^{14}C constraints on the glacial-age ocean circulation and mechanism of deglacial CO_2 rise

Scott Lehman, Tom Marchitto

and

Konrad Hughen (WHOI), John Southon (UCI), Joe Ortiz (Kent St.), Jacqueline Flueckiger (ETH-Zurich)

outline

- *^{14}C systematics*
- *Cariaco Basin archive*
- *deglacial varve-counted calibration (14.5-9 k cal yr)*
    - *reconstructed ATM ^{14}C activity linked to climate*
- *extended calibration in long cores (last 50 k cal yr)*
    - *the glacial "^{14}C redistribution problem"*
- *constraints on the glacial circulation and mechanism of atmospheric CO_2 change from ocean ^{14}C (Baja CA)*
- *PO puzzle?*

^{14}C is cosmogenic,

$$^{1}n_{0} + {}^{14}N_{7} \longrightarrow {}^{14}C_{6} + {}^{1}H_{1}$$

and weakly radioactive,

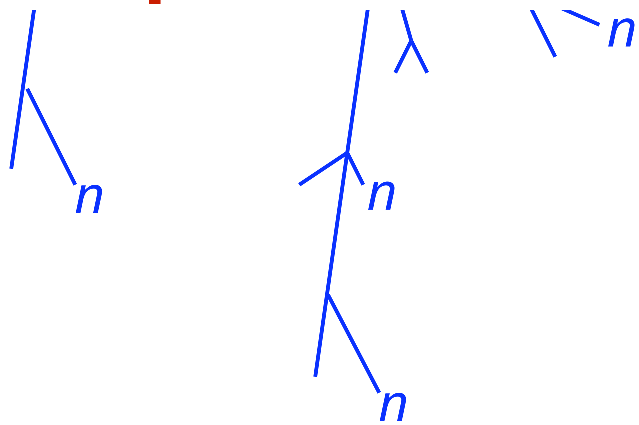
$$^{14}C_{6} \longrightarrow {}^{14}N_{7} + \beta^{-} + \overline{\nu} + Q$$

with $T_{1/2} = 5730 \pm 40$ yr

and abundance today of

1.176×10^{-12} ($^{14}C/C$)

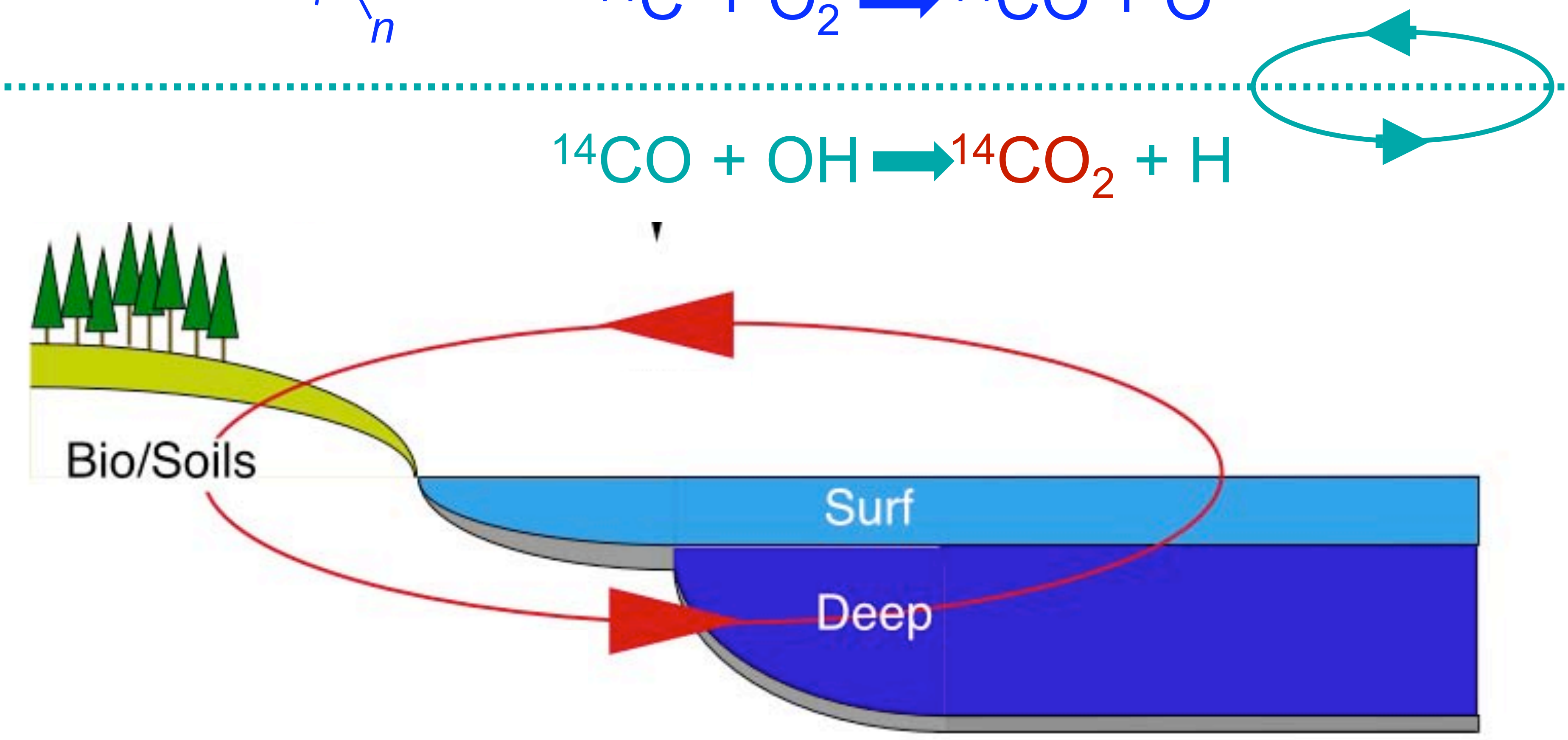
incorporation of ^{14}C into global carbon cycle



