# $^{14}C$, paleoclimate, and the carbon cycle

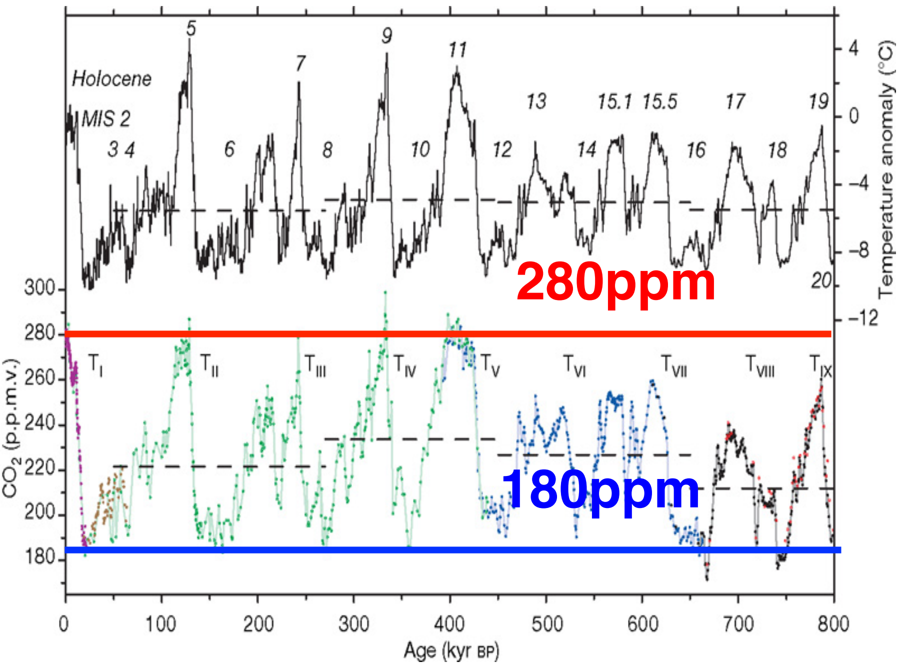
John Southon
Radiocarbon Short Course, Jena, 2017

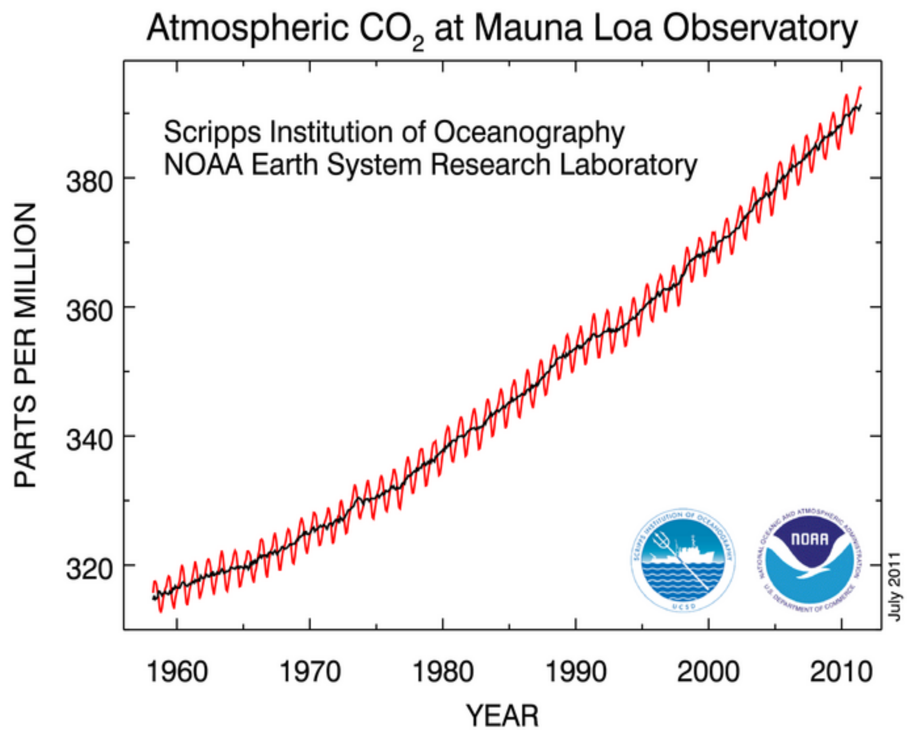
Glacial carbon cycle: where did the missing carbon go?

Radiocarbon calibration: problems and progress

# Why are we here?

Climate change is linked to carbon cycle changes



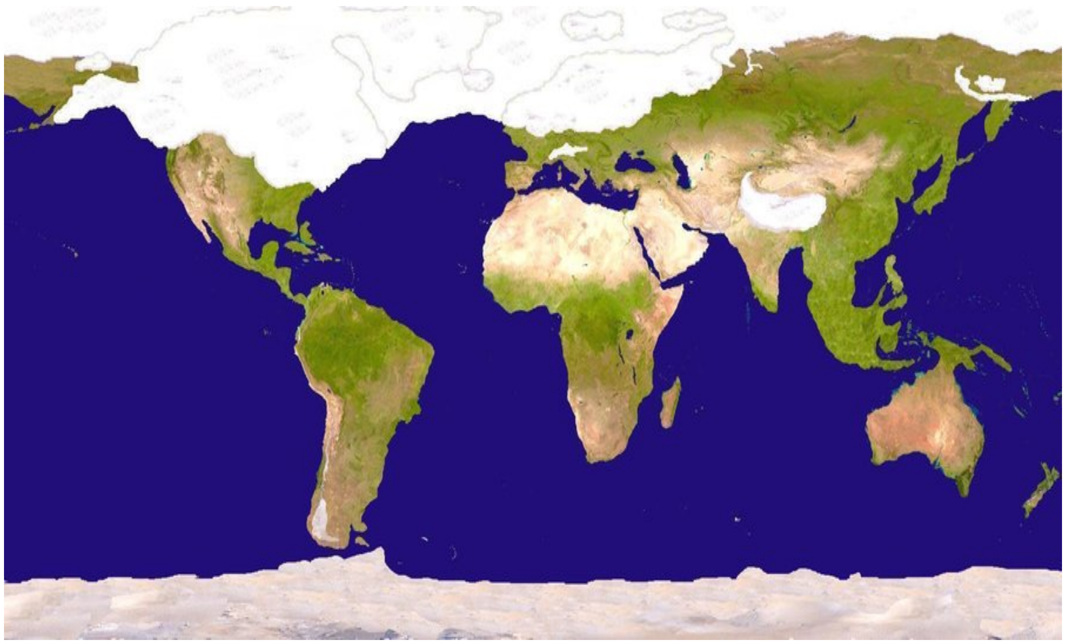



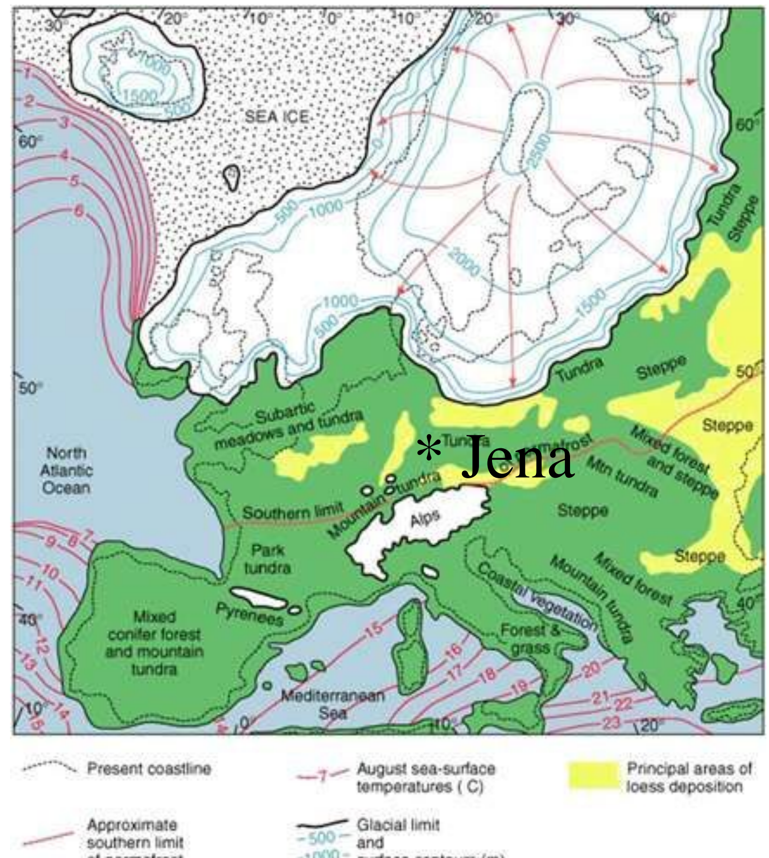

How do we plan for the future?
What does this have to do with paleoclimate?

# Our ability to predict future climate depends on getting climate and carbon cycle models right.

Can they reproduce the past?

Last Glacial Maximum is a laboratory for testing climate models
Orbital changes, drier, dustier, colder, sea level -130m, reduced terrestrial biosphere, changes in ocean chemistry and biology, $pCO_2$ 180-200 ppm

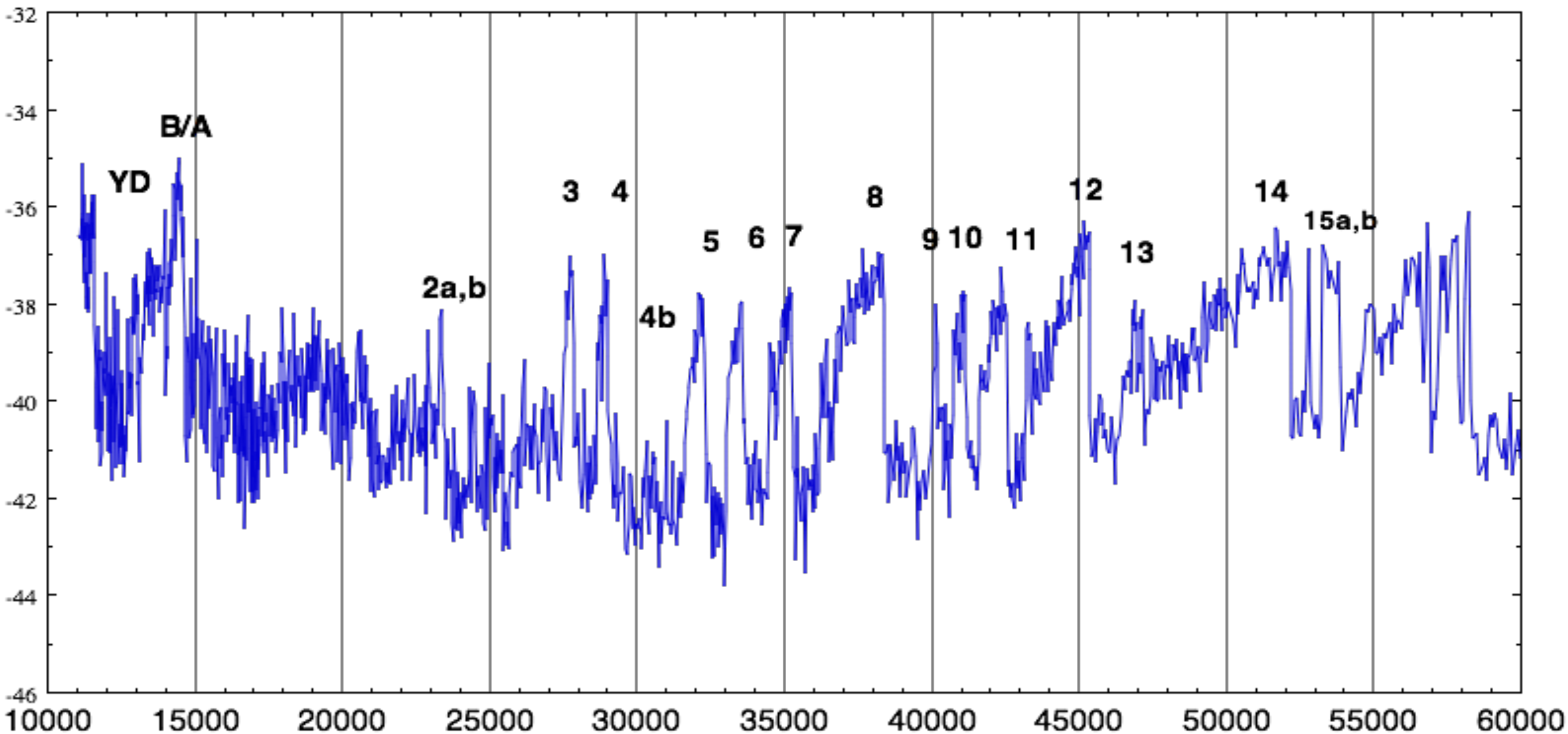





Radiocarbon provides a clock for climate change AND a tracer for the carbon cycle of the past

# Glacial climate: different base state PLUS rapid changes

Dansgaard-Oeschger (D-O) cycles:
$\delta^{18}O$ in Greenland ice cores indicates rapid warming every ~1500 years
Widespread in Northern Hemisphere, not just in Greenland.
Likely cause: changes in ocean circulation




Layer counting time scale

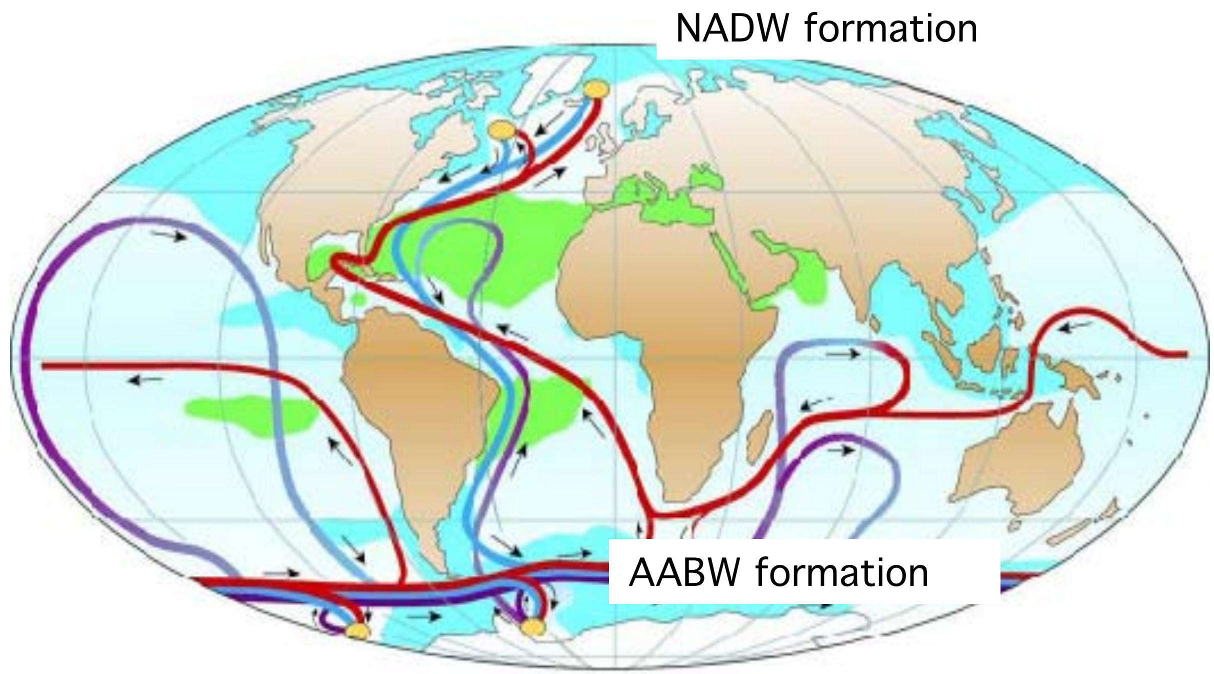
# Broecker's Conveyor Belt
## Meridional Overturning Circulation (MOC)

Different states of the Conveyor:

Interstadial/Holocene "on"

Glacial "on"

Glacial "off" (Drop Dead mode): NADW off.

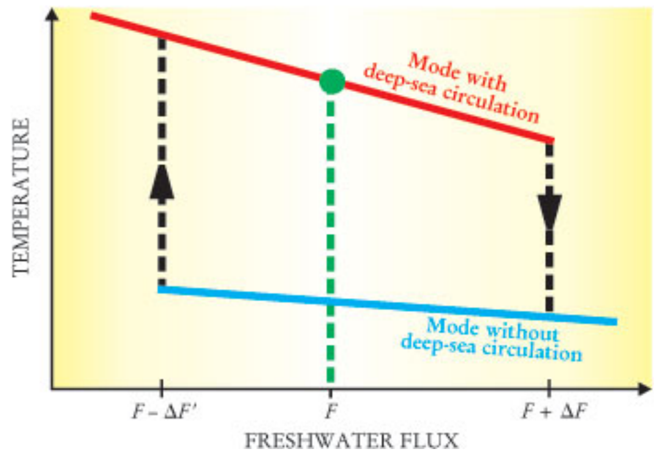



NADW: North Atlantic Deep Water
AABW: Antarctic Bottom Water

What drives the conveyor (push vs pull)?
NADW formation?
Southern Ocean wind stress?
Downward mixing of fresh water and heat?

# Multiple modes of the Overturning Circulation

D-O cycles are interpreted as shifts between “Modern” and “Glacial on”




Conceptual model:
System shows hysteresis in response to meltwater changes

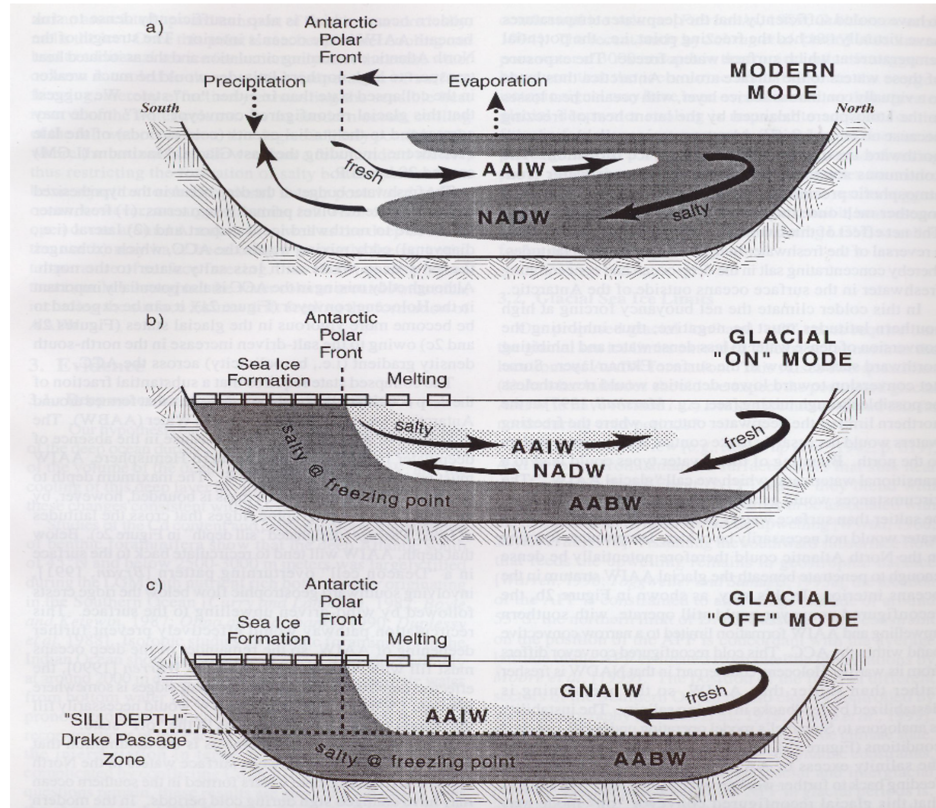



**Figure 2.** Hypothesized three states of the ocean's thermohaline overturning: (a) modern conditions prevailing in Holocene, (b) Glacial "on" state prevailing in interstadial (warm) events of the Pleistocene, and (c) glacial "off" state prevailing in stadial (cold) events of the Pleistocene.

In models, the deep ocean reservoir is isolated in “glacial” conveyor modes.
Could this sequester enough carbon as DIC to explain $pCO_2$ drawdown?

