

Scientific paper

## A bipolar comparison of deep ice cores from Antarctica (Dome Fuji) and Greenland (GRIP)

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**Abstract:** Oxygen isotope ratio and chemistry profiles were compared to find the corresponding interstadials during the Wisconsin Ice Age between the GRIP (Greenland) and Dome Fuji (Antarctica) deep ice core data for the past one hundred and sixty thousand years. Eight interstadials in GRIP  $\delta^{18}\text{O}$  profile were found to correspond to those in Dome Fuji  $\delta^{18}\text{O}$  profile. Eleven interstadials in GRIP  $\delta^{18}\text{O}$  profile were found to correspond to those in Dome Fuji chemistry (calcium, nitrate and sulfate) profile, which is better suited for the purpose of interstadial search than the  $\delta^{18}\text{O}$  profile at Dome Fuji. The Eemian interglacial period at Dome Fuji seems to be much shorter and more stable than that in the GRIP profile. Three major periods having higher contents of calcium, nitrate and sulfate appear at Dome Fuji, ranging (1) between interstadials number 1 and 8, (2) between interstadials number 17 and 19, and (3) before the Eemian, which correspond to relatively cold and stable periods in the GRIP  $\delta^{18}\text{O}$  profile. These findings promise a favorable outcome from more detailed bipolar comparison in the future for an understanding of climatic linkage conditions and the driving forces between northern and southern hemispheres.

**key words:** bipolar, Dome F, GRIP, interstadial, Wisconsin

### 1. Introduction

The Greenland and Antarctic ice sheets preserve palaeo-climate information in the form of physical and chemical stratigraphy. Two deep ice cores have been drilled by international research collaborations at GRIP (72.6°N, 37.6°W (Summit); 1990–1992) and NGRIP (75.1°N, 42.3°W; 1996–2001 and continued) in Greenland to depths of 3029 m (Greenland Ice-core Project (GRIP) Members, 1993; Gundestrup *et al.*, 1994) and 3000 m respectively.

A deep ice core was drilled down to a depth of 2503 m at Dome Fuji Station, East Dronning Maud Land, Antarctica during the 1993–97 JARE inland operations (Dome-F Deep Coring Group, 1998; Dome-F Ice Core Research Group, 1998). Oxygen isotope measurements have been conducted on these ice cores, which present proxy data for paleo-temperature variations for hundreds of thousands of years on the Earth (Dansgaard *et al.*, 1993; Johnsen *et al.*, 2001; Watanabe *et al.*, 1999a,b). Ice core analysis is a comprehensive study effort including multi-factor measurements and correlation studies. Continuous electrical measurements (ECM and DEP) and chemical analysis reveal a history of atmospheric aerosol loading conditions including volcanic activities (Clausen *et al.*, 1997; Fujii *et al.*, 1999; Greenland Ice-core Project Members, 1993; Hondoh *et al.*, 1999; Legrand *et al.*, 1997; Steffensen, 1997; Steffensen *et al.*, 1997). Gas analysis results indicate variations in greenhouse gas contents, which are closely related to Dansgaard-Oeschger events (Chappellaz *et al.*, 1997; Kawamura, 2000; Stauffer, 1998). Physical property studies reveal air bubble-hydrate transformation at deep places in ice sheets (Narita *et al.*, 1999; Pauer *et al.*, 1999; Shoji *et al.*, 2000). Radar echo sounding for a wide range of ice sheets presents an excellent layer structures at depths which are good references for ice sheet flow and chronology studies (Fujita *et al.*, 1999; Jacobel and Hodge, 1995).

The GRIP ice core studies reveal high frequency oscillation in the  $\delta^{18}\text{O}$  profile during the Eemian interglacial time period, similar to the Dansgaard-Oeschger oscillation during the Wisconsin ice age (Johnsen *et al.*, 1997). These rapid changes in temperature are quite unique compared with very stable condition during the Holocene warm period. This might suggest a possible future change in climate if triggered by a change in some key factor. However, visual stratigraphy studies on the ice core have pointed out that the ice flow condition for this depth zone is not simple due to the complicated bottom topography. These rapid changes in  $\delta^{18}\text{O}$  may be caused by ice mixing due to folding and/or boudinage near the ice sheet bottom.

