Stable isotopes and climate history from polar ice cores

- Stable isotopes of oxygen and hydrogen and their use in ice core studies

- Paleoclimate studies on Greenland ice cores over the last 40 years

- Antarctic records of climate history

- Correlation of Greenland and Antarctic records

UH Winter School
Talk # 26
Thorsteinn Thorsteinsson

Stable isotopes of oxygen and hydrogen:

Isotope:	% in nature
^{16}O (8 p + 8 n)	99.76 %
^{17}O (8 p + 9 n)	0.04 %
^{18}O (8 p + 10 n)	0.20 %
^{1}H (1 p)	99.984%
^{2}H (1 p + 1 n; deuterium, D)	0.016%
(^{3}H = tritium, is radioactive)	

Thus 9 H_2O combinations are possible.

Only 2 are important in paleoclimatic research:

- $^{1}H^{2}H^{16}O$ (HDO)
- $^{1}H_2{}^{18}O$

Basis for paleoclimate studies on ice cores, using oxygen isotopes:

Vapour pressure of $H_2^{16}O$ is 10% higher than vapour pressure of HDO
1% higher than vapour pressure of $H_2^{18}O$

Evaporation from a water body thus results in vapour that is *poorer* in the heavier isotopes deuterium and ^{18}O, whereas the remaining water is *enriched* in D and ^{18}O.

At equilibrium, atmospheric vapour contains 10 ‰ less ^{18}O and 100 ‰ less D than mean ocean water.

Condensation: HDO and $H_2^{18}O$ pass more readily from vapour to liquid state. Compared to the remaining vapour, precipitation is enriched in the heavy isotopes.

Result: Vapour becomes more and more depleted in the heavier isotopes!

The isotopic composition of a water sample is expressed as a deviation from the composition in *Standard Mean Ocean Water (SMOW):*

$$\text{ä}^{18}\text{O} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{Sample}} - (^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}}{(^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}} \text{ x } 1000\ ‰$$

δD is defined is defined in a similar way.

<u>Measured in a mass spectrometer</u>:

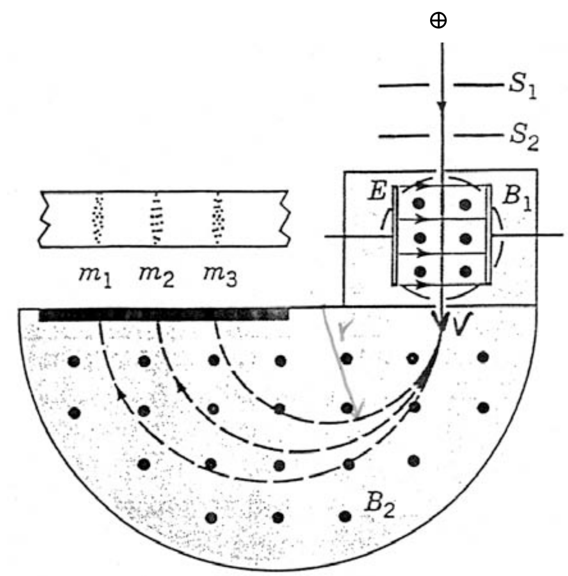
5 cm^3 water sample brought into isotopic equilibrium with CO_2:

$$H_2O^{18} + CO_2^{16} \Leftrightarrow H_2O^{16} + CO^{16}O^{18}$$

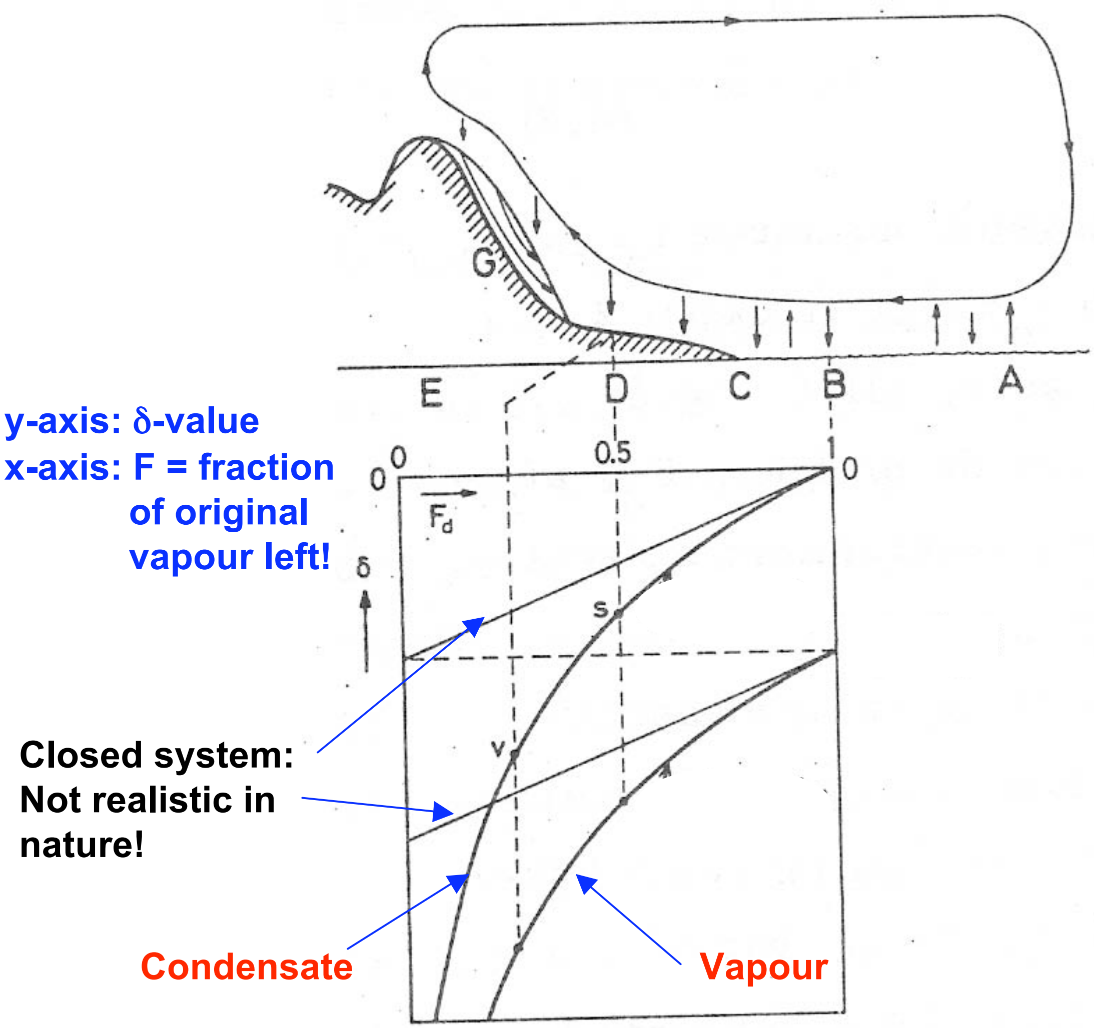
Ionized CO_2 then passed through magnetic field.

The ratio between intensities of ion beams with mass numbers 46 ($CO^{16}O^{18}$) and 44 (CO_2^{16}) is a measure of the concentration of O^{18} in the sample!

Reproducibility: ± 0.1 ‰



Lowering of δ–values in vapour and condensate, as an air mass travels from the ocean to a mountain glacier:

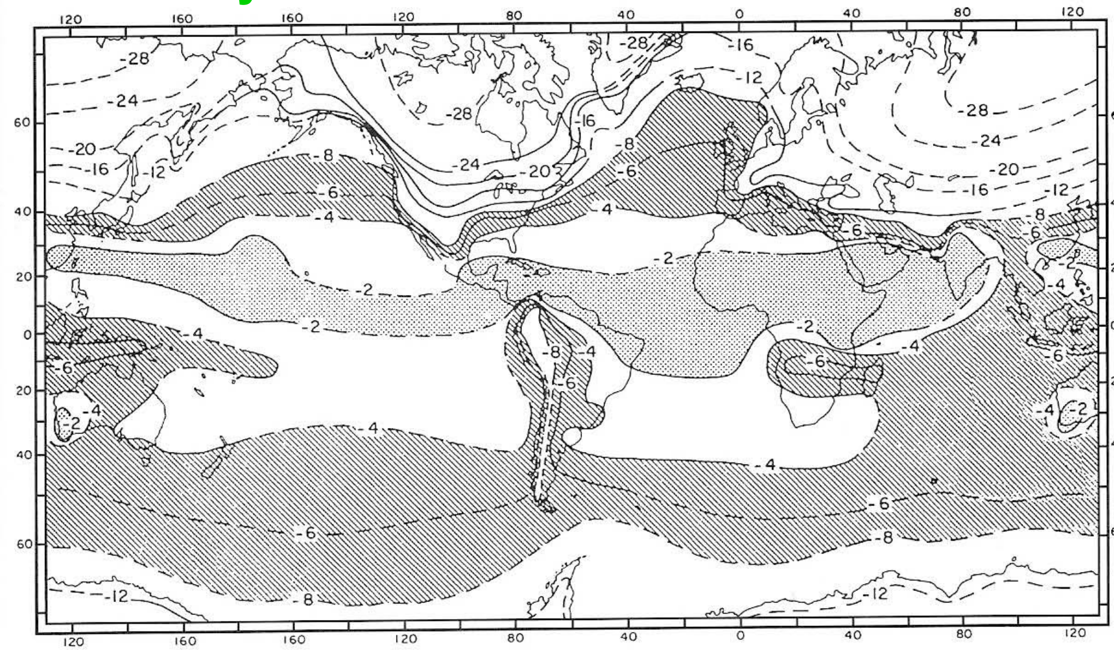


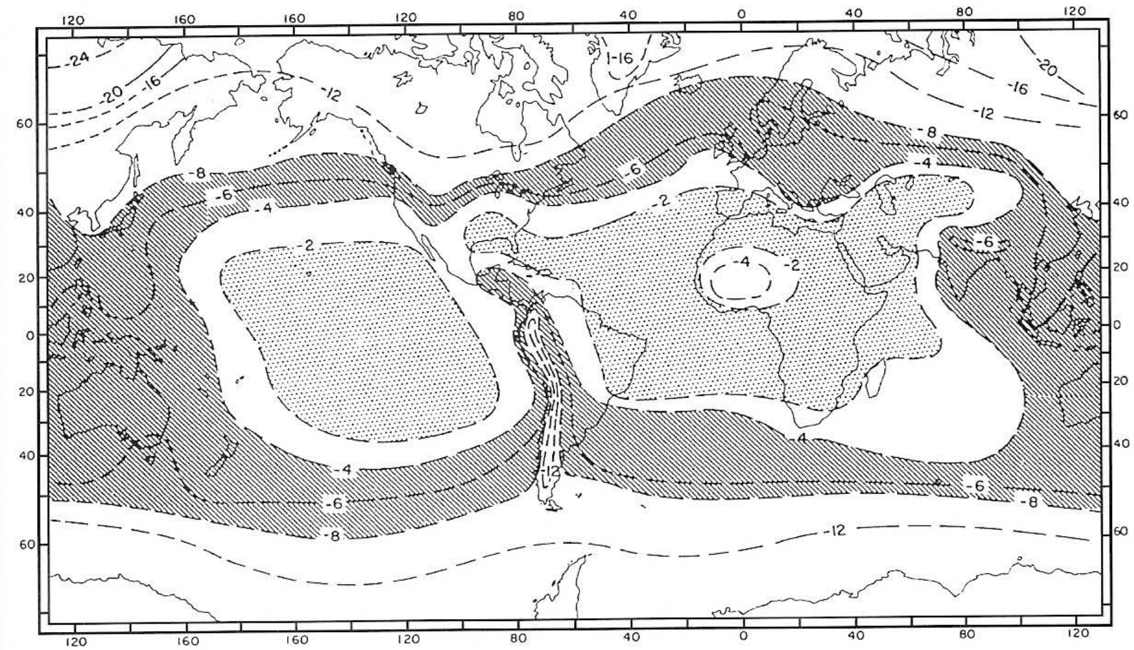
In general, δ-values reflect changes in air temperature:

- **δ lowered as air mass travels to higher latitudes and higher altitudes.**
- **δ displays seasonal variation**
- **δ decreases with distance from moisture source**
- **δ indicates long-term climatic fluctuations**

Rayleigh process: The condensate is removed from the vapour immediately, as precipitation.

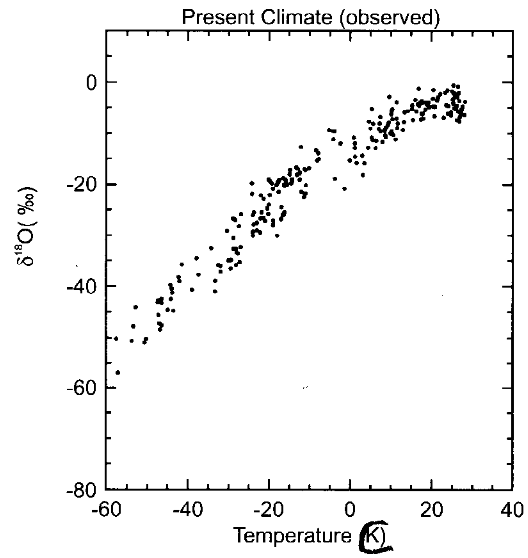
January





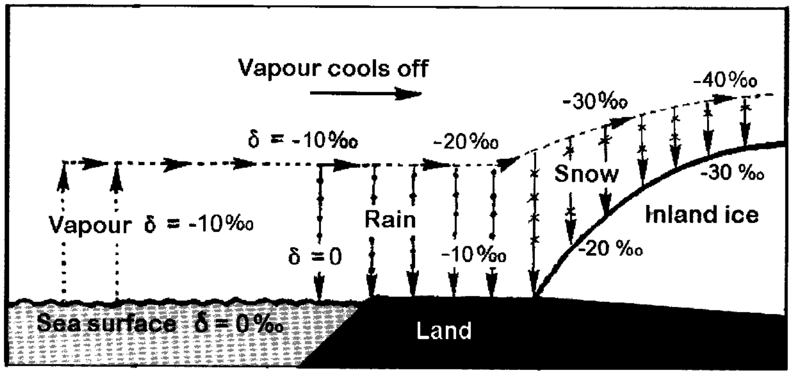
July

Worldwide $\delta^{18}O$ distribution, displaying effects of latitude, altitude, continents and ocean currents.

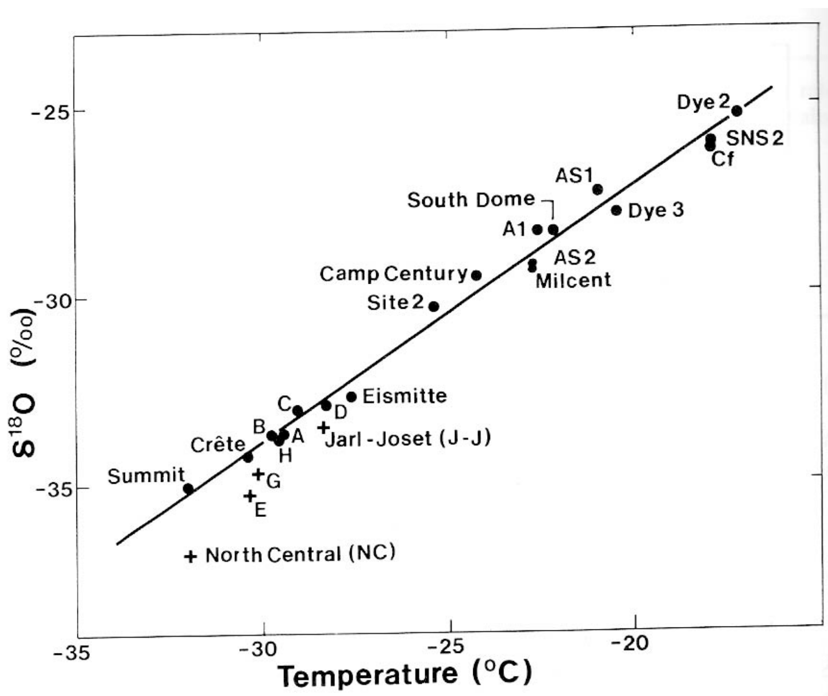


Annual $\delta^{18}O$ in precipitation in relation to mean annual temperature at the same site (Jouzel et al., 1994).

^{18}O depletion en route to ice sheet:



LOCATION	Altitude	Mean annual temperature	$\delta^{18}O$
SMOW			0.0 ‰
Reykjavík	14 m	4.4 °C	- 8.0 ‰
Hofsjökull, Iceland	1800 m	~ - 6 °C	- 12.9 ‰
Greenland summit	3200 m	- 32 °C	- 35.0 ‰
East Antarctica	4000 m	- 58 °C	- 58.0 ‰



Relationship between mean annual values of $\delta^{18}O$ and temperature on the Greenland ice sheet (at present):

$$\delta^{18}O = 0.67T - 13.7 ‰$$

This allows reconstruction of past temperatures from $\delta^{18}O$ measurements on ice cores!

