Ice core records provide an important proxy for climate change.

The global water cycle

Water vapor residence time ~10 days in troposphere

Average global precipitation rate ~1m/year

For precipitation,
- Ocean is net water source
- Land is net water sink

Net transfer of water from subtropics to subpolar latitudes

Warm air holds more water than cold air: as air temperature drops, air becomes saturated with water (the dew point) and water droplets form

Stable isotopes of water

Hydrogen has two stable isotopes:

^{1}H and ^{2}H (Deuterium)

Oxygen has three stable isotopes:

^{16}O, ^{17}O, and ^{18}O

Light isotopes

Heavy isotopes

Possible combinations important for paleo temperature:

$H_2{}^{16}O$, $HD^{16}O$

$H_2{}^{18}O$

(water with more than one heavy isotope is rather rare)

H and O isotopes in ice cores

We report H and O isotope ratios of a sample as *per mil* (‰) deviation from a known standard. For example:

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

Temperature effects

The vapor pressure of $H_2{}^{16}O$ is higher than that of $HD^{16}O$ and $H_2{}^{18}O$

Therefore:

➔ **Evaporation** results in vapor that contains *fewer* D and ^{18}O than the initial water pool (vapor is **depleted**, or **isotopically light**)

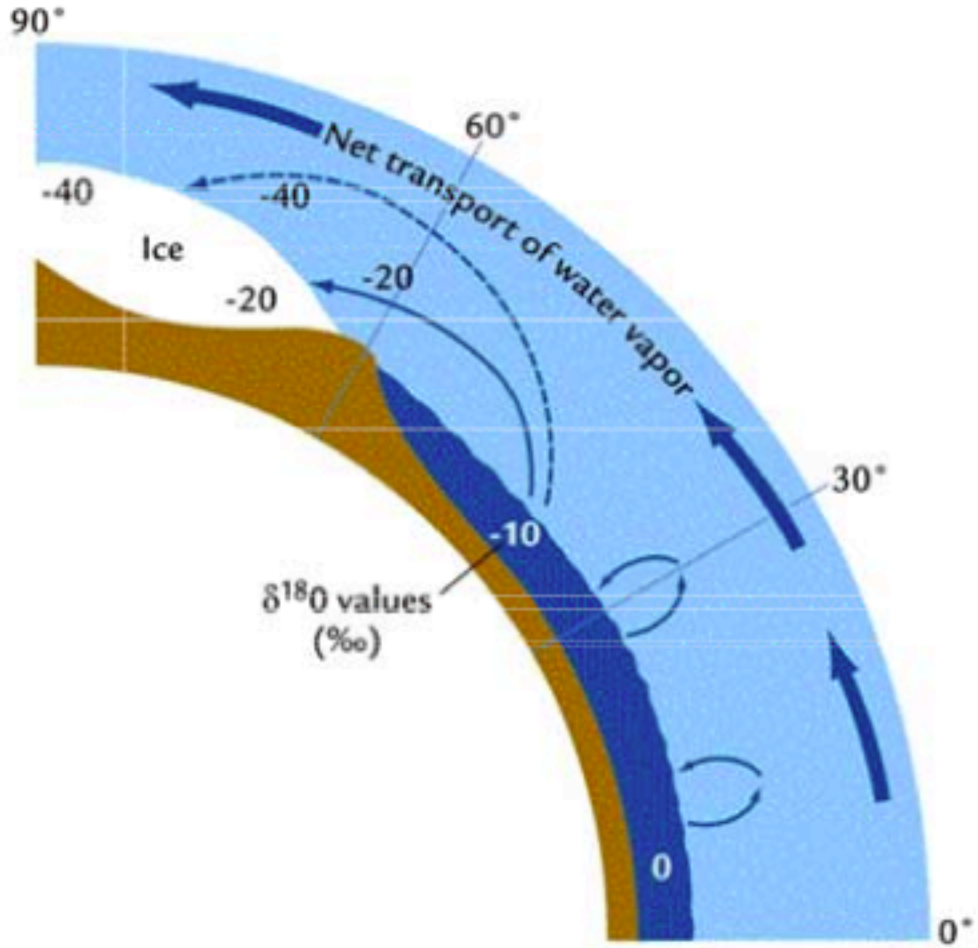
And

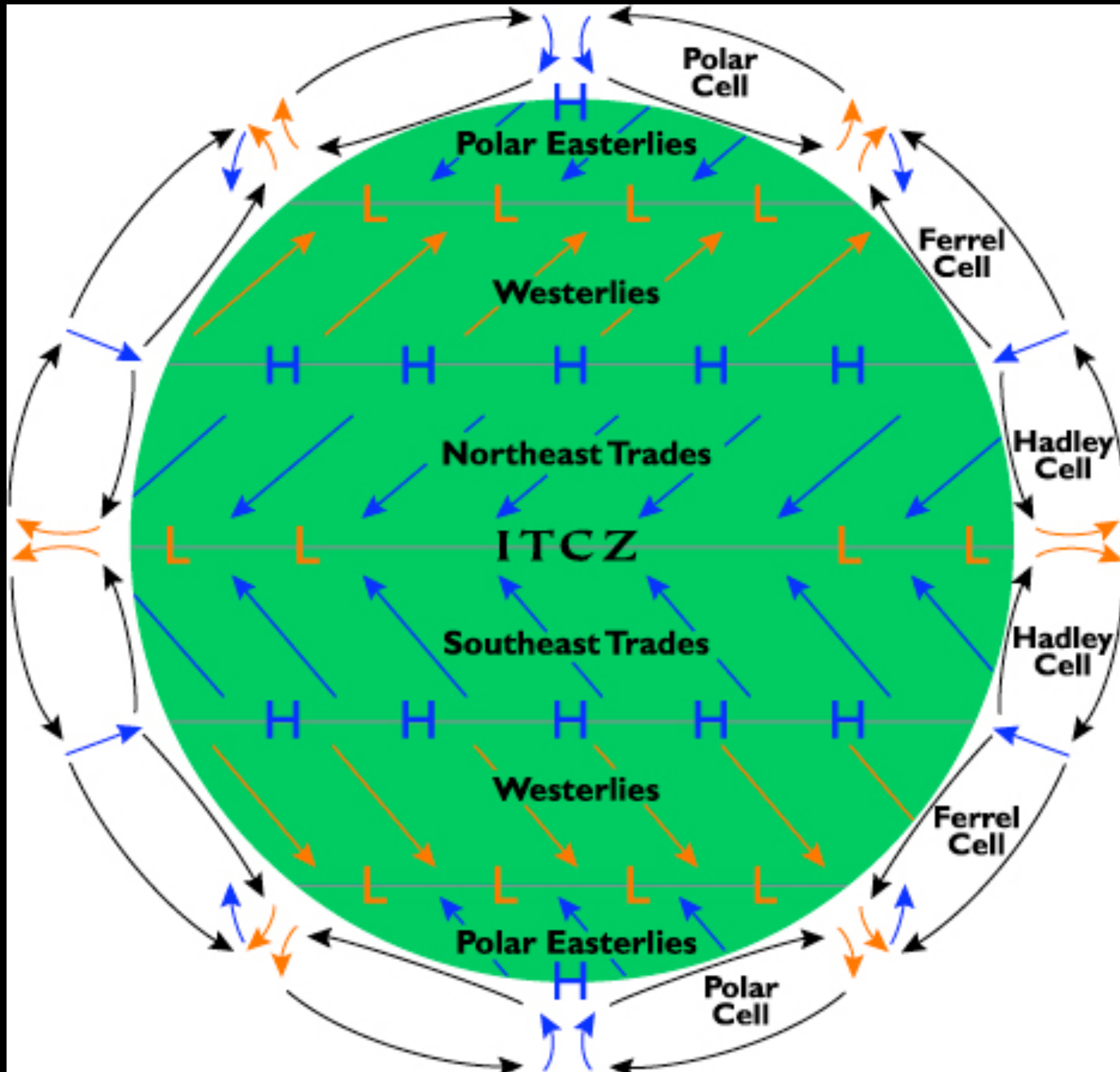
➔ Subsequent **condensation** from the vapor contains *more* D and ^{18}O than the vapor (condensate is **enriched**, or **isotopically heavy**)

Temperature effects

Cooler temperatures result in more condensation, and therefore in a continued enrichment in condensate and a depletion in vapor

$\delta^{18}O$ in precipitation





Simplified model of global atmospheric circulation.

Rayleigh Distillation

Start with a saturated air mass above the ocean surface

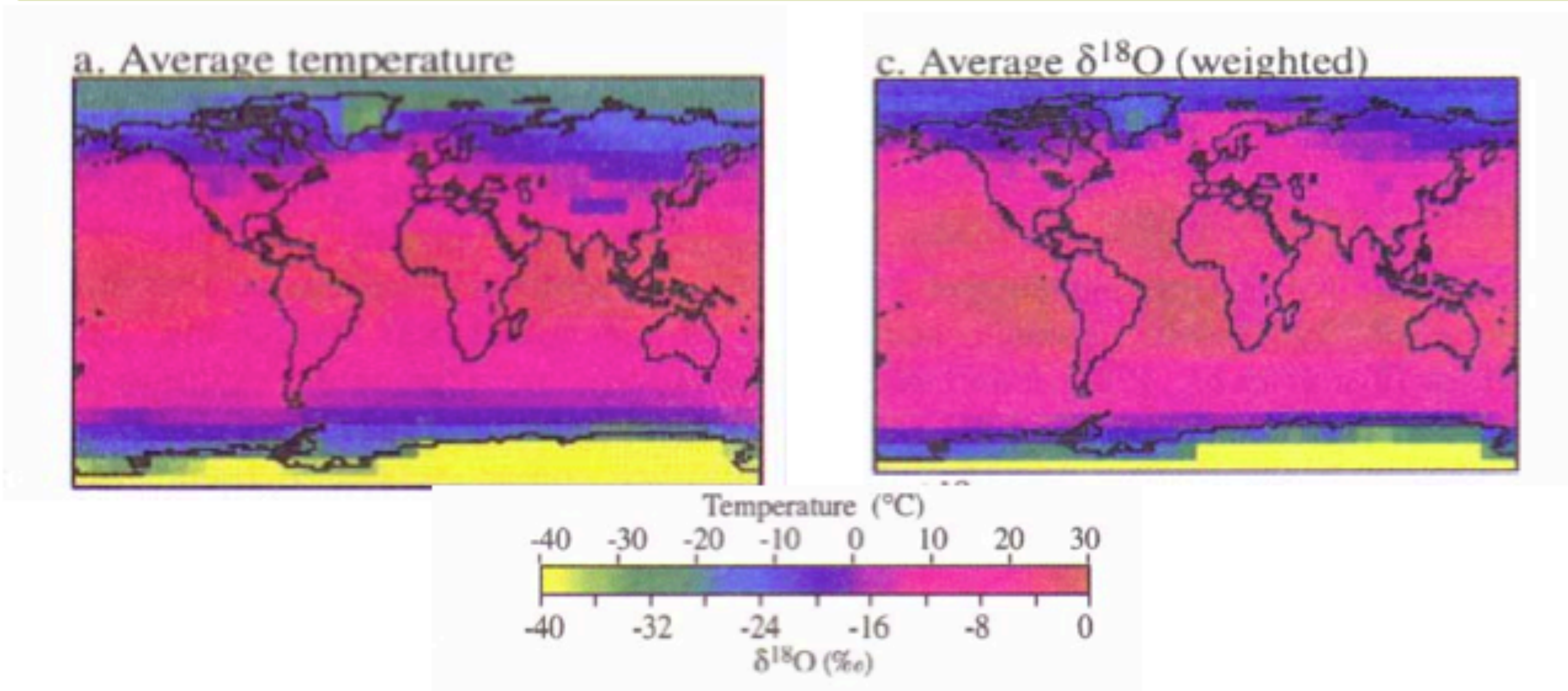
Assume that:

1) As the air travels poleward, it cools.
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 (between vapor and liquid phases)
4) Once water condenses it does not re-evaporate.
5) No new water is added to the airmass.

$$\mathbf{R = R_i * \mathit{f}^{\,(\alpha-1)}}$$

We can determine the isotope ratio of $^{18}O/^{16}O$ at a given time (R) based on the fraction of water vapor remaining in the air mass (f) and the isotopic ratio of the initial water vapor (R_i).

