ESS 431 Principles of Glaciology

Geochemistry of ice sheets - 2

November 21, 2006

Ed Waddington and Eric Steig

Housekeeping for the day

Friday Holiday – no Discussion Section

Homework

- Stable-isotope proxy thermometer
- Posted on web
- Due next Tuesday

Next Week

- Bonnie Light (Applied Physics Lab) on sea ice

Outline

Two lectures:

Last Thursday

1) a) The oxygen isotope paleothermometer

Today

2) a) Obtaining and dating ice cores

b) Gases and other geochemistry in ice cores

c) Some neat results

Dating ice cores

Why is dating important?

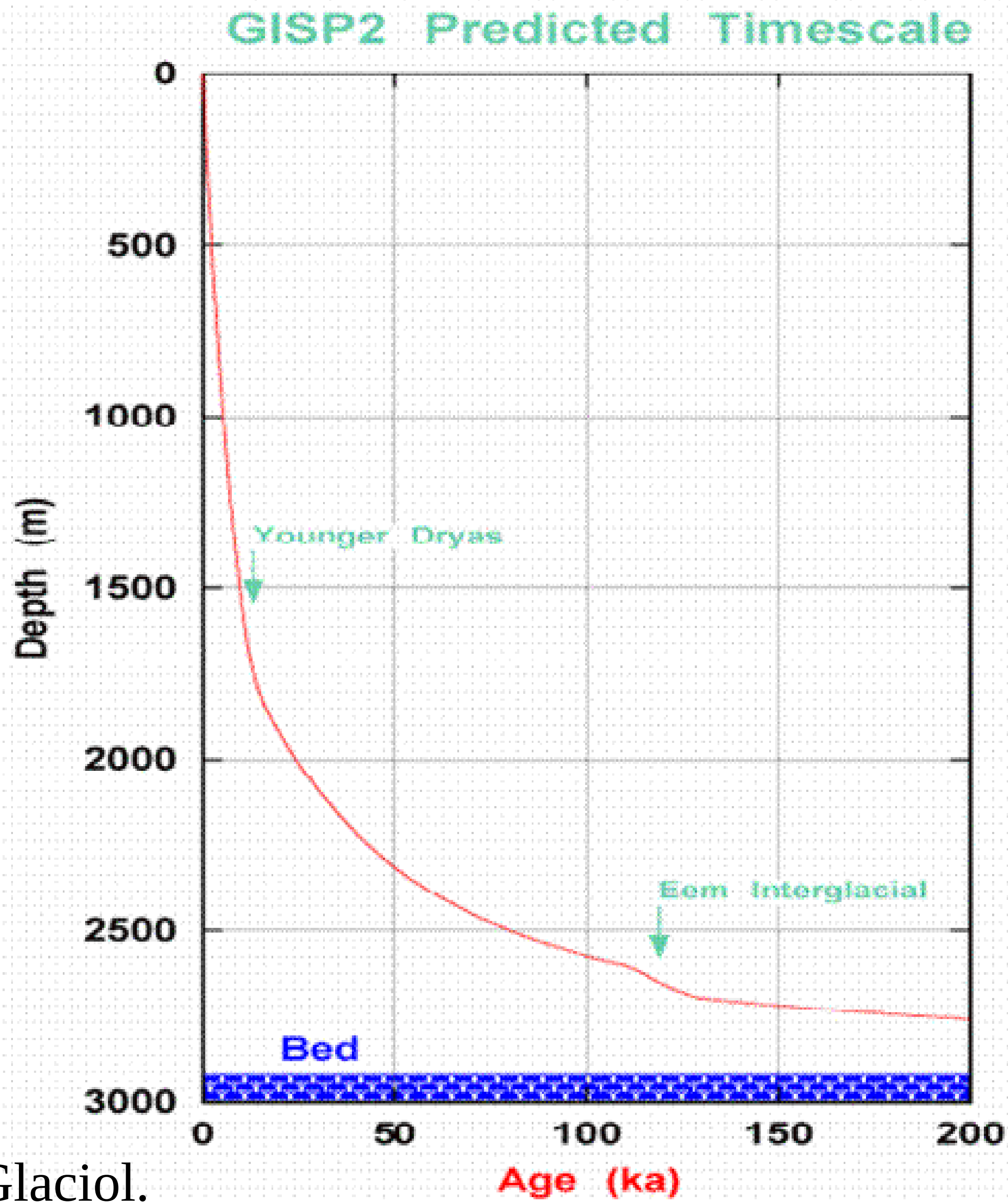
- The interesting questions about climate relate to the timing as much or more than to the values of climate parameters

Dating ice cores

Approaches

- Model-based time scales
- Layer counting
- Match well-dated cores with cores elsewhere (gas-based chronologies)
- Stratigraphic markers - find events whose ages are known

A model-based depth-age relation



Schott et al., 1992. J. Glaciol.

Layer counting - the concept

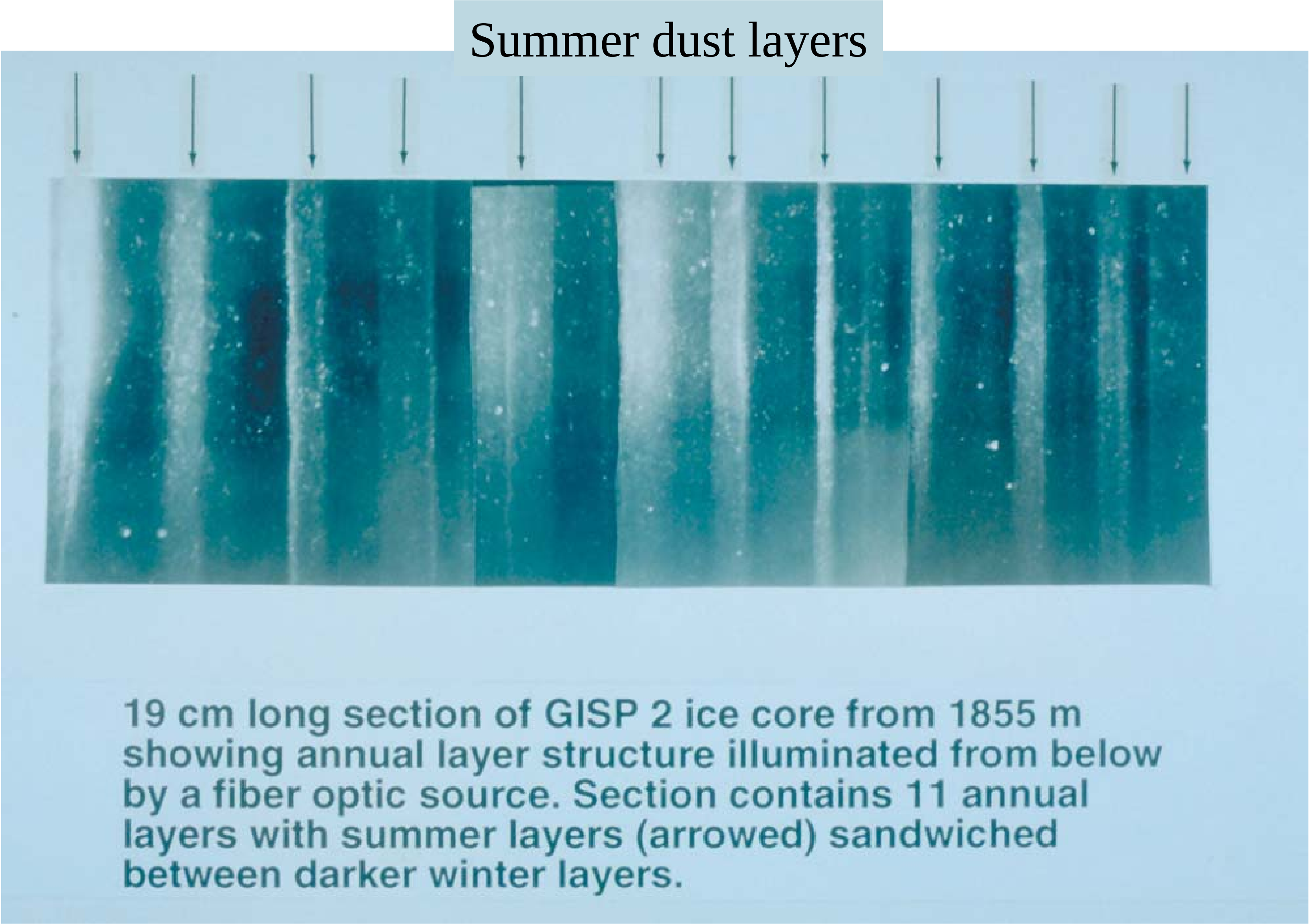
Parameters measured may show seasonal signal

- $\delta^{18}O$ higher in summer than winter
- annual dust layers

Validation/correction with stratigraphic markers

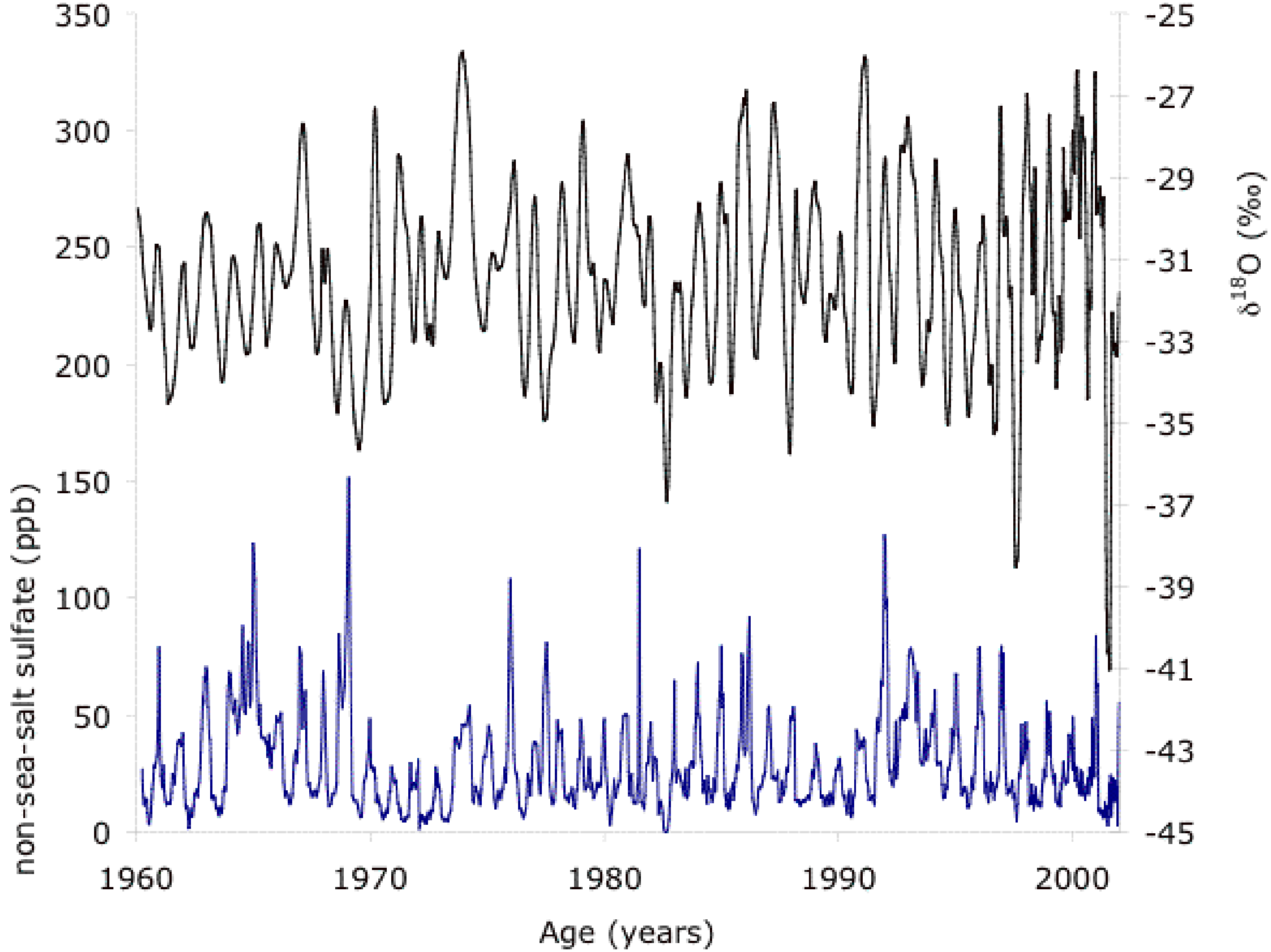
- volcanic ash or sulfate from events of known age

Layer counting - the practice



Seasonal Cycles

Seasonal temperature seen in $\delta^{18}O$



nss sulfate is released by spring blooms of marine plankton

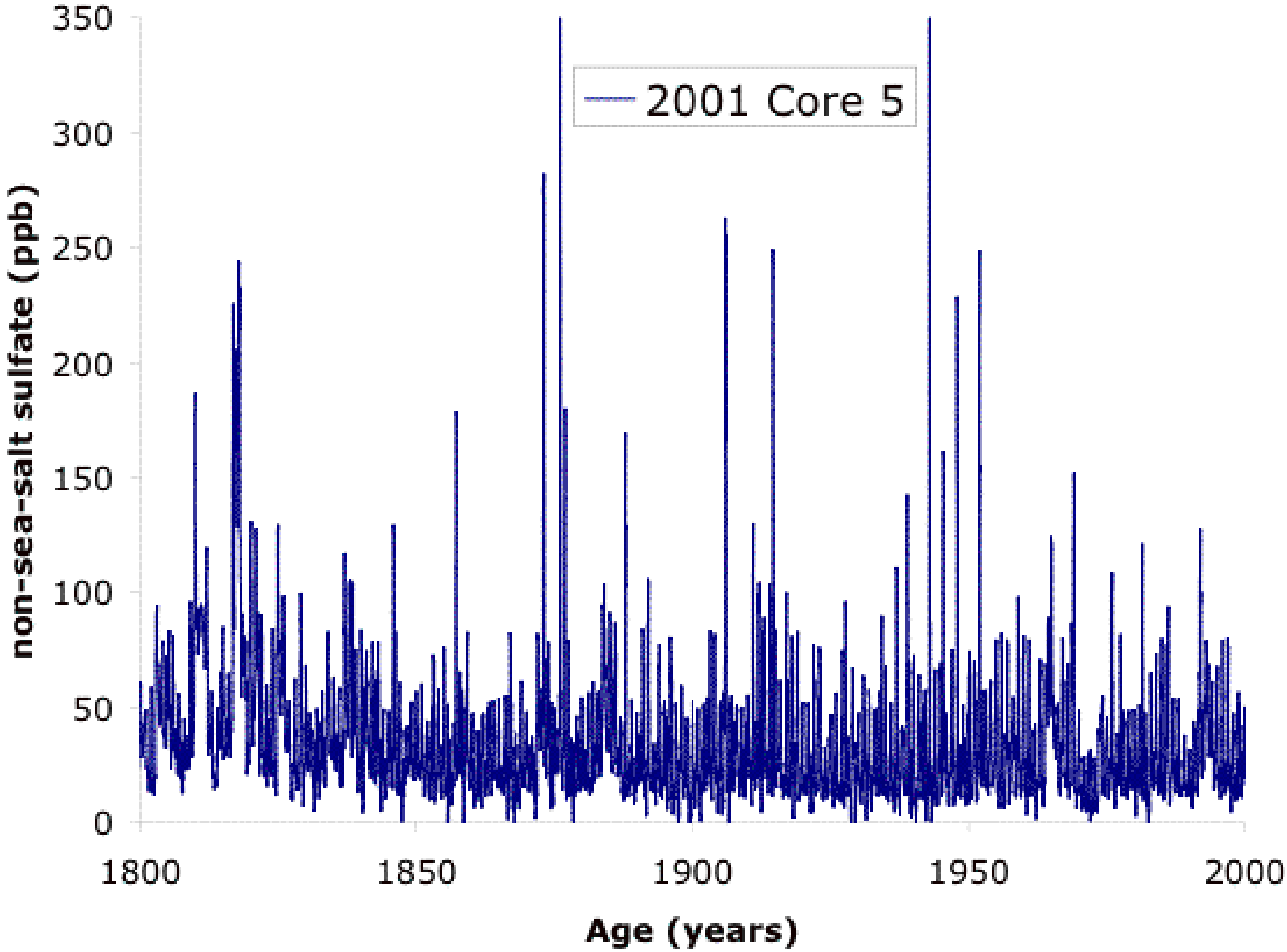
West Antarctica

How high can ***you*** count?

