GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 9, PAGES 1049-1052, MAY 1, 1996

$\delta^{18}O$ of atmospheric oxygen measured on the GRIP Ice Core document stratigraphic disturbances in the lowest 10% of the core.

Andreas Fuchs[1] and Markus C. Leuenberger[2]

Physics Institute, Sidlerstrasse 5, CH-3012 Bern, Switzerland

Abstract. $\delta^{18}O$ measured on oxygen in the bubble air from ice cores is a proxy for continental ice volume and is used to synchronize cores from Greenland and Antarctica. A record measured on ice samples from the Central Greenland deep ice core GRIP, spanning the Last Glacial Maximum and the Holocene, shows that $\delta^{18}O$ of atmospheric oxygen lags $\delta^{18}O$ of ice by about 4000 to 1000 years. The smooth isotope record of atmospheric oxygen shows a steady ice sheet decay beginning around 18'000 years BP taking the time lag into account. However, measurements performed on ice from the GRIP core older than 100 kyrs do not correlate with the corresponding Vostok record and show transitions too fast to be typical for ice sheet build-up or decay. Furthermore, the expected time lag between $\delta^{18}O_{atm}$ and $\delta^{18}O$ of seawater or $\delta^{18}O$ of ice is absent or has even turned into a lead. Climatic interpretation of the fast $\delta^{18}O_{ice}$ transitions is not consistent with our $\delta^{18}O_{atm}$ results. The stratigraphy is possibly irregular and if so, this stops us from constructing a steady age-depth relation in the deepest part of the GRIP ice core.

Introduction

One of the most exciting enigmas in modern paleoclimate research is the possibility that the previous interglacial, the Eem, has been quite unstable as indicated by the GRIP $\delta^{18}O_{ice}$. Several arguments have been forwarded in support of the integrity of the GRIP Eemian record [*Johnsen et al.*, 1995a] and for it's lack of stability. Sea sediment records [*Keigwin et al.*, 1994; *Thouveny et al.*, 1994] further strengthened this view by confirming the instability observed in the GRIP ice core. However this instability of the Eemian was questioned from the beginning. *Kipfstuhl and Thorsteinsson* [1993] found clear evidence of disturbed layers in the lowest 10% of the core. In the case of the GISP ice core *Taylor et al.*, [1993] and *Grootes et al.*, [1993] pointed to disturbed stratigraphy for similar depths. *Bender et al.*, [1994b] already discussed these problems looking at $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$. Here we present $\delta^{18}O_{atm}$ data from the GRIP ice core to further investigate this controversial view of the Eemian.

Ice sheet build-up and decay influences the isotopic composition of seawater, denoted $\delta^{18}O_{seawater}$. The signal herein is transferred via the hydrological cycle and the biosphere (photosynthesis and respiration) to the atmospheric oxygen ($\delta^{18}O_{atm}$). During the last glacial to interglacial transition this parameter varies with an amplitude of about 1.3 ‰ and with a time lag of a few kiloyears with respect to $\delta^{18}O_{seawater}$, which depends on the reservoir size of the biosphere. $\delta^{18}O_{atm}$ is shifted by +23.5 ‰ ("Dole-effect") with respect to the SMOW scale [*Bender et al.*, 1985; *Bender et al.*, 1994a]. The Dole effect reflects oxygen isotope fractionation during photosynthesis, respiration, and hydrologic processes such as evaporation, precipitation, and evapotranspiration. According to *Bender et al.* [1994a], it is nearly constant over glacial to interglacial cycles. The $\delta^{18}O_{atm}$ signal in the atmospheric O_2 is global whereas precipitation and temperature (indicated by $\delta^{18}O_{ice}$ and δD_{ice}) show regional patterns. Therefore, $\delta^{18}O_{atm}$ can be used to synchronize ice cores from Greenland and Antarctica [*Bender et al.*, 1994b; *Sowers and Bender*, 1995].