# Heinrich Events: MOC in the "off" state

Ice rafted debris in northern N.Atlantic
Rapid cooling in N. Hemisphere; S. Hemisphere warms (bipolar seesaw)

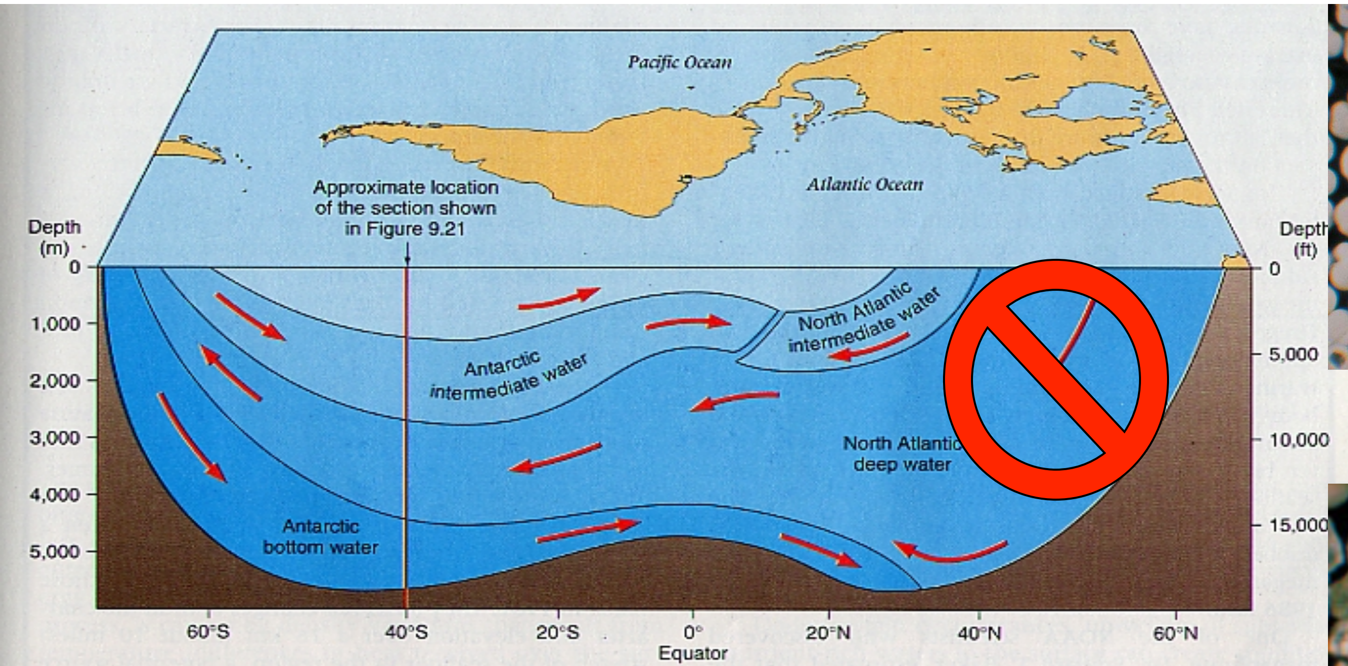
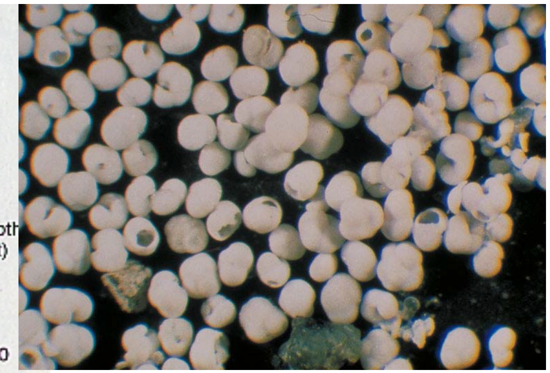
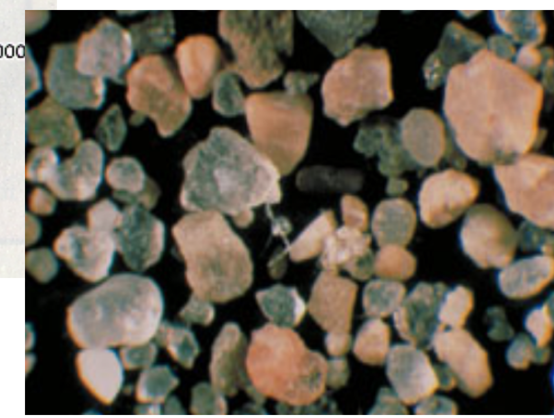



FIGURE 9-20 Diagrammatic section of the major subsurface water masses in the Atlantic Ocean. Line at 40°S indicates approximate location of the section shown in Figure 9-21.



Forams

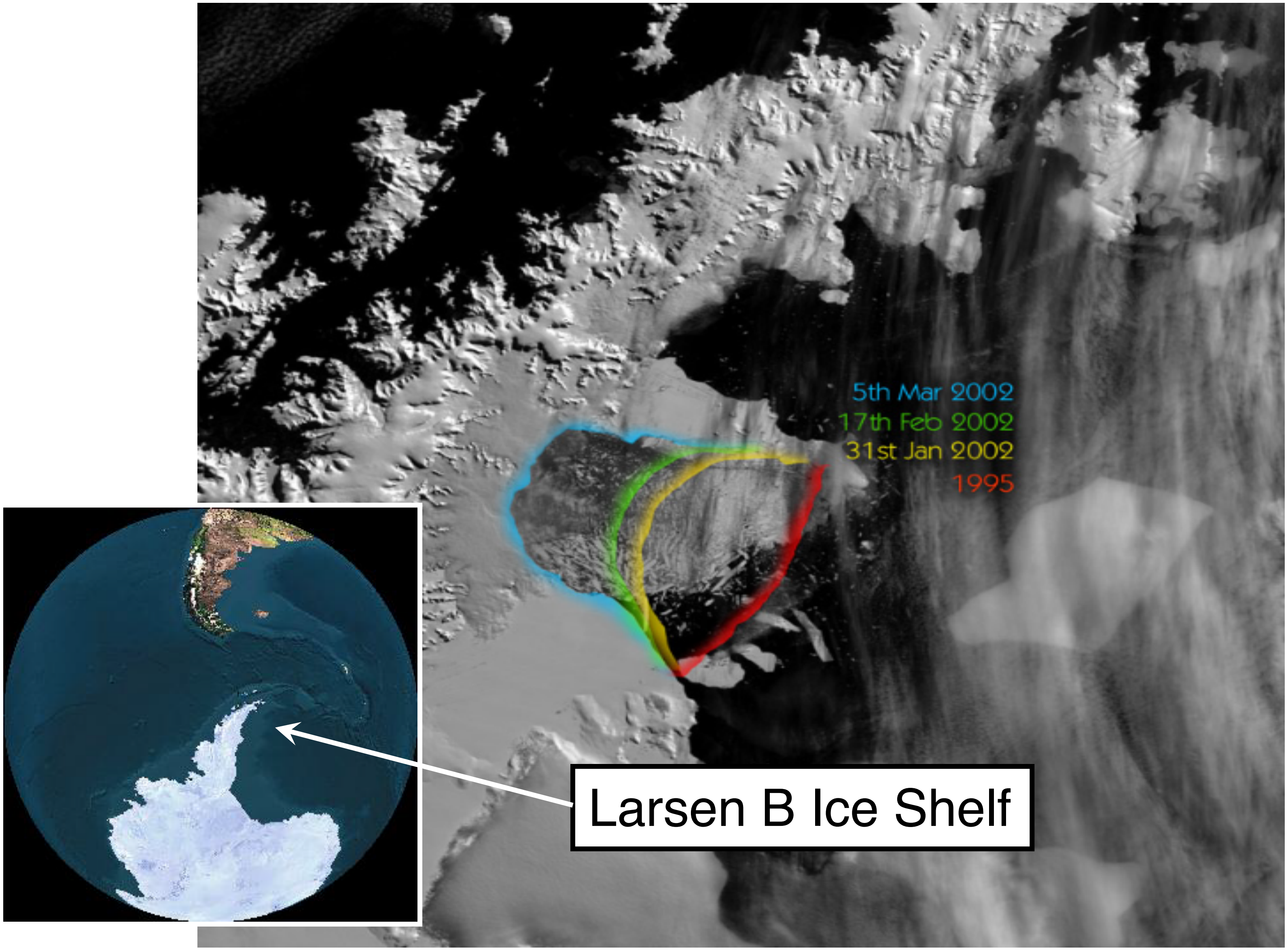


Ice rafted debris (IRD)

Ice sheets surge, meltwater cap covers the N.Atlantic
NADW shuts down, AABW fills the entire deep Atlantic

# Not a Heinrich Event, but is this the mechanism?

Larsen B Ice Shelf breakup, Feb 2002: 1 month, 500 $km^3$



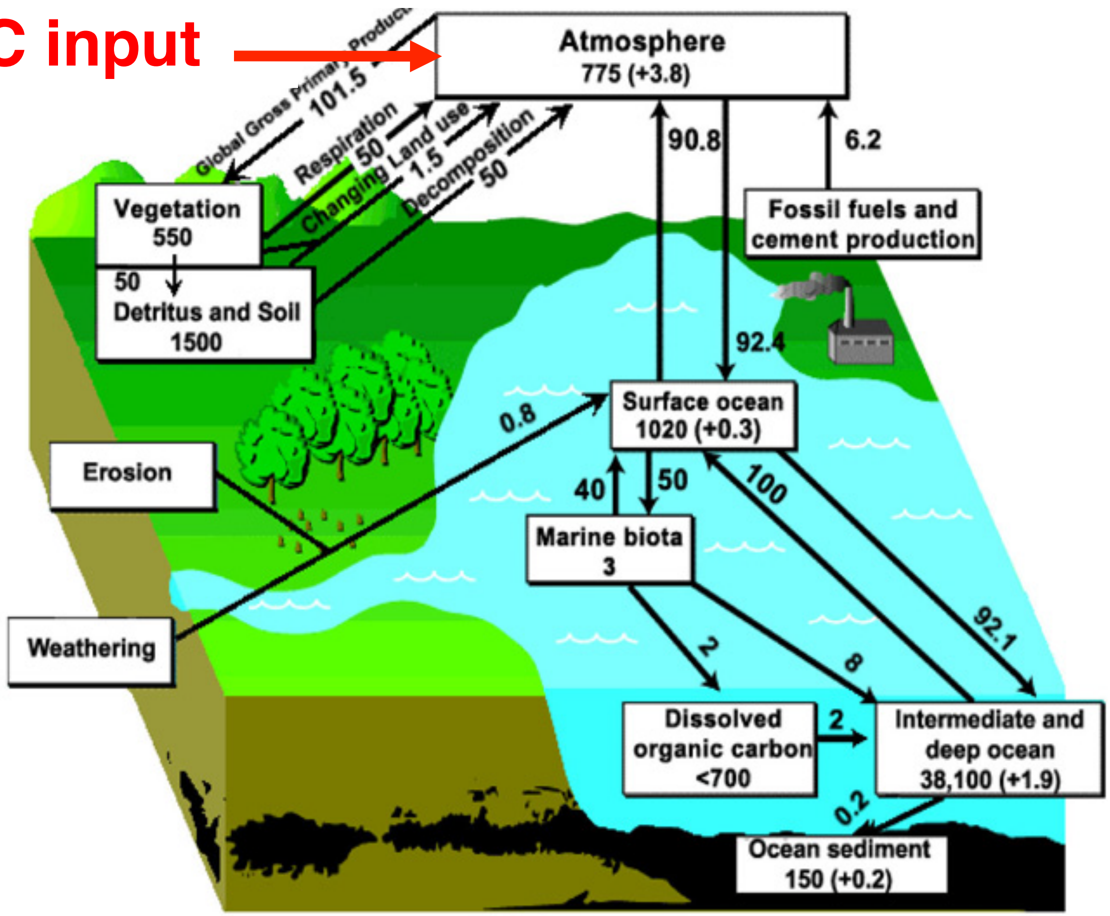
# Where $^{14}C$ fits in: natural $^{14}C$ as a carbon cycle tracer

Made in the atmosphere by cosmic rays, mixes into the carbon cycle as $CO_2$

Most of it decays in the deep ocean

$^{14}C$ ages: deep ocean > surface ocean > atmosphere

**$^{14}C$ input**




**$\Delta^{14}C = 0‰$**

Marine reservoir age

**$\Delta^{14}C = -50‰$**

Benthic- planktic age difference

**$\Delta^{14}C = -160‰$**

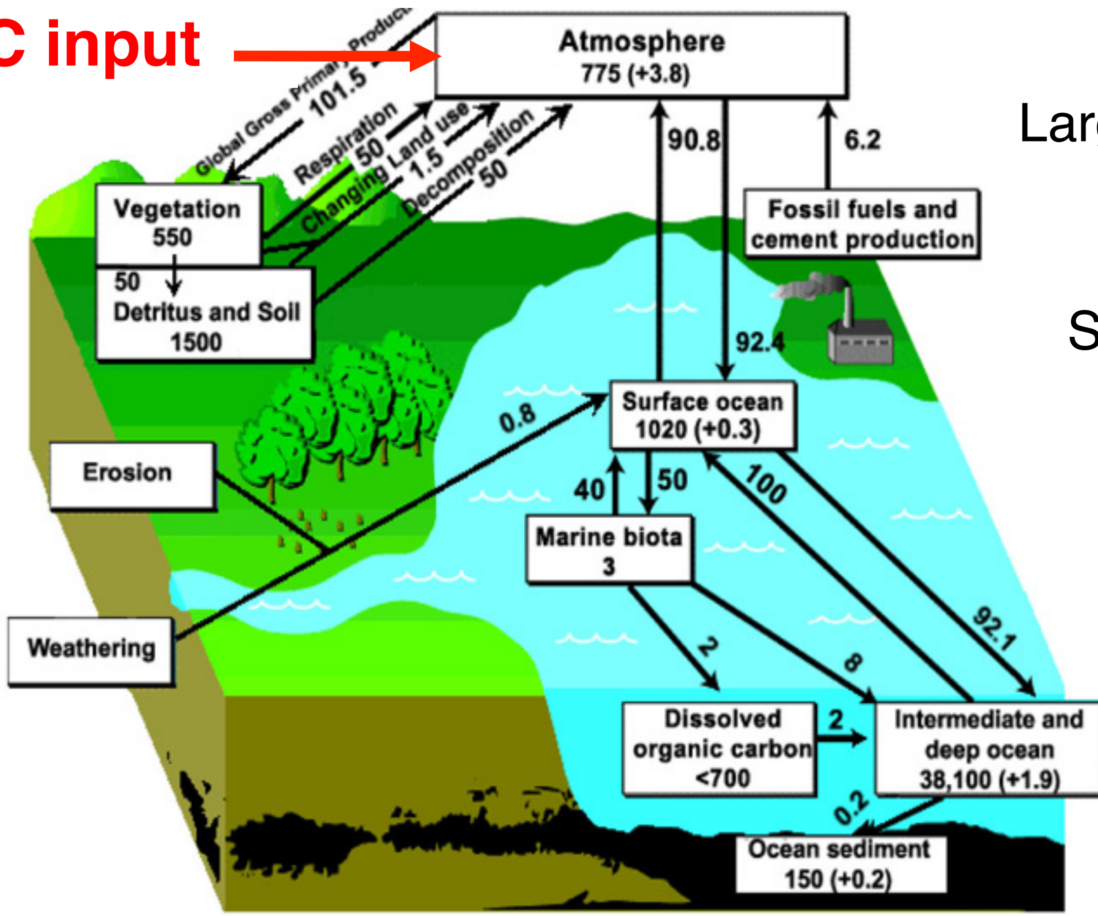
Marine reservoir age: atmosphere-ocean $^{14}C$ offset expressed as a radiocarbon age.

Benthic-planktic age difference: $^{14}C$ age difference between deep and surface ocean

Ventilation age: elapsed time since water was at the sea surface

# What happens if $^{14}C$ production changes?

$^{14}C$ input




Large atmospheric $\Delta^{14}C$ changes (bomb spike = +1000‰)

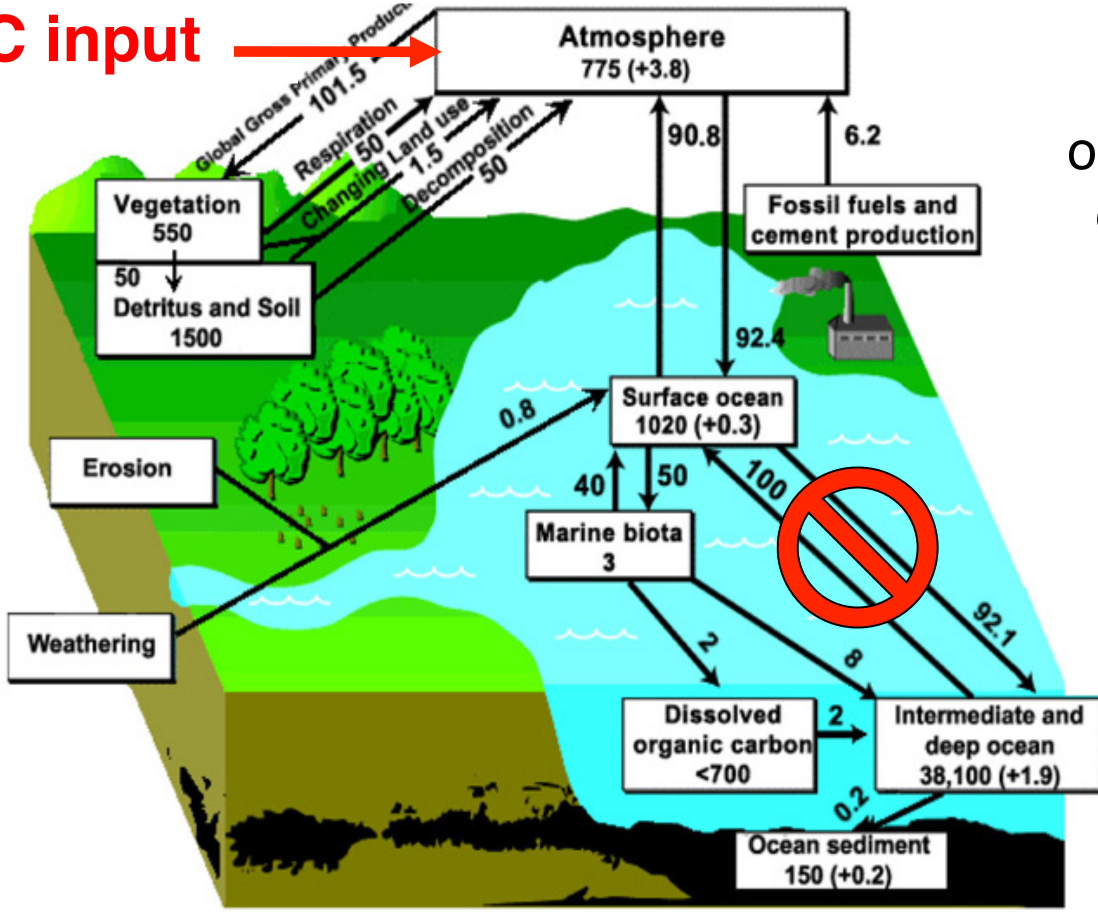
Surface ocean $\Delta^{14}C$ changes much less (bomb spike = +150‰)

Deep ocean $\Delta^{14}C$ changes diluted by the huge DIC pool – this only responds to long term changes

Changes in marine reservoir ages are a proxy for $^{14}C$ production changes
Other cosmogenic isotopes (e.g. $^{10}Be$) co-vary

# What happens if MOC is reduced or shut off?

$^{14}C$ input




Atmosphere and surface ocean $\Delta^{14}C$ increase: newly created $^{14}C$ is diluted in a smaller carbon pool

Deep ocean $\Delta^{14}C$ drops: reduced input of $^{14}C$ from the surface cannot keep up with decay

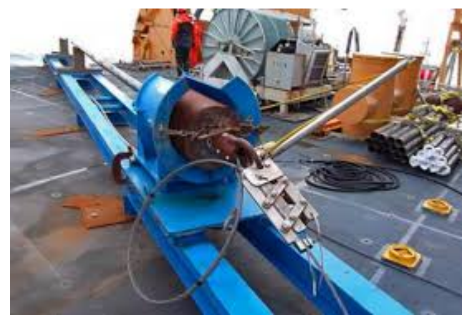
Carbon is sequestered in the deep ocean via the marine biota pool

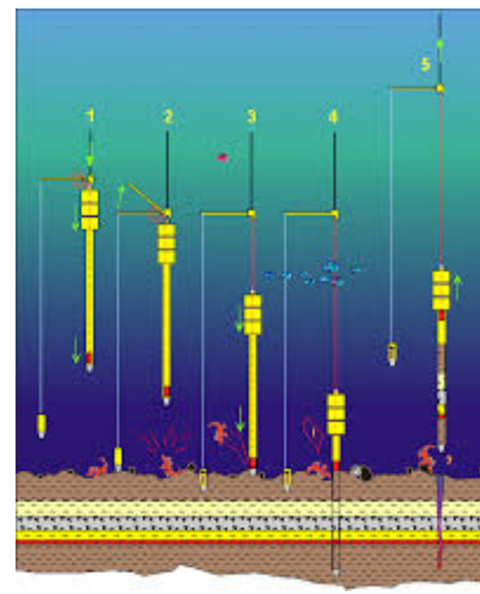
Changes in benthic-planktic age differences are a proxy for MOC changes ($^{14}C$ is one of many proxies: $\delta^{18}O$, Cd/Ca, Pa/Th, $\delta^{13}C$, etc)

# $^{14}C$ records from calcareous marine archives

Surface and deep corals, foraminfera

Collection methods:
Surface corals: core drilling
Deep sea corals: submersibles, ROV's
Forams: sediment coring






