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ICE-CORE DATING OF THE PLEISTOCENE/HOLOCENE BOUNDARY APPLIED TO A CALIBRATION OF THE ^{14}C TIME SCALE

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ABSTRACT. Seasonal variations in ^{18}O content, in acidity, and in dust content have been used to count annual layers in the Dye 3 deep ice core back to the Late Glacial. In this way the Pleistocene/Holocene boundary has been absolutely dated to 8770 BC with an estimated error limit of ± 150 years. If compared to the conventional ^{14}C age of the same boundary a value of $\Delta^{14}C = 53 \pm 13‰$ is obtained. This $\Delta^{14}C$ value suggests that ^{14}C levels during the Late Glacial were not substantially higher than during the Postglacial.

INTRODUCTION

Ice-core dating is an independent method of absolute dating based on counting of individual annual layers in large ice sheets. The annual layers are marked by seasonal variations in ^{18}O, acid fallout, and dust (microparticle) content (Hammer *et al,* 1978; Hammer, 1980). Other parameters also vary seasonally over the annual ice layers, but the large number of samples needed for accurate dating limits the possible parameters to the three mentioned above.

If accumulation rates on the central parts of polar ice sheets exceed 0.20m of ice per year, seasonal variations in ^{18}O may be discerned back to ca 8000 BP. In deeper strata, ice layer thinning and diffusion of the isotopes tend to obliterate the seasonal δ pattern.[1] Seasonal variations in acid fallout and dust content can be traced further back in time as they are less affected by diffusion in ice. Under favorable conditions, annual layers have been traced beyond the Pleistocene/Holocene boundary (Hammer, Clausen & Langway, 1985).

If these chronologies should be applied to an absolute dating of climatic events outside the glaciated areas, a safe correlation between the climatic signal revealed by the $\delta^{18}O$ record of the ice and the variations in other climatic records is required. The rapid climatic amelioration at the transition from Younger Dryas (YD) to the Pre-boreal (PB), *ie,* the Pleistocene/Holocene boundary, provides such an unambiguous signal that can be found in all records that reflect the climatic regime in the North Atlantic. The transition is very pronounced in all pollen diagrams covering this period from northwestern Europe, and is equally conspicuous in the ^{18}O records of the Dye 3 and Camp Century ice cores from Greenland. The new 2037m long Dye 3 deep ice core (Dansgaard *et al,* 1982) offers an opportunity for accurate absolute dating of this transition. A comparison between ice core and ^{14}C dating of this event, therefore, provides an independent calibration of the ^{14}C time scale.

[1] δ designates $\delta^{18}O$ which is defined as the ‰ deviation in $^{18}O/^{16}O$ ratio relative to the SMOW (Standard Mean Ocean Water) standard.

SAMPLING AND MEASURING TECHNIQUE

^{18}O

In the Dye 3 core, the isotopic ^{18}O record presents easily interpretable seasonal variations ca 8000 years back in time. For deeper strata, ^{18}O dating is limited by diffusion of water molecules and complicated by thinning of the annual layers, which makes correct sampling of the ice core difficult (the angle between the annual layer and the ice core axis must be known). A good ^{18}O dating requires ca 8 samples, each of ca 5g of ice, per annual ice layer.

Most samples were cut with a bandsaw in the field and shipped frozen to the laboratory, where they were melted and measured mass-spectrometrically. Results are expressed in the δ scale. The 1785m long Holocene part of the Dye 3 core was covered by 67,000 samples.

Dust Content

Seasonal variations of the dust concentration along the core are less conspicuous than δ variations, but they can be traced further back in time. They can be used for an independent dating of segments of the core and for a cross-check of the seasonal δ variations, thus improving the precision of the ^{18}O dating.

During the Dye 3 deep drilling, a new continuous light scattering technique was applied in order to determine the dust content in the core (Hammer *et al*, 1985). The resolution along the core can be varied. To obtain a high resolution (2mm), a slow melting speed of only 1m/h along the core is required.

If the high resolution is applied, this technique can replace the ^{18}O dating for the deeper layers. However, a fairly large amount of water is needed, and some loss in resolution will take place if the angle between the annual layers and the ice core axis is unknown and the thickness of the layers approach 3 to 6cm. For thin annual layers, the method is rather time consuming, and only a few segments of the deeper ice core strata were measured with high resolution (see Fig 2).

Acidity

The acidity was measured by a solid electrical conductivity method (EMC) (Hammer, 1980), which is fast and offers high resolution (1mm along the core). This resolution reveals seasonal variations, even for thin annual layers.

It is a prerequisite for the method that the ice is acid, which is not the case for the glacial part of the Dye 3 core. The acidity was measured from surface to bedrock, of which the postglacial part is used here. This continuous acidity record is the "backbone" in our dating of ice older than 5500 BC. When possible, the acidity dating was cross-checked by the two abovementioned methods.