[1]Now at Ingenieurschule Bern HTL (ISBE), Morgartenstrasse 2c, 3014 Bern, Switzerland. (e-mail: fuchs@isbe.ch).

[2]To whom the correspondence should be addressed.

Paper number 96GL00588
0094-8534/96/96GL-00588$05.00

Results and Discussion

Samples from the Central Greenland deep ice core GRIP have been analyzed for $\delta^{18}O_{atm}$. Series 1 samples goes back to 50'000 years (959.75 m to 2390.30 m), whereas series-2 samples covers the depth interval 2762.65 m to 2949.10 meter. According to the modeled and presently used timescale series-2 samples originate from the Eemian interglacial and Saale glacial period [*Dansgaard et al.*, 1993; *GRIP Members*, 1993]

Technical details of our ice core analyses were described previously [*Leuenberger et al.*, 1992; *Leuenberger and Siegenthaler*, 1992]: Air from milled ice samples (about 70g for analyses of the air fraction only and about 500g including carbon isotope analyses of CO_2) is condensed at 20 K followed by masspectrometric isotope analysis.

On the air fraction, $\delta^{15}N_{atm}$ (mass ratio 29/28), $\delta^{18}O_{atm}$ (34/32) and mass ratio 32/29, which together with $\delta^{15}N_{atm}$ yields $\delta O_2/N_2$ (32/28), are measured simultaneously. $\delta Ar/N_2$ is measured by peak jumping between the two collectors with optimal sensitivity for that ratio. All measurements are given relative to modern air with by definition 0 ‰. The precision deduced from tests with reference gas and gas free ice including extraction is about 0.05 ‰ for $\delta^{15}N_{atm}$ and about 0.08 ‰ for $\delta^{18}O_{atm,measured}$. $\delta^{15}N_{atm}$ is used to correct for the gravitational enrichment in the firn: The corrected oxygen isotope value is given by

$$\delta^{18}O_{atm} = \delta^{18}O_{atm,measured} - 2 * \delta^{15}N_{atm}.$$

If there are no systematic errors in both $\delta^{15}N_{atm}$ and $\delta^{18}O_{atm}$, then the analytical precision for $\delta^{18}O_{atm}$ finally is 0.13 ‰. The corrections for the gravitational enrichment of $\delta^{18}O_{atm}$ with individual measured $\delta^{15}N_{atm}$ values or with the mean $\delta^{15}N_{atm}$ are nearly identical.

The samples whose stable isotope parameters are presented here stem from depths where the air is located most probably in air hydrates rather than bubbles. Elemental ratios as $\delta O_2/N_2$ and $\delta Ar/N_2$ indicate that air hydrates influence the elemental composition of the extracted air, whereas the isotopes, e.g. $\delta^{15}N_{atm}$ and $\delta^{18}O_{atm}$, do not show such a dependence [*Leuenberger*, 1992]. To test whether both the elemental ratios and the stable isotope composition depend on the duration of the extraction (dissolution of clathrates), two nearby samples supposedly being identical were degassed differently long (10 minutes, typical extraction time, and 13 hours, respectively). Within the error limits, $\delta^{15}N_{atm}$ and $\delta^{18}O_{atm}$ of these two samples were identical whereas $\delta O_2/N_2$ and $\delta Ar/N_2$ differed by up to two permil.

In Fig. 1 GRIP $\delta^{18}O_{ice}$ is plotted along with $\delta^{18}O_{atm}$ (series 1 samples) and the corresponding records from Byrd, GISP 2 and Vostok. Our data is in agreement with *Bender et al.* [1994b] and *Sowers and Bender* [1995], who have shown that (1) cores from the north and the south can be synchronized using $\delta^{18}O_{atm}$, (2) that $\delta^{18}O_{atm}$ lags $\delta^{18}O_{ice}$ by a few thousand years and (3) that $\delta^{18}O_{atm}$ is a proxy for global ice volume. Possible fast transitions in the original isotope seawater signal similar to the Dansgaard-Oeschger events as seen in $\delta^{18}O_{ice}$ are smoothed due to the $\delta^{18}O$ signal transfer through the biosphere.

