JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D18, 4563, doi:10.1029/2002JD003147, 2003

A tentative reconstruction of the last interglacial and glacial inception in Greenland based on new gas measurements in the Greenland Ice Core Project (GRIP) ice core

Amaelle Landais,[1] Jérôme Chappellaz,[2] Marc Delmotte,[2,3] Jean Jouzel,[1] Thomas Blunier,[4] Christine Bourg,[1] Nicolas Caillon,[1,5] Stéphane Cherrier,[1] Bruno Malaizé,[1,6] Valérie Masson-Delmotte,[1] Dominique Raynaud,[2] Jakob Schwander,[4] and Jørgen Peder Steffensen[5]

Received 6 November 2002; revised 2 April 2003; accepted 17 June 2003; published 16 September 2003.

[1] The disturbed stratigraphy of the ice in the lowest 10% of the Greenland GRIP ice core prevents direct access to climatic information older than 110 kyr. This is especially regretful since this period covers the previous interglacial corresponding to marine isotopic stage 5e (MIS 5e, 130–120 kyr B.P.). Here we present a tentative reconstruction of the disturbed GRIP chronology based on the succession of globally well mixed gas parameters. The GRIP $\delta^{18}O_{ice}$ chronological sequence is obtained by comparing a new set of $\delta^{18}O$ of atmospheric O_2 and CH_4 measurements from the bottom section of the GRIP core with their counterpart in the Vostok Antarctic profiles. This comparison clearly identifies ice from the penultimate glacial maximum (MIS 6, 190–130 kyr B.P.) in the GRIP core. Further it allows rough reconstruction of the last interglacial period and of the last glacial inception in Greenland which appears to lay its Antarctic counterpart. Our data suggest that while Antarctica is already entering into a glaciation, Greenland is still experiencing a warm maximum during MIS 5e. *INDEX TERMS:* 1040 Geochemistry: Isotopic composition/chemistry; 1827 Hydrology: Glaciology (1863); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; *KEYWORDS:* interglacial, ice cap, firn

Citation: Landais, A., et al., A tentative reconstruction of the last interglacial and glacial inception in Greenland based on new gas measurements in the Greenland Ice Core Project (GRIP) ice core, *J. Geophys. Res.*, *108*(D18), 4563, doi:10.1029/2002JD003147, 2003.

1. Introduction

[2] Tracers in ice cores, such as water isotopic composition, greenhouse gases and chemical impurities, are used to reconstruct paleoclimatic and environmental conditions at the Earth's surface. Such reconstructions require that the quality and continuity of the records are ensured. These conditions are generally met on the summit of ice sheets or ice domes, where the annual surface temperature is low enough (below −30°C) to prevent summer melting. At such locations dynamic disturbances, such as shearing of the ice, are supposed to be less pronounced than on sloped surfaces. The GRIP (Greenland Ice Core Project, 72°43′N, 37°37′W) and GISP2 (Greenland Ice Sheet Program 2, 72°58′N, 38°48′W) drilling sites in Central Greenland were chosen because they fulfill the above mentioned conditions. The isotopic records recovered from the two cores [*Dansgaard et al.*, 1993; *GRIP Project Members*, 1993; *Grootes et al.*, 1993] agree well on the top 90% of the core lengths. Nevertheless, significant discrepancies appear in the lowest 10%, for ice deeper than 2750 m of depth at GRIP and at GISP2, i.e., older than 105–110 kyr [*Grootes et al.*, 1993].

[3] As the two drill locations are only 30 km apart from each other, the ice isotopic differences encountered in the bottom part of the cores cannot be attributed to different climatic conditions. The most plausible explanation relates to stratigraphic disturbances at the bottom of the ice sheet affecting one or both cores. Several studies, based on texture [*Thorsteinsson*, 1996], chemistry [*Legrand et al.*, 1997; *Yiou et al.*, 1997] and gases [*Bender et al.*, 1994a; *Souchez et al.*, 1995; *Fuchs and Leuenberger*, 1996; *Chappellaz et al.*, 1997a] of the two cores, have indeed demonstrated the existence of such disturbances.

[4] Atmospheric trace gases whose lifetime exceeds the interhemispheric mixing time are tracers on a global scale.

[1]IPSL/Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, Gif sur Yvette, France.
[2]Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, Saint Martin d'Hères, France.
[3]Now at Institut de Physique du Globe de Paris, Laboratoire de Cosmochimie et Géochimie, CNRS, Paris, France.
[4]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland.
[5]Now at Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, USA.
[6]Now at Département de Géologie et Océanographie, UMR CNRS 5805 EPOC, Université Bordeaux 1, Talence, France.
[7]Department of Geophysics, University of Copenhagen, Copenhagen, Denmark.

0148-0227/03/2002JD003147$09.00

By combining several gases, it is possible to attribute the age of an unknown layer by comparison to records from different ice cores. In addition to providing a relative dating of the ice found at different depth levels in the two cores, the method also reveals the location of the ice flow disturbance. Among the four main gas components routinely measured in ice cores (CO_2, CH_4, N_2O, $\delta^{18}O_{atm}$), CH_4 and air O_2 isotopic ratio are preferentially used as such [*Bender et al.*, 1994a; *Sowers and Bender*, 1995; *Blunier et al.*, 1998; *Blunier and Brook*, 2001; *Morgan et al.*, 2002]. On the one hand, CO_2 suffers from in situ production in Greenland ice [*Anklin et al.*, 1995], thus preventing secure comparison between Greenland and Antarctic records. On the other hand, N_2O shows sporadic artifacts in portions of Antarctic ice [*Sowers*, 2001; *Flückiger et al.*, 1999], especially in the cold and dusty ice of stage 6 possibly due to microbial contamination. For these reasons, combined measurements of CH_4 and $\delta^{18}O_{atm}$ [*Chappellaz et al.*, 1997a] currently represent the only available reliable tool for the comparison over long timescales between Antarctic and Greenland records. The $\delta^{18}O_{atm}$ is mainly controlled by the global ice volume [*Sowers et al.*, 1991] and biological productivity [*Bender et al.*, 1994b] and O_2 has a residence time of 1200 yr compared to which the 1 year required for interhemispheric exchange is negligible. Past methane emissions are primarily linked to wetlands extent and temperature [*Chappellaz et al.*, 1993] and potentially to hydrate decomposition [*Kennett et al.*, 2000]. The residence time of CH_4 in the atmosphere is $\sim$10 yr. For most of the glacial-interglacial transitions, the $\delta^{18}O_{atm}$ change lags the CH_4 variations by 4,000 to 8,000 yr [*Petit et al.*, 1999] (Figure 1a). Therefore the combination of the two gas records provides useful constraints in a phase plane representation, as shown in Figure 1b, which depicts the $CH_4/\delta^{18}O_{atm}$ relationship in the Vostok data sets between 390 and 110 kyr B.P. (on the GT4 timescale [*Petit et al.*, 1999]; see also caption of Figure 1). Using an implicit temporal evolution diagram, we clearly depict a distinct trajectory on a $CH_4/\delta^{18}O_{atm}$ phase plane for each major glacial-interglacial transition.

[5] Here we investigate the stratigraphic disturbances in the bottom section of the GRIP core using eighty CH_4/$\delta^{18}O_{atm}$ measurements in the depth range 2750–3005 m, thus extending the work of *Chappellaz et al.* [1997a], which was based on thirty gas measurements. The stratigraphic interpretation relies on the comparison with the Vostok $CH_4/\delta^{18}O_{atm}$ records (Figure 1a), which now encompass four complete climatic cycles, i.e., the last 420,000 years [*Petit et al.*, 1999]. We use these results to identify unambiguously ice sections from marine isotopic stages 5e and 6 (see Figure 1a) and to propose a tentative chronology and reconstruction for the glacial inception in Greenland.

2. Analytical Procedures

2.1. The $\delta^{18}O_{atm}$

[6] The GRIP $\delta^{18}O_{atm}$ measurements (Figure 2a) were performed at the LSCE (pooled standard deviation of 0.04‰ on systematic duplicates) at eighty depth levels using two 10 cm long ice samples per depth level. The air is extracted through a melt-refreeze method [*Severinghaus and Brook*, 1999; *Sowers et al.*, 1989; *Caillon et al.*, 2001] and isotopic ratios ($\delta^{15}N$ and $\delta^{18}O$) are measured on a Finnigan MAT 252 mass spectrometer.