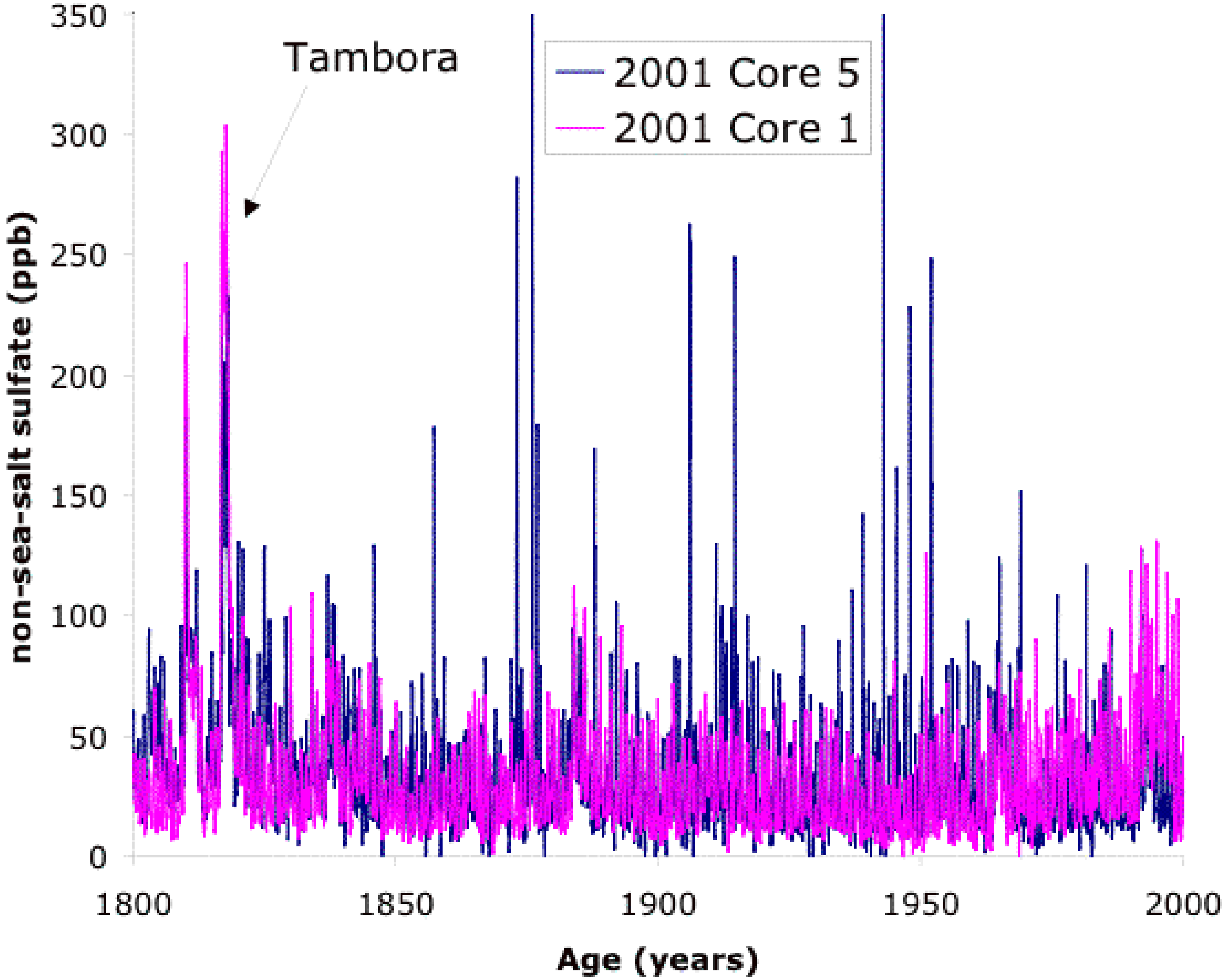
- Annual layers in GISP2 ice core were counted back to ~50 ka in 1994.
- Accuracy estimated to be ~1%

- This was an amazing achievement

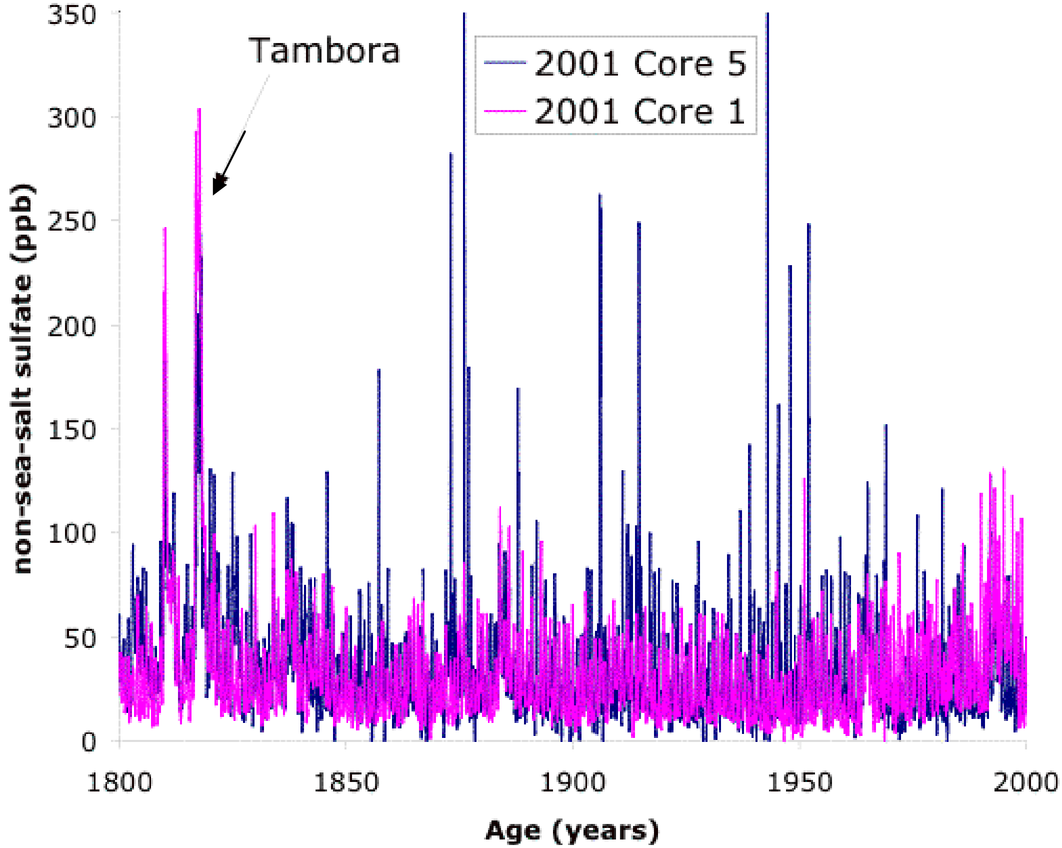
West Antarctic Ice Cores



West Antarctic Ice Cores



West Antarctic Ice Cores

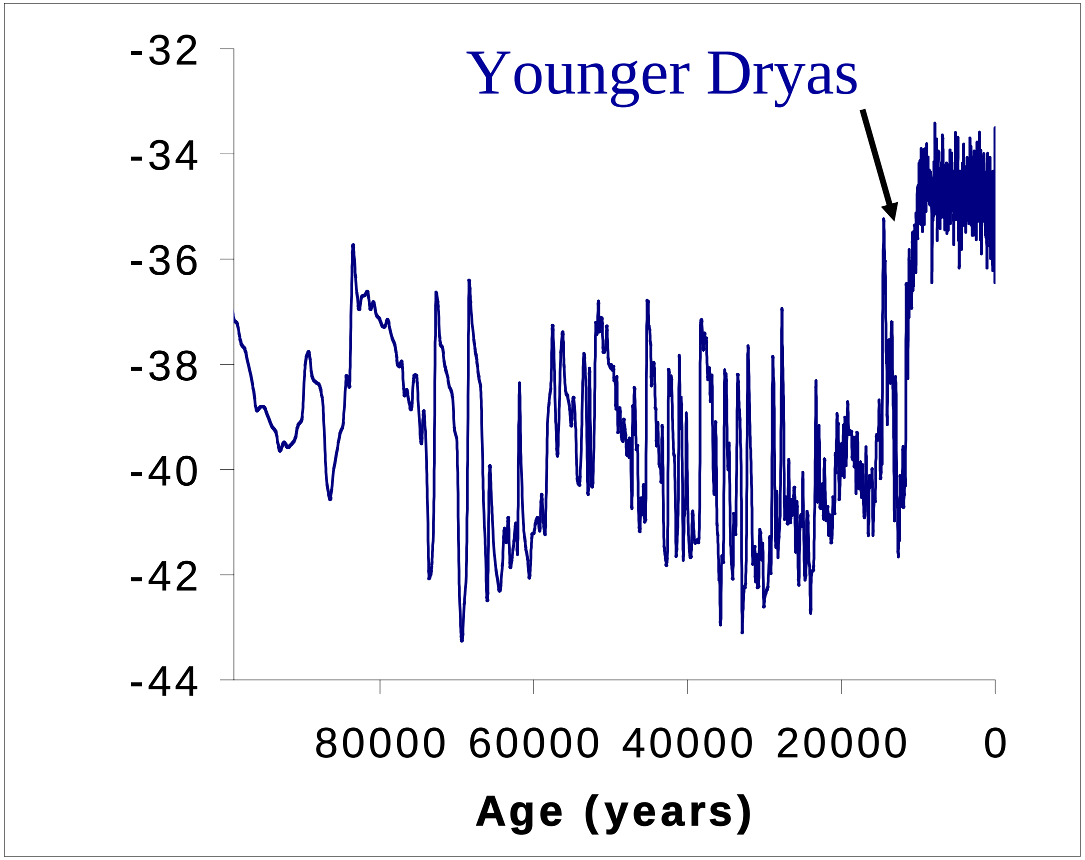


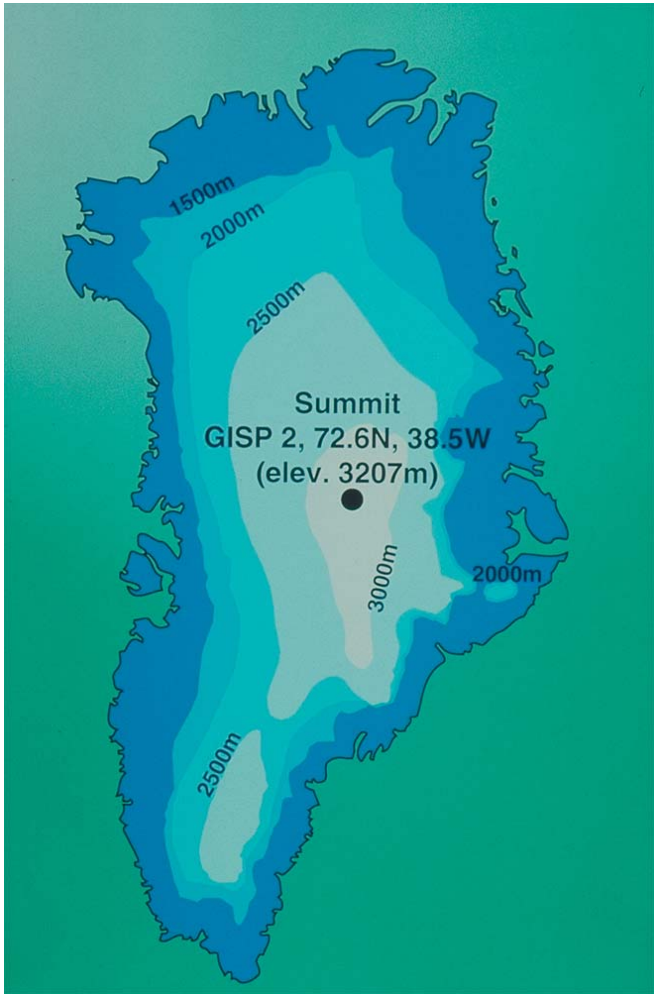
We can be sure the biggest spikes are volcanoes because they show up in cores far away from each other.

Counting seasonal cycles in sulfate shows that the big/wide spike shown by the arrow is at 1815, which is when Tambora volcano erupted in Indonesia. Tambora shows up in Greenland ice cores too.

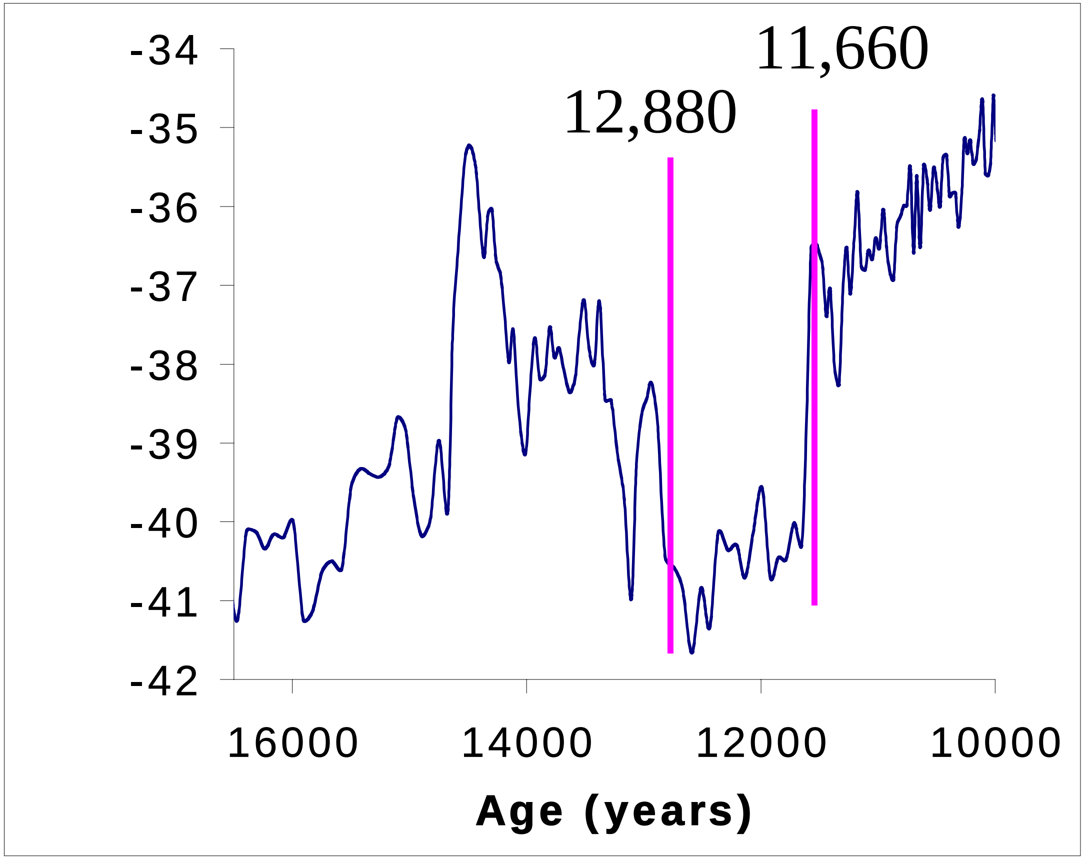
Central Greenland Ice Cores

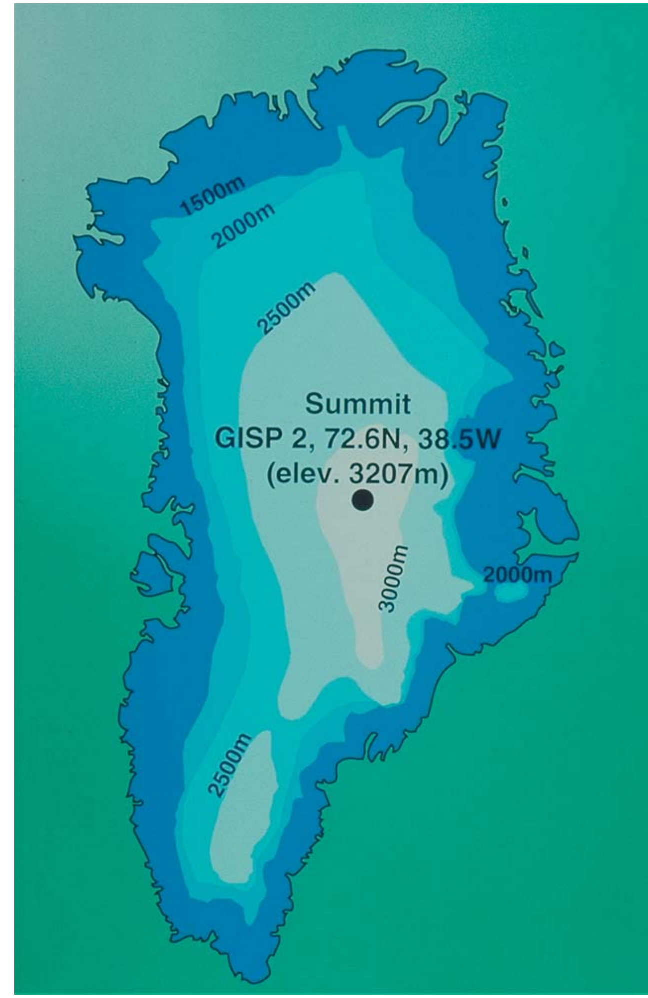
Many fast climate changes





Central Greenland Ice Cores



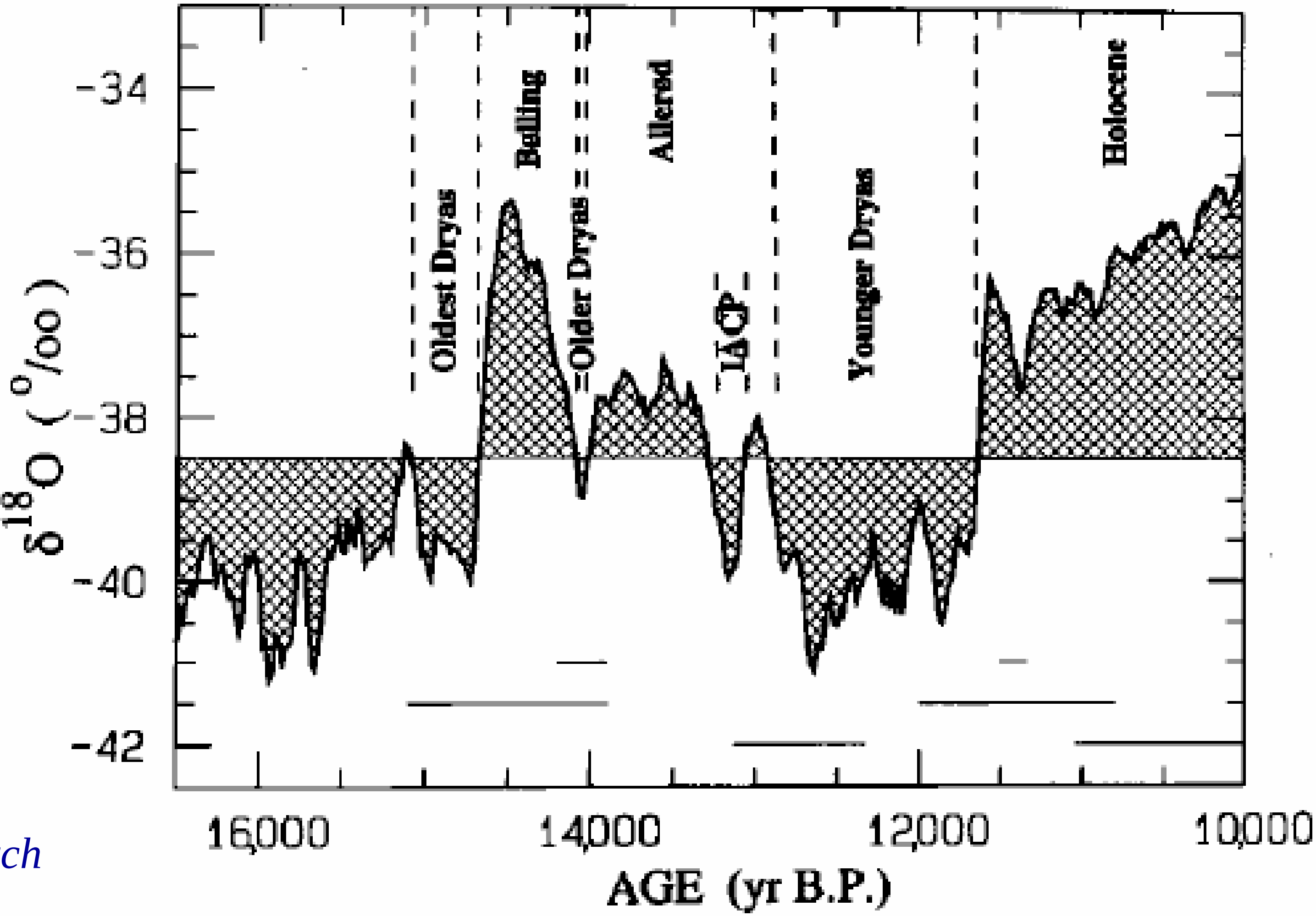


- Younger Dryas ended at 11,660 years.
- independently dated in GISP2 and GRIP.
- Uncertainty less than 100 years, or 1 percent.