The NGRIP program was planned to investigate rapid changes in temperature during the Eemian interglacial period by another deep ice coring/analysis about 315 km northwest along the ice divide from Summit. The Eemian ice was supposed to have been located around 300 m above the bottom at NGRIP according to ice flow modeling. However, the NGRIP ice core analyses during NGRIP-2000/2001 field activity periods reveal that Eemian ice may be located quite close to the bottom. In addition to this, a borehole survey suggests that the bottom ice might be under a pressure melting condition. The bottom 80 m-long ice core will be recovered during the NGRIP-2003 field activity period. A preliminary analysis of the NGRIP deep ice core reveals that both GRIP and NGRIP  $\delta^{18}\text{O}$  profiles show quite similar features to each other back approximately one hundred thousand years in time at least.

The Dome Fuji ice core study reveals that the paleo-temperature variation recorded is quite similar to that of the Vostok deep ice core for the past 320000 years (Watanabe *et al.*, 2003). This confirms that the temperature variations form a representative profile for the southern hemisphere. Three glacial-interglacial cycles obtained show quite similar successions of changes in each climate cycle in general. The transition from the Wisconsin Ice Age to the Holocene warm period took place almost simultaneously in the northern and southern hemispheres. The Dansgaard-Oeschger oscillation is not so clearly shown in the Dome Fuji core compared with the GRIP and NGRIP ice cores, except for atmospheric trace gas contents.

## 2. Bipolar comparison and discussion

### 2.1. $\delta^{18}\text{O}$ profiles

Detailed comparisons were made between ice core data from Dome Fuji and GRIP. Before the comparison, all data from  $\delta^{18}\text{O}$  measurements on the Dome Fuji ice core were treated so that each data point shows an average value for approximately a 200 year time-span. Each data point from chemistry on the Dome Fuji core contains a 7 cm average value with an approximately 200 year sampling interval. The data set from the GRIP core contains 55 cm average  $\delta^{18}\text{O}$  values. Then each GRIP  $\delta^{18}\text{O}$  data point covers approximately one to one thousand year time span. Figure 1 shows both of the oxygen isotope ratio ( $\delta^{18}\text{O}$ ) profiles for the last one hundred and sixty thousand years. It is clearly shown that some of the high frequency oscillations in the GRIP profile coincide well with those in the Dome Fuji profile during the Wisconsin Ice Age, although the amplitude is much suppressed in Dome Fuji. Numbers are given for interstadials (Dansgaard *et al.*, 1993) only when corresponding peaks (positive Dansgaard-Oeschger events) can be seen in both profiles. Eight interstadials having the numbers 12, 14, 17, 19, 20, 21, 23 and 24 are recognized in Dome Fuji. This ensures that some of the high frequency oscillations are global events. The interstadial number 1 seems to show up in both profiles, although the amplitude is low in Dome Fuji as shown in a bracket in Fig.1. Timing of occurrence for the corresponding interstadial differs within approximately two thousand years between Dome Fuji and GRIP, but this difference could be caused by the chronological calculation error. Interstadials between number 1 and 12 can