In Fig. 2, we plotted the atmospheric oxygen isotopes parallel to the stable isotopes of GRIP ($\delta^{18}O_{ice}$) and Vostok (δD, *Jouzel et al.*, [1993]) which indicate temperature variations. In the time interval from ≈210 to ≈150 kyrs BP before the Eemian, the mismatch of $\delta^{18}O_{atm}$ from GRIP and Vostok is evident (Fig. 2) even though the resolution is coarse. We believe the Vostok record to be stratigraphically reliable, because it extends back to before 210 kyrs and was measured on ice from 700-1000 m above bedrock [*Jouzel et al.*, 1993]. Since the GRIP time scale is only a first approximation for this depth domain [*Johnsen et al.*, 1995a], we can not discuss this time period any further.

We like to focus on two time sequences during the marine isotope stage (MIS) 6 (Saale glacial) and MIS 5 (Eemian warm period) with unexpected $\delta^{18}O_{atm}$ variations. (1) In GRIP ice the transition of $\delta^{18}O_{atm}$ from MIS 6 to 5 leads the transition of $\delta^{18}O_{ice}$. We call this part of the core Problem Zone no. 1 (PZ 1). (2) During the warm Eemian in GRIP (MIS 5e5; see Fig. 2 for denomination of MIS 5e's) two abrupt jumps were measured for $\delta^{18}O_{atm}$ that have no counterpart in the Vostok record and are unlikely too be real for an ice-volume proxy (see below). We therefore name this depth range Problem Zone no. 2: The jump from MIS 5e5 to 5e4 (127 kyrs) is designated PZ 2a, the jump from MIS 5e3 to 5e2 (119 kyrs) is called PZ 2b. PZ2 is shown in detail in the blow-up of Fig. 2. It is an overlay of $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ on the GRIP time axis from 132 kyrs to 110 kyrs BP and illustrates the very small time lags of these two isotope records during the jumps PZ 2a and 2b. The lag is less than 1 kyr in both cases and with more samples measured, it would possibly become smaller. The large amplitudes indicate massive ice sheet build up in about 1 kyr, taking $\delta^{18}O_{atm}$ as a proxy for ice volume and according to the presently used age-depth relation. This rapidness contradicts the picture obtained from the last transition (Fig. 1), where the amplitude of $\delta^{18}O_{atm}$ for the transition from full glacial to the warm Holocene (about 7 kyrs) is 1.3 ‰ at most. Therefore, at least differential thinning of the ice in which these jumps are found must have taken place. To account for such an effect the age-depth relation would have to be modified in such a way that the $\delta^{18}O_{atm}$ slopes become less steep.

Besides differential thinning we might think of processes like boudinage, intrusion of ice layers between others by wandering of the dome or folding which could lead to features as measured in the presented $\delta^{18}O_{atm}$ record. Overturned folding would change the stratigraphic order in contrast to the other two processes. *GISP and GRIP Members* [1995] documented layers with 20° dipping relative to the normal core axis as well as small scale z-shaped folding in the deepest 300 m of the cores. Whether this dipped layers could be a result of large scale folding cannot completely ruled out despite the fact that it was not „yet" possible to find layers of identical isotopic and chemical compositions. If we assume for now that large scale folding is possible then it could be that the measured GRIP Eemian sequence actually contains the „real Eemian" part three times with 5e2 older and 5e4 younger ice than the Eemian (z-shape folding). The sequences 5e2 and 5e4 would then be reversed in time as well as the middle Eemian part. The shape of $\delta^{18}O_{ice}$ at these depth levels could be an indication for this time reversal which is just the reverse from the ones seen during glacial times (slow cooling, abrupt warming). Folding could also explain the lead of $\delta^{18}O_{atm}$ compared to $\delta^{18}O_{ice}$ as seen in PZ1. On the other hand it is imaginable that intrusions of ice layers had led to a splitting of the Eemian part. However there is hardly any knowledge present how folding and intrusion of ice layers can occur and whether it is actually possible or not.