Calibration of ^{14}C dating

- ^{14}C is produced by cosmic rays hitting N atoms in N_2 gas in the stratosphere
- Living organisms maintain levels of ^{14}C in equilibrium with the atmosphere until they die.
- To get a radio-carbon age, we measure the remaining ^{14}C and calculate the time since isolation, based on the radioactive decay of ^{14}C, with half life of 5,730 years.
- But what if the initial concentration in the atmosphere also changed over time?
- The radio-carbon time scale must be ***calibrated***

Ice-core records correlate with known climate events



Stuiver et al., 1995
Quaternary Research

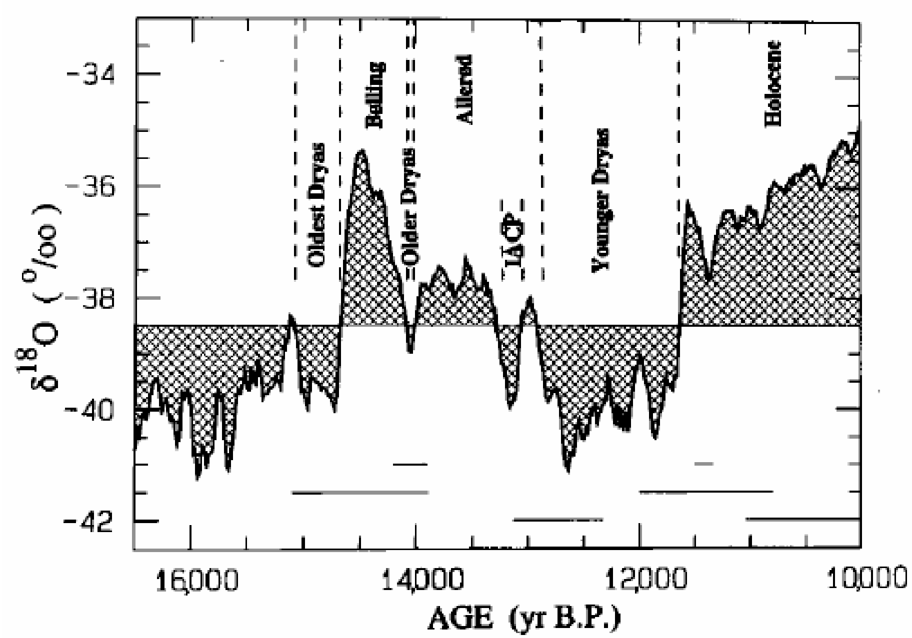
Climate intervals, known prior to ice-core drilling from European geological record, annotated on the GISP2 $\delta^{18}O$ data

Ice Cores and ^{14}C Dating

- Age of the YD is also independently dated with ^{14}C from corresponding vegetation changes in Europe
- Use ice-core stratigraphy to date chronostratigraphic intervals already known from the ^{14}C-dated geological record
- Obtain independent radiocarbon calibration

Assumptions:

- ice core is correctly dated
- climatic intervals in Greenland are the same as those identified in the pollen records from Europe.



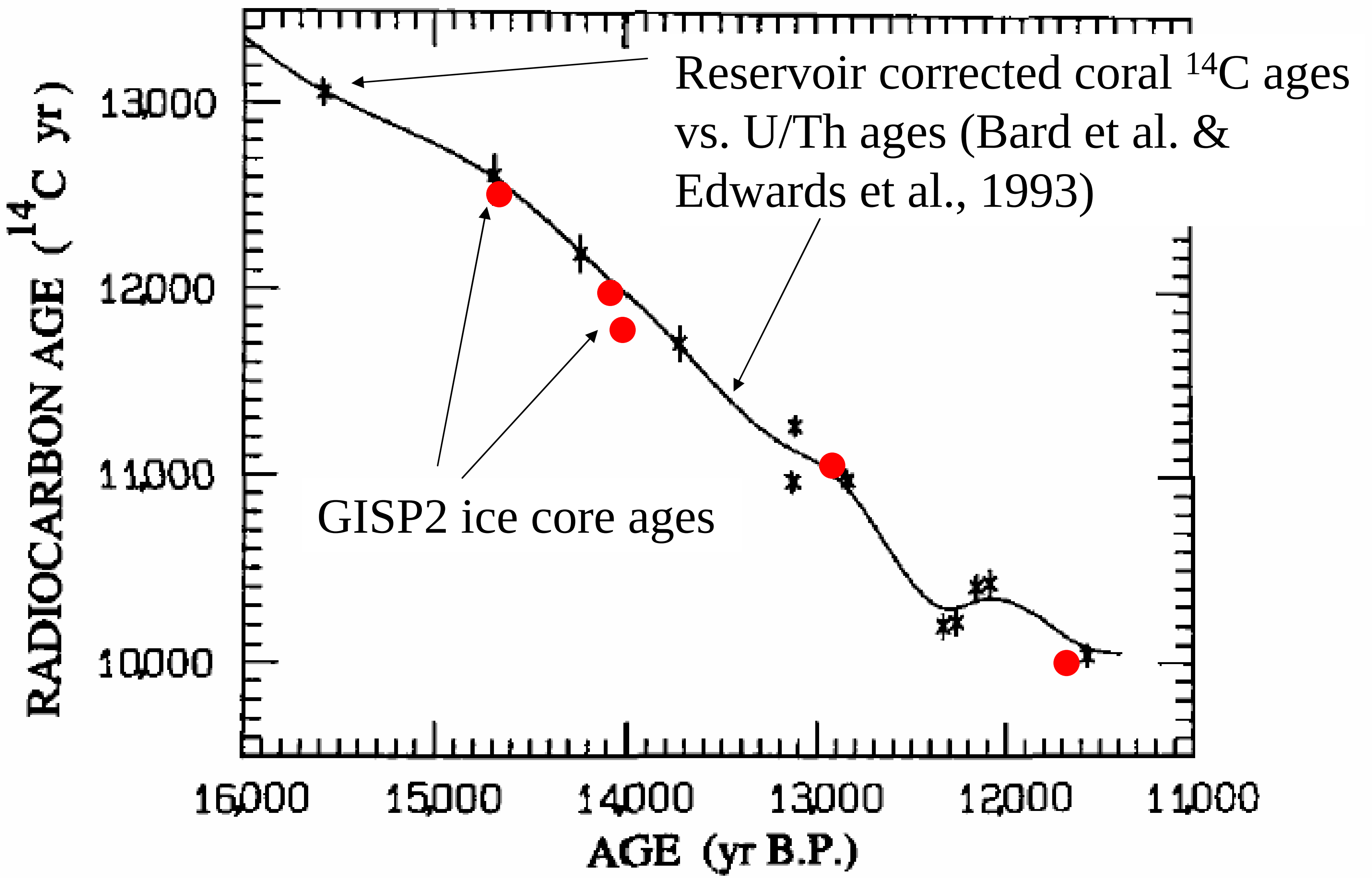
Stuiver and others, 1995. Quaternary Research.

Ages of Stratigraphic Boundaries

Chronostratigraphy	14C age (yr B.P. 1950)	Ice layer count (cal yr B.P.)
Younger Dryas ends	10,000	11,650
Allerod ends	11021+/-25	12,890
Older Dryas ends	11,800	14,010
Bolling ends	12000	14090
Oldest Dryas ends	12500	14670

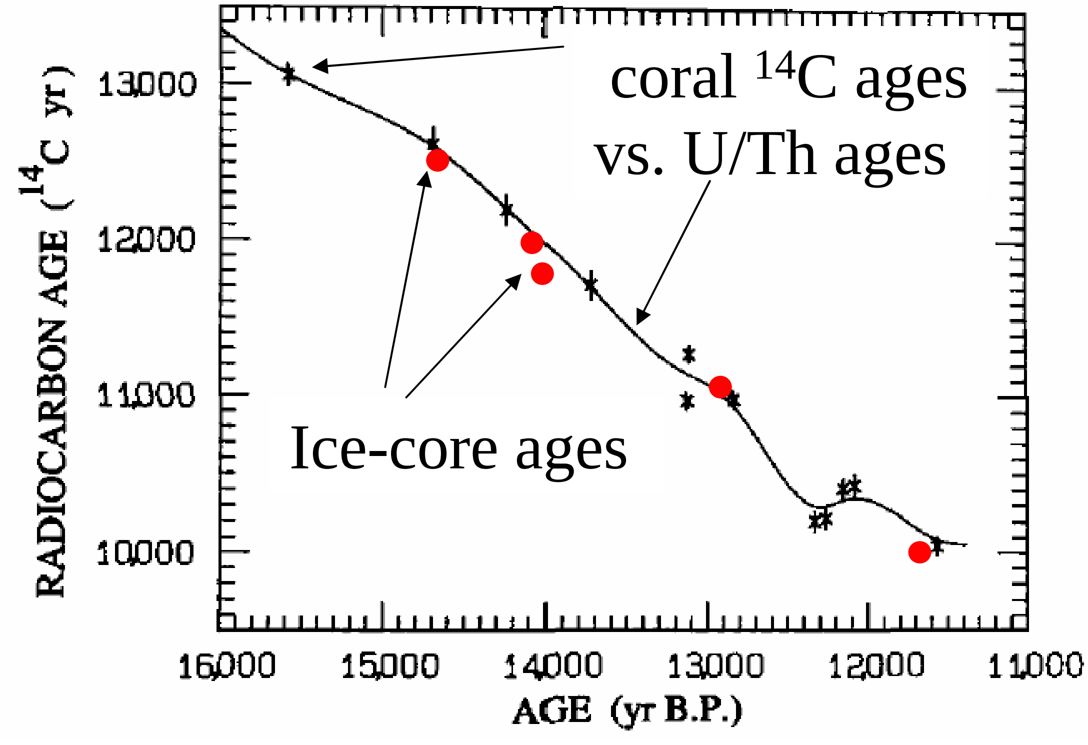
after Stuiver and others, 1995

Ice vs. coral radiocarbon calibration



Ice vs. coral radiocarbon calibration

Relative to the best available ^{14}C-calibration (from corals), the dating of the GISP2 ice core during this interval is not only precise, but is also accurate to within about 100 years