[7] Several slight corrections are applied to the measured $\delta^{15}N$ and $\delta^{18}O$ according to standard procedure [*Bender et al.*, 1994c]. For $\delta^{15}N$, a correction stands for the influence of CO^+ (of mass 28) from the ionization of CO_2. However, the main source of analytical uncertainty results from the sensitivity of the $\delta^{18}O$ mass spectrometer measurements to variations in $\delta N_2/O_2$. Indeed, the relative ionization efficiencies of ^{18}O and ^{16}O in the mass spectrometer source are affected by differences in sample and standard N_2/O_2 ratios, which is currently defined as the "chemical-slope" [*Bender et al.*, 1994c; *Severinghaus et al.*, 2001, 2003]. We experimentally determined a $\delta^{18}O$ correcting factor on the order of 0.3‰ for a $\delta N_2/O_2$ enrichment of 30‰. The chemical slope has been checked weekly during all the duration of measurements and proved to be a constant value of 0.01 ‰/‰ with a 1σ error of 0.001‰/‰ ($\delta^{18}O$ per $\delta N_2/O_2$). In addition, standard to standard comparison measurements were performed every day (overall 1σ = 0.003‰ for $\delta^{15}N$ and 0.006‰ for $\delta^{18}O$) to prevent bias in the mass spectrometer measurements. Finally as $\delta^{18}O_{atm}$ results are expressed using atmospheric air as standard, we regularly checked (at least twice a week) our laboratory standard versus atmospheric air to prevent any deviations in the standard isotopic composition (overall 1σ = 0.004‰ for $\delta^{15}N$ and 0.007‰ for $\delta^{18}O$).

[8] A comparison between previous [*Chappellaz et al.*, 1997a] and new $\delta^{18}O$ of O_2 series revealed the existence of a significant loss of O_2 from the ice. We attributed this effect to ice storage as already observed by *Bender et al.* [1995]. Typically we observed a loss of O_2 on the order of 3% (occasionally up to 8%) between the new series of samples and those previously analyzed in 1997, which were not at all or only slightly affected by this effect. We also observed an increase in the $\delta^{18}O$ of O_2 that seems to be directly related to the O_2 loss (a rough dependence between the two variables appeared with a R^2 = 0.6), the maximum effect being on the order of 0.2‰ in the case of a very high loss of O_2. Because of the uncertainty associated with such correction, we chose to not correct the measured $\delta^{18}O$ of O_2 depending on the O_2 loss but we arbitrarily excluded the $\delta^{18}O_{atm}$ data when an O_2 loss higher than 5% was observed.

[9] Indeed, we checked the O_2 loss effect from the Vostok core by measuring $\delta^{18}O_{atm}$ on 6 duplicate samples from Termination II and by comparing them to results obtained by *Sowers et al.* [1993] (corrected by *Bender et al.* [1994b]) 14 years ago at URI. In 1997 [*Chappellaz et al.*, 1997a], the analytical systems at URI and at LSCE were roughly intercalibrated. The comparison between both data sets showed a systematic shift of +0.07‰ (1σ = 0.04‰) for the new $\delta^{18}O_{atm}$. This experiment confirms the storage effect, and we have such decreased the GRIP $\delta^{18}O_{atm}$ measurements by 0.07‰ to make them comparable with the Vostok record over the last 400 kyr [*Sowers et al.*, 1993; *Bender et al.*, 1994a; *Malaizé et al.*, 1999; *Bender et al.*, 1999] although the latter is a composite of samples stored over different time periods.

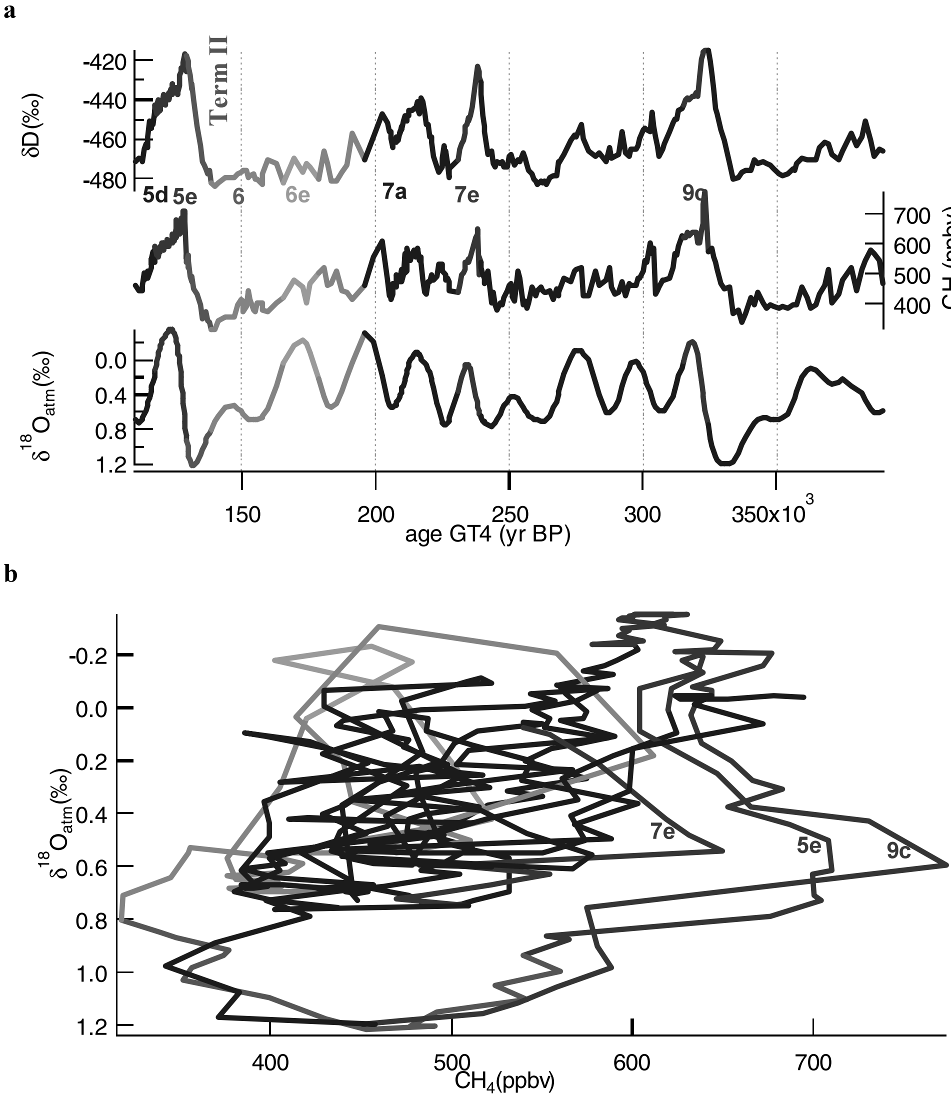


Figure 1. (a) Vostok δD, CH_4, and $\delta^{18}O_{atm}$ time series with indication of some marine isotopic stages (MIS) between 110 and 390 kyr B.P. (data are from *Petit et al.* [1999]). The marine isotope stage boundaries (initially described by *Martinson et al.* [1987]) are taken as the midtransition of the $\delta^{18}O_{atm}$ profile, with a 2 kyr time lag taking into account the $\delta^{18}O_{atm}$ delay on ice volume change [*Sowers et al.*, 1991]. Termination II is taken as the penultimate glacial-interglacial transition between stage 6 and stage 5e, but according to *Martinson et al.* [1987], it is part of MIS 6. (b) Vostok $\delta^{18}O_{atm}/CH_4$ phase plane between 110 and 390 kyr B.P. The $\delta^{18}O_{atm}$ record is interpolated on the better resolved CH_4 record. Colors were chosen to indicate the clearest sequences: red for Termination II and purple for interglacial; light green for the high insolation maximum (6e) during stage 6 (green); blue for the remaining glacial variability. See color version of this figure at back of this issue.

[10] The instrument-corrected $\delta^{18}O$ of O_2 was then corrected for gravitational fractionation by subtracting twice the $\delta^{15}N$, supposed to be strictly of gravitational origin. A possible additional correction concerned the thermal diffusion. Sensitivity tests have been conducted; assuming a $\delta^{15}N$ thermal fractionation of 0.1‰ (maximum effect), we calculated a maximum deviation of +0.03‰ on the final $\delta^{18}O_{atm}$ value, considering the ratio of thermal sensitivity between the two pairs of isotopes [*Severinghaus et al.*, 2001]. With regard to our experimental uncertainty and the extreme thermal effect considered in the above calculation (which might not old true for the present GRIP study), we thus neglected this effect.

