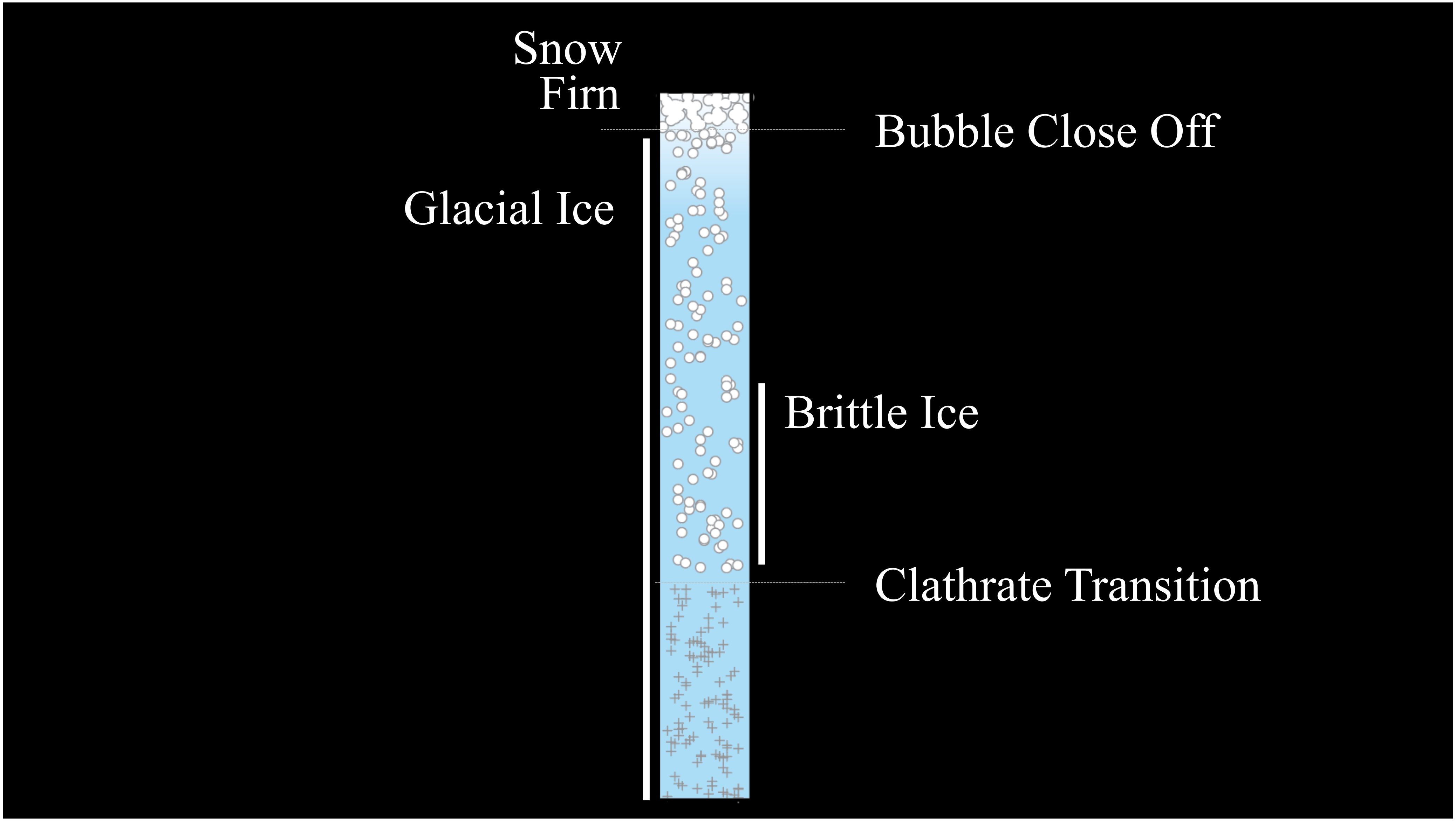
Paleoclimate and Ice Ages I: Ice core science and climate reconstruction

ESS431: Principles of Glaciology
ESS505: The Cryosphere

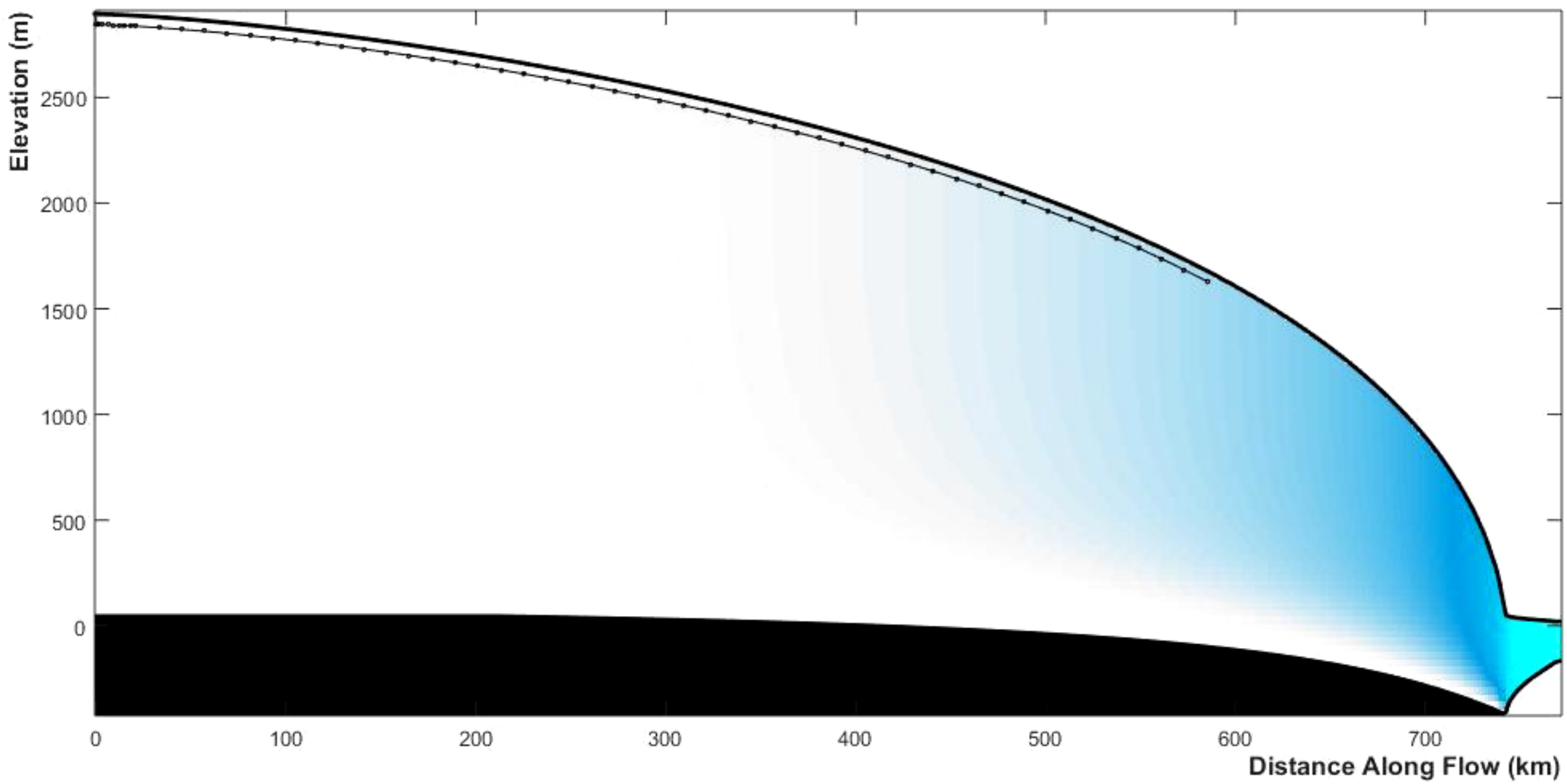
Friday, 11/16 – Knut Christianson

Today's Objectives:

- What are ice cores? How are they collected, and how are their sites chosen?
- What types of information can ice cores provide about past climate?
- What are the challenges of interpreting the climate proxies?


Snow
Firn
Bubble Close Off
Glacial Ice
Brittle Ice
Clathrate Transition

[redacted]



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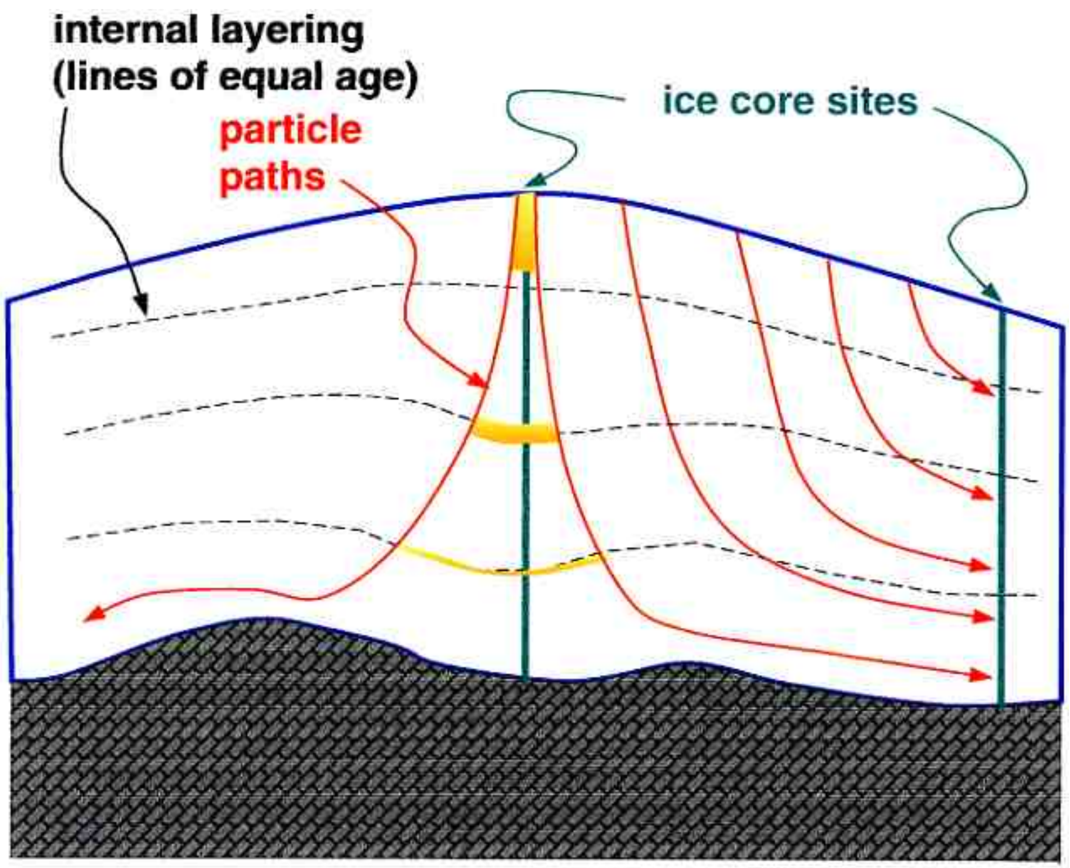
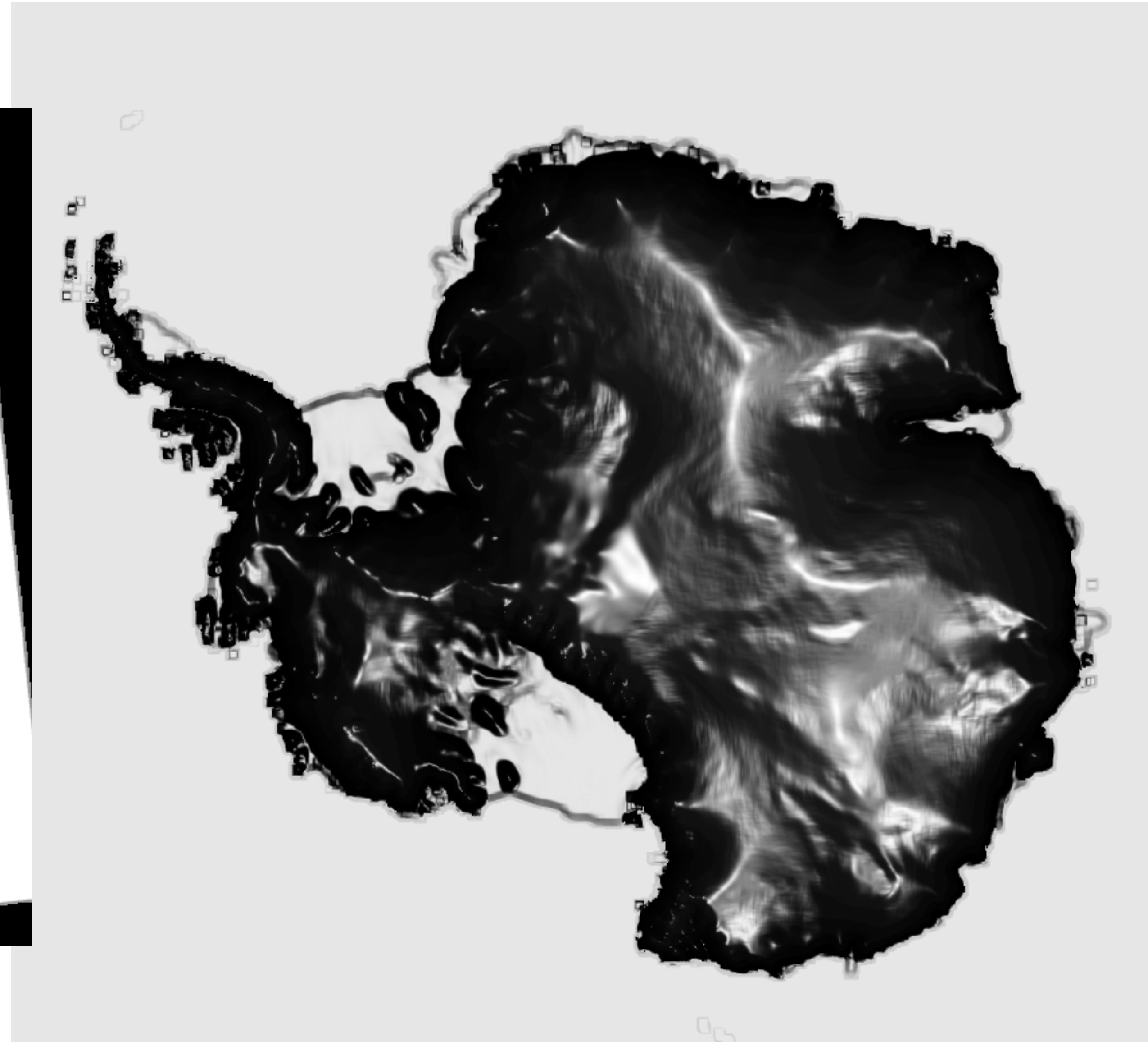
Choosing an Ice-Core Site



Near the summit is good.

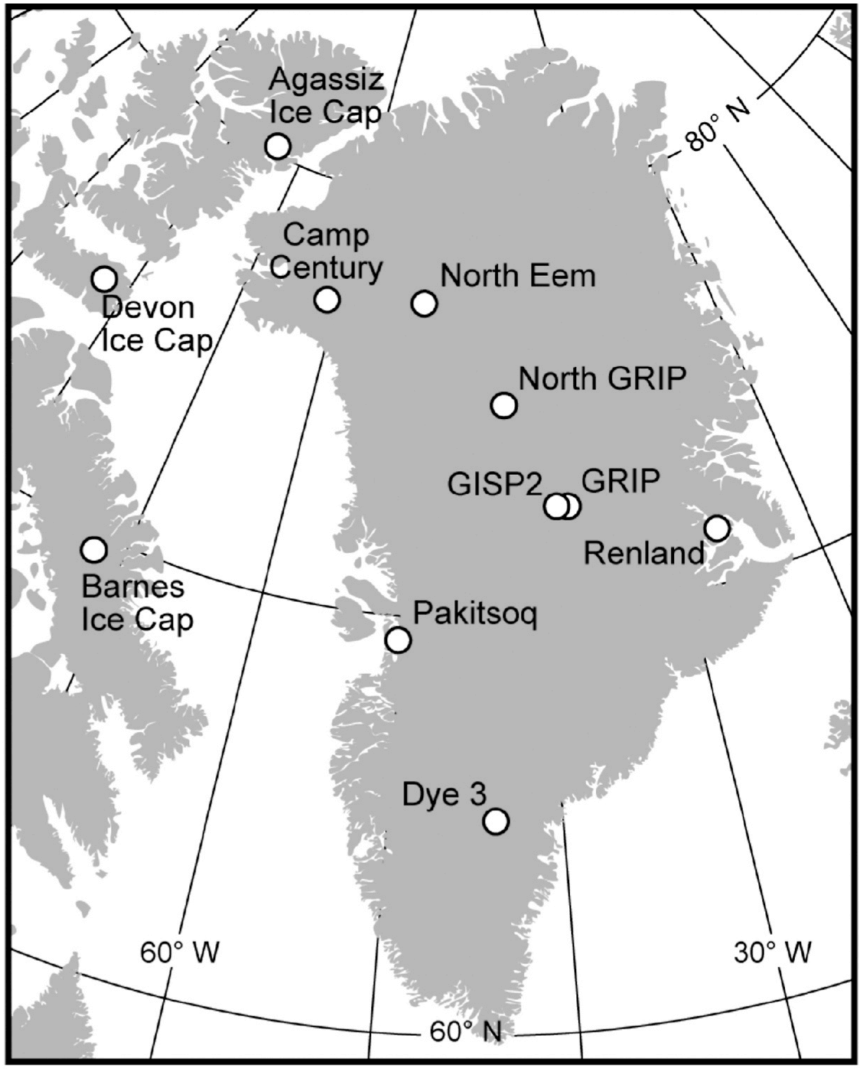
- Climate signal relates to the same place for ice of all ages.

Layers get thinner over time due to flow.