Piston coring:
When sensors detect bottom, the weighted outer core barrel is released to free-fall past a stationary inner piston into the sediment.
This technique can retrieve tens of meters of core from water depths of thousands of meters

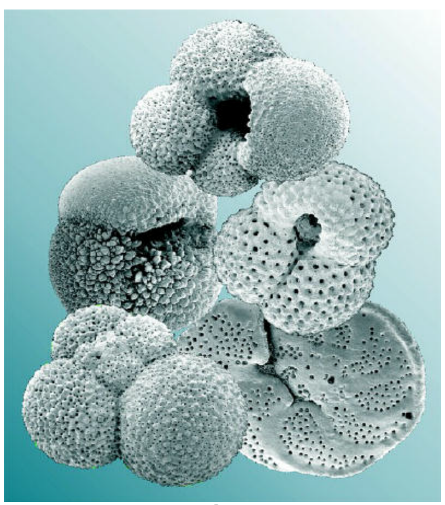
# Foraminifera from ocean sediment cores

Planktic forams and reef corals record surface water and upper thermocline conditions

Benthic forams and deep sea corals record bottom water

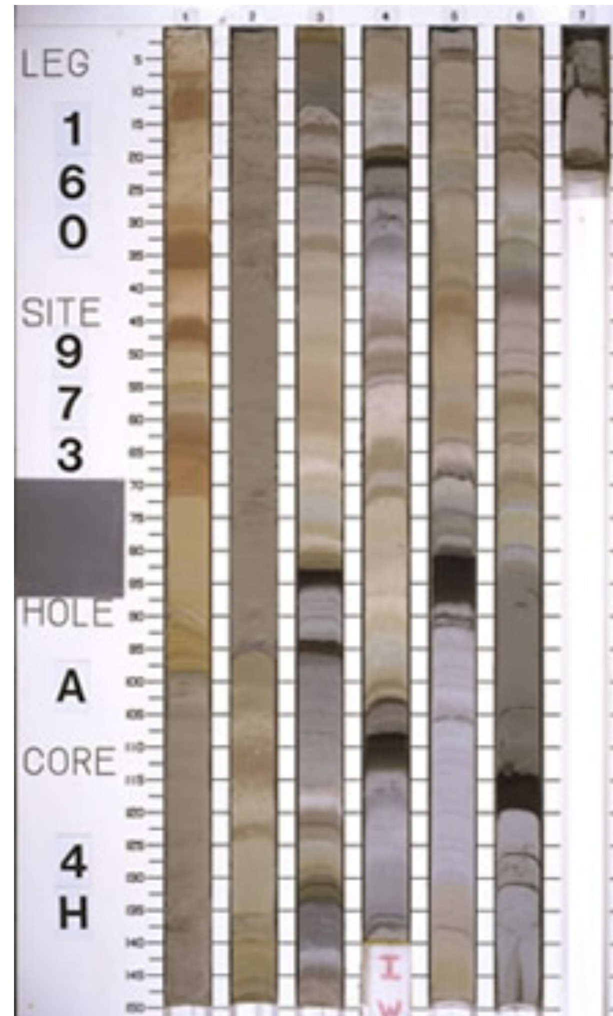
Typically, 500 – 2000 forams = 1mg of carbon

Picked individually from sieved sediment



0.5 mm


Archived ODP core

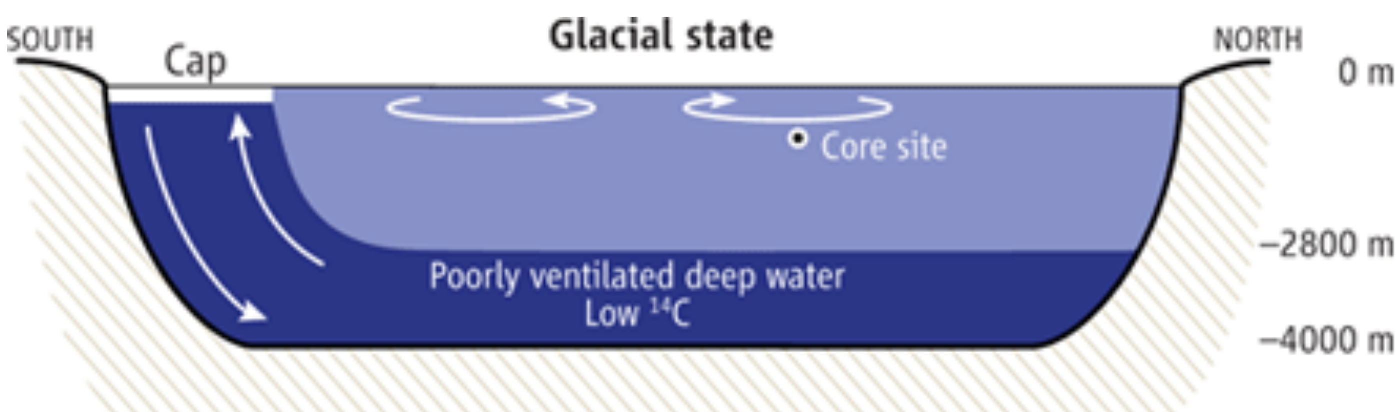


# To recap: was the missing $CO_2$ in the deep ocean?

In models, the deep ocean reservoir is isolated in “glacial” conveyor modes.

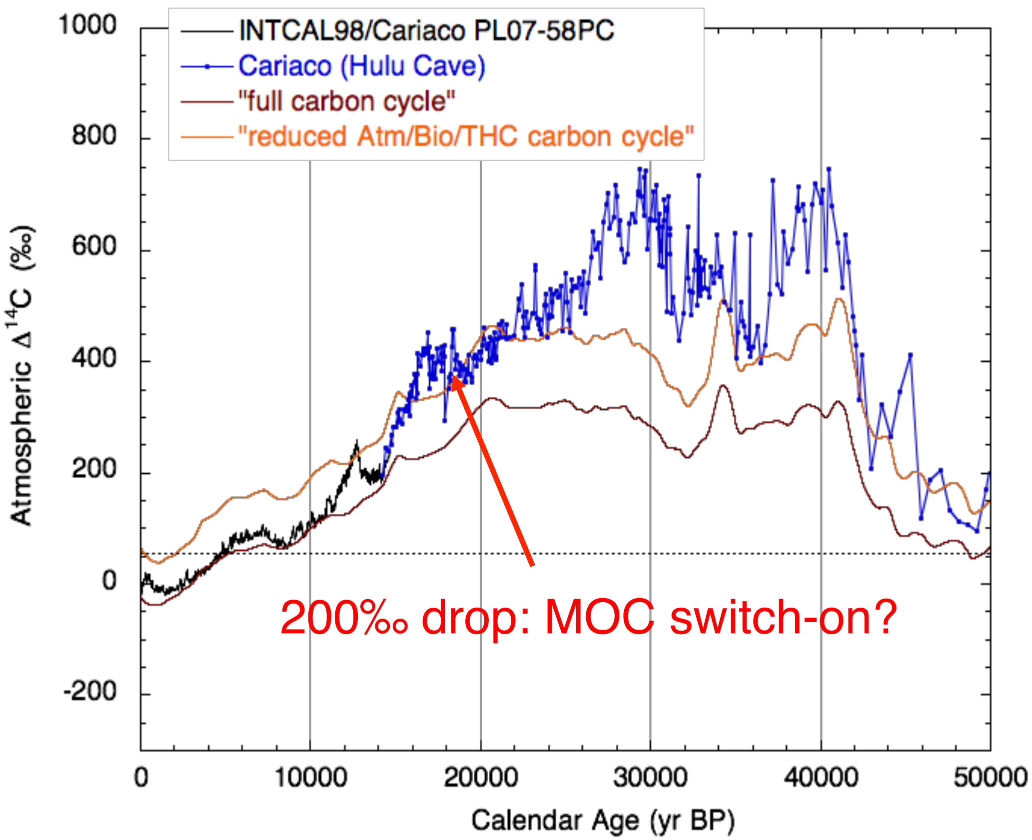
The Dissolved Inorganic Carbon in the deep isolated reservoir has high $pCO_2$ and very low $^{14}C$

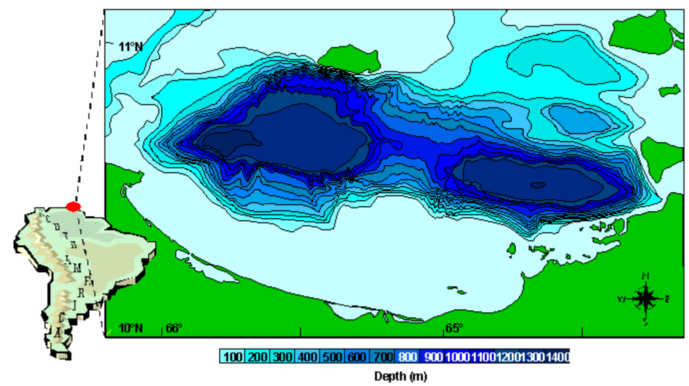
$^{14}C$ is correspondingly elevated in terrestrial and surface marine carbon pools
Can we find radiocarbon evidence for this?



# High glacial terrestrial and surface marine $\Delta^{14}C$

$^{14}C$ production changes based on paleomagnetic data cannot explain high $\Delta^{14}C$




$^{14}C$ in planktic forams from Cariaco Basin, Venezuela.

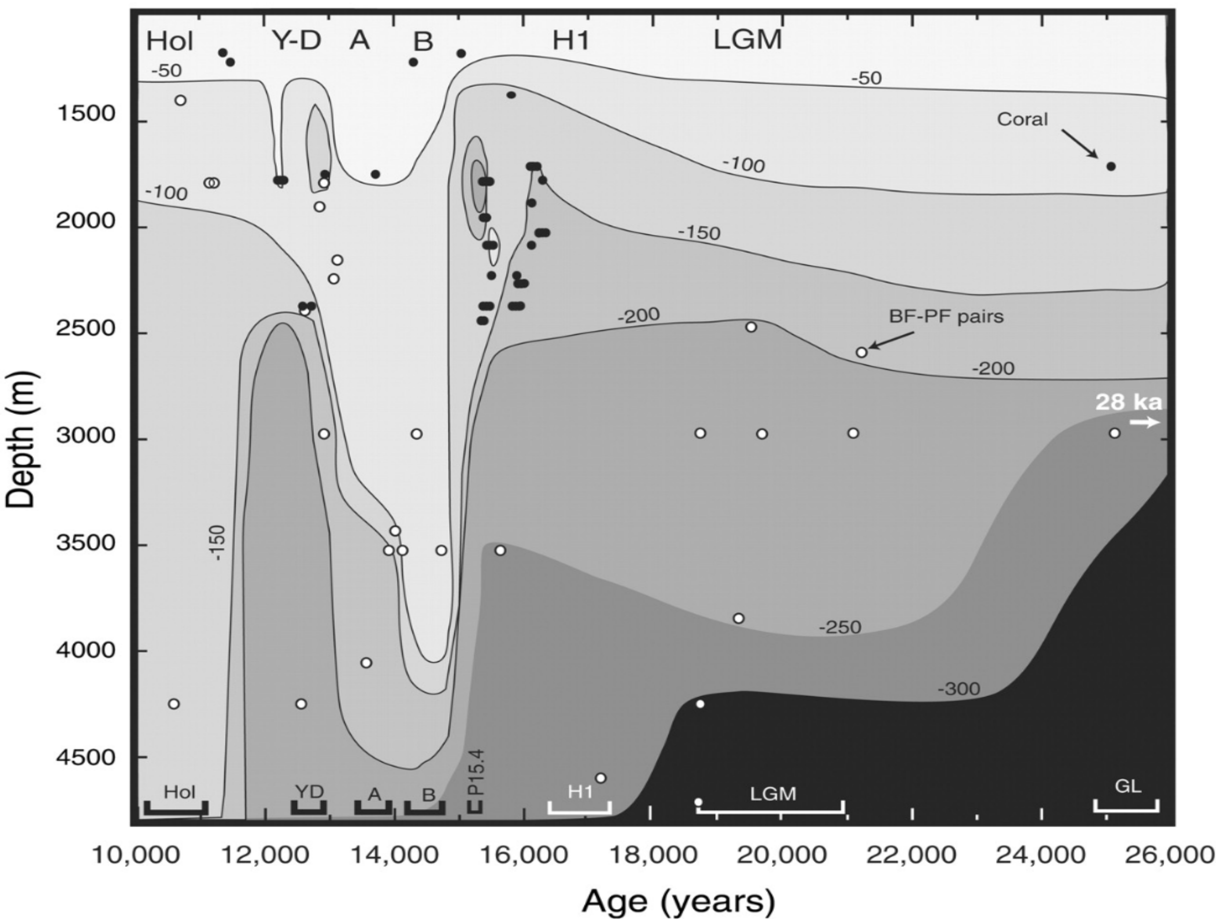
Independent timescale via correlation of sediment geochemistry with U/Th-dated speleothems

Data consistent with (but don't prove) deep ocean carbon storage

Steep drop during deglaciation = MOC switch-on?

# Low $\Delta^{14}C$ in the deep North Atlantic >18 kyr BP

Is this the edge of the old deep water reservoir?



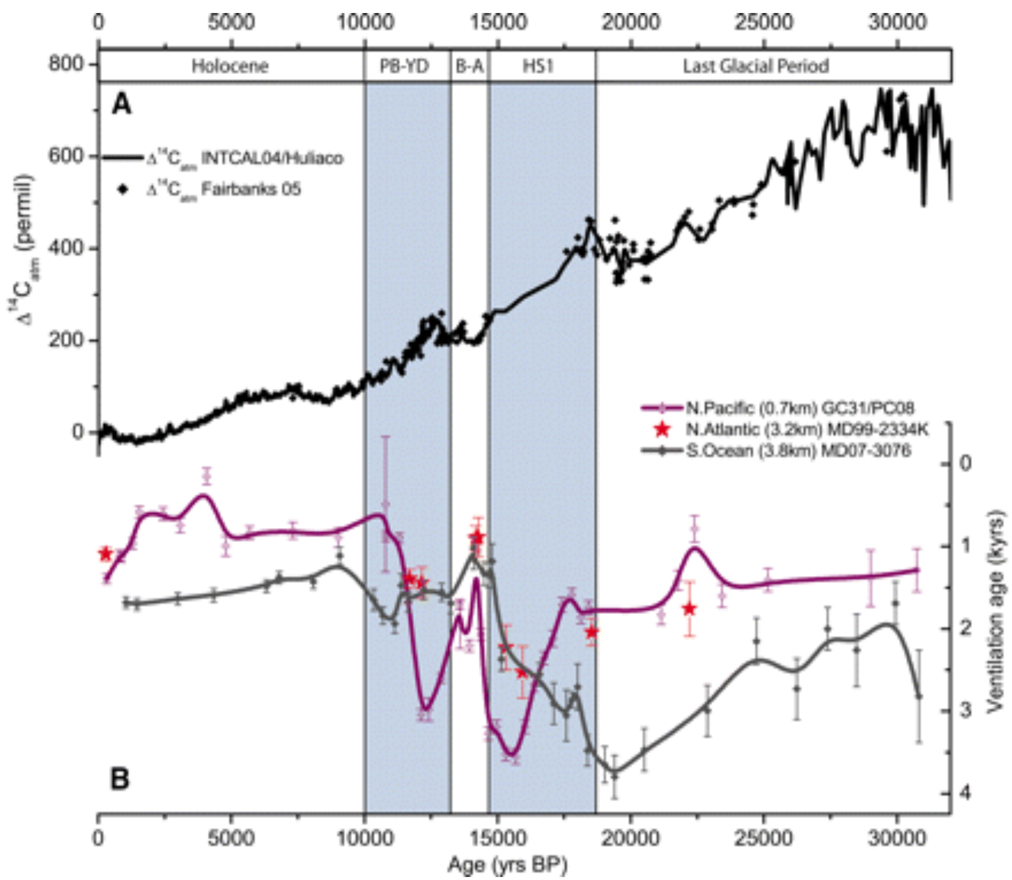

Robinson et al, Science 310 (2005) 1469

Benthic-planktic foram pairs plus U-Th dated deep sea corals

Hol = Holocene
Y-D = Younger Dryas
A = Allerød
B = Bølling
H1 = Heinrich Event 1
LGM = Last Glacial Maximum

# High ventilation ages in the S. Atlantic ~20 kyr BP

Old deep reservoir?



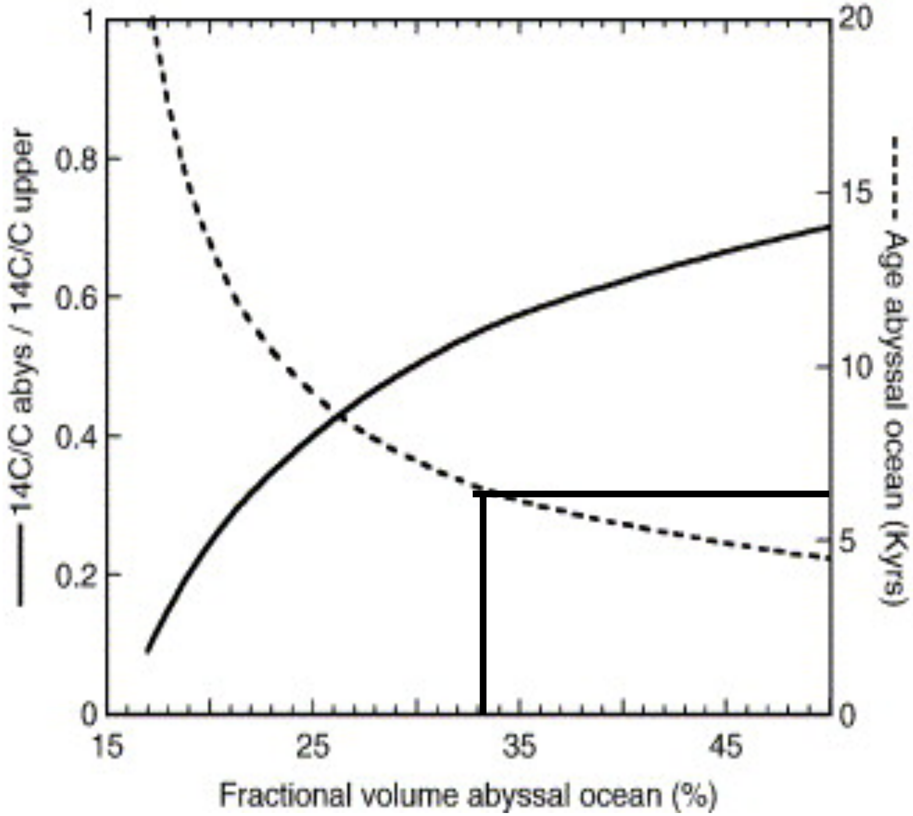

Skinner et al, Science 328 (2010) 1147

Benthic-planktic foram pairs from the edge of the Southern Ocean (black curve).

# MOC turned on during deglaciation (?)

$\Delta^{14}C$ in upper ocean/atmosphere/biosphere dropped by 200‰

How large and how old would the old reservoir need to be?

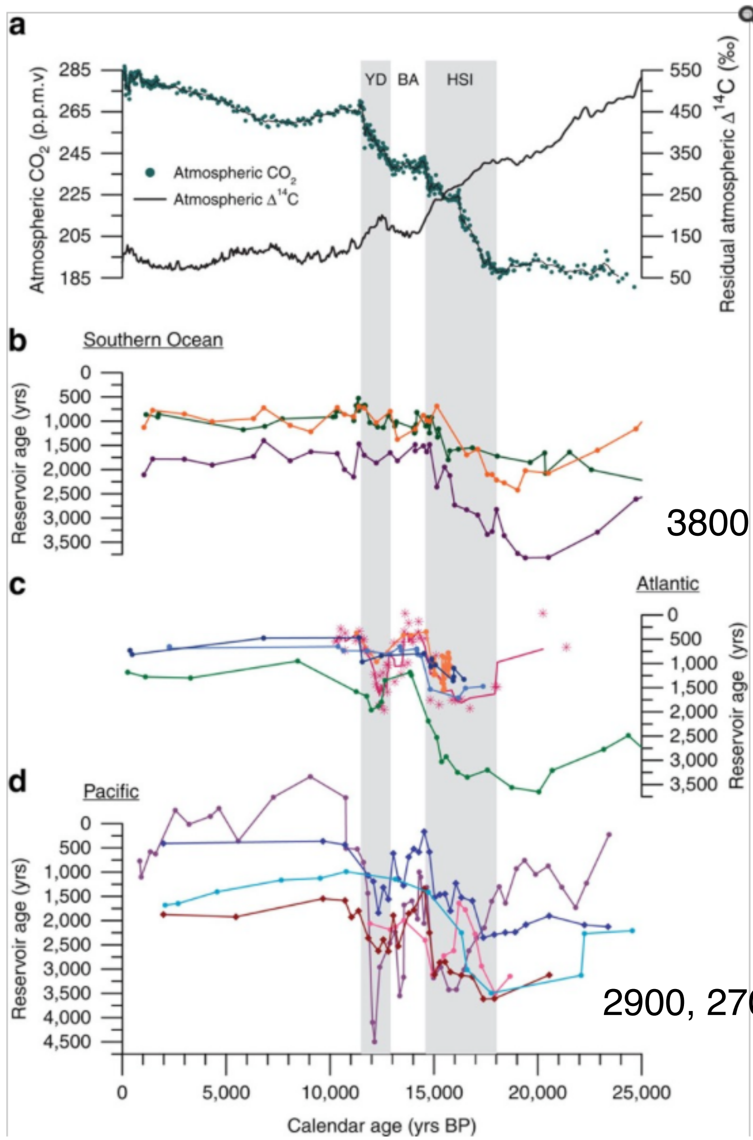



Suppose the deep reservoir contained ~1/3 of the total ocean (>2700m depth).