More complex models show similar relationships between T and $\delta^{18}O$



These plots show model simulations of temperature and $\delta^{18}O$. The similarity between the plots indicates that there is a strong spatial relationship between $\delta^{18}O$ and temperature. This suggests that our simple Rayleigh model is a pretty good description of the system.

Rayleigh Distillation

Using a Raleigh Distillation model, Dansgaard (1964) predicted the following relationships over a 20ºC to -20ºC range:

Change in $\delta^{18}O$ = 0.58 ‰ per ºC

Change in δD = 4.8 ‰ per ºC

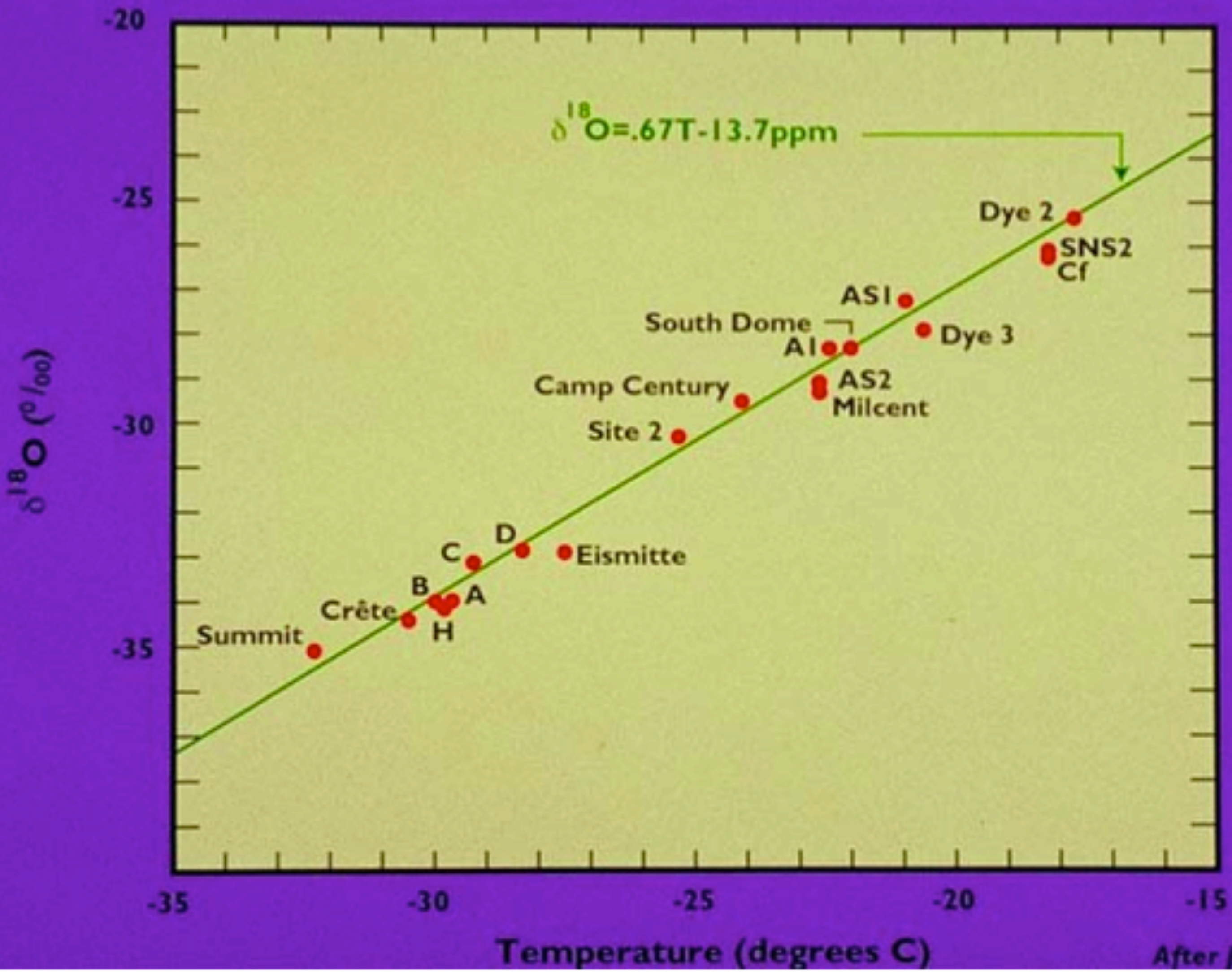
Relationship between water isotopes and temperature

Observed:

$$\delta^{18}O = 0.69 * T(^{o}C) - 13.6‰$$

$$\delta D = 5.6 * T(^{o}C) - 100‰$$

Modern mean annual values of δ^{18}O and snowpack temperature from the Greenland Ice Sheet show an extremely close correspondence.



After Johnsen et al. (1988)

Paleo temperature reconstruction from ice cores

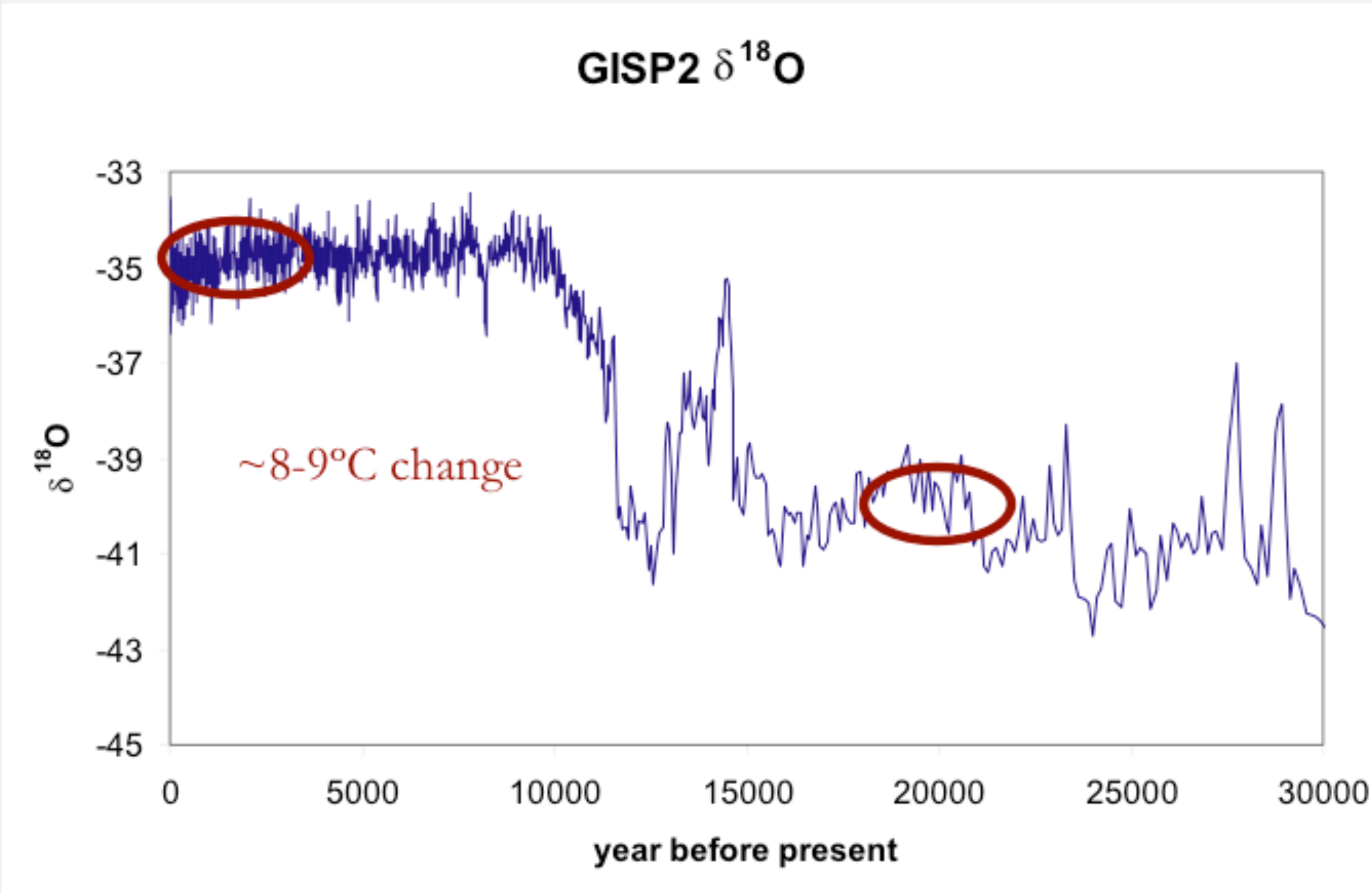
- Measure $\delta^{18}O$ (or δD) of an ice core
- Date the ice core
- Measure today's $\delta^{18}O$ vs. temperature relationship near the ice core site
- Estimate paleo temperature record from measured $\delta^{18}O$ vs time (in ice core) and today's $\delta^{18}O$ vs. temperature relationship

What assumption is made?

Dating of the upper portion of the ice core record can determined using layer counting.

Ice formed near the divide will be plastically deformed (thinned) with depth.

The ice sheet is considered to be frozen to a horizontal base, for modeling purposes.



Present day $\delta^{18}O \approx 0.67‰$ per °C

Antarctica

Range of $\delta^{18}O$ in Antarctic ice cores:

-34‰ (*today*) to **-42**‰ (*20,000 years ago*)

Present day temperature relationship in Antarctica

$$\delta^{18}O \approx 0.9 \text{ ‰ per } ^{\circ}C$$

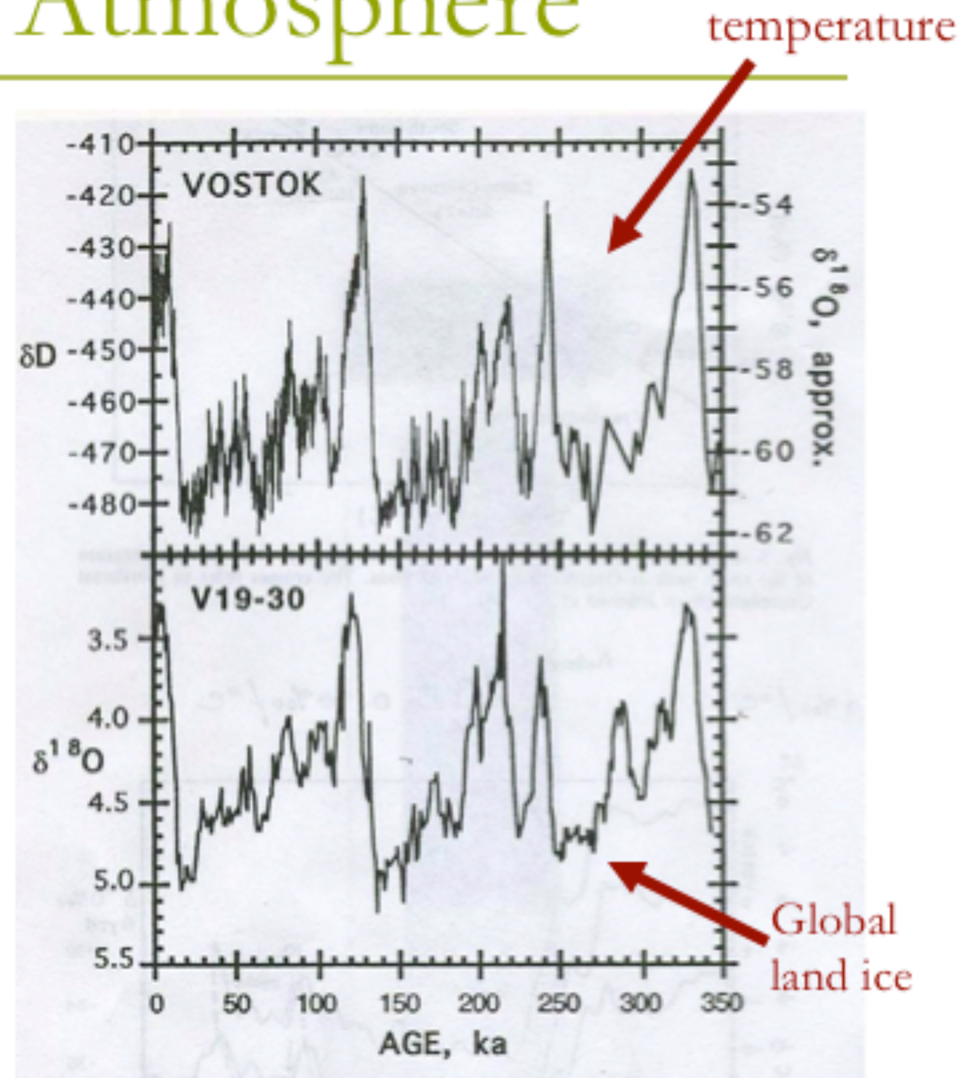
➔Implies 9°C cooler air temperature during last glacial period