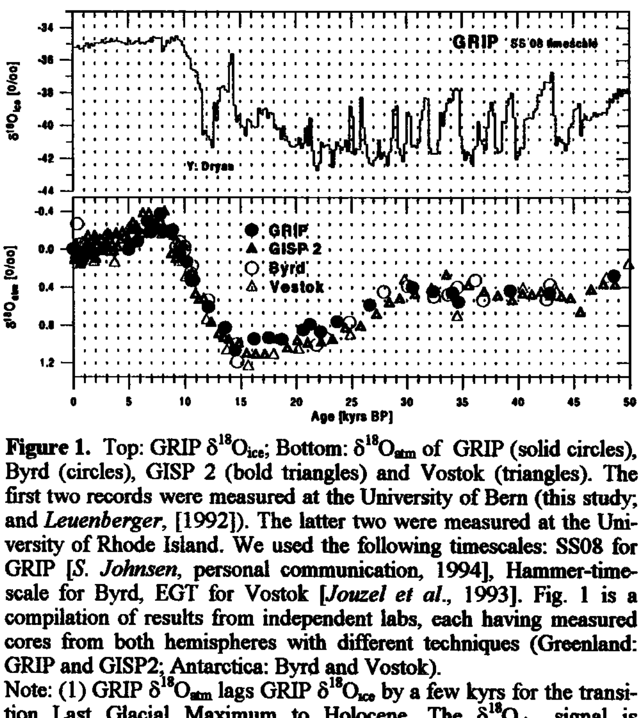

Figure 1. Top: GRIP $\delta^{18}O_{ice}$; Bottom: $\delta^{18}O_{atm}$ of GRIP (solid circles), Byrd (circles), GISP 2 (bold triangles) and Vostok (triangles). The first two records were measured at the University of Bern (this study; and *Leuenberger*, [1992]). The latter two were measured at the University of Rhode Island. We used the following timescales: SS08 for GRIP [*S. Johnsen*, personal communication, 1994], Hammer-timescale for Byrd, EGT for Vostok [*Jouzel et al.*, 1993]. Fig. 1 is a compilation of results from independent labs, each having measured cores from both hemispheres with different techniques (Greenland: GRIP and GISP2; Antarctica: Byrd and Vostok).
Note: (1) GRIP $\delta^{18}O_{atm}$ lags GRIP $\delta^{18}O_{ice}$ by a few kyrs for the transition Last Glacial Maximum to Holocene. The $\delta^{18}O_{atm}$ signal is smoother than its corresponding $\delta^{18}O_{ice}$ record due to its transfer through the biosphere. Therefore only the main features (transition) but not the $\delta^{18}O_{ice}$ details (Dansgaard-Oeschger Events) can be recognized. (2) $\delta^{18}O_{atm}$ records from Central Greenland, GRIP and GISP 2, agree well with the southern records from Byrd and Vostok.