The required $^{14}C$ age is 7 kyr

# Glacial deep ocean reservoir ages

Old, but are they old enough?




3800 m

3100 m

2900, 2700, 3600 m

# Have we found where the $CO_2$ was hiding?

We do see high $\Delta^{14}C$ in the atmosphere and surface ocean in the glacial.

We do see older bottom water in parts of the world ocean.

We cannot rule out the existence of a deep glacial reservoir of old DIC.

BUT
The observed $^{14}C$ depletions are too small.

The required $^{14}C$ depletions could not be maintained – too much turbulent mixing.

Bottom sediments did not go anoxic.

No sufficiently large and old abyssal ocean reservoir has been found.
This may be part of the answer but it's not all of it.
So what else is there?

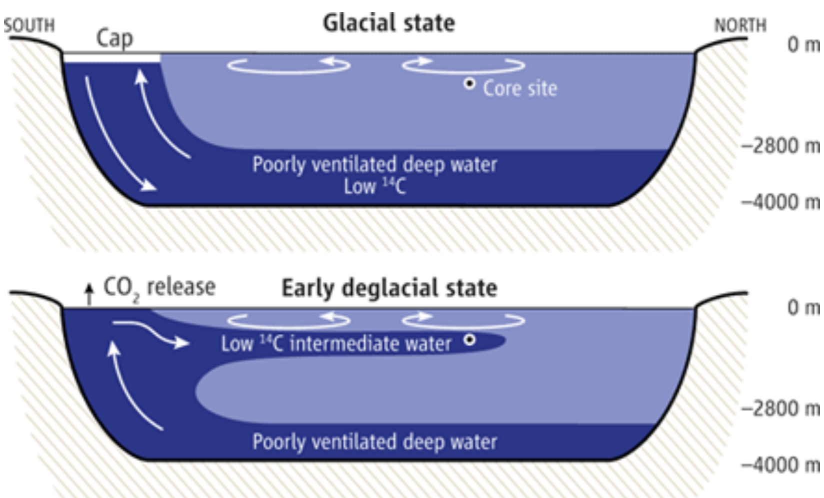
# Old water at thermocline depths

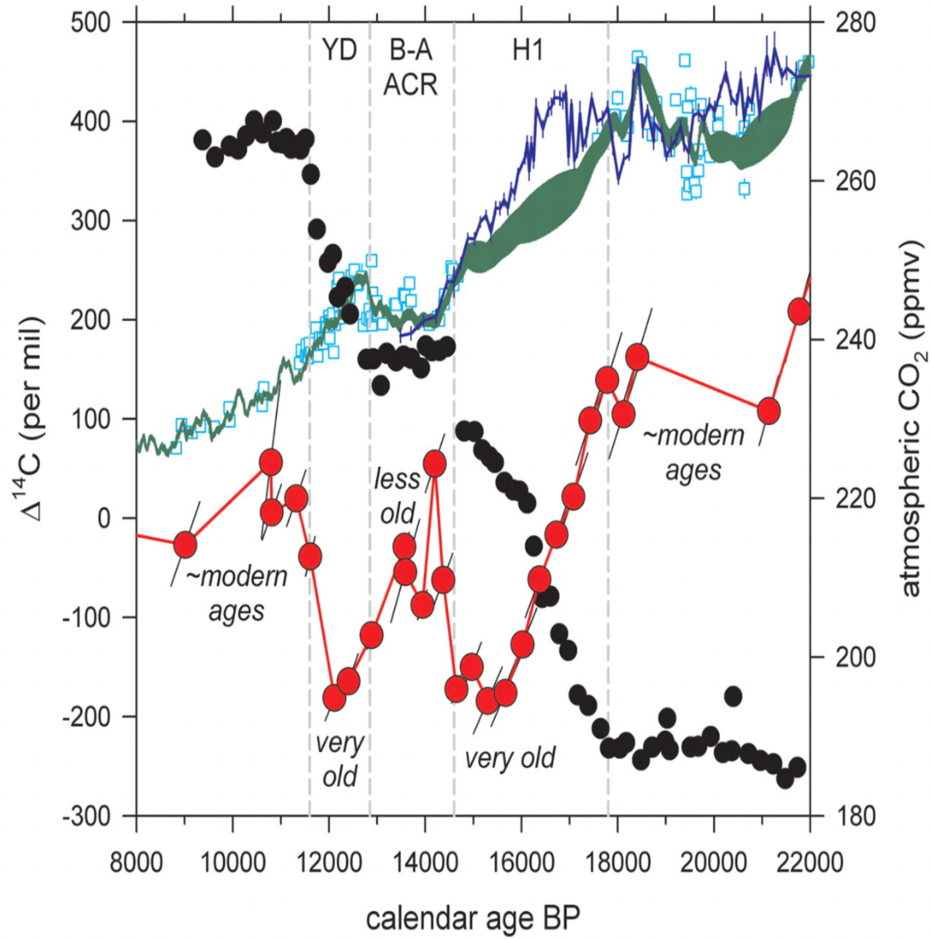
Core from 700m off Baja California

Chronology by correlating sediment color (geochemistry) with Greenland $\delta^{18}O$

2 events, coincident with $pCO_2$ rise in air from Antarctic ice cores

Benthic forams are 400-500‰ below contemporary atmosphere

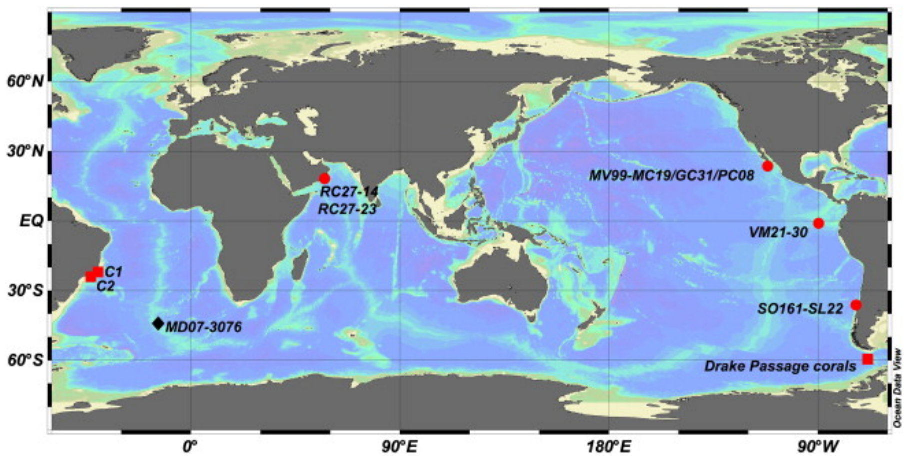


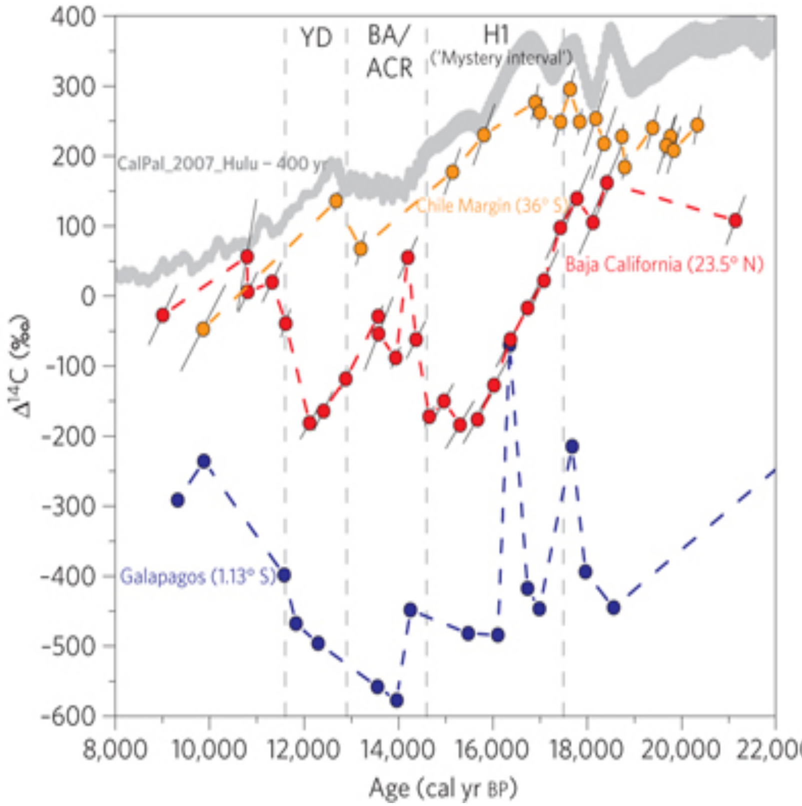




Marchitto et al., Science 316 (2007) 1456

# Very old intermediate water during deglaciation

From the Southern Ocean via Antarctic Intermediate Water (AAIW)?




Old benthic forams:
Baja California
Galapagos
Arabian Sea
N. edge of the Southern Ocean
Off Iceland

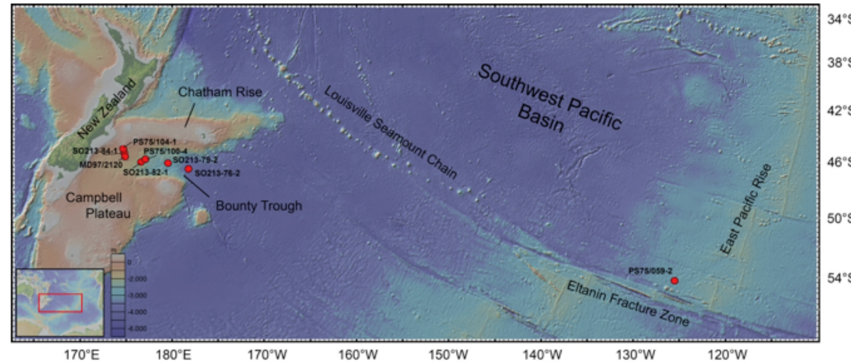
Old deep sea corals:
Brazilian Margin
Drake Passage

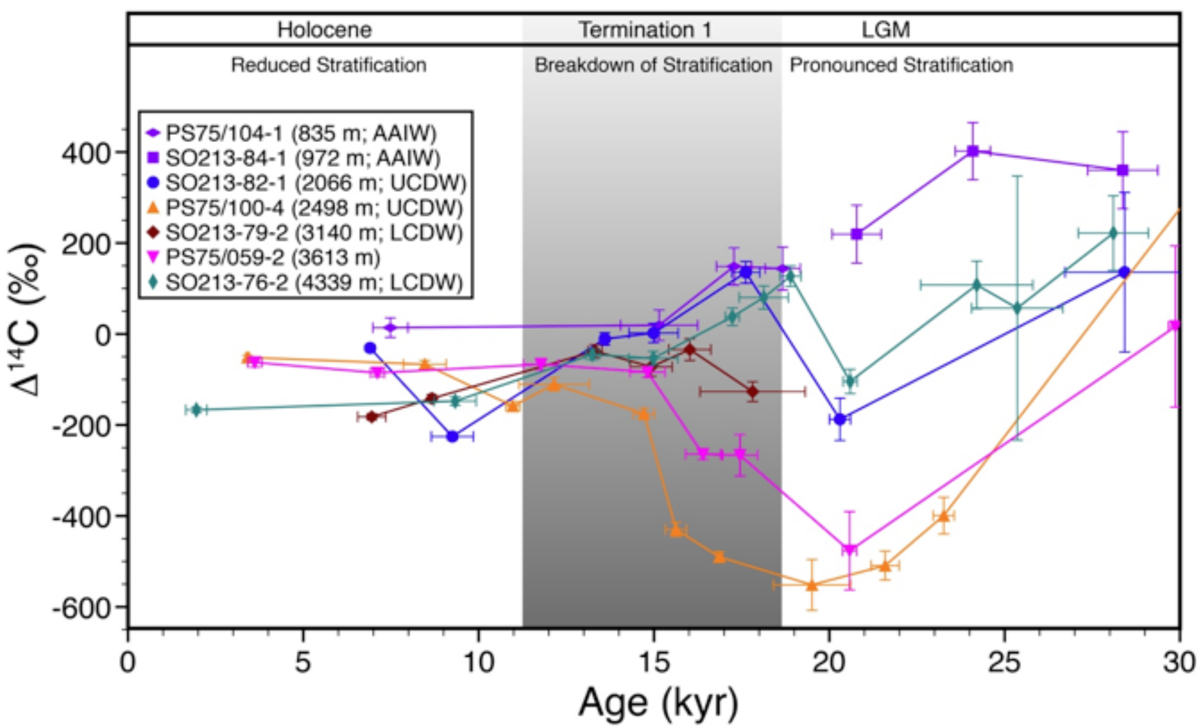
Benthic forams - Baja 700m (red)
Benthic forams - Galapagos 620m (blue)
Benthic forams - Chile 1000m (orange)

# Pacific transect has lowest Δ$^{14}$C at mid depths – why?

Ronge et al., 2016, Nature Comm. 7, doi:10.1038/ncomms11487

Depth transect off New Zealand, plus East Pacific Rise (EPR)



# Something new:

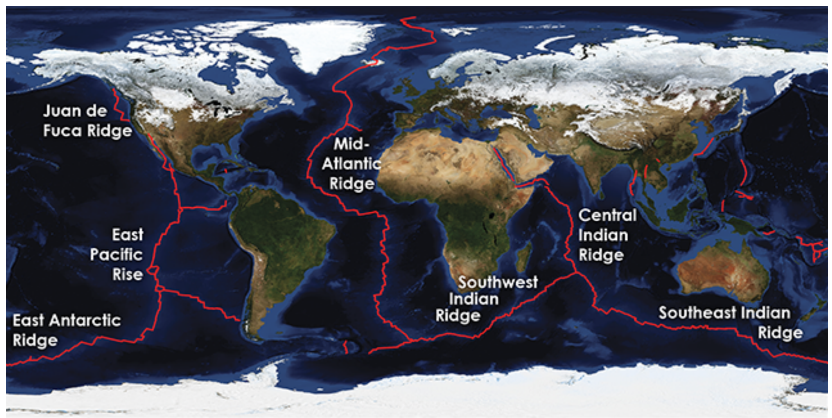
Do sea level changes alter rates of magma (and $CO_2$) injection?

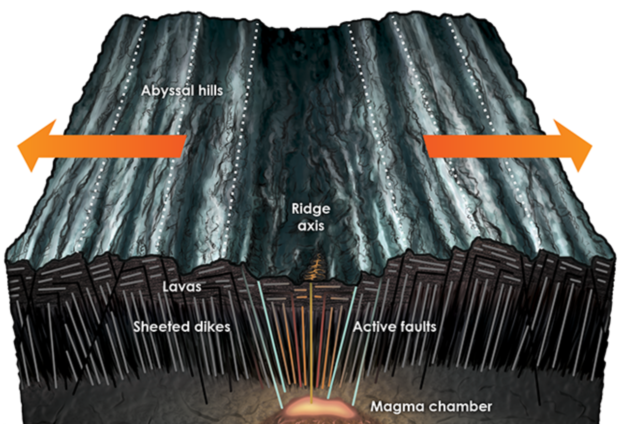
Lund and Asimow 2011, Geo3 12 Q12009

Milankovich cycles in Mid-Ocean Ridge (MOR) bathymetry?

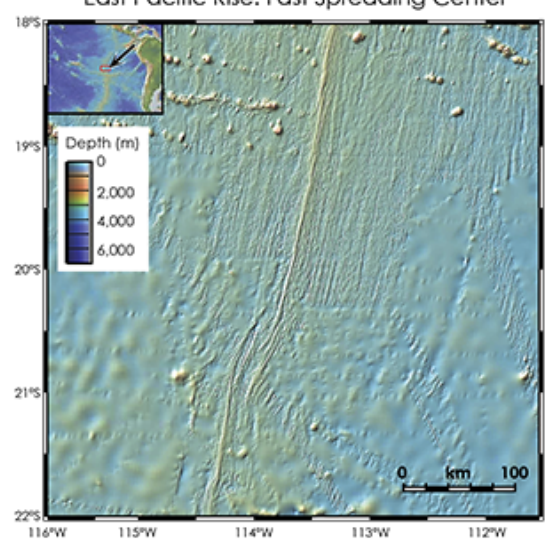
Crowley et al 2015 Science 347: 1237

Tolstoy 2015 GRL 42: 1346

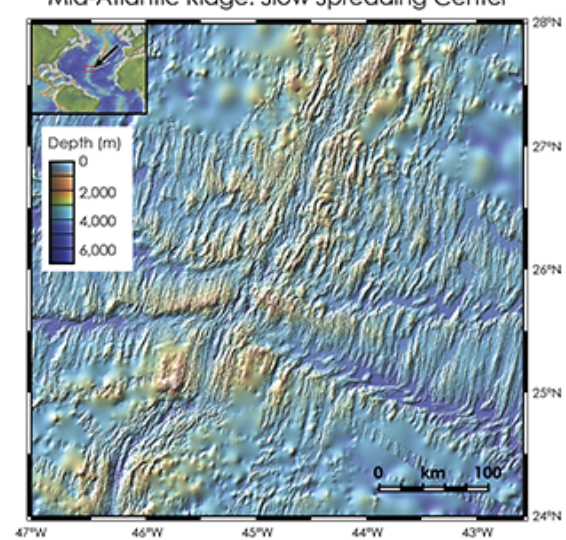



East Pacific Rise: Fast Spreading Center



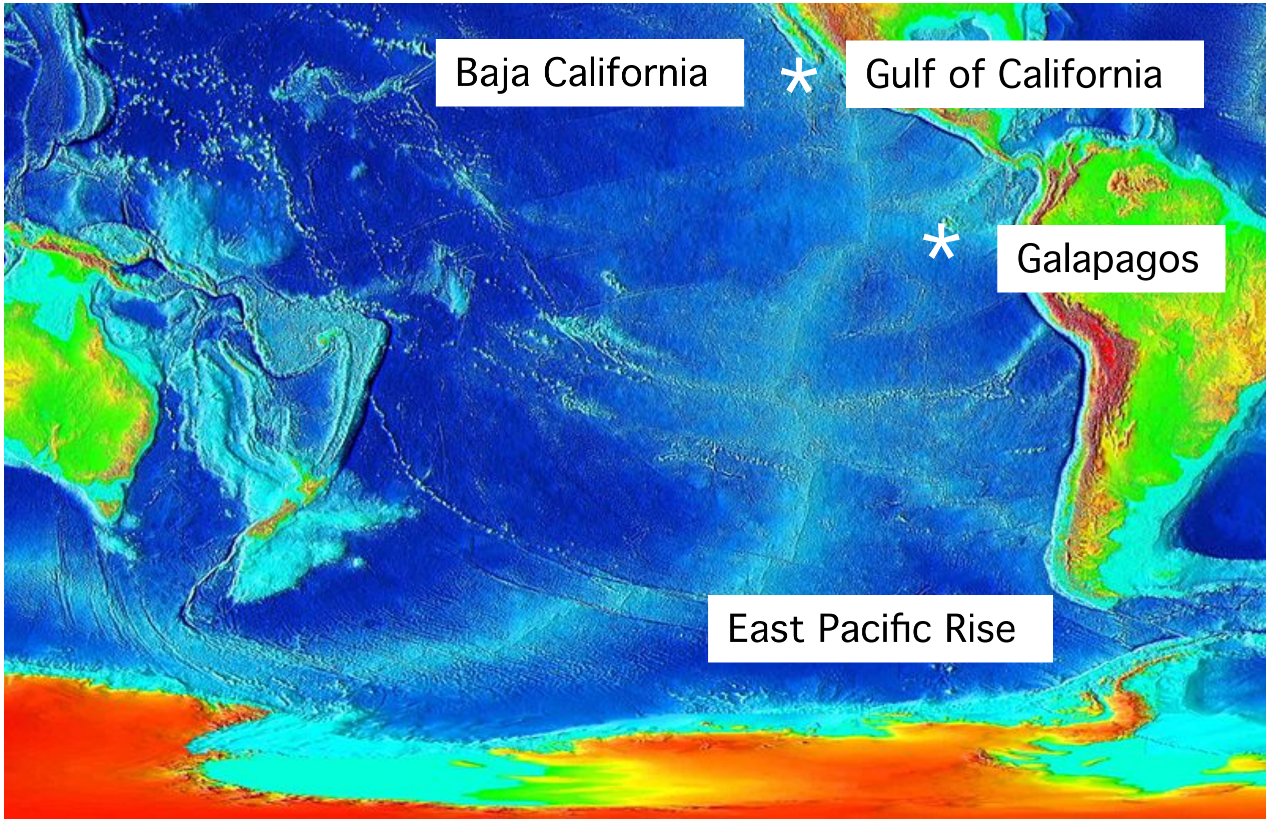

Mid-Atlantic Ridge: Slow Spreading Center

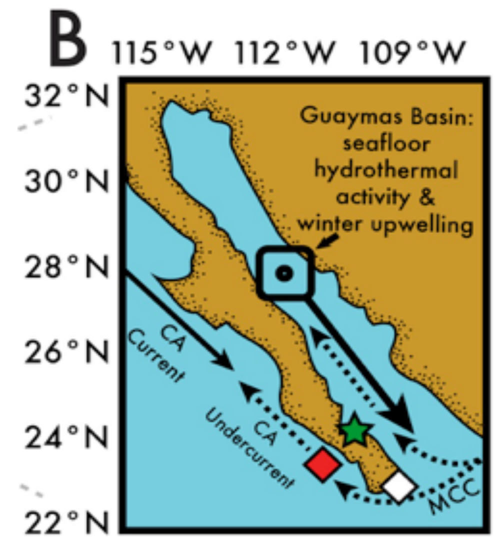


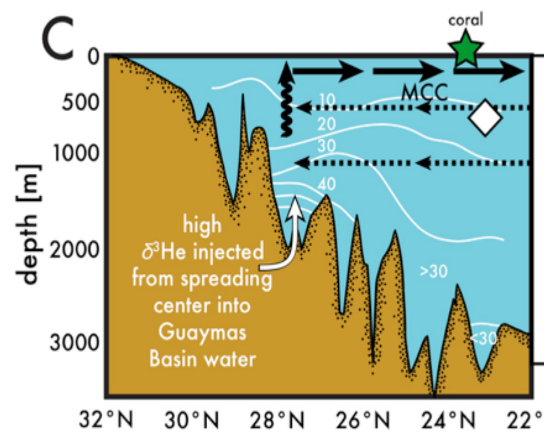
# Did spreading centers emit excess $CO_2$?