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

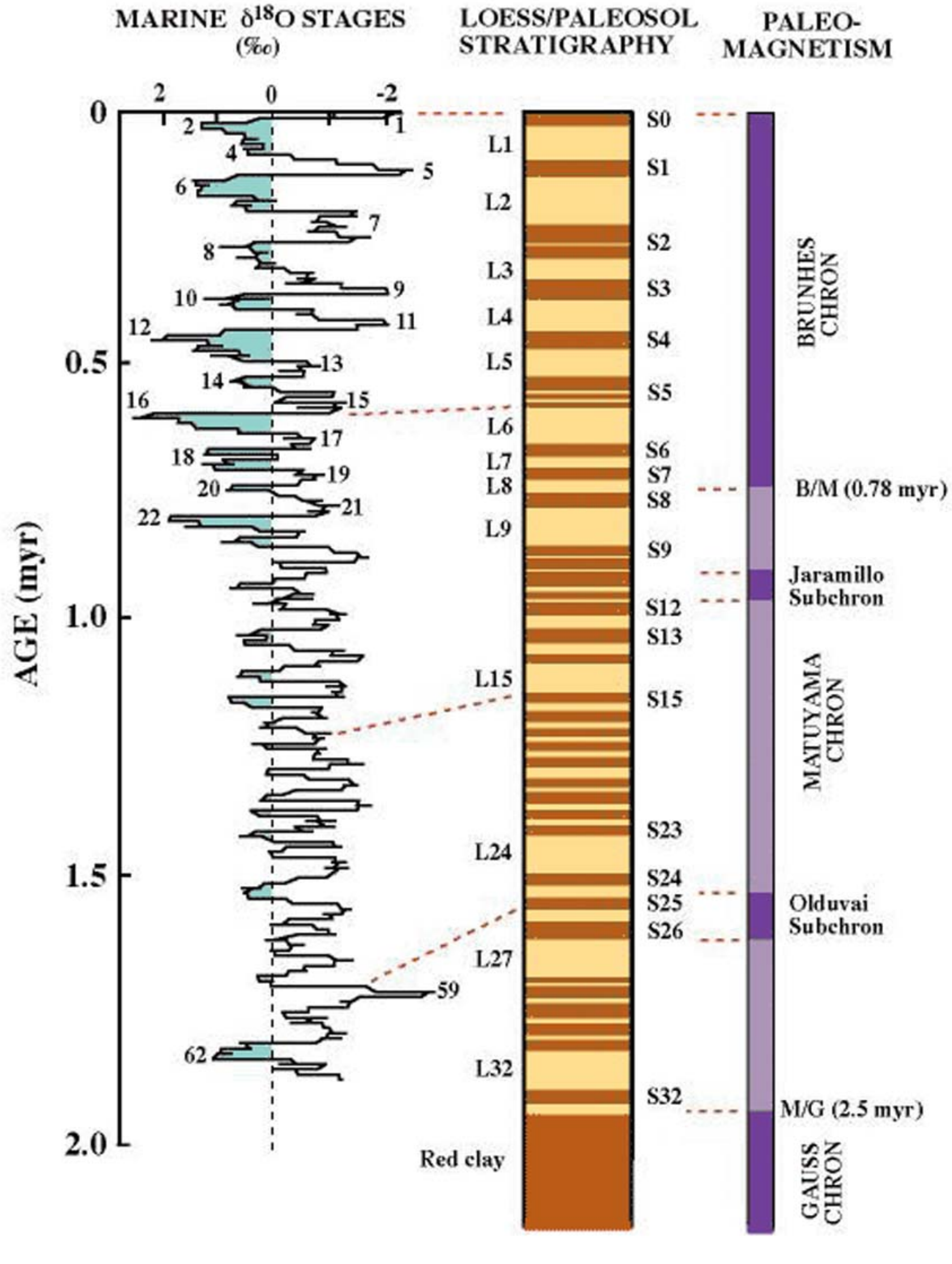
As the ice sheets build up during glaciations, they are preferentially made up of lighter water isotopes.

Thus the ocean gets enriched in heavier water isotopes.

Benthic (bottom-dwelling) foraminifera take up O from surrounding waters when forming $CaCO_3$ shells. Hence analysis of $\delta^{18}O$ in benthic forams provide a record of global ice volume.



Vostok $\delta^{18}O$ (top) and $\delta^{18}O$ of benthic forams (bottom) show similar trends



Marine sediment and loess records. Oxygen isotope measurements of benthic foraminifera provide a proxy of global ice volume change. Paleomagnetic record of past 2 million years is shown on the right.

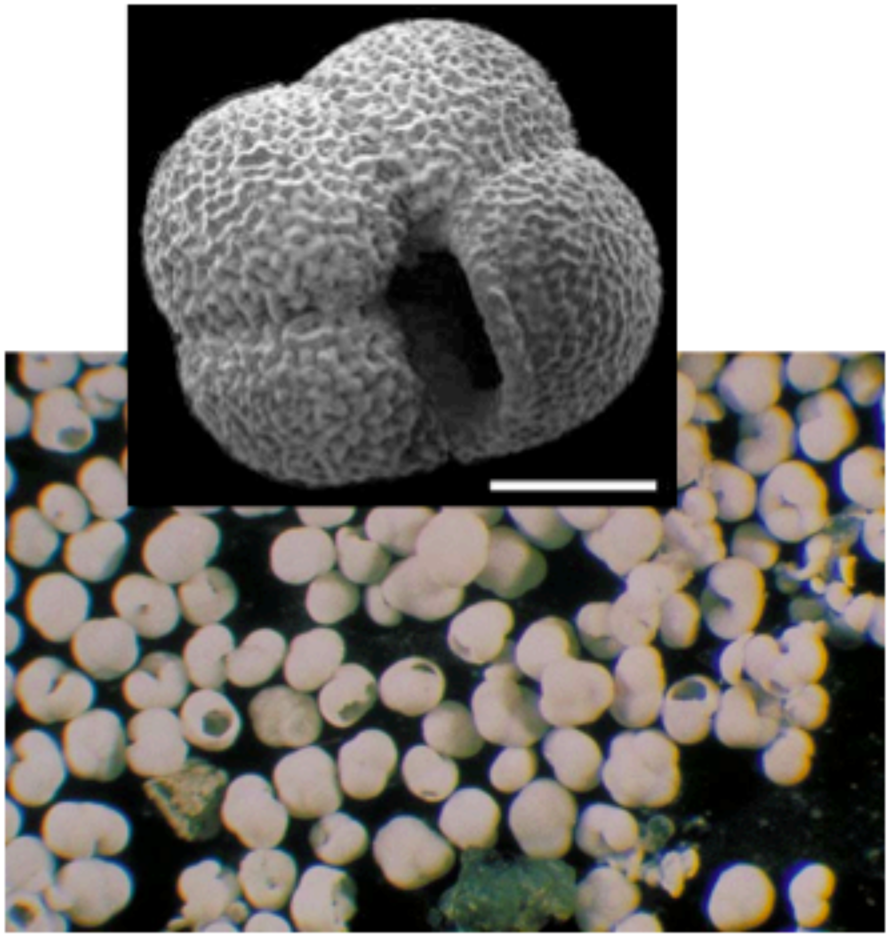
Land ice vs. ocean level

$\delta^{18}O$ of benthic forams show 1‰ (±0.1‰) change in $\delta^{18}O$ of oceans between today and 20,000 years ago.

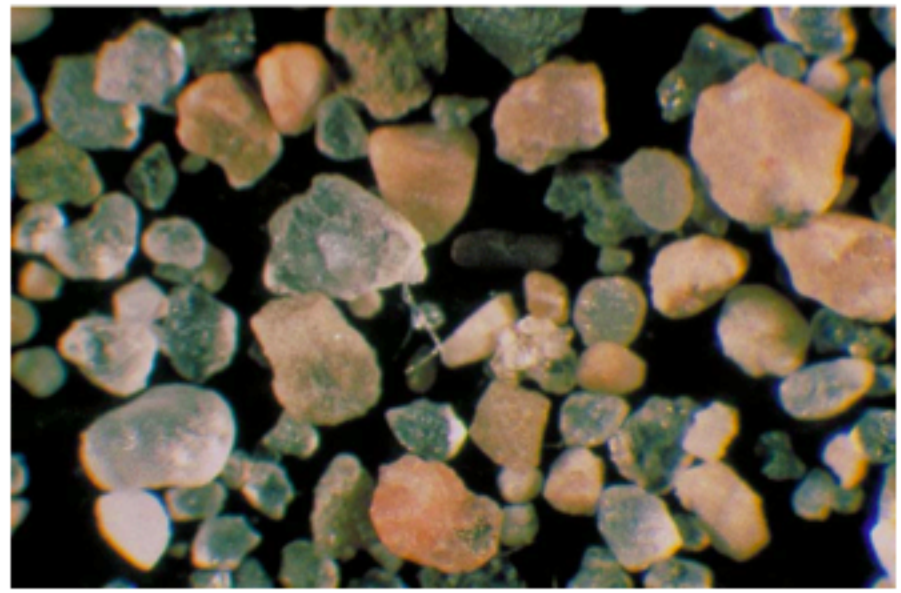
Using this value and the $\delta^{18}O$ of land ice (known from ice cores), we can determine the sea level change between today and 20,000 years ago.

→At the last glacial maximum (20,000 years ago), the maximum thickness of the Laurentide ice sheet was 3.5 to 4 km. The formation of this amount of ice required the evaporation of *a lot* of water, lowering sea level by ~120 meters.