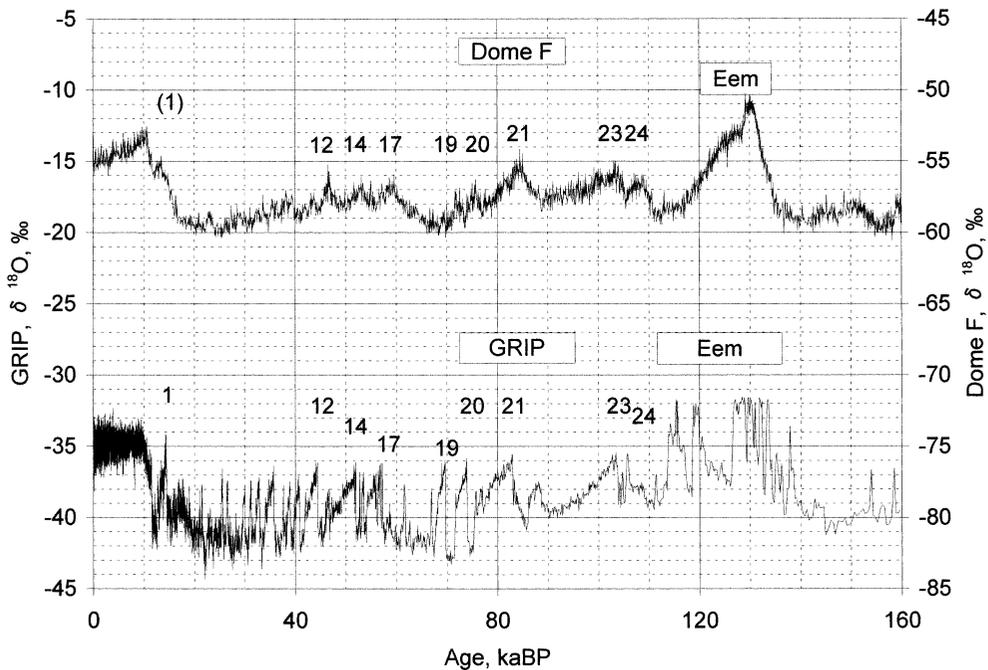


Fig. 1.  $\delta^{18}\text{O}$  profiles of the GRIP, Greenland ice core and the Dome Fuji, Antarctic ice core.

be detected in Dome Fuji in the future when more detailed studies are made. For the Eemian interglacial period, the Dome Fuji profile shows a shorter duration of the Eemian and the lack of high frequency oscillation in  $\delta^{18}\text{O}$  values compared with the GRIP profile. However, the initiation time of the Eemian seems to coincide quite well in both profiles. High  $\delta^{18}\text{O}$  oscillations should be expected during the glacial period before the Eemian in GRIP because low but significant  $\delta^{18}\text{O}$  oscillations exist in Dome Fuji. This depression/disappearance of high  $\delta^{18}\text{O}$  oscillations in GRIP could be caused by molecular diffusion after ice mixing due to folding and/or boudinage near the ice sheet bottom as mentioned in the previous section.

## 2.2. Calcium profile

Greenland deep ice core analyses hitherto conducted reveal that dust and  $\text{Ca}^{2+}$  contents are high during negative Dansgaard-Oeschger events. Strong stormy conditions may enhance the transportation of dust with high  $\text{Ca}^{2+}$  content during cold periods. Measured values of calcium content in Dome Fuji ( $\mu\text{mol/liter}$ ) are shown in Fig. 2 together with the GRIP  $\delta^{18}\text{O}$  profile. Again, some of the high frequency oscillations (interstadials) in the GRIP profile coincide well with those in the Dome Fuji profile during the Wisconsin Ice Age. Eleven interstadials having numbers 2, 4, 8, 12, 14, 17, 19, 20, 22, 23 and 24 are recognized. Interstadials number 2, 4 and 8 marked in square boxes have much larger amplitude compared than others. Two unique correlations are also to be seen around the ends of glacial periods as shown by broken arrows. The Younger Dryas cold event cannot be recognized in Dome Fuji easily. Correlation patterns in short term periods between Dome Fuji  $\text{Ca}^{2+}$  and GRIP  $\delta^{18}\text{O}$  might be different between the glacial/interglacial shift period and the glacial time period. The high frequency oscillation before the Eemian at Dome Fuji contrasts with relatively cold and stable conditions in GRIP, although data reliability in GRIP profile before 120