Paleothermometry

The Greenland ice sheet remembers the last ice age

Recall thermal diffusion time

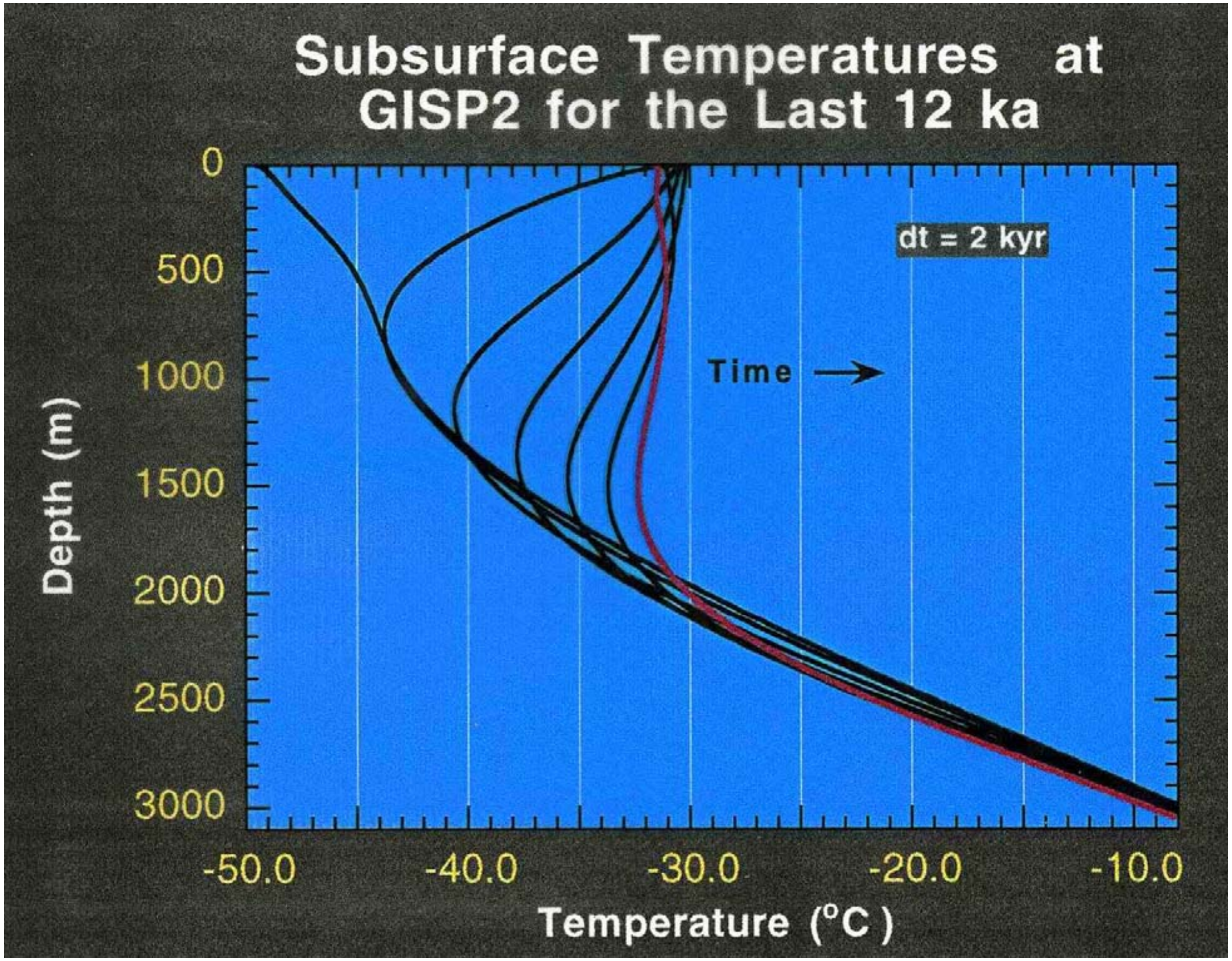
$\tau_{therm} = H^2/\kappa$

$\approx 200{,}000$ yr

and advection time

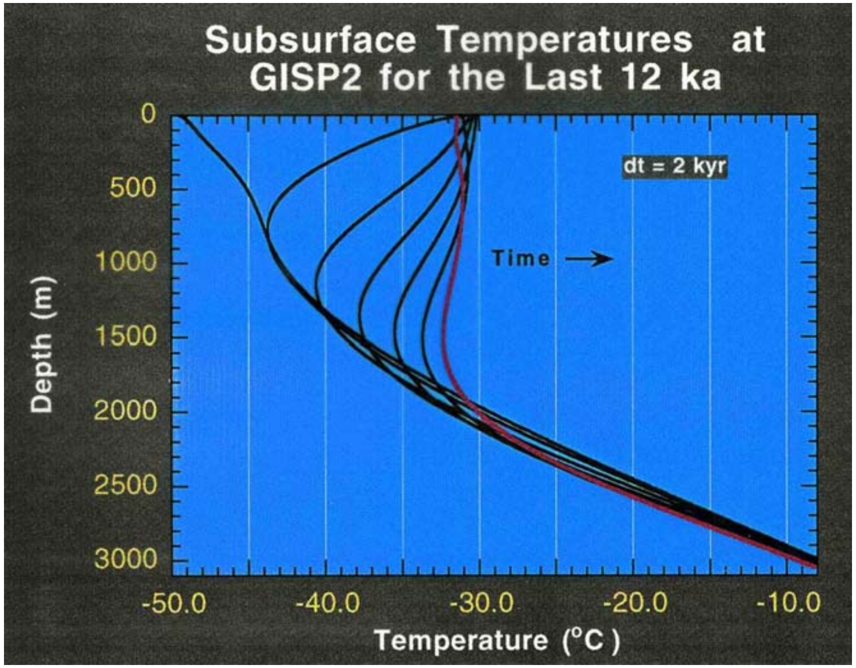
$\tau_{flow} = H/\dot{b}$

$\approx 10{,}000$ yr



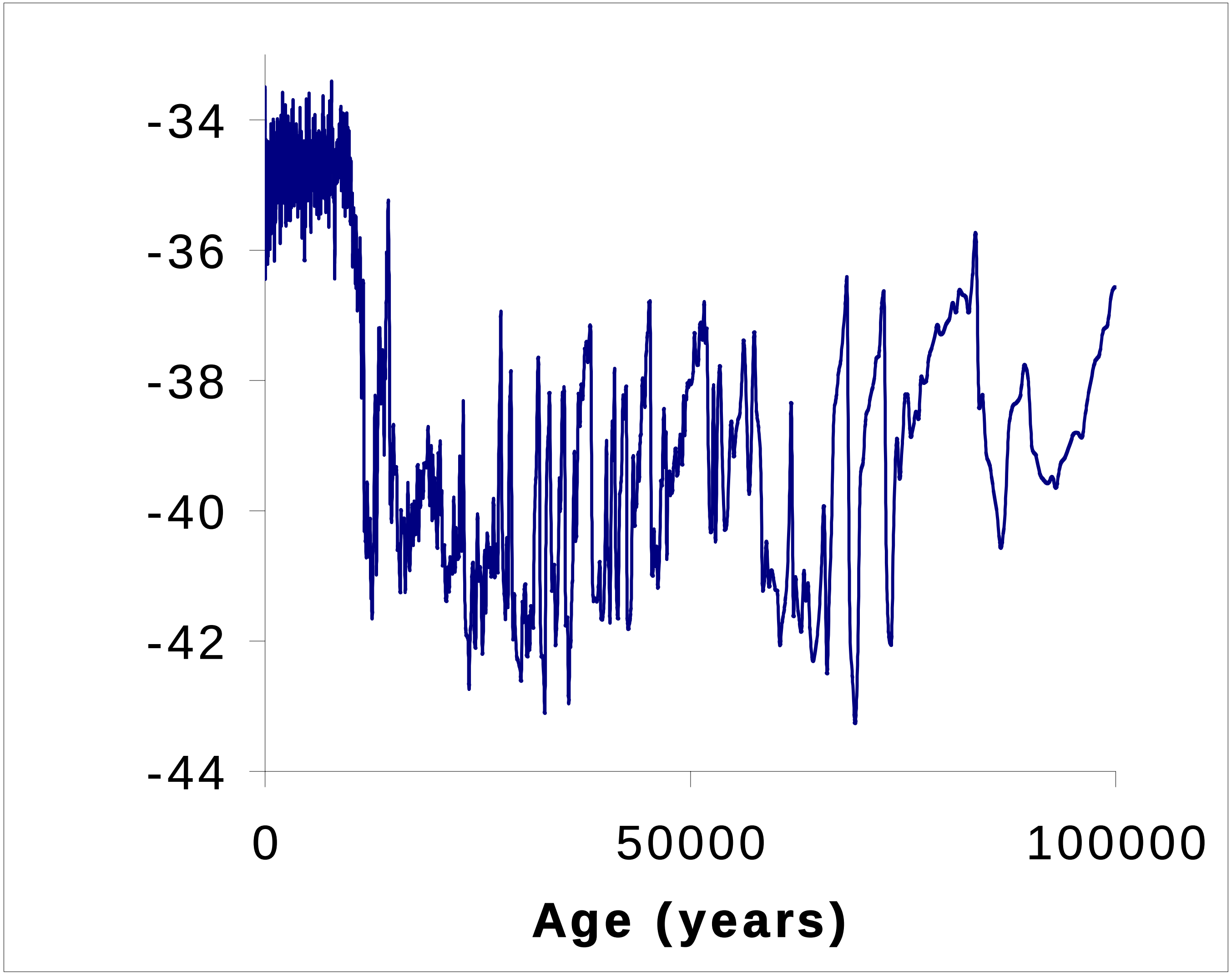
Paleothermometry

Using thermal advection-diffusion models, we can infer the actual temperature during the ice age from the shape of the temperature-depth profile today.



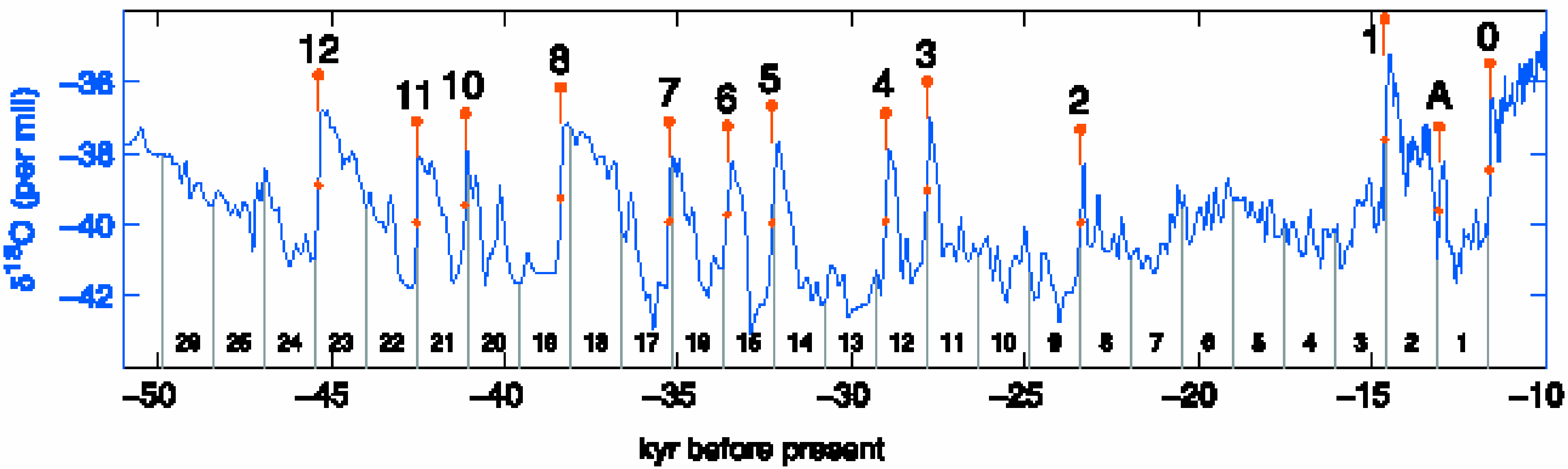
The Greenland summit was nearly 20°C colder at ~20 ka

Central Greenland Ice Cores



Evidence for fast climate change

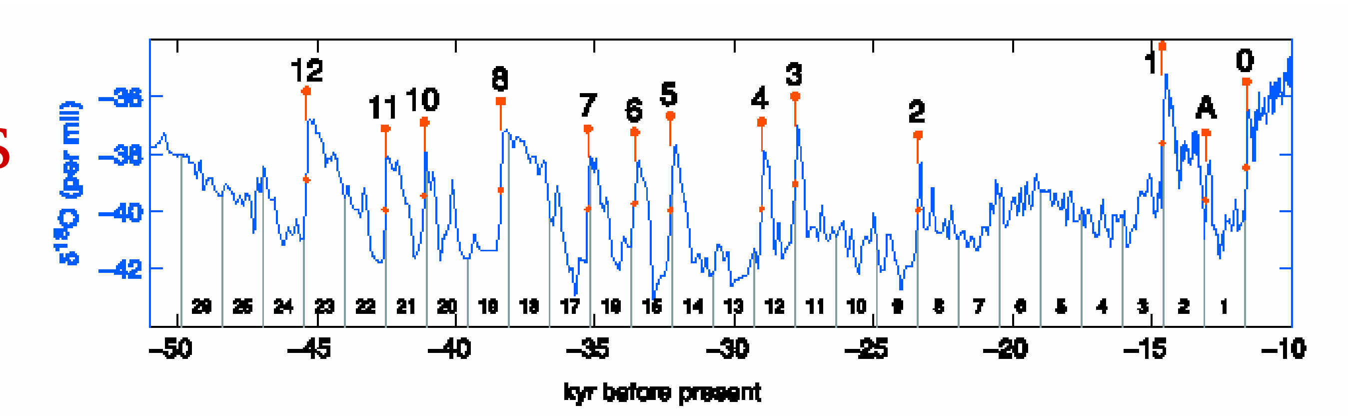
Rahmstorff's "Clock"



GISP2 rapid events occur with remarkable regularity on a 1,470 year clock, remembering phase to within 8% over more than 40,000 years.

- ***Stochastic Resonance***

Rahmstorff's "Clock"



stochastic resonance (Alley)

- sometimes a beat is skipped, but the next beat still occurs at the right time
- some underlying 1470-year cycle combines with threshold events -- presumably discharges of icebergs -- that can only occur at the top of a cycle.

Stochastic Resonance

- An oscillating system is always changing, subjected to random prodding
- The prodding may drive system into a new state
- But only if prodded at the right time

- What is the oscillation in the climate system?
- What are the nudges that push it over the edge?

- Wish we knew …

What can we learn from ice cores besides past temperatures?

Ice-Core Stories

Temperature

- stable isotopes $\delta^{18}O$ and δD; ^{15}N and ^{40}Ar
- borehole temperatures

Precipitation

- annual layer thicknesses,
- ^{10}Be - constant fallout diluted by snowfall

Synoptic systems and Wind

- dust – amount and provenance

Greenhouse gases

- air trapped in bubbles

Modes of Deposition

Dry fallout

- SO_4^{2-}, ^{10} Be, dust

Wet deposition

- Na^+, Cl^-, SO_4^{2-}

Gas occlusion in bubbles

- CO_2, CH_4

Temperature and Accumulation Rate

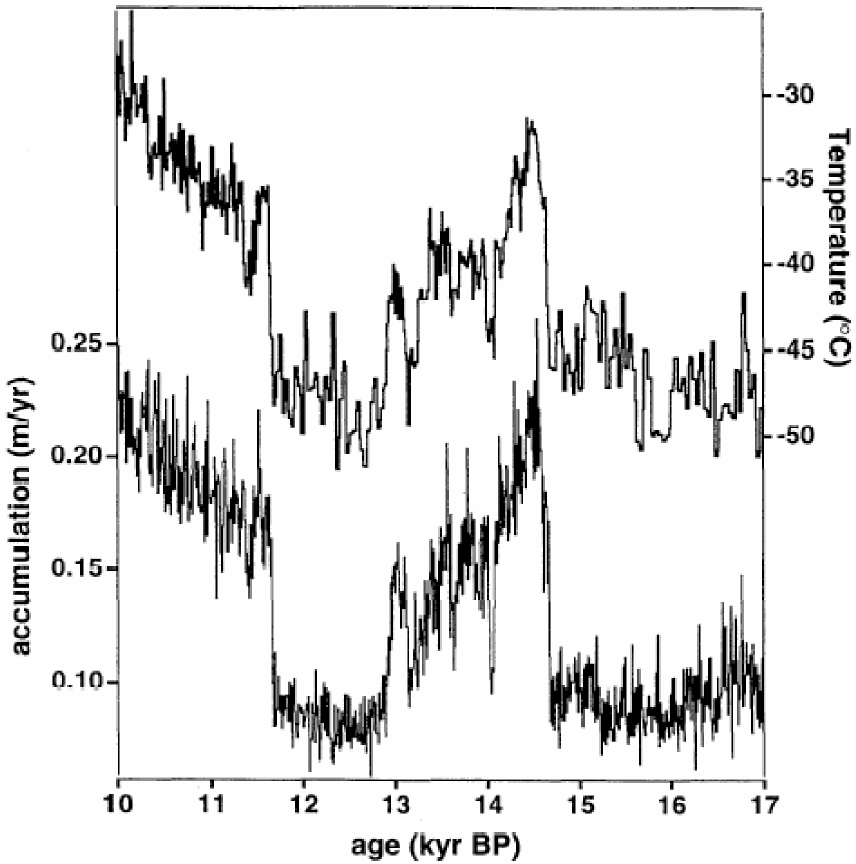
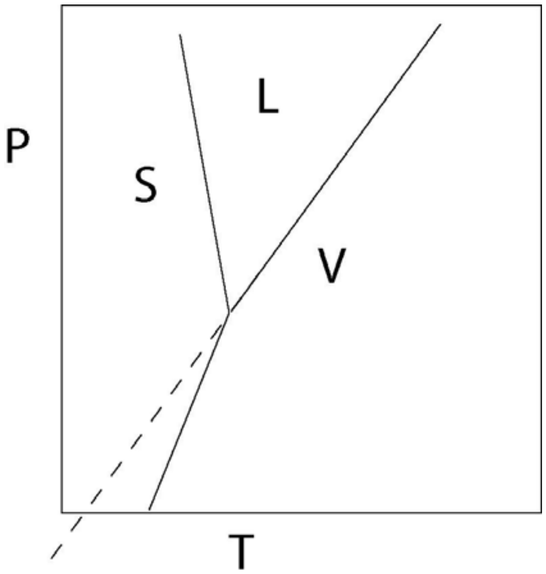


Figure 4. Comparison of the accumulation and δ records at the GISP2 site for the period between 18 and 10 kyr B. P. (adapted with permission from *Nature* [*Kapsner et al.*, 1995]; copyright Macmillan Magazines Limited), in using a calibration of 0.33‰/°C instead of 0.53‰/°C (see text).

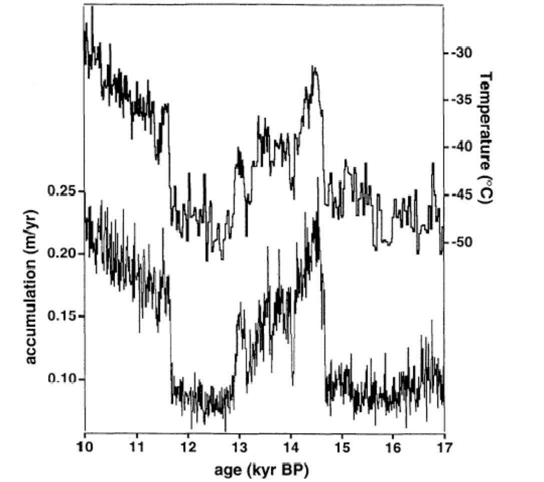
Is accumulation controlled by saturation vapor pressure?

Remember the phase diagram for H_20



Temperature and Accumulation Rate

- On time scales of thousands of years, there is a very strong correlation between precipitation rate and $\delta^{18}O$ (shown here converted to temperature) on the Greenland ice sheet



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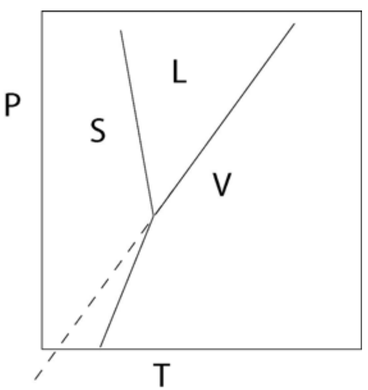
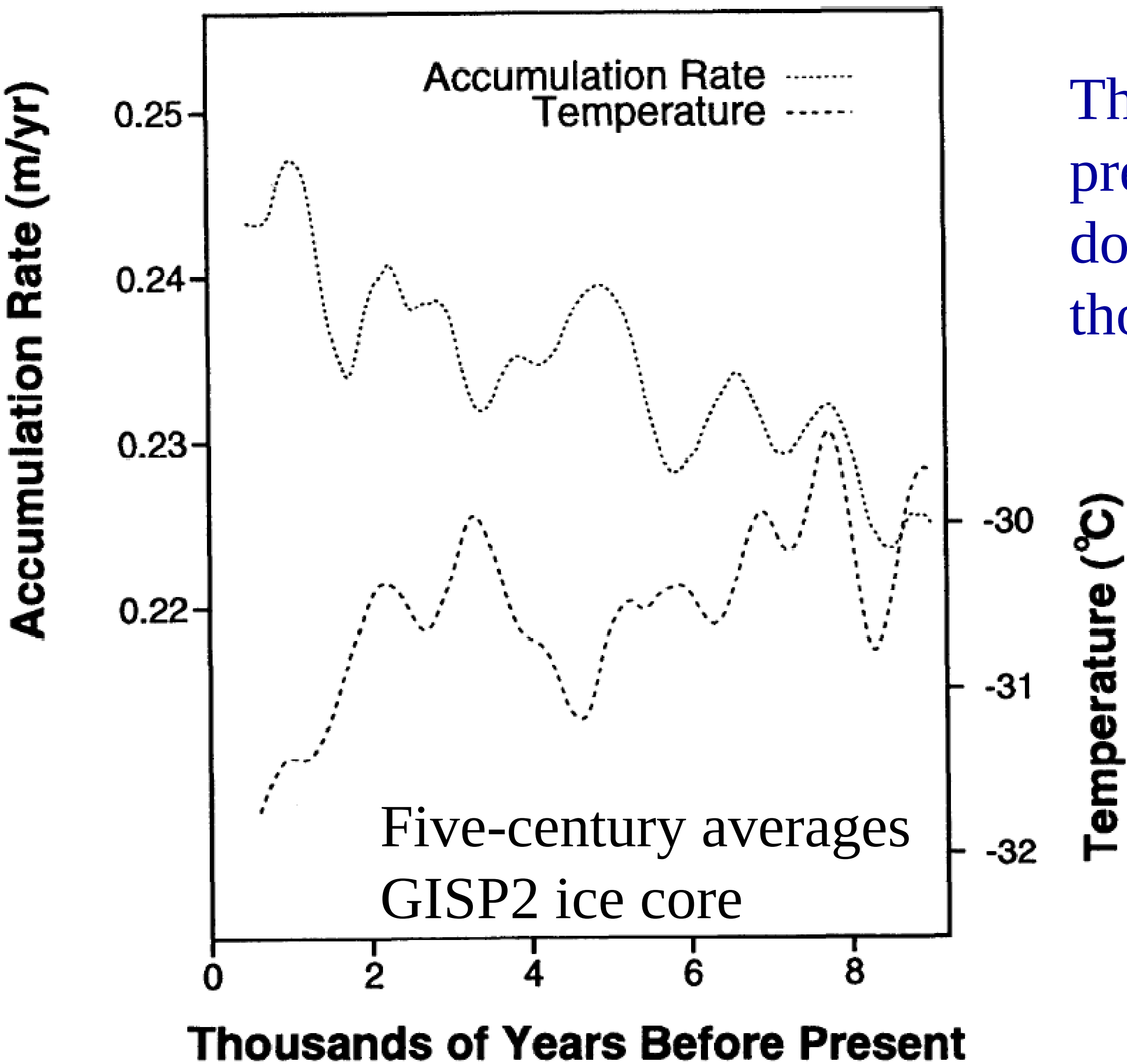
So what?