Collecting an Ice Core

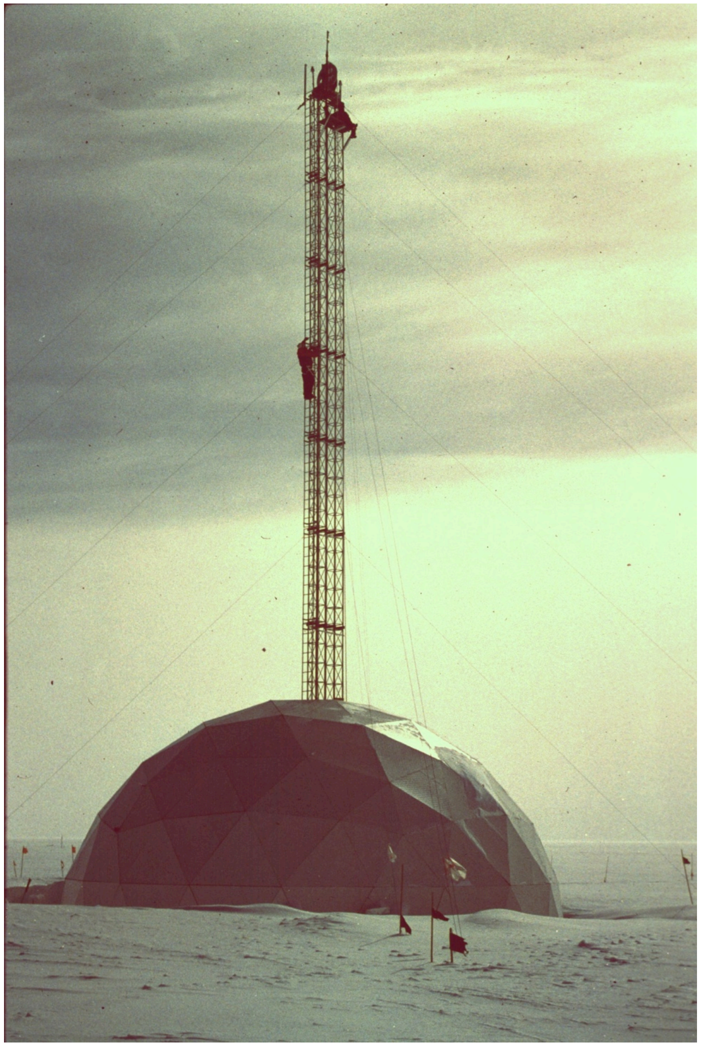
Arctic Ice-core Sites

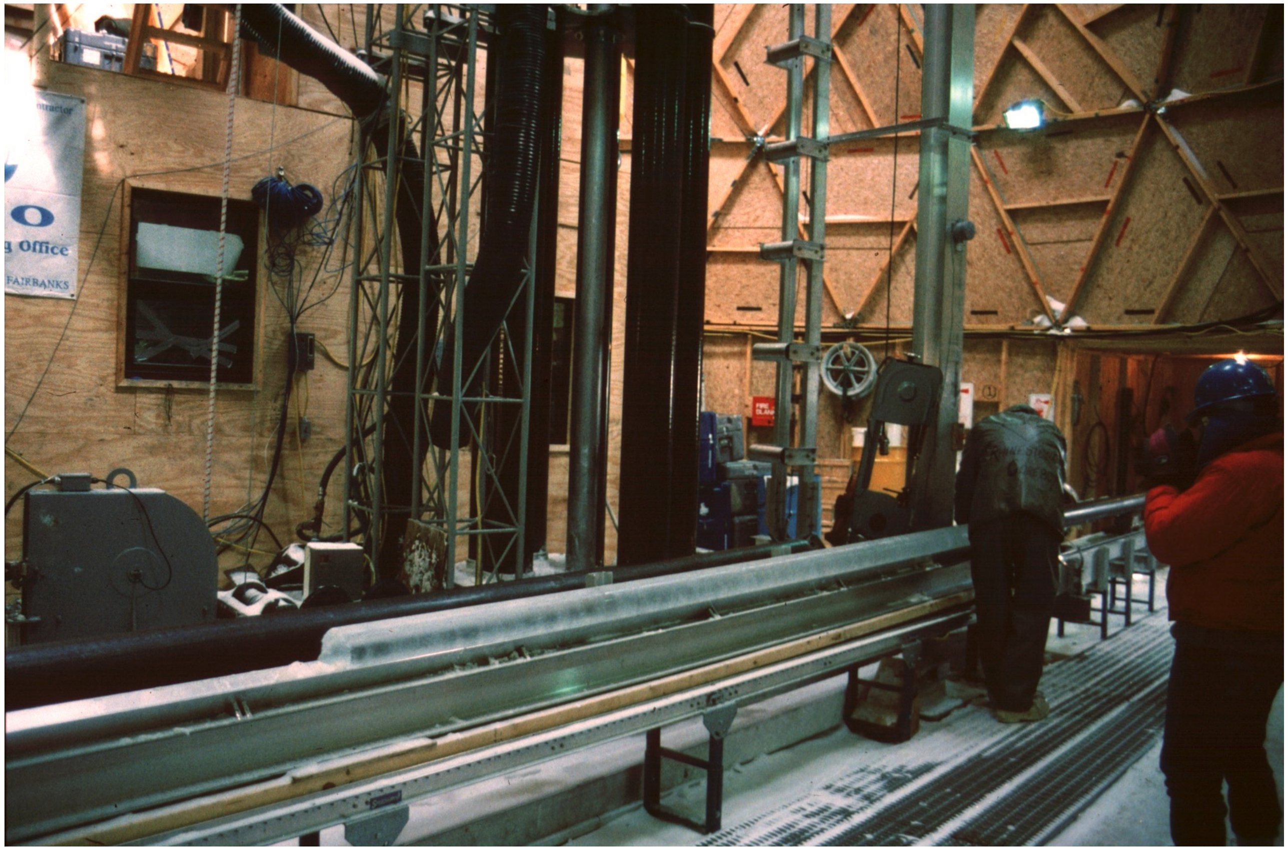


Cuffey and Paterson 2010.
***The Physics of Glaciers*.**
Fig. 15.1

Ice Core at Greenland Summit

- Greenland Ice Sheet Project 2 (GISP2)
- The drill inside this dome reached bedrock 3 km (10,000 ft) below the ice-sheet surface.
- The science team recovered a record of past climate going back more than 100,000 years.





Inside the GISP2 Drill Dome

- The drill is lowered into the hole on a long cable.
- It brings up a 6-meter-long piece of ice core on each run.

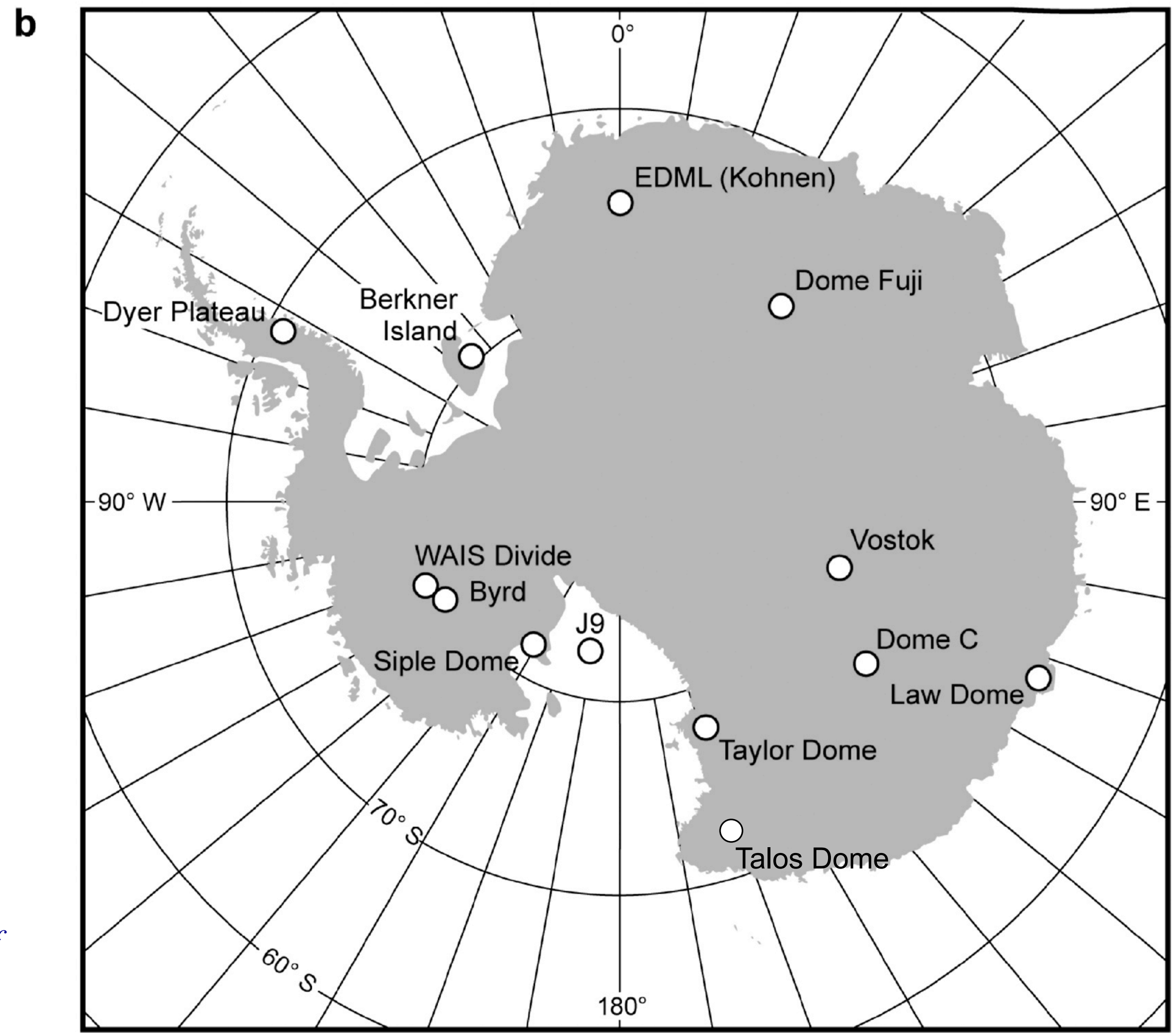
Science in a Labyrinth

- Ice cores are analyzed in Labs connected by tunnels under the snow.

A Natural Freezer

- The cores are stored in a cave dug in the snow, where the temperature is always –30^{o} Celsius.
- ooops … the ceiling is sagging a little bit after 3 years …

EGRIP

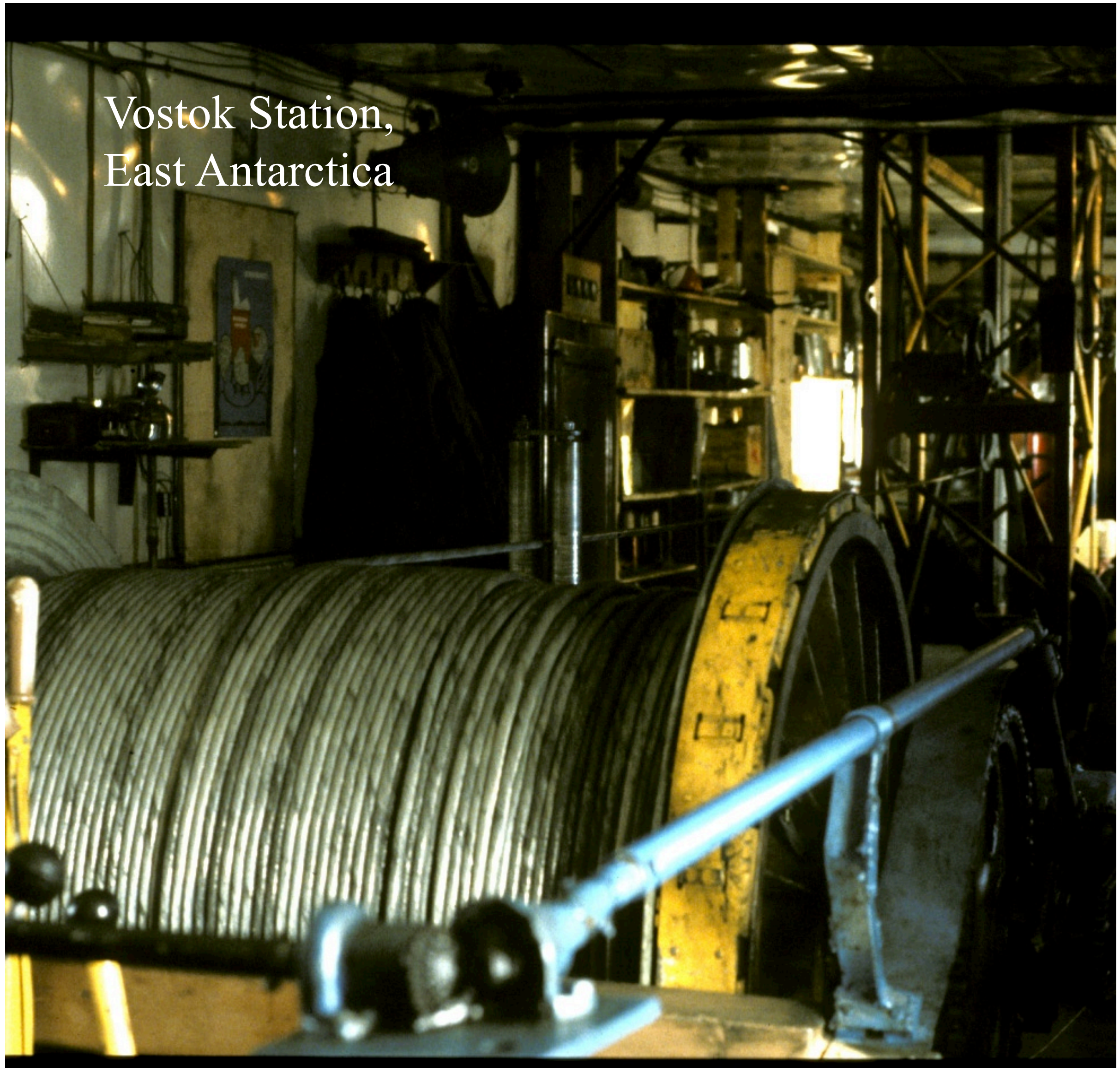


Base map:
Cuffey and Paterson 2010. *The Physics of Glaciers*. Fig. 15.1

Where might this be?

Vostok Station,
East Antarctica

S.G.Warren photo



S.G.Warren

S.G.Warren


WAIS Divide drilling arch Jan 2006
WAIS http://www.waisdivide.unh.edu/

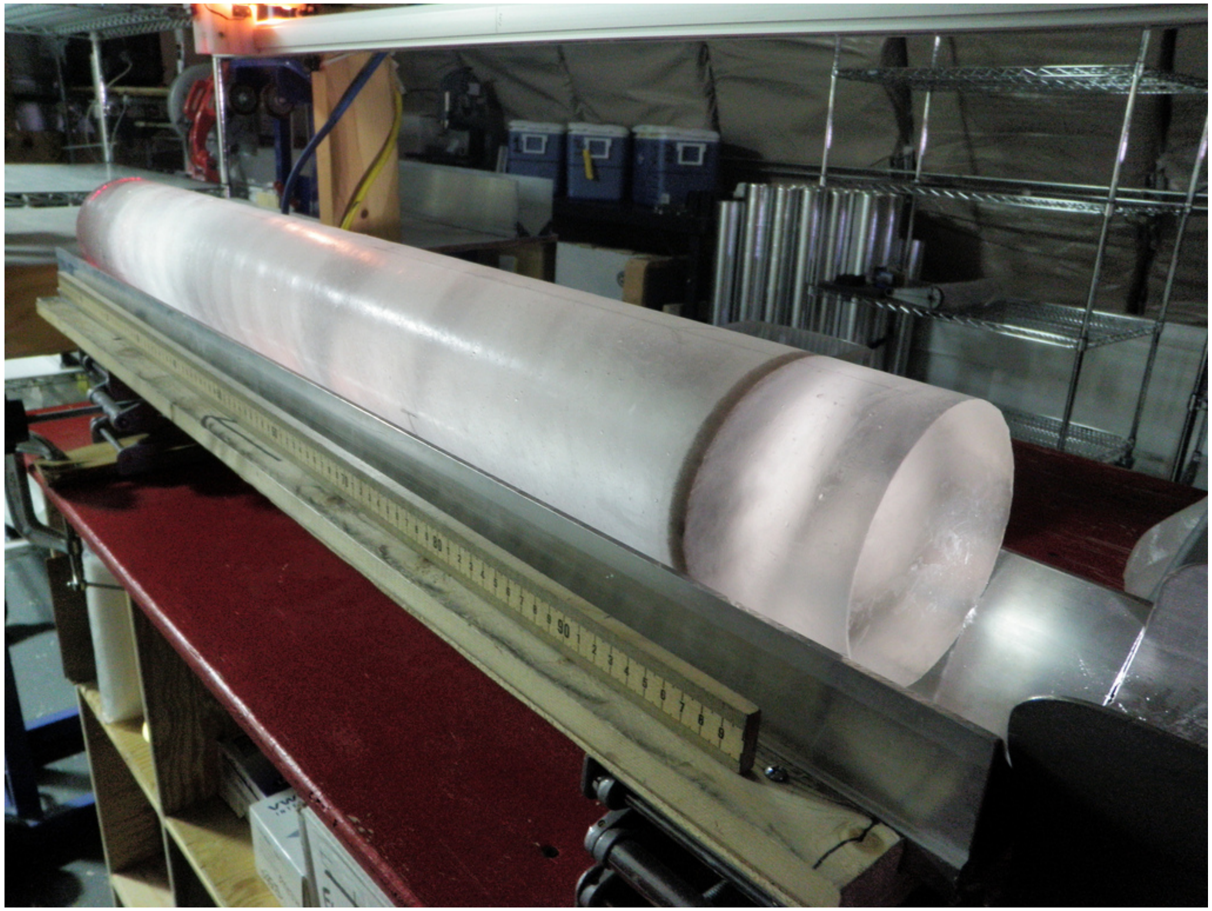
WAIS Divide
drilling arch
December 2014

WAIS Tilting-Tower drill

WAIS http://www.waisdivide.unh.edu/


Logan
HARD-CORE FONDLERS
Tommy
Cox
EDW

Ash layer in WAIS core



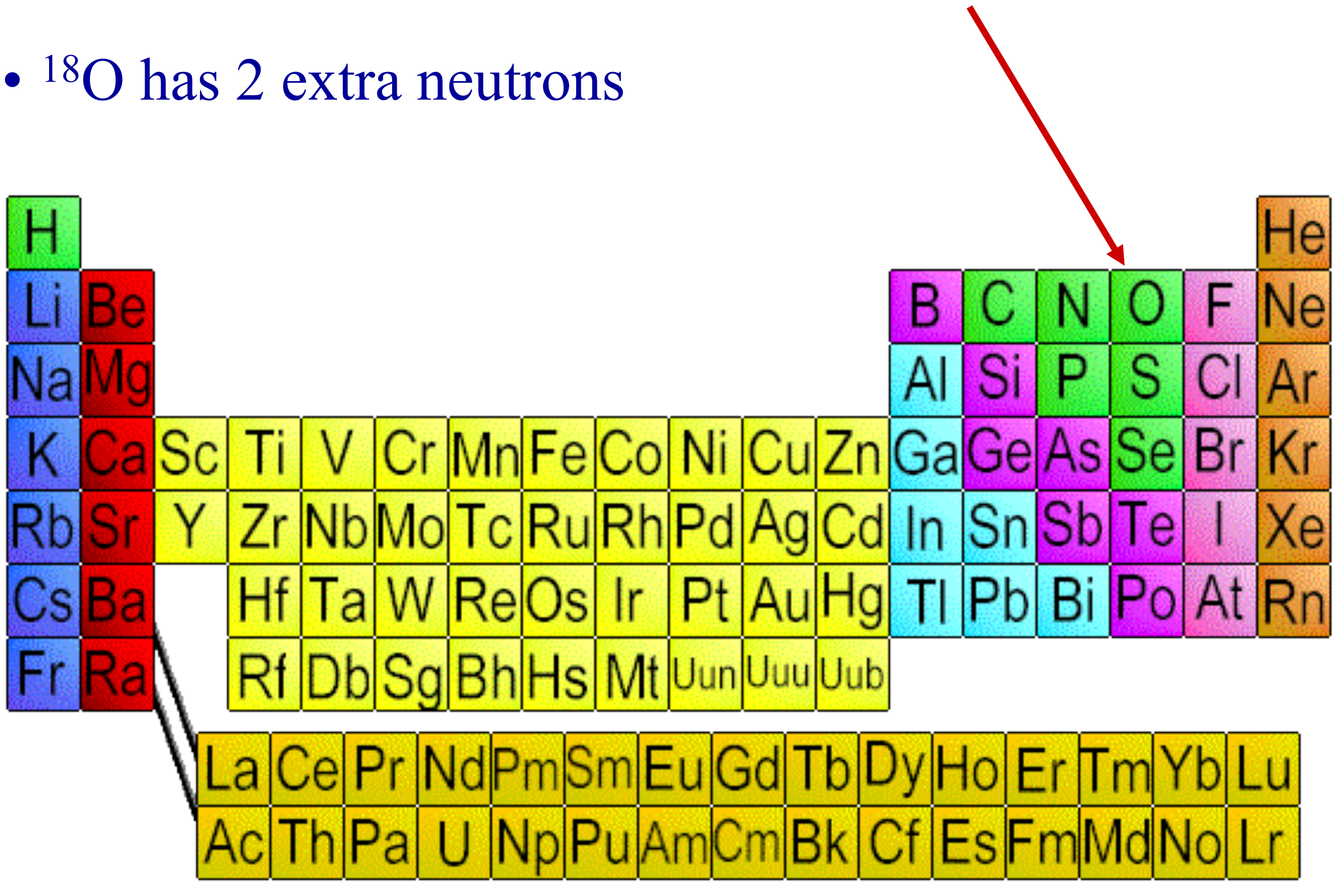
WAIS http://www.waisdivide.unh.edu/

Measurements from the Core and Borehole

Core Measurements	Borehole Logging

^{18}O – What is it?