The δ-T relationship probably varies with climatic conditions, especially between interglacial and glacial periods. Reasons:

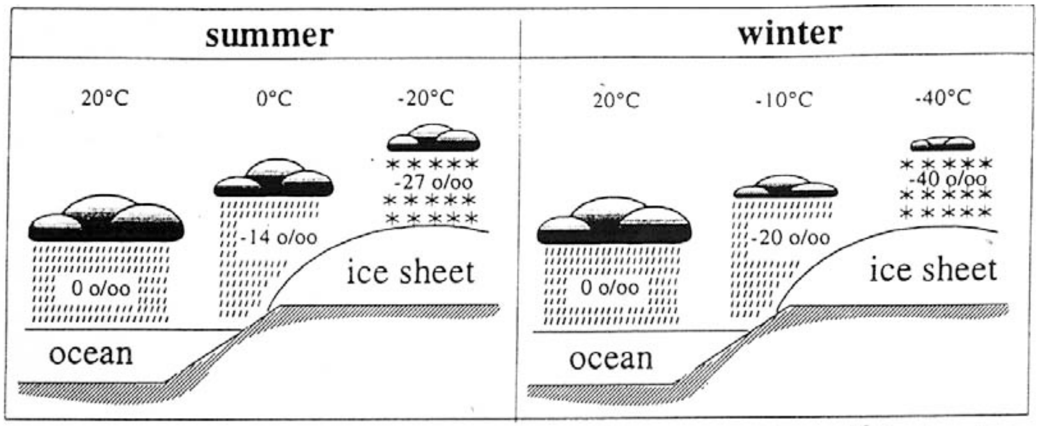
- **Ice thickness can change (greater during glacial period; i.e. lower δ)**
- **More extensive sea-ice cover during glacial periods increases distance to moisture source, lowering δ**
- **Isotopic composition of oceans changed during the glacial periods (δ-depleted water stored in large ice sheets)**

Current evidence indicates a δ-T relationship of

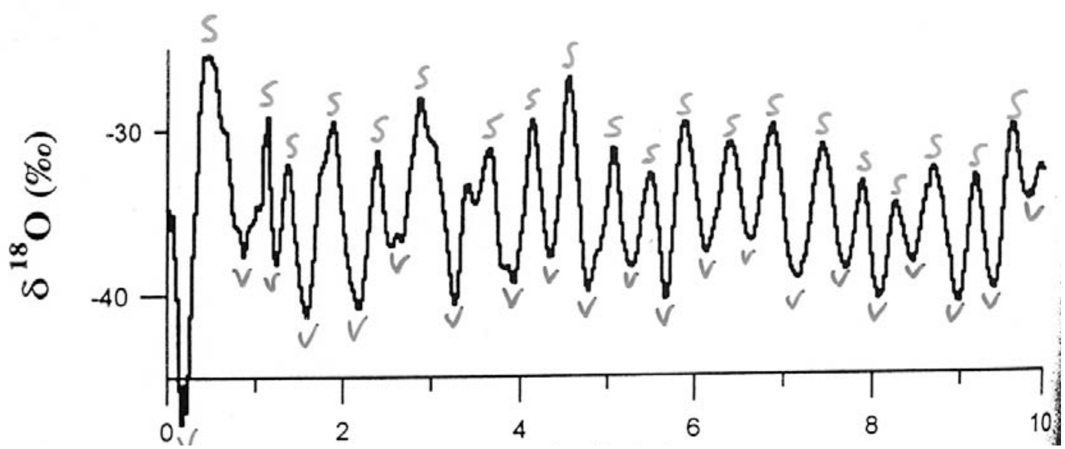
$$\delta^{18}O = 0.33T - 24.8\ ‰$$

for the glacial period (12-100 ka BP) in Greenland.

Seasonal variation in $\delta^{18}O$ in snow, firn and ice



Little seasonal variation in temperature at moisture source (~35 °N), large seasonal variation over ice sheet.



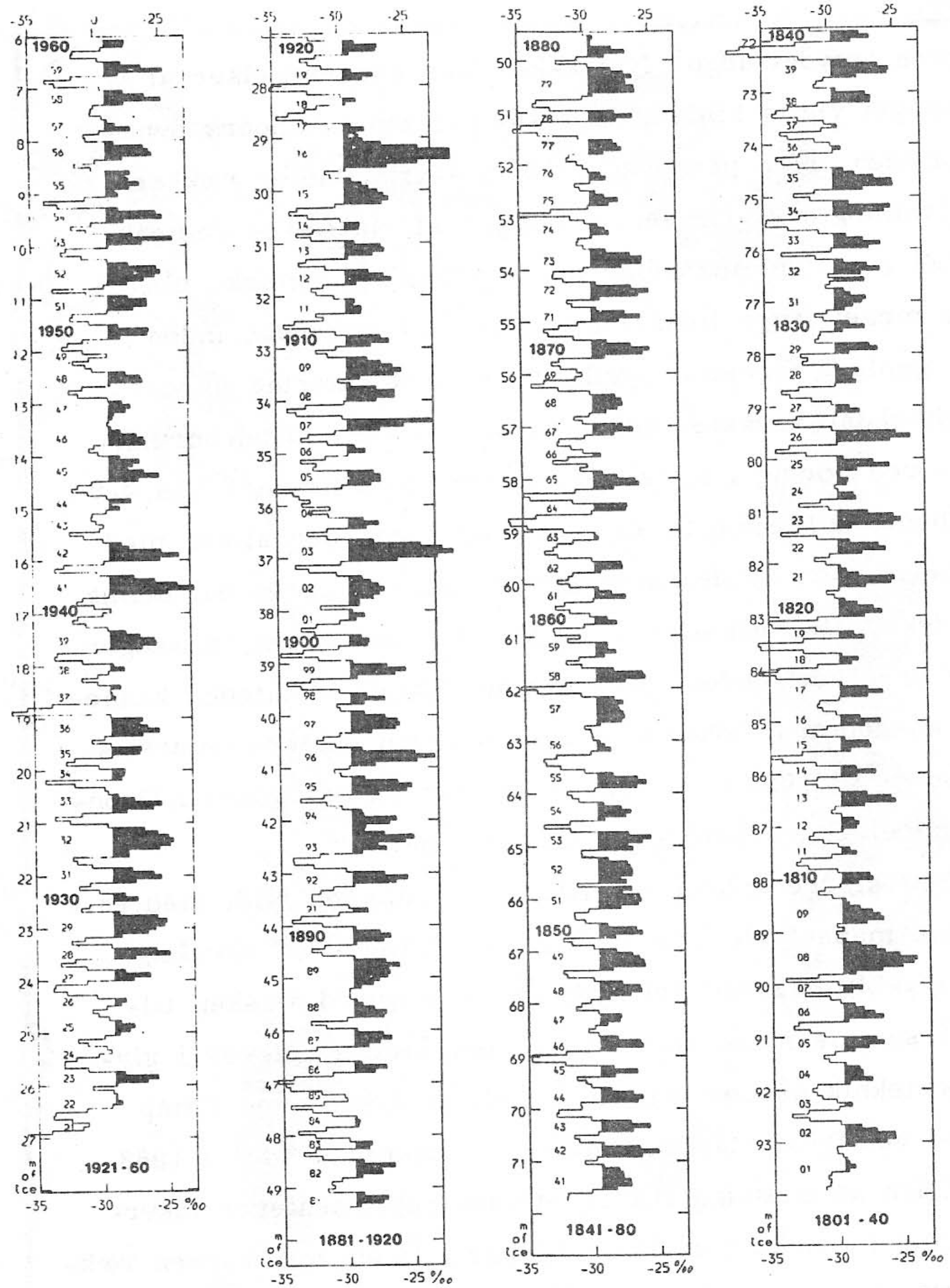
Seasonal variation in $\delta^{18}O$ in a 10 m snow pit at Summit, Central Greenland.

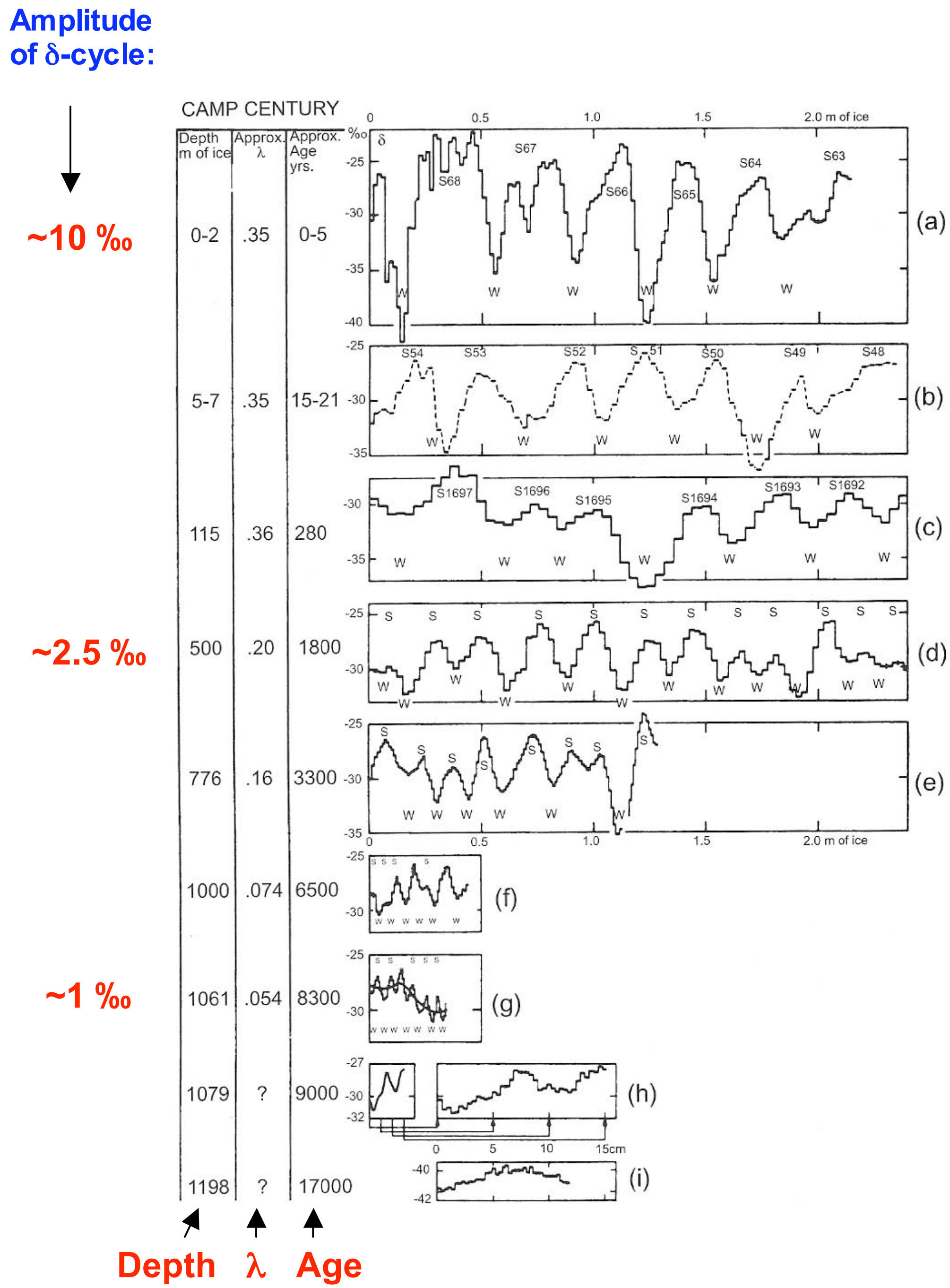
20 years in 10 meters: 0.5 m snow/year = 0.23 m ice/year

Seasonal variation in δ^{18}O at Milcent station, Central Greenland

Depth interval: 6-94 m

Period: 1801-1960 AD





Seasonal variation in $\delta^{18}O$ at different depths and ages in the Camp Century ice core, NW Greenland.

Short term δ variations in snowpack quickly obliterated by mass exchange.

Thinning of annual layers by plastic deformation, seasonal gradients in $\delta^{18}O$ increase, and molecular diffusion leads to smoothing of the annual cycles.

Annual layers have been counted throughout the Holocene (last 11,500 years) in the Greenland deep cores!

"Back-diffusion" – a model that restores smoothed δ–cycles!

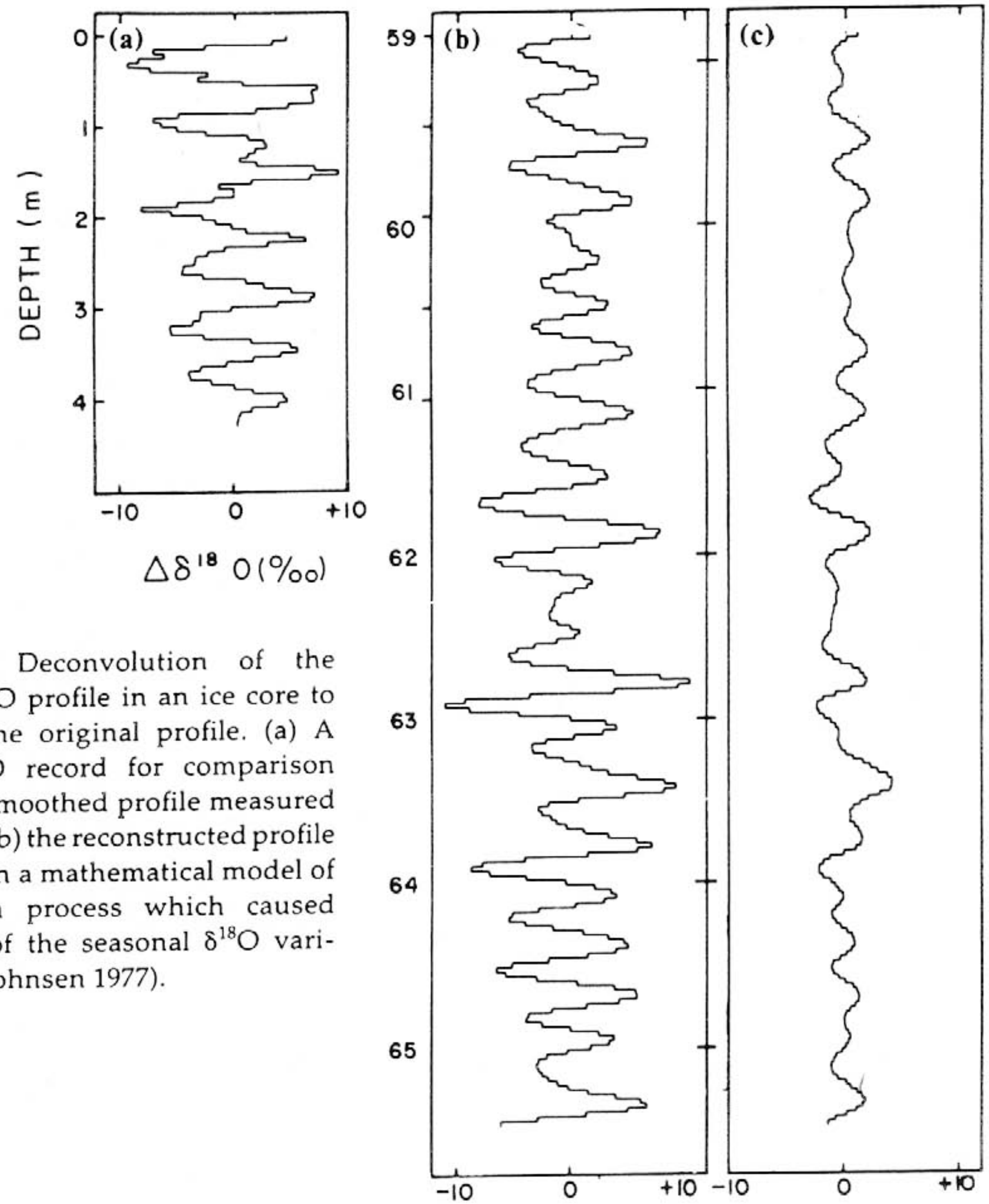
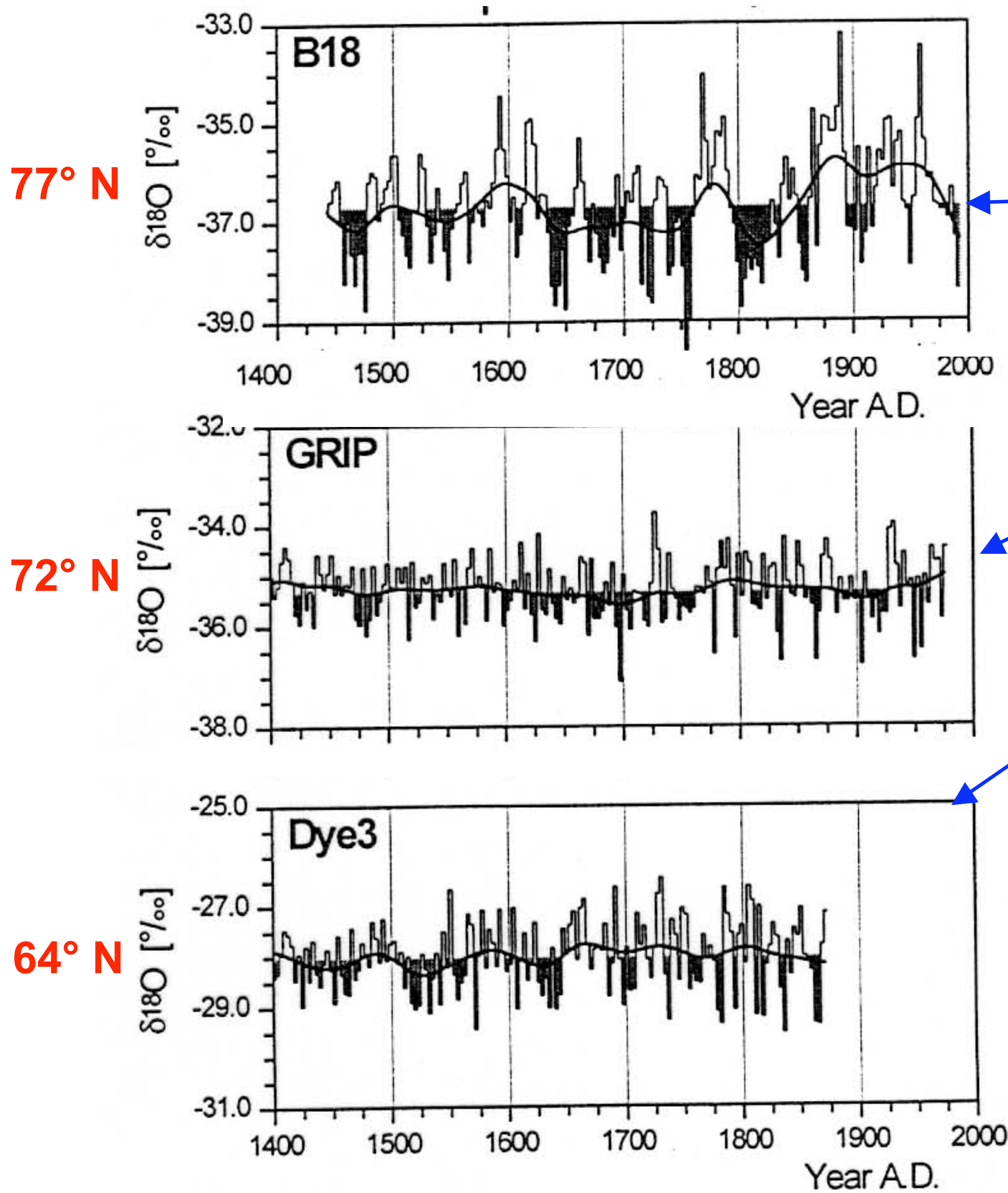
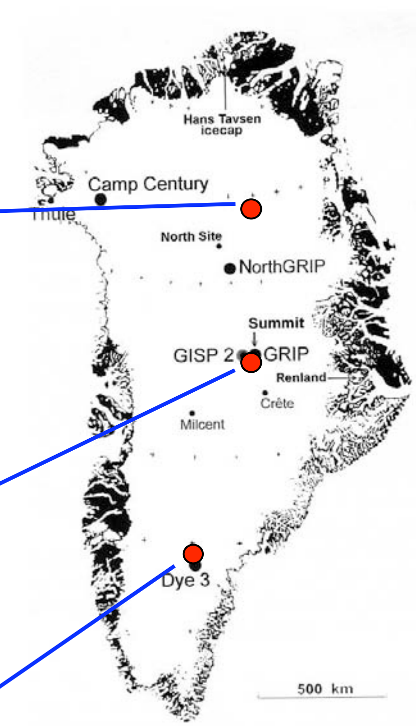