$$^{14}N\ (n,p)\ ^{14}C^{*}$$

$$^{14}C^{*} + O_2 \rightarrow\ ^{14}CO + O$$

$$^{14}CO + OH \rightarrow\ ^{14}CO_2 + H$$



Basic assumption of ^{14}C dating:

^{14}C production is constant, thus a steady state inventory is reached at which loss by decay balances production (i.e. $(^{14}C/C)_{form.}$ is constant)

then;

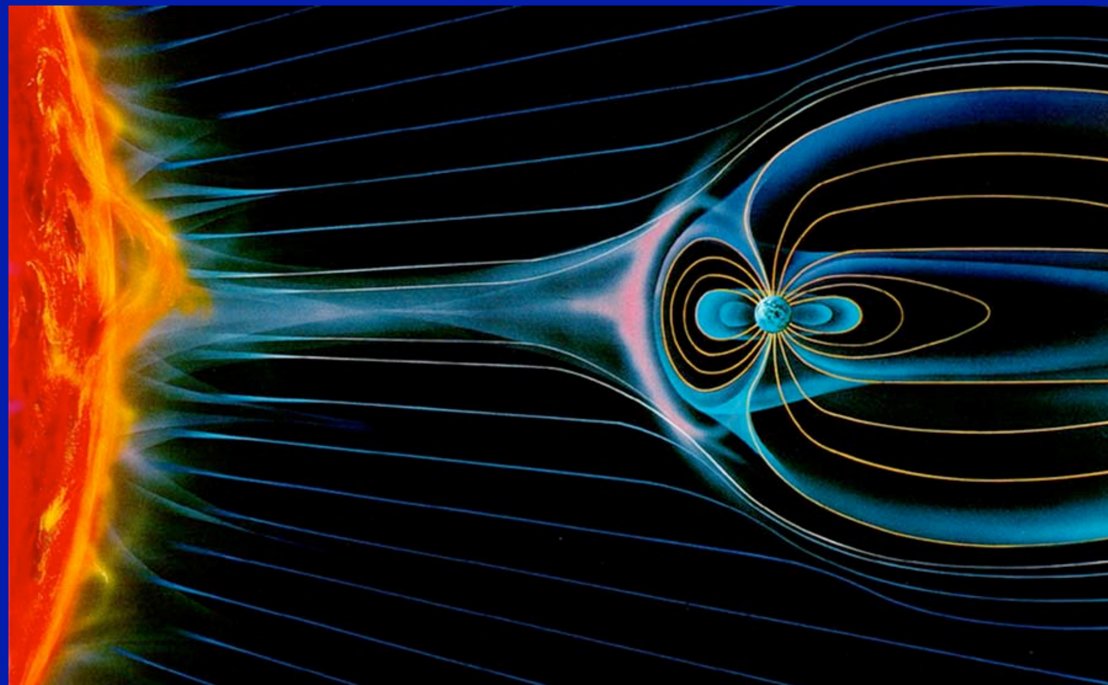
$$(^{14}C/C)_{meas.} = (^{14}C/C)_{form.}\ e^{-\lambda t}$$

where λ = decay constant or 1/8033 yr

(for $T_{1/2}$ = 5568 yr)