2.2. CH_4

[11] CH_4 mixing ratio measurements (Figure 2a) are performed at the LGGE using an automated and recently improved wet extraction method (Chappellaz et al., in preparation, 2003). Eighty samples were analyzed at exactly the same depths as the 80 $\delta^{18}O_{atm}$ samples with a 10 cm resolution. Each sample was analyzed three times with a Flame Ionization Detector equipped gas chromatograph resulting in a 10 ppbv internal reproducibility (1σ). As

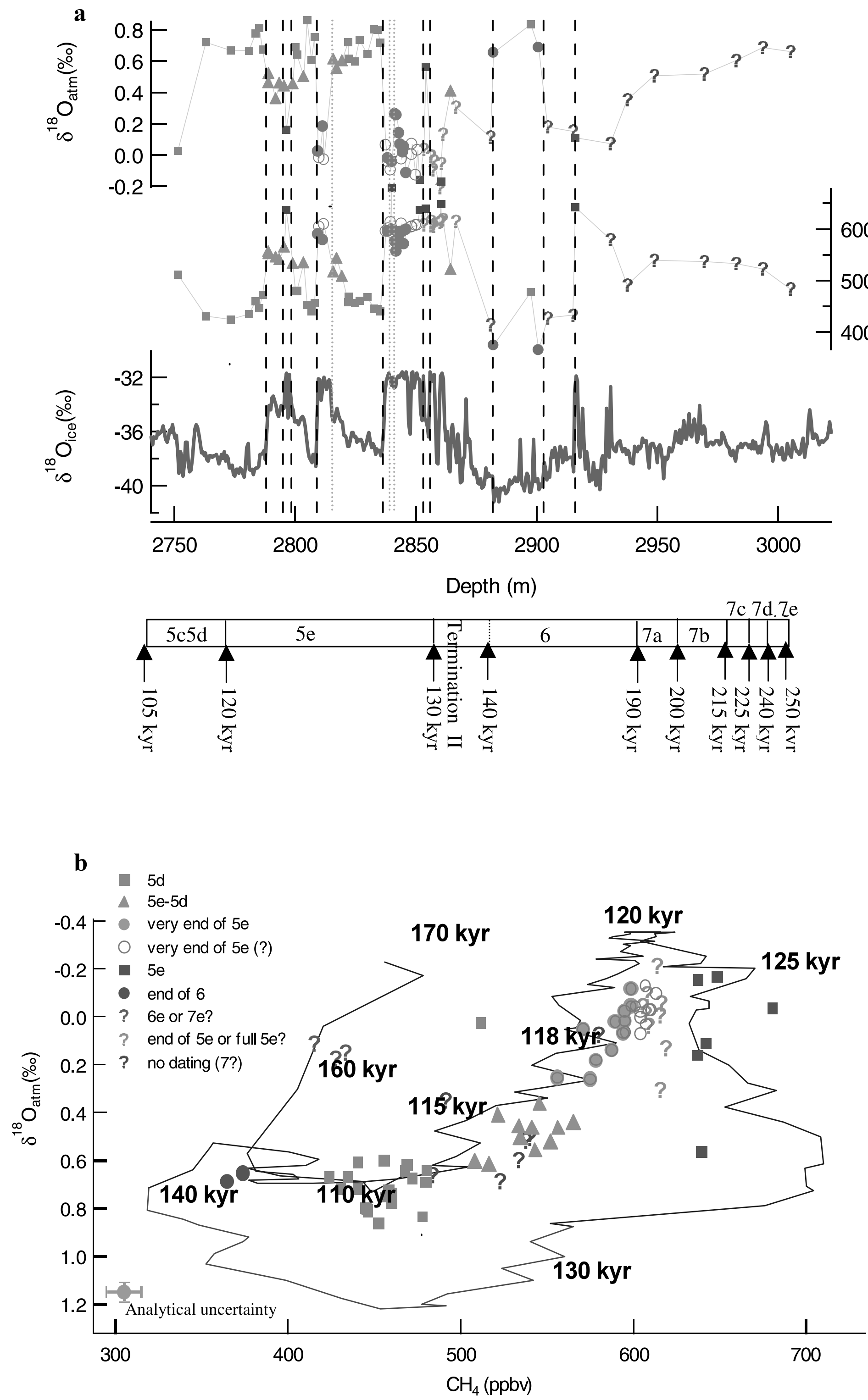


Figure 2. (a) CH_4, $\delta^{18}O_{atm}$, and $\delta^{18}O_{ice}$ profiles for the bottom of the GRIP ice core. The GRIP dating here is estimated by an ice flow model assuming no mixing [*Johnsen et al.*, 1993]. (b) $CH_4/\delta^{18}O_{atm}$ data pairs from the bottom part of the GRIP core compared with the Vostok phase plane (line) between 110 and 170 kyr with Termination II (indicated in red). The uncertainty envelope around Vostok trajectory accounts for experimental uncertainty in Vostok measurements and for uncertainty in the estimation of interhemispheric gradient. The GRIP data pairs were divided into nine zones marked with signs and colors corresponding to their positions with regard to the Vostok trajectory (Termination II again indicated with red line). Note that the same legend is used for Figures 2a and 2b. See color version of this figure at back of this issue.

CH_4 sources are essentially located in the Northern Hemisphere, a slight interpolar gradient must be taken into account when comparing Antarctic and Greenland records [*Chappellaz et al.*, 1997b; *Dällenbach et al.*, 2000]. Between cold and warm periods this gradient varies from 5 to 8% of the Greenland CH_4 mixing ratio. Most of the observed CH_4 levels in the bottom part of the GRIP core correspond to intermediate or interglacial mixing ratios. Therefore for the comparison with Vostok CH_4, a systematic interglacial correction of -7% has been applied to GRIP data.

[12] New CH_4 measurements on 6 samples of the Vostok core over Termination II were performed. No significant difference appeared with the original Vostok CH_4 series (initially measured with the previous LGGE methane analytical system (*Chappellaz et al.* [1990], corrected by *Chappellaz et al.* [1997a])) and thus no analytical correction was required for comparing GRIP and Vostok CH_4 data sets.

[13] This new $CH_4/\delta^{18}O_{atm}$ data set is an extension of the data set presented by *Chappellaz et al.* [1997a]: neighboring depth samples were analyzed and gave similar results. However, we present here only the new data set since (1) all $CH_4/\delta^{18}O_{atm}$ measurements were performed at exactly the same depth (which was not the case in the paper of 1997), thus eliminating any bias due to differences in the gas mixing ratio between neighboring samples, and (2) the analytical uncertainty on $\delta^{18}O_{atm}$ measurements has been significantly reduced.

2.3. Vostok $CH_4/\delta^{18}O_{atm}$ Phase Plane Over Four Climatic Cycles

[14] The mean time resolution of the Vostok $\delta^{18}O_{atm}$ and CH_4 profiles (Figure 1a) is 1800 yr and 1200 yr, respectively. The Vostok $\delta^{18}O_{atm}$ record has high enough resolution compared to the mean residence time of atmospheric oxygen ($\sim$1200 yr) to fully capture its past variability. This, however, is not the case for the CH_4 record, especially during stages 6 and 7 when the resolution is 5 kyr compared to an atmospheric residence time of 10 yr.

[15] During the past 110 kyr, there is apparently no stratigraphic disturbance in the two Greenland summit deep cores, GRIP and GISP2 [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993], which precludes the possibility for the corresponding ice to be encountered in the bottom part of the two cores. To identify the GRIP bottom sections with respect to Vostok, analogous gas sequences are searched for in the undisturbed $CH_4/\delta^{18}O_{atm}$ phase plane from Vostok between 110 and 390 kyr B.P. (Figure 1b).

[16] The full Vostok phase plane cannot be used to unambiguously constrain the GRIP chronology. Indeed most of the glacial phase plane sequences are shared between consecutive climatic cycles and within glacial cycles themselves (especially the center of the phase plane on Figure 1b pictured with blue lines). Only sequences of glacial-interglacial transitions, interglacial optima and glacial inceptions provide clear and specific $CH_4/\delta^{18}O_{atm}$ data pairs that can be used to constrain the chronology [*Raynaud et al.*, 2003].

3. Results: GRIP and Vostok $CH_4/\delta^{18}O_{atm}$ Phase Plane

[17] Assuming no stratigraphic disturbances, GRIP ice flow calculations show that ice from stages 7d and 7e near 3000 m of depth should be strongly affected by thinning [*Dansgaard et al.*, 1993] (Figure 2a) and therefore suggest a very weak probability of finding a significantly thick layer of ice older than stage 8. Moreover, the lowest values of $\delta^{18}O_{atm}$ found in the GRIP profile are not compatible with ice from stage 7 and the highest GRIP methane mixing ratio is too low to fit the maximum of MIS 9. For these reasons and due to the ambiguity of $CH_4/\delta^{18}O_{atm}$ data pairs over stage 7 on the Vostok phase plane making the identification difficult, we restrict the search for analogous pairs of $CH_4/\delta^{18}O_{atm}$ between GRIP (above 2920m) and Vostok to the time period between 110 and 170 kyr B.P. (from stage 5d to stage 6). This assumption constitutes the main limit to our approach as we have no proof yet that ice older than 170 kyr B.P. is absent from GRIP sections above 2920 m.

[18] The resulting ages proposed for GRIP sections are relative to the Vostok GT4 timescale (which has an accuracy better than 15 kyr [*Petit et al.*, 1999]) and are in no way claimed to be absolute or independent ages. In order to attribute Vostok ages to $CH_4/\delta^{18}O_{atm}$ pairs from GRIP, we superimposed them to the Vostok phase plane trajectory (Figure 2b) which includes by quadratic addition error bars due to interhemispheric CH_4 gradient (20 ppbv) and analytical errors on Vostok measurements (10 ppbv for CH_4 and 0.07‰ for $\delta^{18}O_{atm}$). This comparison enables the attribution of constrained ages for several ice layers and leads to the following conclusions :

[19] 1. The lack of samples with high $\delta^{18}O_{atm}$ confirms previous gas studies conducted on both GRIP and GISP2 cores [*Chappellaz et al.*, 1997a; *Bender et al.*, 1994a] and indicates that no ice from Termination II (defined as the transition between full glacial and interglacial in Antarctica, Figure 1a) can be identified in Greenland Summit cores so far. Note that lack of detailed measurements in the depth range 2860–2880 m prevents reaching a definite conclusion on such absence.