Gulf of California is an extension of the East Pacific Rise

Is there evidence for anomalous $CO_2$ emission during deglaciation?




Mexican Coastal Current (MCC) (500-1000m) feeds both the Gulf of California and the California Undercurrent

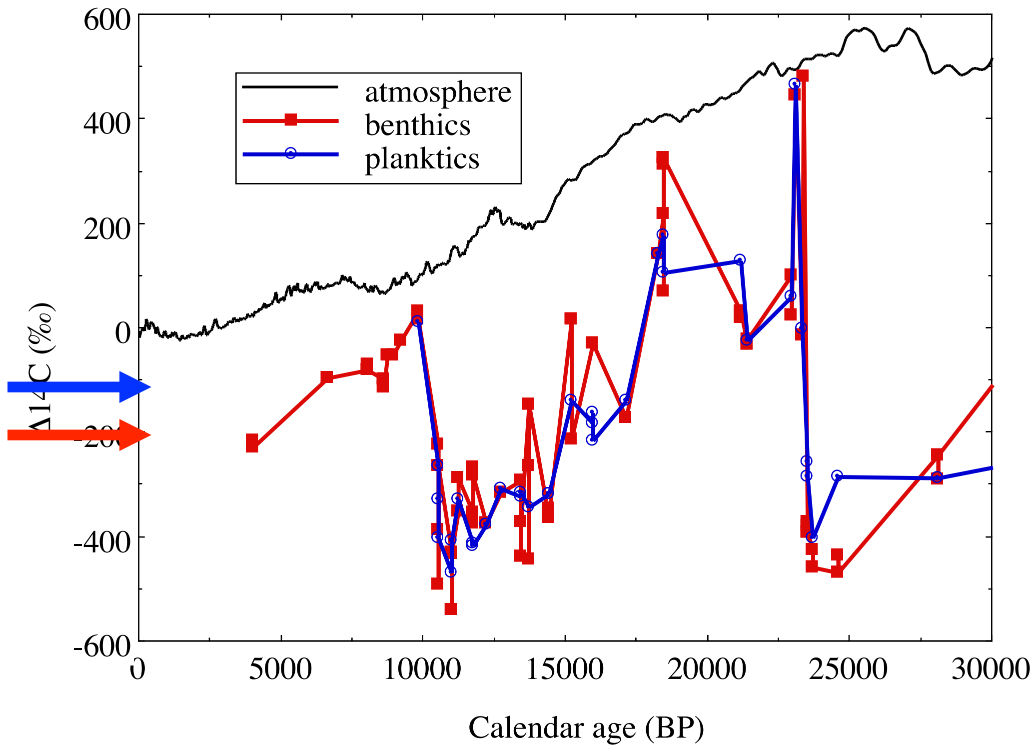
MCC water (and hydrothermal input) upwells in the Gulf and exits near the surface

# Deglacial Gulf of California

Benthic and planktic foram $\Delta^{14}C$ records

Benthics sample subsurface water entering the Gulf

Planktics sample surface waters upwelled in the Gulf and advected south past our core site




Deglacial planktic and benthic records in the Gulf of California are unique: both show extreme $^{14}C$ depletions.

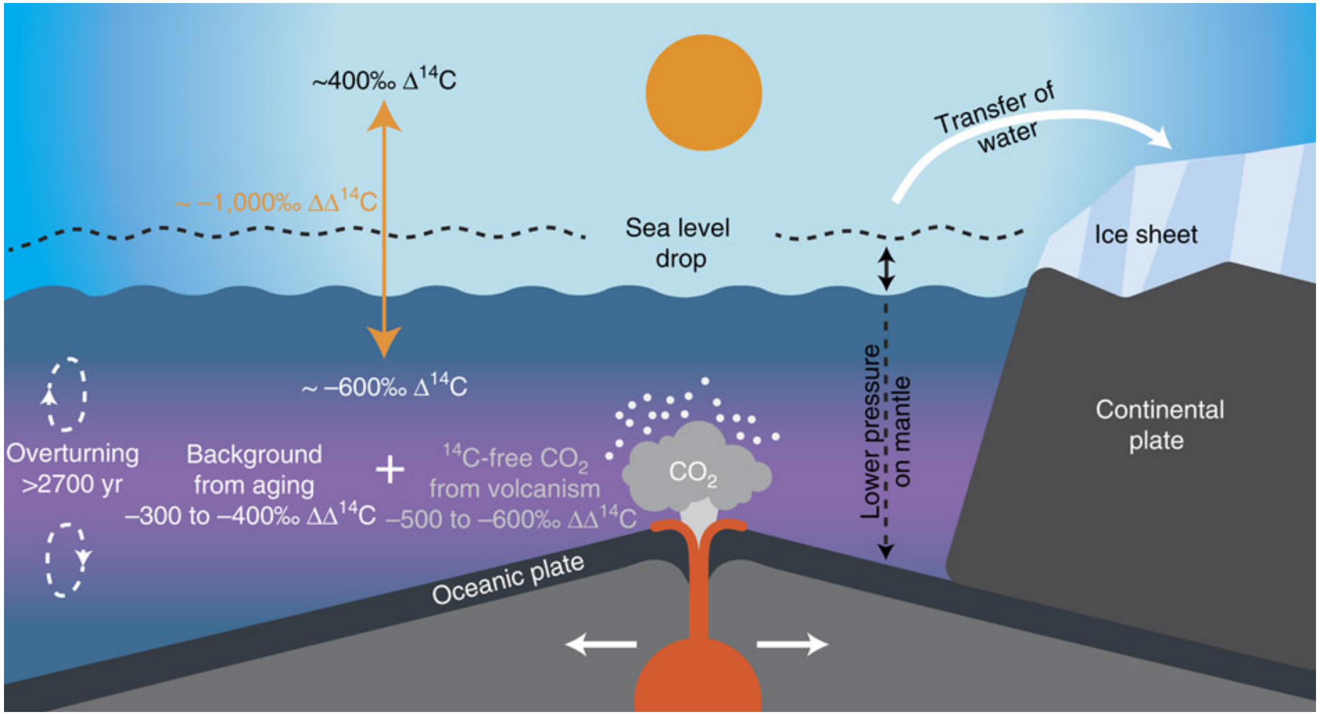
Possible causes::

i) extreme upwelling (several times as strong as today)

ii) addition of old carbon to the bottom waters prior to upwelling

# How this might work:

Sea level drops due to ice sheet buildup
Ocean stratified – lower circulation cut off from atmosphere
Delayed increase of hydrothermal $CO_2$ flux from MOR
Oldest water is at mid-depths, not bottom water
As ocean warms, stratification breaks down and $CO_2$ is released
Injection into the upper ocean may be regional or even local
More warming, sea level rises, eventually magma flux decreases



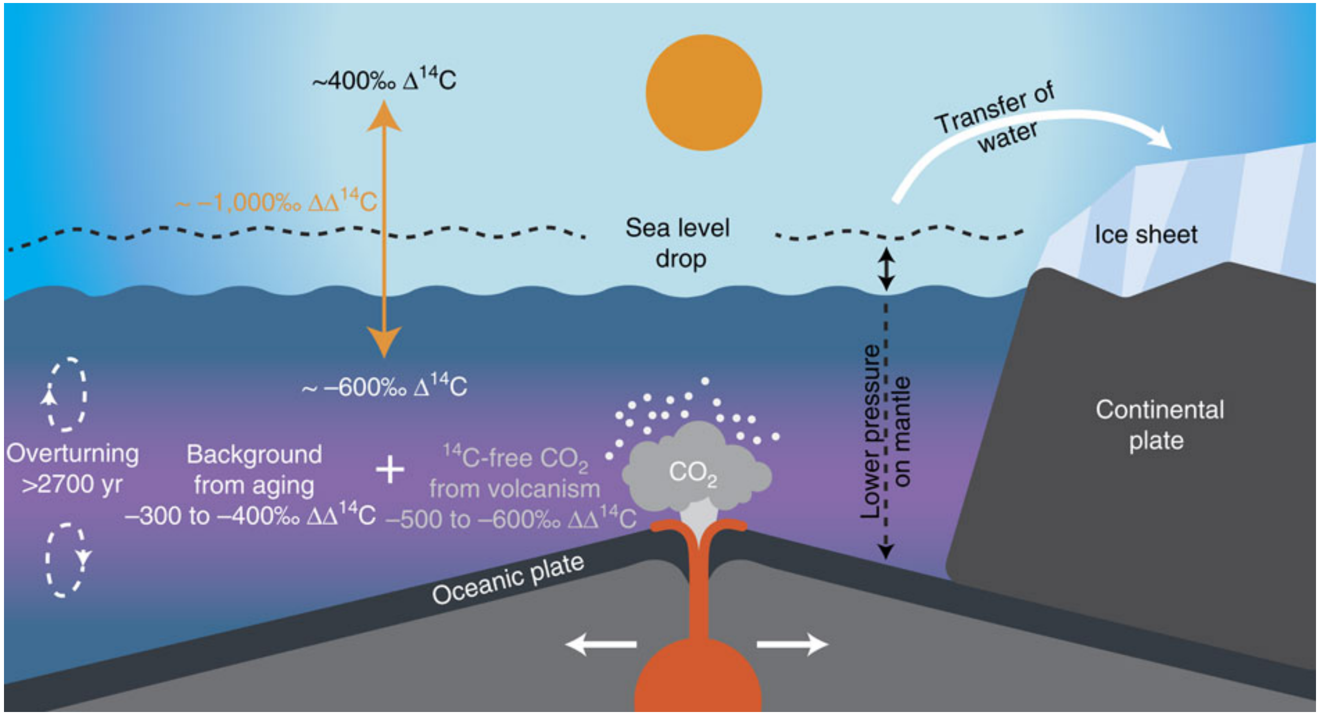
# Why was $\Delta\Delta^{14}C$ (atmosphere – deep ocean $\Delta^{14}C$ difference) so large in the glacial ocean?

Partly due to increased $^{14}C$ production

Partly due to carbon storage in the deep ocean

There's still a missing piece: is it addition of mantle $CO_2$ during deglaciation?

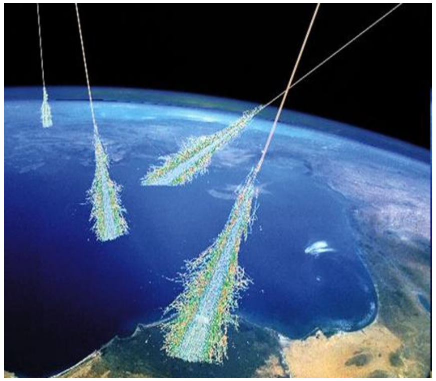
# Why was $\Delta\Delta^{14}C$ (atmosphere – deep ocean $\Delta^{14}C$ difference) so large in the glacial ocean?

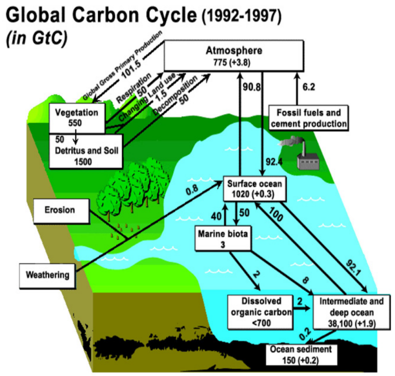



**HEY STUPID, IT'S PLATE TECTONICS!**

# Radiocarbon calibration: problems and progress

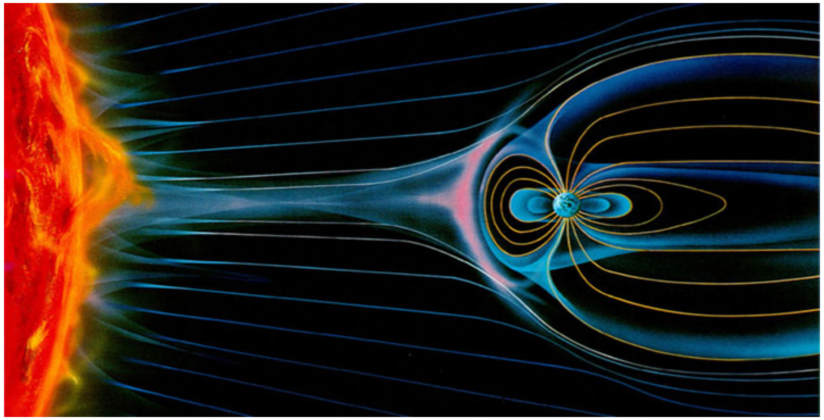
Remember the basics:






Cosmic rays make neutrons
Neutrons make $^{14}C$ (and $^{10}Be$ and $^{26}Al$ and…).

Solar and geomagnetic shielding affect the cosmic ray flux interacting with the upper atmosphere



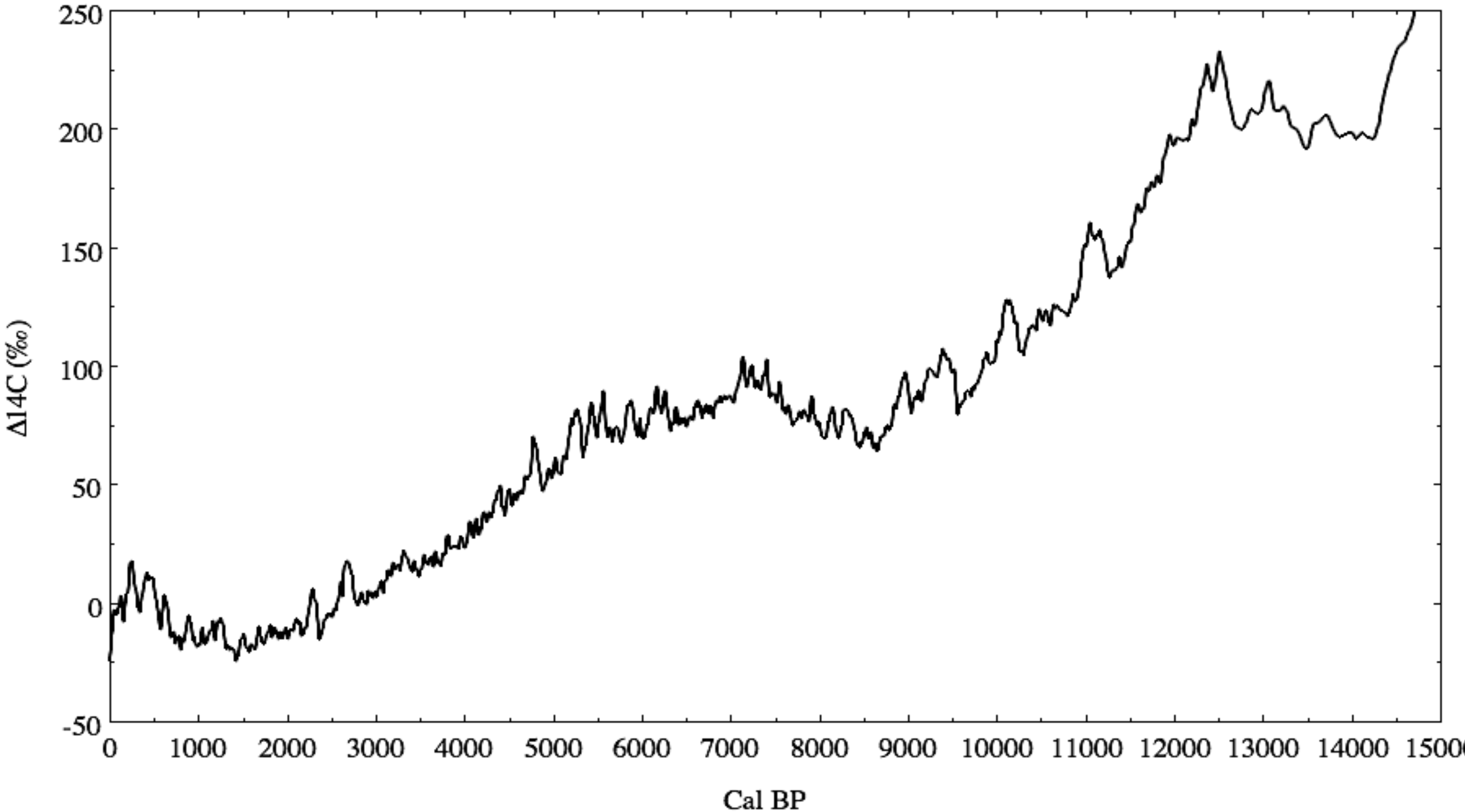
Carbon cycle changes affect the distribution of $^{14}C$ among carbon reservoirs

All of these have varied over time

# $\Delta^{14}C$ 0-15,000 BP

Long term changes are geomagnetic

Centennial-scale events are heliomagnetic



# $^{14}$C calibration (IntCal13): the last 14kyr

Based on dendro-dated trees (“The Gold Standard”)

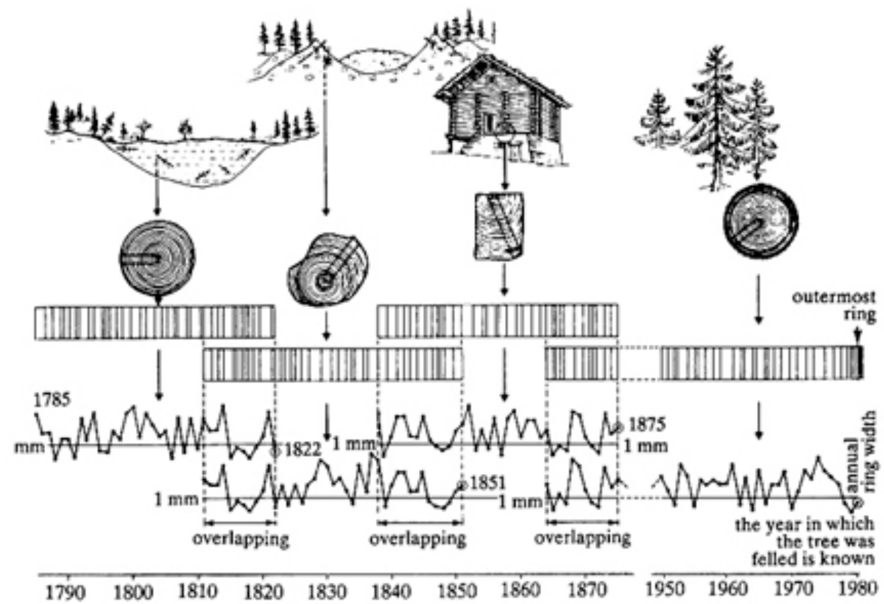
Regardless, there can be problems – be careful

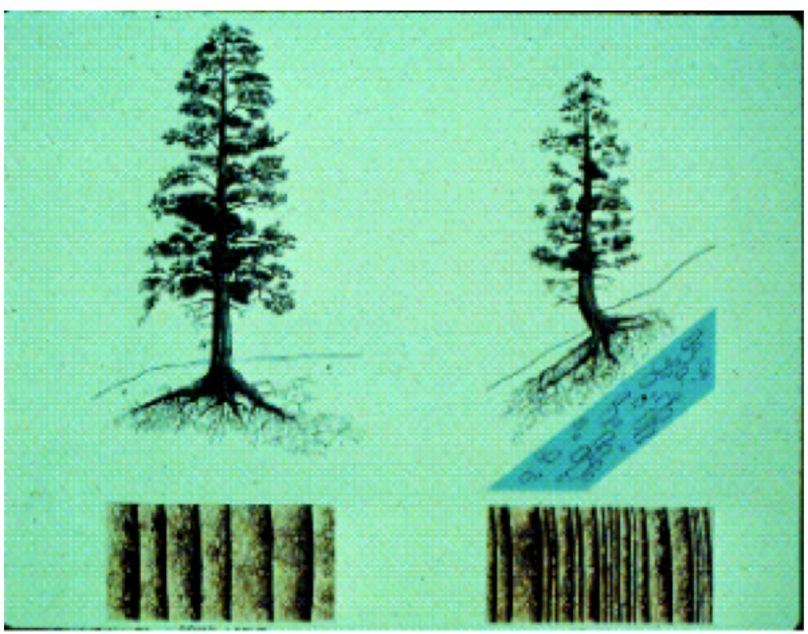
Site selection for stressed trees.