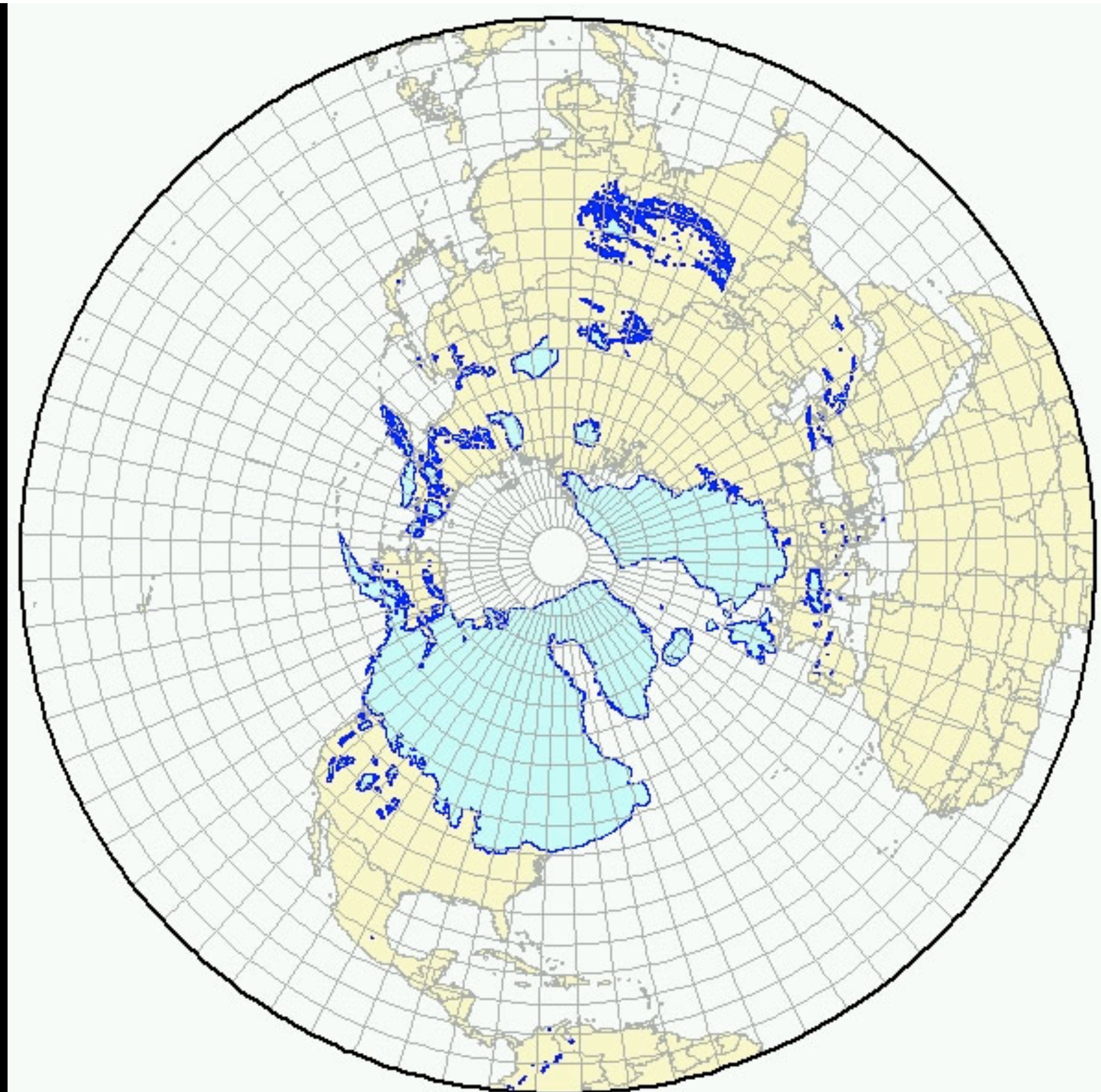
Sand size fraction from 670-672cm depth (H2)



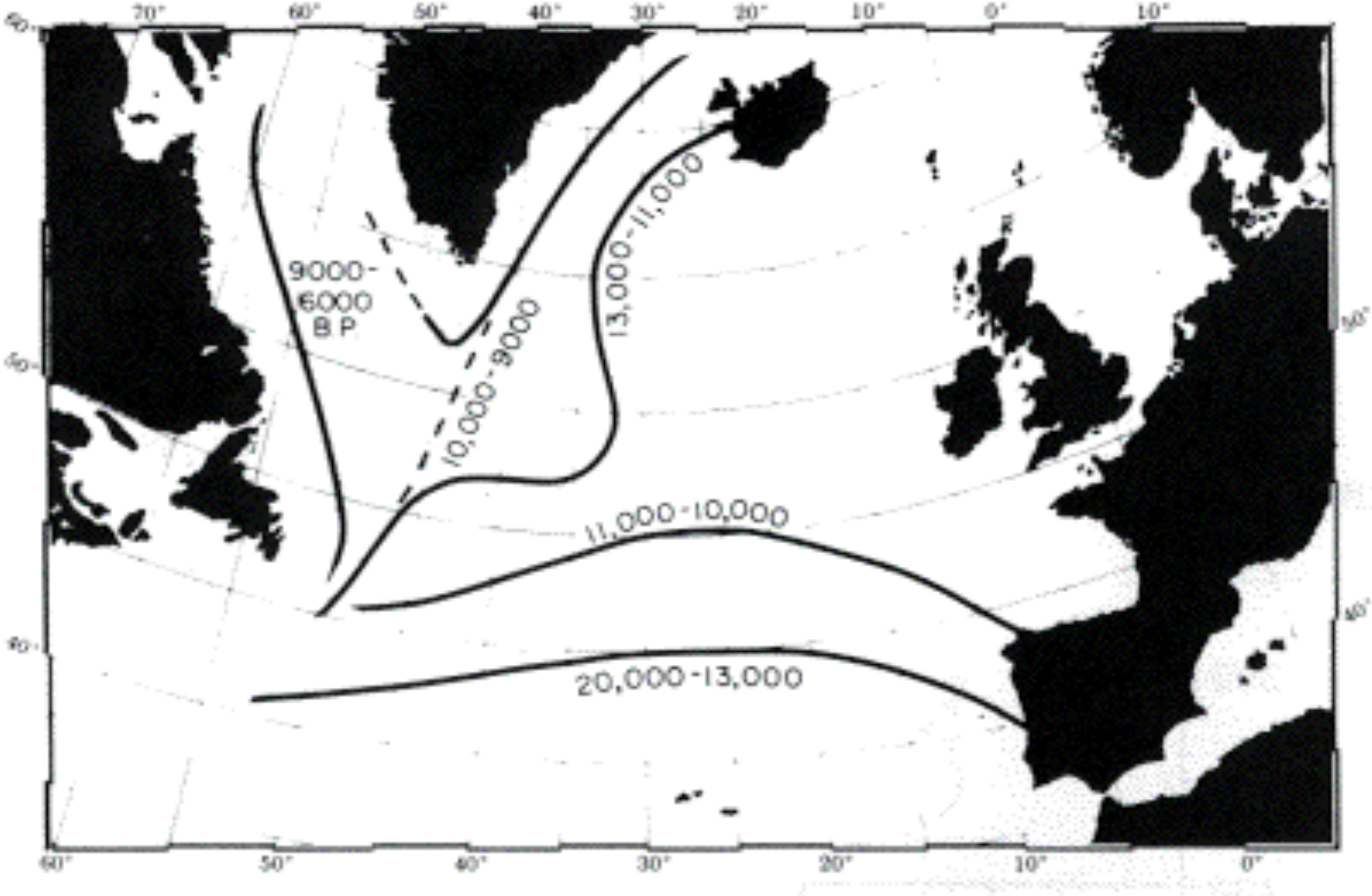
N. pachyderma (left coiling)
planktonic (surface dwelling) foraminifera
that live in colder waters



large lithic fragments
(>150 microns; primarily detrital
carbonate)



Northern hemisphere ice sheets during the LGM (~20 ka).



Position of the polar front based on presence of G. pachyderma in marine sediment cores.

Abrupt climate change

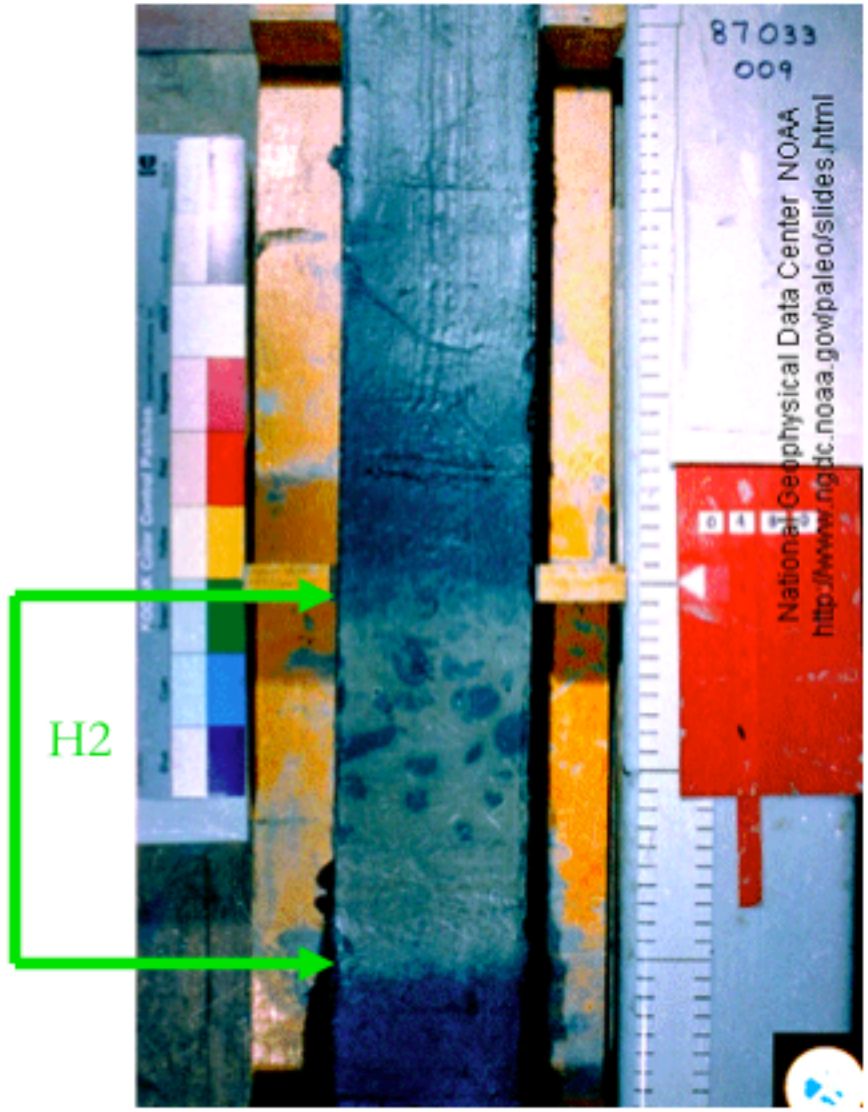
Climate change (temperature, precipitation, etc.) that occurs on a timescale faster than the responsible forcing.

Examples:

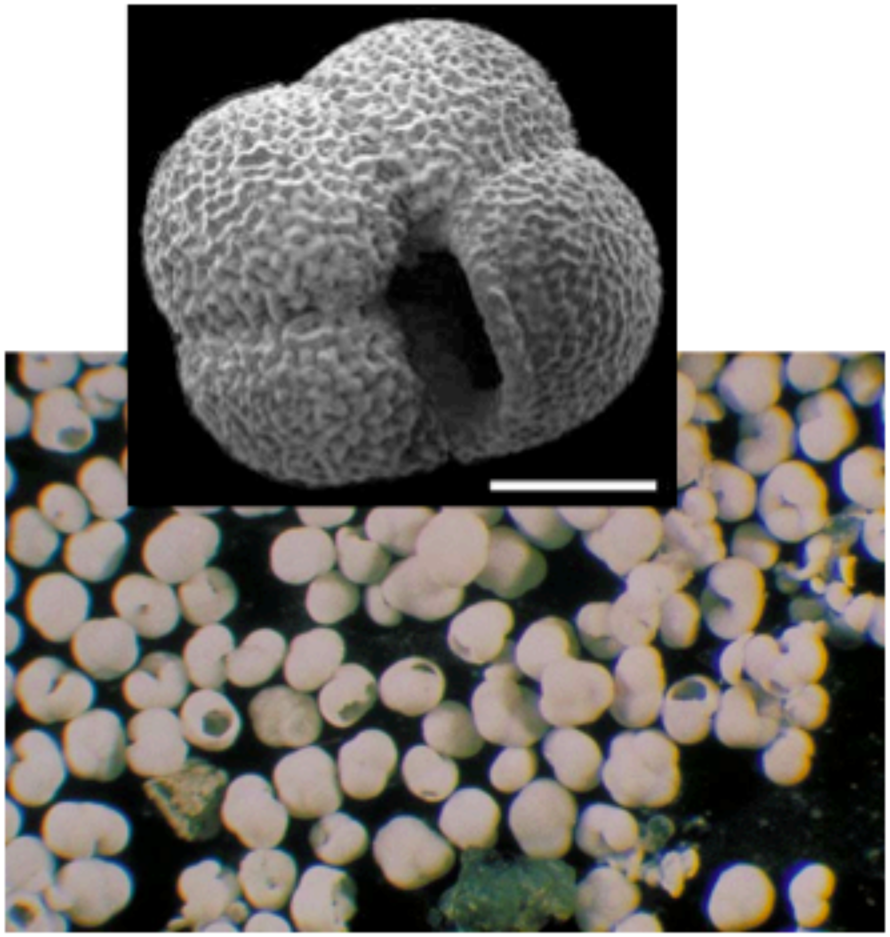
- Decadal scale change (Younger Dryas transition)
- Centennial to millennial scale change (a green Sahara, Heinrich events)

Heinrich Events: Armadas of icebergs!