DATING OF THE DYE 3 CORE

Ice core segments from various depths are used to illustrate the seasonal variations of the three dating parameters (Fig 1). Note the reduced

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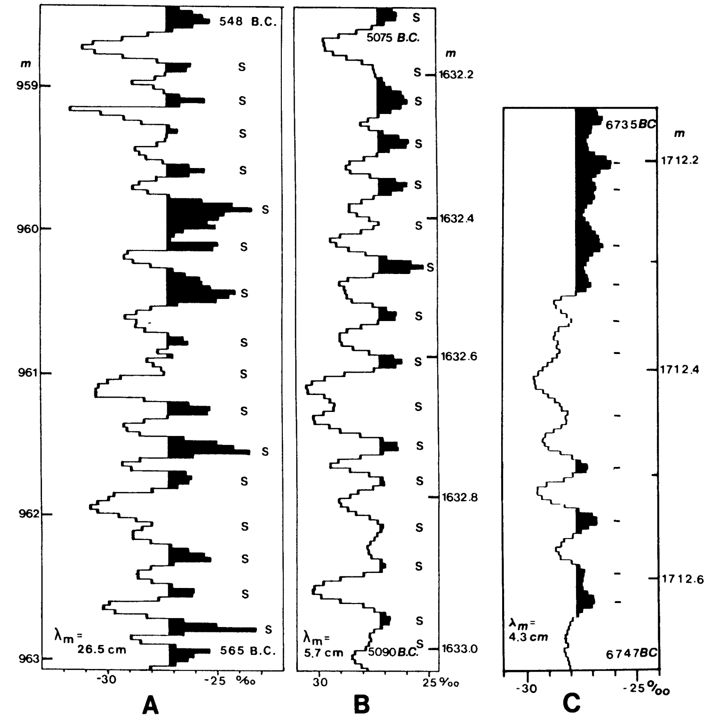

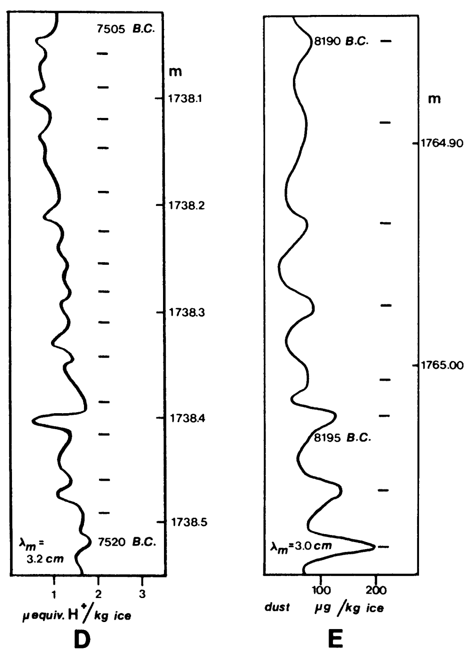

Fig 1. Seasonal $\delta^{18}O$ variations at various depths in the Dye 3 core (1A–C). The effect of diffusion of water molecules on the amplitude of the $\delta^{18}O$ values in the deeper strata is illustrated by (C). Seasonal variations can be tracked to deeper layers by acidity (D) or dust measurements (E).

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amplitude of the δ variations (Fig 1C), as compared to Figure 1A and B. Below ca 1700m dating based solely on δ variations becomes increasingly difficult and must be replaced by dating based on variations in dust content and/or acidity (Fig 1D, E).

Dating the Dye 3 core back to the Pleistocene/Holocene boundary was accomplished in the four steps shown in Table 1 by means of a continuous acidity curve back to the YD/PB boundary, a continuous δ curve back to 3870 BC, and dust and δ measurements on selected segments between 3870 BC and the YD/PB boundary. In Figure 2 the counting of all individual annual layers are plotted *vs* depth for the time interval 5500 BC to YD, together with average annual layer thicknesses (λ) for each 5m depth interval. In this way, the Pleistocene/Holocene boundary was dated to 8770 BC.

Figure 2 also shows a few annual layer estimates in the YD. They show a definite drop in λ values at the transition, indicating a rapid change (within a few decades) of the average precipitation rate over the Greenland ice sheet during the transition period. Similar drastic changes over the YD/PB boundary have also been demonstrated for the ^{18}O values (Dansgaard *et al*, 1984; Fig 3), for dust content and acidity (Hammer *et al*, 1985), and for concentration of chemical components (Herron & Langway, 1985). Such changes must reflect a drastic change in the general circulation of the atmosphere in the North Atlantic region, and it is this rapid transition which is dated to 8770 BC.