- This supports the concept that $\delta^{18}O$ in precipitation is controlled by temperature via the “fraction of water remaining”.



- This idea also works well for the Antarctic ice sheet

Temperature and Accumulation Rate

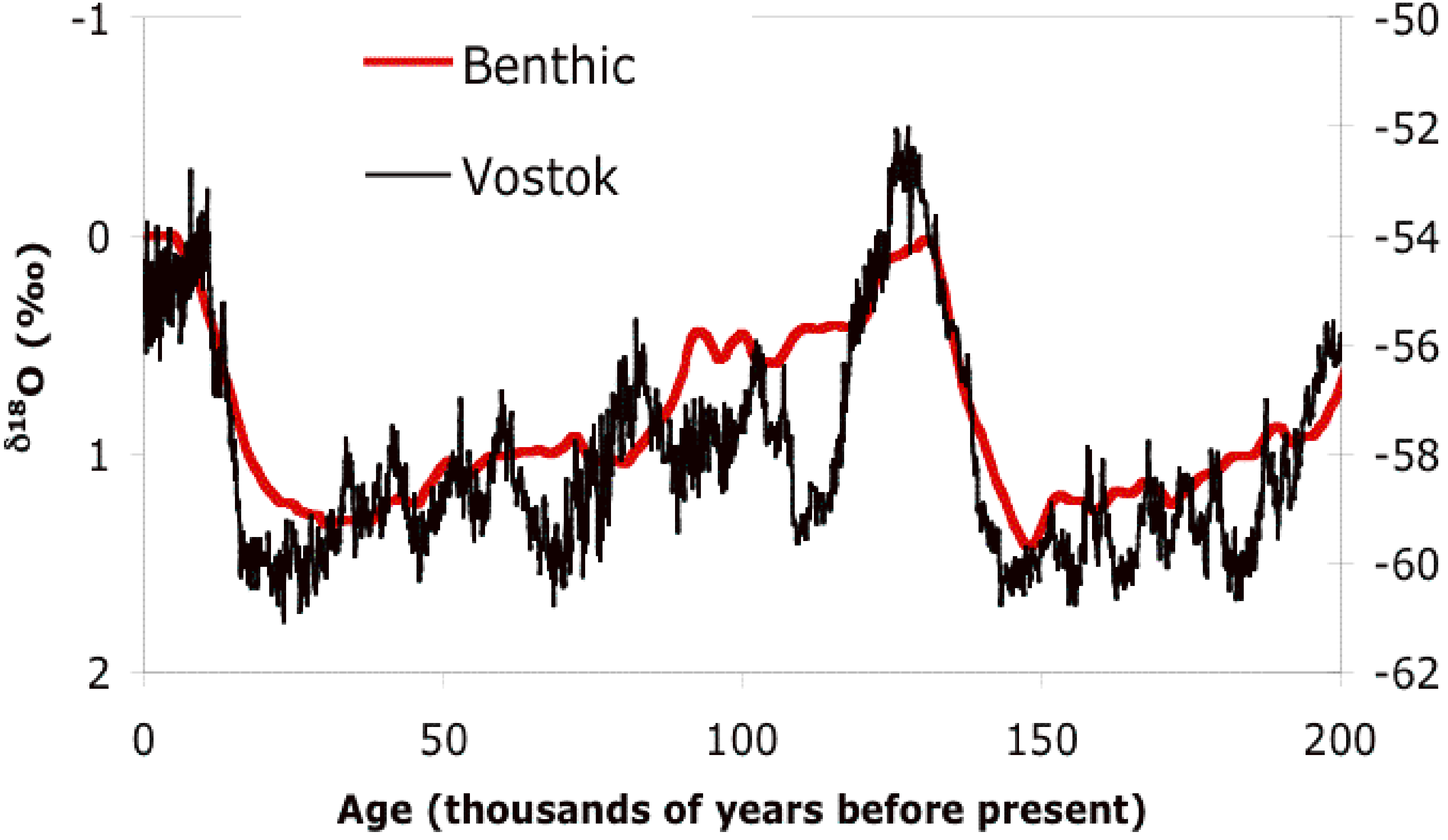


The saturation vapor pressure connection doesn't always work though …

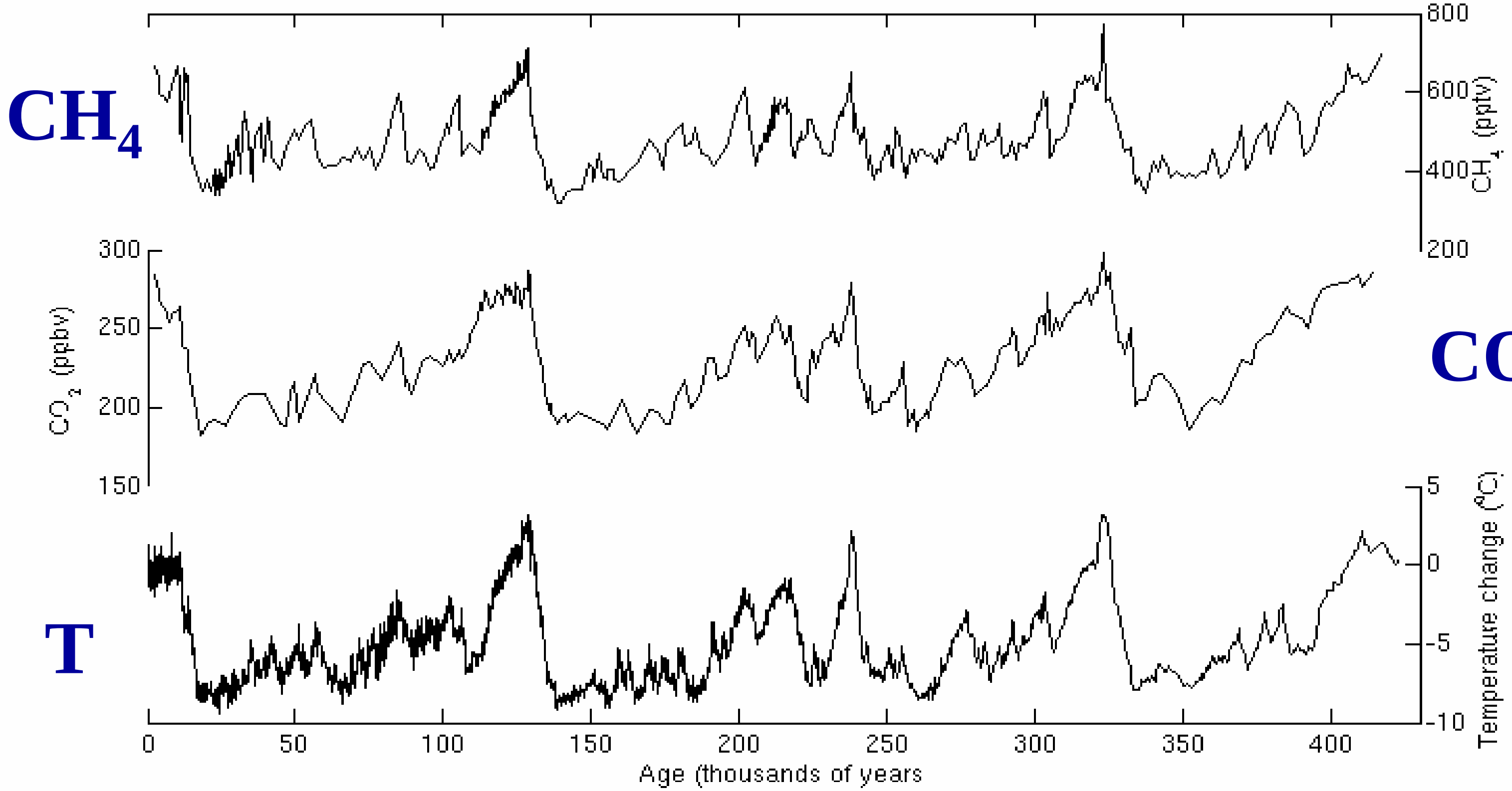
Why not?

Cuffey K.M. and G.D. Clow. 1997. *JGR* 102(C12).

Temperature and Ice Volume



Greenhouse Gases and Ice-Age Temperature

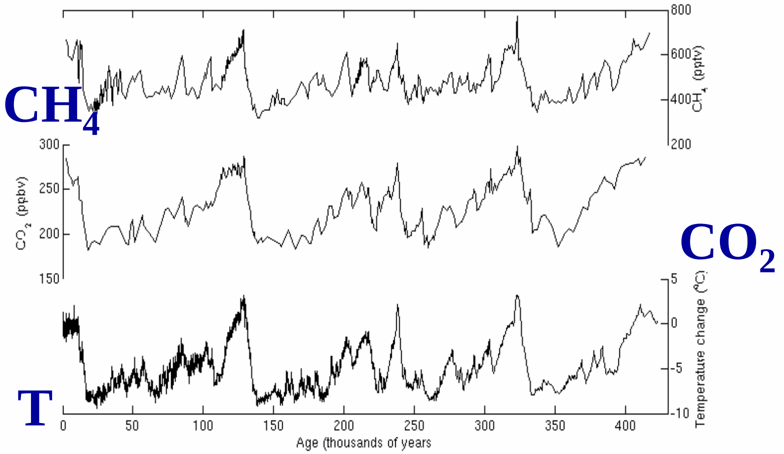


Temperature (isotopes), CO_2 and CH_4 (methane) for the last 420 ka from Vostok ice core, East Antarctica

A Major Discovery through Ice Cores

- Not only did temperature and ice volume follow each other through the ice ages, so did greenhouse gases.
- Does T lead CO_2 or the reverse?
- This turns out to be an important but difficult problem, because even though the CO_2 and the isotopes are from the same core, their relative ages are not known directly.

Why not?



Ice holds samples of our past atmosphere

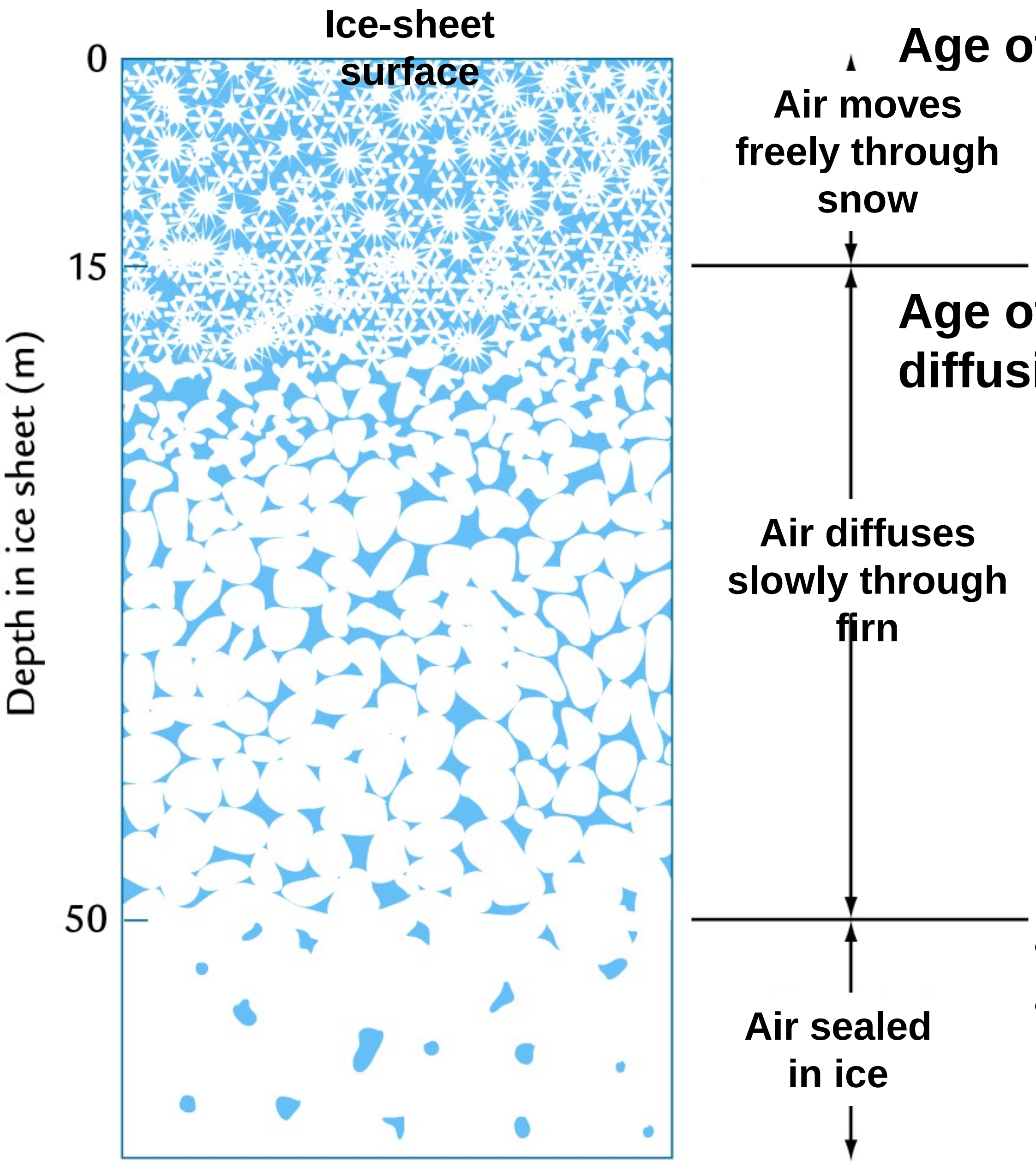
Ice core from Peru, (with Lonnie Thompson, right) is clear (with distinct annual layers, too), but bubbly.

Troubles with dating

Why can't we directly know the age relationship between gas concentrations and water isotopes in ice cores?