- Heinrich (1988) observed 6 layers of lithic fragments in sediment cores from the N. Atlantic
- Each layer contained a high percentage of lithics and a **specific** cold-dwelling planktonic foraminifera (*N. pachyderma*)
- Above and below these layers the core is predominantly composed of various other types of foraminifera
- The transitions surrounding these layers indicated an abrupt change



Sand size fraction from 670-672cm depth (H2)



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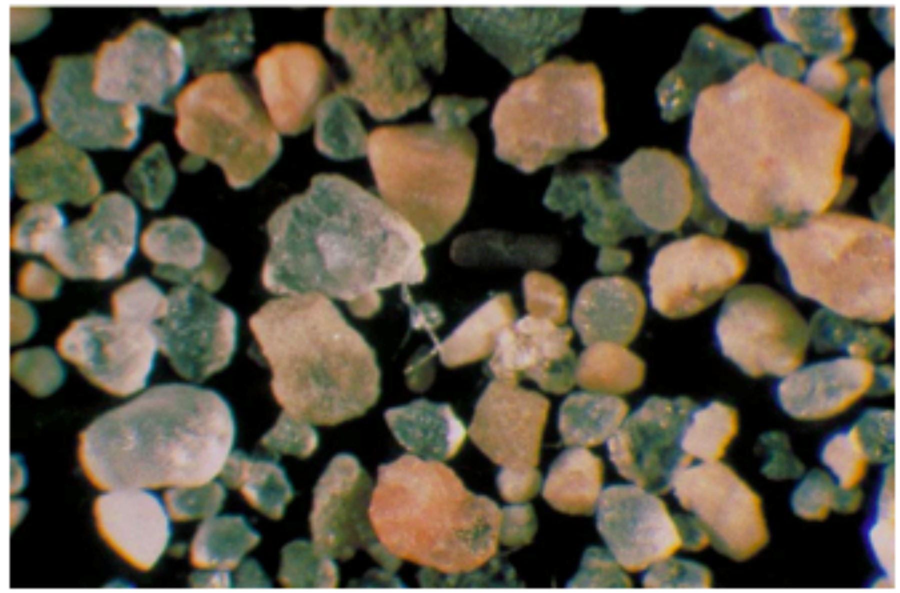
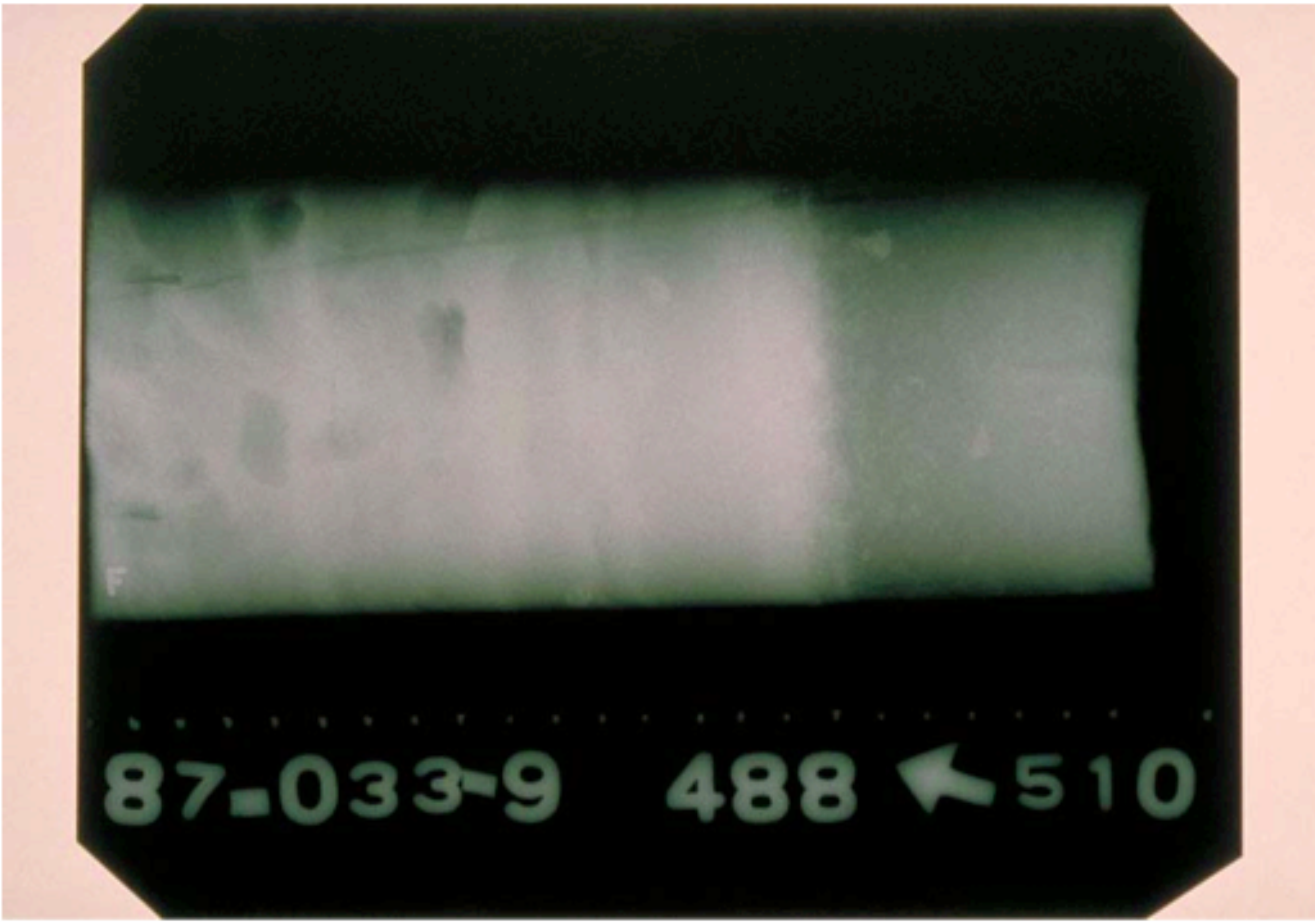


large lithic fragments
(>150 microns; primarily detrital
carbonate)

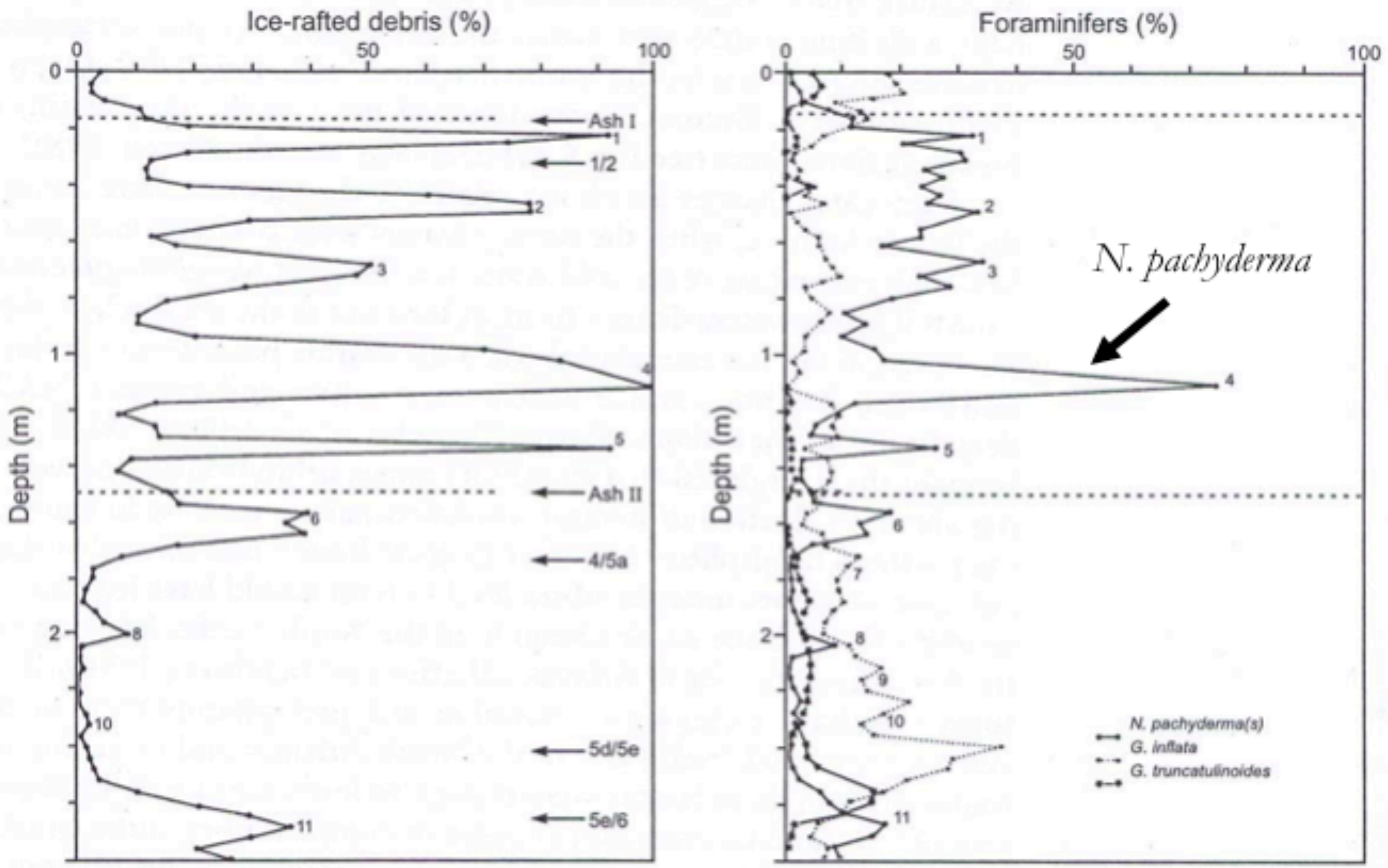
X-ray of a Heinrich event in ocean sediment core



Dark layers are predominantly foraminifera; light layers contain more lithic fragments. Notice the outlines of dropstones in the lithic layer!