Figure 5.11 Deconvolution of the smoothed $\delta^{18}O$ profile in an ice core to reconstruct the original profile. (a) A core-top $\delta^{18}O$ record for comparison with (c) the smoothed profile measured at depth and (b) the reconstructed profile of (c) based on a mathematical model of the diffusion process which caused obliteration of the seasonal $\delta^{18}O$ variations (after Johnsen 1977).





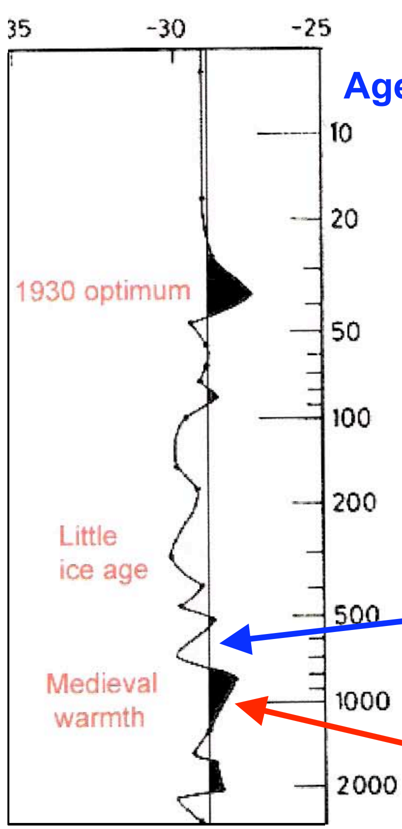
Climate records from shallow cores

δ-profiles 1400-2000 AD at locations in Northern, Central and Southern Greenland.

"Little ice age" cooling most prominent in the northernmost core, especially 1630-1760 and first half of 19th century!

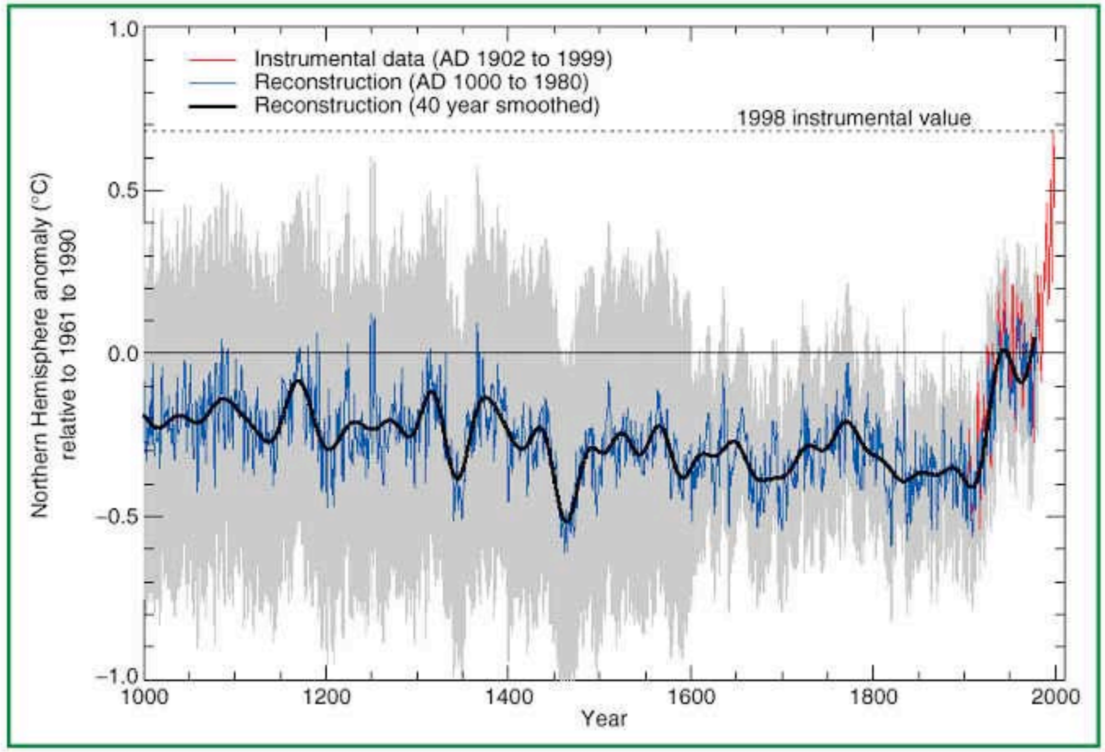
The Camp Century δ-profile shows:

- The Medieval Warm Period
- The Little Ice Age
- The warm period 1920-1940



Camp Century

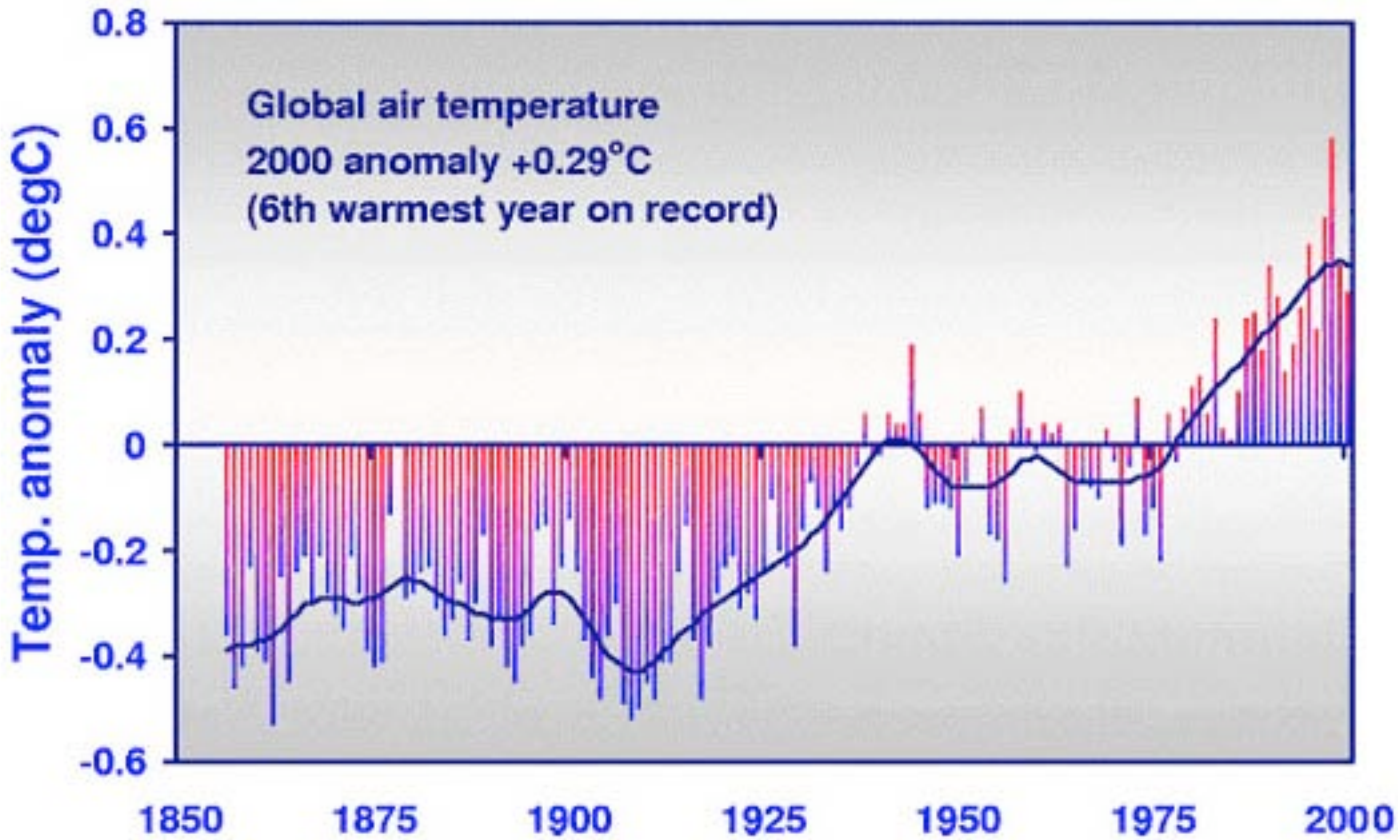
IPCC



Northern Hemiphere temperature reconstruction over the last 1000 years, based on tree rings, corals, ice cores and historical records.

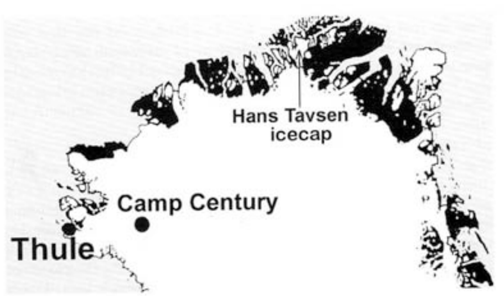
Decline of the Nordic population in Greenland

Settlement of Iceland (870-930 AD) and Greenland (985-1030). Viking Age voyages to North America.

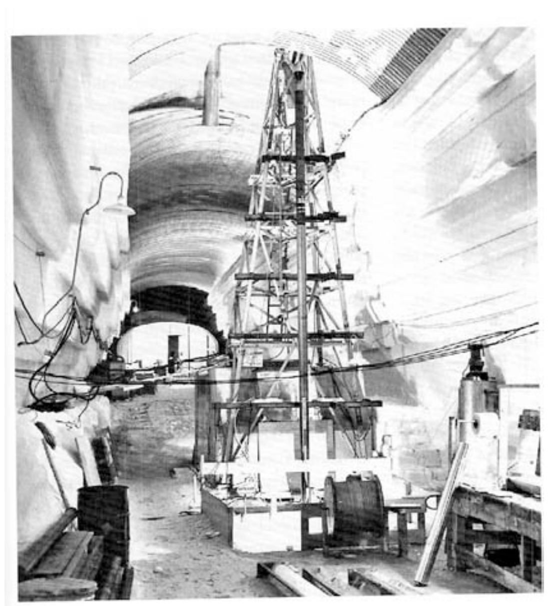


Global temperature changes 1850-2000

Camp Century: The first paleoclimate profile from a deep ice core



Camp Century: A Cold War military installation beneath the ice surface 1960-1966

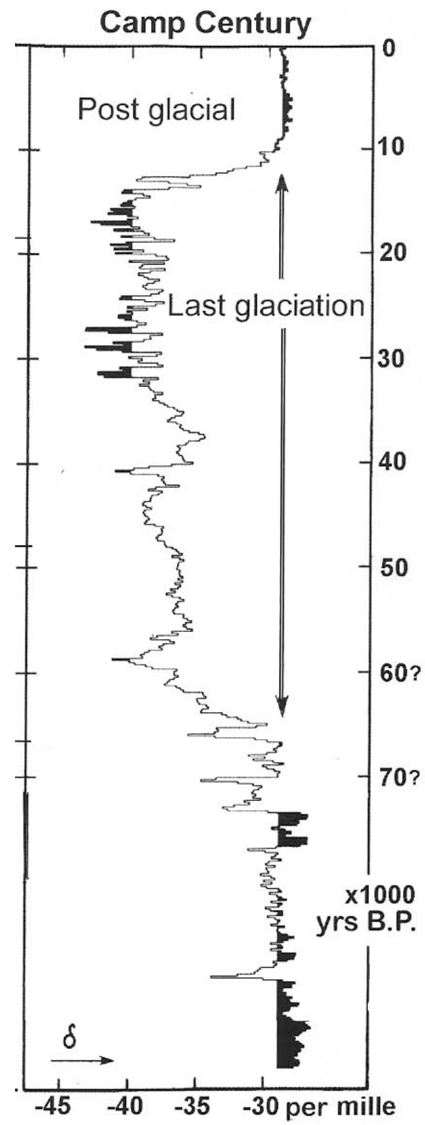


Drilling rig

$\delta^{18}O$ 10-12 ‰ lower during the glaciation than during the Holocene (Post glacial).

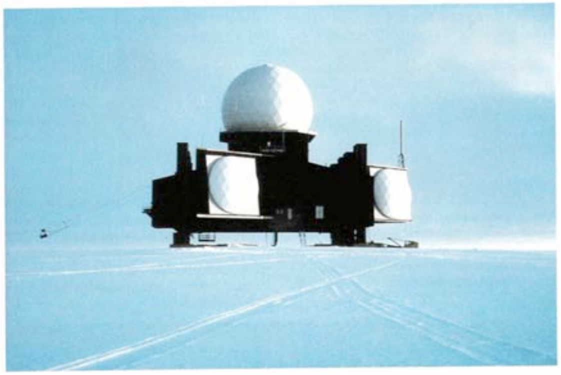
Note rapid variations in the period 12-32 ka BP.

Detected in the early ´70s, not generally accepted until 20 years later!



Timescale was later revised!