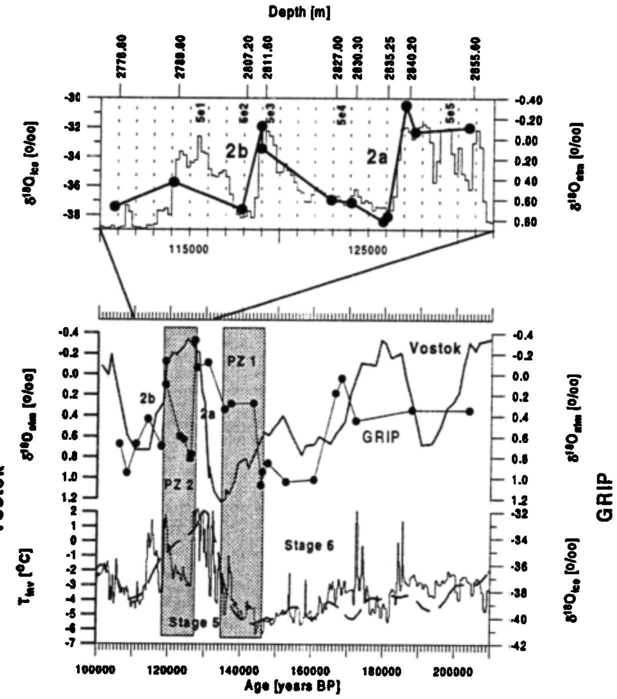

Figure 2. Bottom: GRIP $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ (thin lines; right scale) plotted with δD transformed into temperature and $\delta^{18}O_{atm}$ from Vostok, corrected for the „3G" effect (-0.2 ‰) as discussed in *Bender et al.*, [1994a] (bold lines; left scale) on the respective age scales: GRIP on SS08, Vostok on EGT timescale [*Jouzel et al.*, 1993]. If the SPECMAP [*Sowers et al.*, 1993] instead of the EGT timescale is used records from below 2762.65 m in GRIP still can not be correlated with Vostok. The problem zones 1 and 2 (PZ1, PZ2) are hatched.
Top: Blow-up of PZ2: The 5e's denote the marine isotope stages (MIS) according to ref. *GRIP Members* [1993] and *Johnsen et al.*, [1995].

Differential thinning does result in steeper gradients and a reduced time lag for $\delta^{18}O_{atm}$ and $\delta^{18}O_{ice}$. However it would certainly be inappropriate to stretch the timescale in such a way that the large variations seen in $\delta^{18}O_{atm}$ would correspond to subsequent glacial-to-interglacial cycles (hence solving the problems with time lag and steep gradient), since the $\delta^{18}O_{ice}$ values as well as CH_4 results show intermediate values similar as seen during interstadials (J. Chappellaz et al., submitted to J. Geophys. Res., 1996). Therefore it is rather unlikely that differential thinning is responsible for the fast $\delta^{18}O_{atm}$ variations presented here since their amplitudes are similar to the last and penultimate transition as documented in several ice cores (Fig.1, Fig.2). However, the $\delta^{18}O_{atm}$ variations in the Vostok ice core below 170,000 years are nearly as large as the variations during PZ2 which lowers the conclusiveness of this statement.

Boundinage can be discussed like differential thinning since some layers may thicken at the cost of others. In layers where enhanced thinning takes place we expect time lags to be too small since such effects are not included in determining layer thickness. On the other hand we would expect too large time lags for layers which had extensively thickened. Layer thickness would have to be changed significantly (200 % of the present layer thickness, ≈5 mm at 2800 m depth) to increase the measured time lag of less than 1000 years (PZ2) to the expected time lag of more than 2500 years (*Sowers et al.*, [1993] and M. Leuenberger, submitted to J. Geophys. Res., 1996).

We do not expect a final answer what happened and still is happening at the bottom part of the Greenland ice sheet but we like to discuss the above mentioned mechanisms leading to stratigraphic disturbances from the view-point of gas compositions and their associated implications in more detail in the following paragraphs.