Lithic material is Ice Rafted Debris (IRD)

Photo courtesy of NOAA Paleoclimatology



Ash I deposited ~ 10.8ka
Ash II deposited ~ 54ka

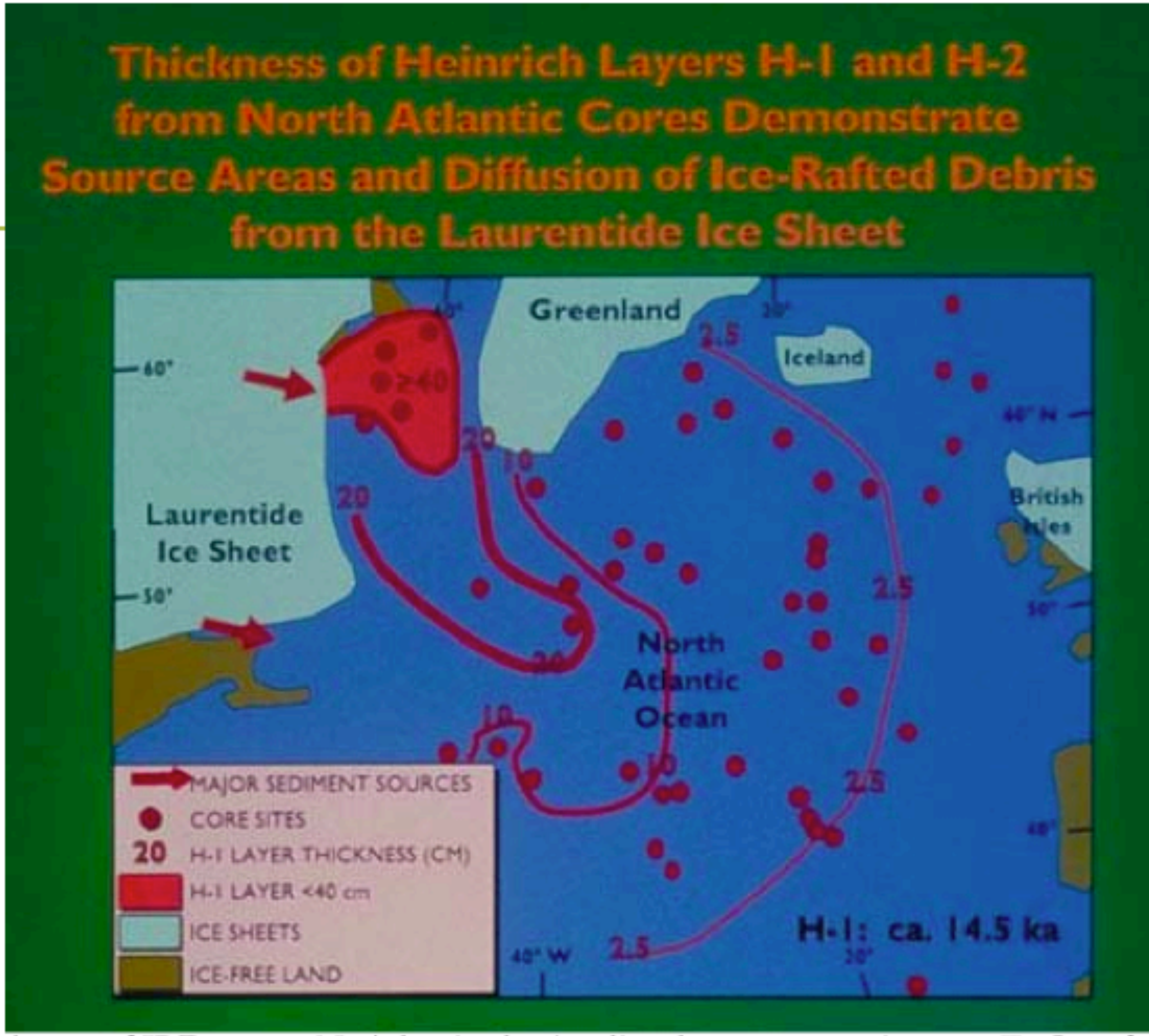
Bradley 1999

Provenance of IRD

- K/Ar, Nd, Sr, Pb isotopic studies
- petrographic studies to identify major lithological components

The provenance of IRD is distinctive.

Heinrich IRD is composed primarily of limestones and dolomite that derive from a small region near the Hudson Strait.



Thickness of IRD across N. Atlantic also implies that source region was E. Canada. We expect to find thicker IRD layers closer to the iceberg source.

Diagram courtesy of UBC

Calving ice contains sediment that was entrained at the base of the ice sheet

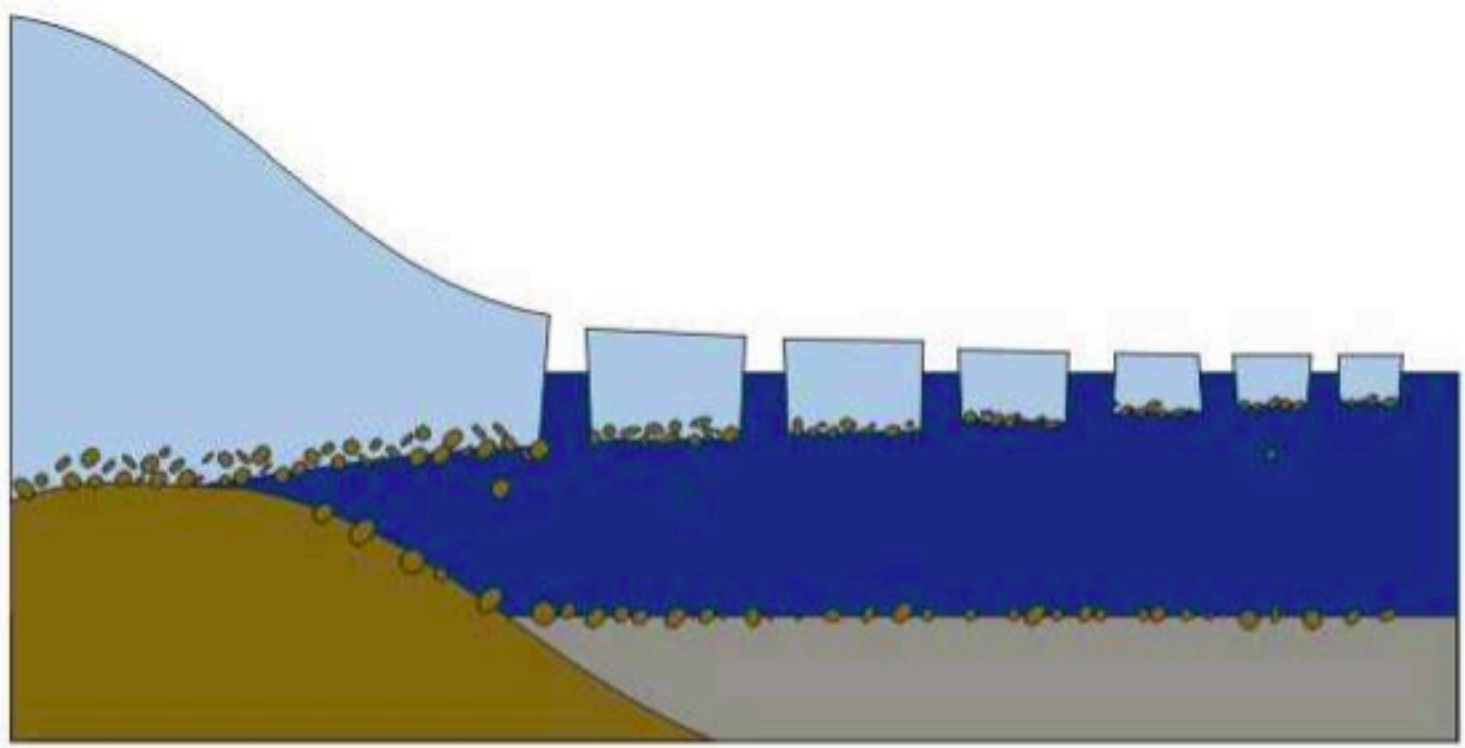
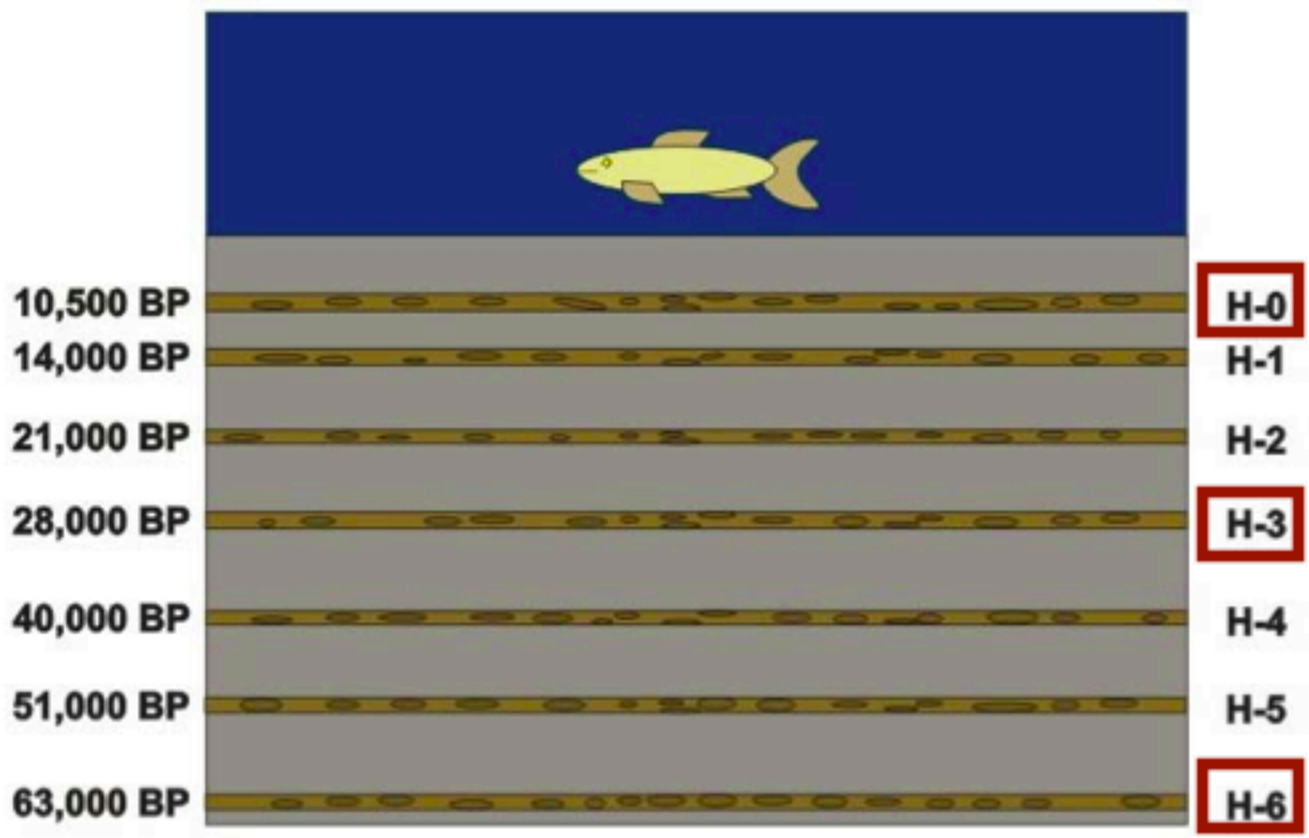


Diagram courtesy of UBC

As icebergs melt, IRD is deposited across the ocean



H0, H3, H6 are different!

Note that Heinrich events only occur during cold periods.