[20] 2. Two ice sections (at 2882 and 2900 m depth) with low CH_4 levels and relatively high $\delta^{18}O_{atm}$ correspond to a quite well-defined region, at the end of stage 6 ($\sim$140–145 kyr B.P. on Vostok timescale). The identification of ice from the penultimate glacial stage is confirmed at these depths by three gas measurements from *Chappellaz et al.* [1997a] and small crystal sizes [*Thorsteinsson et al.*, 1997].

[21] 3. Most GRIP samples from 2780 to 2850 m lie on the Vostok phase plane trajectory characteristic of the 5e-5d glacial inception. The sequence of these data pairs with increasing depth shows back-and-forth between the 5d and 5e regions along this specific trajectory, probably reflecting several fold axes in this 100 m thick layer.

[22] 4. A few data pairs with relatively high CH_4 levels can be attributed unambiguously to stage 5e according to the Vostok gas trajectory.

[23] Some of the data pairs in Figures 2a and 2b (open green circles) attributed to the end of stage 5e may be questioned. Their attribution is indeed based on the high correlation of water isotopic composition and chemical data between adjacent ice samples marked with open and closed circles. Moreover, this high correlation warrants that the following reconstruction of $\delta^{18}O_{ice}$ is independent of the presence of those data pairs.

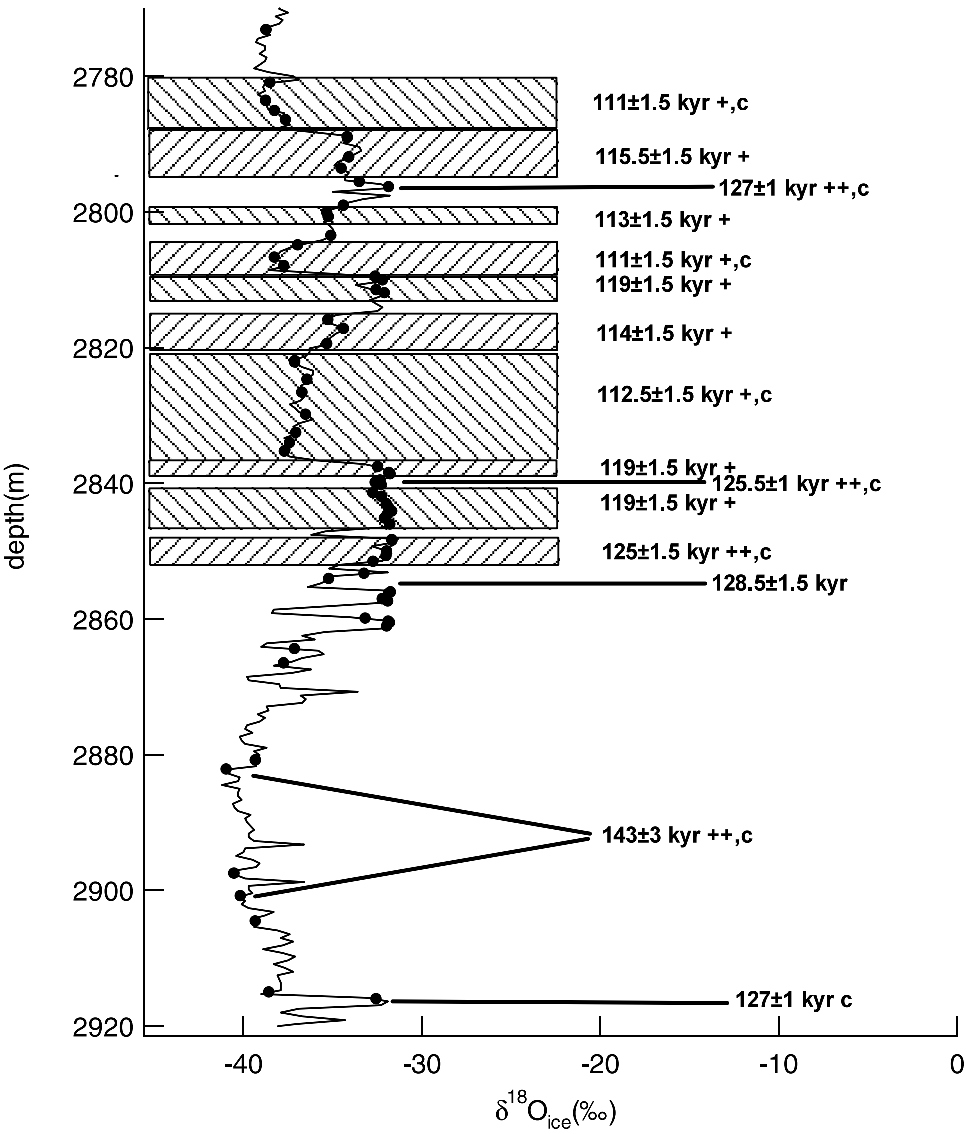
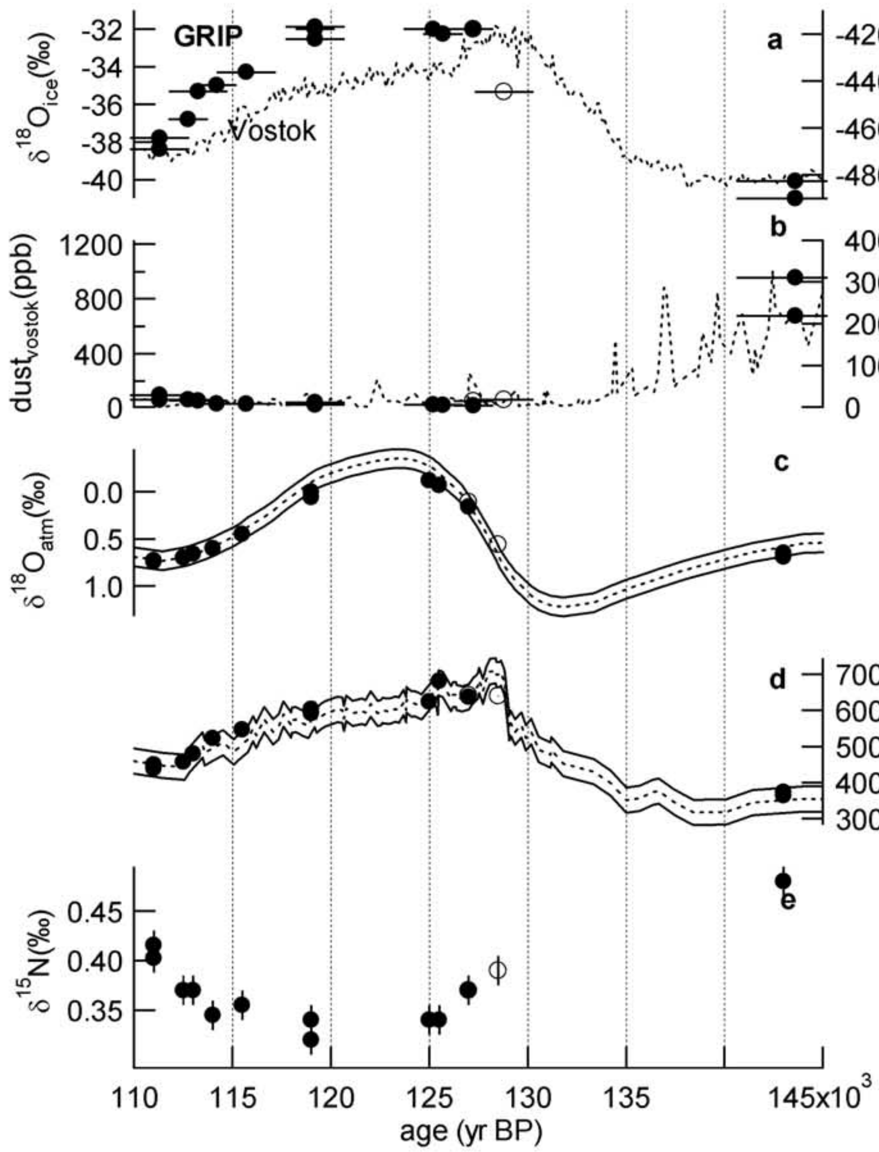