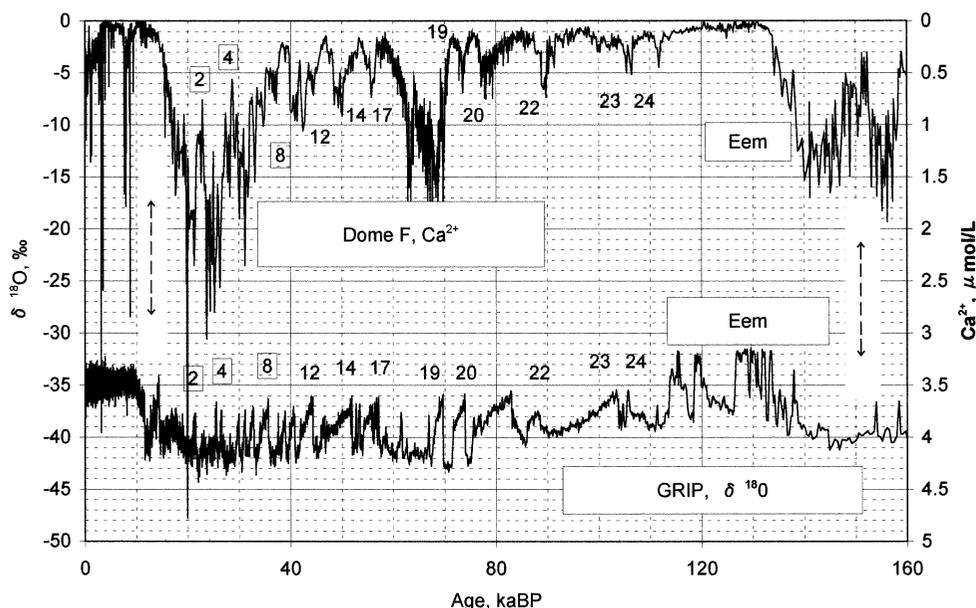


Fig. 2. Calcium concentration ( $\mu\text{mol/liter}$ ) in the Dome Fuji ice core and  $\delta^{18}\text{O}$  of the GRIP ice core.

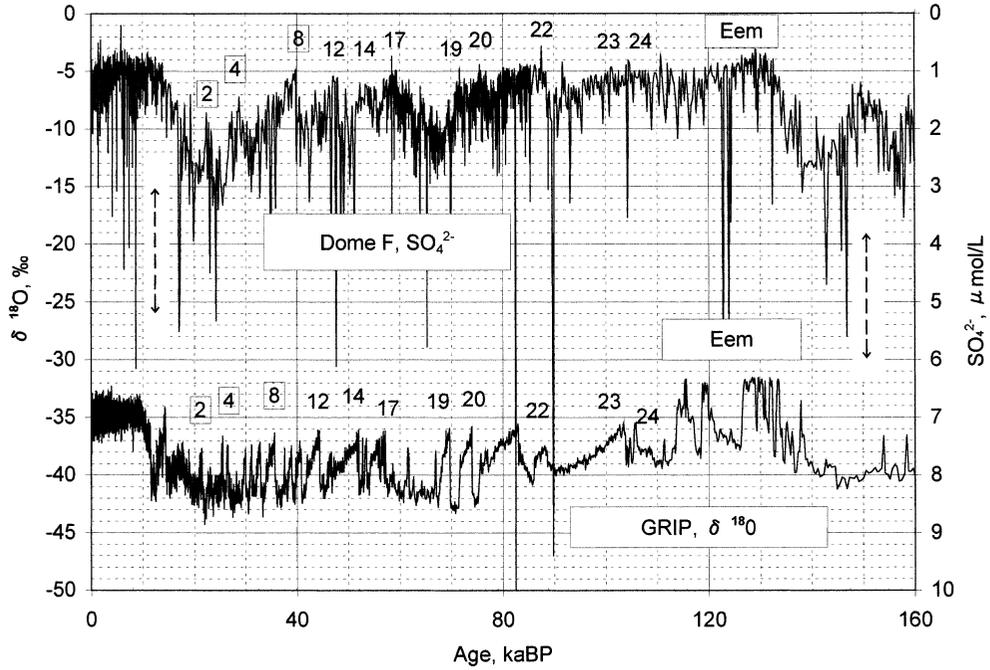


Fig. 3. Sulfate concentration ( $\mu\text{mol/liter}$ ) in the Dome Fuji ice core and  $\delta^{18}\text{O}$  of the GRIP ice core.