Diagram courtesy of UBC

Leading theory…

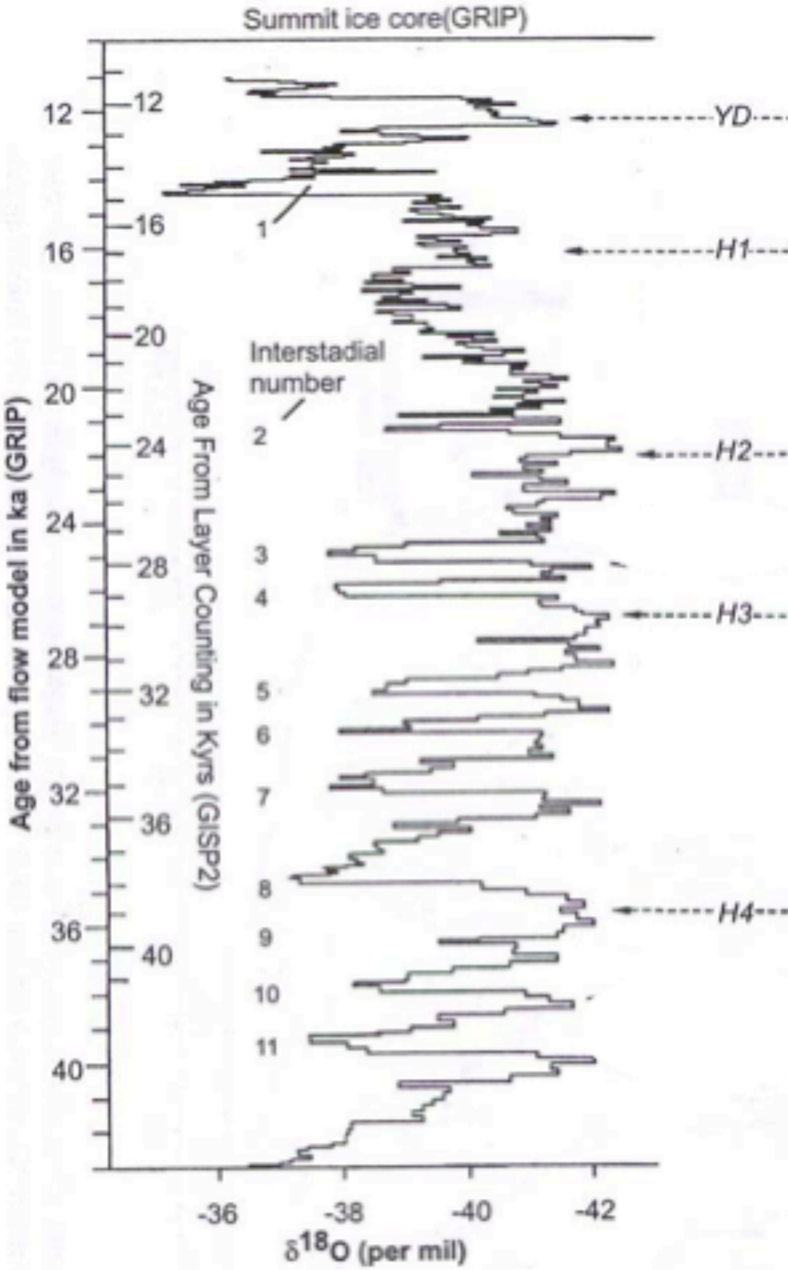
Heinrich events (thick IRD layers) are driven by ice sheet dynamics.

In other words: an ice stream in the Hudson Strait was surging (and calving).

In general, calving rate scales with ice accumulation:

more ice = more calving.

How do we get more ice?



Do you see an obvious temperature trend before/during/after Heinrich events?

Bradley 1999

Outstanding questions

Dynamics of ice sheet calving is complex!

Problem = statistics of small numbers.

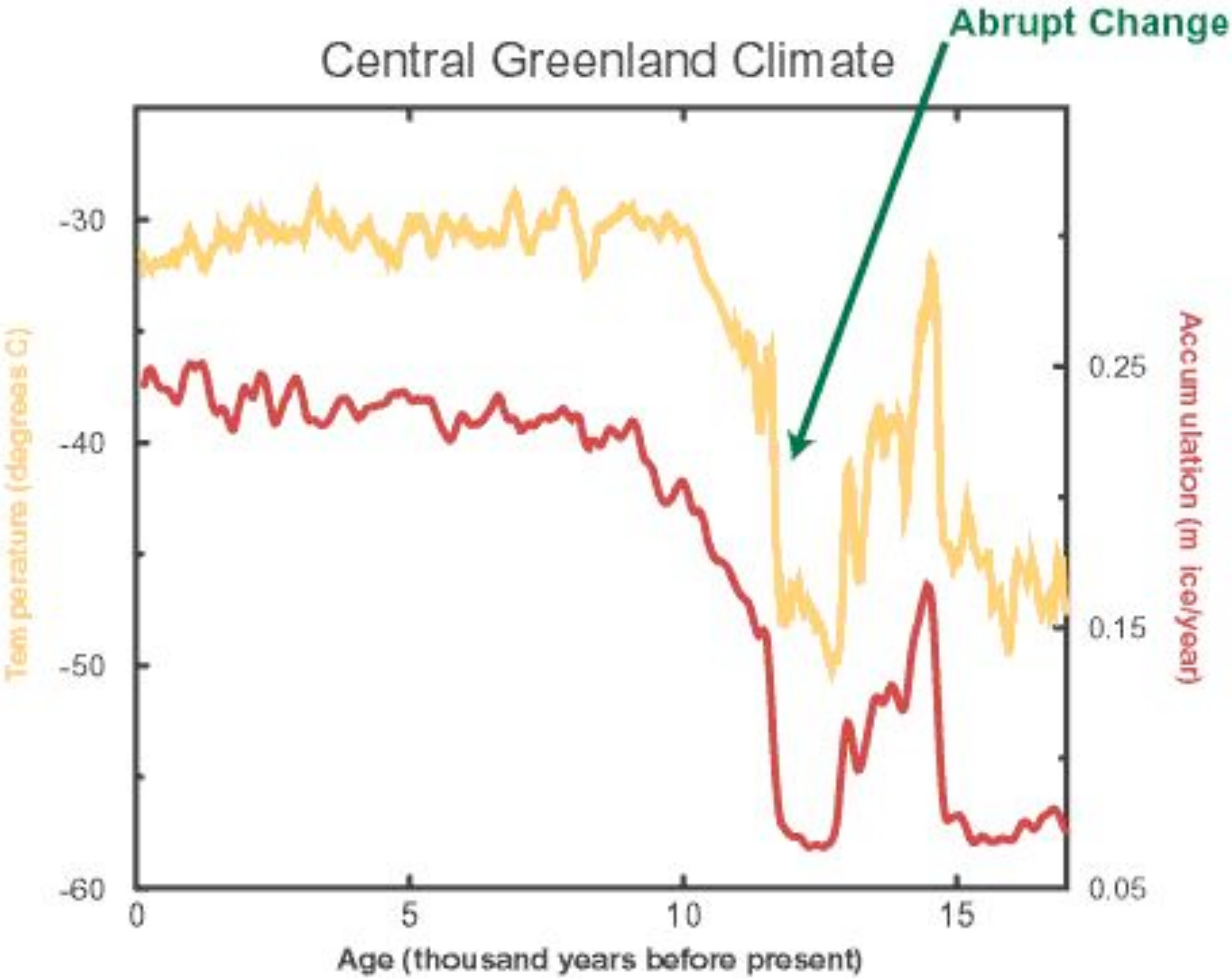
- What causes the ice sheet to undergo significant calving events during Heinrich times?
- Why were these calving events so abrupt?
- Do ice sheets have a threshold above which calving is more rapid?

- Is there a climate forcing?
- A climate response?
- How widespread is the climate signal?

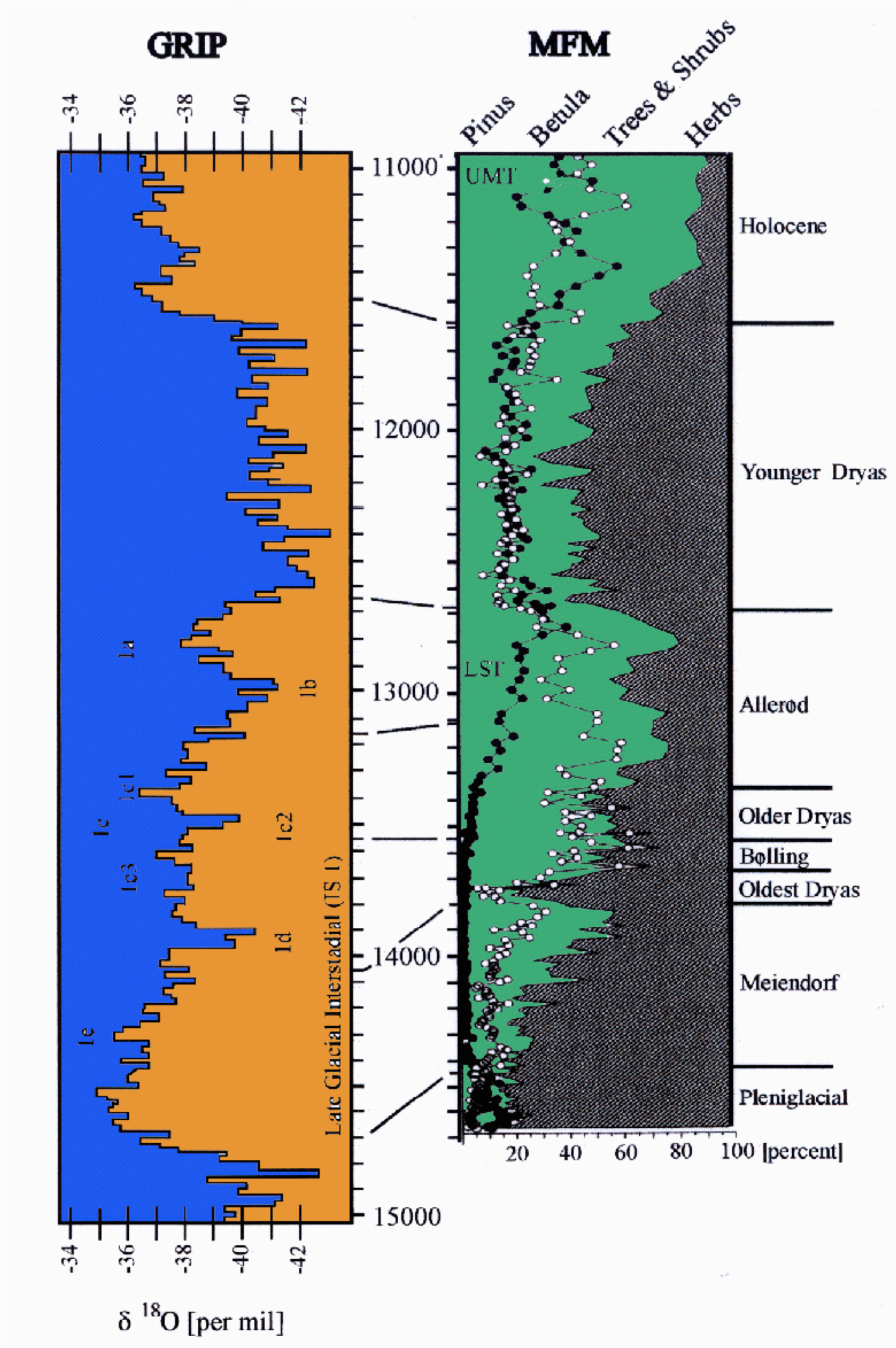
Younger Dryas (~12,000 years BP)

- As temperatures were warming near the end of the last glacial period, there was a rapid return to near-glacial conditions (named after the Dryas pollen, common to this time period)
- Onset of near-glacial conditions occurred over ~100 years
- Near-glacial conditions persisted for ~1,000 years…
- …and ended rapidly: some places may have warmed by 10ºC in ~10 years!