and

$$t = -8033 \ln[(^{14}C/C)_{meas.} / (^{14}C/C)_{form.}]$$



changes in ^{14}C production rate

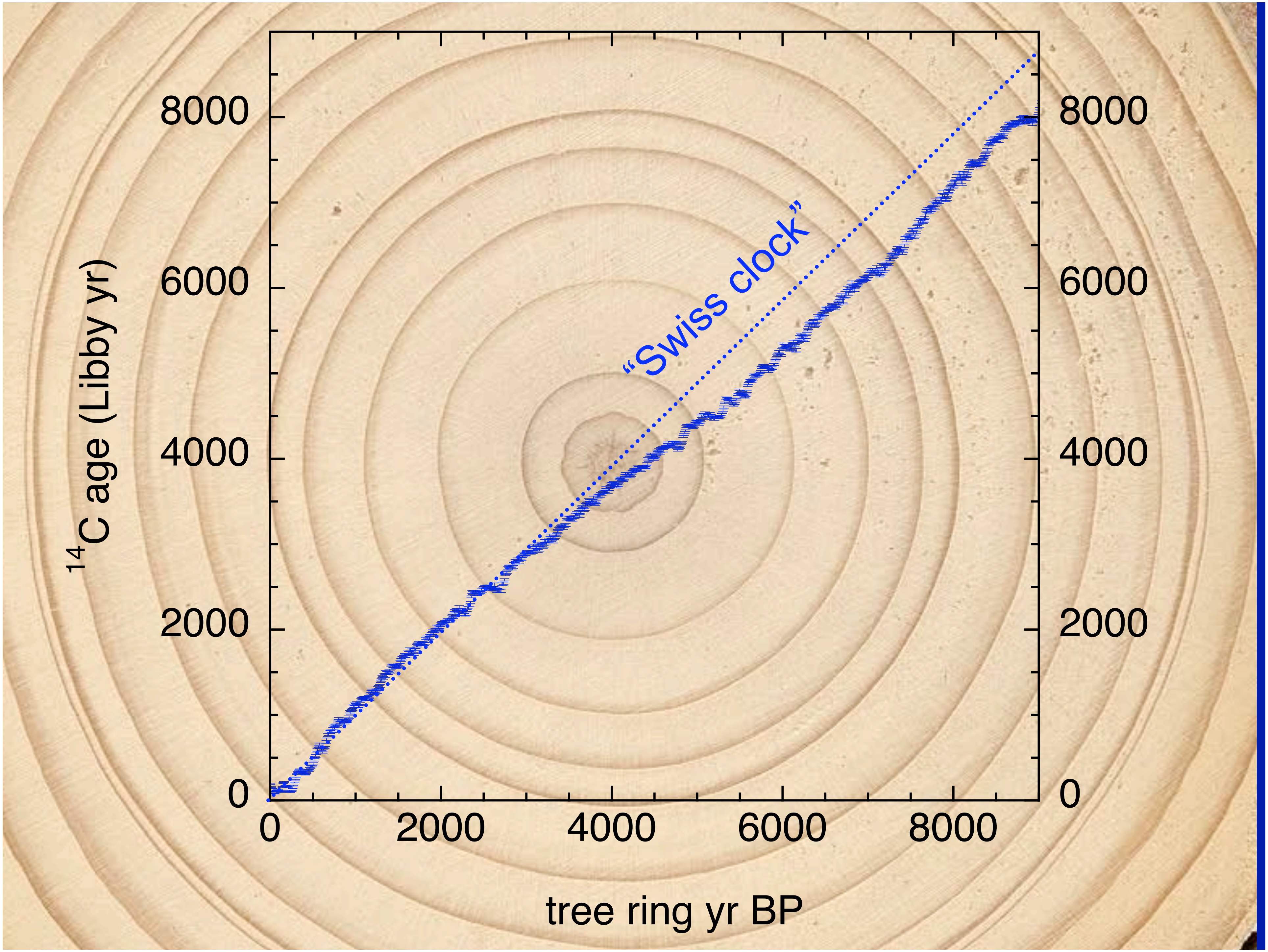
geomagnetic field variations (>10^3 yr)

greater field strength ⟶ less production

solar variations (10^1-10^2 yr)