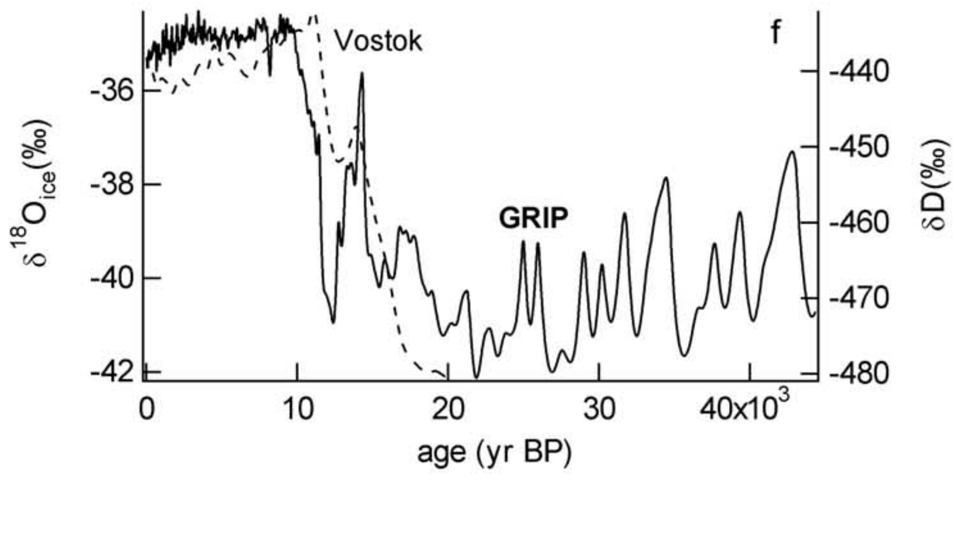
Figure 3. Succession of identified layers between 2780 and 2920 m with associated gas ages from identification of $\delta^{18}O_{atm}/CH_4$ data pairs with Vostok trajectory. Solid circles indicate the exact depth on the GRIP $\delta^{18}O_{ice}$ profile where gas measurements were performed and then where ice data were used for reconstruction (Figure 4). The boxes stand for a set of gas measurements suggesting the same age assignation. The confidence levels for each layer is indicated by symbols: zero, one, or two crosses indicate high, little, or no ambiguity for GRIP $CH_4/\delta^{18}O_{atm}$ compared to Vostok values; the letter "c" stands for agreement between available chemistry data and the characteristic values of glacial and interglacial stages in Greenland (all available data in the GRIP bottom part agree with chemical tendencies between cold and warm stages). Dating uncertainties take into account the errors in delta ages calculations for Vostok (around 10% of the delta age) and for GRIP (200 years). Note that the dating is only relative to Vostok GT4 used as a temporal reference here.

[24] Two main GRIP depth sections could not be dated without ambiguity : from 2860 to 2880m, and beneath 2920m. For the former, the depth covers the GRIP region originally supposed to belong to the Eemian and shows surprising chemical measurements difficult to reconcile with ice mixing [*Steffensen et al.*, 1997]. For the latter, ice crystal studies show no abrupt transition [*Thorsteinsson et al.*, 1997] suggesting the absence of stratigraphic

Figure 4. (opposite) Reconstitution of (a) the GRIP (solid circles) $\delta^{18}O_{ice}$ and (b) calcium profiles against ice age (bottom scale: GRIP age deduced from the Vostok GT4 scale and from the gas-ice age differences evaluated thanks to GRIP $\delta^{15}N$ reconstructed profile (Figure 4e)). Comparison is made with measured Vostok profiles (dotted lines) of (a) δD and (b) dust. (c) The $\delta^{18}O_{atm}$ and (d) CH_4 at GRIP and Vostok (with associated uncertainty envelope). (f) comparison between Vostok δD [*Petit et al.*, 1999] and GRIP $\delta^{18}O_{ice}$ [*Dansgaard et al.*, 1993] profiles for the Holocene period against age. The open circles represent questionable reconstructed points.



GRIP
Vostok
a
b
c
d
e
$\delta^{18}O_{ice}$(‰)
δD(‰)
$dust_{vostok}$(ppb)
Ca_{GRIP}(ppb)
$\delta^{18}O_{atm}$(‰)
CH_4(ppbv)
$\delta^{15}N$(‰)
age (yr BP)



Vostok
GRIP
f
$\delta^{18}O_{ice}$(‰)
δD(‰)
age (yr BP)

disturbance. On the contrary, small scale (of the order 1–8 cm) visible folding [*Dahl-Jensen et al.*, 1997] and flat water stable isotope profile as in Vostok bottom ice sections [*Souchez et al.*, 2002] suggest ice layer mixing at a scale inferior to the gas and ice sampling resolution. Here GRIP bottom $CH_4/\delta^{18}O_{atm}$ measurements showing stage 7 or older stable levels do not enable to discriminate between the two hypotheses.

[25] Each of the $CH_4/\delta^{18}O_{atm}$ discontinuities (GRIP depth trajectory inconsistent with Vostok temporal evolution) has a parallel in the $\delta^{18}O_{ice}$ record (Figure 2a). Moreover, the calculated correlation between chemistry data from neighboring bags is low where $CH_4/\delta^{18}O_{atm}$ show discontinuities. These discontinuities could result from strong local shearing in the stratigraphy of the bottom part of the GRIP core [*Alley et al.*, 1997] and/or ice flow convergence following bedrock irregularities and leading to random ice-layer mixing, both mechanisms bringing into contact ice layers from very different ages. Note that we probably missed several other discontinuities, simply because the sampling resolution of our $CH_4/\delta^{18}O_{atm}$ data pairs (10 cm samples at depth ranges between 55 cm and several meters) is far smaller than the $\delta^{18}O_{ice}$ resolution (2.5 cm).

4. A Tentative Reconstruction of Greenland MIS 5e and Glacial Inception

[26] On the basis of the Vostok-GRIP gas comparison, we propose a stratigraphy for the bottom section of the GRIP ice core (Figure 3). We can now directly compare the reconstructed climatic signal from Greenland ($\delta^{18}O_{ice}$) to its Antarctic counterpart (Vostok δD record, Figure 4). Instead of representing each individual data pair in the sequence, we choose to average neighboring data pairs (3 to 4 on average) and the associated ice-$\delta^{18}O$ climate proxy. The comparison between discrete chemical measurements conducted on the bottom parts of GRIP [*Steffensen et al.*, 1997] and GISP2 cores [*Legrand and Mayewski*, 1997] reinforces the validity of our reconstruction with higher values of calcium, magnesium, potassium, chloride and sulfate during cold periods (here stage 6) than during warm periods (here stage 5e). Figure 3 also displays confidence levels for the dating of each ice layer on a gas-age scale (see legend). Note that this dating is not suitable for $\delta^{18}O_{ice}$ because it does not take into account the age differences between the trapped gas and surrounding ice (Δage) at GRIP. To obtain the best estimation of the Δage we extracted the mean $\delta^{15}N$ signal (supposed to be strictly gravitational) for each ice layer (Figure 4e). This reconstructed signal combined with different possible temperature evaluations from the isotopic paleothermometer ($\delta^{18}O_{ice}$ [*Jouzel*, 1999]) gives a rough estimation of the close-off depth (COD) and of the Δage [*Schwander et al.*, 1997]. The different temperature scenarios [e.g., *Cuffey and Marshall*, 2000] lead to small changes in COD (<3 m) compared to the 70 m/90 m COD corresponding to MIS 5e/full glacial. The Δage for the different ice sections was thus evaluated to lie between 200 and 600 years with an associated uncertainty of 200 years (upper evaluation with extreme values of $\delta^{15}N$ and of temperatures). The age indicated in Figure 4 for ice measurements ($\delta^{18}O_{ice}$ and Ca) is then corrected from Δage and errors bars account for uncertainties on the dating relative to Vostok (Figure 2b) and on Δage.

[27] Figure 4 displays the tentatively-reconstructed temporal evolution for GRIP $\delta^{18}O_{ice}$ [*Dansgaard et al.*, 1993], a proxy of temperature change and calcium [*Fuhrer et al.*, 1993], an indicator of past atmospheric transport and/or continental dust source. The attribution of an age to each GRIP 10 cm ice layer through gas measurements leads to a discrete and poorly detailed $\delta^{18}O_{ice}$ reconstruction. Nevertheless, the reconstructed GRIP $\delta^{18}O_{ice}$ and the Vostok δD profiles clearly show that the last interglacial ended later in Greenland than in Antarctica : $\delta^{18}O_{ice}$ remains very high during the stage 5e in Greenland whereas δD drops sooner in Antarctica, only 2 kyr after the interglacial optimum. At the same time, CH_4 undergoes a long period with high values (10 kyr) compared to the relatively short maximum of $\delta^{18}O_{atm}$.

[28] This relatively long and warm period in Greenland compared to Antarctica finds agreement with pollen records in the lake sediments and off the Iberian margin [*Kukla et al.*, 2002; *Sanchez-Goñi et al.*, 1999] that describes a long and stable interglacial in Central Europe lasting around 13,000 yr [*Turner*, 2002]. Directly relevant to Greenland climate are proxy records for the deep North Atlantic circulation and North Atlantic sea-surface temperatures which show a persistent interglacial maximum for approximately 10 kyr [*Adkins et al.*, 1997; *Cortijo et al.*, 1999]. This reconstruction is then a supplementary argument in favor of a long interglacial in northern Europe at the same time as the onset of continental ice caps as indicated by our $\delta^{18}O_{atm}$ measurements (Figure 4). A comparison with Holocene on Figure 4 confirms that climate was warmer during 5e than nowadays [*Dansgaard et al.*, 1993]. Interestingly, a single data pair at 2854.15 m of depth, with intermediate $\delta^{18}O_{atm}$ and relatively elevated CH_4 levels (dated at 128.5 kyr according to the Vostok chronology), provides a $\delta^{18}O_{ice}$ value significantly lower than other 5e data pairs. On the reconstructed Greenland isotopic profile, it seems to pin-point the very end of the deglaciation, at a time when Antarctica is already showing full interglacial conditions. The lack of other data pairs with similar characteristics prevents us to ascertain this feature but if real, Termination II would thus share the same pattern as observed for the end of Termination I, with a significant delay of Greenland maximum warming compared to Antarctica.