If we would interpret the $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ records as being real, then the transition from warm (MIS 5e5) to cold climate (5e4), at 127 kyrs according to the GRIP age scale, would have been catastrophic: Temperature would have dropped much faster than in Vostok at the end of the Eemian and an ice sheet of about 70% the volume of the Wisconsinian ice sheet would have developed (according to $\delta^{18}O_{atm}$) within a few hundred years. A substantial part of the biosphere existing at these times suffering such conditions probably would have collapsed. Decomposition of huge amounts of organic material should have produced either peaks in the CH_4 or CO_2 history. Records reconstructed from the Vostok core show neither of them [*Jouzel et al.*, 1993; *Chappellaz et al.*, 1990]. Furthermore, phase lags shorter than 1 kyr as seen in GRIP at 127 and 119 kyrs could be explained by an increased biosphere and hence a bigger GPP (Gross Primary Production) compared to the biosphere at the transition to the Holocene. However, more than doubling of the biosphere would be required in order to explain these short lags, which seems unrealistic having in mind the estimated biosphere change of about 20% for the last transition [*Leuenberger and Siegenthaler*, 1992; *Duplessy et al.*, 1988; *Adams et al.*, 1990]. In contrast to the jumps PZ 2a and 2b in the GRIP core, the transition from the Saale cold period into the Eemian, as seen in the Vostok core [*Sowers et al.*, 1991], was accompanied by a large time lag between $\delta^{18}O_{ice}$ (indicated by δD) and $\delta^{18}O_{atm}$. This indicates that the biosphere that should have allowed the small lag at the 127 kyrs transition must have been built up only during the warmest part of the Eemian MIS 5e5, but not before. According to the time scale, period 5e4 lasted more than 4 kyrs and was cold, $\delta^{18}O_{atm}$ indicating high continental ice volume. To transmit the $\delta^{18}O_{seawater}$ signal with a time lag of only 1 kyr to the atmosphere during the 119 kyrs transition the extent of the biosphere must have been voluminous and must have remained nearly constant from the warm period of the Eemian 5e5 onwards throughout the cold period 5e4 and warm period 5e3, since the latter (5e3), with a duration of about 1 kyr, would have been too short to allow for the build-up of a considerable biosphere. Again, this seems very unlikely.

In the following, we discuss further possible explanations of the unrealistic fast slopes in our $\delta^{18}O_{atm}$ record:

One could argue that the information given by $\delta^{18}O_{atm}$ in this depth range in the GRIP core is not representing atmospheric values since that signal could have been modified by physical or chemical processes after bubble close-off. It is reasonable to ask this question also because $\delta^{18}O_{atm}$ and $\delta^{18}O_{ice}$ show virtually no time lag at PZ 2a and 2b. But firstly, no process is known that would allow oxygen-atom exchange between $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$; and secondly, if such an effect would exist, the mean $\delta^{18}O_{atm}$ value of about +23.5 ‰ SMOW would converge with increasing depth towards the mean $\delta^{18}O_{ice}$ of about -35 to -42 ‰ SMOW for the GRIP ice. This is not seen in our nor other $\delta^{18}O_{atm}$ records as demonstrated by Fig.1. Other chemical reactions influencing the isotopic composition of oxygen is rather unlikely since no chemical reaction products were found. If the acid-carbonate reaction, which is most probably responsible for enriched CO_2 concentrations in Greenland ice [*Anklin et al.*, 1995] would release oxygen, $\delta^{18}O_{atm}$ would not measurably be changed assuming a rather large fractionation in the order of the Dole effect (e.g. 20‰). Stratigraphic disorder is more likely. This is further strengthened with the following arguments:

(1) PZ1: During PZ1 $\delta^{18}O_{atm}$ leads $\delta^{18}O_{ice}$ which contradicts the findings for the last glacial-to-interglacial transition for several ice cores from both hemispheres. The lead of $\delta^{18}O_{atm}$ relative to $\delta^{18}O_{ice}$ can in no way be interpreted by a variable gas-ice age difference which can never be negative. *Sowers et al.* [1991] showed by studying the Vostok core that during the Saale-Eemian transition the lag of