Dye 3 ice core drilled in Southern Greenland 1979-1981



Radar station at Dye 3

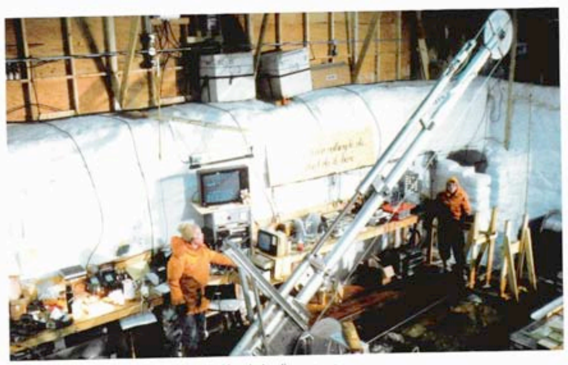
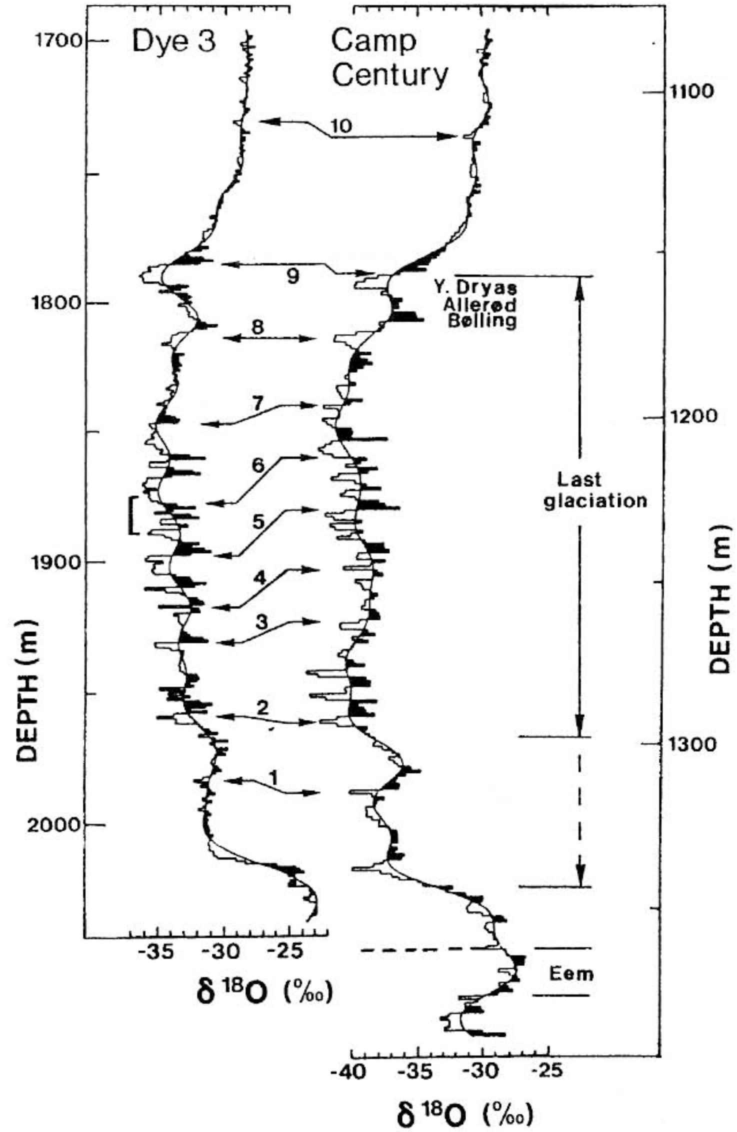


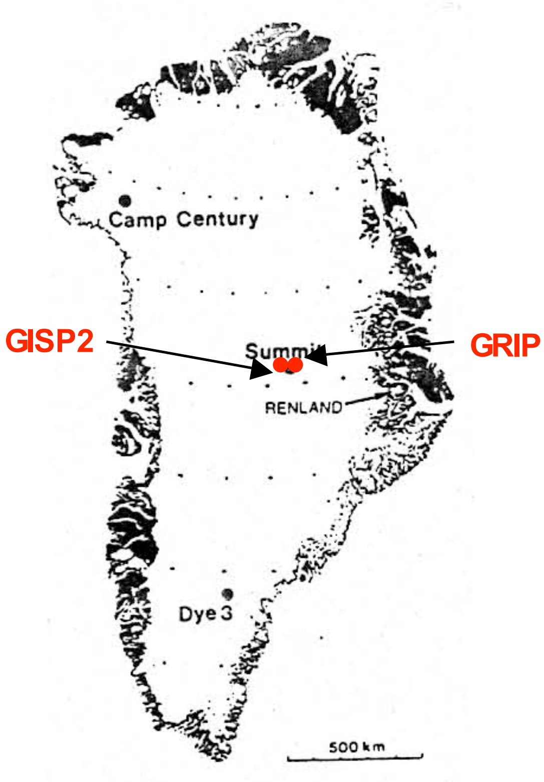
Fig. 10.2 The drill hall. ISTUK is being tilted by a hydraulic pump system.

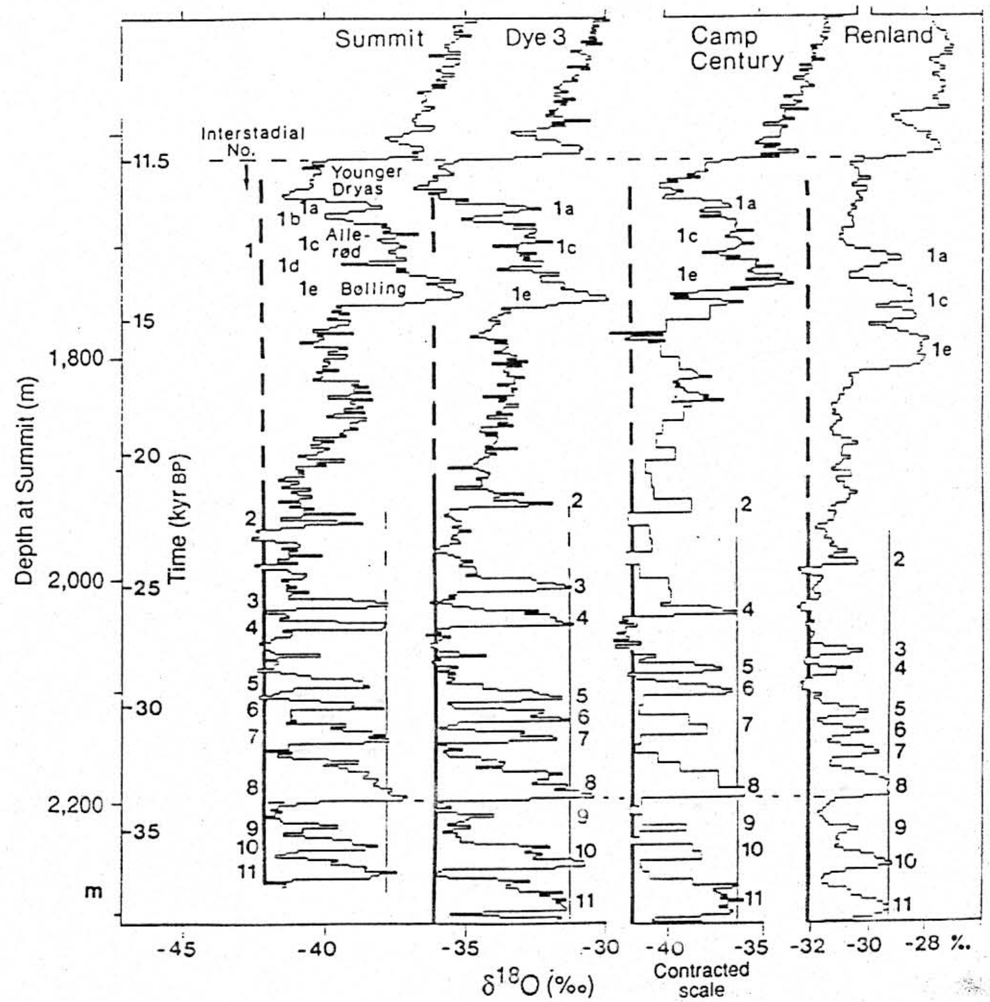
Working in drill trench

More indications of rapid climate variations during the glacial period!



GRIP core from Greenland Summit (1989-1992):

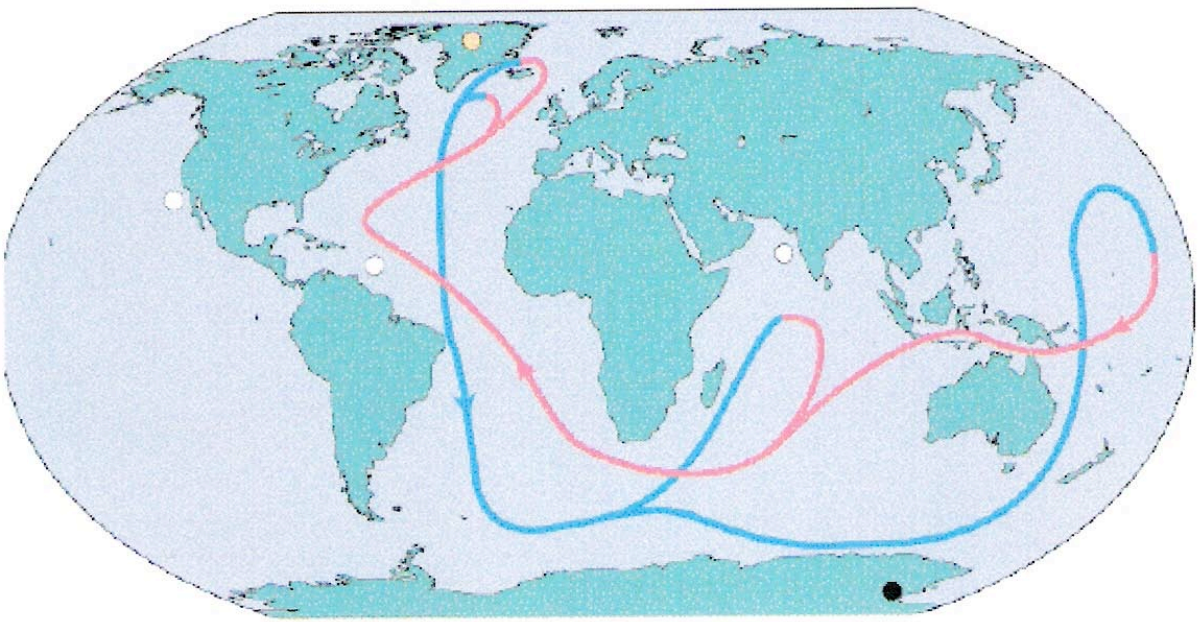




Confirmation of mild interstadials during the glacial period, lasting 500-2000 years.

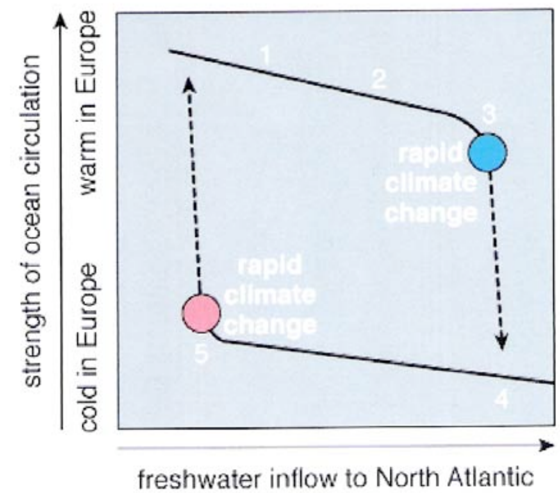
Now called *Dansgaard-Oeschger events*.

Leading hypothesis on causes of the rapid Dansgaard-Oeschger variations during the glacial period: Changes in the mode of oceanic circulation



Summit   high time-resolution ocean core   Vostok
warm, fresh, less dense, shallow water   cold, salty, dense, deep water

S. Rahmstorf

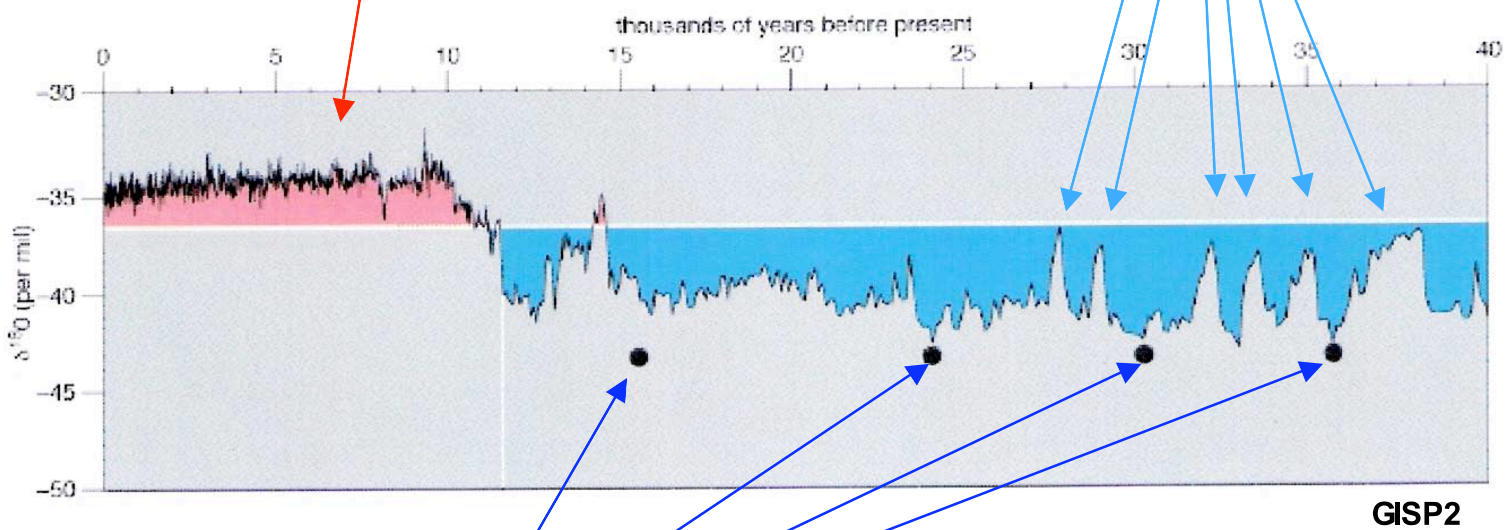


The ocean-current conveyor belt can switch between two stable modes of operation, or be shut down!

Increased freshwater inflow to the North Atlantic could trigger a rapid switch to colder conditions in Europe!

Present mode (warm interglacial): Deep water formation north and south of Iceland

Dansgaard-Oeschger Interstadials: Gulf Stream does not reach Iceland, deep water formation only takes place south of Greenland and Iceland



Coldest glacial conditions: Shutdown of the oceanic conveyor belt!

<u>Full profile from the GRIP ice core</u>:

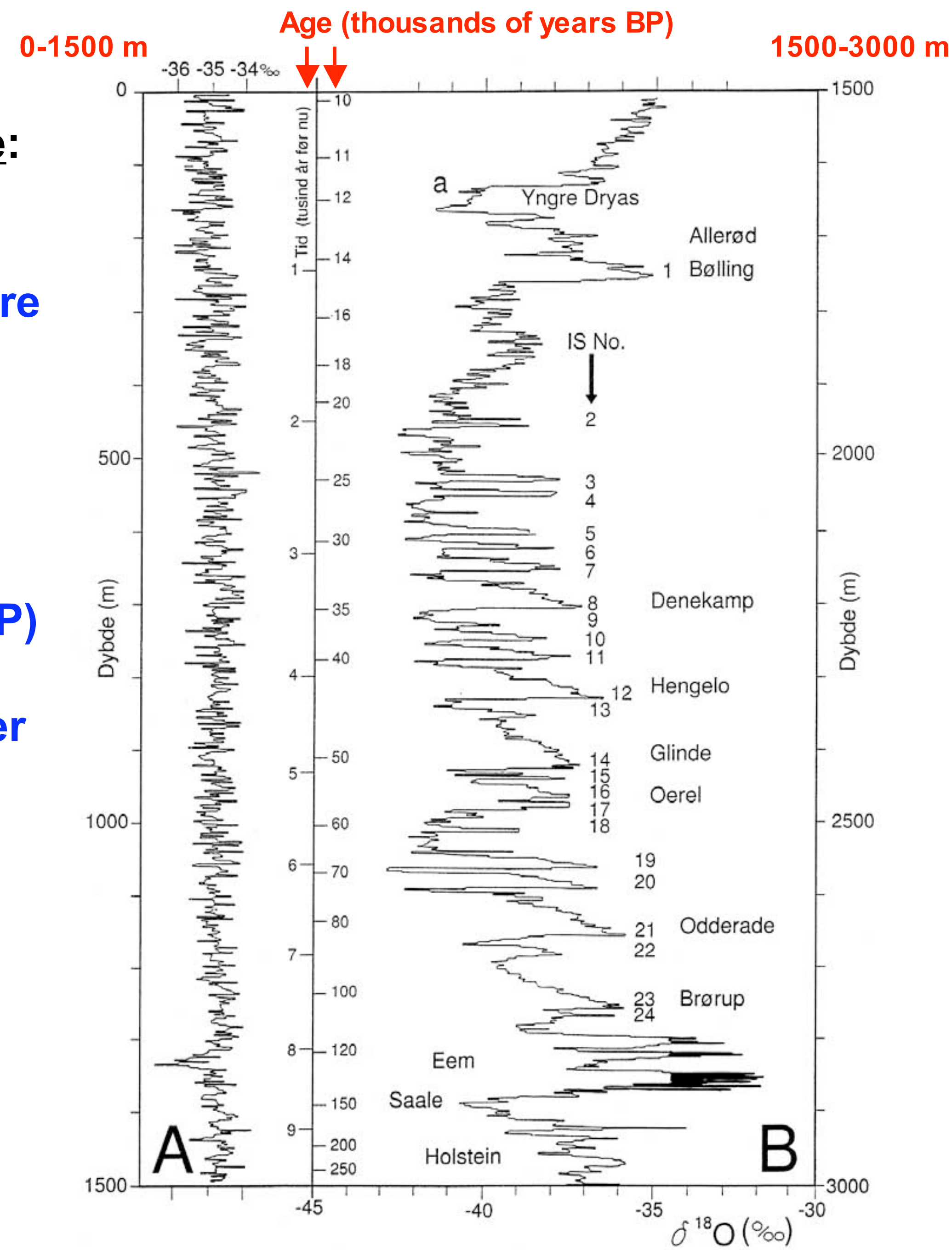
A reference for all paleoclimate studies in the Northern Hemisphere (last 100,000 years).