[29] Apart from the data pair at 2854.15 m, it remains very surprising that no ice from the Termination II period (130–140 yr BP) can be identified in the bottom part of GRIP. According to ice flow models, at least 20 meters of such ice should be observed in GRIP core after normal thinning. A possible explanation may be linked to very small grains supposed to characterize such ice [*Thorsteinsson et al.*, 1997; *Dahl-Jensen et al.*, 1997], making it particularly sensitive to shear stress, and hence easier to be thinned and folded on a centimeter scale.

[30] An extreme scenario could be envisaged where the Greenland Eemian reached climatic conditions leading to complete surface melting in Greenland [*Koerner*, 1989], hiatus of accumulation, and ablation of the ice previously accumulated during the deglaciation. This would still be imprinted in the GRIP ice, through refrozen ice layers associated with low gas content and anomalous deuterium

excess. Indeed GRIP air content measurements [*Raynaud et al.*, 1997] do not reveal such features and suggest that the elevation at Summit remained above 3000 m. In addition ice sheet modeling [*Cuffey and Marshall*, 2000; *Huybrechts*, 2002] suggests a persistency of the center Greenland ice sheet during the MIS 5e with similar elevation at the summit as nowadays. Finally deuterium excess measurements (additional data obtained outside of this work) remain within the normal range (4–11‰) observed during the 100 kyr at Summit. A partial deglaciation that lowers the ice sheet elevation is therefore unlikely to be the cause of the lack of Termination II ice through massive melting or sublimation. To emphasize this conclusion, it must be noticed that Koerner's study was based on two coastal sites in Greenland (Dye3 and Camp Century) that modeling studies show to be ice free during MIS 5e.

[31] The most probable scenario explaining the lack of Termination II ice in the GRIP core involves divides of ice flow along bedrock irregularities, bringing apart ice layers depending on their rheology. Moreover the lack of measurements in the bottom part where ice is possibly mixed on a very small scale could explain that we can not identify the ice from Termination II even if some is present on the GRIP bottom section.

[32] Our results suggest that between 2780 and 2920 m the ice mixing still preserves part of the chronology with ice layers from 5d-5e transition preferentially at the top of the sequence and ice from the penultimate glacial or older (stage 6) at the bottom section near 2920m. This is not inconsistent with alternative estimates of very old basal ice (2.4 million years from *Souchez* [1997] or 400,000 years from $^{10}Be/^{36}Cl$ (Muscheler and Beer, personal communication)).

5. Conclusions

[33] The new sets of measurements of $\delta^{18}O_{atm}$ and CH_4 in the bottom sections of the GRIP core show a complex stratigraphy below 2780 m depth. The comparison between those data pairs and the Vostok $CH_4/\delta^{18}O$ phase plane between 110 and 170 kyr leads to a quite unambiguous identification of several discrete ice layers. It confirms the identification of ice from the latest part of Stage 6 deep in Greenland Summit ice. Our gas-based reconstruction of the MIS 5e is confirmed by the reconstructed time sequences of $\delta^{18}O_{ice}$ and dust indicators compared to Vostok records or north Atlantic marine sediment temperature reconstructions.

[34] Although somehow disappointing due to missing ice layers, impossibility to date other layers that are problematic regarding chemistry data, our method still provides the only glacial inception reconstruction from existing Greenland ice cores. The lag between cross-dated GRIP and Vostok $\delta^{18}O$ during this glacial onset reaches several thousands of years, Antarctica getting colder significantly before Greenland. The drilling of the last 80 m at North GRIP in 2003 may provide soon a more complete picture of this time period.

[35] **Acknowledgments.** This work was supported by EC within the Pole-Ocean-Pole project (EVK2-2000-22067), the French Centre National de la Recherche Scientifique, the Programme National d'Etudes de la Dynamique du Climat, and the Institut Paul Emile Victor. It is a contribution to the Greenland Ice Core Project (GRIP) organized by the European Science Foundation. We thank all GRIP participants for their cooperative effort. We also wish to thank Gabrielle Dreyfus for contributing to the clarity of the text. This is LSCE contribution 0972.

References

Adkins, J. F., E. A. Boyle, L. Keigwin, and E. Cortijo, Variability of the North Atlantic thermohaline circulation during the last interglacial period, *Nature*, *390*, 154–156, 1997.

Alley, R. B., A. J. Gow, D. A. Meese, J. J. Fitzpatrick, E. D. Waddington, and J. F. Bolzan, Grain-scale processes, folding, and stratigraphic disturbances in GISP2 core, *J. Geophys. Res.*, *102*, 26,819–26,830, 1997.

Anklin, M., J.-M. Barnola, J. Schwander, B. Stauffer, and D. Raynaud, Processes affecting the CO_2 concentrations measured in Greenland ice, *Tellus, Ser. B*, *47*, 461–470, 1995.

Bender, M., T. Sowers, M. L. Dickson, J. Orchado, P. Grootes, P. A. Mayewski, and D. A. Meese, Climate correlations between Greenland and Antarctica during the last 100,000 years, *Nature*, *372*, 663–666, 1994a.

Bender, M., T. Sowers, and L. D. Labeyrie, The Dole effect and its variation during the last 130,000 years as measured in the Vostok core, *Global Biogeochem. Cycles*, *8*(3), 363–376, 1994b.

Bender, M., P. P. Tans, J. T. Ellis, J. Orchardo, and K. Habfast, A high precision isotope ratio mass spectrometry method for measuring the O_2/N_2 ratio of air, *Geochim. Cosmochim. Acta*, *58*, 4751–4758, 1994c.

Bender, M., T. Sowers, and V. Lipenkov, On the concentrations of O_2, N_2, and Ar in trapped gases from ice cores, *J. Geophys. Res.*, *100*(D9), 18,651–18,660, 1995.

Bender, M., B. Malaize, J. Orchado, T. Sowers, and J. Jouzel, High precision correlations of Greenland and Antarctic ice core records over the last 100 kyr, in *Mechanisms of Global Climate Change at Millennial Time Scales*, *Geophys. Monogr. Ser.*, vol. 112, edited by, pp. 149–164, AGU, Washington, D. C., 1999.

Blunier, T., and E. J. Brook, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, *Science*, *291*, 109–112, 2001.

Blunier, T., et al., Asynchrony of Antarctic and Greenland climate change during the last glacial period, *Nature*, *394*, 739–743, 1998.

Caillon, N., J. Severinghaus, J. M. Barnola, J. Chappellaz, J. Jouzel, and F. Parrenin, Estimation of temperature change and gas age-ice age difference, 108 kyr B.P., at Vostok, Antarctica, *J. Geophys. Res.*, *106*(D23), 31,893–31,901, 2001.

Chappellaz, J., J. M. Barnola, D. Raynaud, Y. S. Korotkevich, and C. Lorius, Atmospheric CH_4 record over the last climatic cycle revealed by the Vostok ice core, *Nature*, *345*, 127–131, 1990.

Chappellaz, J., I. Fung, and A. M. Thompson, The atmospheric CH_4 increase since the Last Glacial Maximum: Sources estimates, *Tellus, Ser. B*, *45*, 228–241, 1993.

Chappellaz, J., E. Brook, T. Blunier, and B. Malaizé, CH_4 and $\delta^{18}O$ of O_2 records from Greenland ice: A clue for stratigraphic disturbance in the bottom part of the Greenland Ice Core Project and the Greenland Ice Sheet Project 2 ice cores, *J. Geophys. Res.*, *102*(C12), 26,547–26,557, 1997a.

Chappellaz, J., T. Blunier, S. Kints, A. Dallenbach, J.-M. Barnola, J. Schwander, D. Raynaud, and B. Stauffer, Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Holocene, *J. Geophys. Res.*, *102*(D13), 15,987–15,997, 1997b.

Cortijo, E., S. Lehman, L. Keigwin, M. Chapman, D. Paillard, and L. Labeyrie, Changes in meridional temperature and salinity gradients in the North Atlantic Ocean (30°–72°N) during the last interglacial period, *Paleoceanography*, *14*(1), 23–33, 1999.

Cuffey, K. M., and S. J. Marshall, Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet, *Nature*, *404*, 591–594, 2000.

Dahl-Jensen, D., T. Thorsteinsson, R. Alley, and H. Shoji, Flow properties of the ice from the Greenland Ice Core Project ice core: The reason for folds?, *J. Geophys. Res.*, *102*(C12), 26,831–26,840, 1997.

Dällenbach, A., T. Blunier, J. Flückiger, B. Stauffer, J. Chappellaz, and D. Raynaud, Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the last glacial and the transition to the Holocene, *Geophys. Res. Lett.*, *27*(7), 1005–1008, 2000.

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

Flückiger, J., A. Dällenbach, T. Blunier, B. Stauffer, T. F. Stocker, D. Raynaud, and J. M. Barnola, Variations in atmospheric N_2O concentration during abrupt climatic changes, *Science*, *285*, 227–230, 1999.

