figure. The record has been converted into a Greenland temperature record covering the last 150 ka on the time scale derived for the deep ice core from Vostok, Antarctica (Lorius *et al.*, 1985). The Greenland isotopic temperatures indicate large temperature variations in Emiliani's isotopic stage 5 (EIS 5, approximate age 130–75 ka B.P.), with a climate warmer than at present in substage 5e and 5c and also during a short period of substage 5a (for details see Reeh *et al.*, 1991). These indications refer to the conditions in central Greenland around Summit (Fig. 2) where the snow was originally deposited.

The international GRIP project (Greenland Ice Core Project) has undertaken deep ice core drilling at Summit since 1990. In summer 1992 the project succeeded in retrieving a 3029 m ice core from the surface to the bottom of the ice sheet. This will allow $\delta^{18}O$ records from Paakitsoq and Summit to be compared over a period of at least one full glacial cycle.

In order to optimise the comparison between Paakitsoq and Summit a more detailed sampling of the Paakitsoq record was required. The surface ice sampling pro-

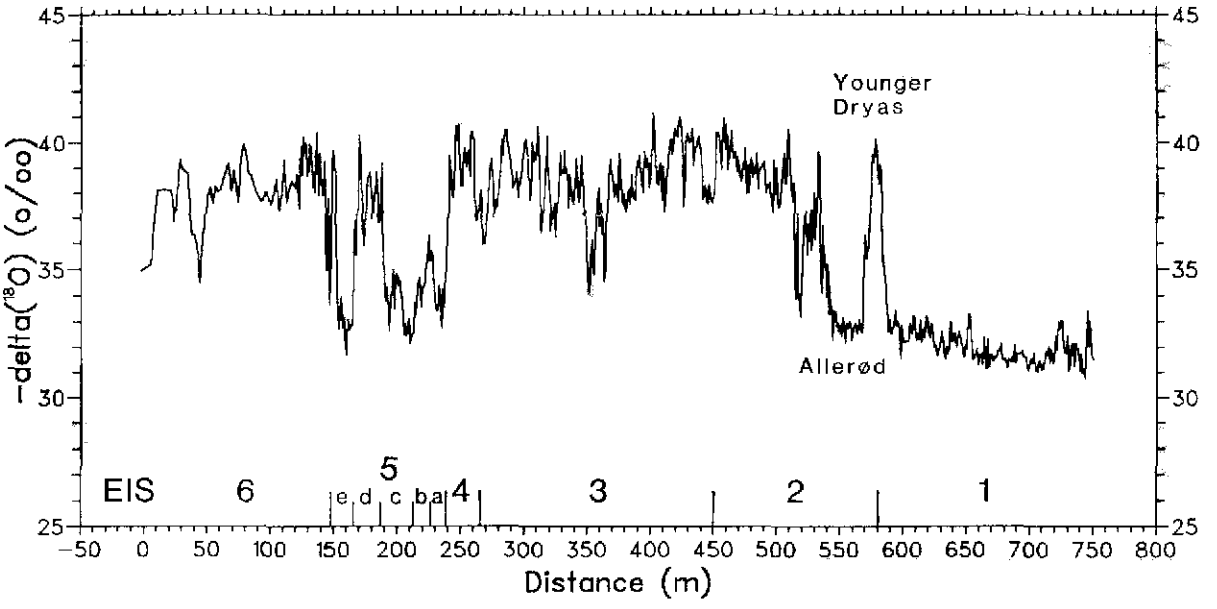

Fig. 3. The $\delta^{18}O$ record from the ice margin at Paakitsoq, West Greenland, showing interpretation of the 1988 record in terms of Emiliani isotopic stages (EIS).

gramme at Paakitsoq was therefore continued in summer 1992, and a 500 m section of the ice margin covering the Pleistocene period was continuously sampled at 20 cm intervals. The samples are at present being analysed for $\delta^{18}O$ at the Alfred Wegener Institute in Bremerhaven, Germany, and the results are expected to be available by the beginning of 1993.

The resulting $\delta^{18}O$ record will provide an optimal basis for correlation with the Summit $\delta^{18}O$ record, and hence provide a basis for evaluating the continuity of the Paakitsoq record, and the potential of ice margin locations for supplying large samples of Pleistocene ice that can be fitted into the Summit ice core chronology.

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N. R., Danish Polar Center, Strandgade 100 H, DK-1401 Copenhagen K, Denmark.

H. H. T., Geological Survey of Greenland, Copenhagen.

C. E. B., Alfred Wegener Institute for Polar and Marine Research, Postfach 120161, Columbusstrasse, D-2850 Bremerhaven, Germany.