Dryas octopetala



Abrupt Change
Central Greenland Climate
-30
-40
-50
-60
0
5
10
15
Age (thousand years before present)
0.25
0.15
0.05
Temperature (degrees C)
Accumulation (m ice/year)



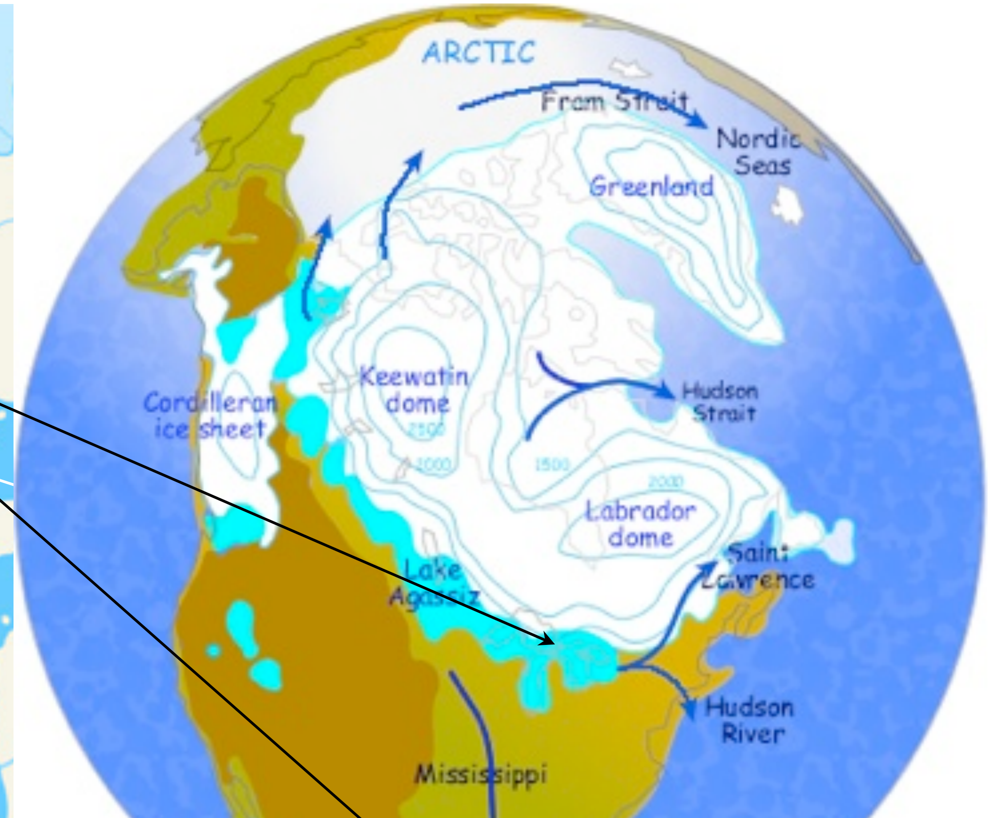
European pollen records are consistent with the Greenland ice core (Grip) record. During the YD interval arctic herbs dominate the pollen record as glacial conditions returned to Europe. The YD interval ended abruptly and warm conditions returned to Europe.

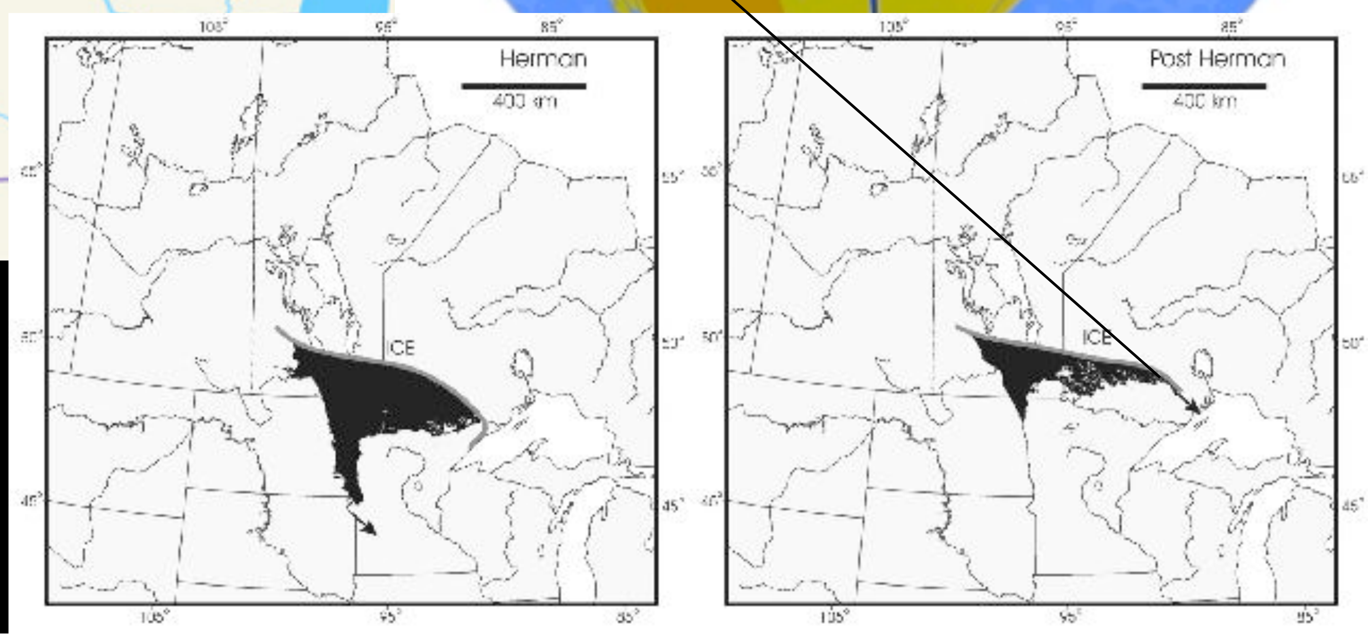
Younger Dryas transition

- Pulse of meltwater (cold and fresh) into N. Atlantic caused a decrease in salinity and density of the surface waters

- This led to a decrease in the formation of deepwater in the N. Atlantic

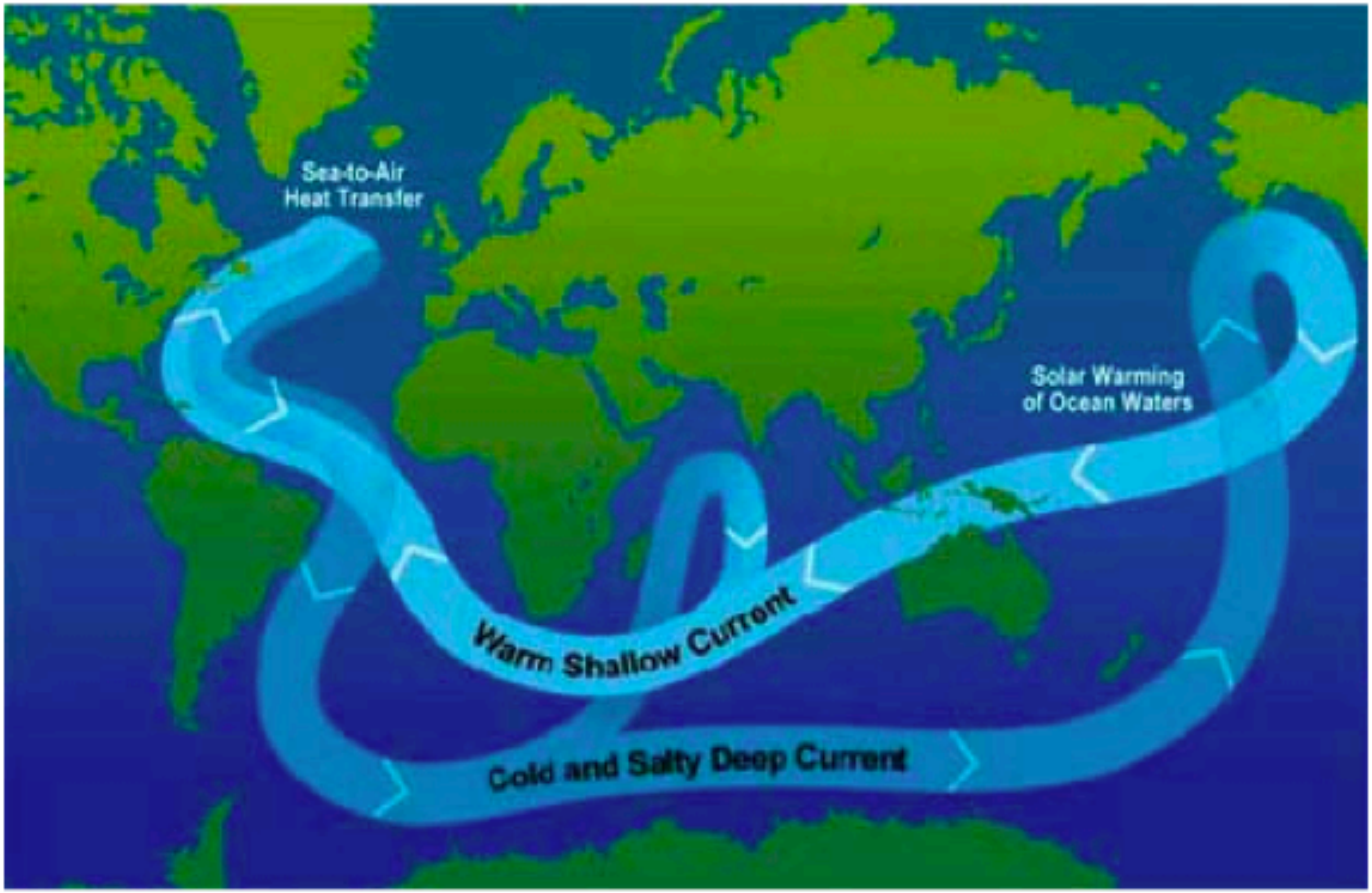
→Not as much warm water reached the N. Atlantic, causing a return to colder conditions



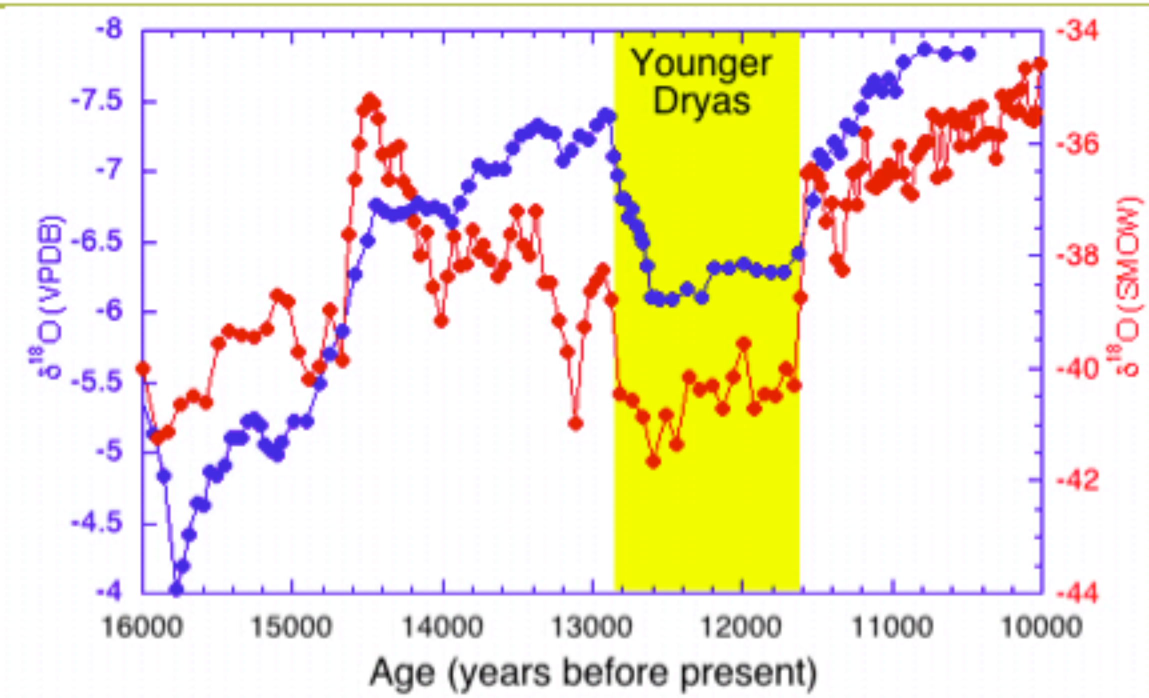


Did the drainage of glacial Lake Agassiz into the North Atlantic trigger the YD?

Thermohaline Circulation (simplified)



YD changes elsewhere in the world



GISP2 $\delta^{18}O$ and Hulu Cave, China stalagmite

A change occurred in summer rainfall on the other side of the world! $\delta^{18}O$ in Hulu record indicates that the summer monsoon was weaker during YD.