- Normal Oxygen is ^{16}O, with 8 neutrons.
- ^{18}O has 2 extra neutrons



Oxygen isotopes in ice cores

H_2O is composed of both $H_2{}^{16}O$ and $H_2{}^{18}O$

$$\delta^{18}O_{ice} = \frac{\left(\dfrac{H_2{}^{18}O}{H_2{}^{16}O}\right)_{ice} - \left(\dfrac{H_2{}^{18}O}{H_2{}^{16}O}\right)_{SMOW}}{\left(\dfrac{H_2{}^{18}O}{H_2{}^{16}O}\right)_{SMOW}} * 1000 \text{ ‰}$$

Deuterium isotopes in ice cores

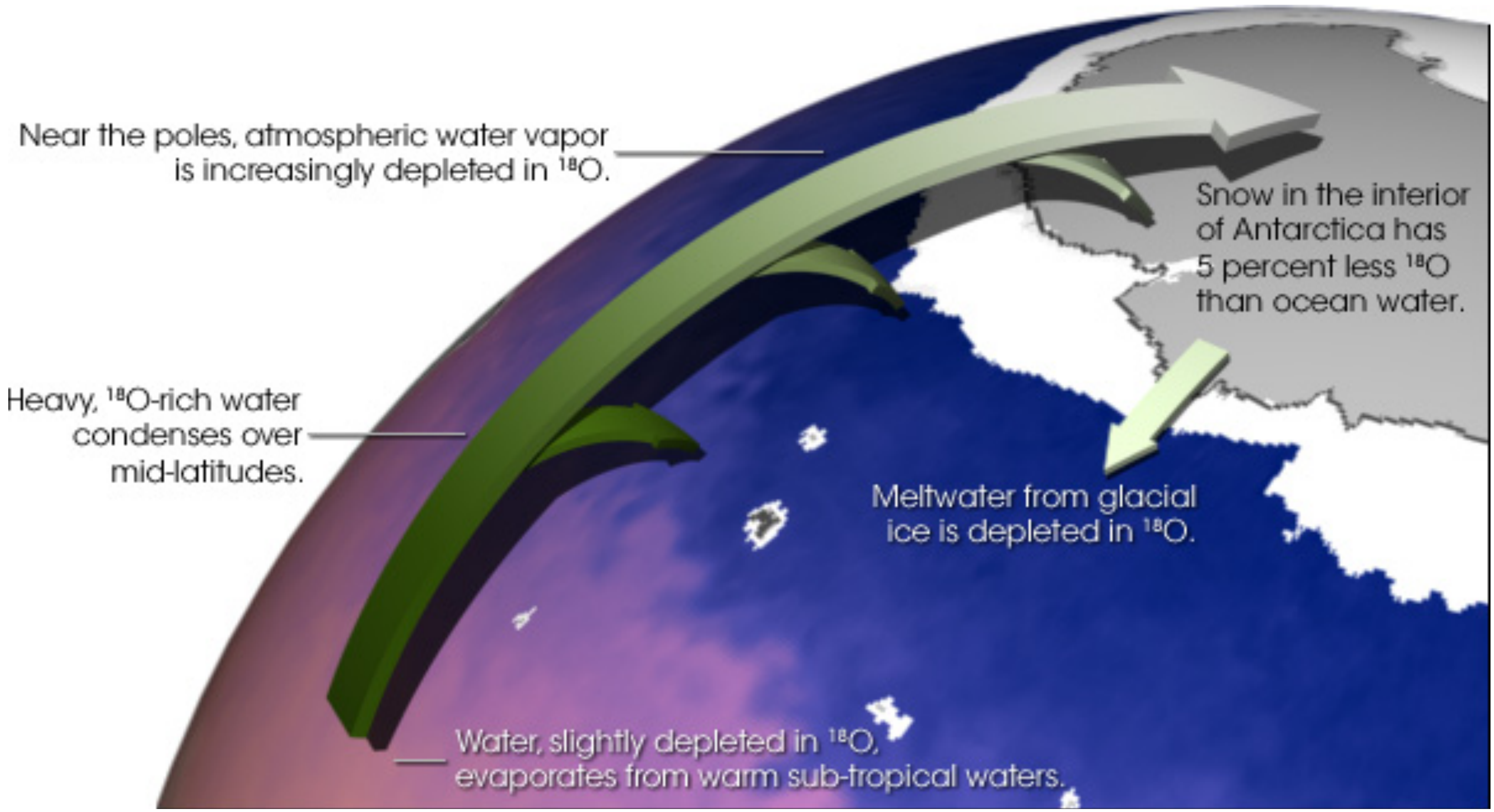
H_2O also contains heavy hydrogen (^{2}H), also known as deuterium (D).

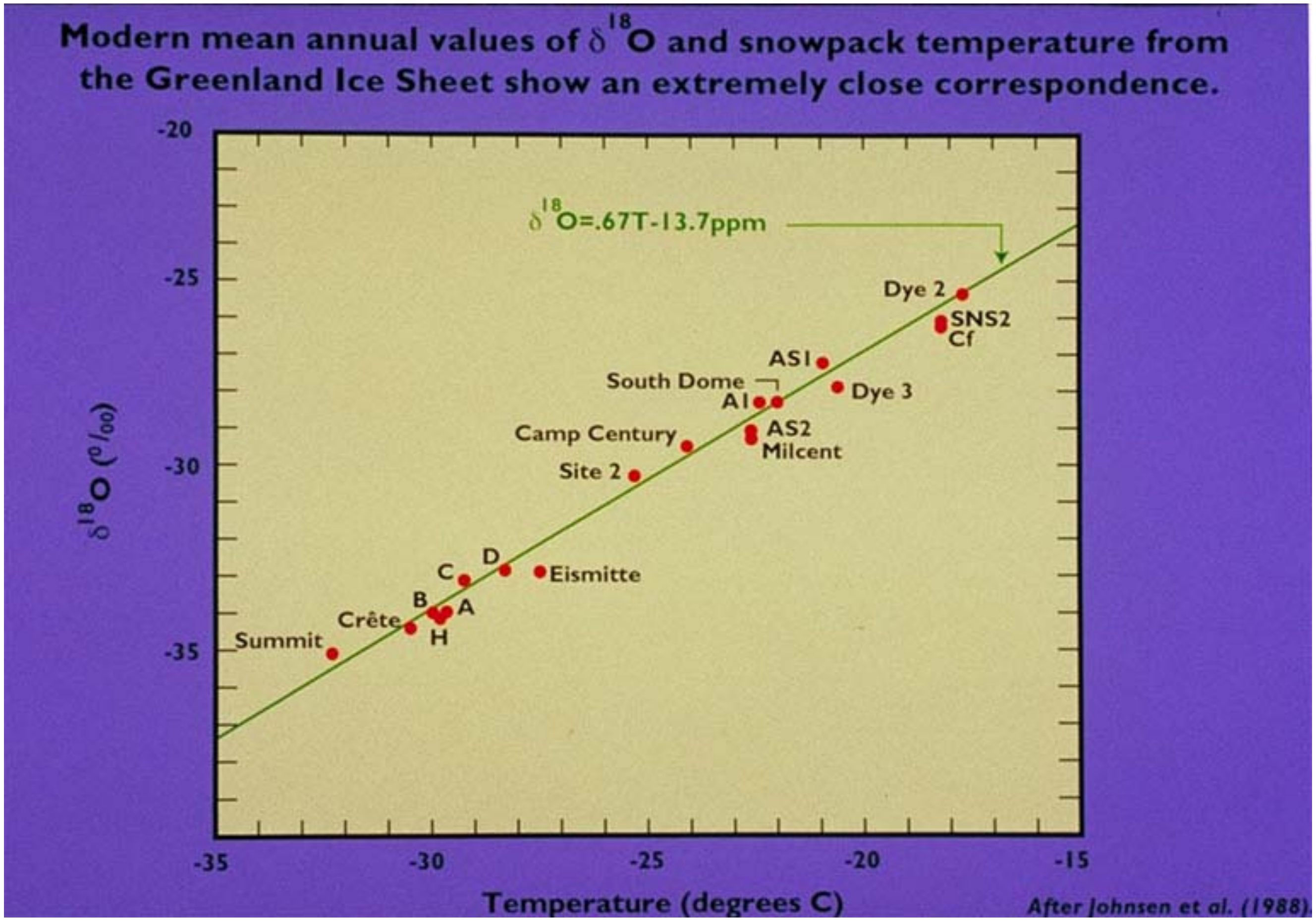
$$\delta D_{ice} = \frac{\left(\frac{D}{H}\right)_{ice} - \left(\frac{D}{H}\right)_{SMOW}}{\left(\frac{D}{H}\right)_{SMOW}} * 1000 \text{ ‰}$$

What is fractionation?

- ^{18}O and ^{16}O act the same way in chemical reactions (they are both oxygen molecules)
- They differ in subtle ways during phase changes.
- ^{18}O has a slightly greater tendency to be in the lower-energy state.
- During evaporation, the vapor is slightly depleted in ^{18}O relative to the water.
- During condensation, the condensing water is slightly enriched in ^{18}O relative to the vapor.

$\delta^{18}O$ as a Temperature Proxy



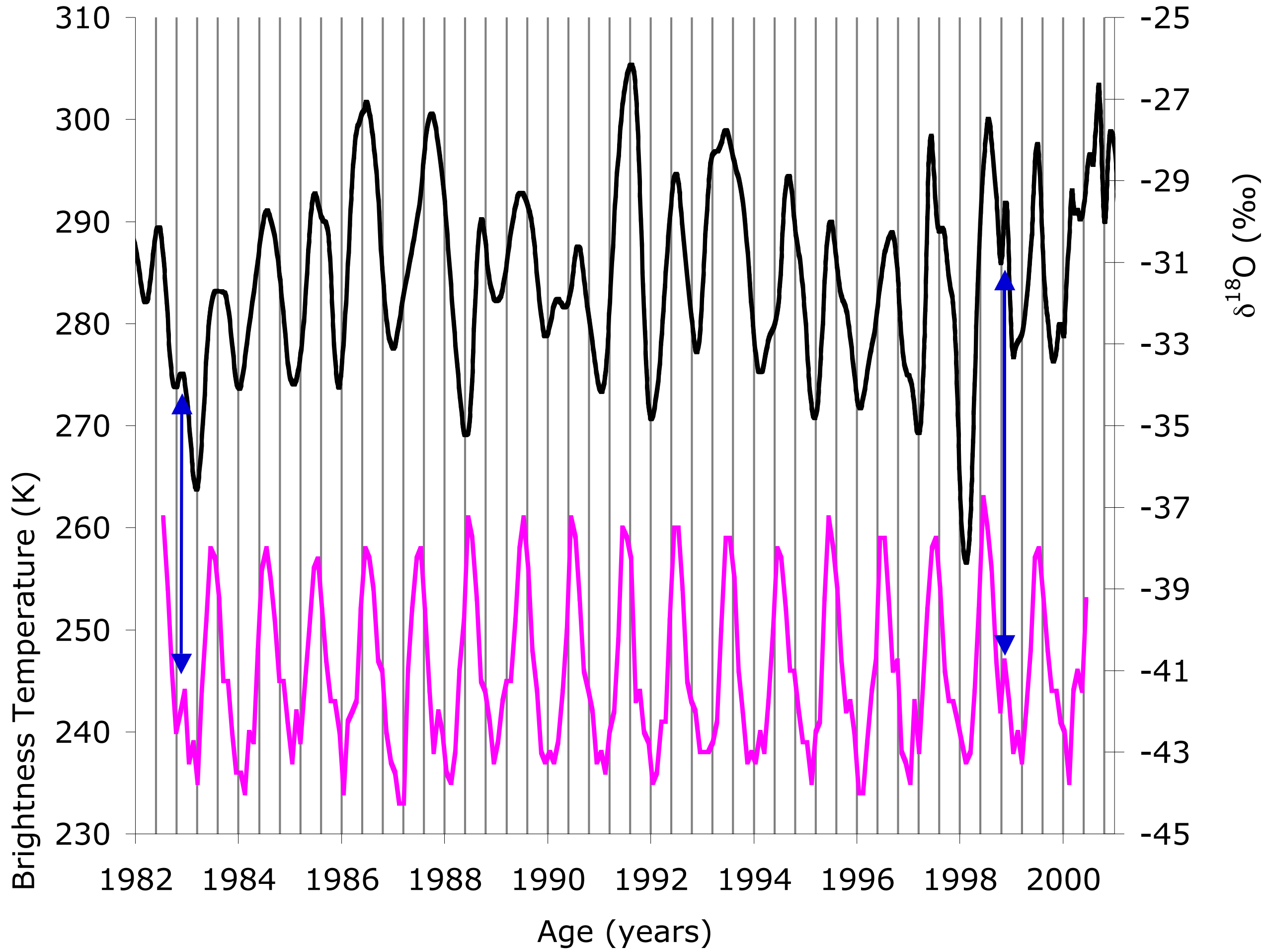

Modern mean annual values of δ18O and snowpack temperature from the Greenland Ice Sheet show an extremely close correspondence.
δ18O=.67T-13.7ppm
Dye 2
SNS2
Cf
AS1
South Dome
A1
Dye 3
AS2
Milcent
Camp Century
Site 2
D
C
Eismitte
B
A
Crête
H
Summit
-20
-25
-30
-35
δ18O (‰)
-35
-30
-25
-20
-15
Temperature (degrees C)
After Johnsen et al. (1988).

Rayleigh Distillation

Start with a saturated air mass above the ocean surface

Assume that:

1) As the air travels poleward, it cools adiabatically.
2) The amount of water vapor remaining in the air at any point is determined by the saturation vapor pressure of water.
3) All isotopic exchange occurs in equilibrium.
4) Once water condenses, it does not re-evaporate.
5) **No new water is added to the air mass.**



310
300
290
280
270
260
250
240
230
Brightness Temperature (K)
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Age (years)
-25
-27
-29
-31
-33
-35
-37
-39
-41
-43
-45
δ18O (‰)

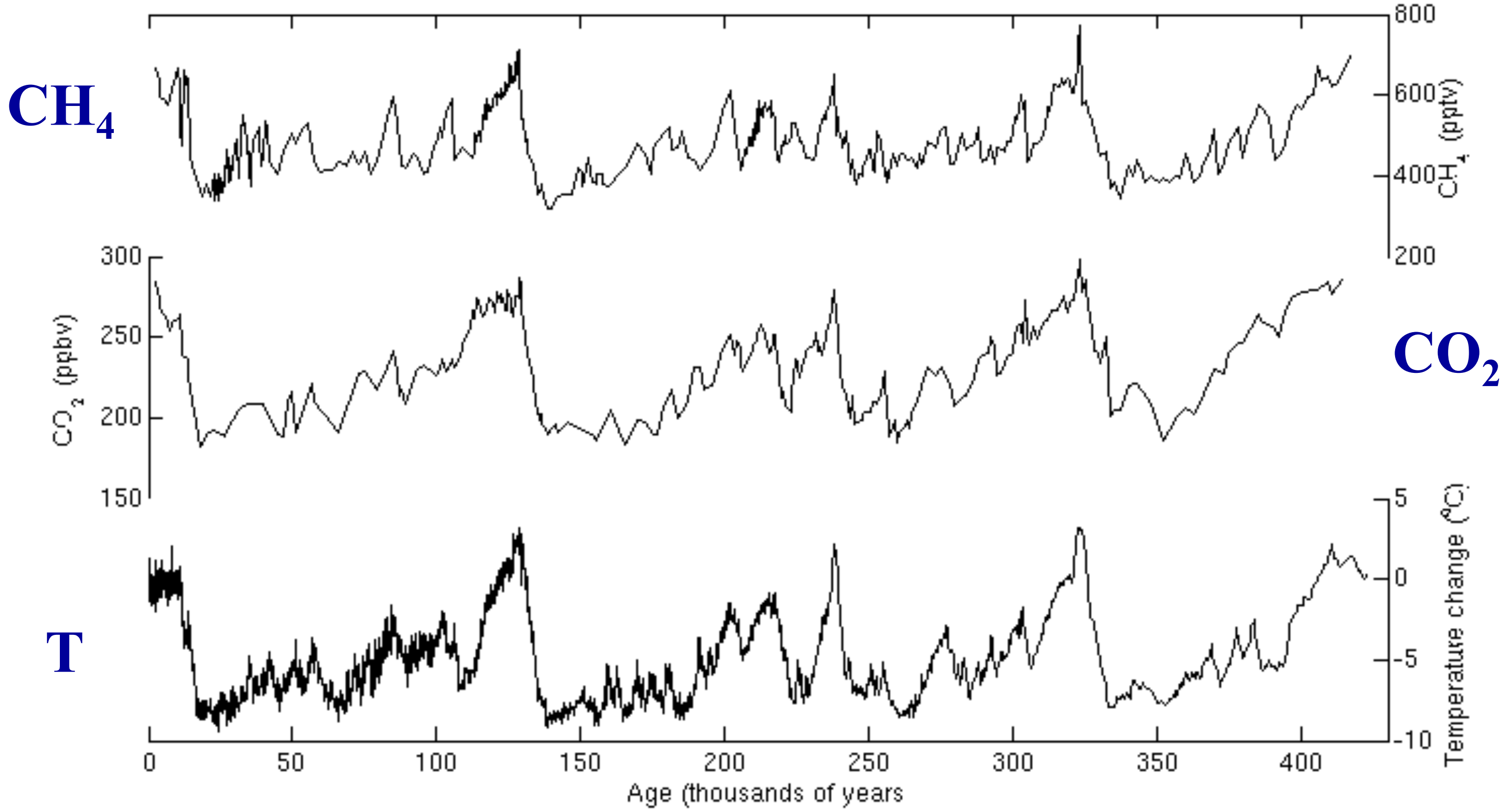
UW Stable Isotope Lab

- All the comforts of the UW campus at –30 degrees C.
- These scientists will determine how cold it was in Greenland in the Last Ice Age.