Fuchs, A., and M. C. Leuenberger, $\delta^{18}O$ of atmospheric oxygen measured on the GRIP ice core document stratigraphic disturbances in the lowest 10% of the core, *Geophys. Res. Lett.*, *23*(9), 1049–1052, 1996.

Fuhrer, K., A. Neftel, M. Anklin, and V. Maggi, Continuous measurements of hydrogen peroxide, formaldehyde, calcium and ammonium concentrations along the new GRIP ice core from Summit, central Greenland, *Atmos. Environ.*, *12*, 1873–1880, 1993.

GRIP Project Members, Climatic instability during the last interglacial period revealed in the Greenland summit ice-core, *Nature*, *364*, 203–207, 1993.

Grootes, P. M., M. Stuiver, J. W. C. White, S. J. Johnsen, and J. Jouzel, Comparison of the oxygen isotope records from the GISP2 and GRIP Greenland ice cores, *Nature*, *366*, 552–554, 1993.

Huybrechts, P., Sea-level change at the LGM from ice-dynamic reconstruction of the Greenland and Antarctic ice sheets during the glacial cycles, *Quat. Sci. Rev.*, *21*, 203–231, 2002.

Jouzel, J., Towards a calibration of the isotopic paleothermometer, *Science*, *286*, 910–911, 1999.

Kennett, J. P., K. G. Cannariato, I. L. Hendy, and R. J. Behl, Carbon isotopic evidence for methane hydrate instability during quaternary interstadials, *Science*, *288*, 128–130, 2000.

Koerner, R. M., Ice core evidence for extensive melting of the Greenland ice sheet in the last interglacial, *Science*, *244*, 964–968, 1989.

Kukla, G. J., et al., Last interglacial climates, *Quat. Res.*, *58*, 2–13, 2002.

Legrand, M., and P. Mayewski, Glaciochemistry of polar ice cores: A review, *Rev. Geophys.*, *35*(3), 219–243, 1997.

Legrand, M., C. Hammer, M. De Angelis, J. Savarino, R. Delmas, H. Clausen, and S. J. Johnsen, Sulfur-containing species (methanesulfonate and SO_4) over the last climatic cycle in the Greenland Ice Core project (central Greenland) ice core, *J. Geophys. Res.*, *102*(C12), 26,663–26,680, 1997.

Malaizé, B., D. Paillard, J. Jouzel, and D. Raynaud, The Dole effect over the last two glacial-interglacial cycles, *J. Geophys. Res.*, *104*(D12), 14,199–14,208, 1999.

Martinson, D. G., N. G. Pisias, J. D. Hays, J. Imbrie, T. C. Moore, and N. J. Shackleton, Age dating and the orbital theory of the ice ages: Development of a high-resolution 0–300,000 years chronostratigraphy, *Quat. Res.*, *27*, 1–30, 1987.

Morgan, V., M. Delmotte, T. van Ommen, J. Jouzel, J. Chappellaz, S. Woon, V. Masson-Delmotte, and D. Raynaud, Relative timing of deglacial events in Antarctica and Greenland, *Science*, *297*, 1862–1864, 2002.

Petit, J. R., et al., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–436, 1999.

Raynaud, D., J. Chappellaz, C. Ritz, and P. Martinerie, Air content along the Greenland Ice Core Project core: A record of surface climatic parameters and elevation in central Greenland, *J. Geophys. Res.*, *102*(C12), 26,607–26,613, 1997.

Raynaud, D., M. F. Loutre, C. Ritz, J. Chappellaz, J. M. Barnola, J. Jouzel, V. Y. Lipenkov, J. R. Petit, and F. Vimeux, Marine Isotope Stage (MIS) 11 in the Vostok ice core: CO_2 forcing and stability of East Antarctica, in *Earth's Climate and Orbital Eccentricity*: *The Marine Isotope Stage 11 Question*, *Geophys. Monogr. Ser.*, vol. 137, edited by A. Droxler, R. Poore, and L. Burckle, AGU, Washington, D. C., 2003.

Sanchez-Goñi, M. F., F. Eynaud, J.-L. Turon, and N. J. Shackelton, High resolution palynological record off the Iberian margin: Direct land-sea correlation for the last interglacial complex, *Earth Planet. Sci. Lett.*, *171*, 123–137, 1999.

Schwander, J., T. Sowers, J. M. Barnola, T. Blunier, A. Fuchs, and B. Malaizé, Age scale of the air in the summit ice: Implication for glacial-interglacial temperature change, *J. Geophys. Res.*, *102*(D16), 19,483–19,493, 1997.

Severinghaus, J. P., and J. Brook, Abrupt climate change at the end of the last glacial period inferred from trapped air in polar ice, *Science*, *286*, 930–934, 1999.

Severinghaus, J. P., A. Grachev, and M. Battle, Thermal fractionation of air in polar firn by seasonal temperature gradients, *Geochem. Geophys. Geosyst.*, *2*, Paper number 2000GC000146, 2001.

Severinghaus, J. P., A. Gratchev, B. Luz, and N. Caillon, A method for precise measurement of argon 40/36 and krypton/argon ratios in trapped air in polar ice with application to past firn thickness and abrupt climate change in Greenland and at Siple Dome, Antarctica, *Geochim. Cosmochim. Acta*, *67*(3), 325–343, 2003.

Souchez, R., The buildup of the ice sheet in central Greenland, *J. Geophys. Res.*, *102*(C12), 26,317–26,323, 1997.

Souchez, R., M. Lemmens, and J. Chappellaz, Flow-induced mixing in the GRIP basal ice deduced from the CO_2 and CH_4 records, *Geophys. Res. Lett.*, *22*, 41–44, 1995.

Souchez, R., J.-R. Petit, J. Jouzel, J. Simões, M. de Angelis, N. Barkov, M. Stievenard, F. Vimeux, S. Sleewaegen, and R. Lorrain, Highly deformed basal ice in the Vostok core, Antarctica, *Geophys. Res. Lett.*, *29*(7), 401–404, 2002.

Sowers, T., N_2O spanning the penultimate deglaciation from the Vostok ice core, *J. Geophys. Res.*, *106*(D23), 31,903–31,914, 2001.

Sowers, T., and M. Bender, Climate records covering the last deglaciation, *Science*, *269*, 210–214, 1995.

Sowers, T. A., M. L. Bender, and D. Raynaud, Elemental and isotopic composition of occluded O_2 and N_2 in polar ice, *J. Geophys. Res.*, *94*(D4), 5137–5150, 1989.

Sowers, T., M. Bender, D. Raynaud, Y. S. Korotkevich, and J. Orchado, The $\delta^{18}O$ of atmospheric O_2 from air inclusions in the Vostok ice core: Timing of CO_2 and ice volume change during the penultimate deglaciation, *Paleoceanography*, *6*(6), 669–696, 1991.

Sowers, T., M. Bender, L. D. Labeyrie, J. Jouzel, D. Raynaud, D. Martinson, and Y. S. Korotkevich, 135,000 year Vostok-SPECMAP common temporal framework, *Paleoceanography*, *8*(6), 737–766, 1993.

Steffensen, J. P., H. Clausen, C. Hammer, M. Legrand, and M. De Angelis, The chemical composition of cold events within the Eemian section of the Greenland Ice Core Project ice core from Summit, Greenland, *J. Geophys. Res.*, *102*(C12), 26,747–26,754, 1997.

Thorsteinsson, T., Textures and fabrics in the GRIP ice core, in relation to climate history and ice deformation., Alfred Wegener Inst. für Polar und Meeresforsch., Bremerhaven, Germany, 1996.

Thorsteinsson, T., J. Kipstuhl, and H. Miller, Textures and fabrics in the GRIP ice core, *J. Geophys. Res.*, *102*(C12), 26,583–26,599, 1997.

Turner, C., Problems of the duration of the eemian interglacial in Europe north of the Alps, *Quat. Res.*, *58*, 45–48, 2002.

Yiou, F., G. M. Raisbeck, C. Hammer, S. J. Johnsen, J. Jouzel, J. Lestringez, M. Stievenard, and P. Yiou, Beryllium 10 in the Greenland Ice Core Project ice core at Summit, Greenland, *J. Geophys. Res.*, *102*(C12), 26,783–26,794, 1997.

C. Bourg, S. Cherrier, V. Masson-Delmotte, J. Jouzel, and A. Landais, IPSL/Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, 91191 Gif sur Yvette, France. (landais@lsce.saclay.cea.fr)

T. Blunier and J. Schwander, Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.

N. Caillon, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA.

J. Chappellaz and D. Raynaud, Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, 54, rue Molière BP 96, 38402 Saint Martin d'Hères, France.

M. Delmotte, Institut de Physique du Globe de Paris, Laboratoire de Cosmochimie et Géochimie, CNRS, 4, place Jussieu tour 14, 75252 Paris Cedex 05, France.

B. Malaizé, Département de Géologie et Océanographie, UMR CNRS 5805 EPOC, Université Bordeaux 1, Avenue des Facultés, 33405 Talence cedex, France.