Cross-dating.

Replication.

Precise and accurate, but...



False ring?

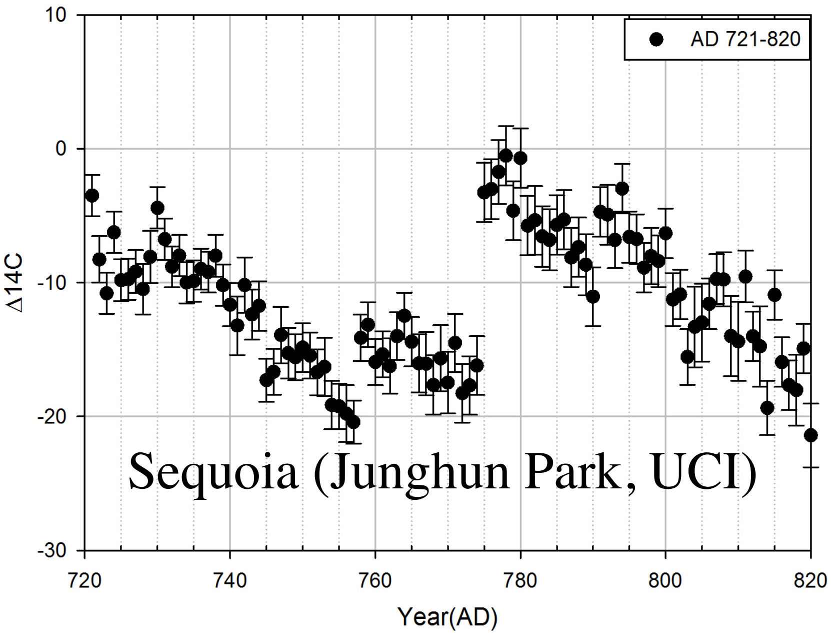
Missing ring

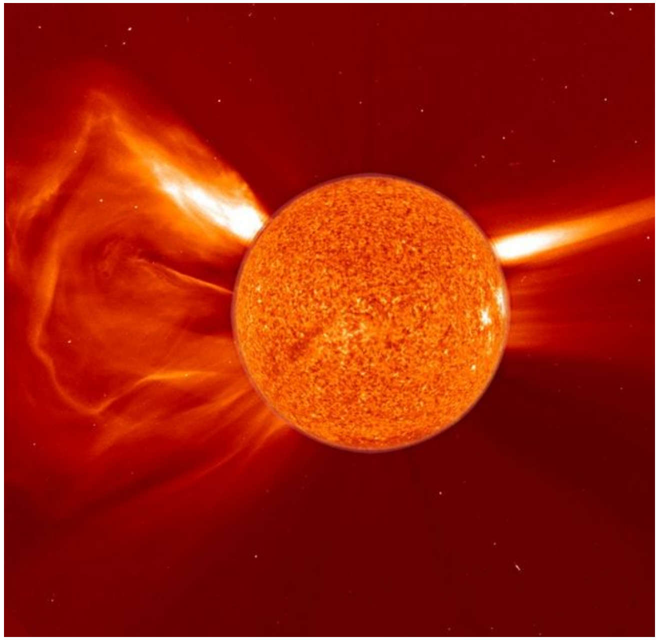
# $^{14}C$ in tree rings: potential problems
# Abrupt $^{14}C$ changes are invisible in 10-year data

Miyake et al., 2012: $^{14}C$ ages changed by ~100 years 775-776 AD

Global $\Delta^{14}C$ increase (both hemispheres), probably from a Coronal Mass Ejection event (not a comet, not a gamma ray burst, not a supernova….)

Abrupt $\Delta^{14}C$ changes have probably occurred throughout the $^{14}C$ record

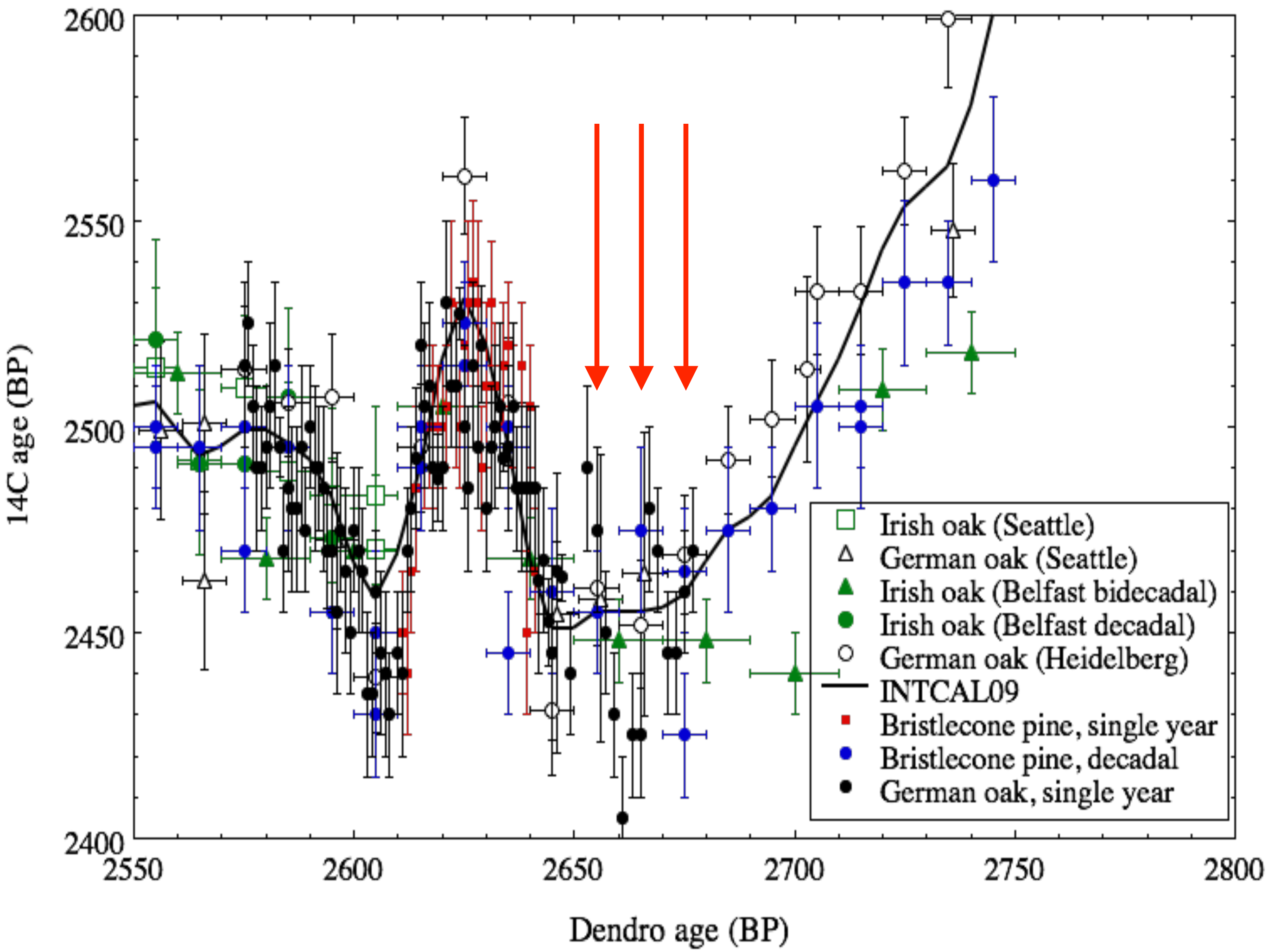


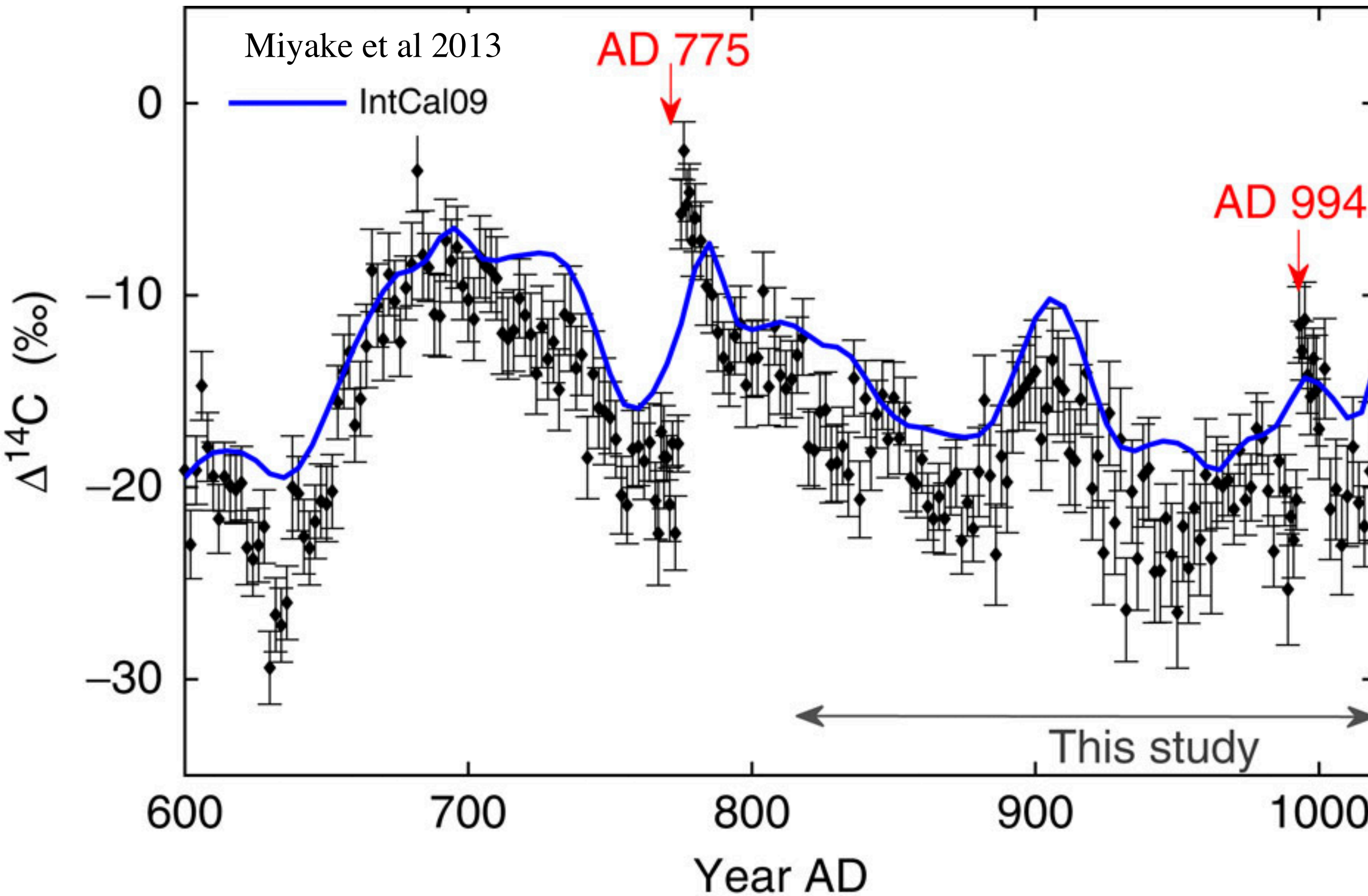
10-year calibration data is NOT the whole story for short-lived samples

# $^{14}$C in tree rings: potential problems
# 11 year solar cycle is invisible in decadal data

Anomalously large solar cycle 2650-2680 BP?

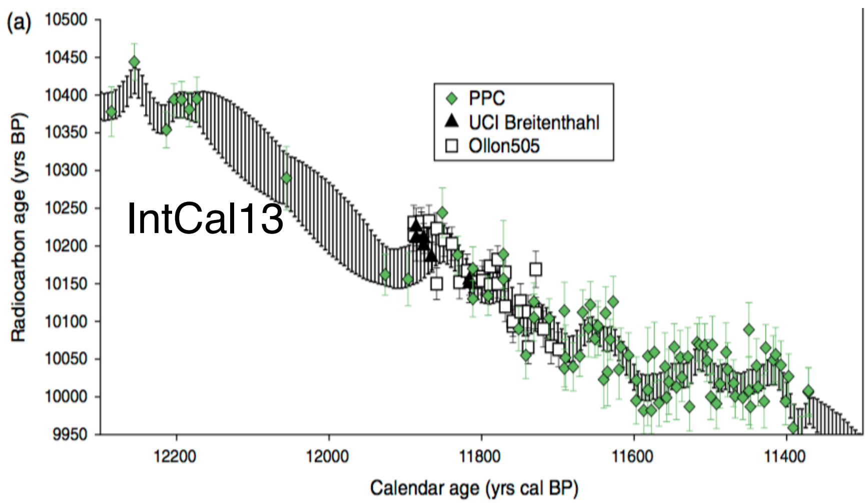


# $^{14}C$ in tree rings: potential problems
# Regional offsets or interlab biases (or both)?

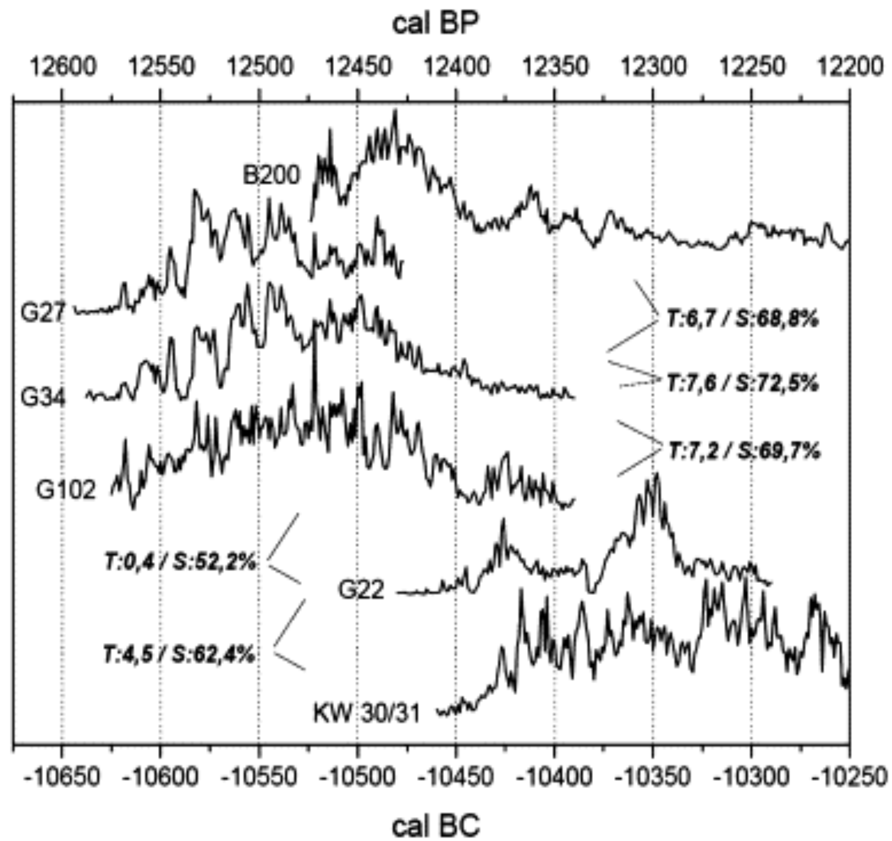


# New for IntCal13: tree rings extended to 14 kyr

Floating Allerød pine joined to master tree ring series via dendro-dating
However, dendrochronology in mid Younger Dryas has problems




Previously $^{14}C$ dated Ollon505 sequence shifted 160 years younger: dendro-links were not correct.
This leaves very few $^{14}C$ dates in IntCal13 on dendro-dated wood 11.9 – 12.3 kyr BP




Dendro-linkages doubtful 12.0 – 12.4 kyr BP

# $^{14}C$ Calibration in the early Younger Dryas

Patching the weak Northern Hemisphere section with Southern Hemisphere trees


New Zealand Kauri logs from bogs and swamps: UCI/Waikato/Oxford collaboration

*Certificate of Authenticity*

We pledge that these pieces, listed below, are Ancient Kauri timber that is aged from 30,000 to more the 50,000 years old.

This prehistoric Kauri timber is from forests buried during the last Ice Age, which are located on the Northern Island of New Zealand in the South Pacific Ocean.

Our company, Ancientwood, Ltd. is satisfied that extensive and conclusive independent Radio Carbon Dating tests verify this age beyond doubt.

Robert Teisberg, President

EXAMPLE

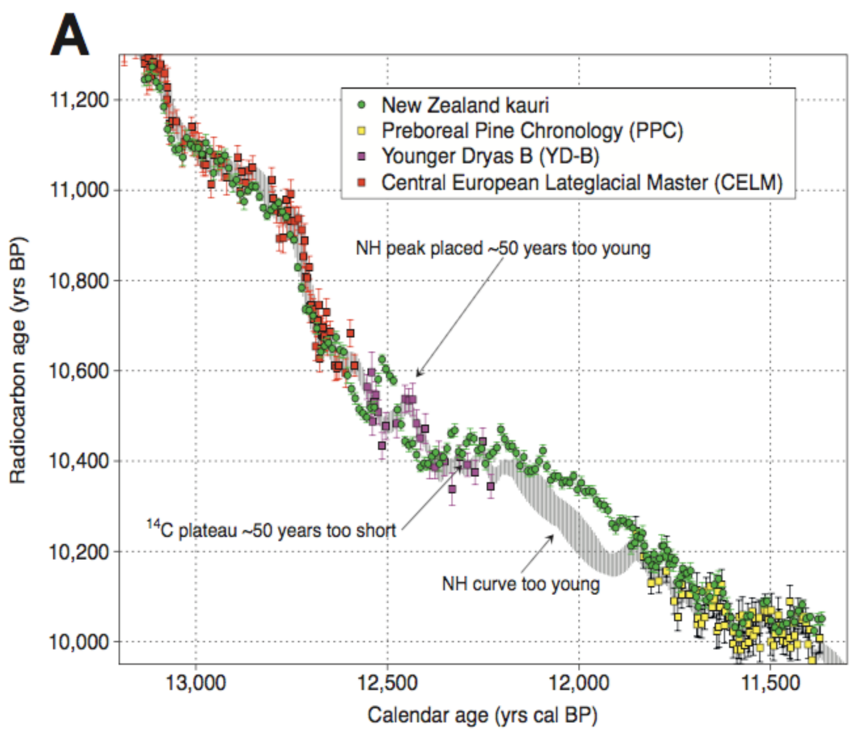
CERTIFIED ANCIENTWOOD LTD BY

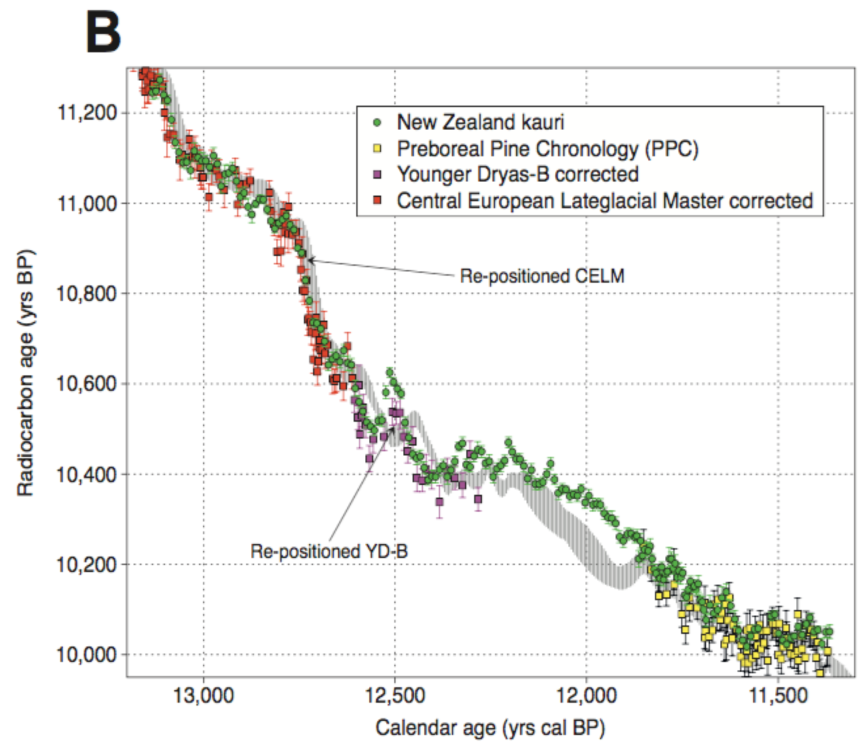
ANCIENTWOOD, LTD.