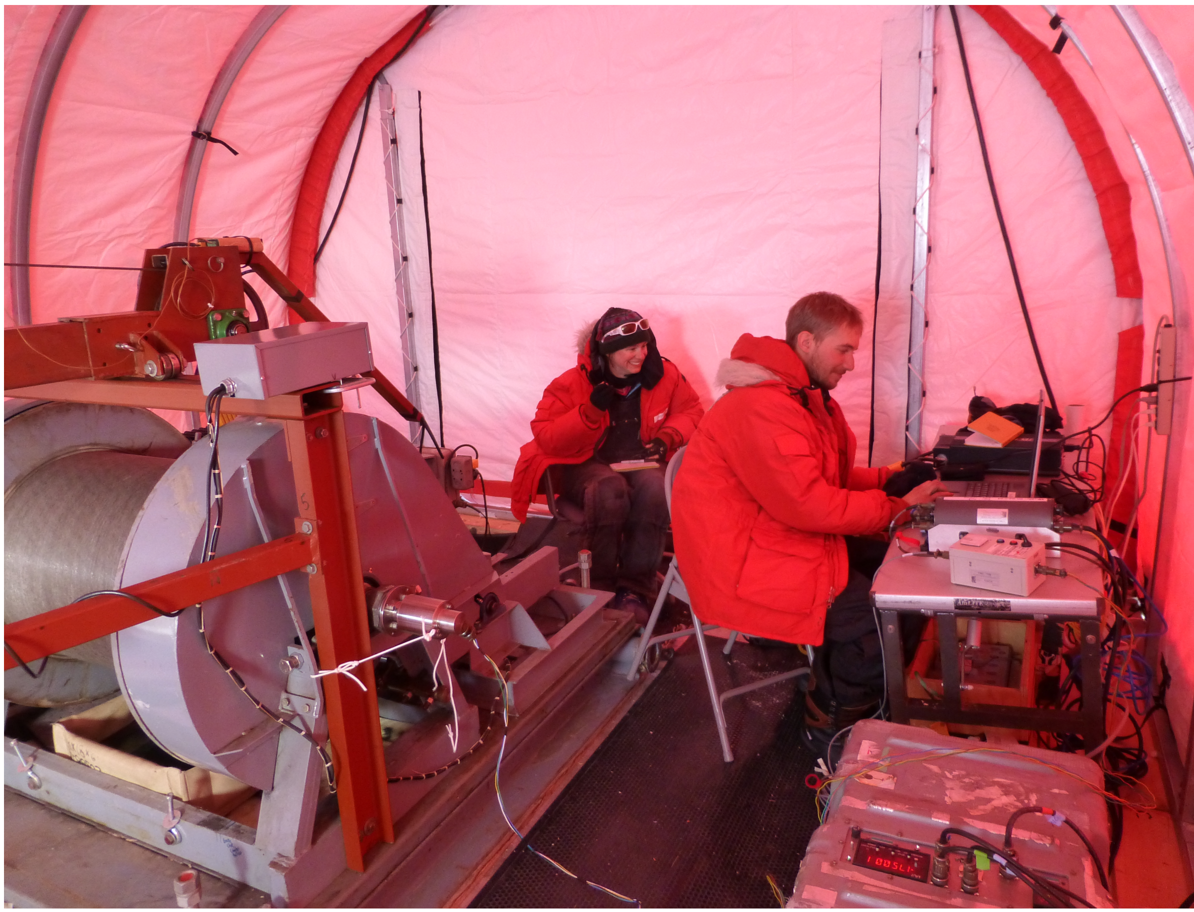
Ice holds samples of our past atmosphere


It's in the
bubbles …

Greenhouse Gases and Ice-Age Temperature



Borehole Logging



Borehole Logging

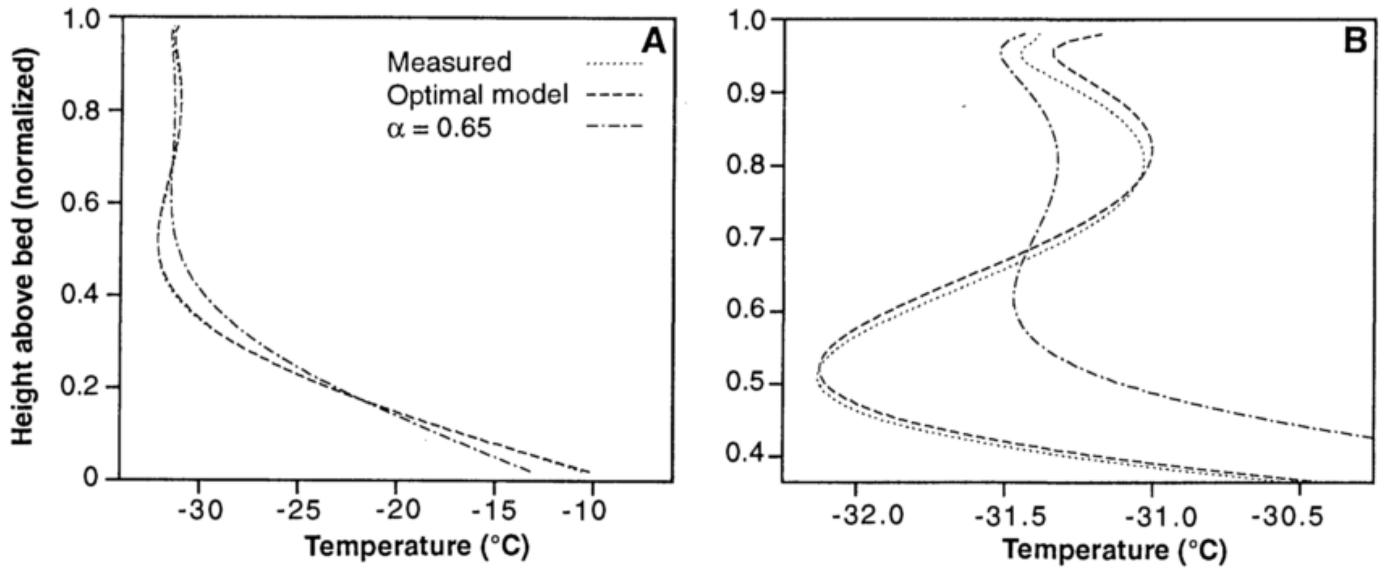
Lots of Glaciologically interesting variables

- Ice Fabric
- Dust content of the layers
- Acoustic / Electromagnetic properties
- Borehole size

Precise measurements of Ice Temperature

Large Arctic Temperature Change at the Wisconsin-Holocene Glacial Transition

Kurt M. Cuffey,* Gary D. Clow, Richard B. Alley, Minze Stuiver, Edwin D. Waddington, Richard W. Saltus

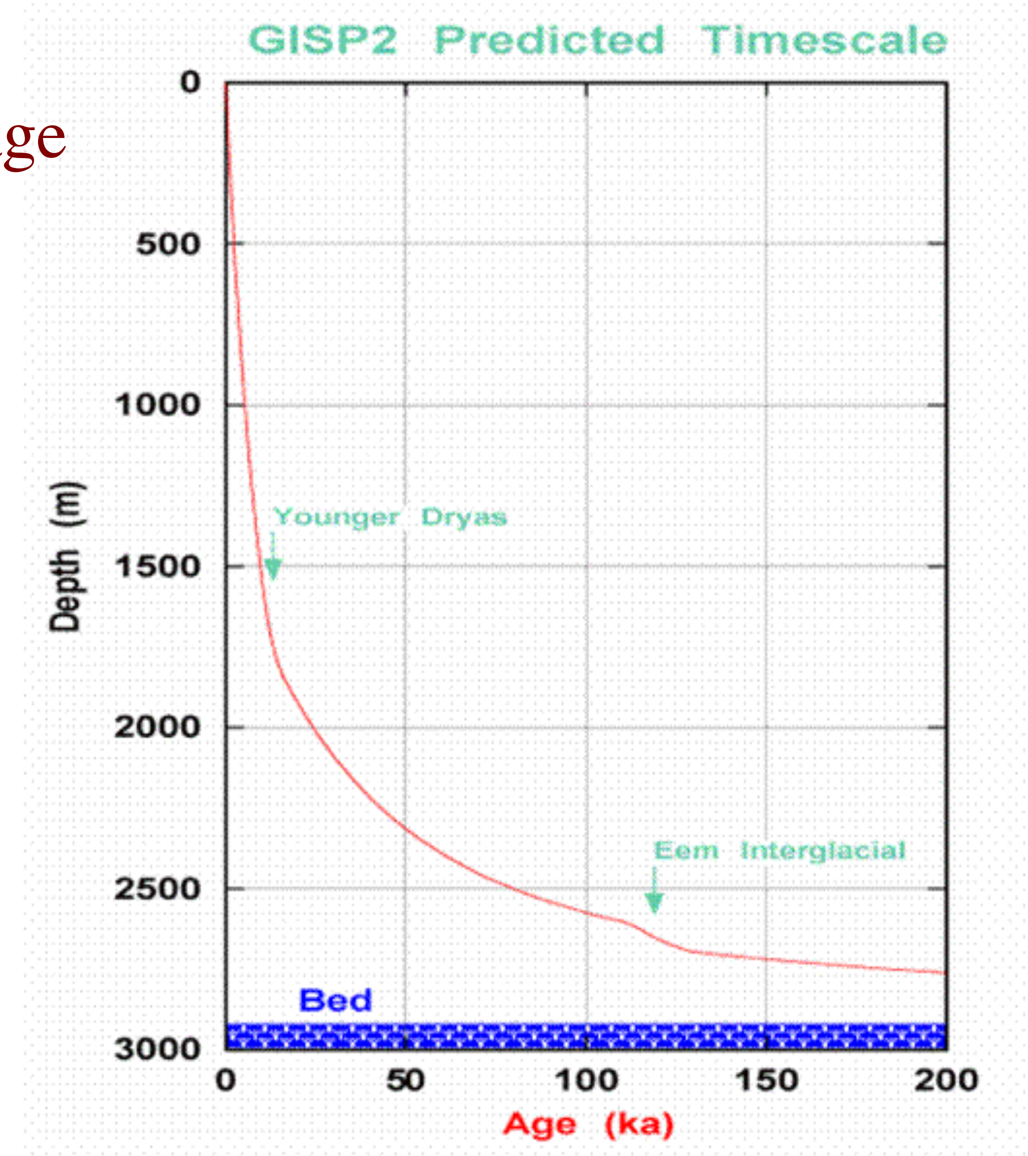


Dating the Ice Core

- Model-based time scales
- Layer counting
- Matching well-dated cores with cores elsewhere (gas-based or dust chronologies)

GISP2 depth-age

Predicted by an ice-flow model before the core was drilled, with a good guess at the history of net snowfall.



Layer counting - the concept

Seasonal timing of parameters being measured

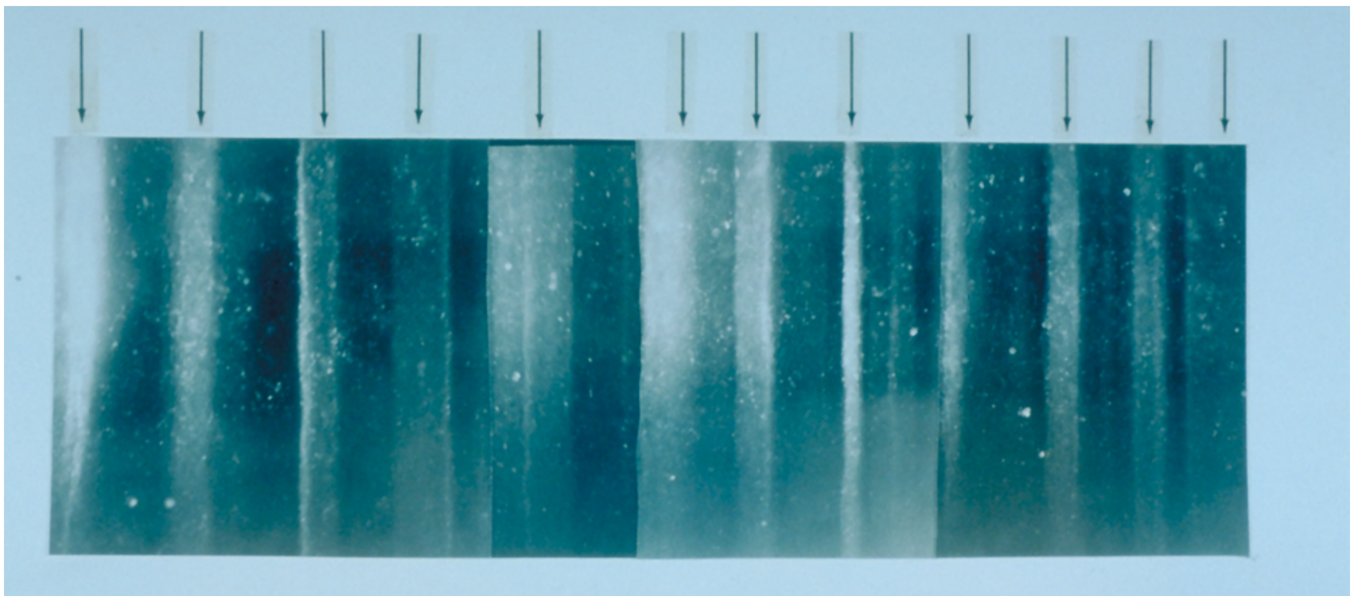
- e.g. $\delta^{18}O$ higher in summer than winter
- Dust varies seasonally with exposed bare ground (sources) and with wind speed (transport).
- Many others …

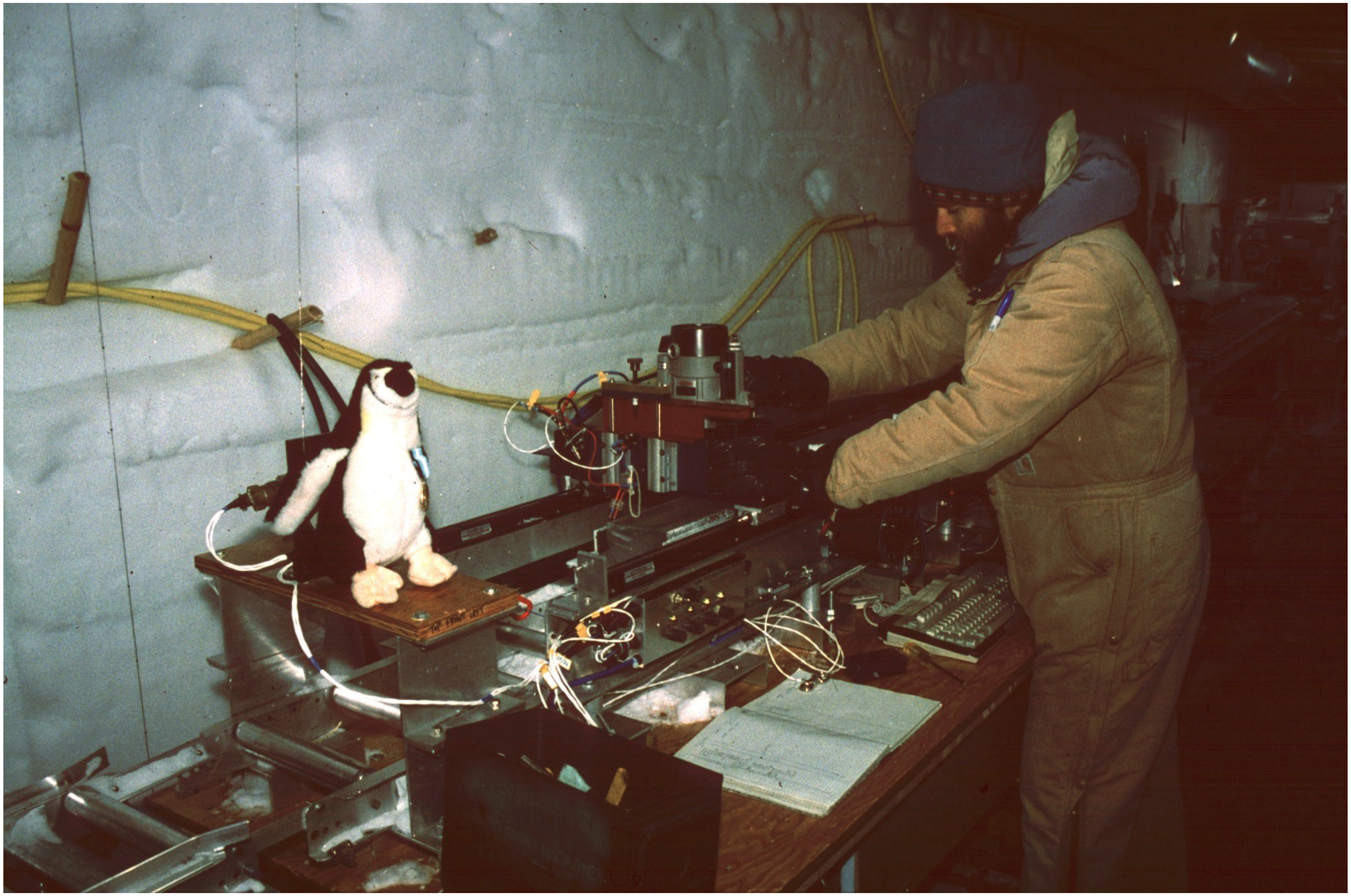
Validation/correction with stratigraphic markers

- e.g. volcanic events of known age (rocks dated at the volcano)

Layer counting - the practice

Summer layers, GISP2, Greenland ~20 kyr

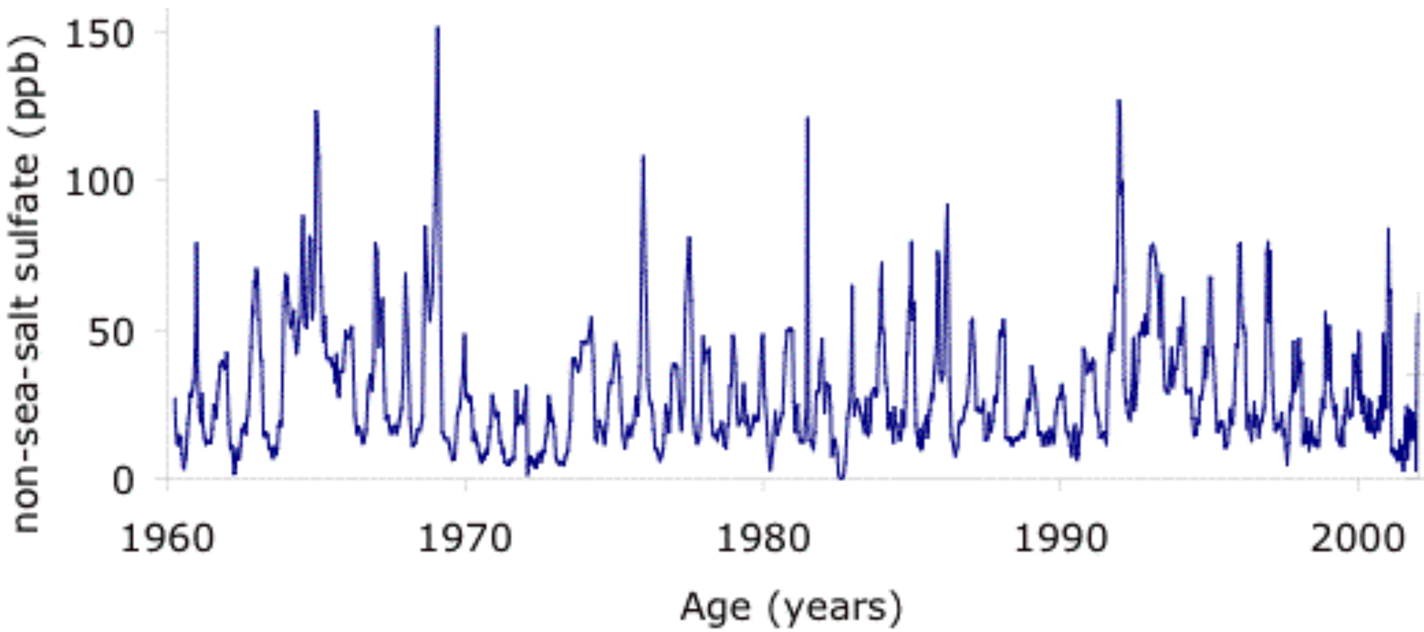




Electrical Conductivity Method (ECM)

Seasonal Cycles

Spring plankton bloom
in the Southern Ocean



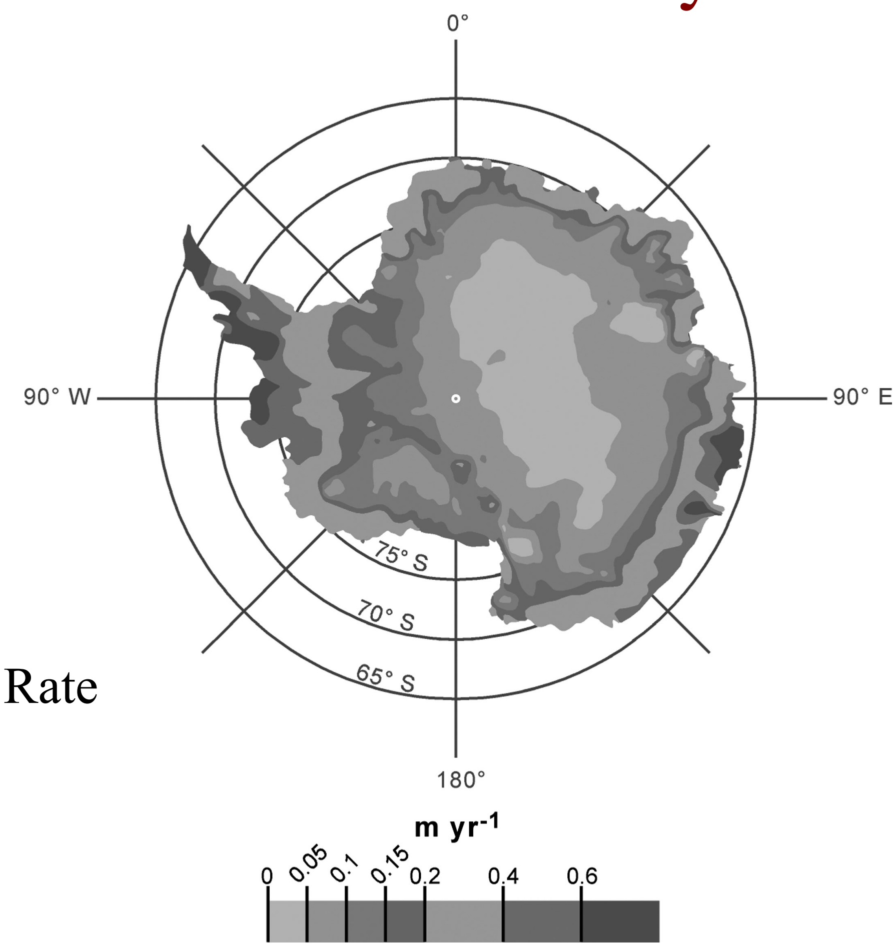
How high can we count?