J. P. Steffensen, Department of Geophysics, University of Copenhagen, DK1017 Copenhagen K, Denmark.

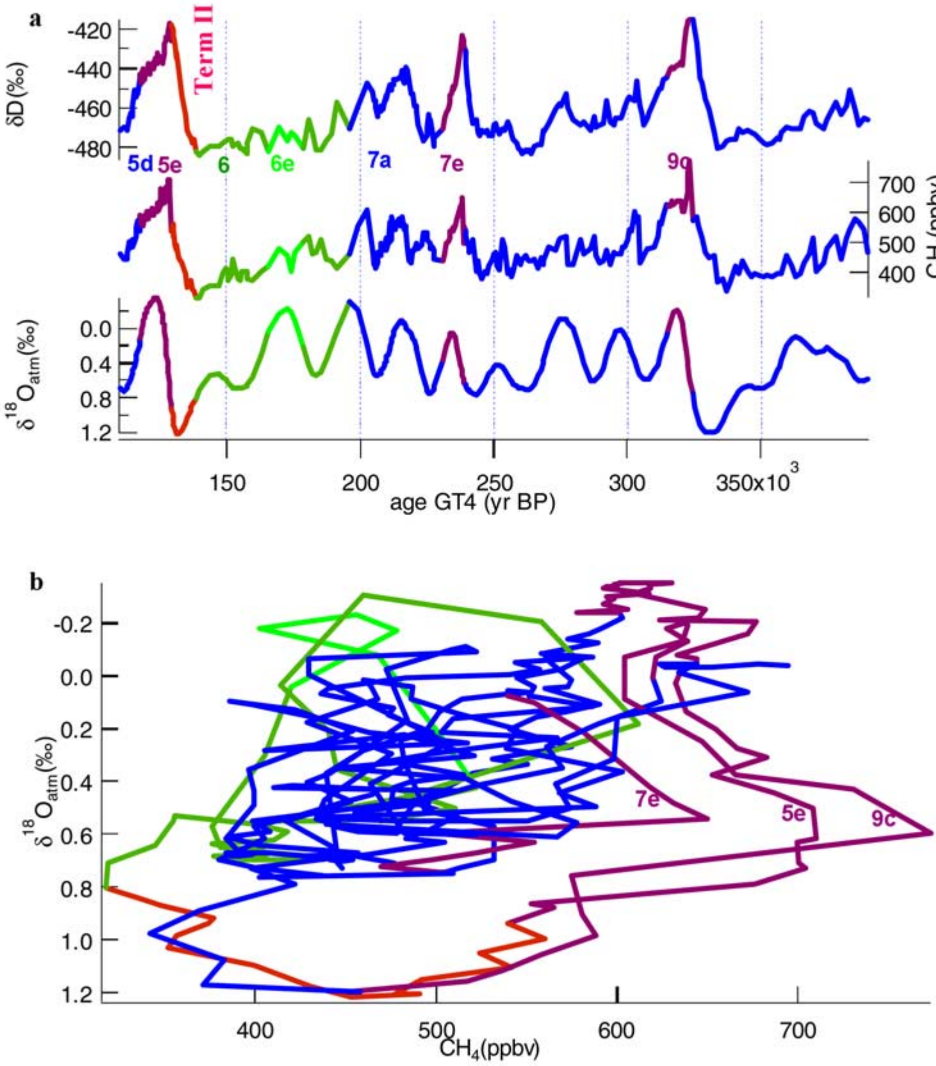


Figure 1. (a) Vostok δD, CH_4, and $\delta^{18}O_{atm}$ time series with indication of some marine isotopic stages (MIS) between 110 and 390 kyr B.P. (data are from *Petit et al.* [1999]). The marine isotope stage boundaries (initially described by *Martinson et al.* [1987]) are taken as the midtransition of the $\delta^{18}O_{atm}$ profile, with a 2 kyr time lag taking into account the $\delta^{18}O_{atm}$ delay on ice volume change [*Sowers et al.*, 1991]. Termination II is taken as the penultimate glacial-interglacial transition between stage 6 and stage 5e, but according to *Martinson et al.* [1987], it is part of MIS 6. (b) Vostok $\delta^{18}O_{atm}/CH_4$ phase plane between 110 and 390 kyr B.P. The $\delta^{18}O_{atm}$ record is interpolated on the better resolved CH_4 record. Colors were chosen to indicate the clearest sequences: red for Termination II and purple for interglacial; light green for the high insolation maximum (6e) during stage 6 (green); blue for the remaining glacial variability.

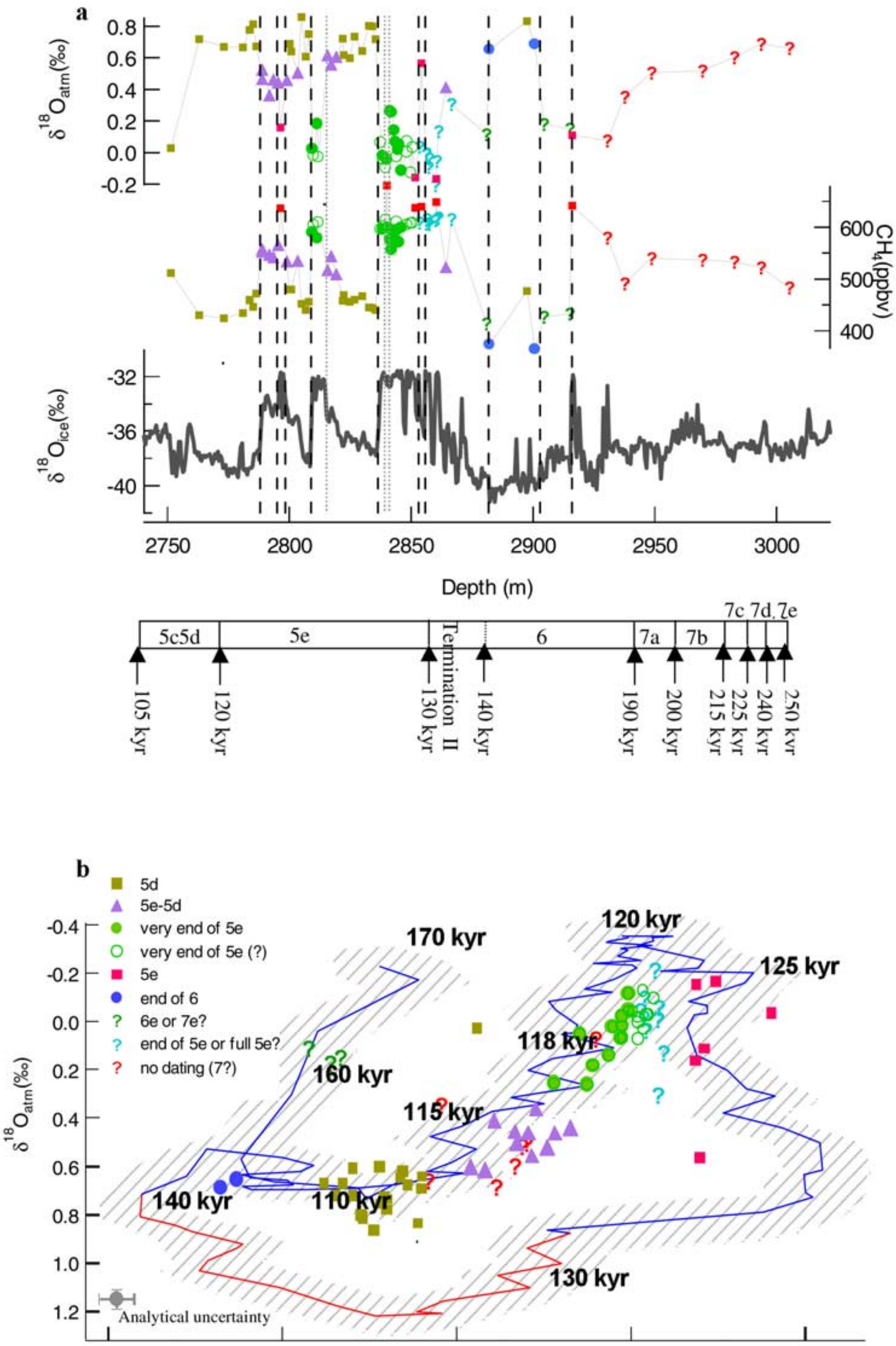


Figure 2. (a) CH_4, $\delta^{18}O_{atm}$, and $\delta^{18}O_{ice}$ profiles for the bottom of the GRIP ice core. The GRIP dating here is estimated by an ice flow model assuming no mixing [*Johnsen et al.*, 1993]. (b) $CH_4/\delta^{18}O_{atm}$ data pairs from the bottom part of the GRIP core compared with the Vostok phase plane (line) between 110 and 170 kyr with Termination II (indicated in red). The uncertainty envelope around Vostok trajectory accounts for experimental uncertainty in Vostok measurements and for uncertainty in the estimation of interhemispheric gradient. The GRIP data pairs were divided into nine zones marked with signs and colors corresponding to their positions with regard to the Vostok trajectory (Termination II again indicated with red line). Note that the same legend is used for Figures 2a and 2b.