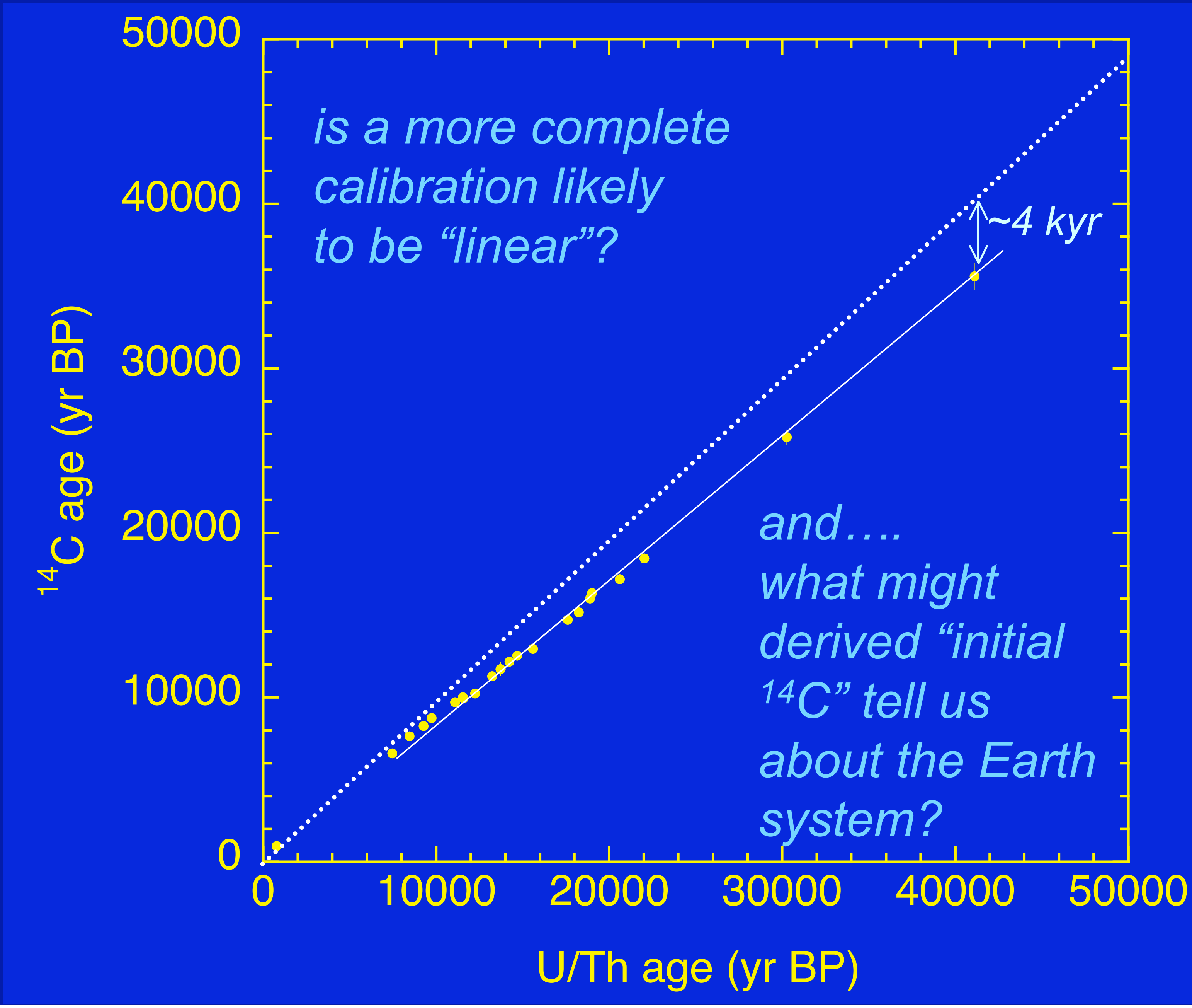
greater intensity ⟶ less production

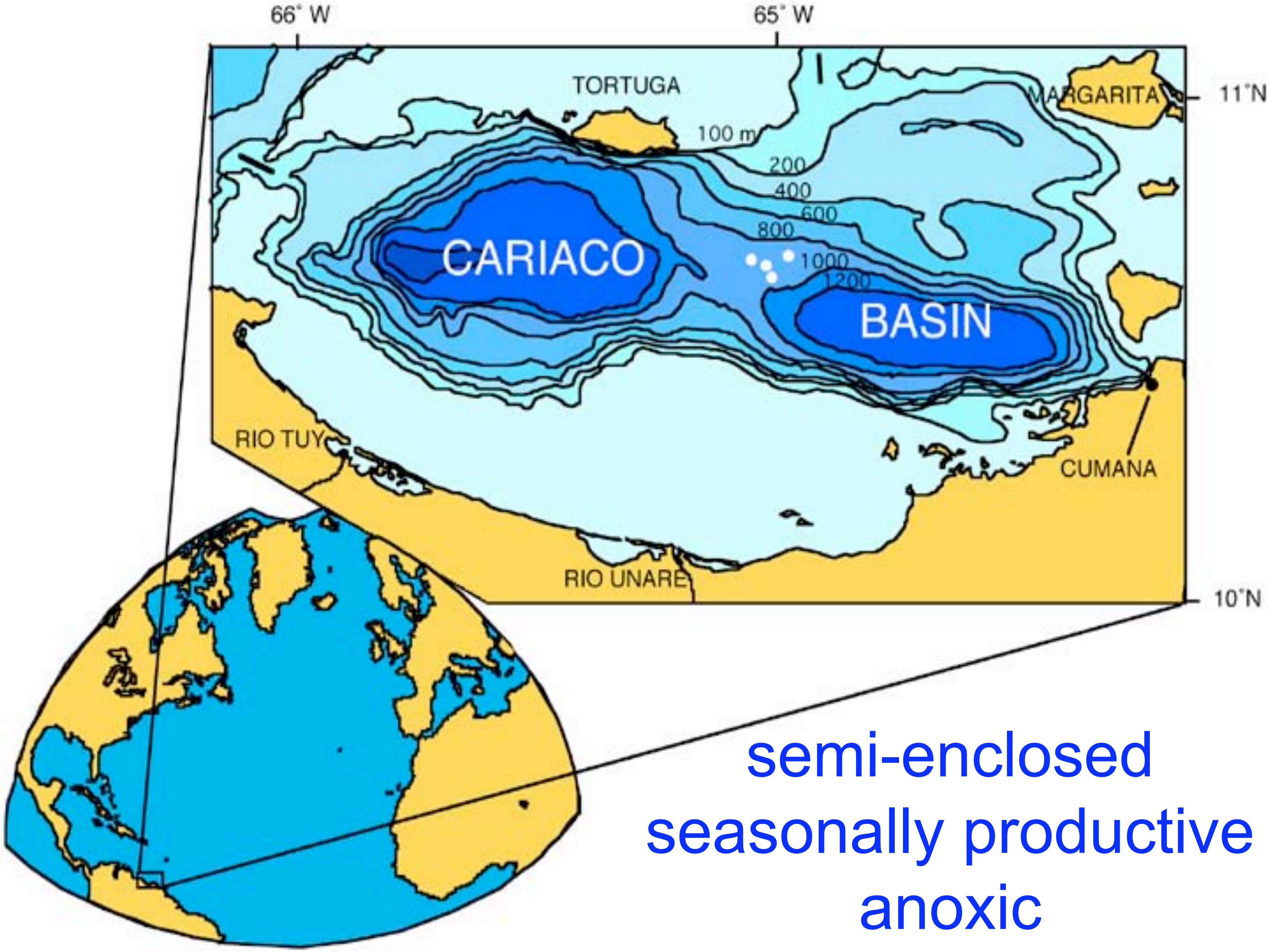
redistribution amongst reservoirs