- It has to do with the way snow traps gas, as it is transformed to ice


It’s in the
bubbles …



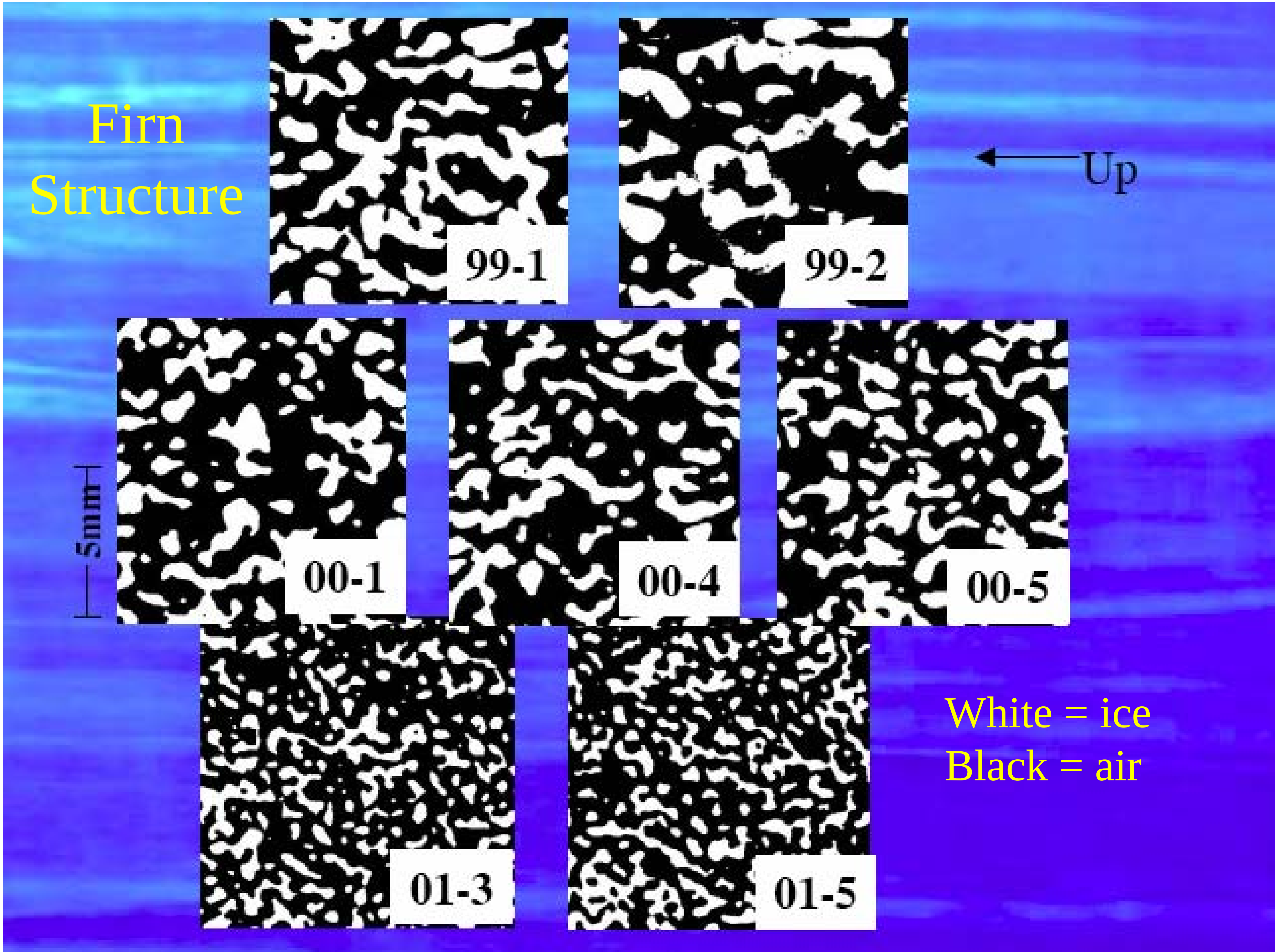
Age of ice at surface = 0 years

Age of gas at top of diffusive zone = 0 years

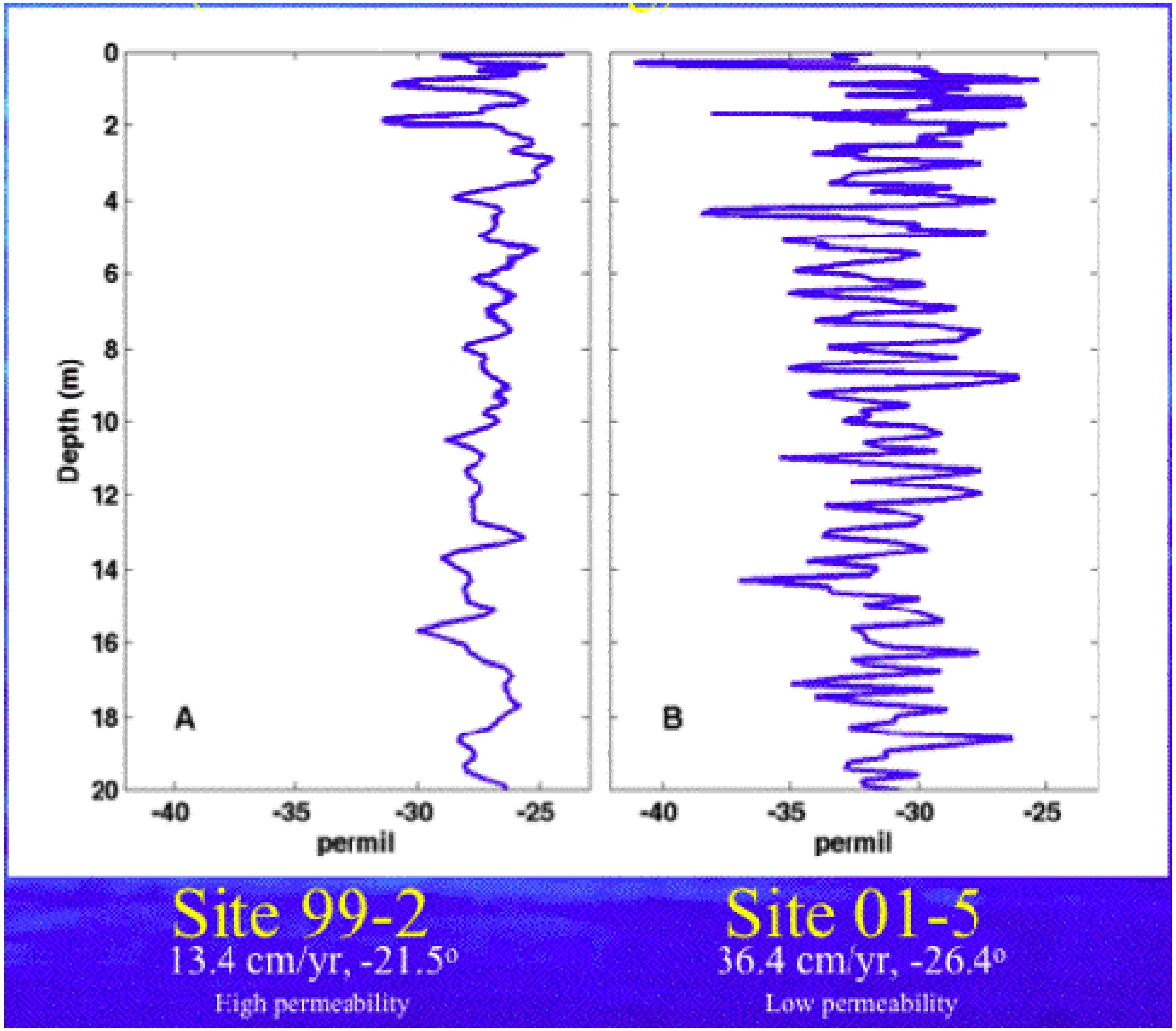
ΔAge

- gas is young
- ice is old

But how much older?

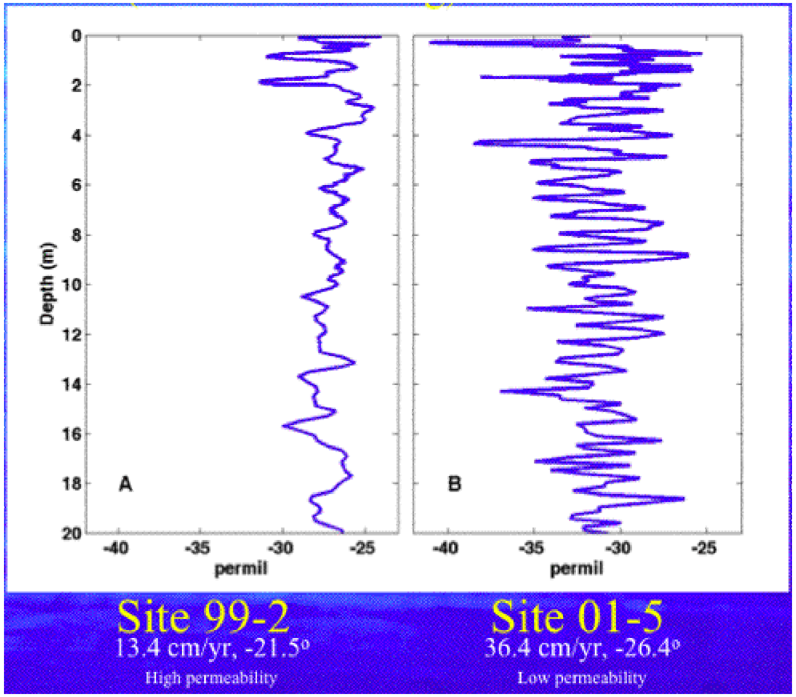

Firn
Structure
99-1
99-2
Up
5mm
00-1
00-4
00-5
01-3
01-5
White = ice
Black = air

Evidence for Gas Mobility in Firn



Permeability: high low

Evidence for Gas Mobility in Firn



- In pore spaces, H_2O is sublimating and re-depositing
- With open pore spaces, gases such as water vapor (including water isotopes) can move and mix.
- This tends to smooth the stable isotope signal over time.

Calculating Δage

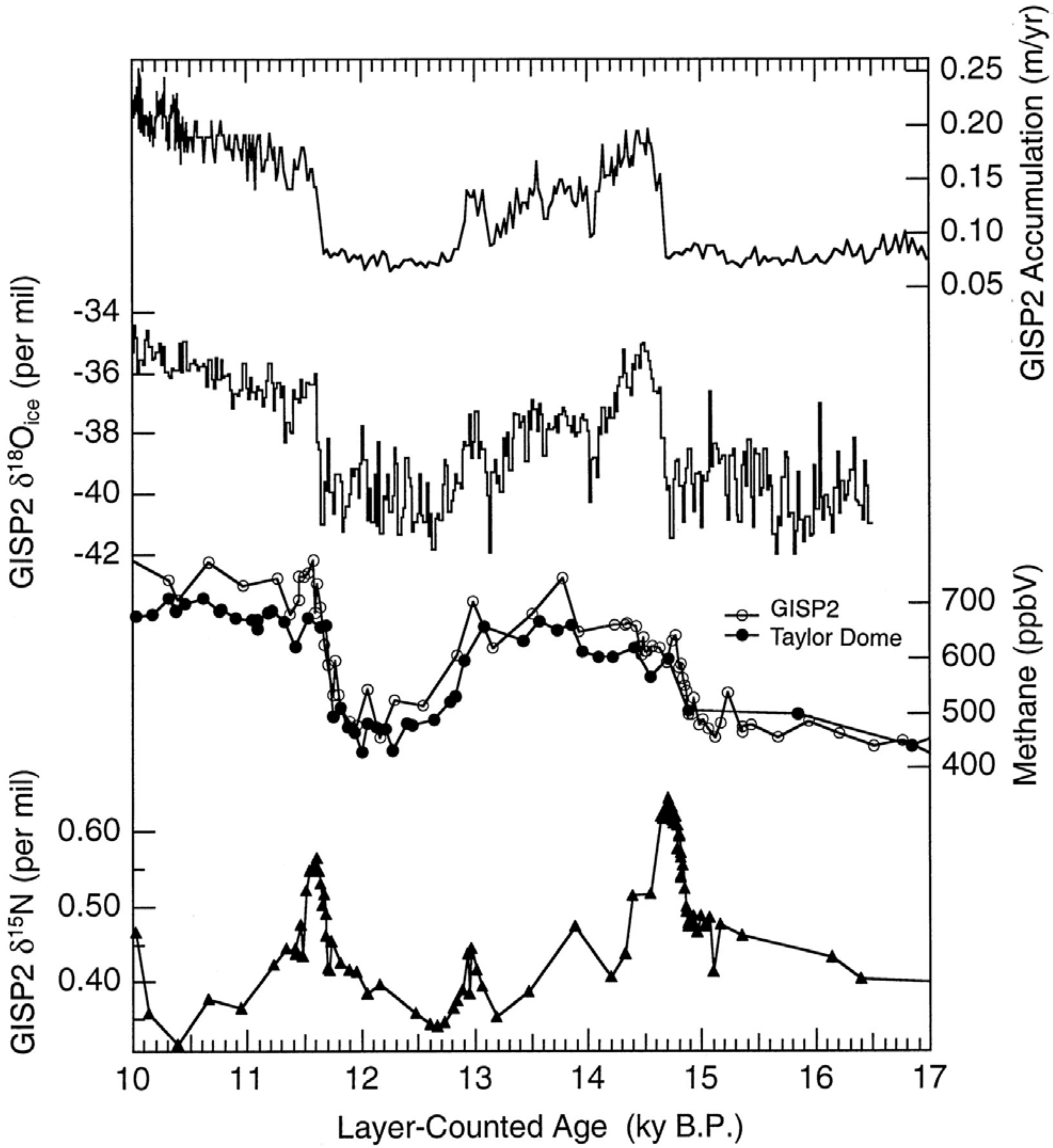
- Δage is the age difference between the gas bubbles and the ice surrounding them.
- Δage depends on the processes converting snow to firn and eventually ice, sealing off air bubbles
- These processes are dependent on **temperature** and **snow accumulation** rate; wind and other meteorological factors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

Other isotopic indicators of fast climate change

- $\delta^{15}N$ measures enrichment of rare isotope ^{15}N
- Note spikes at times of fast climate change



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

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 temperature change

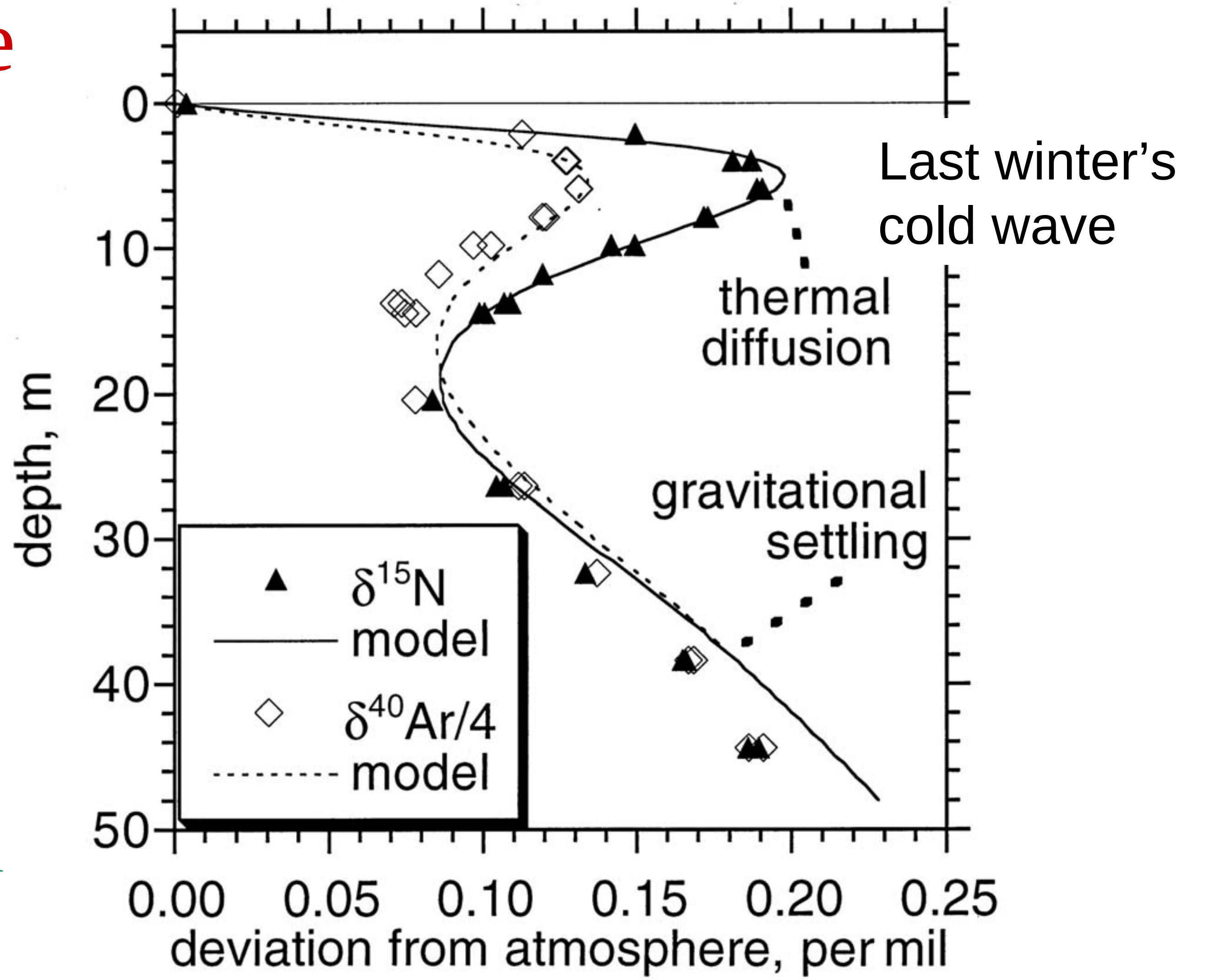
N_2 gas is largest component of atmosphere.

In still air in pore spaces, gas with heavy isotope e.g. ^{15}N tends to

- Settle to bottom
- Move toward cold

- Here we see seasonal effects

Summer on the ice cap



How can this be exploited?

In steady state, gas with heavy isotopes is

- Drawn downward by gravity
- Drawn upward to cold surface

- Competing effects minimize differences between free atmosphere and closing bubbles at depth

Result: $\delta^{15}N \approx 0$ in trapped bubbles

How can this be exploited?

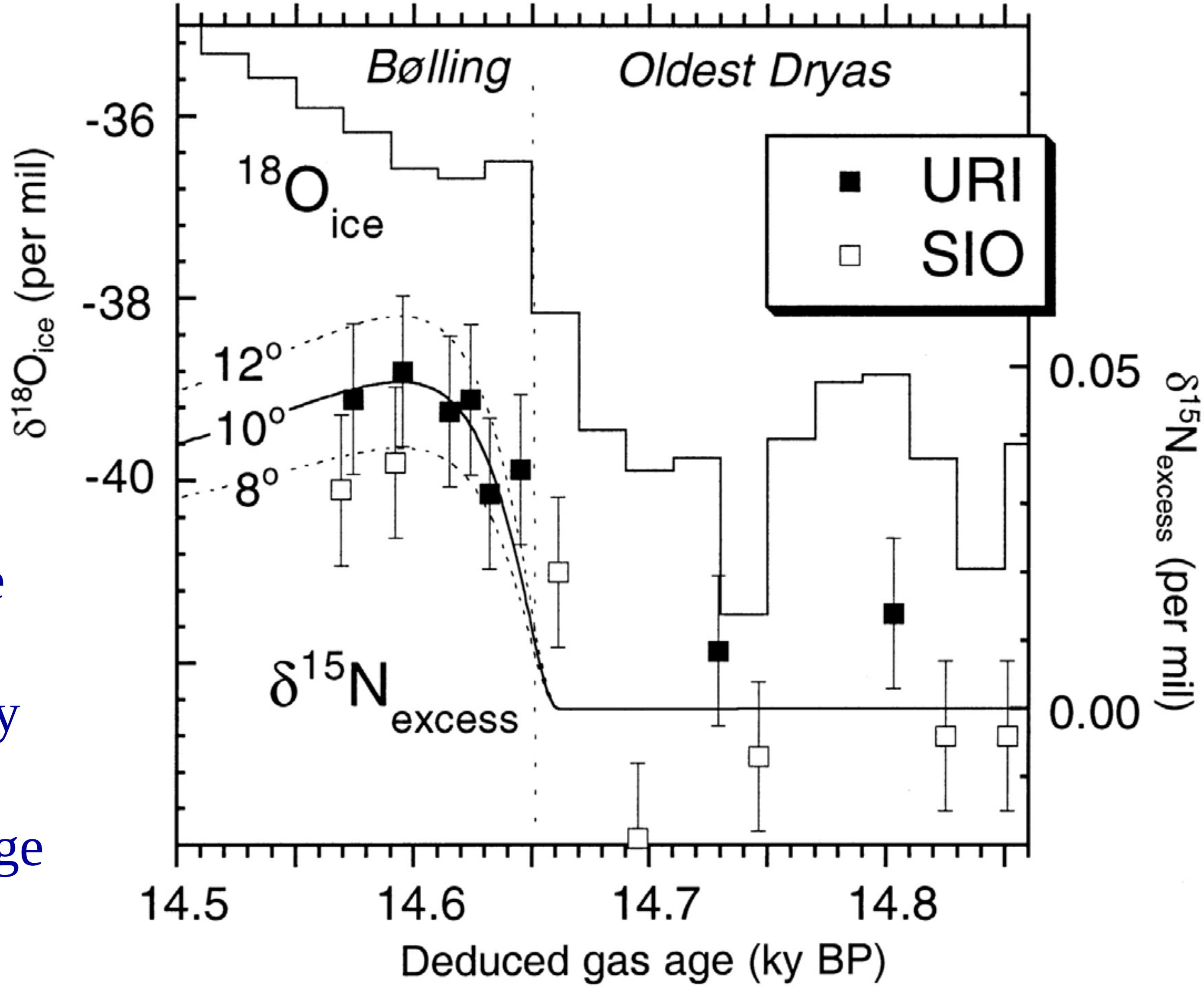
After rapid climate warming, gas with heavy isotopes is