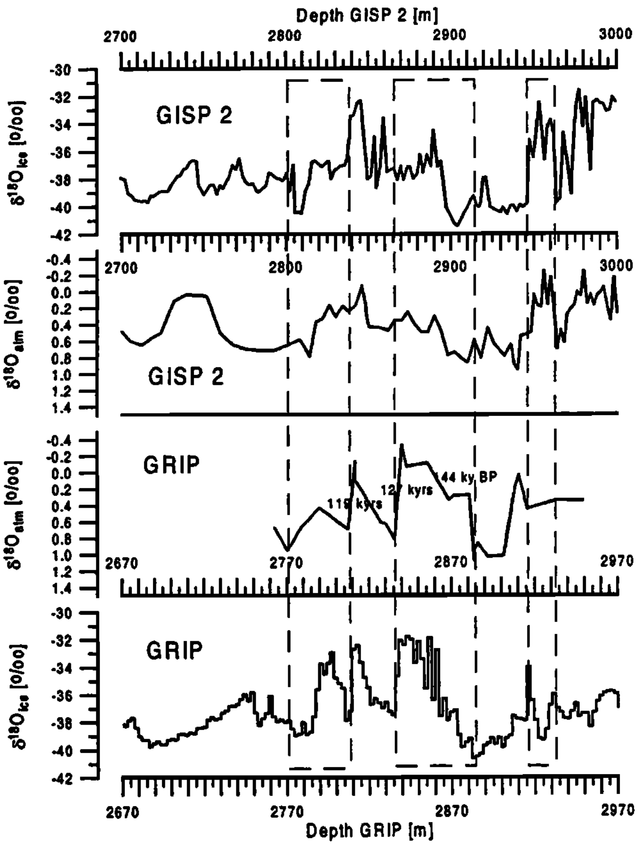

Figure 3. The $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ records of GRIP and GISP 2 [*Grootes et al.*, 1993] on depth scales shifted by 30m.

$\delta^{18}O_{atm}$ and δD was even larger than during the Wisconsin-Holocene transition. The gas-ice age difference changed from 6000 years for Saale-glacial times to 2500 years for Eemian-interglacial times. Even though these numbers are large, Fig. 1 illustrates that during the last transition the Vostok data correlates well with data from all the other cores, for which the gas-ice age-difference is more than ten times smaller, about 200 years for Central Greenland (GRIP and GISP 2) [*Schwander et al.*, 1993]. These 200 years are much less than the expected lag of $\delta^{18}O_{ice}$ and $\delta^{18}O_{atm}$ of a few thousand years. More recent results suggests a highly variable gas-ice age-difference [*Schwander*, personal communication, 1996] based on the larger temperature variations [*Johnsen et al.*, 1995b; *Cuffey et al.*, 1995], however still smaller than the transfer time of the oxygen isotope signal from the ocean to the atmosphere. If $\delta^{18}O_{atm}$ is used as a proxy for ice volume, then $\delta^{18}O_{atm}$ leading $\delta^{18}O_{ice}$ would mean that the ice sheet, built up during the Saale cold period, melted away before the earth system warmed up. This seems unrealistic and suggests irregular stratigraphy. *Kipfstuhl and Thorsteinsson* [1993] as well as *GISP 2 and GRIP Members* [1995] support this hypothesis with visible stratigraphic features that indicate disturbances below the GRIP Eemian.

(2) PZ2: The transition from the warm Eemian into the glacial Wisconsinian as seen in Vostok (Fig. 2) is steady and quite slow, in contrast to GRIP with two peaks in $\delta^{18}O_{ice}$ (5e3 and 5e1, Fig.2). Neither the temperature-indicating stable isotope records ($\delta^{18}O_{ice}$ and δD_{ice}) nor the records of the global parameter $\delta^{18}O_{atm}$ (GRIP and Vostok, as well as GISP2) do match. $\delta^{18}O_{ice}$, Ca^{2+} [*GRIP Members*, 1993] and electrical conductivity measurements [*Taylor et al.*, 1993] show that the ice of the Eemian cold events MIS 5e4 and 5e2 can not be of pure cold glacial origin [*Johnsen et al.*, 1995a], since it records medium values between cold and warm conditions. On the other hand these measurements can not exclude intrusion of ice into 5e2 and 5e4 with similar acidity and $\delta^{18}O_{ice}$ values as some interstadials show [*Wolff et al.*, 1995].