"Swiss clock"
^{14}C age (Libby yr)
tree ring yr BP
0
2000
4000
6000
8000

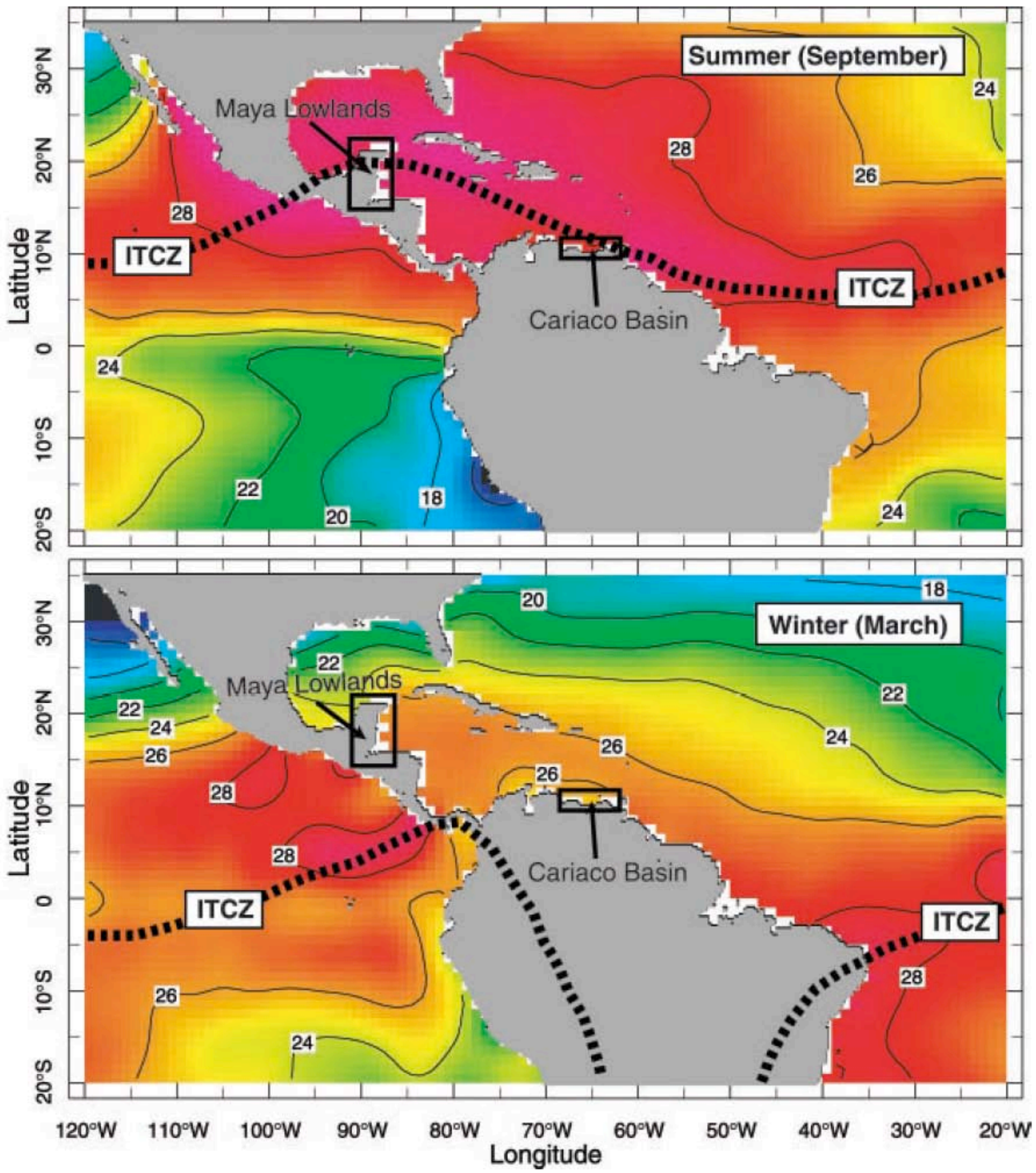