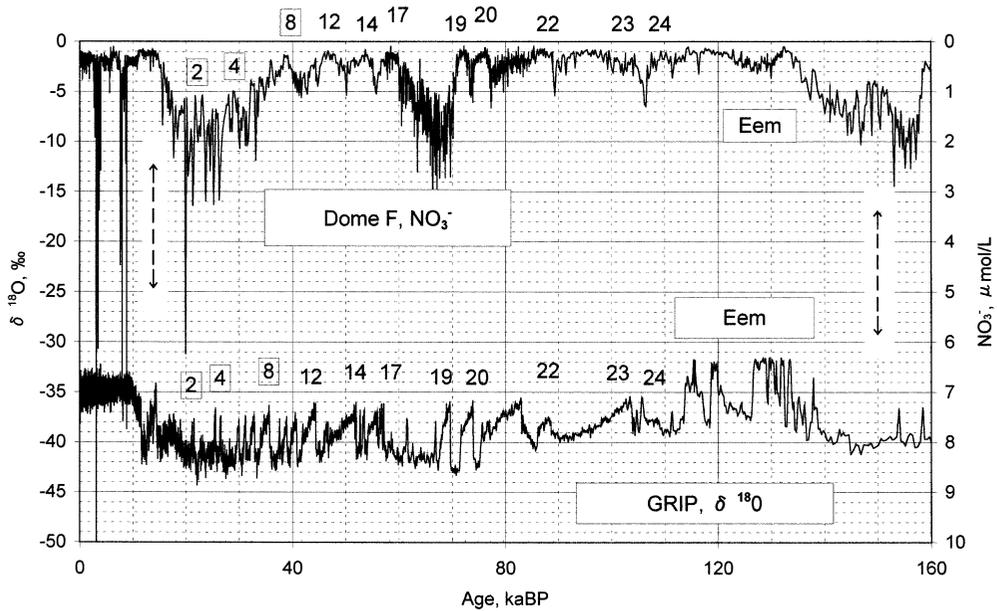


Fig. 4. Nitrate concentration ( $\mu\text{mol/liter}$ ) in the Dome Fuji ice core and  $\delta^{18}\text{O}$  of the GRIP ice core.

kaBP could be quite low, as mentioned before.

Three periods with higher  $\text{Ca}^{2+}$  content at Dome Fuji; (1) between interstadials number 1 and 8, (2) between interstadials number 17 and 19, and (3) before the Eemian, correspond to relatively cold and stable conditions in the GRIP  $\delta^{18}\text{O}$  profile.

### 2.3. Sulfate and nitrate profiles

Measured values of sulfate and nitrate contents in the Dome Fuji core ( $\mu\text{mol/liter}$ ) are shown in Figs. 3 and 4 respectively, together with the GRIP  $\delta^{18}\text{O}$  profile. The same correlations as for the calcium profile were obtained for sulfate and nitrate profiles with the GRIP  $\delta^{18}\text{O}$  profile. Although the variability of sulfate content seems a little bit higher than those of the other two chemical species, it was not difficult to find the corresponding interstadials.

## 3. Conclusions

$\delta^{18}\text{O}$  and chemistry profiles were compared to find the corresponding interstadials between the northern (GRIP) and southern (Dome Fuji) hemispheres for the past one hundred and sixty thousand years.  $\delta^{18}\text{O}$  to  $\delta^{18}\text{O}$  comparison gave eight interstadials which matched.  $\delta^{18}\text{O}$  (GRIP) to chemistry (Dome Fuji) comparison gave eleven interstadials matched. Twenty-four interstadials are first defined during the Wisconsin age period with the GRIP Greenland  $\delta^{18}\text{O}$  profile. However, chemistry profile such as calcium content could be more useful to find interstadials than the  $\delta^{18}\text{O}$  profile due to the lower amplitude of the  $\delta^{18}\text{O}$  profile at Dome Fuji.

The Younger Dryas cold period is quite difficult to recognize in the Dome Fuji profile. For the Eemian interglacial period, the duration in the Dome Fuji profile seems to be much shorter than in the GRIP profile. The Dome Fuji profile does not show rapid oscillations during the Eemian as shown in the GRIP profile, which might have resulted from ice mixing near the bottom at the GRIP site.

Three major periods of higher calcium, sulfate and nitrate contents appear at Dome Fuji which range (1) between interstadials number 1 and 8, (2) between interstadials number 17 and 19, and (3) before the Eemian, which corresponds to relatively cold and stable conditions in the GRIP  $\delta^{18}\text{O}$  profile.

These findings ensure the potential outcome from more detailed bipolar comparison in the future for understanding of climatic linkage conditions and the driving forces between the two hemispheres.

Detailed multi-factor, cross-correlation analyses between deep ice cores from the two hemispheres just started (Blunier *et al.*, 1998; Blunier and Brook, 2001) and should be continued for better climatological understanding, including chronological investigations of the Dome Fuji ice core.

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