Bender et al. [1994b] have shown that short, fast events trackable in Greenland ice cores (Dansgaard-Oescher-events) occurring during glacial times are not resolved in the Antarctic Vostok core. One could suppose that the same is true for our short and fast events seen in $\delta^{18}O_{atm}$ in the Eemian warm period (PZ2a, PZ2b). Since the air is mixed in the firn before being trapped in the ice, fast atmospheric events shorter than the width of the gas-age distribution of the air at close-off depth are not archived. The firn acts like a low pass filter. Theoretically, the fast transitions documented by trapped gases in the GRIP ice core could have been smoothed out in the Vostok core due to its low accumulation rate and hence wide age distribution; but since the Younger Dryas event is seen in the Vostok CH_4 record [*Chappellaz et al.*, 1990], we exclude this possibility. Our GRIP $\delta^{18}O_{atm}$ data compared to the Vostok $\delta^{18}O_{atm}$ data again suggests that these fast "cold" events do not represent „real" climatic variations.

Fig. 3 shows $\delta^{18}O_{atm}$ of GISP 2, [*Bender et al.*, 1994b], and GRIP plotted against their depth scales. The scales are shifted by 30 m to account for the differences in elevation, ice thickness and flow regime at GRIP and GISP2. The extent of mismatch is astonishing when one considers the fact, that GISP 2 is located approx. 30 km (only about 5 % of today's ice sheet east-west extension) to the west of GRIP, which is at today's ice divide. The GRIP $\delta^{18}O_{atm}$ signal is much more structured than the signal in GISP 2. One possible explanation of such discrepancies could be a wandering dome which could lead to disturbances and mixing of ice layers as has already been seen in the basal ice of GRIP [*Souchez et al.*, 1995] and was shown by modeling likely to occur during glacial-to-interglacial cycles [*Anandakrishnan et al.*, 1994].

Summary and Outlook

In contrast to the last 50 kyrs $\delta^{18}O_{atm}$ measured on GRIP ice with ages assigned to the Eemain warm time can not be synchronized with the Vostok $\delta^{18}O_{atm}$ record (Fig. 2). Even more surprising, the sister record from the nearby GISP 2 ice core looks very dissimilar (Fig. 3). The uppermost feature of our $\delta^{18}O_{atm}$ data that can not be interpreted as being atmospheric is the transition at 2810 m (at 119 kyrs). This is the depth range where *Keigwin et al.* [1994], could not continue to synchronize the deep sea sediment core GPC9 with the GRIP ice core.

We conclude, therefore, that processes unknown prior to the deep drilling projects GRIP and GISP 2 influence the stratigraphy of the deepest 10 % of the Central Greenland Ice Sheet. The previously given evidence for supporting the integrity of the GRIP Eemian sequence is not compatible with our measurements hence has to be taken as inconclusive if accepting ours. The large and abrupt changes in $\delta^{18}O_{atm}$ in GRIP ice could result from differential thinning of ice layers, boudinage, intrusion of layers between others by wandering of the dome, or even folding, and maybe a combination of several of these processes. All these processes do influence the depth-age relation. In *Bender et al.*, [1994b] first hints for an improved dating of the deepest ice are given, but even with all records available today no final timescale can be established [*Johnsen et al.*, 1995].

More detailed studies of the physical parameters in GRIP ice core and high resolution records of global parameters like $\delta^{18}O_{atm}$ and the trace gases CH_4, CO_2 and N_2O should allow the identification of layers as long as corresponding measurements on stratigraphically undisturbed Antarctic cores of comparable time resolution exist.

Acknowledgments. The deep ice core at Summit was obtained by the Greenland Ice core Project (GRIP) and ESF associate program, with Belgium, Denmark, France, Germany, Great Britain, Iceland, Italy and Switzerland participating. The laboratory work was supported by the Swiss National Science Foundation and the Swiss Department of Energy.

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(Received December 8, 1995; revised January 29, 1996;
accepted February 6, 1996.)