160 Madeline Island, La Pointe, WI 54850 USA Website www.ancientwood.com
Email info@ancientwood.com Phone 888-201-7544

# New calibration results

We now have well replicated YD data from the Southern Hemisphere
NH data before 12.2 kyr BP shifted 50 years older in calendar time

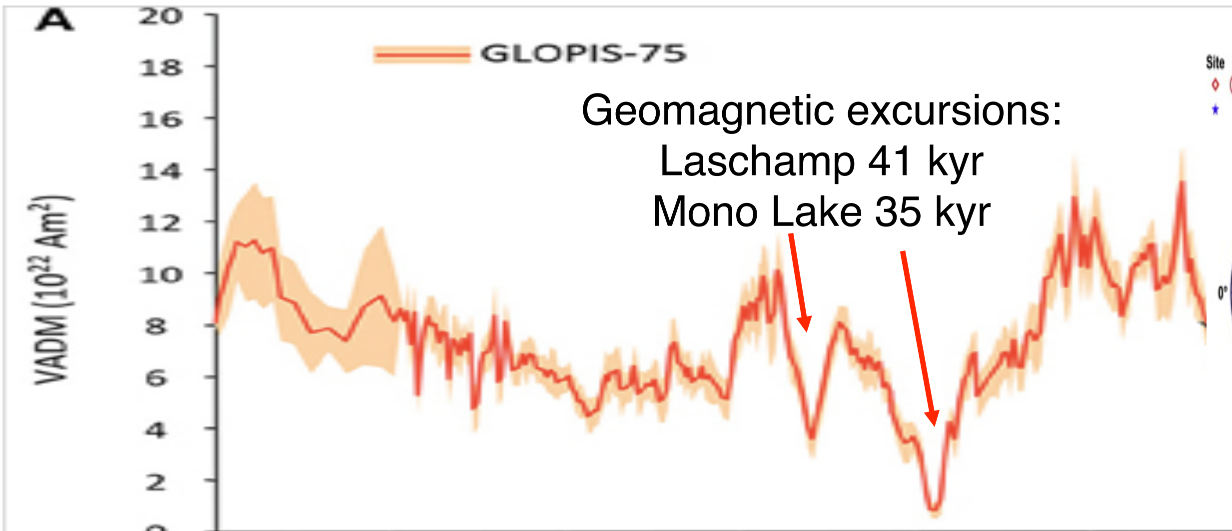


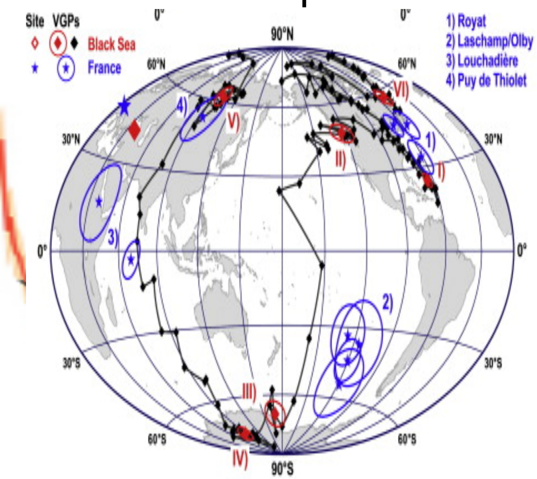
# Long-term changes in geomagnetic field

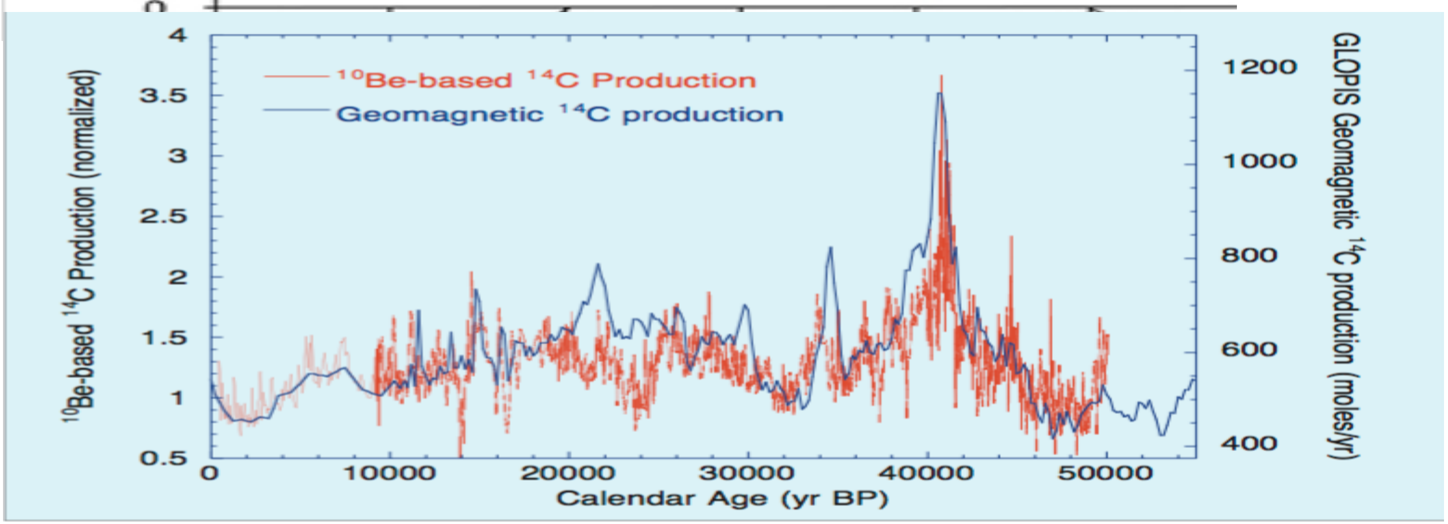
Estimates from paleomagnetic signals in sediments

Short weak-field events plus long term increase from ~20 kyr BP (= $^{14}$C decrease)



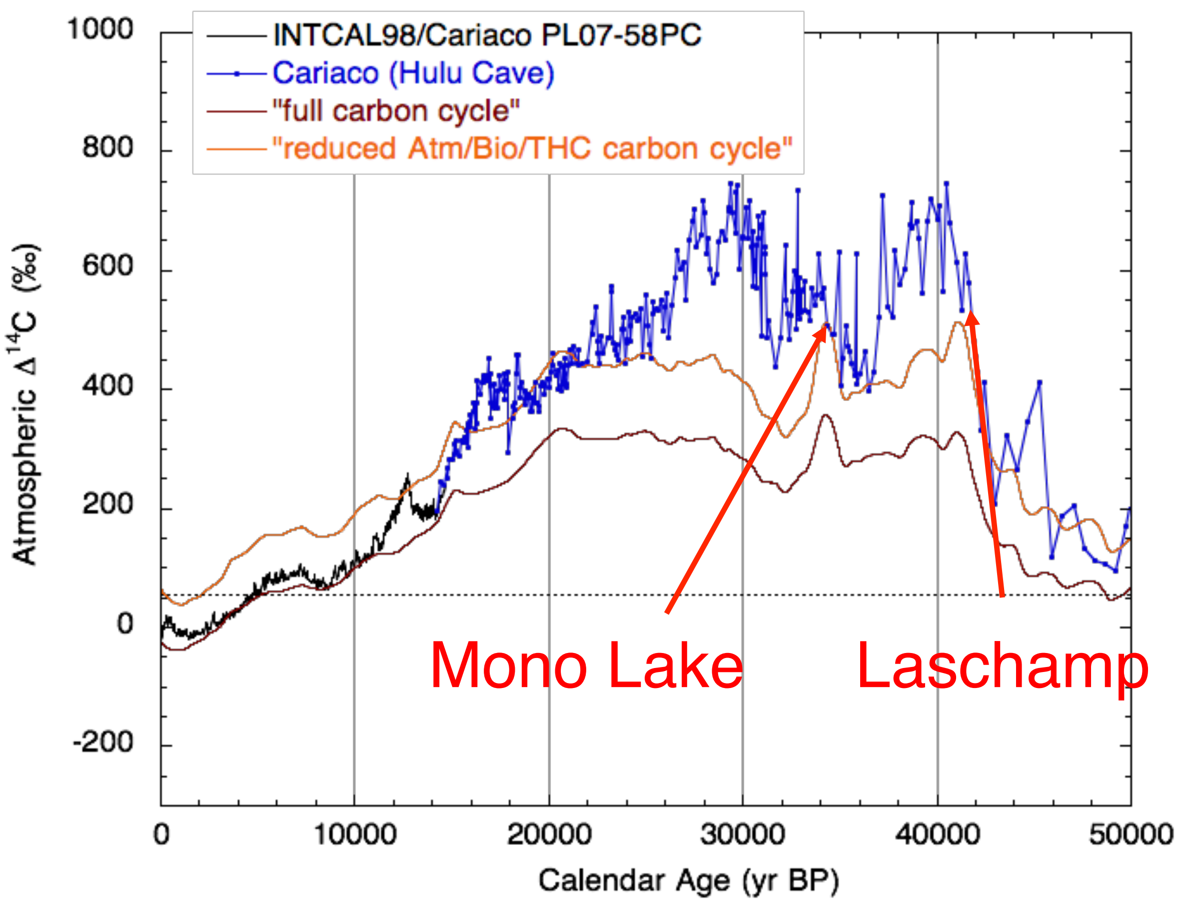

Laschamp VGP



# High glacial $\Delta^{14}C$ – models vs data

C cycle box model forced with geomagnetic-based $^{14}C$ production
Production changes can explain some (but not all) of the high $\Delta^{14}C$



# $^{14}$C Calibration beyond tree rings

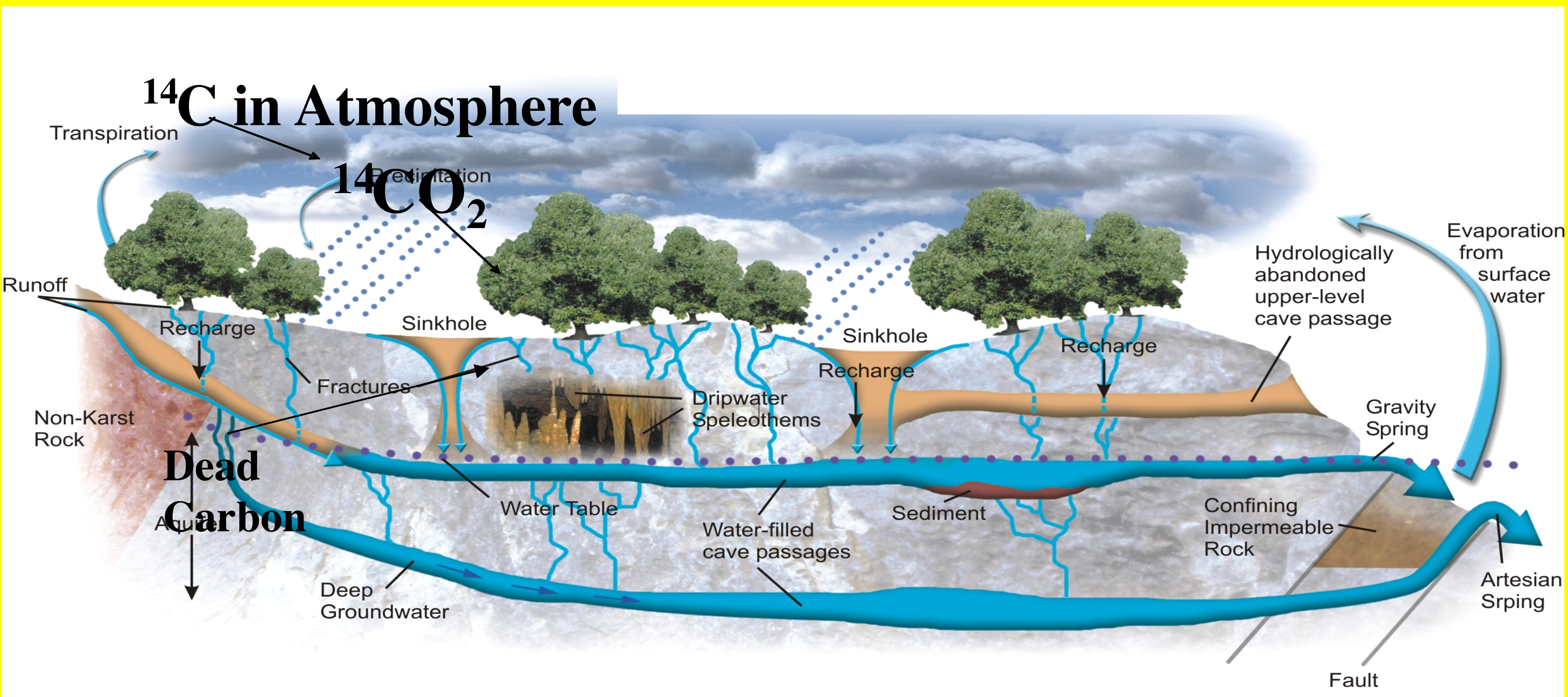
- Dendro-dated trees (to 14kyr only – few trees in Europe).
- Lake Suigetsu macrofossils (varved lake).
- U/Th dated speleothems – Bahamas, Hulu H82.
- Cariaco Basin 58PC forams (marine varves).
- Cariaco Basin ODP 1002D forams (sediment color matched to Hulu Cave $\delta^{18}O$).
- Other wiggle-matched marine cores (Iberian Margin, Pakistani Margin)
- U/Th dated corals (Barbados, Pacific).

All available records have significant problems.

However, if disparate records agree, the data probably approximate a true representation of $\Delta^{14}C$ over time.

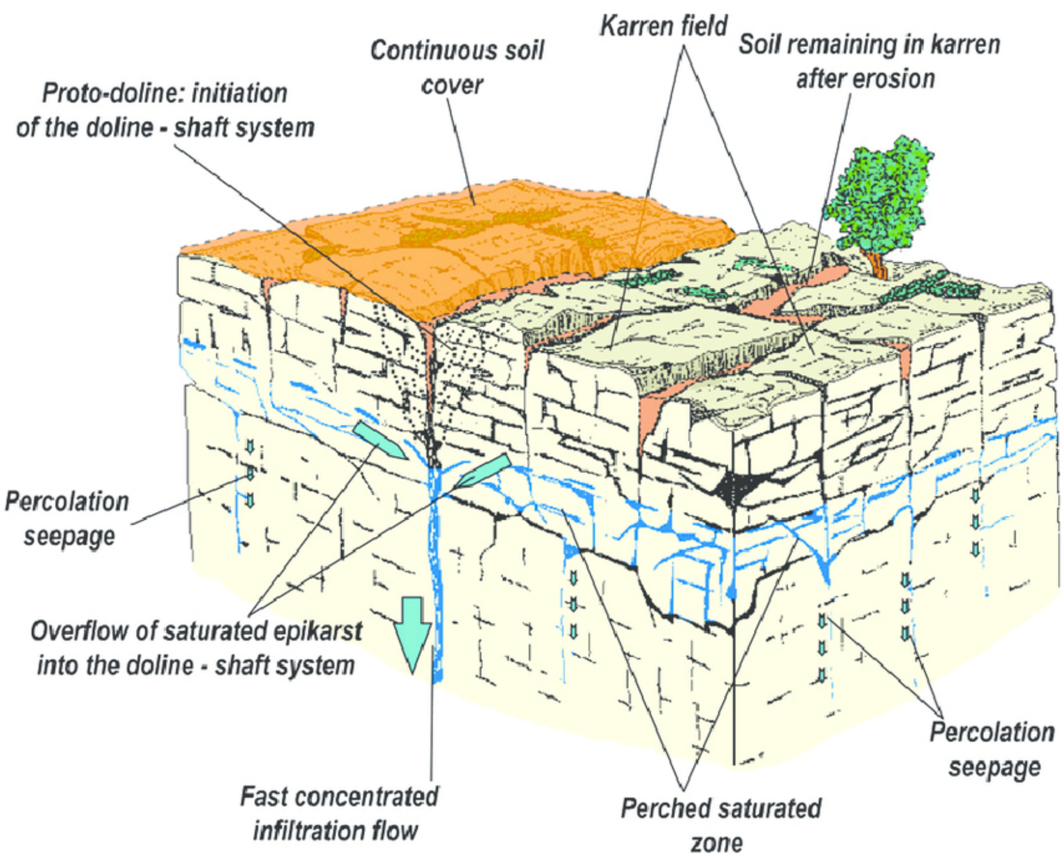
# Speleothems as $^{14}C$ archives

- Formed from supersaturated cave drip waters.
- Clean, dense, calcite - closed for U-Th and for $^{14}C$ - sometimes.
- Dateable by U-Th with minimal detrital Th corrections - sometimes.
- $^{14}C$ must be corrected for Dead Carbon Fraction (DCF) – always!

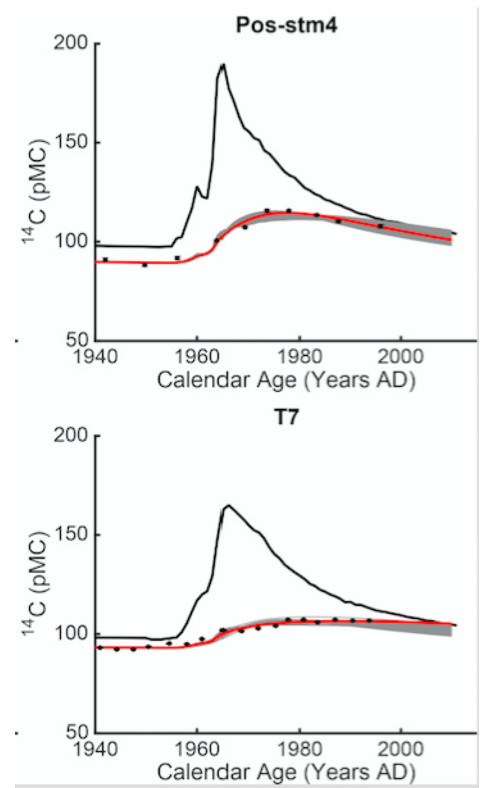


# Open vs closed system equilibration

- DCF correction: compensates for incorporation of “dead” (and/or old) carbon
- $CO_2(aq) + H_2O \rightarrow H_2CO_3$ , $H_2CO_3 + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$
- Closed system: 1 mole of $CaCO_3$ will neutralize 1 mole of $H_2CO_3$
- Open system: continuing exchange with gaseous $CO_2$
- Soil $CO_2$ is very close to modern, $CO_2$ in the epikarst may be old