Main features:

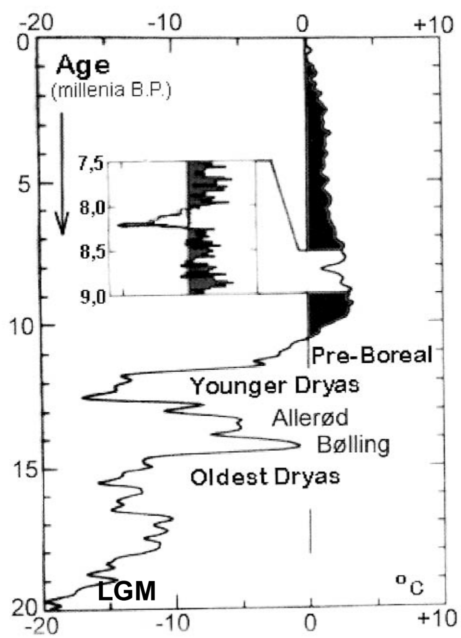
Very stable climate during the Holocene interglacial (0-11.5 ka BP)

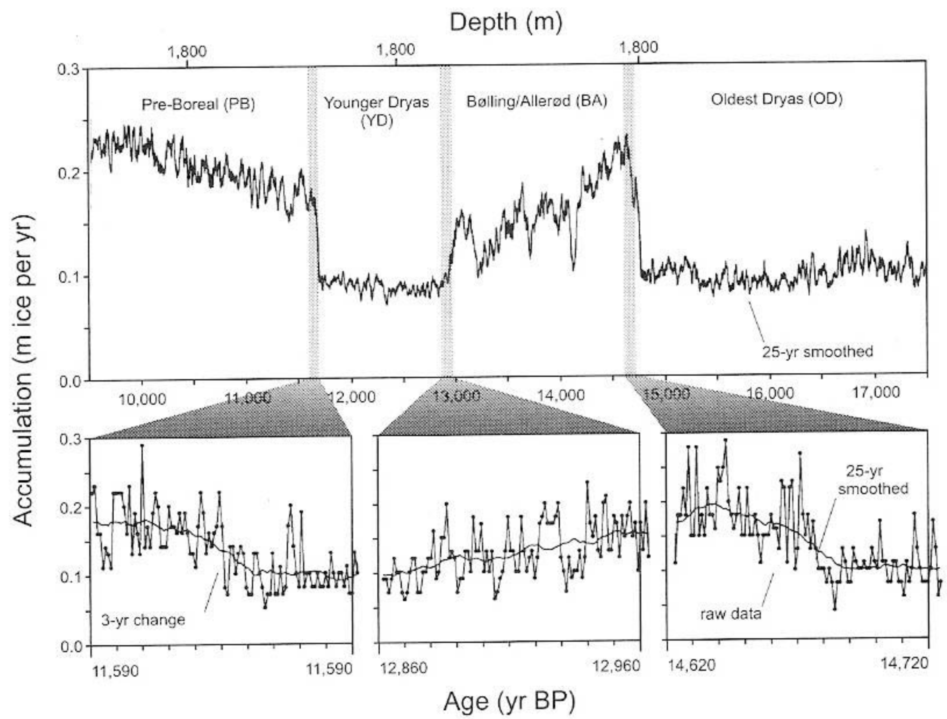
23 confirmed Dansgaard-Oeschger interstadials during the glacial period (11.5-110 ka BP).

Unexpected results indicating climate instability during the last interglacial period, the Eemian (110-135 ka BP).



The end of the last glacial period in the Summit cores:



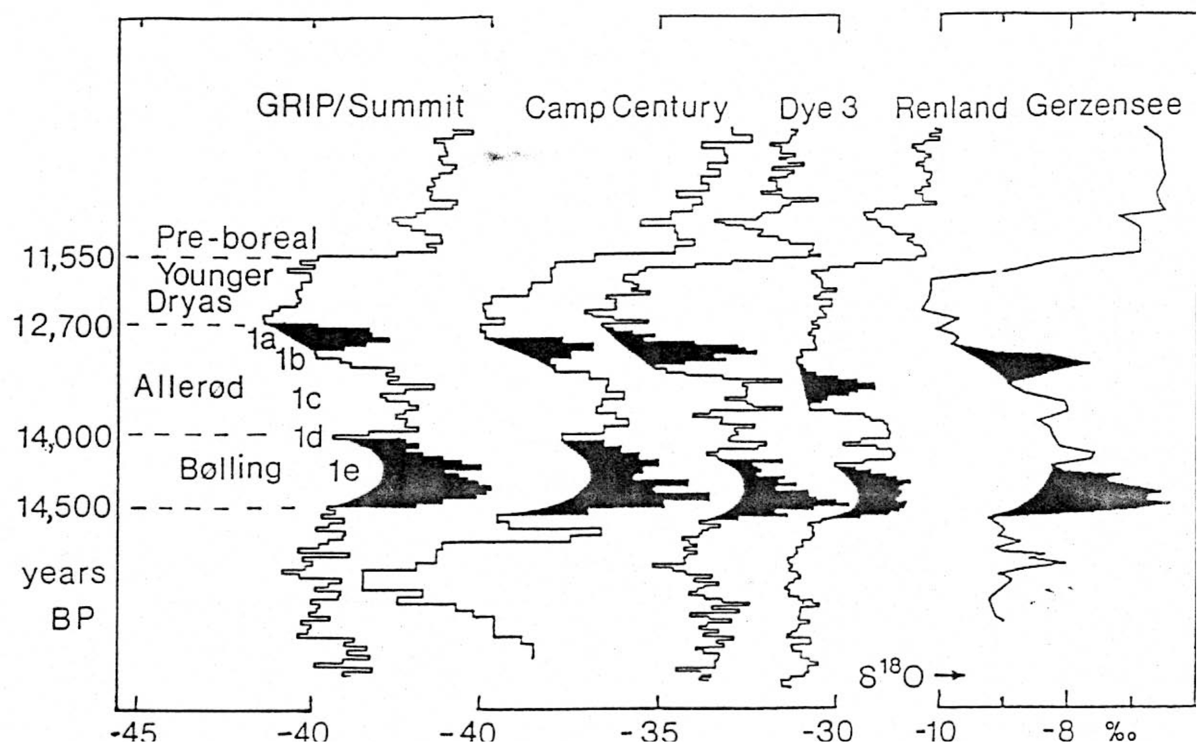


Temperature changes at Summit during the last 20,000 years, derived from GRIP isotope and borehole temperature data. 20 °C difference between LGM (Last Glacial Maximum) and present!

Accumulation variations at Summit in the period 9,500-17,500 years ago, derived from annual layer counting in the GISP2 core. Snow accumulation during the glacial period was ~35-40% of the present value!

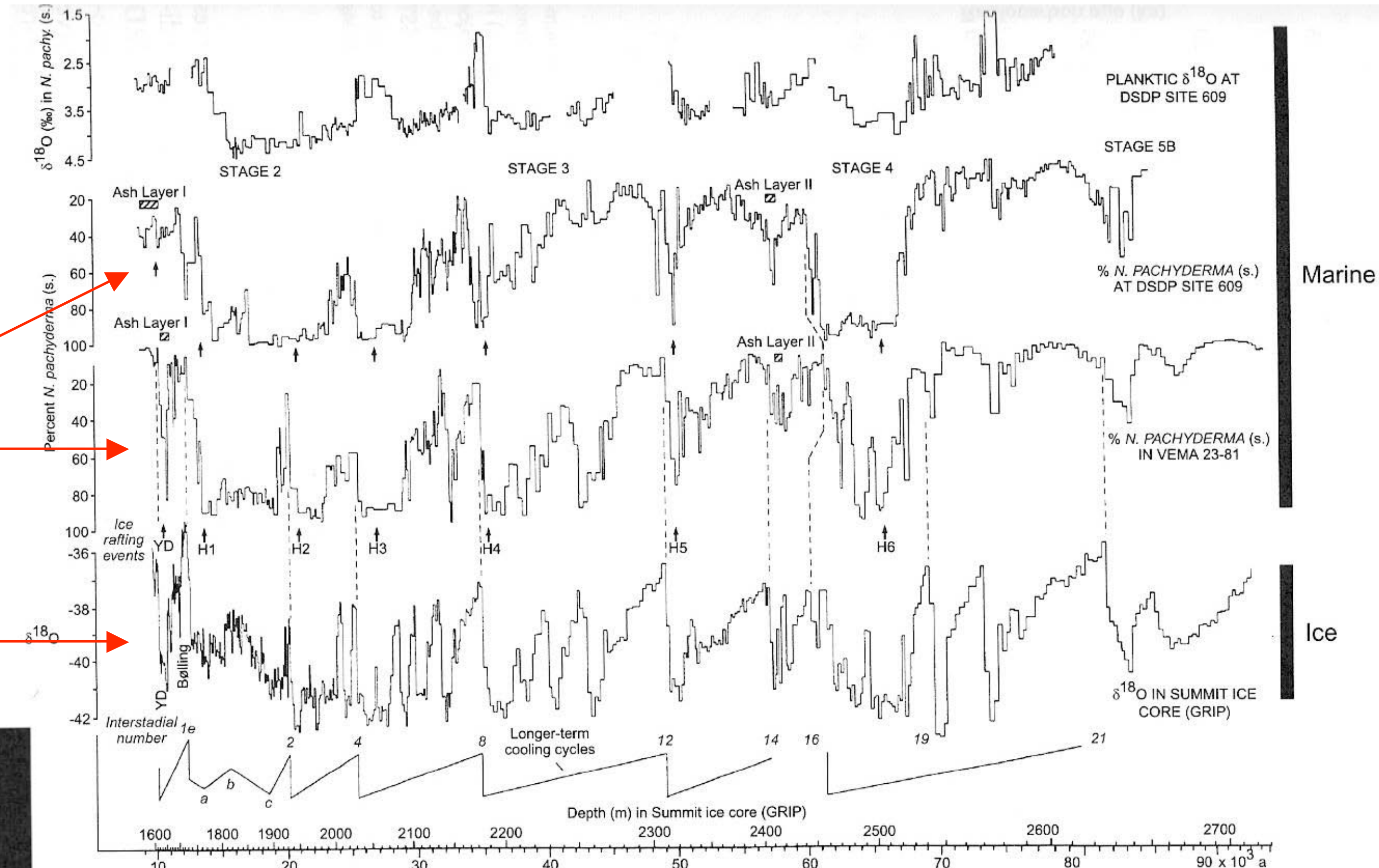
Younger Dryas: A ~1200 year cold spell at the end of the Weichsel/Wisconsinan glacial period!

The glacial termination ("Termination 1") in four Greenland cores and in Lake Gerzensee, Switzerland:



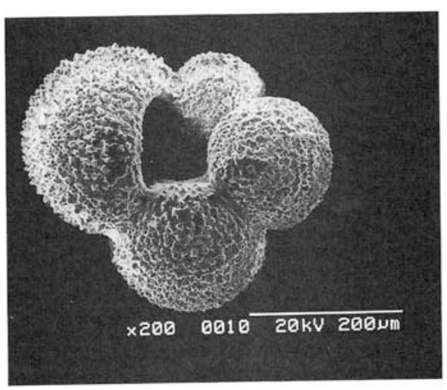
The Younger Dryas has now been identified in climate records all over the Northern Hemisphere.

Comparison of the GRIP isotope record (10-90 ka BP) with climate indicators from marine sediments in the North Atlantic:



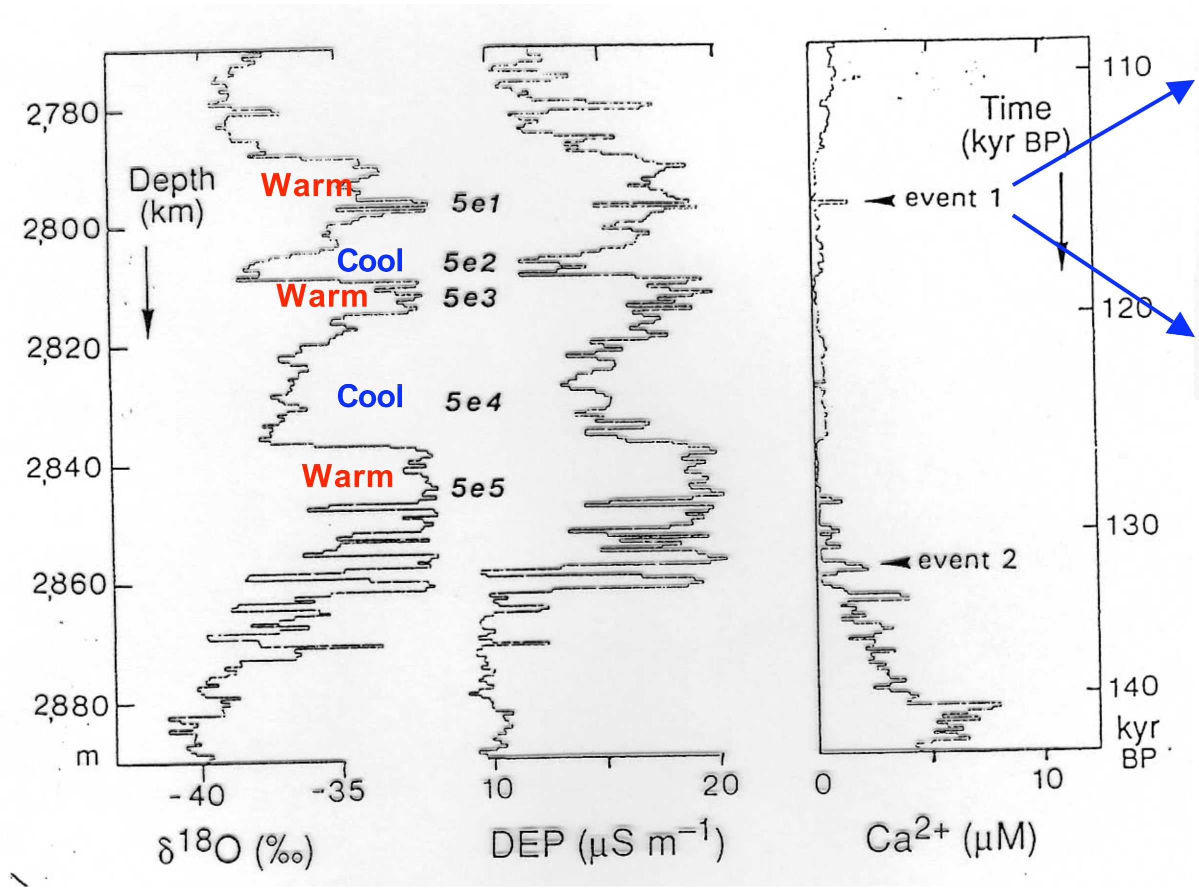
Percentage of the planktonic cold water foraminifera *Neogloboquadrina pachyderma* in two sediment cores

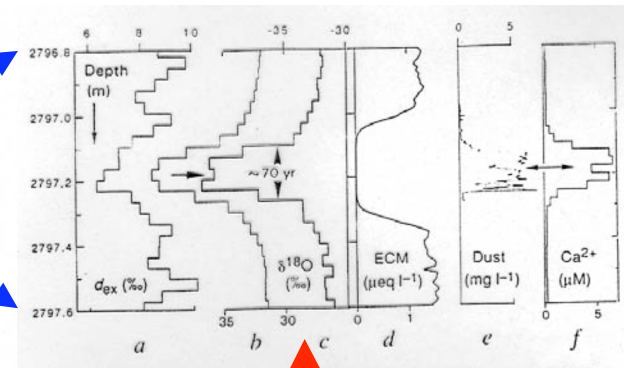
GRIP δ^{18}O



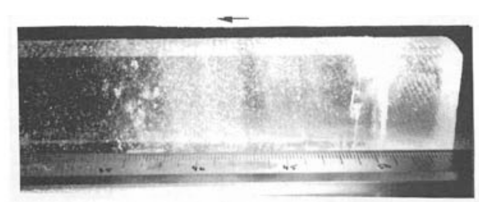
Neogloboquadrina pachyderma

GRIP results published 1993 indicated that the warm Eemian interglacial had been interrupted by two cold periods, and that a brief, very cold event had occurred near the end of the Eemian:



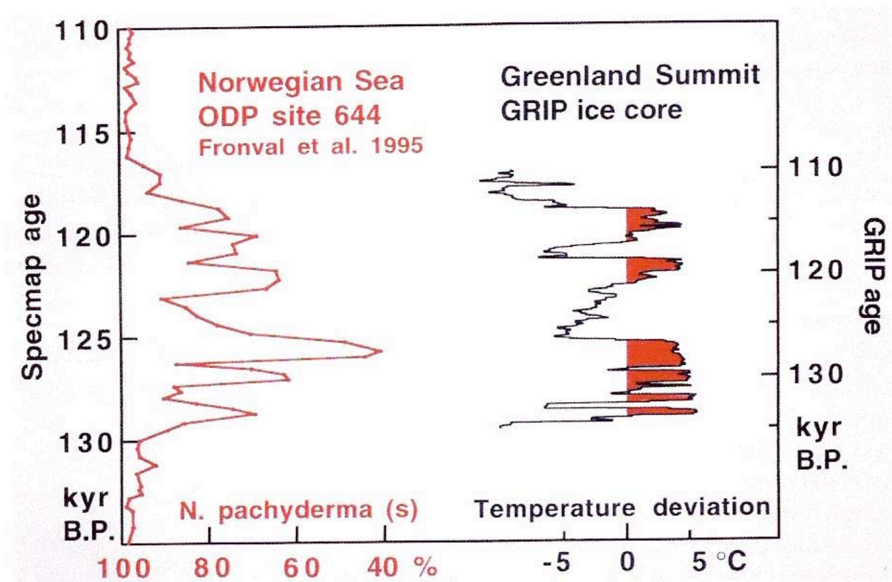


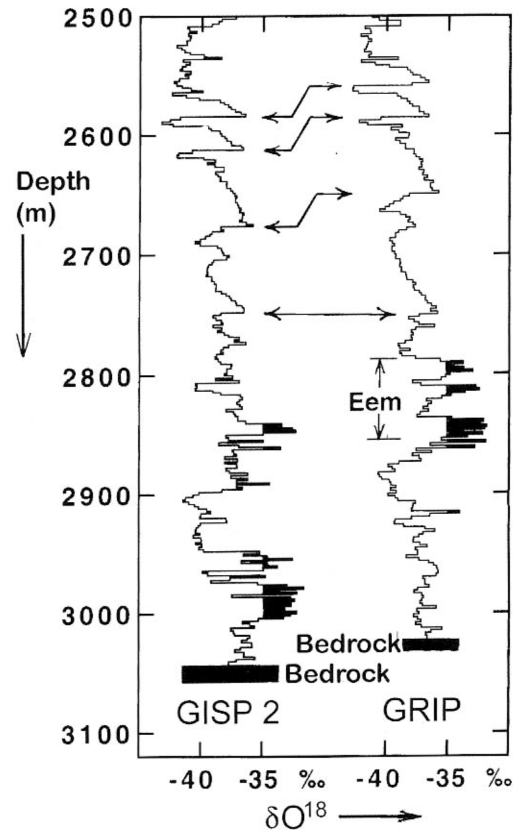
A 20 cm layer indicating a ~70 year cold spell 114,000 years ago!