Bard *et. al.* '91 U-dated corals





semi-enclosed
seasonally productive
anoxic

seasonal migration of the ITCZ

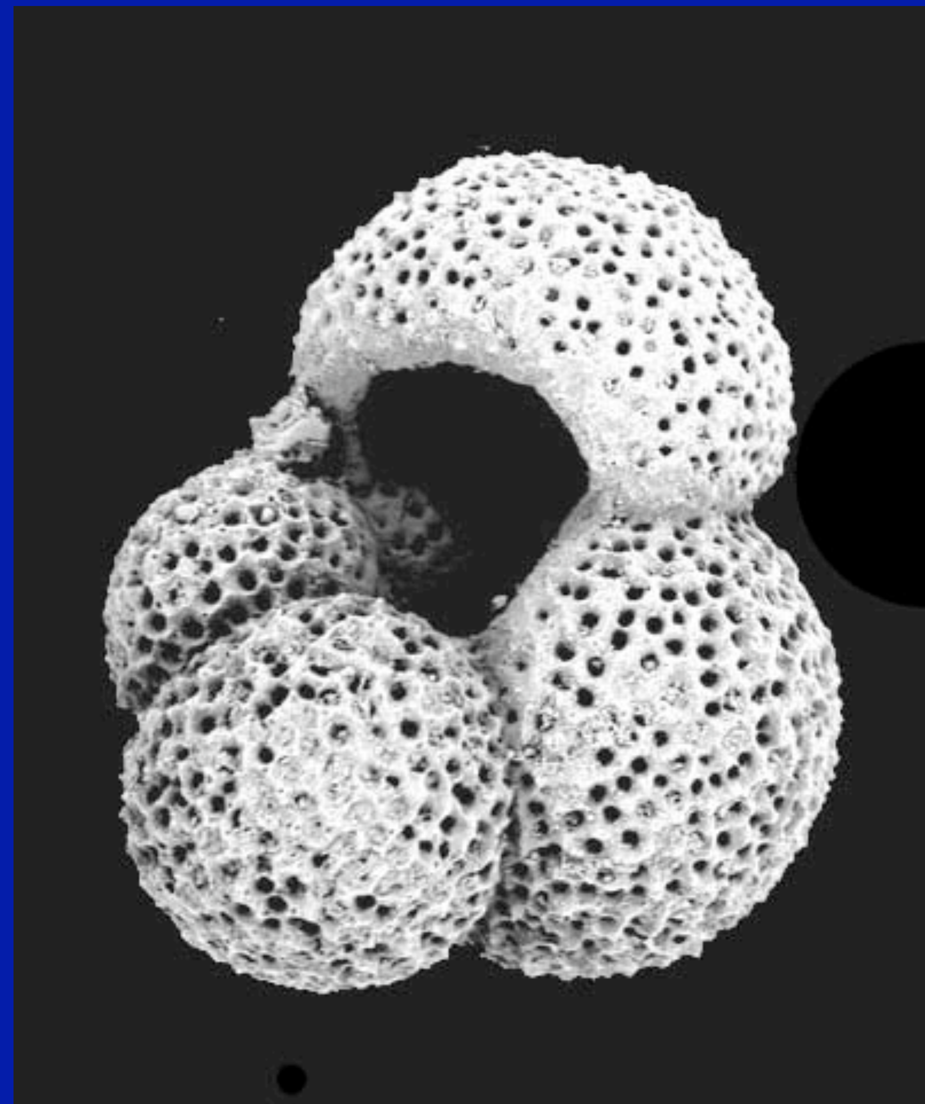