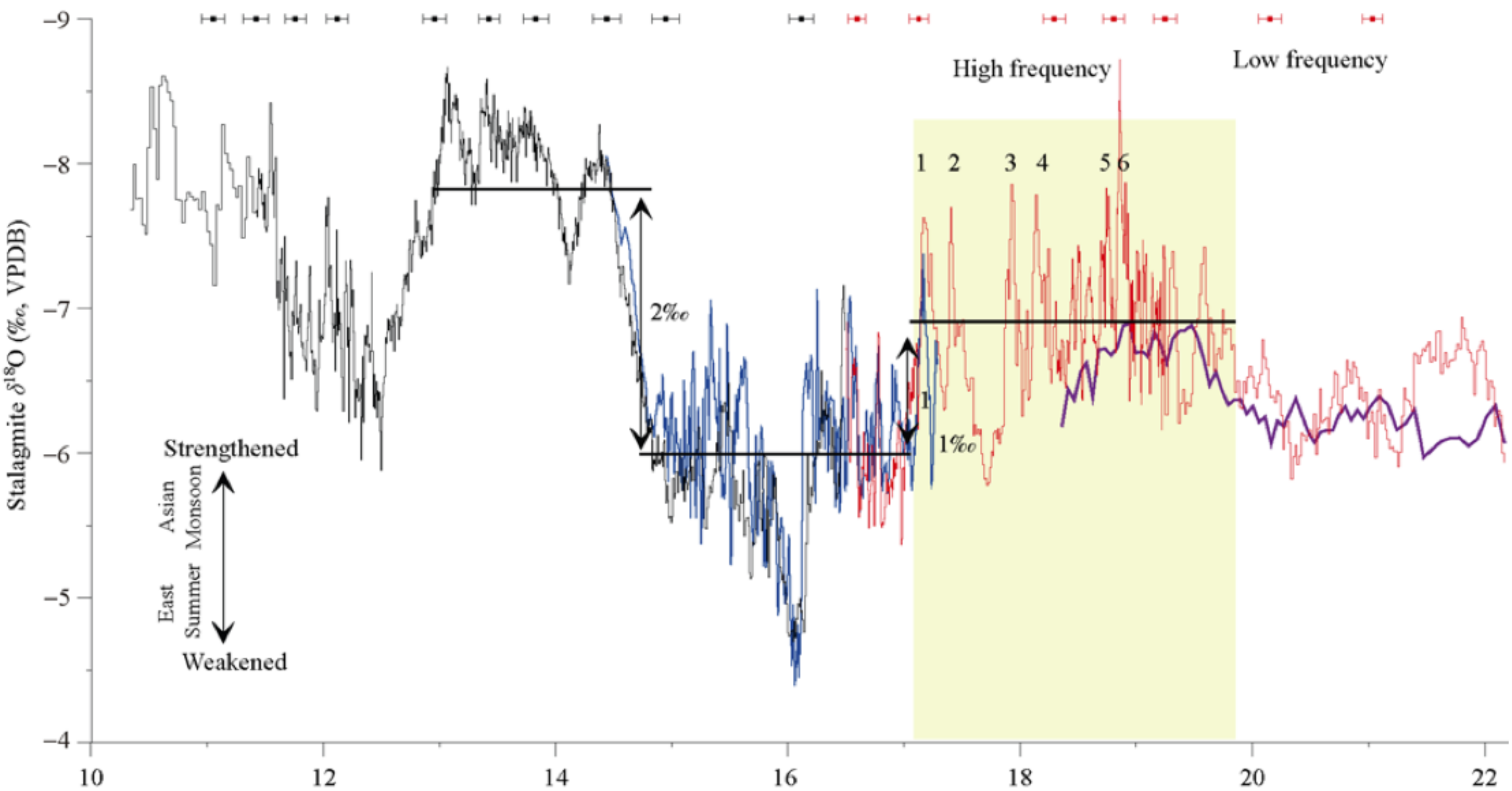



Noronha et al., 2015, QSR



# Speleothems as climate archives: Hulu Cave $\delta^{18}O$

- $\delta^{18}O$ influenced by monsoon strength (ITCZ): D-O and Heinrich-like features
- U/Th: Wang et al., Science 294 (2001) 2345 , Yuan et al. Science 304 (2004) 575
- Extended hi-res $\delta^{18}O$: Wu et al. Sci. in China D 52 (2009) 360

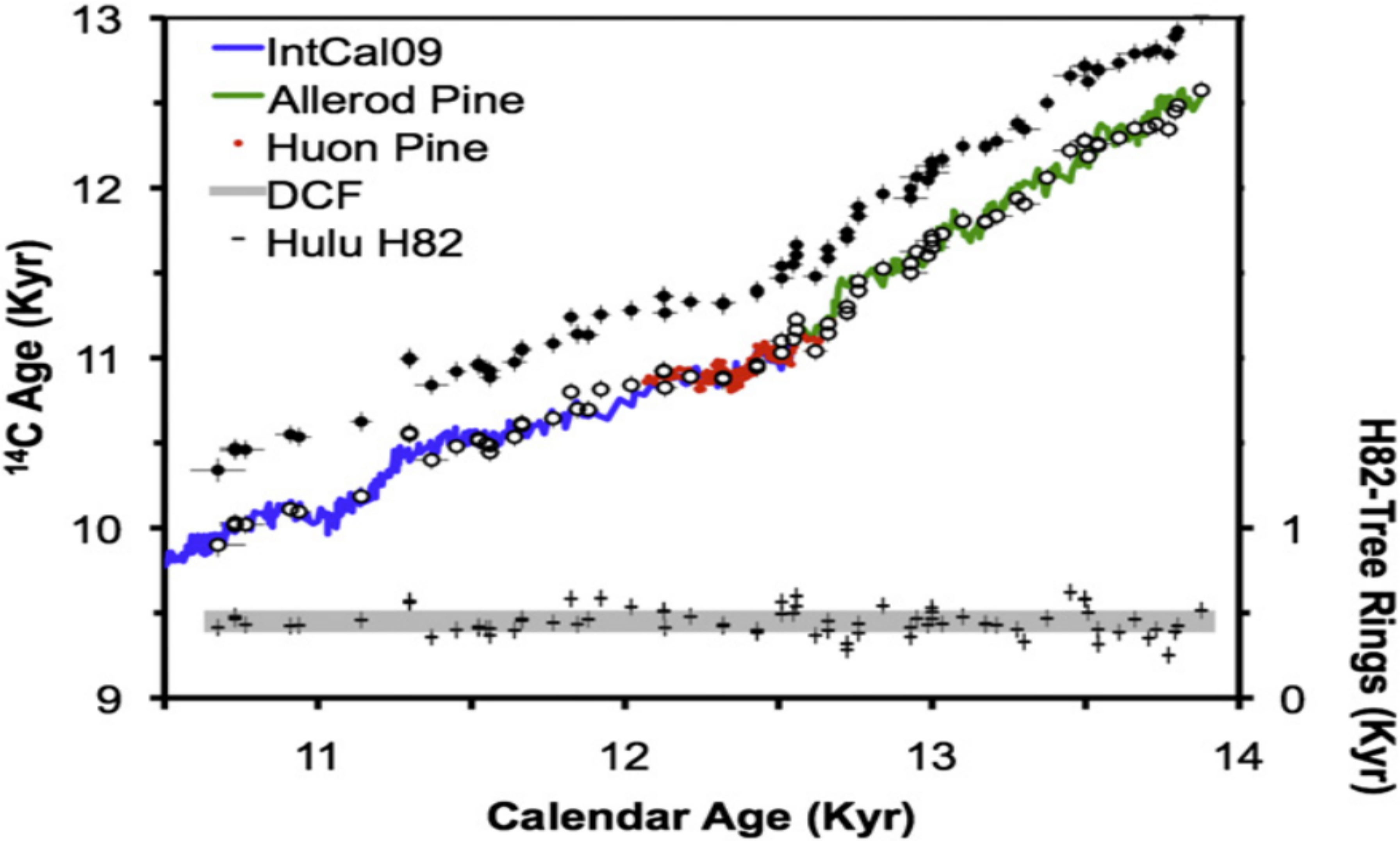



U/Th age (kyr BP)

# H82 DCF is constant across the Younger Dryas

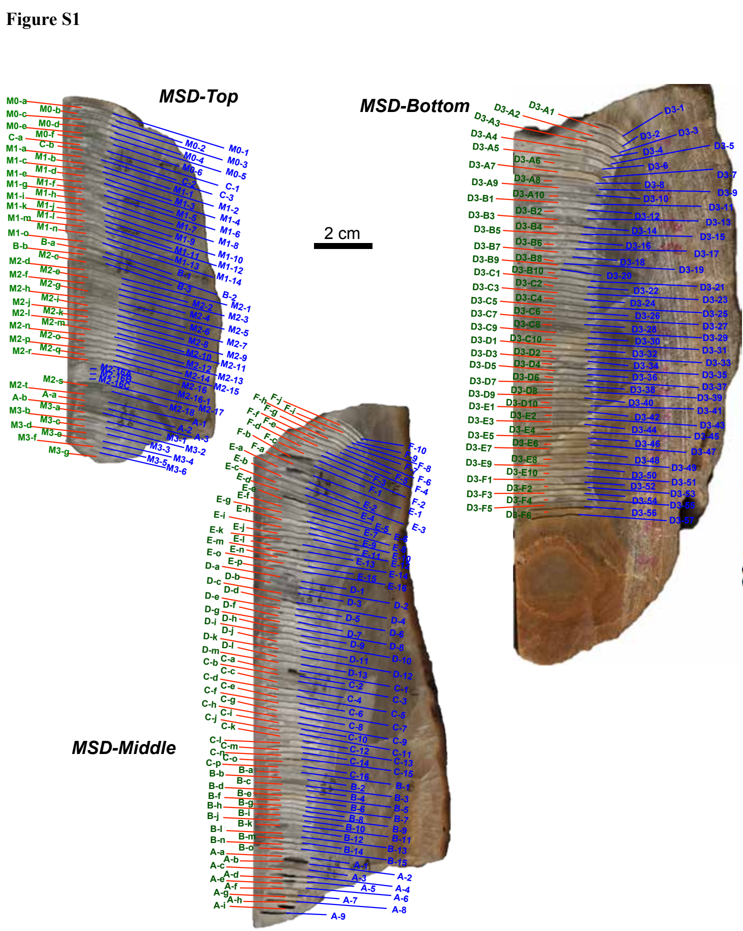
Hulu $\delta^{18}O$ record shows major climate/monsoon variations

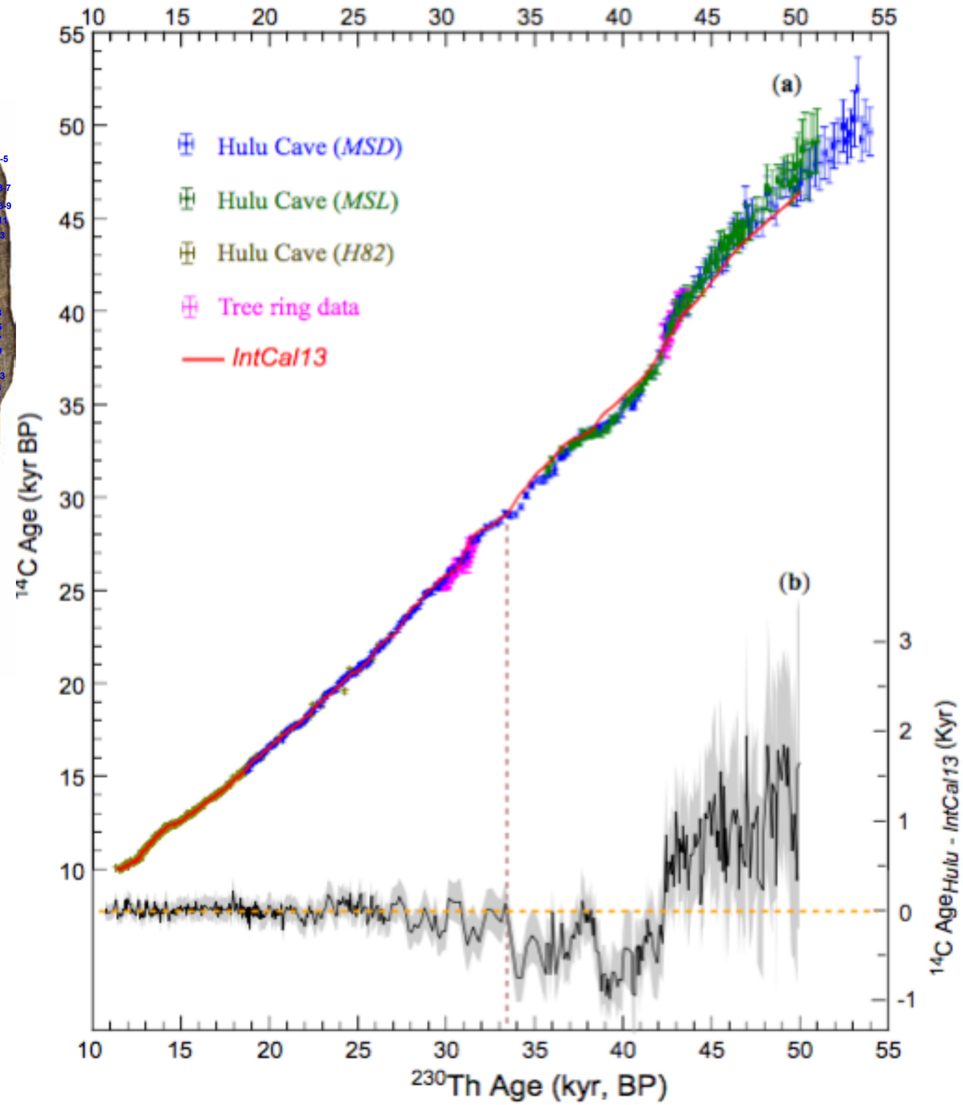
Why was DCF so stable across hydrologic/vegetation changes?



# H82, MSD, MSL: 10 – 50 kyr record

Three speleothems overlap and give consistent results



# Why was the Hulu DCF small and stable?

The answer is above the cave (and in the museum)

Tangshan National Geopark Museum, Nanjing

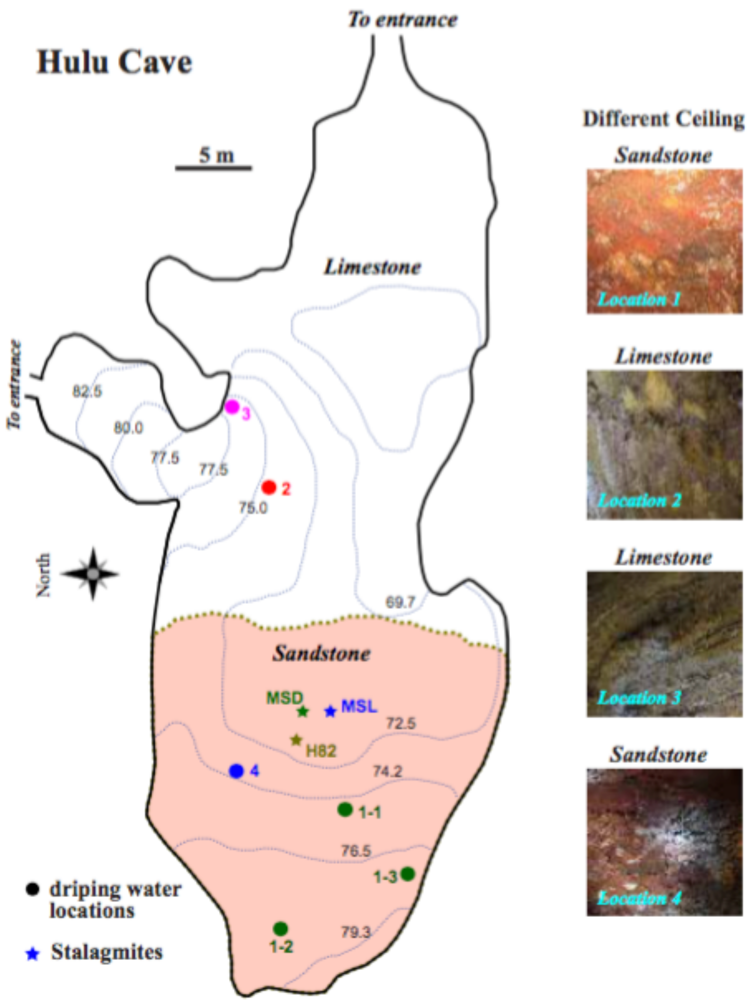
Hulu Location 1

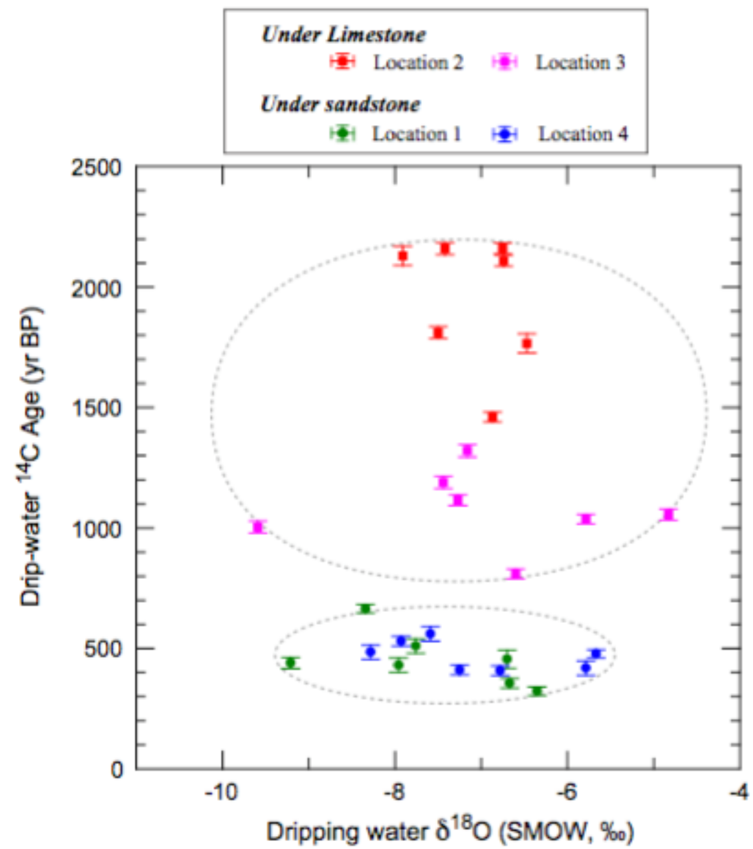
Hulu Location 2

# H82 MSD and MSL all formed under sandstone

Meteoric water equilibrates in the soil layer, not in the karst.

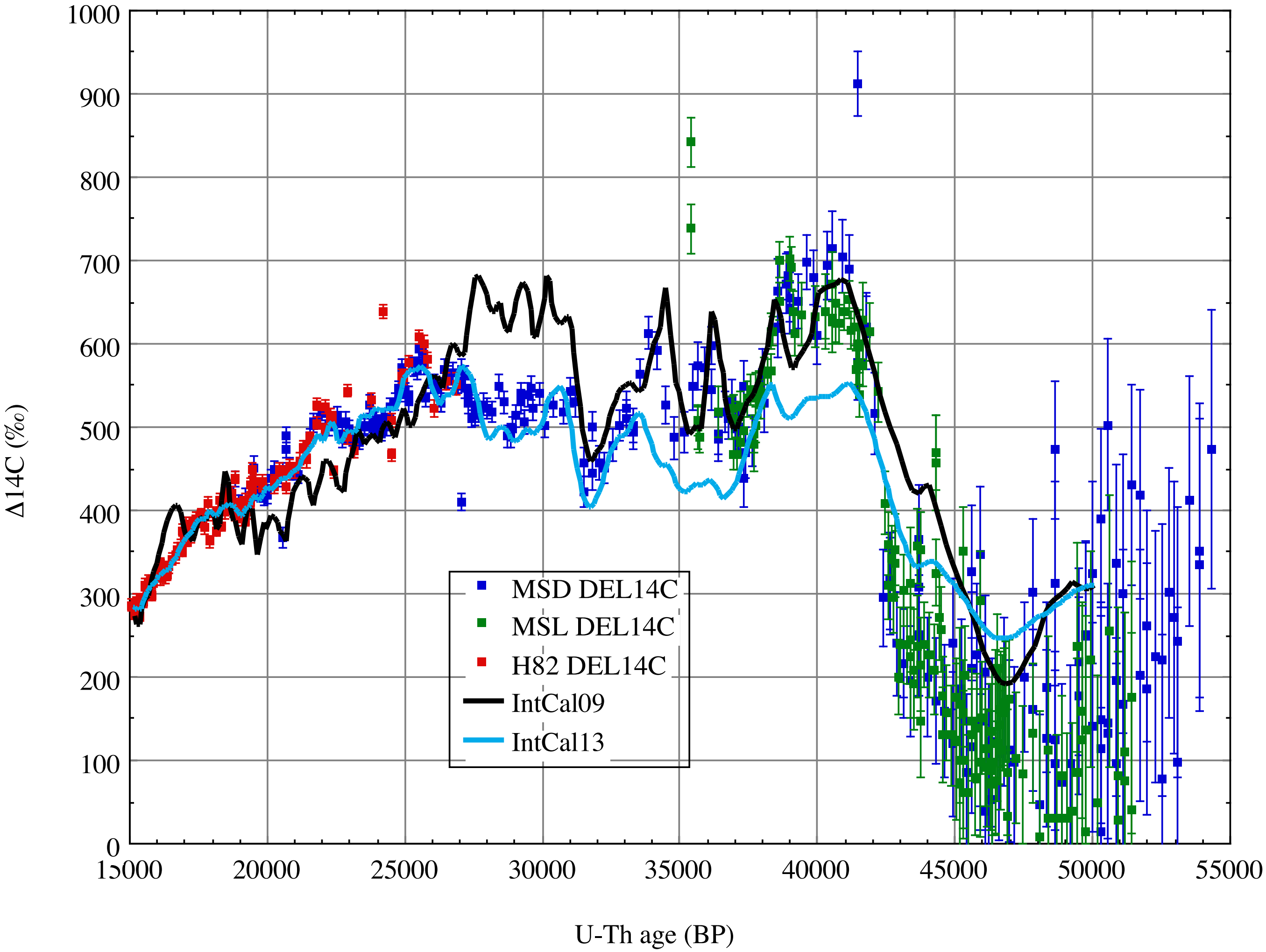
Open system conditions = low DCF, probably true for the entire record



# $^{14}C$ Calibration: Hulu vs IntCal09 and IntCal13

10-33 kyr: Hulu and IntCal13 agree
31-42 kyr: Hulu and IntCal09 agree
>42 kyr: Hulu $\Delta^{14}C$ lower than ‘09 or ‘13



# The Last Word

$^{14}$C calibration data evolves: every version is different.
NEVER quote calibrated ages without also giving the original $^{14}$C data

In critical cases do NOT just rely on the calibration curve: look at the calibration data itself

IntCal13 plots at www.radiocarbon.org (IntCal13 Supplementary Information)

IntCal13 database at www.chrono.qub.ac.uk (Resources)