- Drawn downward by gravity
- Drawn downward away from warm surface

- Complementary effects maximize differences between free atmosphere and closing bubbles at depth

Result: strongly positive $\delta^{15}N$ in older ice trapping bubbles at time of warming climate

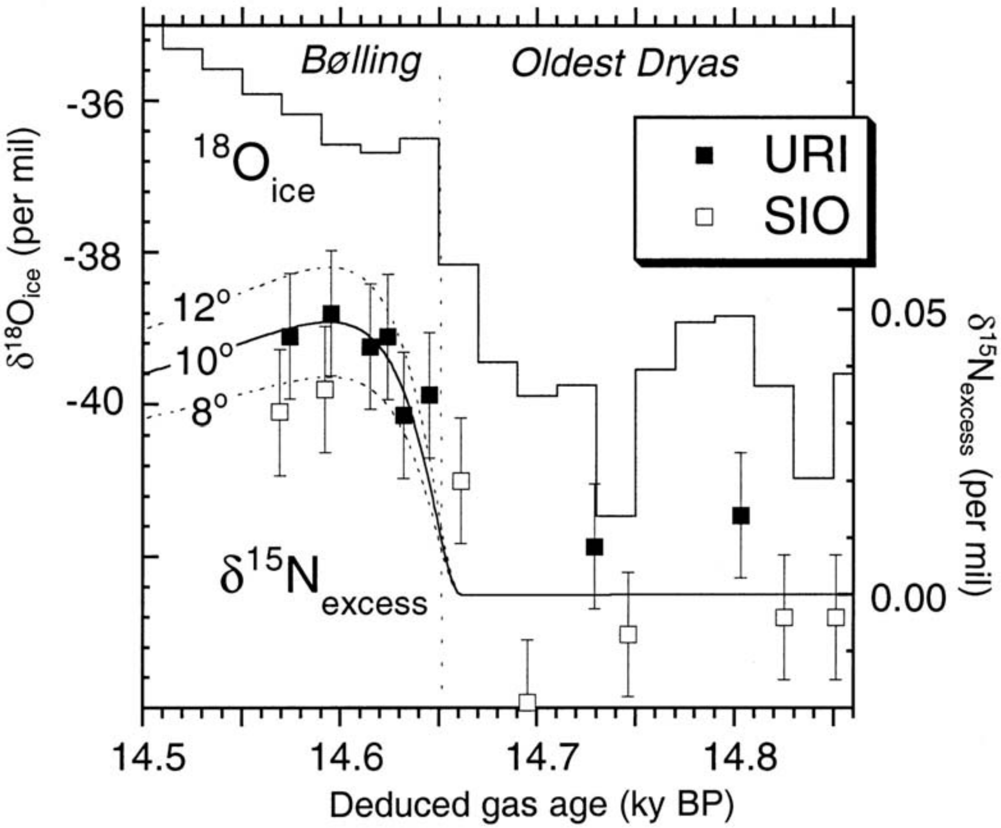
Fast Temperature Change in Greenland



$\delta^{15}N$ signal is found in older ice than the $\delta^{18}O_{ice}$ temperature proxy signal

- Difference is Δage

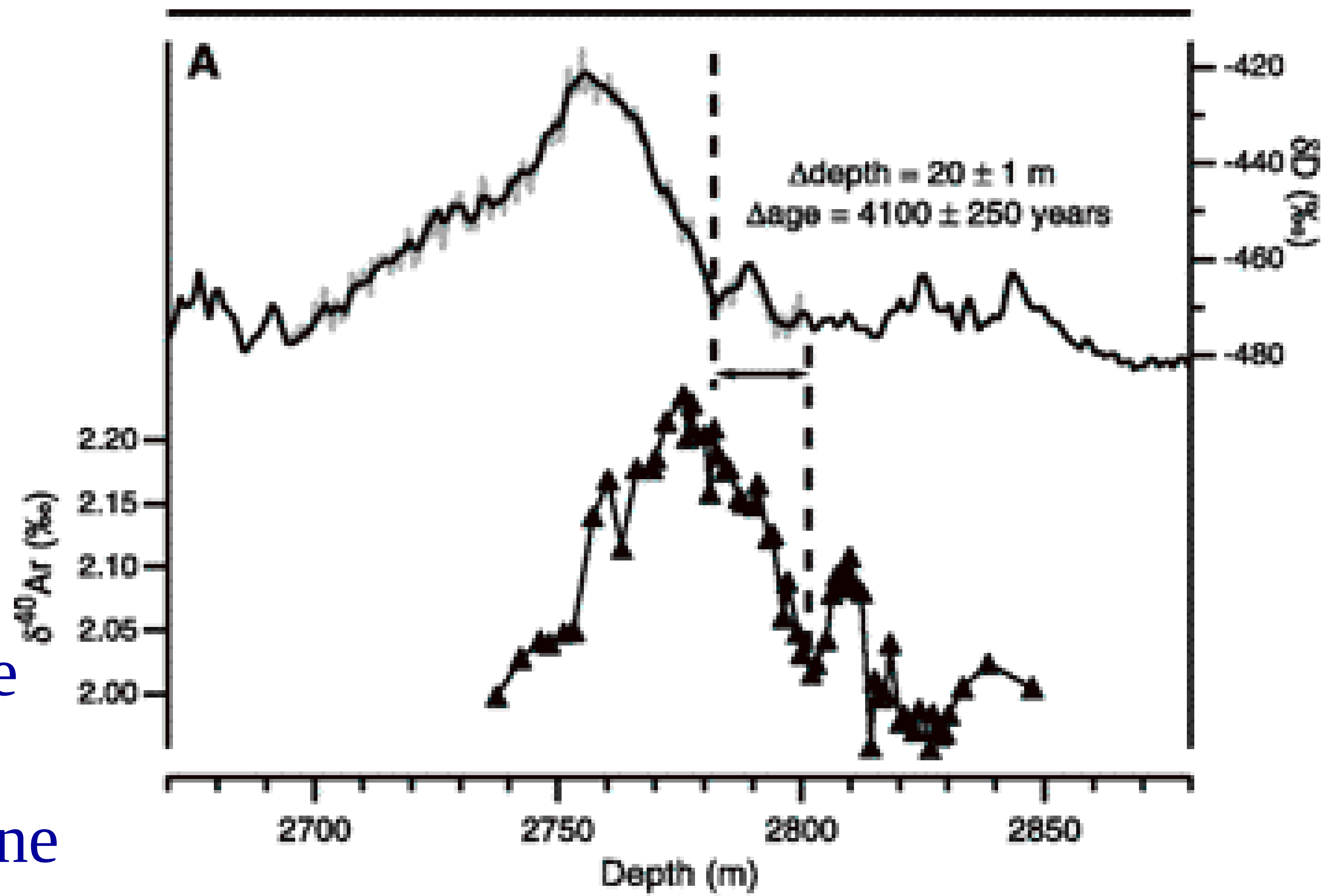
How *large* was this temperature change?



Gas kinetic theory can be used to infer how large and how fast the temperature change had to be to create the observed δ^{15}N signal.

- The answer is between 8 and 15°C over about 50 years.
- This is huge!

δ^{40}Ar and Δage

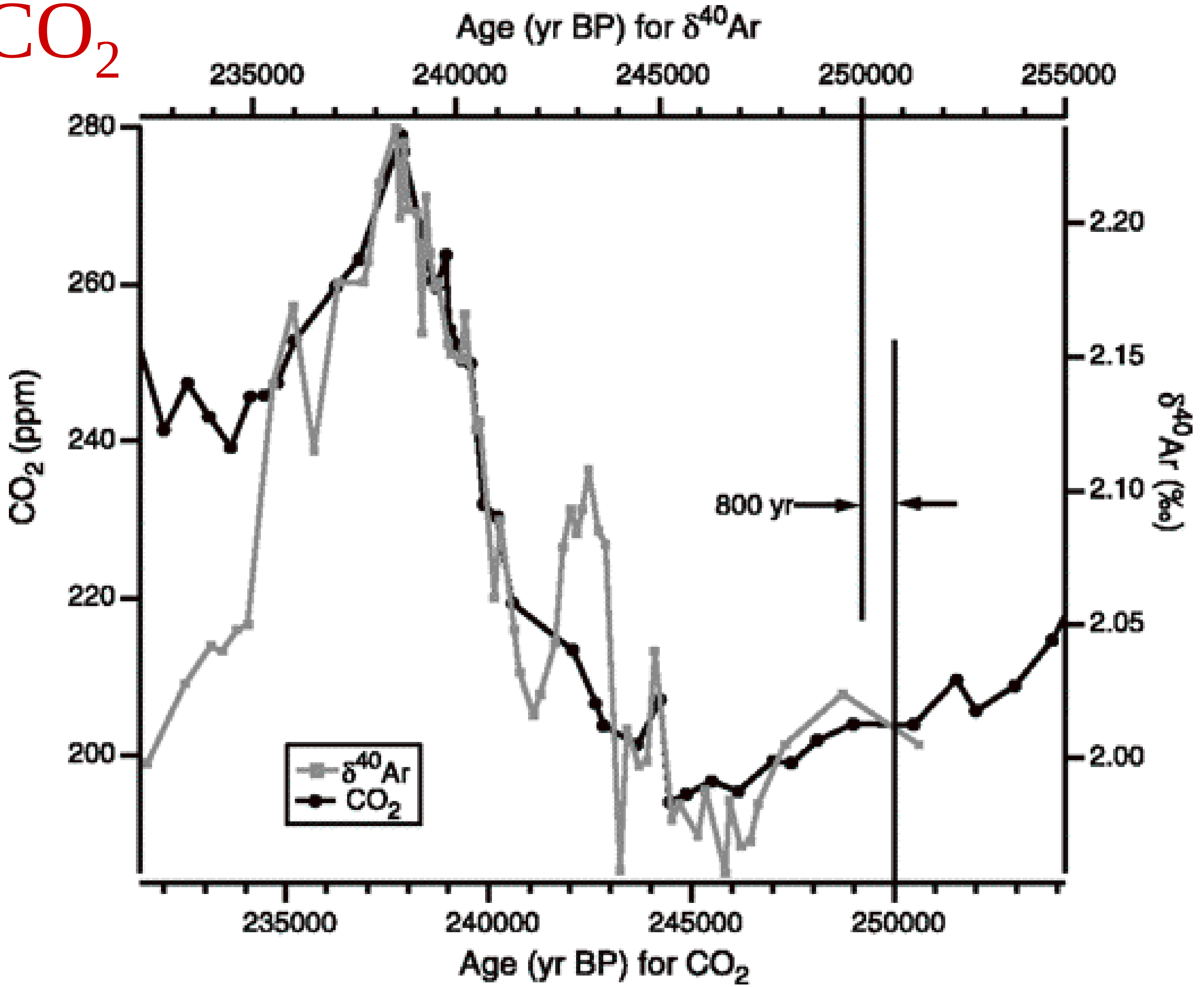


Both are temperature signals.

- We can line them up to find Δage directly

Temperature and CO_2

- both from gases
- CO_2 leads by 800 years



Steps in gas-correlation dating

- Get layer-counted ice core (A) with known age-depth $age^{(ice)}(z)$
- Calculate ice age-gas age difference Δage_A
- Get $age^{(gas)}$ of gas in the ice at site A

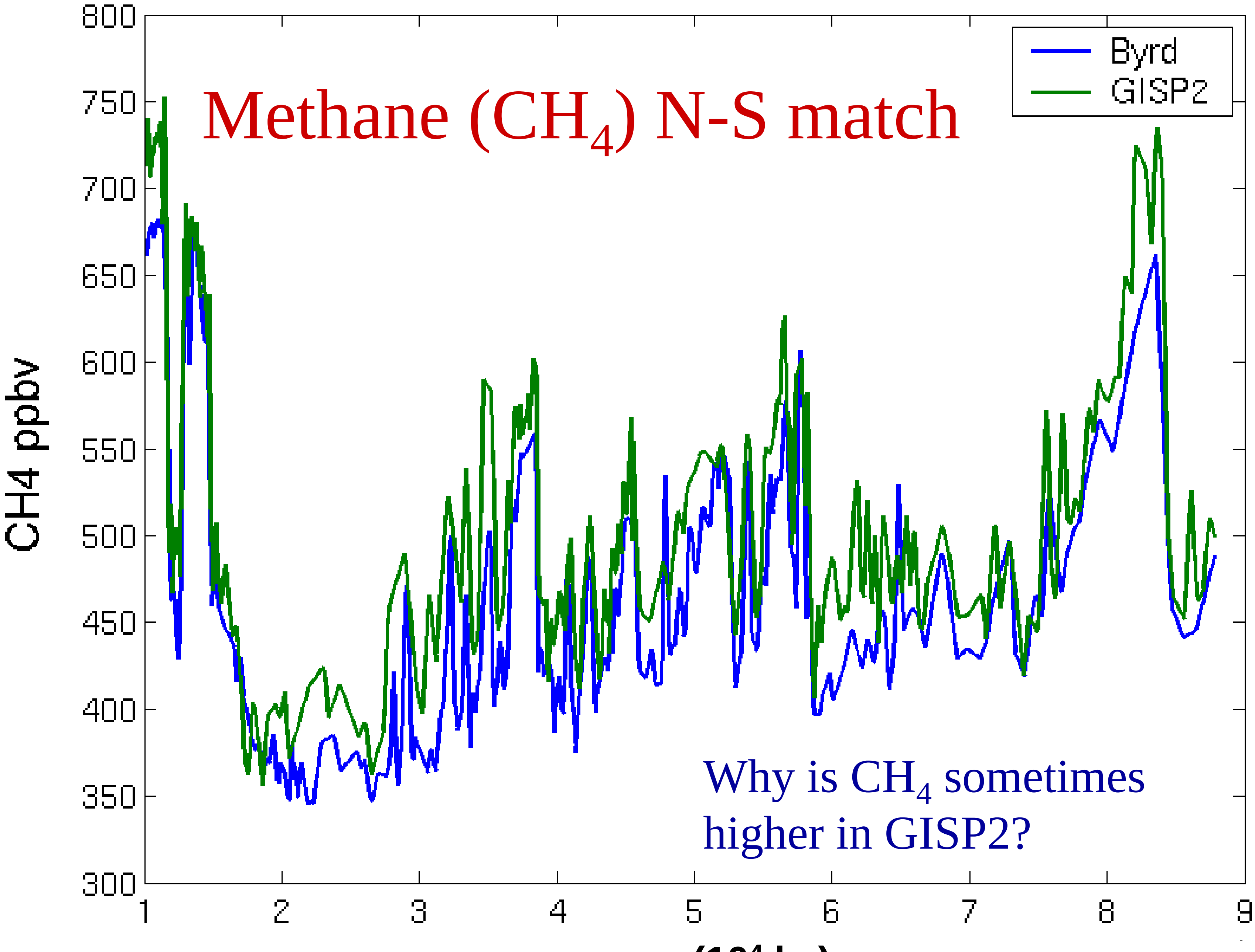
  $$age^{(gas)} = age^{(ice)} - \Delta age_A$$

- Match time series of globally mixed gases (CH_4, $\delta^{18}O$ of O_2, CO_2) between cores A and B. This identifies ice in core B containing gas of $age^{(gas)}$
- Calculate Δage_B at site B
- Determine age of ice in core

  $$age^{(ice)} = age^{(gas)} + \Delta age_A$$

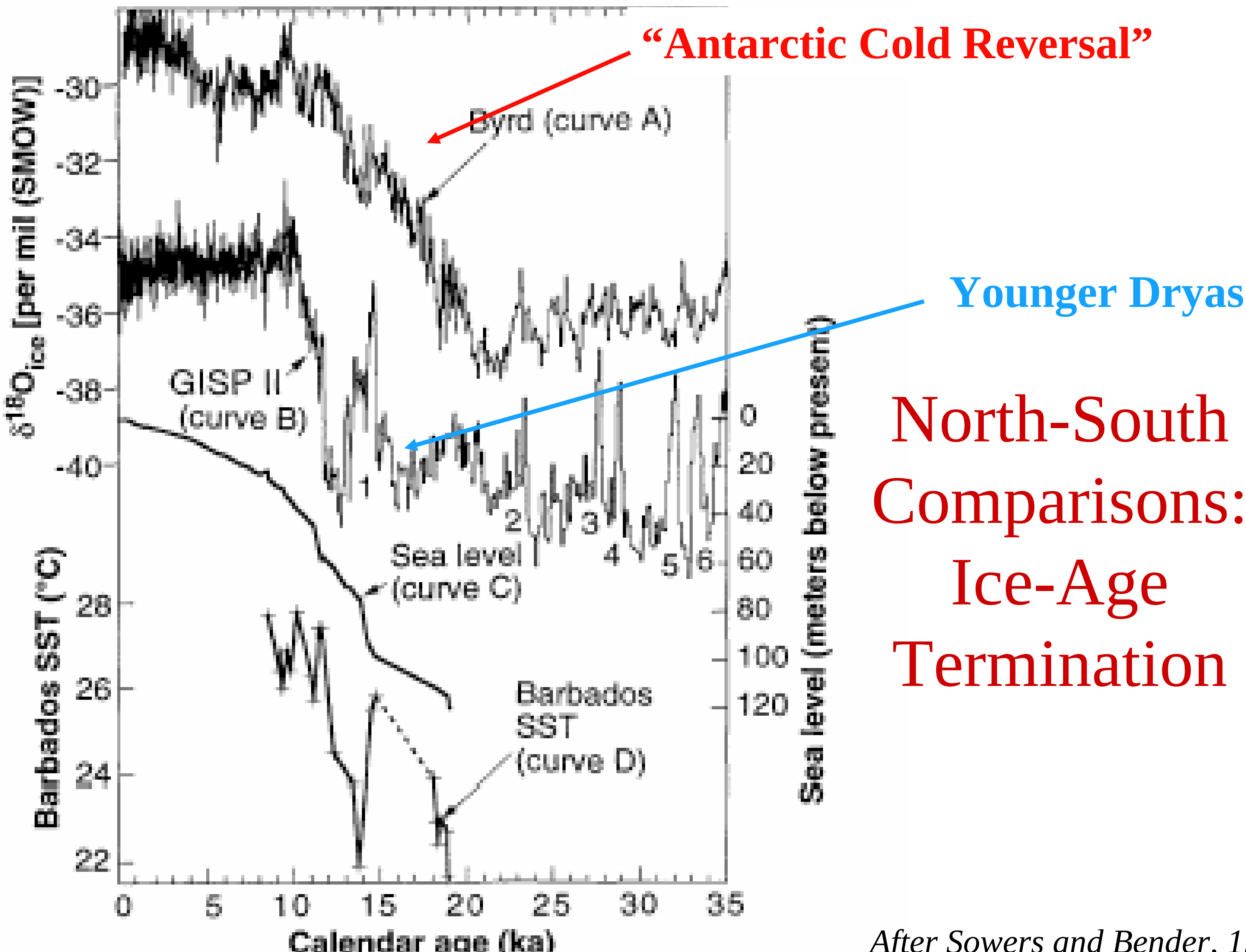
Note that we must know Δage in both cores …

Methane (CH_4) N-S match



Why is CH_4 sometimes higher in GISP2?