- Annual layers in GISP2 ice core were counted back to ~50 ka
- accuracy estimated to be ~1-2%

- This was an amazing achievement

- Current WAIS Divide ice core layer-counted to more than 30 ka

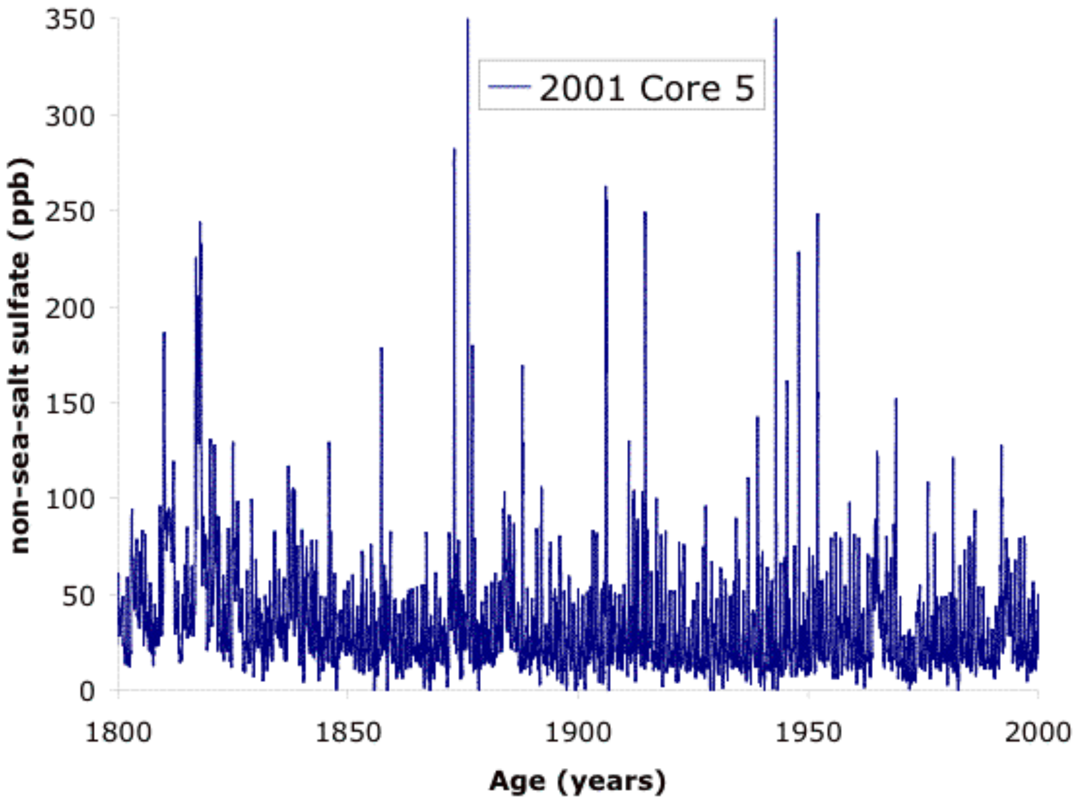
What if we cannot count annual layers?



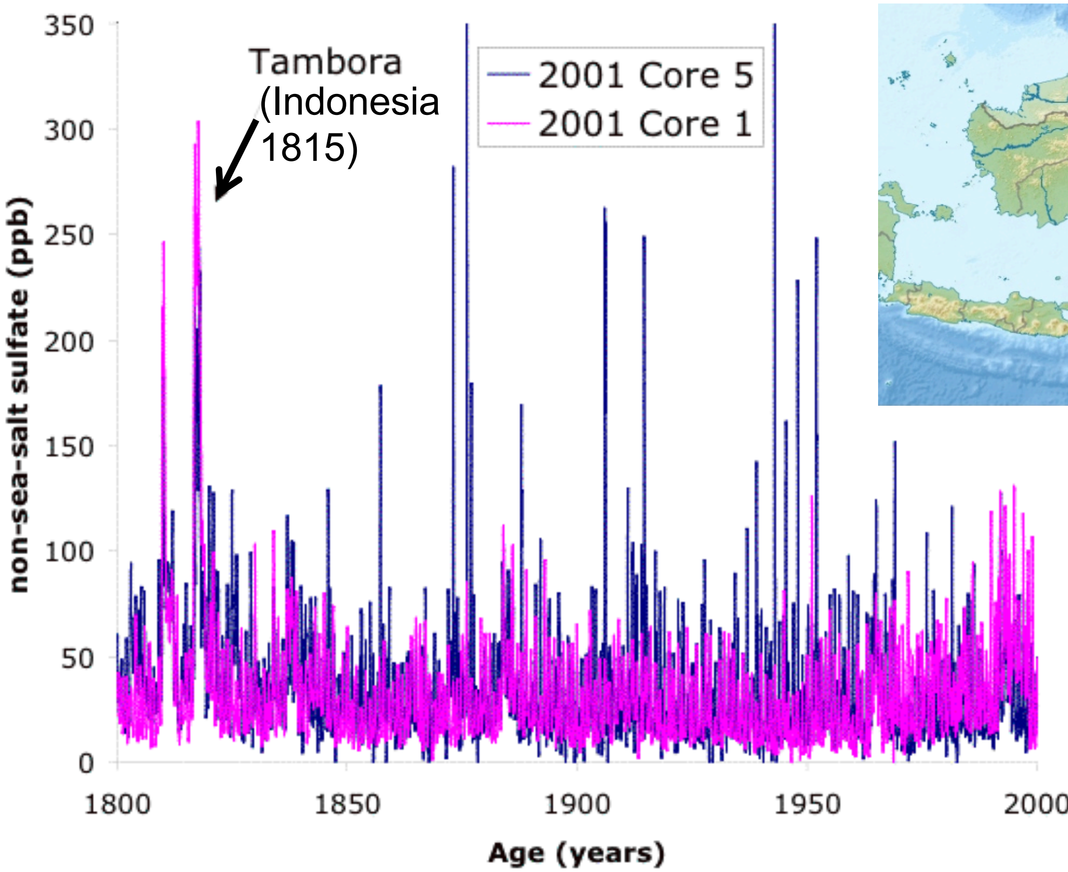
Antarctic
Accumulation Rate

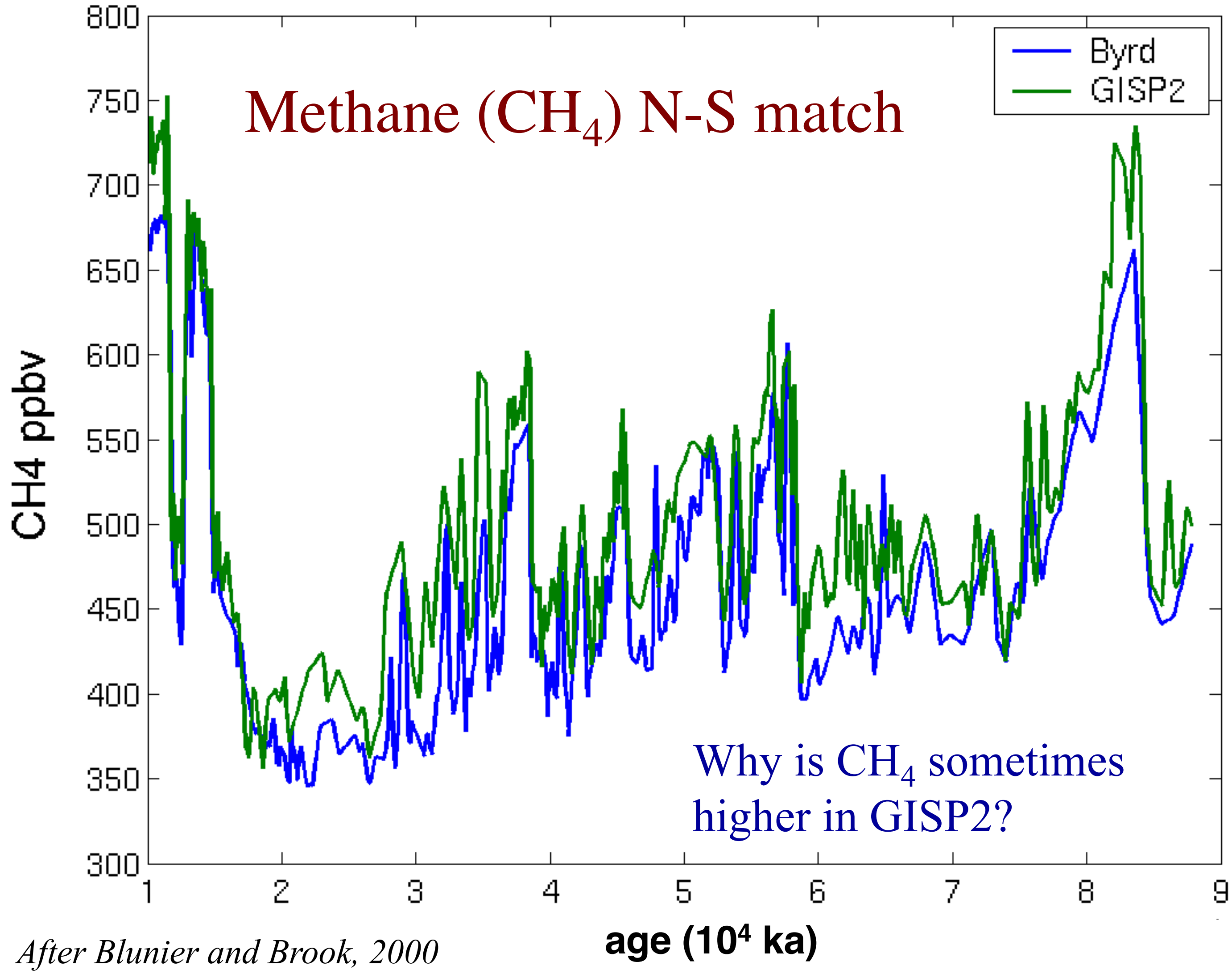
Cuffey and Paterson (2010) *The physics of glaciers*. FIGURE 4.16

West Antarctic Ice Cores



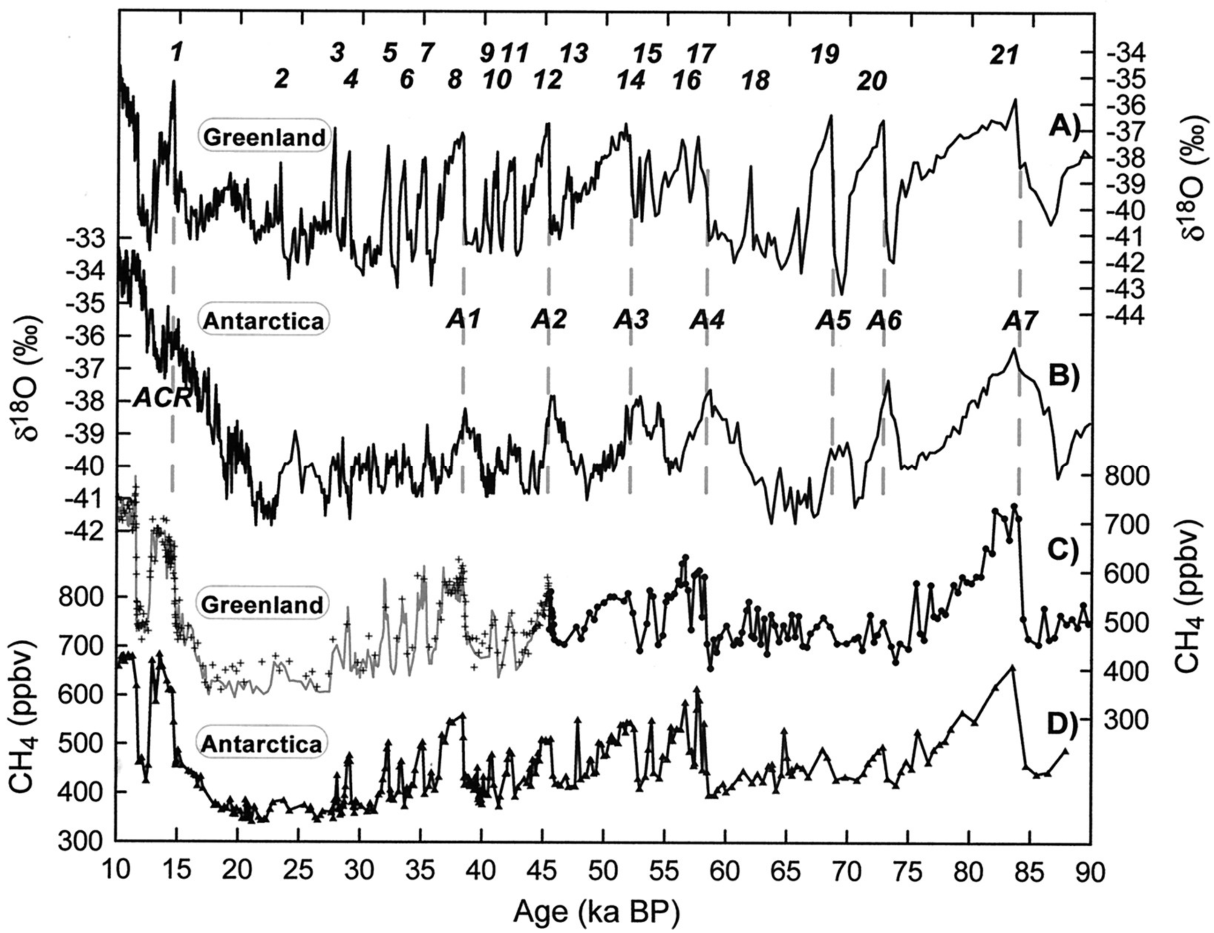
West Antarctic Ice Cores





After Blunier and Brook, 2000

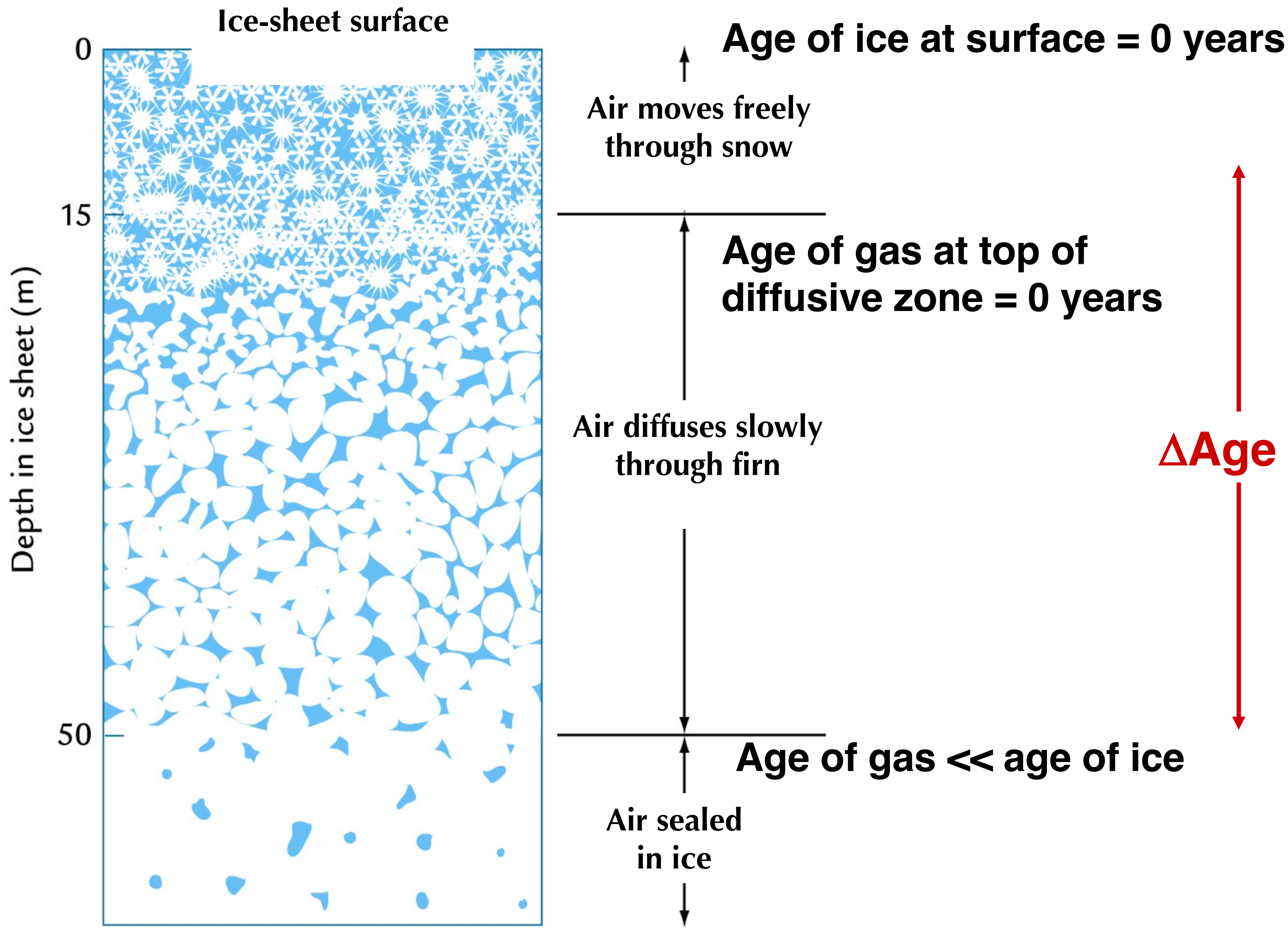
Gas-based correlation



Steps in gas-correlation dating

- From layer-counted ice core (A), calculate age of gas in the ice
- Match time series of globally mixed gases (CH_4, $\delta^{18}O$ of O_2, CO_2) between cores A and B
- Determine age of ice in core B