The estimated errors in the ice-core dating are indicated in Table 1. The main part of the dating uncertainty is connected with the interval 3870 to 8770 BC, and especially with the interval 5500 to 8770 BC, when seasonal ^{18}O measurements and dust data are relatively sparse. The total estimated error limit is ±150 years.

Recently, the YD/PB transition has also been dated by means of the newly revised Swedish clay varve chronology, which has now been connected directly with the present (Cato, 1985). The new varve date for this

TABLE 1
Dating methods and dating precision in various depth intervals

Depth interval (m)	Time interval	Dating precision	Dating methods: Continuous	Dating methods: Selected segments
0–980	AD 1979 625 BC	625 BC ± 5 (estimated standard deviation)	Acidity $\delta^{18}O$	Dust
980–1540	626–3870 BC	3870 BC ± 10 (estimated standard deviation)	Acidity $\delta^{18}O$	
1540–1656	3871–5500 BC	5500 BC with est error limit of 30 yr	Acidity	$\delta^{18}O$
1656–1785	5501–8770 BC	8770 BC with est error limit of 150 yr	Acidity	$\delta^{18}O$ Dust

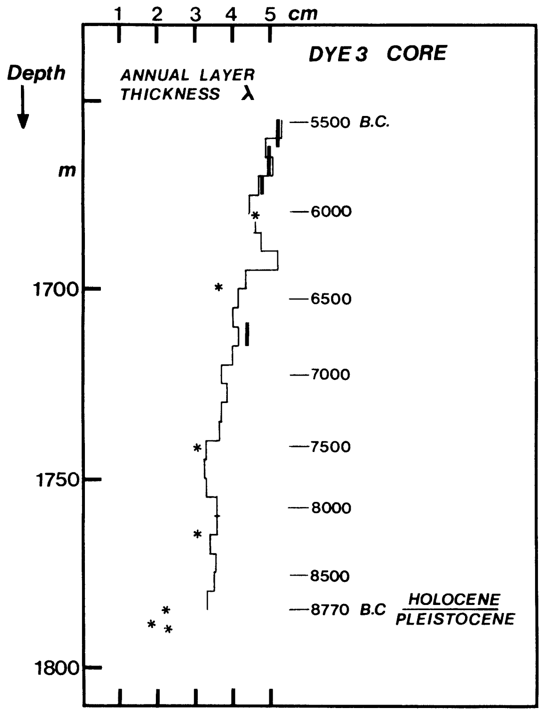

Fig 2. Average annual layer thickness λ for each 5m depth interval and the corresponding ages in the Dye 3 core between 5500 BC and the Younger Dryas. The λ values have been inferred from the continuous acidity measurements (thin line), from $\delta^{18}O$ values (heavy bars), and from dust contents (*). The three lowest dust measurements (*) are from layers in the Younger Dryas.

transition is 8750 $\pm^{50}_{150}$ BC (Strömberg, 1985), in close agreement with the figure obtained from ice-core dating.

The YD/PB transition is also very conspicuous in the ^{18}O profile of the Camp Century deep ice core. Here, the transition was dated by application of a combination of λ data and a semi-empirical flow model, to 8100 BC ±300 yr (Hammer *et al*, 1978). The comparison of the ^{18}O profiles from the Camp Century core and the Dye 3 core in Figure 3 shows a closely concordant development back to the Late Glacial. We therefore conclude that the age of the YD/PB transition should be the same in the two cores, and that an accumulated error of some 670 years must have been introduced in the previous dating of this transition in the Camp Century core. The error seems to be connected with the dating of the Camp Century core in the interval between 6000 BC and the Younger Dryas, where the λ data were nearly absent. This is also suggested, if it is assumed that the major oscillatory feature in the two ^{18}O records (marked with asterisks in Fig 3) occurred simultaneously. This unique feature represents the lowest δ value in both records during the Holocene (apart from the section of increasing δ values