"Catastrophic Event 1" at 2797 m depth in the GRIP core.

The unstable GRIP Eemian: Comparison with other records



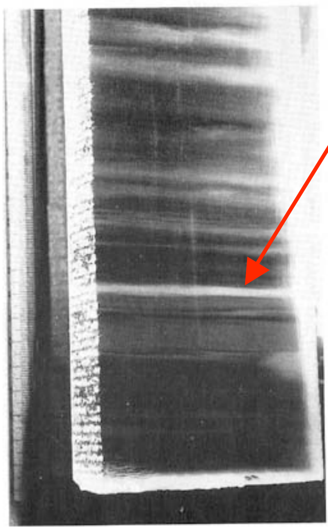


A foraminiferal record from the Norwegian Sea seemed to indicate climatic instability during the Eemian, like the GRIP core!

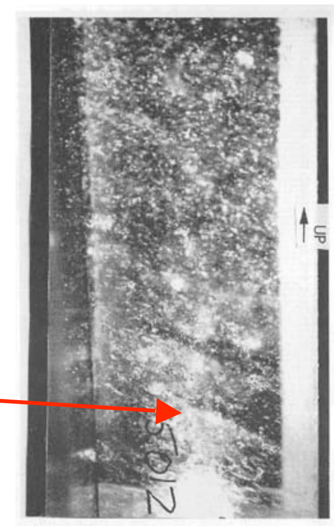
BUT!

The otherwise excellent match between the GRIP and GISP2 cores ceased at 2750 m depth and no sign was seen of the tripartite Eemian in the GISP2 core!

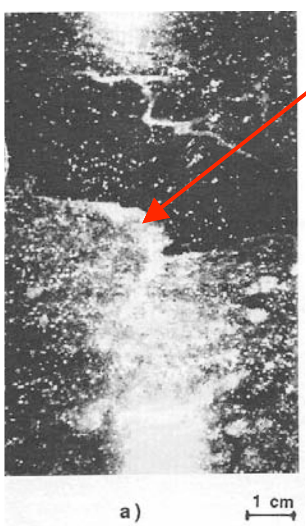
A close look at the visual stratigraphy of the GRIP and GISP2 cores revealed inclined layering and folding in the lowest 300 m of both cores:



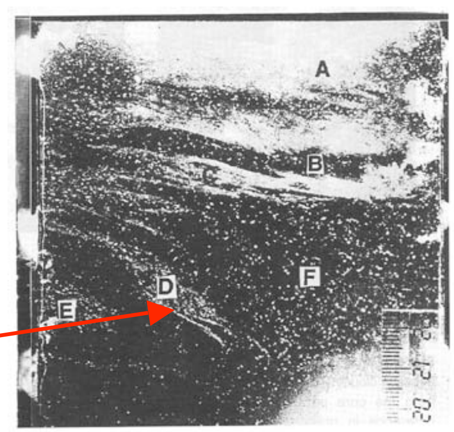
Undisturbed cloudy bands in ice above 2500 m depth.



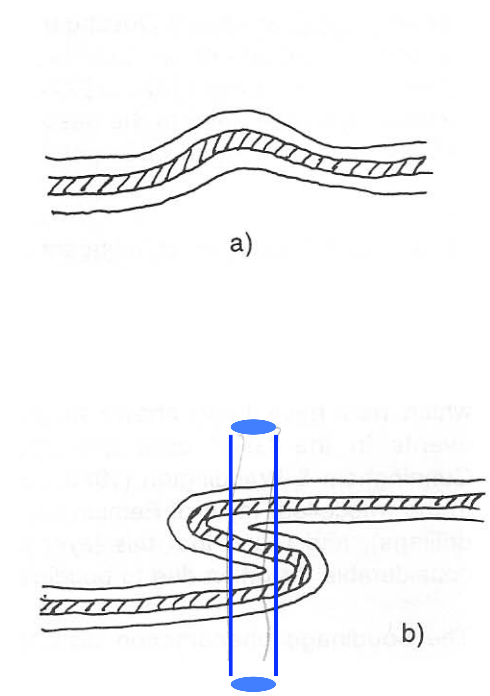
Inclined layering at 2757 m depth in the GRIP core!



A distorted layer at 2873 m.



A folded layer at 2923 m.

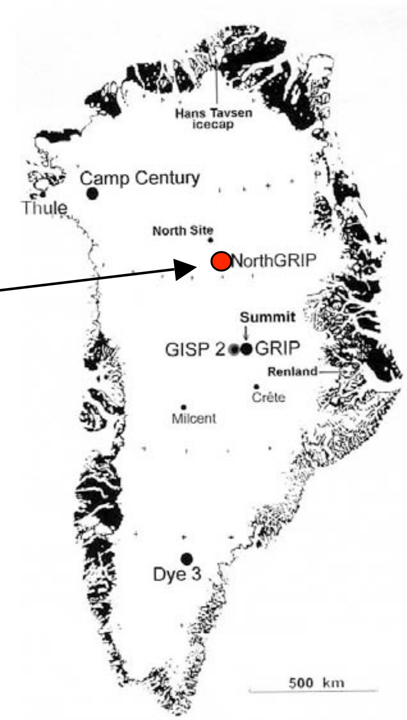


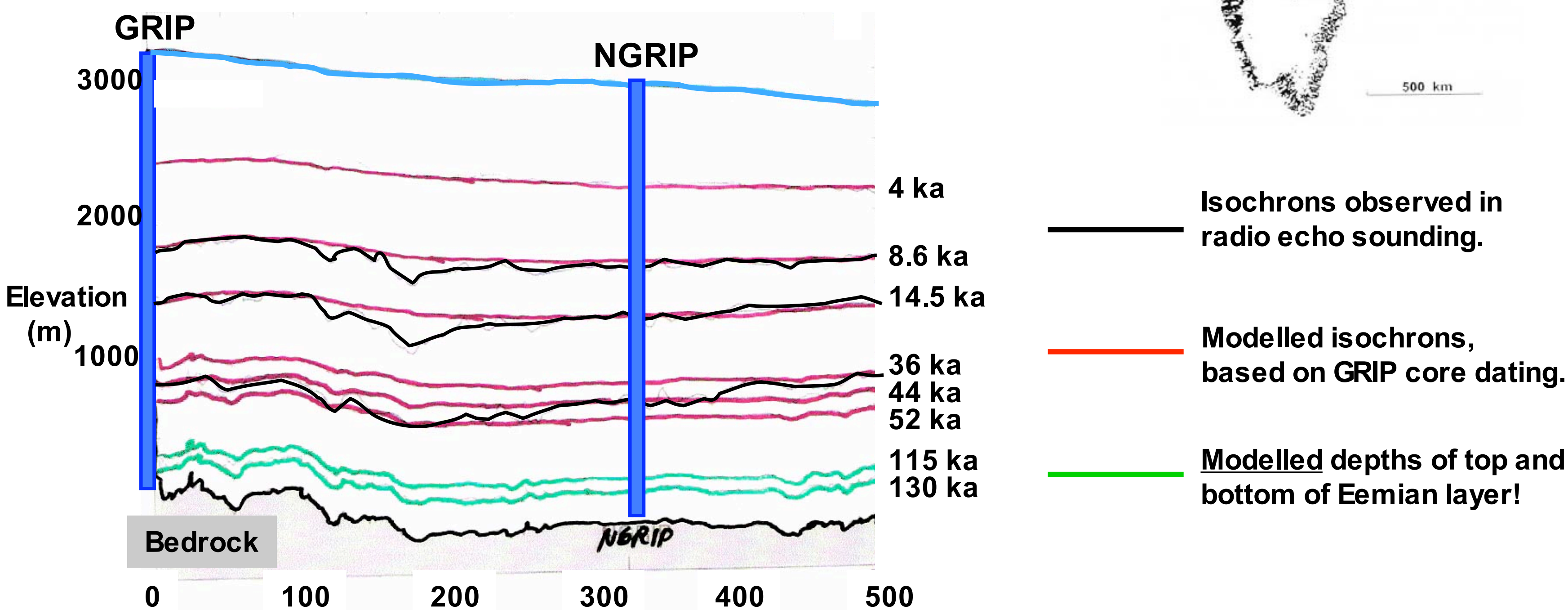
In case of large-scale folding, a drill core could penetrate the same layer three times!

It became clear that the only way to resolve the Eemian controversy was to drill another deep core in Greenland.

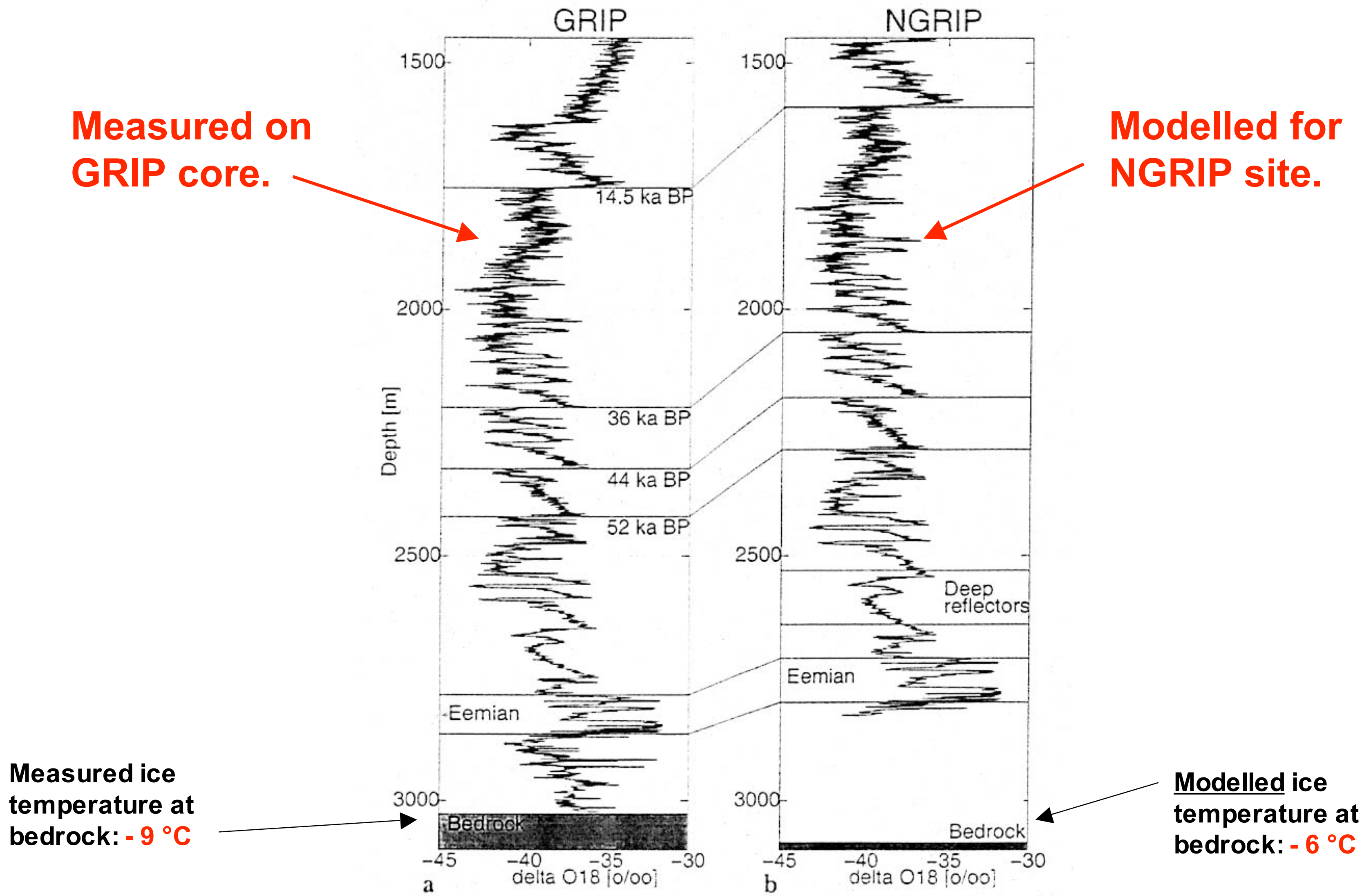
The North Greenland Ice Core Project (NGRIP) was started in 1996, completed 2004.

Several mishaps and surprises along the way!

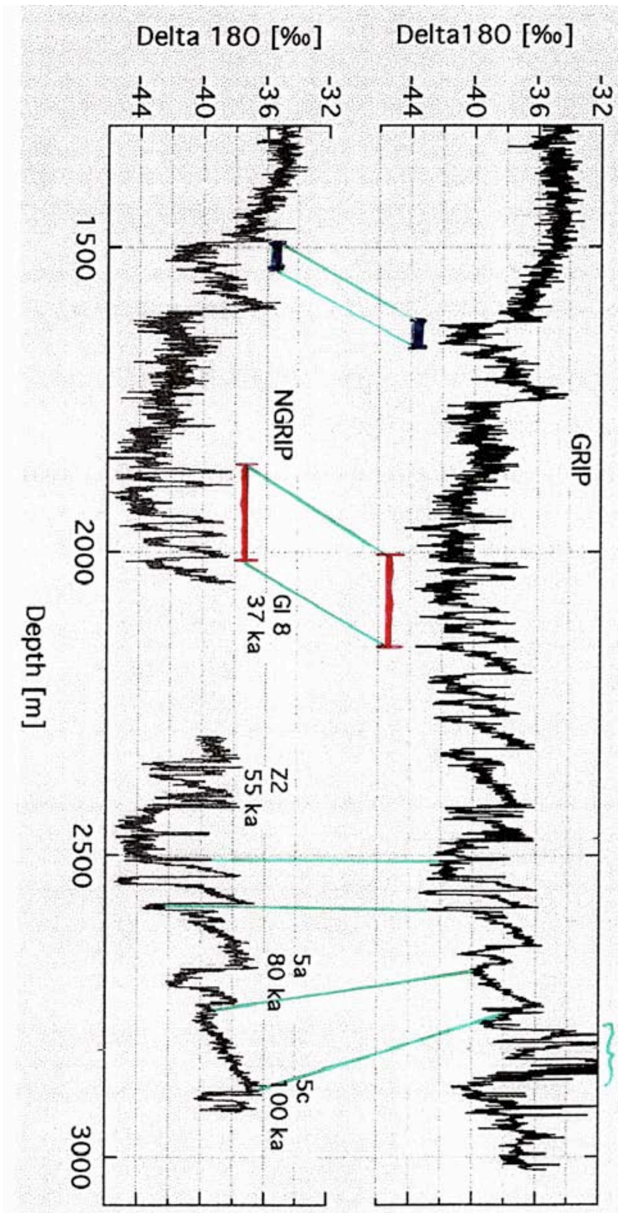




Everything seemed in favour of NGRIP: Low accumulation (0.19 cm ice/year) high ice thickness and flat bedrock!



Modelled NGRIP depths of isochrons and climatic periods prior to drilling, compared with depths at GRIP.



NGRIP GRIP

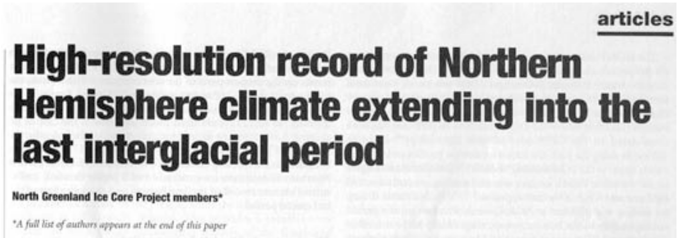
An unexpected surprise:

Below 2600 m depth, NGRIP layers turned out to lie <u>deeper</u> than the corresponding layers at GRIP.

<u>Explanation</u>: The ice sheet must be at melting point at the bed at NGRIP. removal of ice by melting (7 mm/yr) affects the thinning rate in the lowest 1 km of the ice sheet.