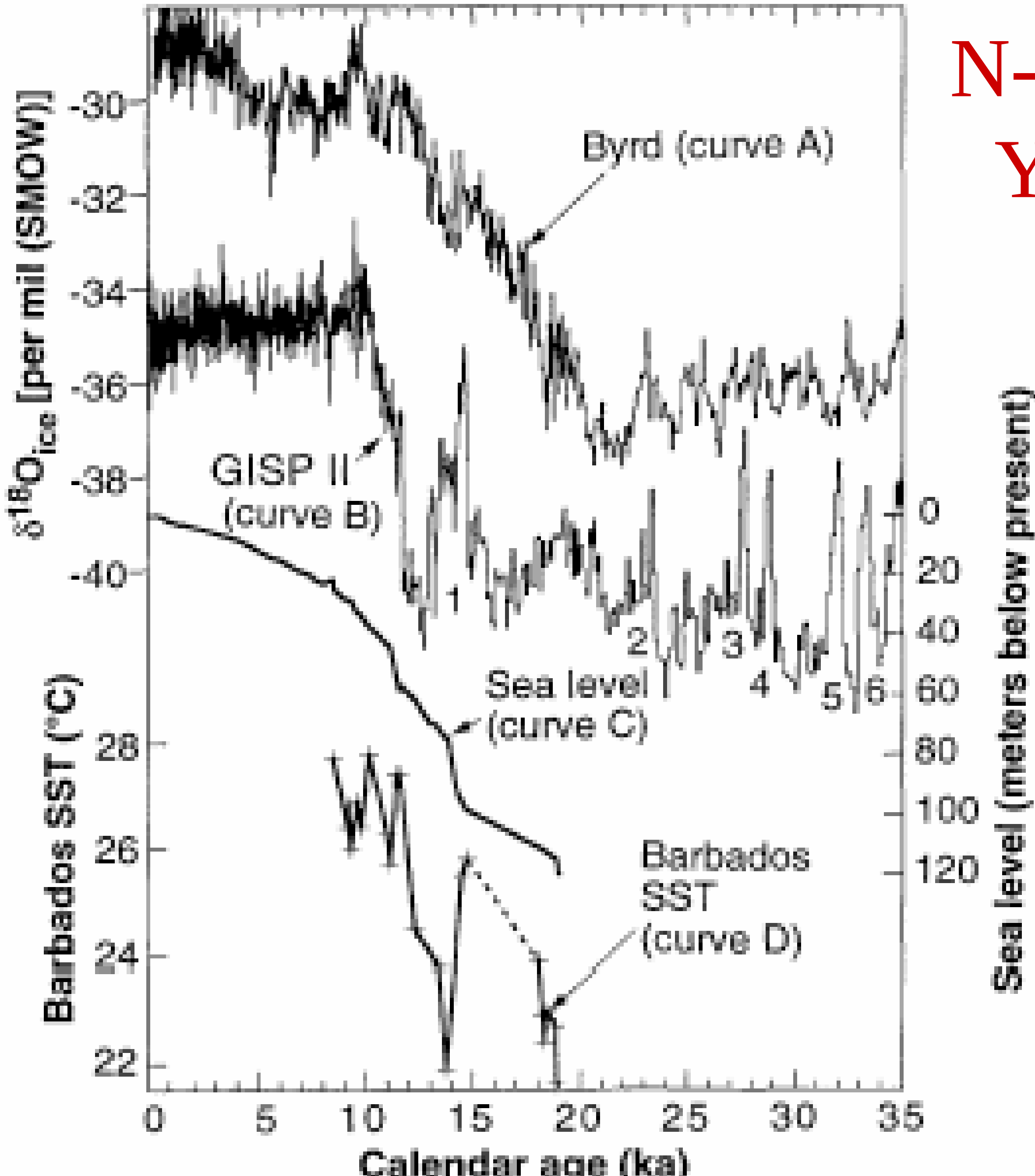
After Blunier and Brook, 2000



North-South Comparisons: Ice-Age Termination

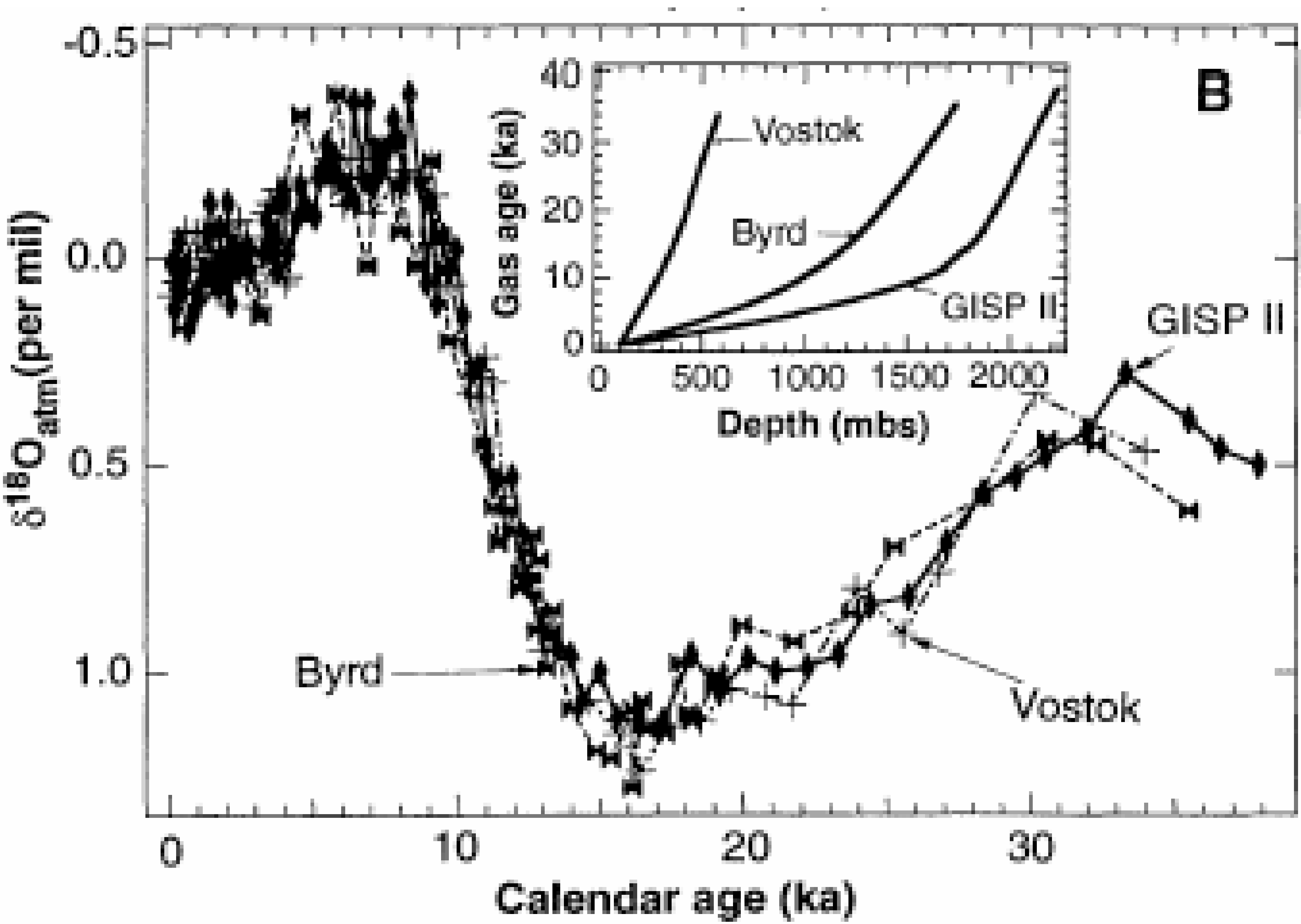
After Sowers and Bender, 1995

N-S comparisons: Younger Dryas Results



Cold ACR in Antarctica was simultaneous with warm Bolling-Allerod interval in Greenland!

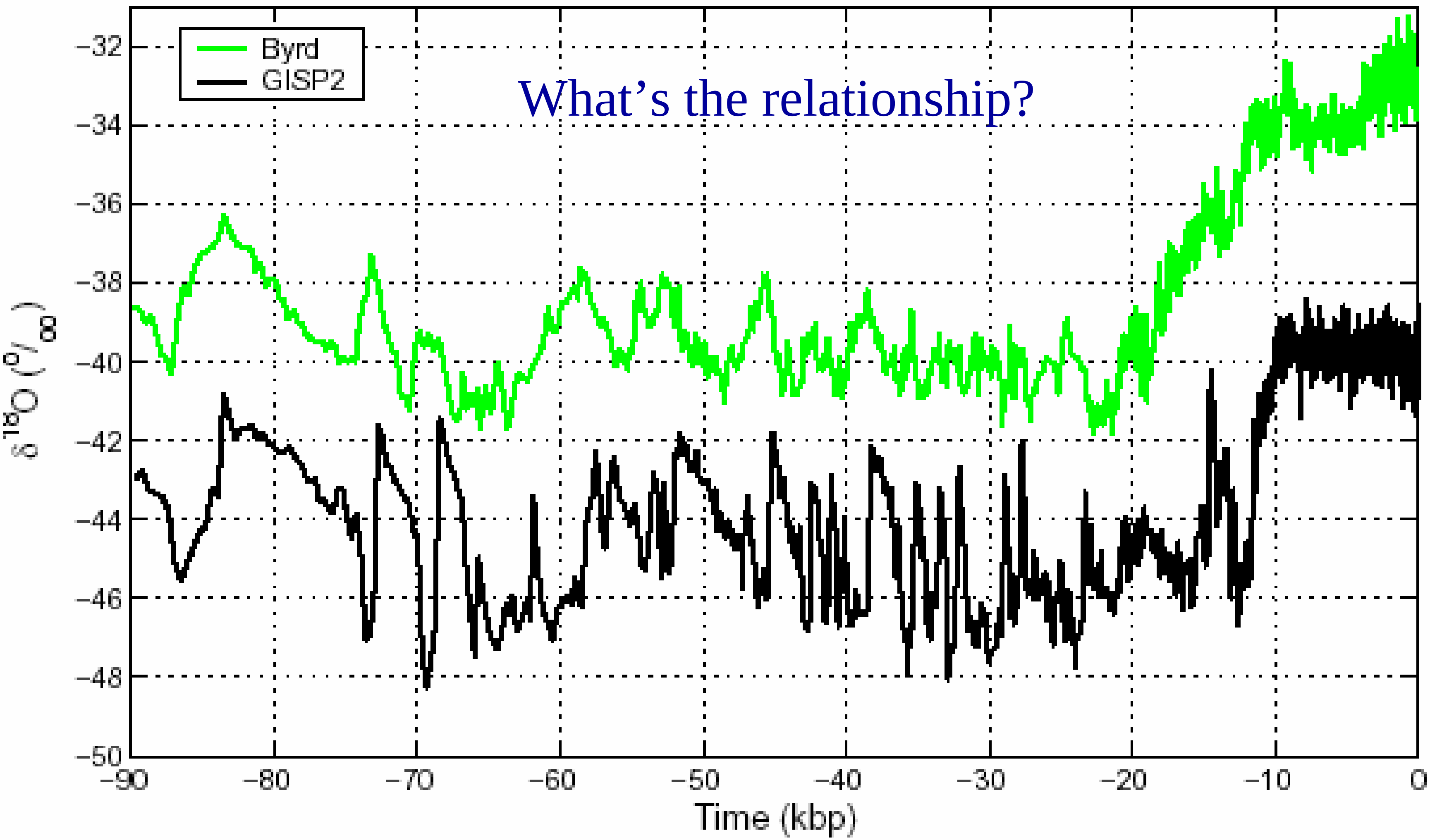
After Sowers and Bender, 1995



$\delta^{18}O$ in O_2 Gas

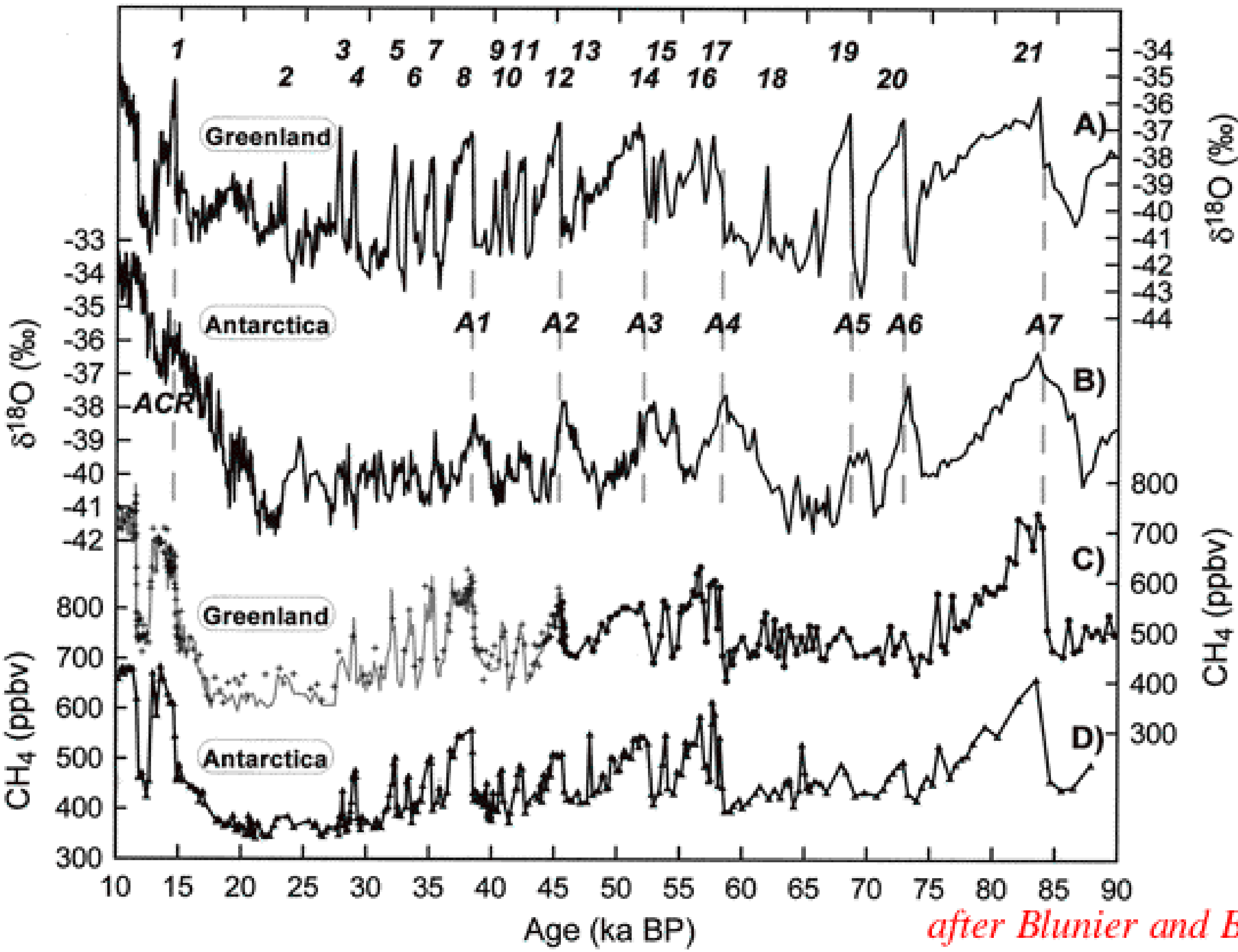
After Sowers and Bender, 1995

N-S Comparison on common time scale from $\delta^{18}0$ of O_2



Warming happens first in Antarctica, but Greenland warms faster

Gas-based correlation



after Blunier and Brook, 2000

Anthropogenic Impacts

See ICWG document on class e-reserves

- CO_2
- N_2O
- CH_4
- CFC
- Pb

Ice-core Questions

1. What might happen to the ice-age/gas-age difference in central Antarctica when the climate cools by 10^{o}C in an ice age?

2. Detecting annual layers is a way to date an ice core absolutely, in calendar years. How well would you expect to be able to date a core using dust? Using δD? Explain your reasoning.

3. After experiencing a summer of near-continuous sunlight, the Greenland ice sheet undergoes strong daily cycles during autumn. Where and when would you expect to see hoar layers forming? Why?

4. Suppose a layer of surface hoar formed every autumn on an ice sheet. Could you use this to date the core? Would this work for ice older than the pore-closeoff age?

The End

Have a great holiday!