Note that we must know Δage in both cores …


Ice-sheet surface
Depth in ice sheet (m)
0
15
50
Age of ice at surface = 0 years
Air moves freely through snow
Age of gas at top of diffusive zone = 0 years
Air diffuses slowly through firn
ΔAge
Age of gas << age of ice
Air sealed in ice

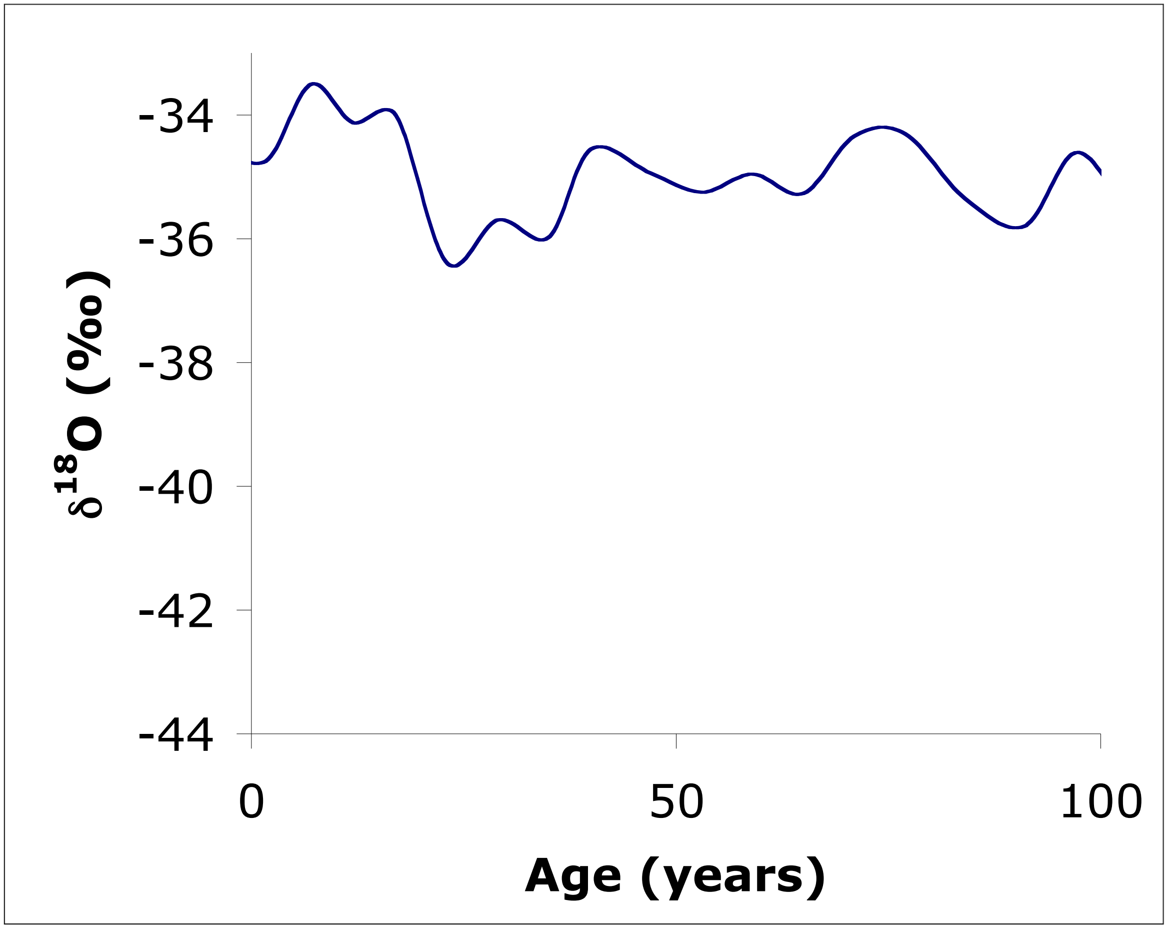
Calculating Δage

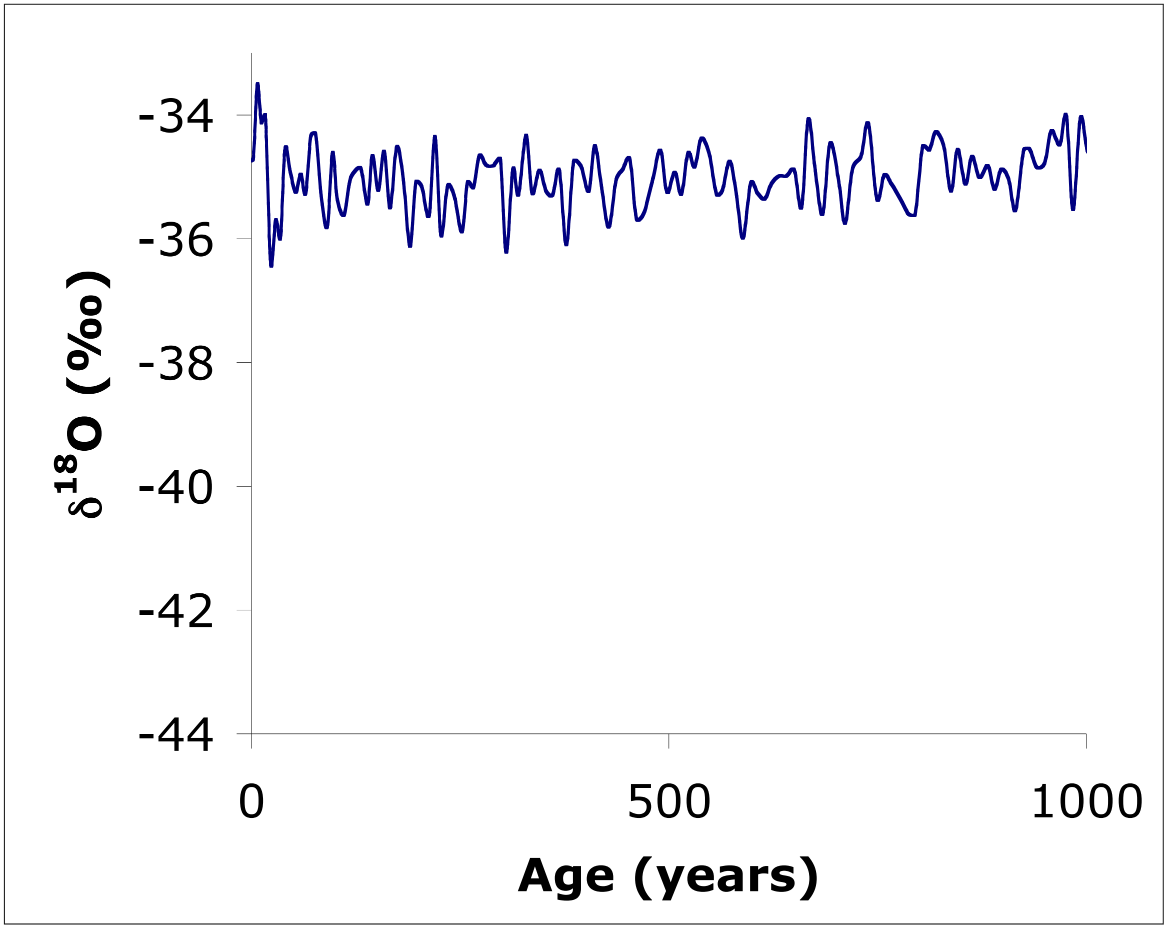
- Δage is the age difference between the gas bubbles and the ice surrounding them.
- Δage depends on the processes converting snow to firn and eventually ice, sealing off air bubbles
- These processes are dependent on **temperature** and **snow accumulation** rate; wind and other meteorological factors may also play an important role.

Uncertainties in Δage

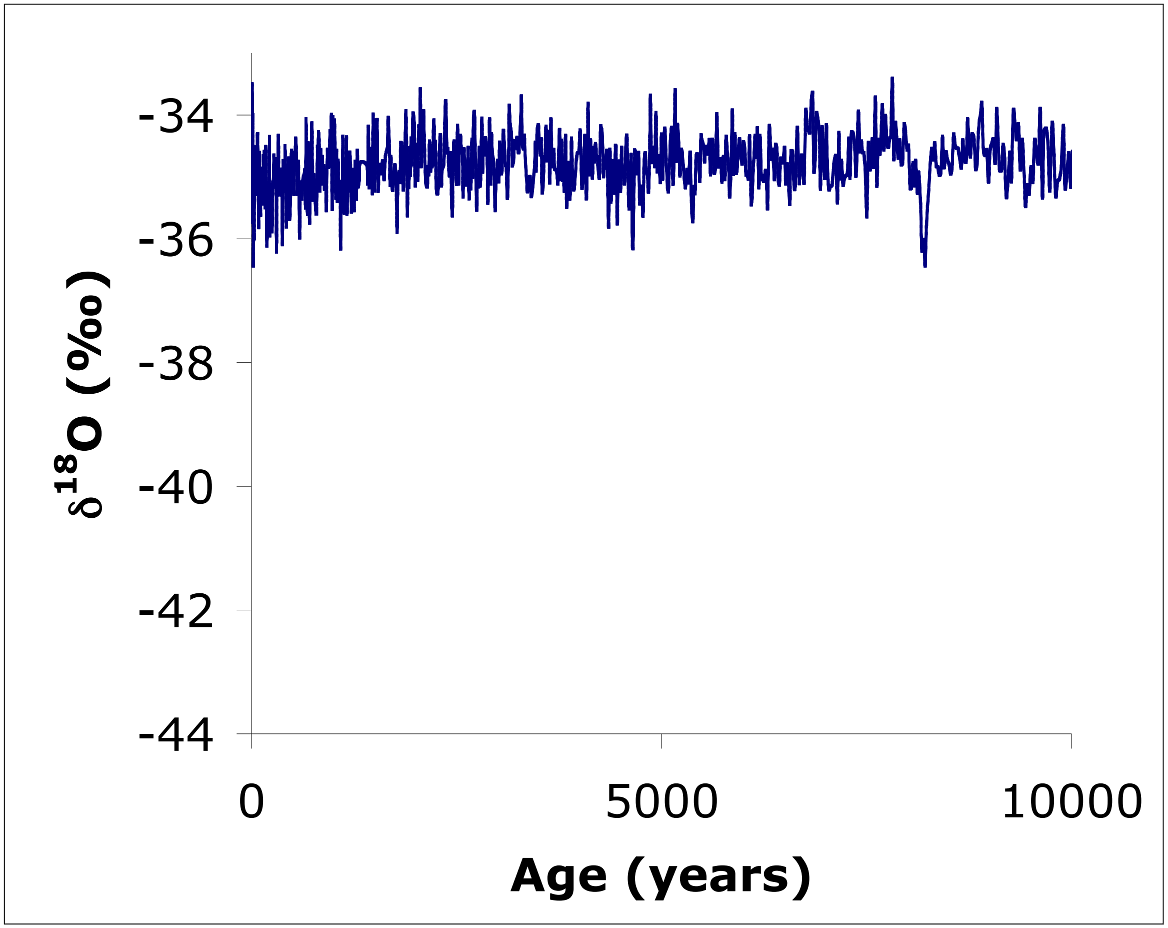
Item	How determined	How well known for sites with	
		low accumulation	high accumulation
Bubble close-off process	Empirical and theoretical models of firn densification (conversion of snow to ice)	poorly	well
Temperature history	Stable isotope profiles, borehole thermometry, gas isotopes (for selected time periods only)	moderately well, but variable	
Accumulation history	Inferred from geochemistry or isotopes	well	poorly

What have we learned from ice cores?

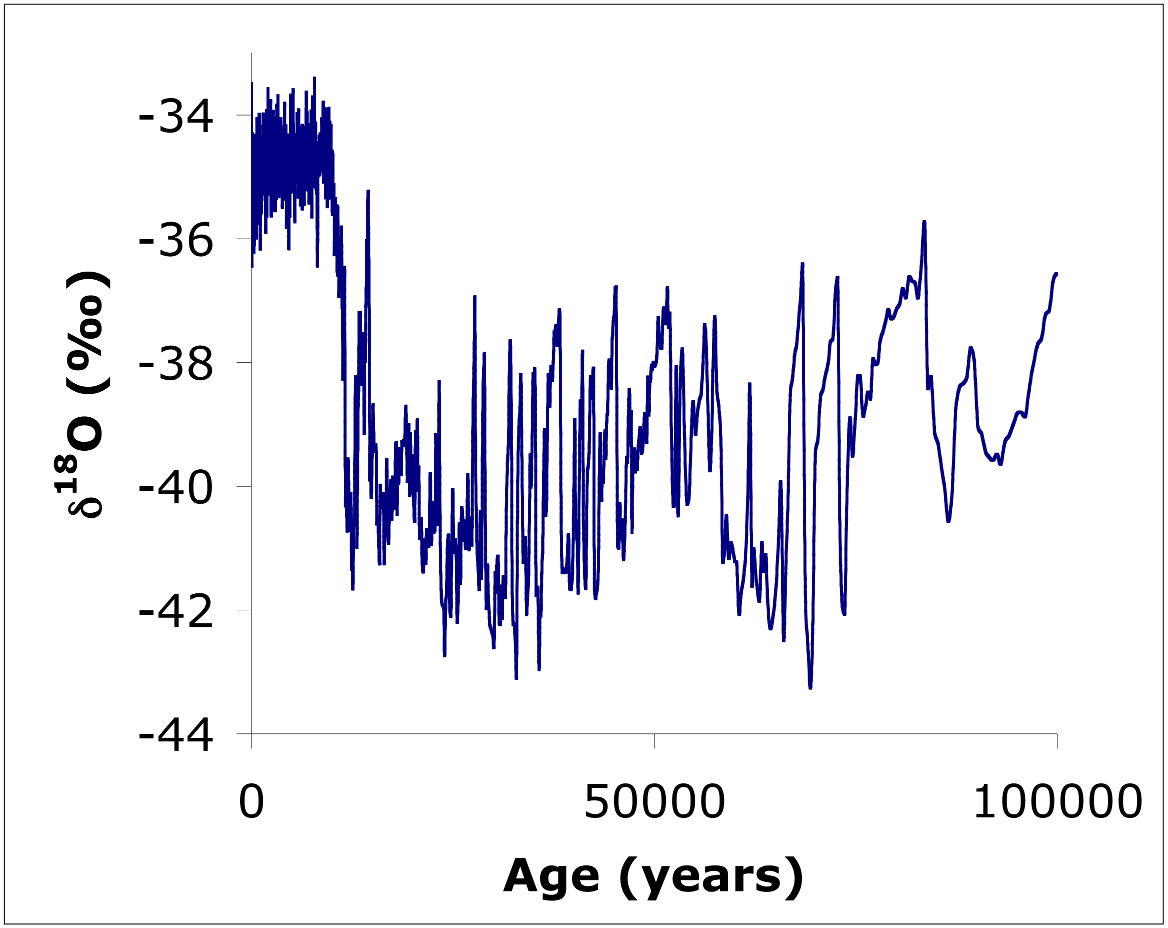

-34
-36
-38
-40
-42
-44
δ18O (‰)
0
50
100
Age (years)



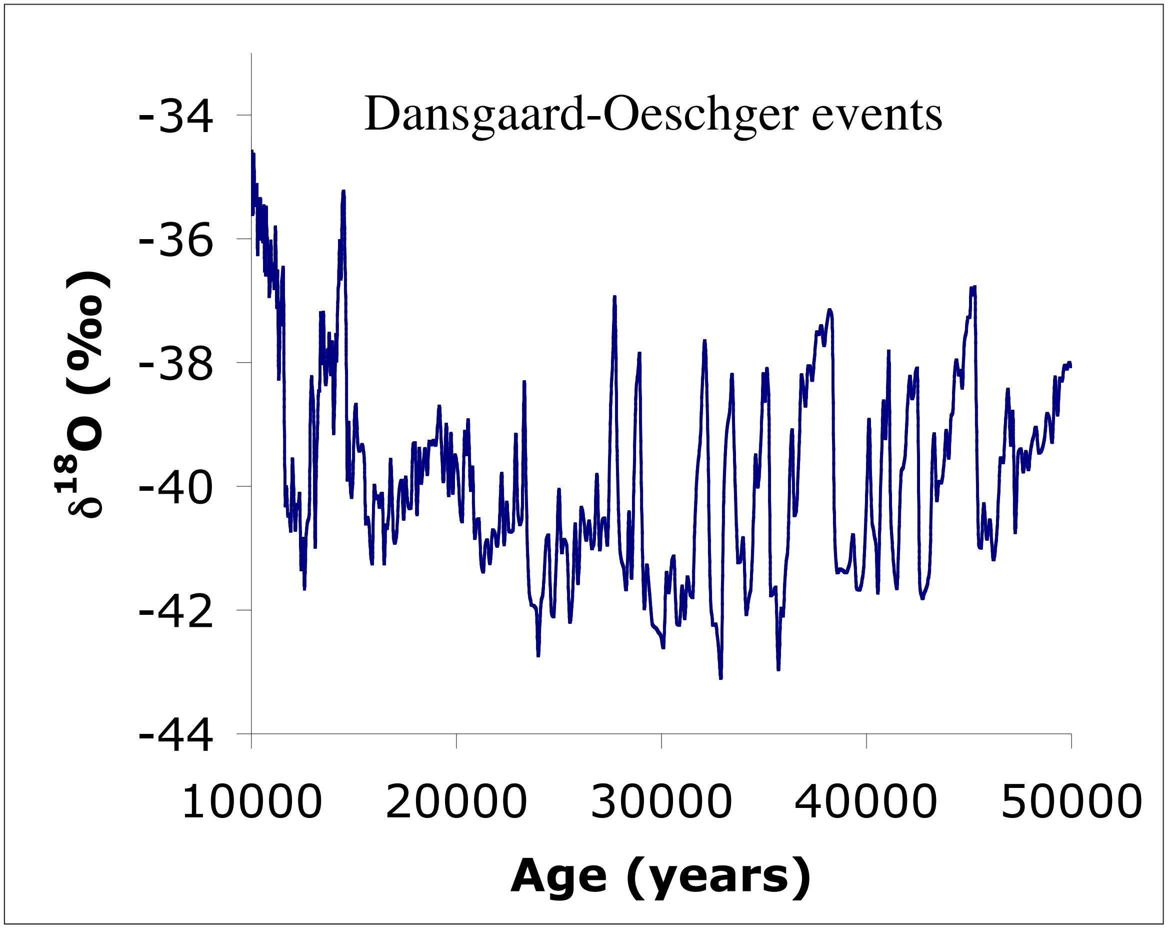
-34
-36
-38
-40
-42
-44
δ18O (‰)
0
500
1000
Age (years)