wet:
increased run off
and terrigenous
sedimentation
(dark)

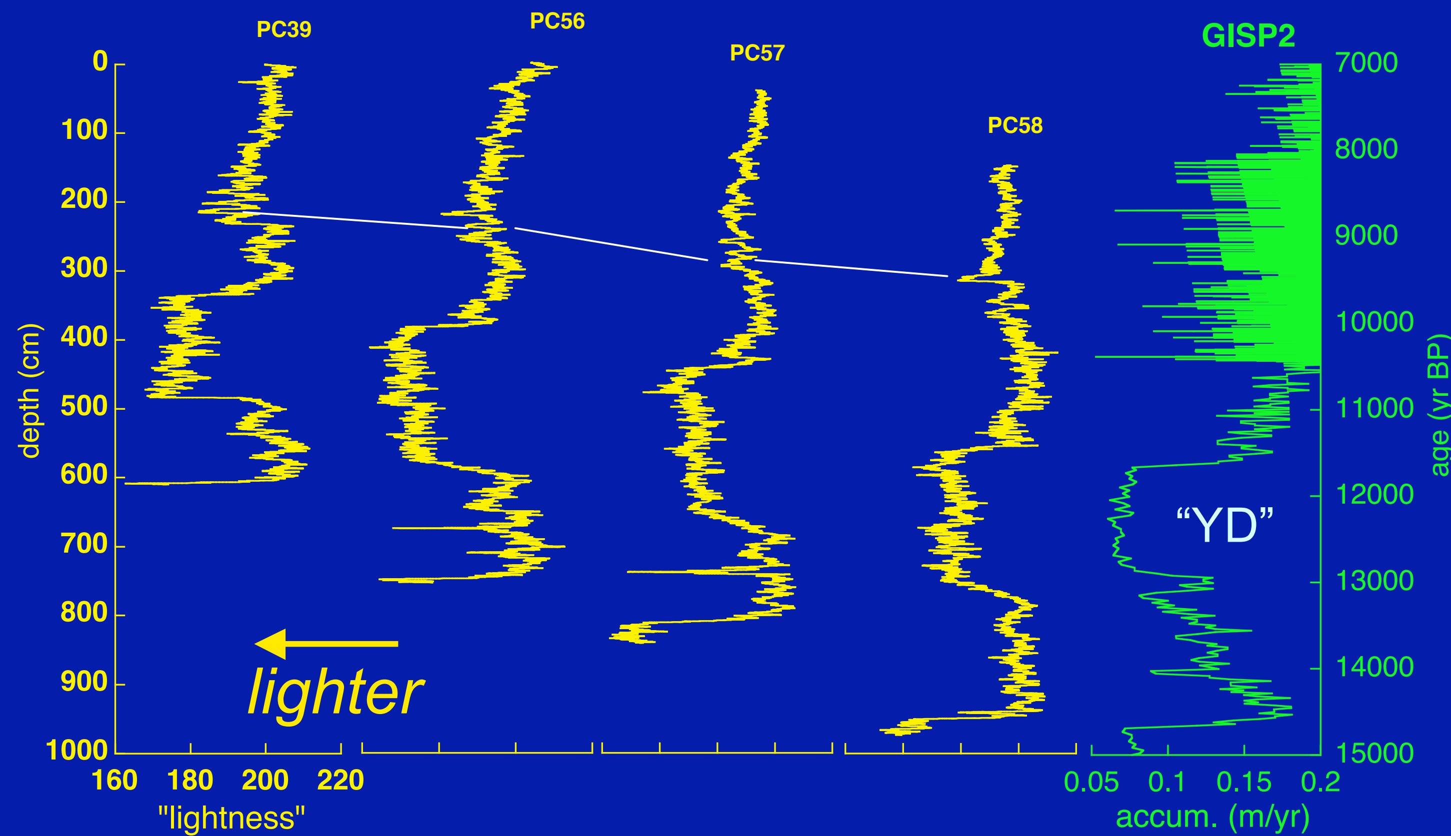
annual couplet (Pb etc.)