Bedrock temperature at Greenland deep drilling sites:

Camp Century	**- 13 °C**
Dye 3	**- 13 °C**
GRIP	**- 9 °C**
GISP2	**- 9 °C**
NGRIP	**- 2.7 °C**

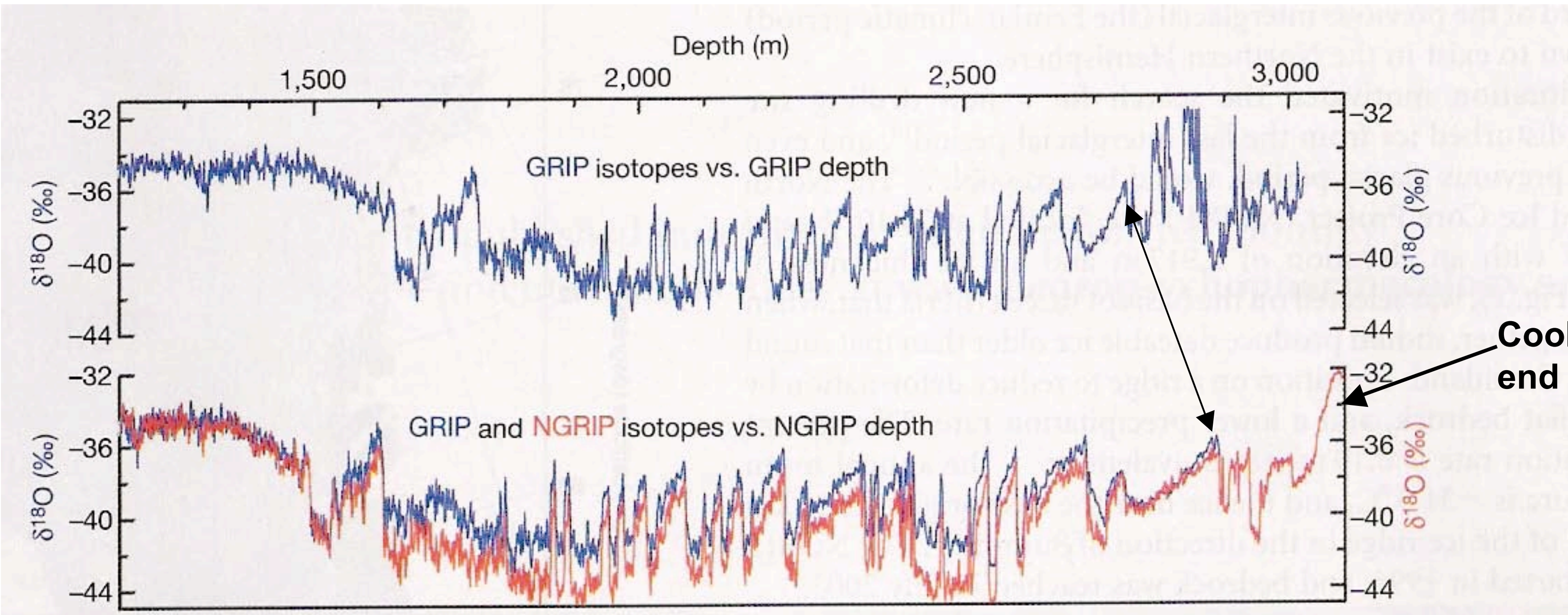

articles

High-resolution record of Northern Hemisphere climate extending into the last interglacial period

North Greenland Ice Core Project members*

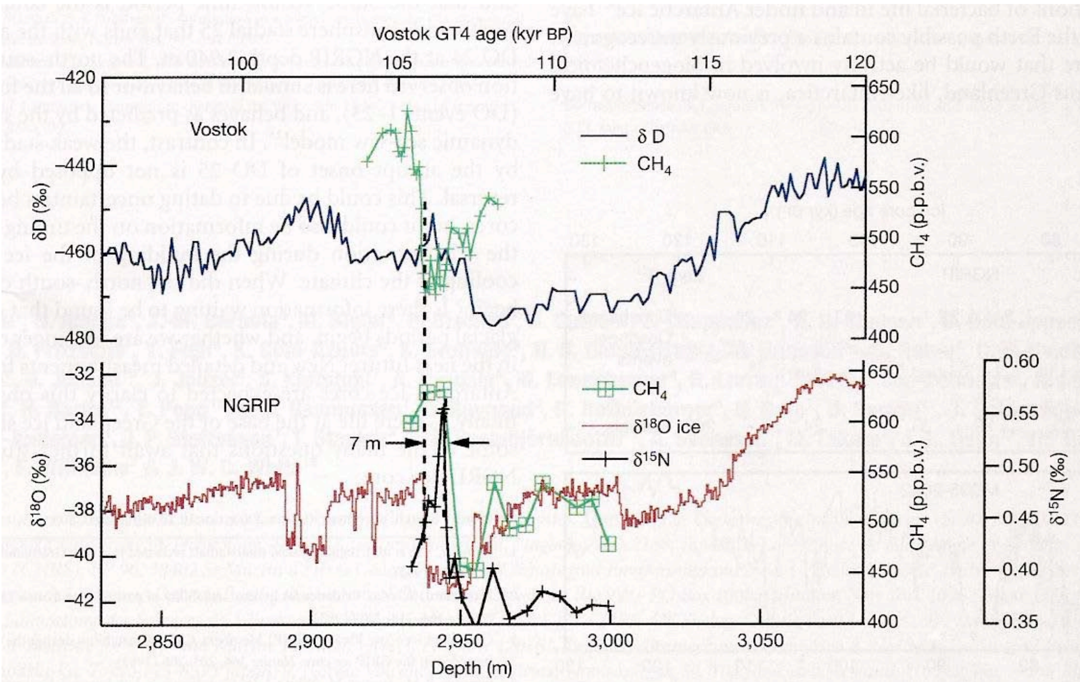
*A full list of authors appears at the end of this paper

The NGRIP core contains the termination of the Eemian interglacial. No sign of the instabilities observed in the GRIP core!

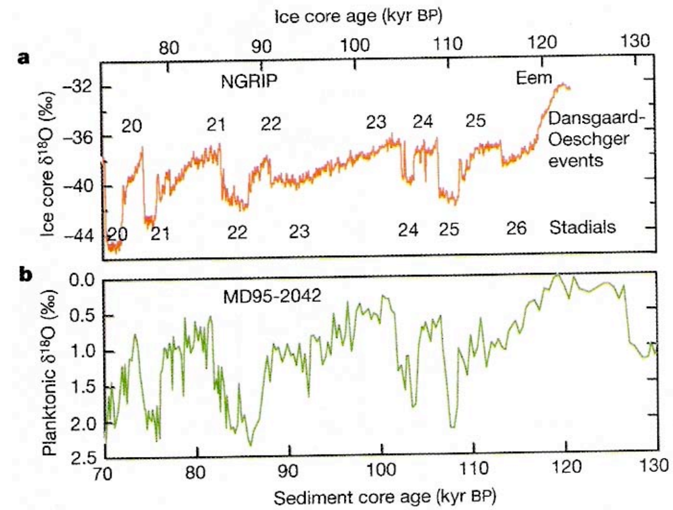


Cooling at end of Eem!

<u>NGRIP results (cont´d)</u>:



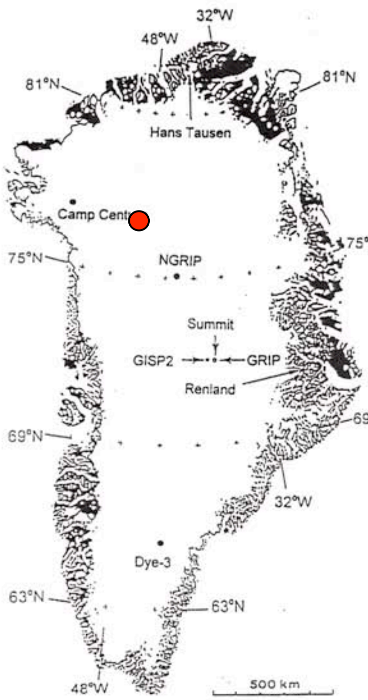
Termination 1: Comparison between NGRIP and Vostok, Antarctica.



70-123 ka BP: Comparison between NGRIP and $\delta^{18}O$ in planktonic foraminifera in a sediment core from the Iberian margin.

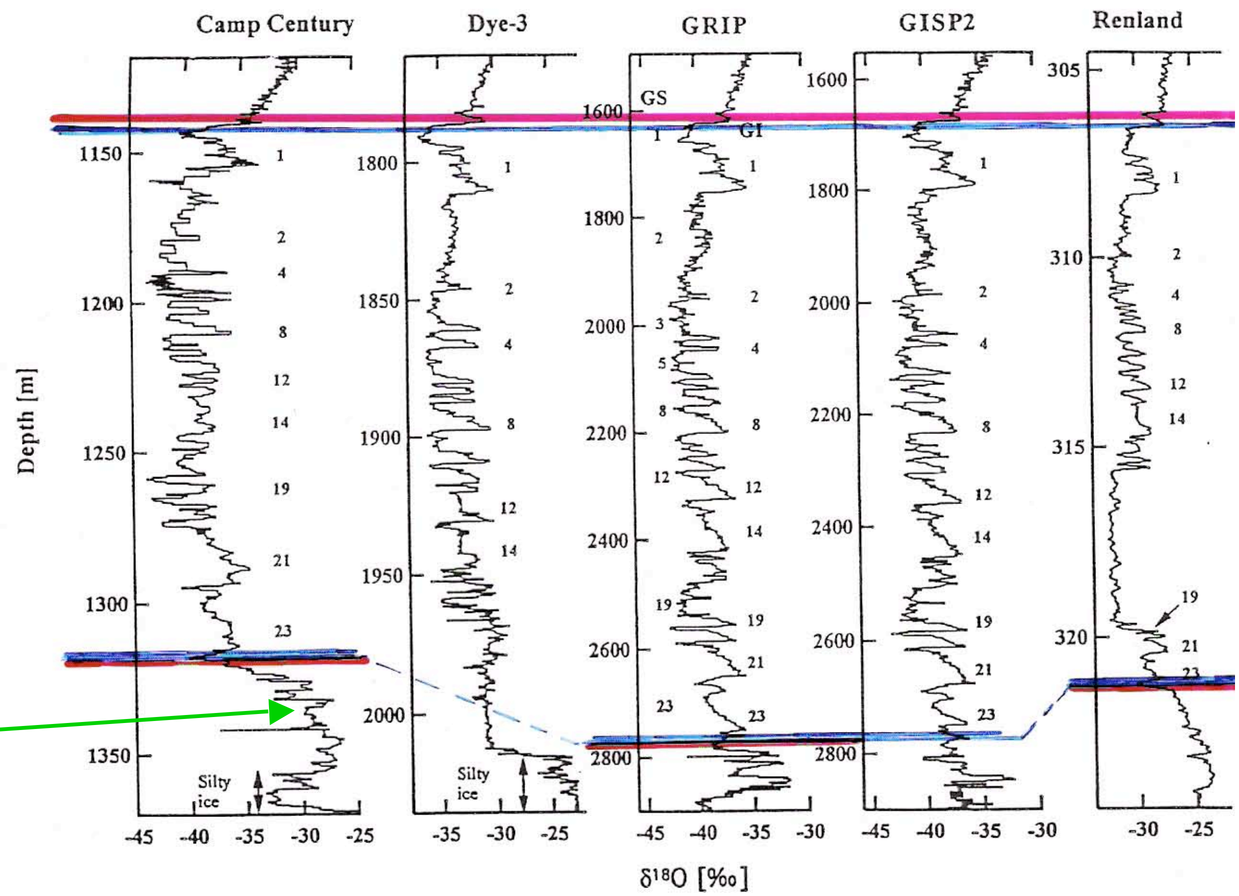
The NGRIP record prolonged the Greenland isotope climate curve from 90 ka to 123 ka, but did not penetrate the Eemian interglacial.

One more Greenland deep drilling will be needed!



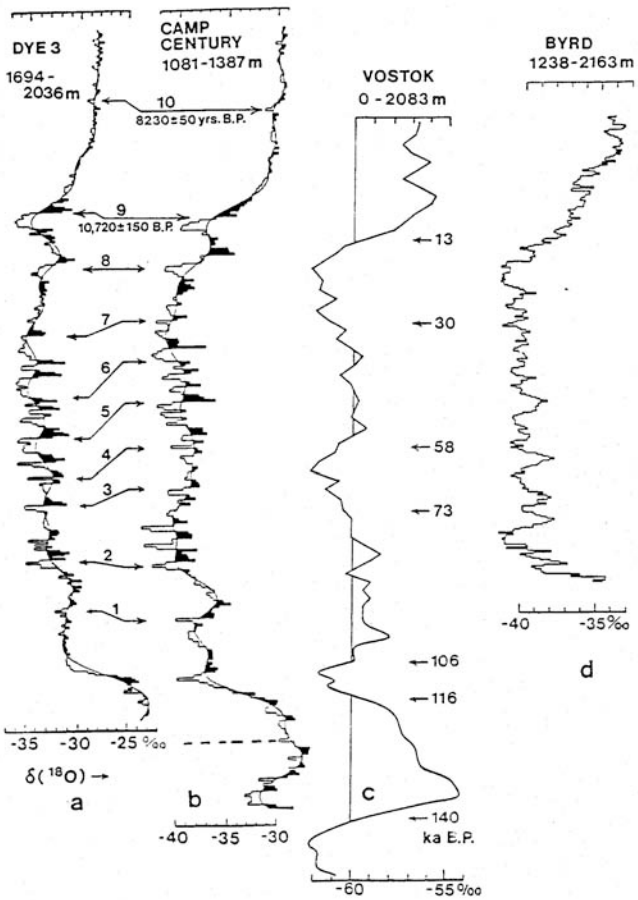
At present, the most likely site for a new deep drilling attempting to recover the entire Eemian period is between NGRIP and Camp Century!

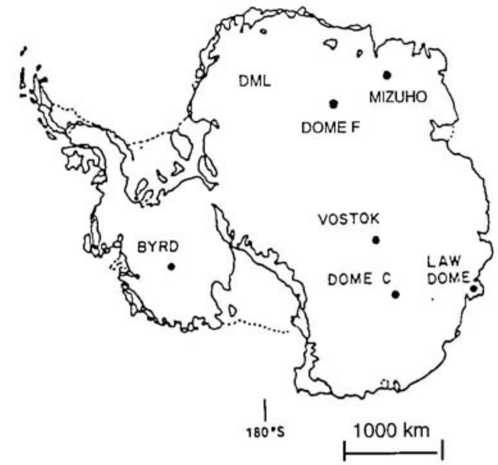
That core may yield the oldest ice available in Greenland (at least 150 ka BP).

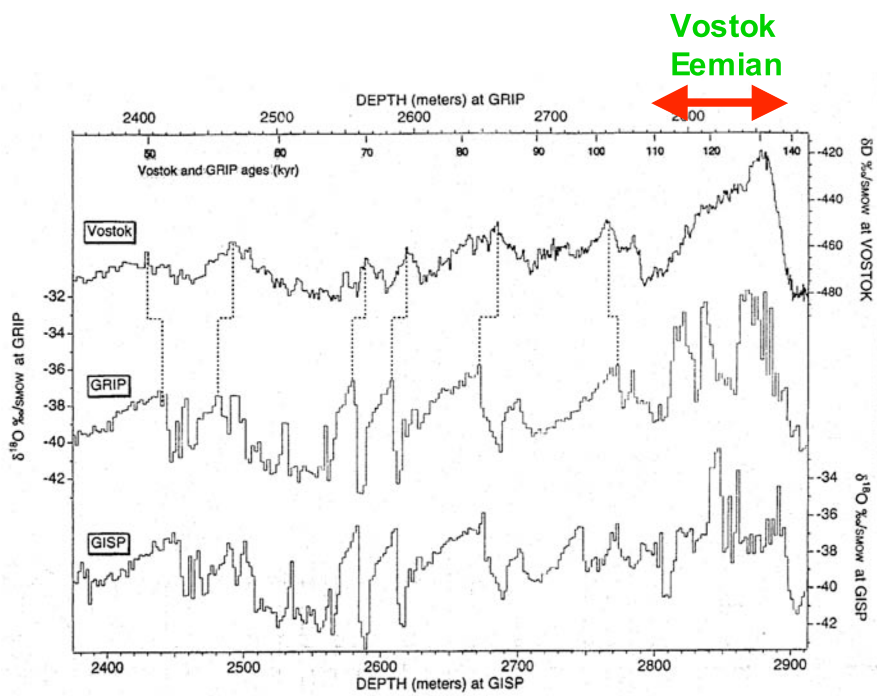


Eemian ice in the Camp Century Core?