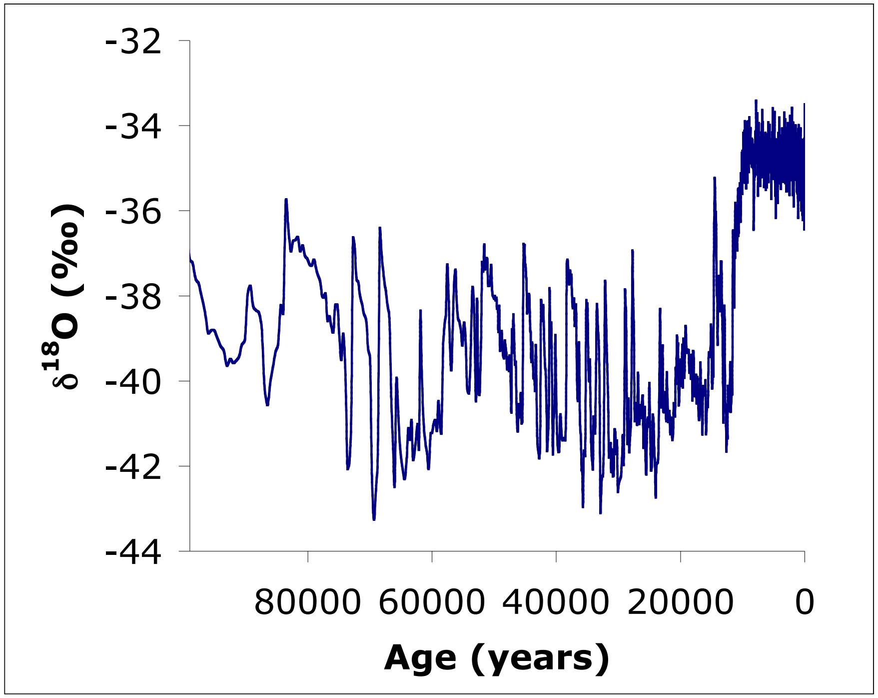
-34
-36
-38
-40
-42
-44
δ18O (‰)
0
5000
10000
Age (years)

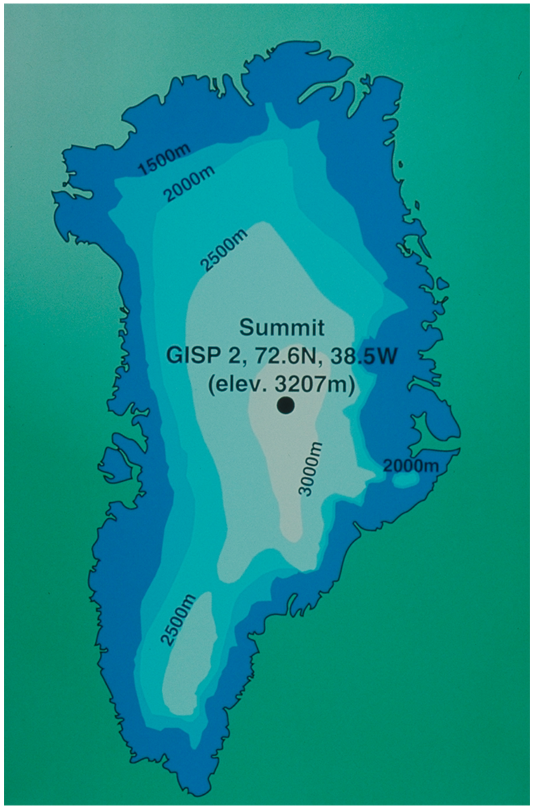


-34
-36
-38
-40
-42
-44
δ18O (‰)
0
50000
100000
Age (years)

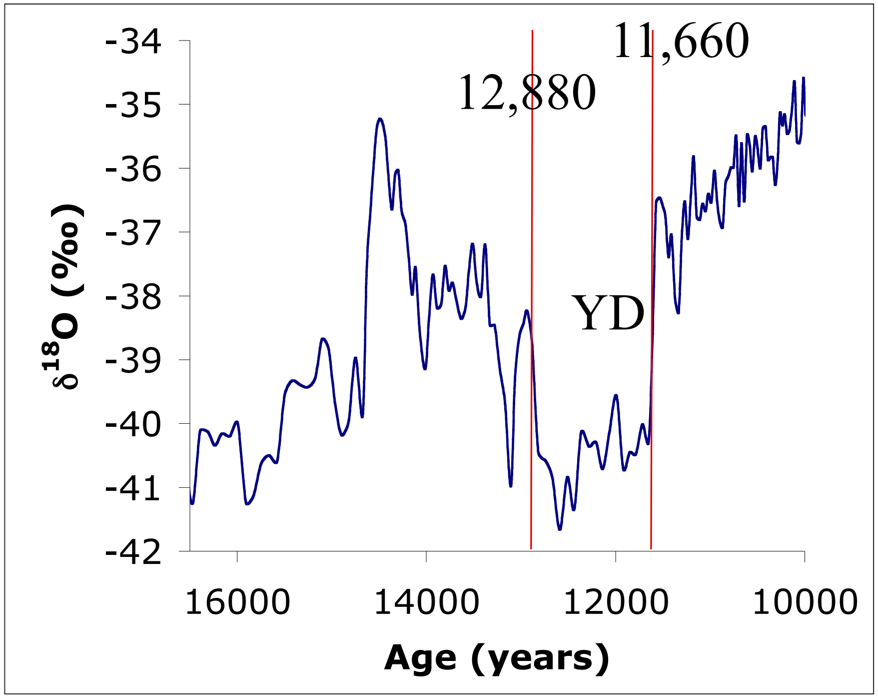

Dansgaard-Oeschger events
-34
-36
-38
-40
-42
-44
δ18O (‰)
10000
20000
30000
40000
50000
Age (years)

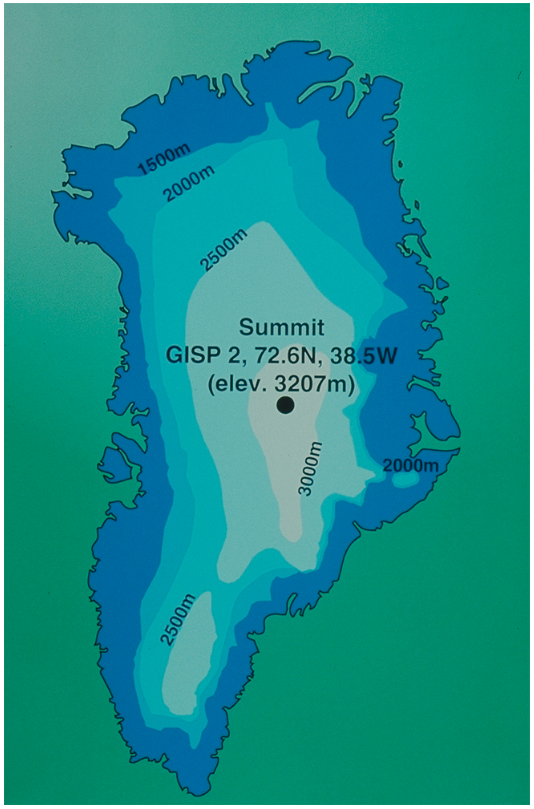
Central Greenland Ice Cores





Central Greenland Ice Cores





Temperature and Accumulation Rate

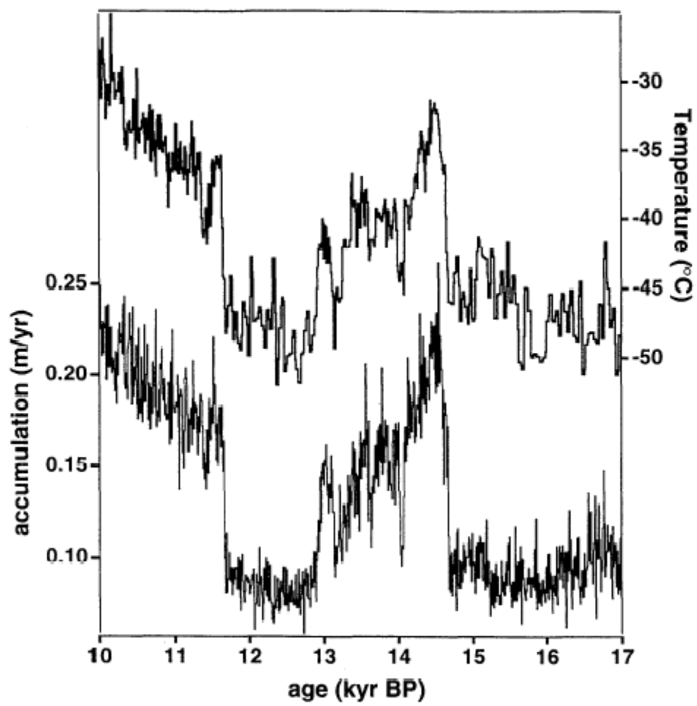
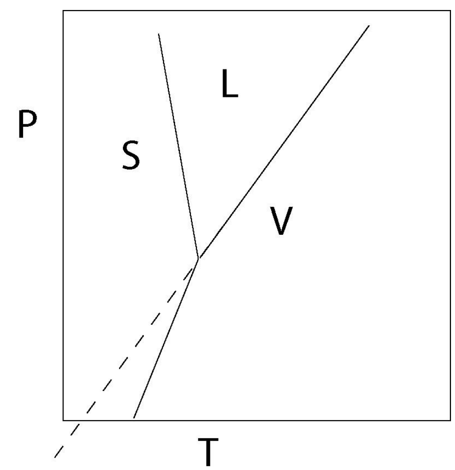


Figure 4. Comparison of the accumulation and δ records at the GISP2 site for the period between 18 and 10 kyr B. P. (adapted with permission from *Nature* [*Kapsner et al.*, 1995]; copyright Macmillan Magazines Limited), in using a calibration of 0.33‰/°C instead of 0.53‰/°C (see text).

Controlled by saturation vapor pressure?

Remember the phase diagram for H_20



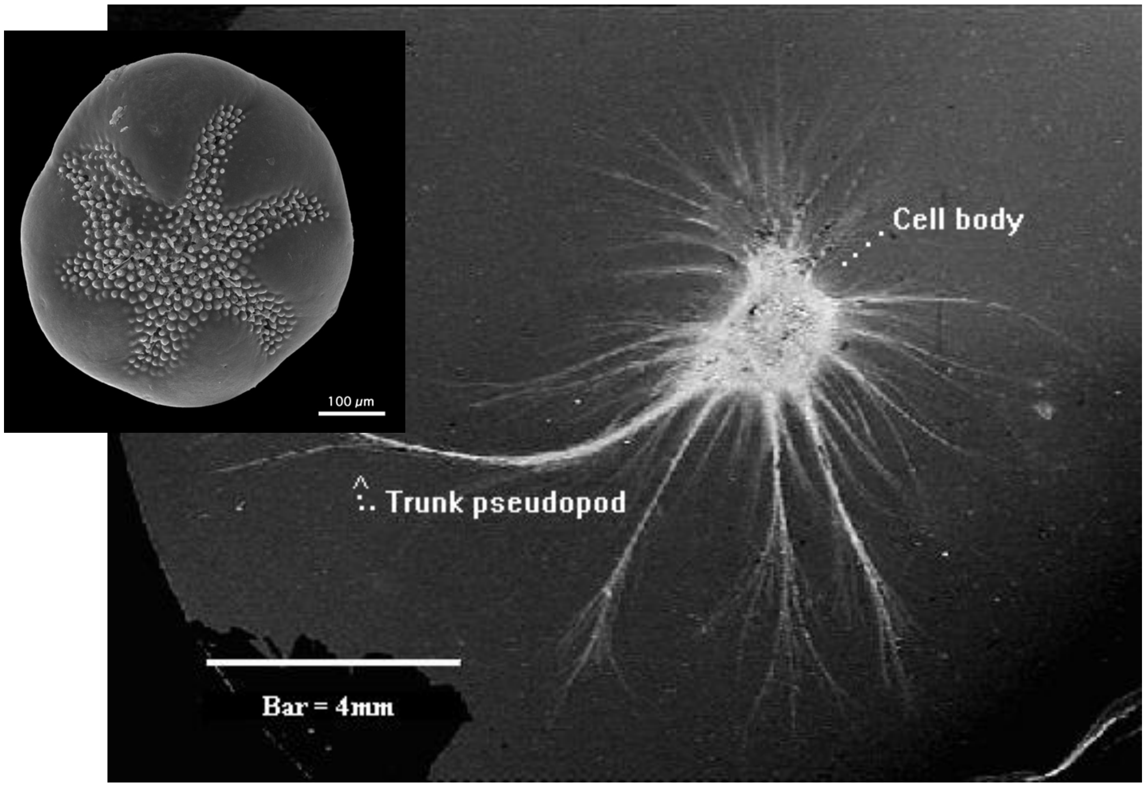
$\delta^{18}O$ in Ocean vs. Atmosphere

As the ice sheets build up during glaciations, they are preferentially made up of lighter isotopes.

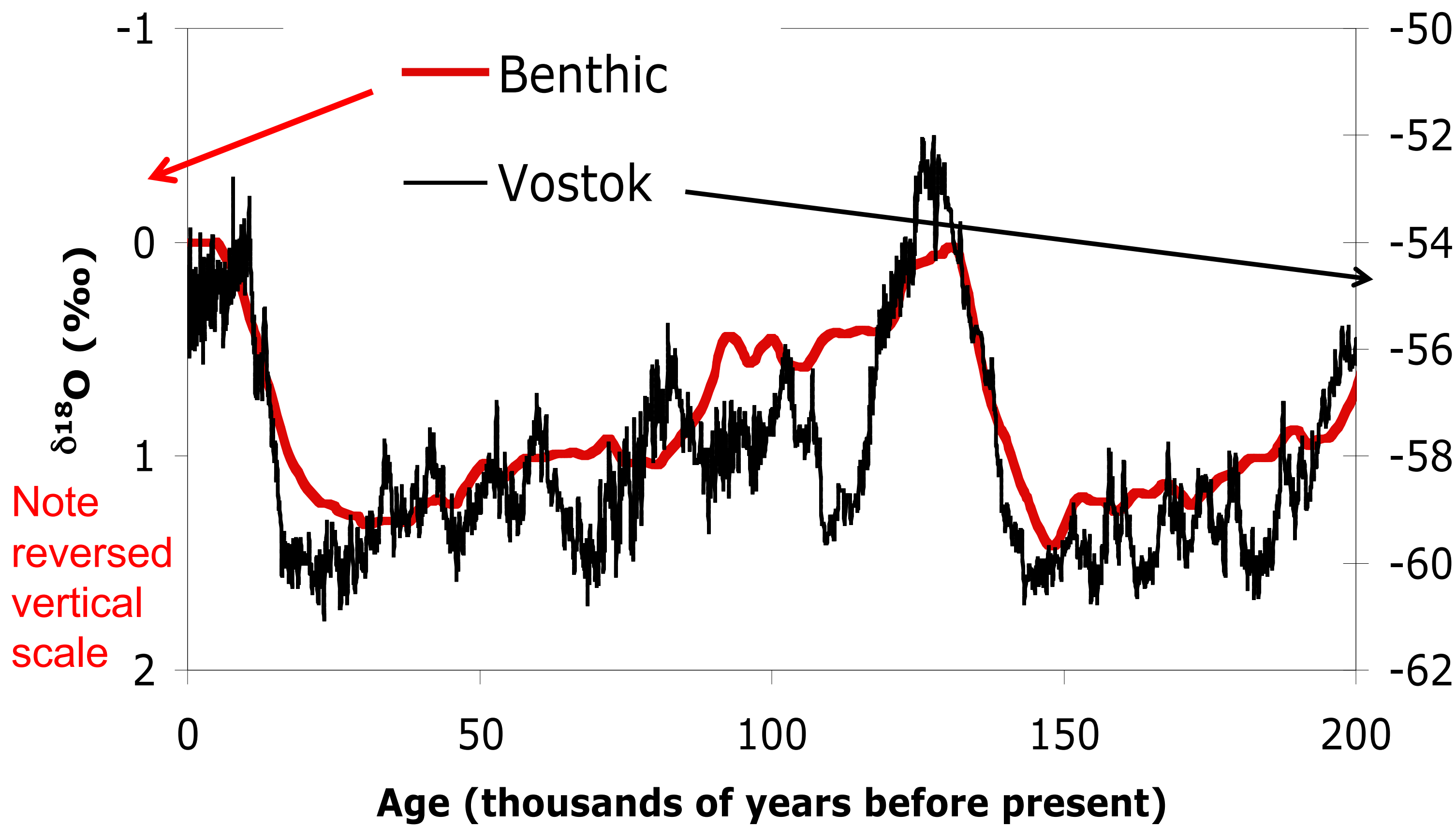
The consequence is that the ocean gets isotopically heavier as ice sheets grow.

TOP
87033
009
0700
KODAK Color-Control Patches

Planktonic and Benthic Foraminifera



$$CaC^{16}O_3 + H_2{}^{18}O \xleftrightarrow{equilibrium} CaC^{16}O_2{}^{18}O + H_2{}^{16}O$$



Benthic
Vostok
δ18O (‰)
Note reversed vertical scale
-1
0
1
2
-50
-52
-54
-56
-58
-60
-62
0
50
100
150
200
Age (thousands of years before present)

What story Does Antarctica Tell?

Vostok Station

- 4 glacial cycles

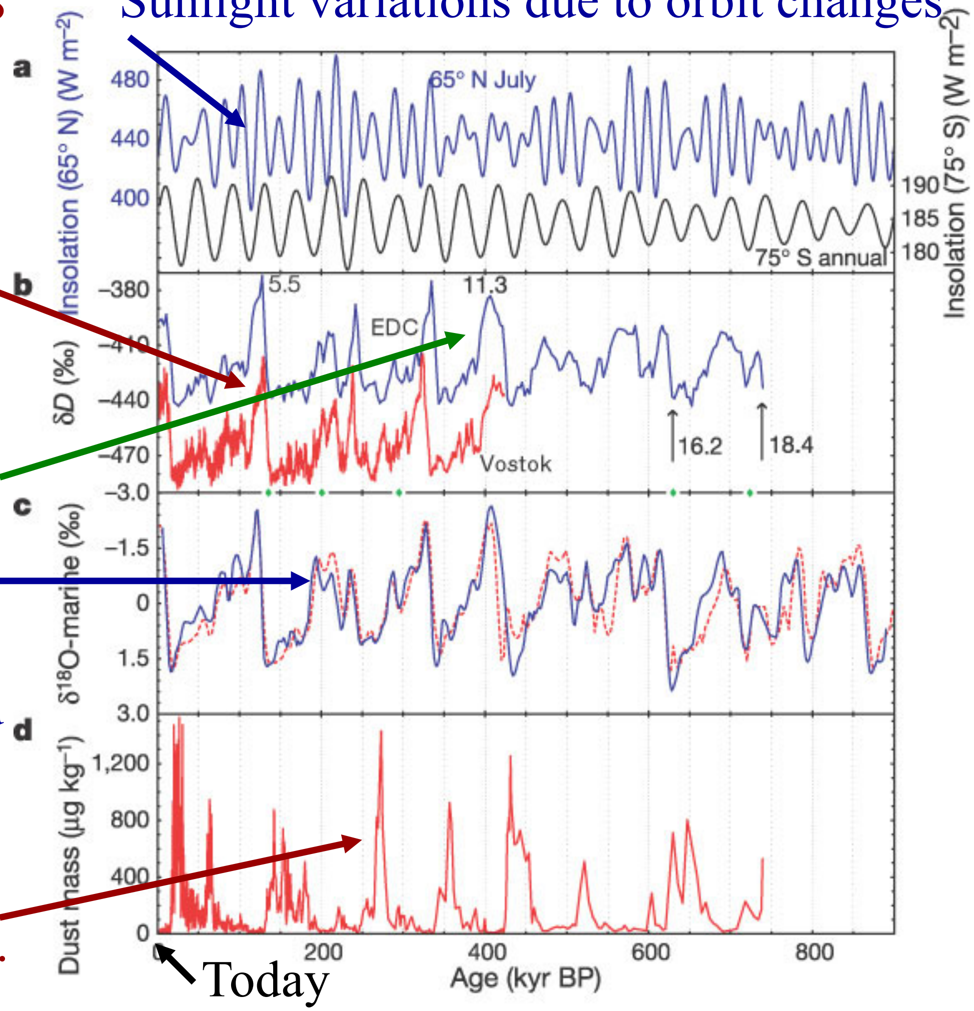
EPICA Dome C

- 8 glacial cycles

- Isotopes from ocean floor record the volume of ice on land in ice sheets.