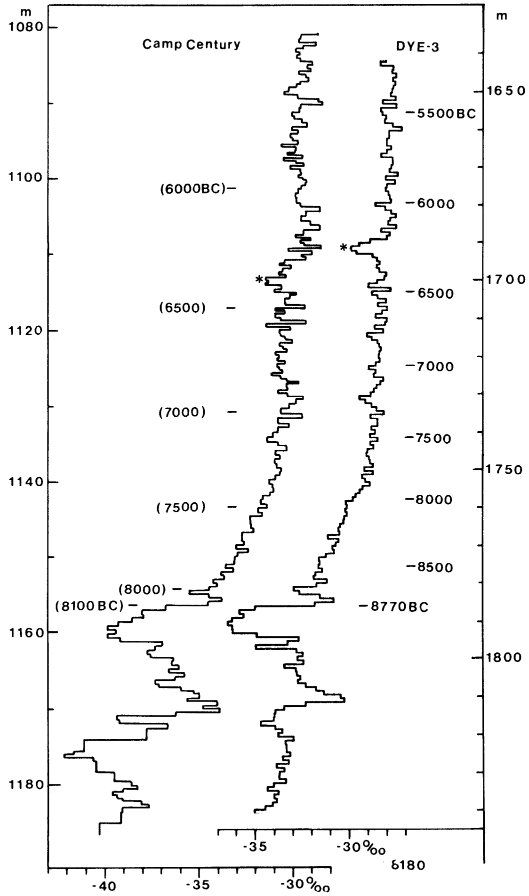

Fig 3. Comparison between dates and $\delta^{18}O$ profiles of the Camp Century core (Hammer *et al*, 1978) and the Dye 3 core. The YD/PB boundary and the strong δ oscillations (*) in the two cores are supposed to be simultaneous. The ages (in brackets) for the lower part of the Camp Century core therefore need considerable correction in order to agree with the more accurate dates of the Dye 3 core.

in the Pre-boreal). We have no suggestions as to what this feature may correspond to in climatic terms, but if it could be correlated with climatic oscillations in other records, eg, in pollen records, it could be used as another important calibration point for the ^{14}C time scale.

CALIBRATION OF THE ^{14}C TIME SCALE AT 8770 BC

The ice-core dating of the YD/PB boundary may be compared to the ^{14}C age of peat and gyttja samples from the same transition. In northwest Europe this transition is often marked by a short but pronounced peak in *Juniperus* pollen, which is usually interpreted as a more profuse flowering of local junipers that had survived the Younger Dryas. It thus serves as the

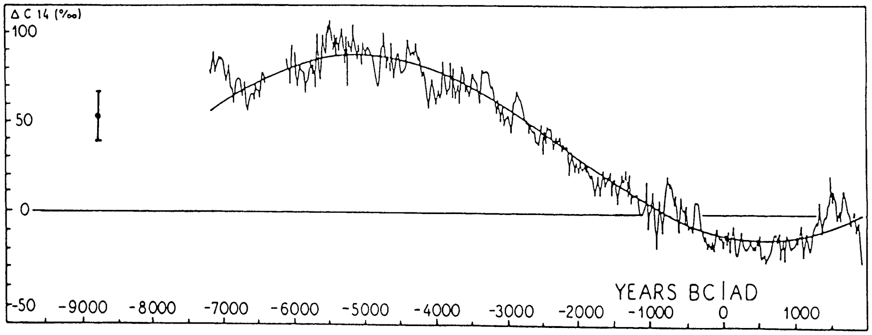

Fig 4. Atmospheric ^{14}C level at 8770 BC calibrated by ice-core dating and dendrochronologically-derived ^{14}C levels from 7200 BC to the present according to Bruns *et al* (1983).

first indication of a somewhat warmer climate. In pollen diagrams, the *Juniperus* peak is followed by a fast rise in *Betula* and/or *Pinus* pollen, which marks the change to real postglacial conditions. The *Juniperus* transitional period in southern Scandinavia is ^{14}C dated to 10,200 to 10,000 BP in conventional ^{14}C years (Mangerud *et al,* 1974; Berglund, 1979).

As mentioned in the previous section, the ice-core dating of 8770 BC applies to a time when an atmospheric circulation pattern, characterized by vigorous dust storms and by low precipitation rates and low $\delta^{18}O$ values in the Greenland ice sheet, had been definitely replaced by a less stormy postglacial circulation, and where $\delta^{18}O$ values were as high as in the warm Allerød period. The date thus refers to a time when the North Atlantic late glacial circulation had definitely come to an end. In the pollen diagrams, this corresponds most likely to a time at the end of the *Juniperus* period, or ca 10,000 ± 75 BP.

At ca 8770 BC in absolute age, the difference between calendar years and conventional ^{14}C years thus amounts to ca 720 years. If the estimated error limit of ± 150 years in the ice-core dating is assumed to correspond to an estimated standard deviation of ±75 years, the difference of 720 years corresponds to a value of $\Delta^{14}C = 53 \pm 13‰$, when calculated on the basis of a half-life of 5730 years. As shown in Figure 4, this $\Delta^{14}C$ value suggests that the rapid decrease in $\Delta^{14}C$ from 7200 to 6600 BC, which is indicated by dendrochronologically-dated wood samples (Bruns *et al,* 1983; Linick, Suess & Becker, 1985), is only part of a transitory oscillation and cannot be taken as an indication of a substantially higher ^{14}C level during the preceding glacial period. This conclusion may be further substantiated by stratigraphic ice-core dating into the Late Glacial period, which is presently being investigated, and by comparisons between ^{14}C ages and the revised varve dates for the Late Glacial (Strömberg, 1985).

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