Antarctic ice core records of climate history:





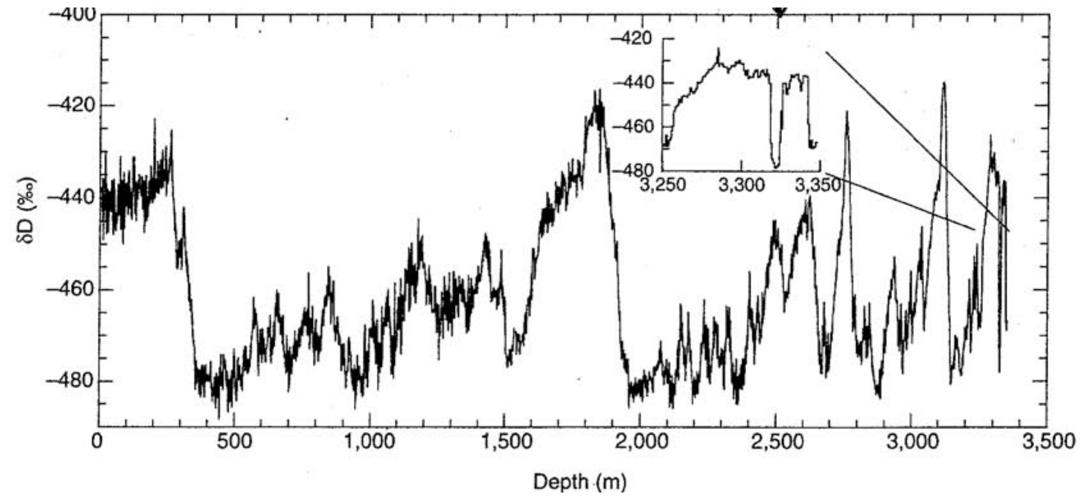


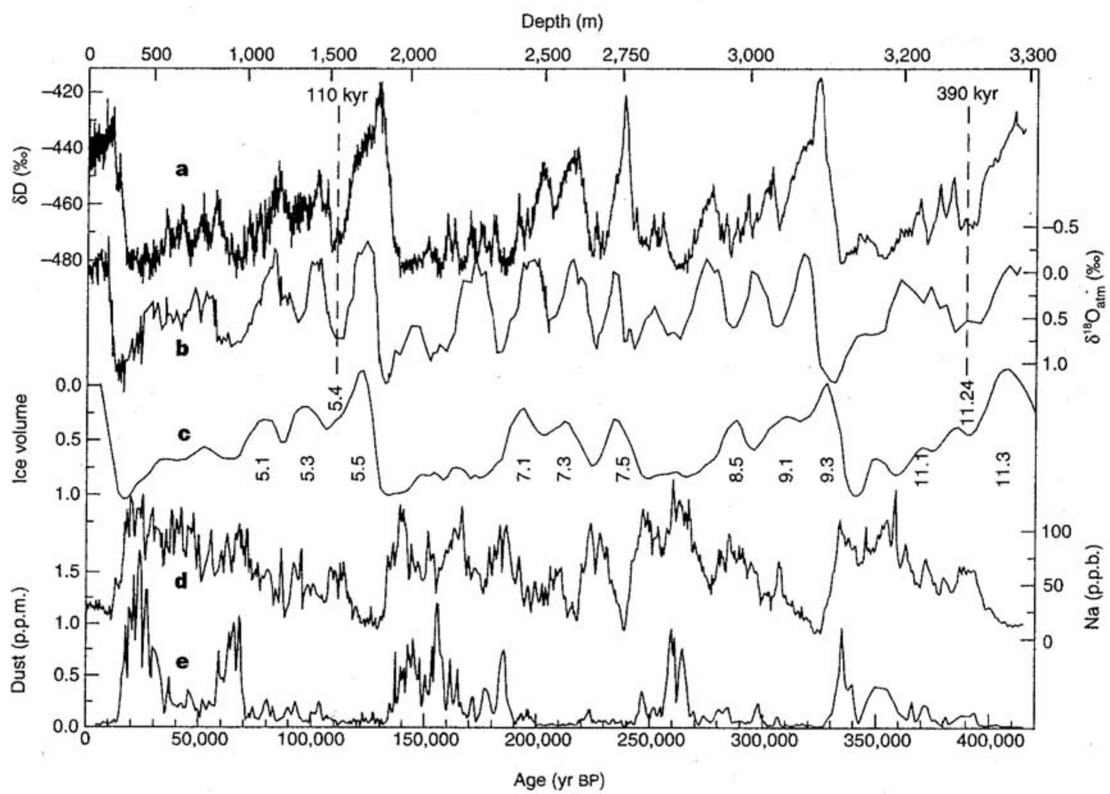
The Byrd and Vostok records show some variability during the glacial period, but not the rapid changes seen in the Greenland ice cores!

No sign of the unstable “GRIP Eemian” in the Vostok core!

The Vostok deuterium record (0-3350 m):

420,000 years of climate history.
Four glacial-interglacial cycles!



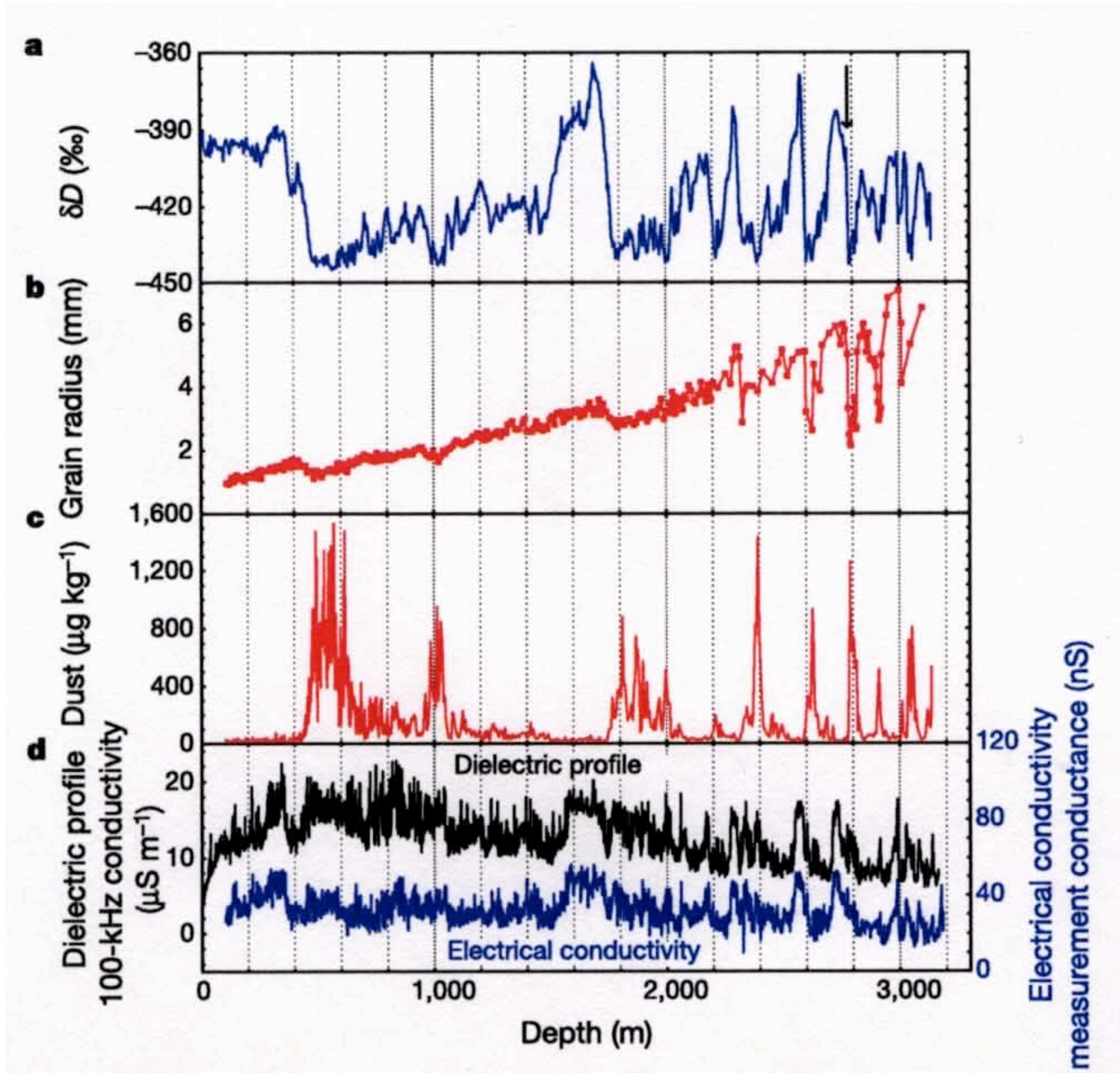


Vostok:

- **Deuterium**
- **Ice volume curve**
- **Sodium concentration**
- **Dust concentration**

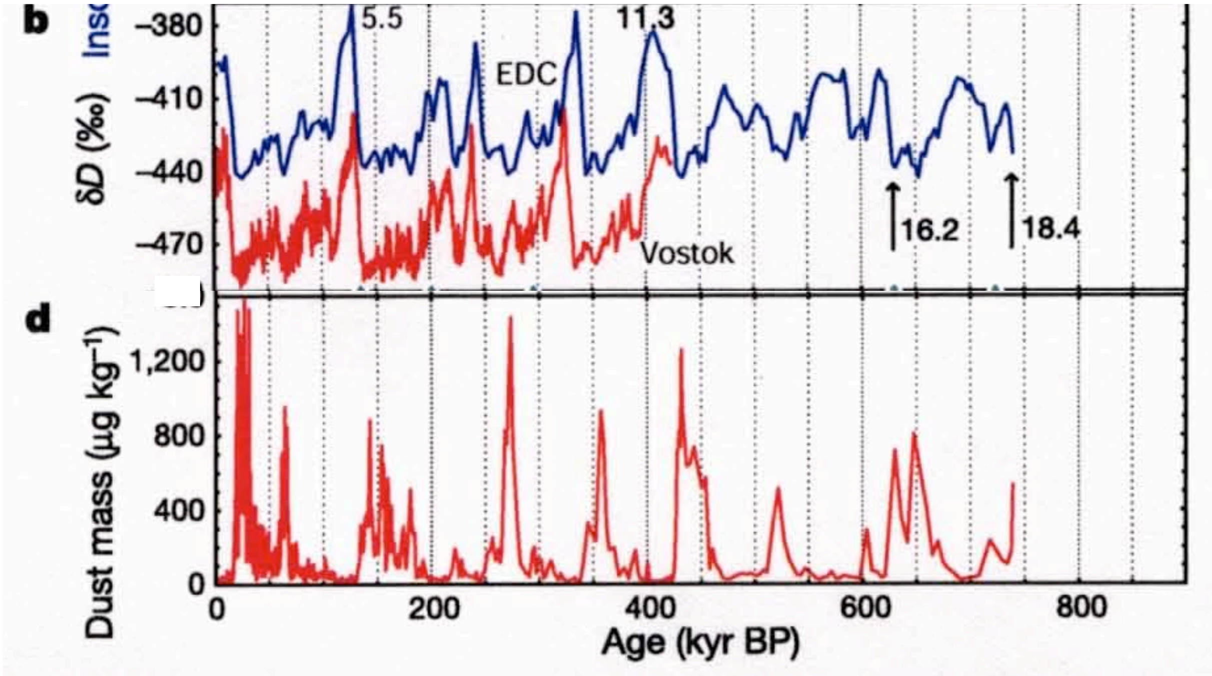
The new Dome C record:

Eight glacial-interglacial cycles (0-3100 m)!



Dome C:

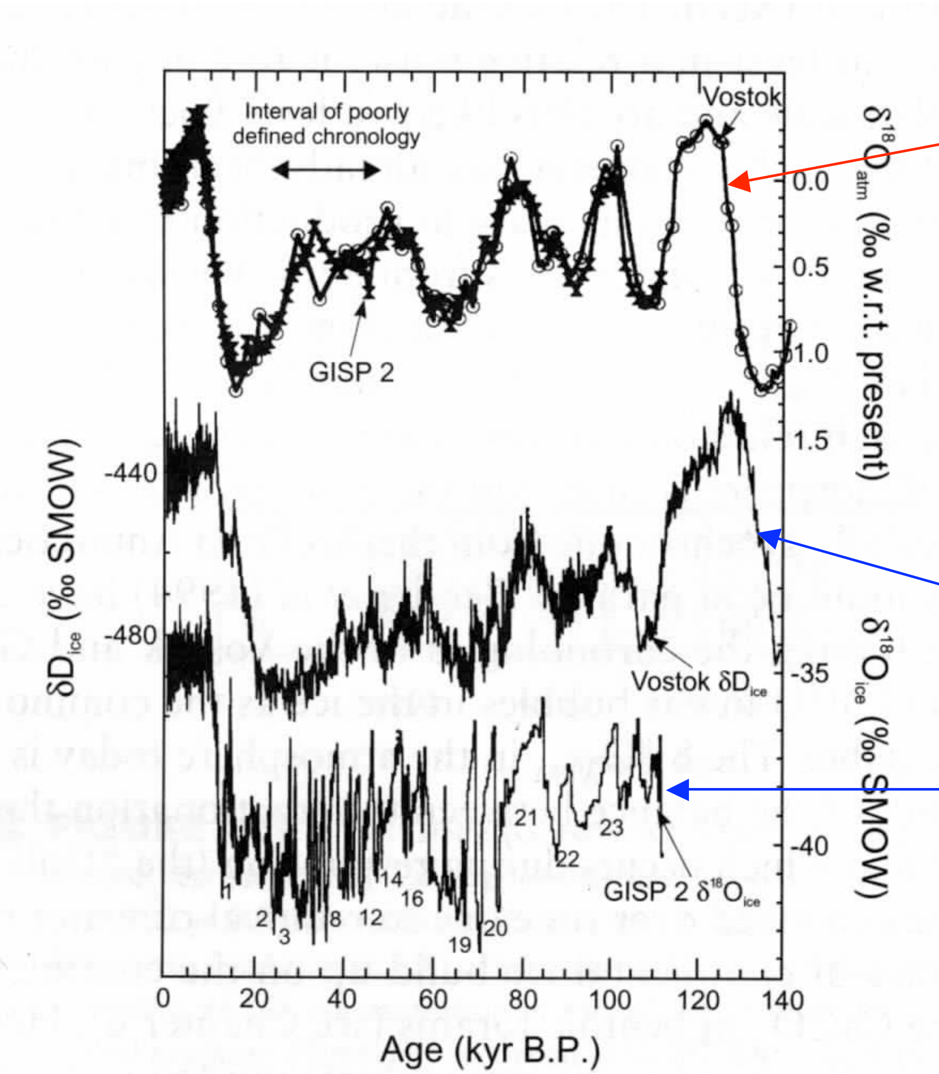
Oldest ice on Earth!



A 740,000 year record of atmospheric temperature and composition from the Dome C core published in 2004.

More to come!

Synchronizing the timescales of the Greenland and Antarctic records



$\delta^{18}O_{ATM}$ **measured on *old air in bubbles.***

Atmospheric mixing time short (1-2 years), hence this parameter varies in parallel in both hemispheres. This can be used to correlate ice core records.

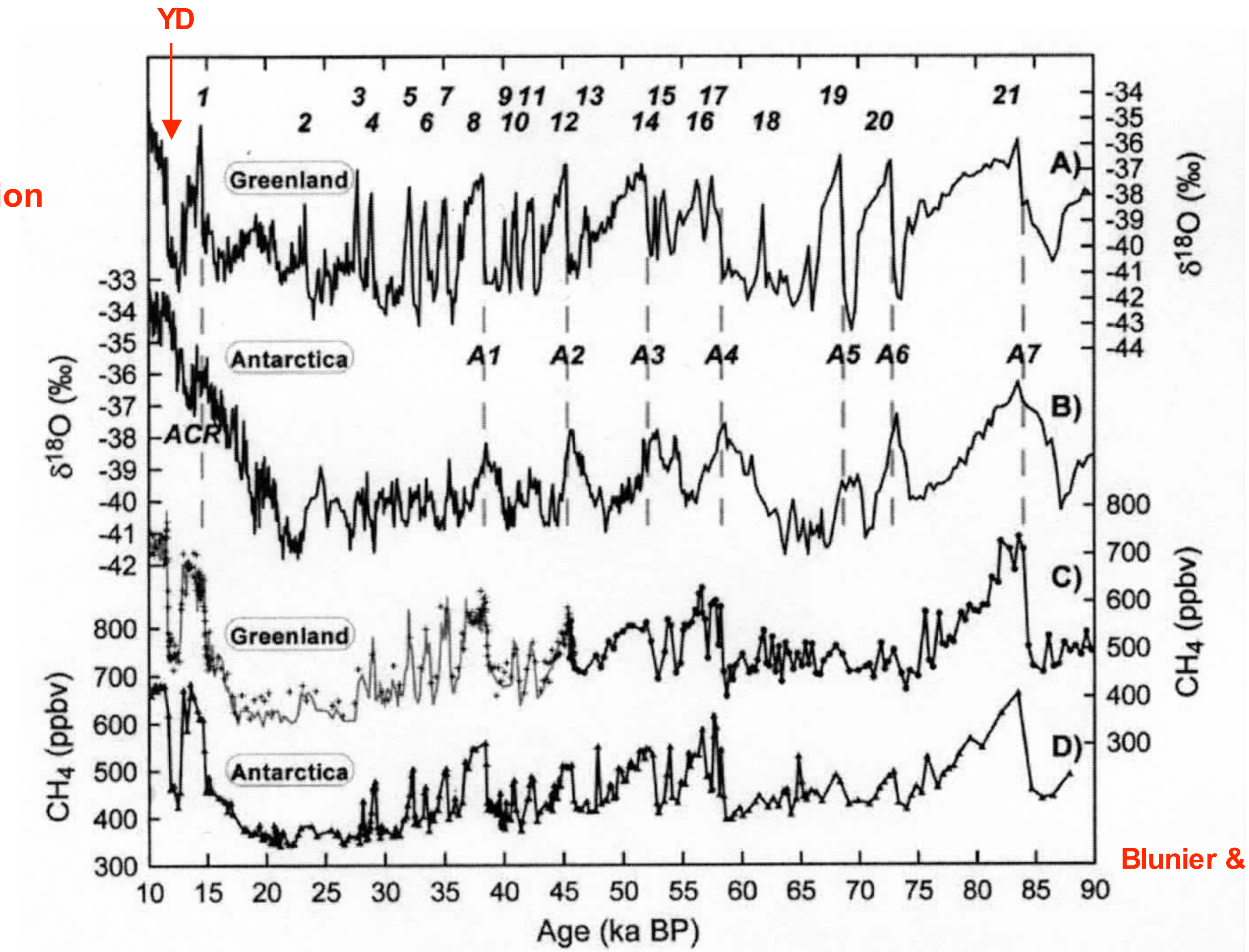
Vostok δD_{ice}

GISP2 $\delta^{18}O_{ice}$

Atmospheric methane used to correlate ice core records:

Data from:

GRIP, GISP2
and Byrd Station



Blunier & Brook, 2001

1. Greenland abrupt warmings (D-O events) occur at the end of gradual Antarctic warmings.
2. During the glacial termination, Antarctic warming preceded Greenland warming by a few thousand yr.
3. The *Antarctic Cold Reversal (ACR)* is <u>not</u> synchronous with the *Younger Dryas (YD)* in Greenland.