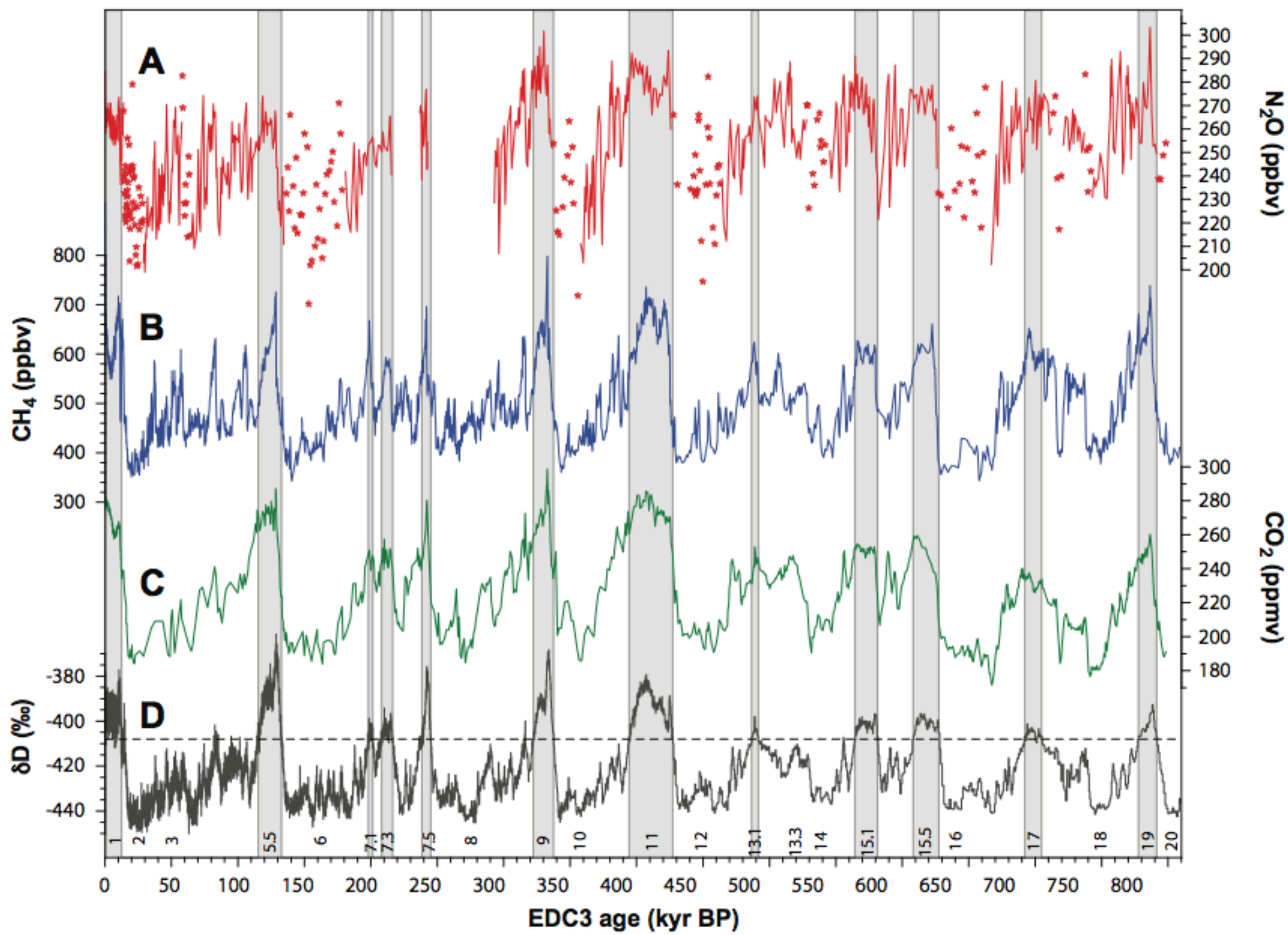
- Dust in ice reveals windiness in the past.

Sunlight variations due to orbit changes



Nature 429, 623-628 (10 June 2004) Eight glacial cycles from an Antarctic ice core

Epica Dome C – 800 ka



Rare isotopes in Air

Air contains N_2 O_2, and Ar

- These gases contain atoms with rare but stable isotopes ^{15}N (vs ^{14}N), ^{36}Ar (vs ^{40}Ar), and ^{18}O (vs ^{16}O)
- Content of ^{15}N and ^{40}Ar can be expressed in δ notation $\delta^{15}N$ and $\delta^{40}Ar$, just like $\delta^{18}O$
- Gas with these rare isotopes behaves slightly differently to normal gas when temperature changes.

In still air in pore spaces, gas with a heavy isotope tends to:

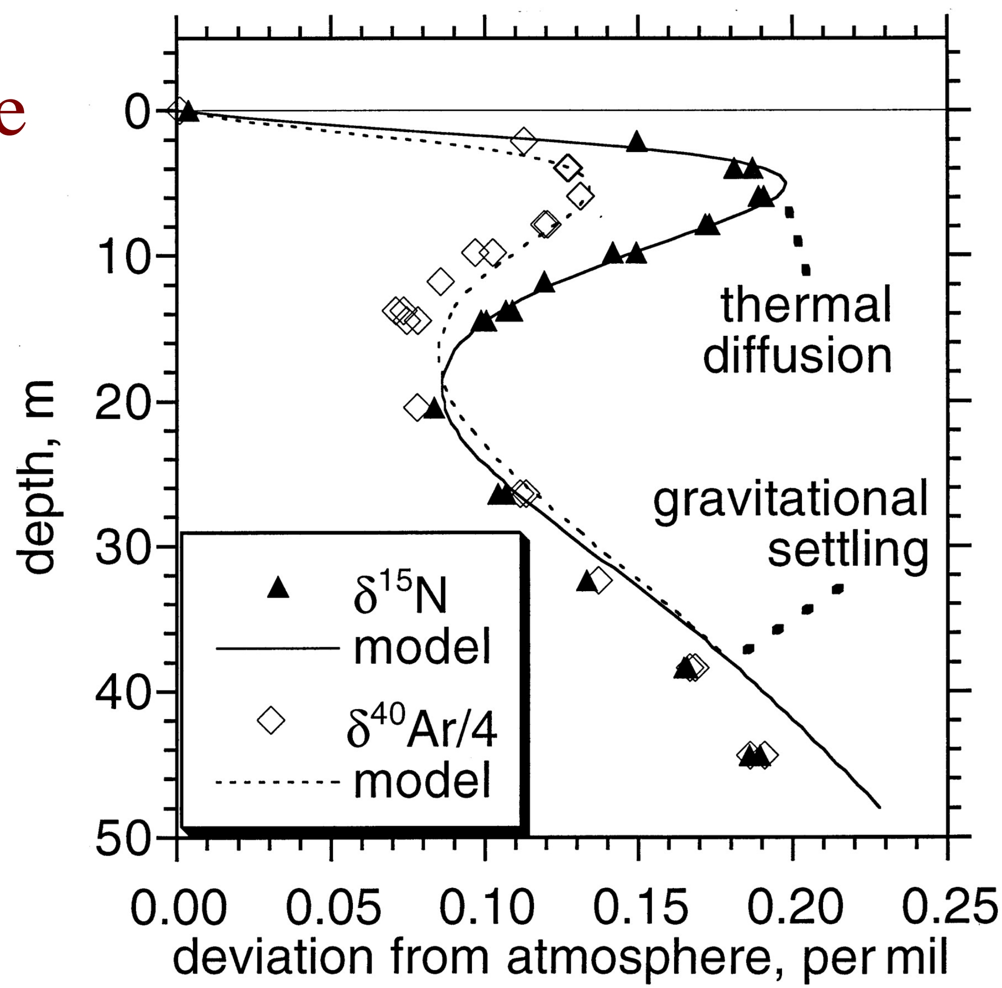
- Settle to bottom
- Move toward colder places

$\delta^{15}N$ and fast climate change

N_2 gas is largest component of atmosphere.
In still air in pore spaces, gas with heavy isotope e.g. ^{15}N or ^{40}Ar tends to

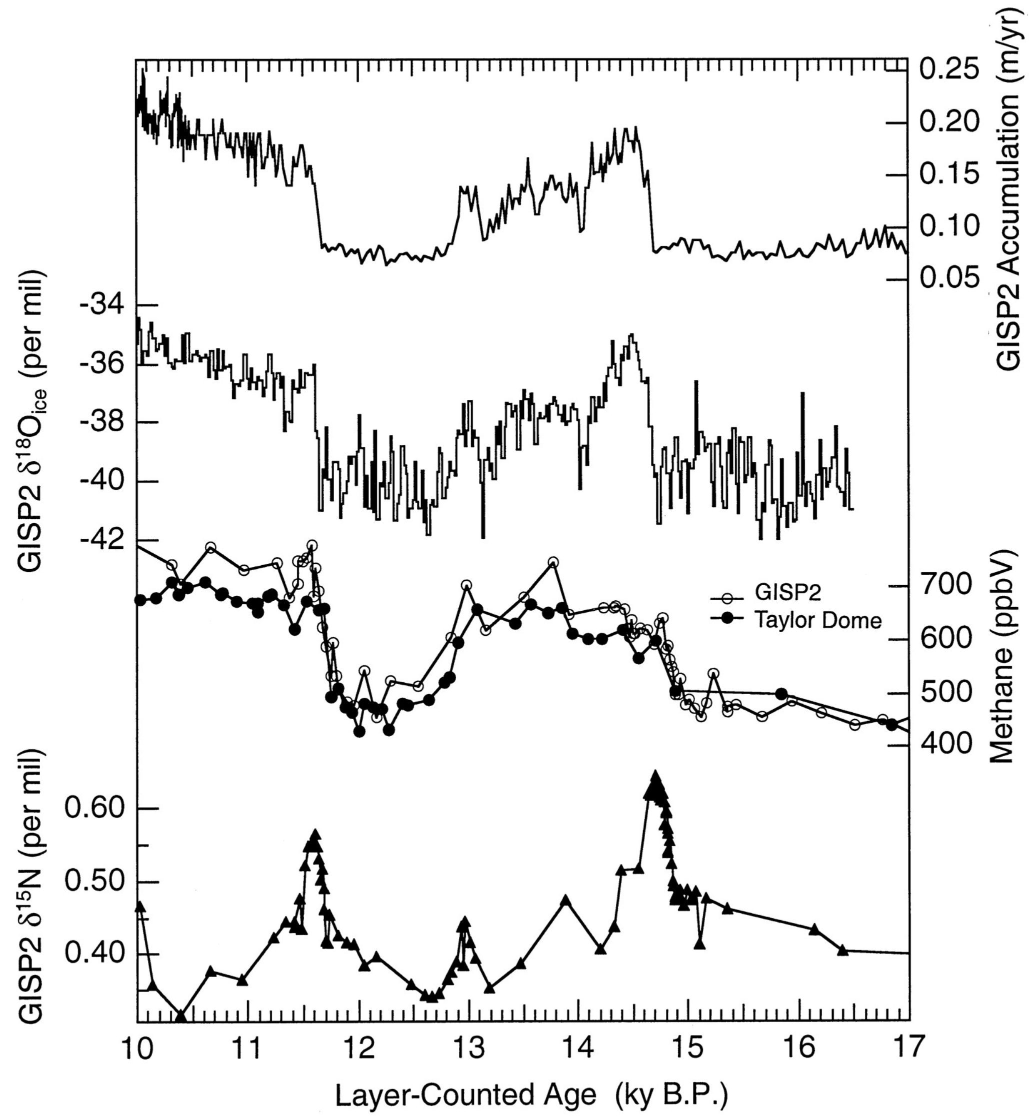
- Settle to bottom
- Move toward cold

- Why are $\delta^{15}N$ and $\delta^{40}Ar$ so positive at 8 meters depth?



How large were fast temperature changes?

Size of the $\delta^{15}N$ spikes is related to the size of the fast shift in temperature



Nature 484, 5 April 2012

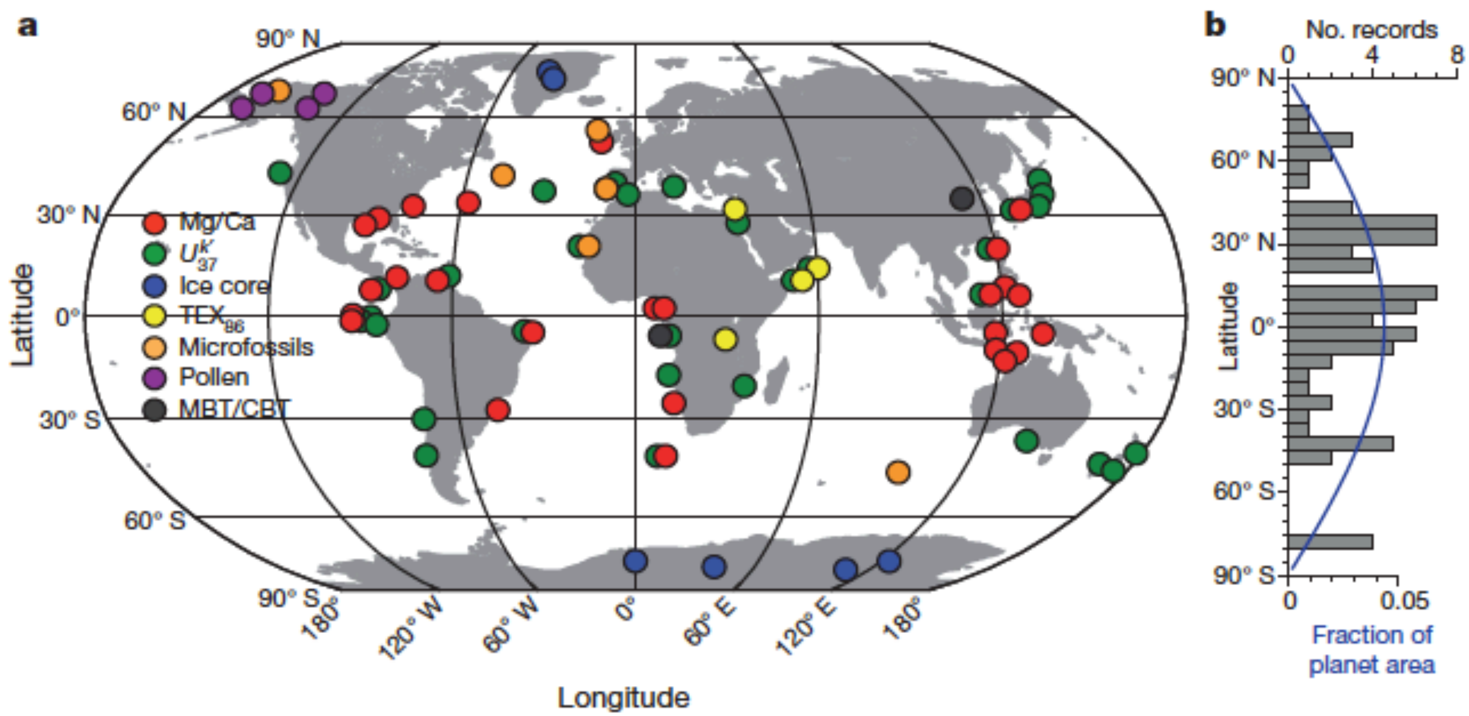
ARTICLE

doi:10.1038/nature10915

Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation

Jeremy D. Shakun[1,2], Peter U. Clark[3], Feng He[4], Shaun A. Marcott[3], Alan C. Mix[3], Zhengyu Liu[4,5,6], Bette Otto-Bliesner[7], Andreas Schmittner[3] & Edouard Bard[8]

Sites with climate records – (temperature)



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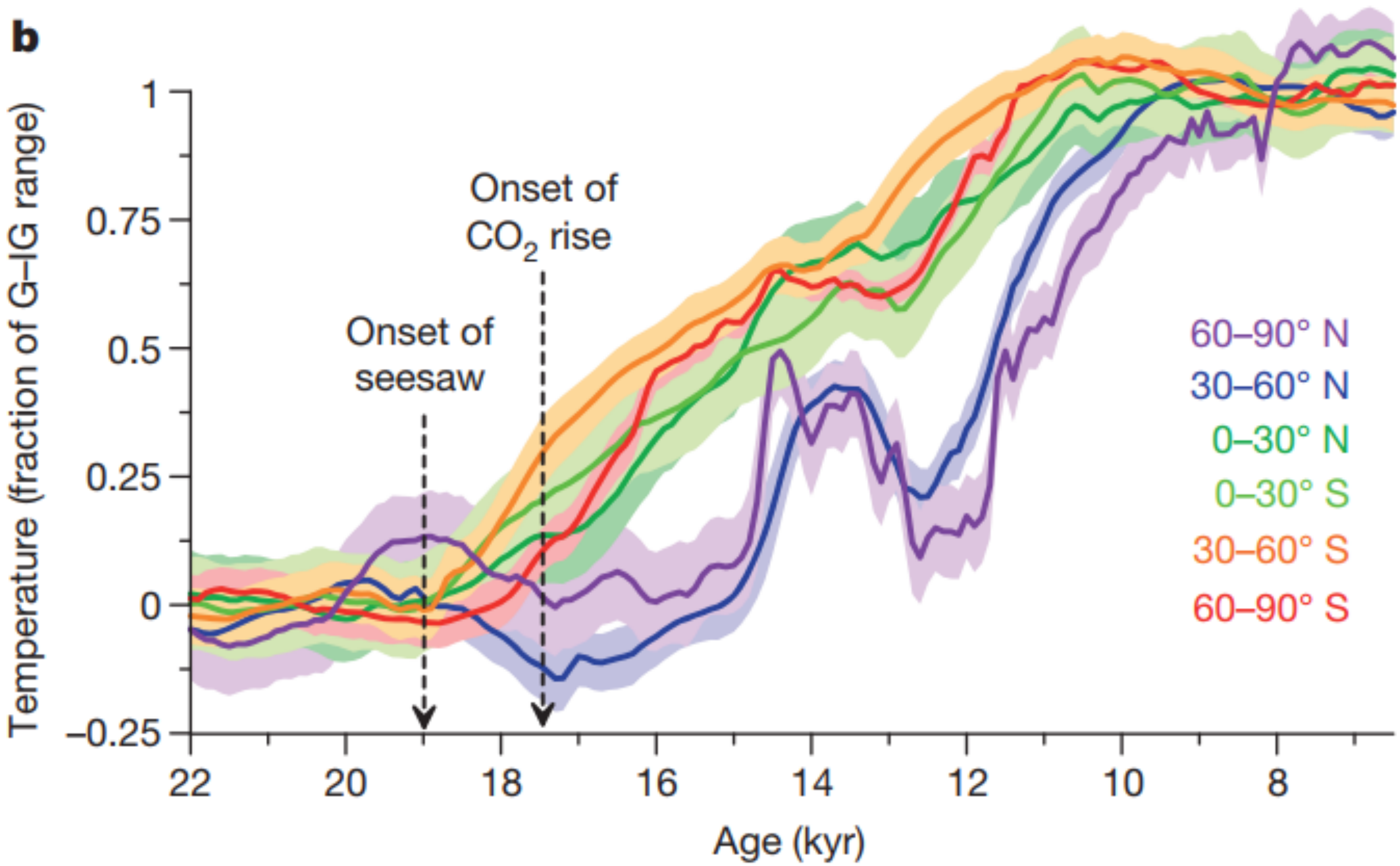

b
Temperature (fraction of G–IG range)
1
0.75
0.5
0.25
0
−0.25
Onset of
CO2 rise
Onset of
seesaw
60–90° N
30–60° N
0–30° N
0–30° S
30–60° S
60–90° S
22
20
18
16
14
12
10
8
Age (kyr)