dry, windy:
increased upwelling
and marine biogenic
sedimentation
(light)

AMS ^{14}C date foraminifera from laminated sediments

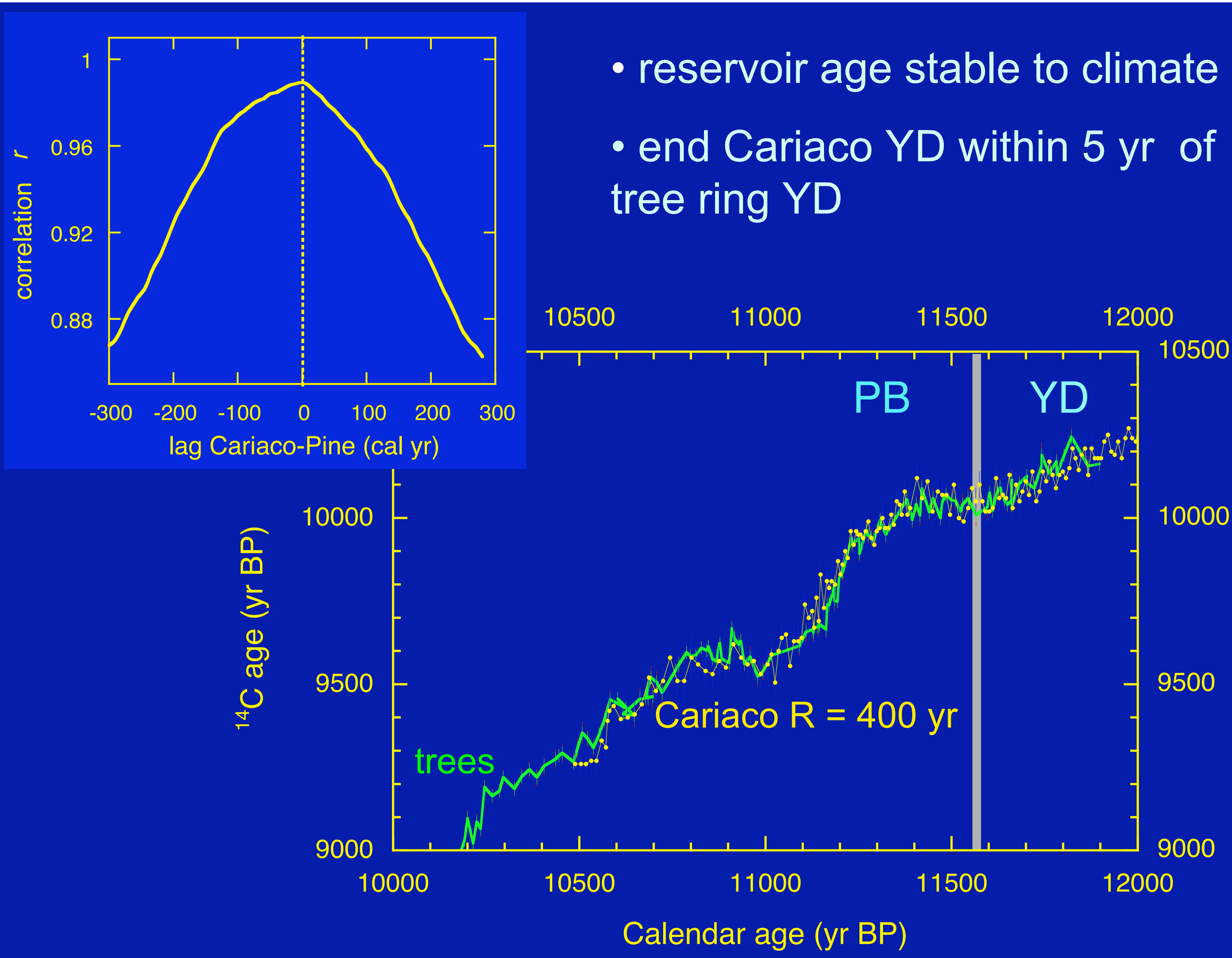


Cariaco sediment “lightness” v. Greenland accumulation

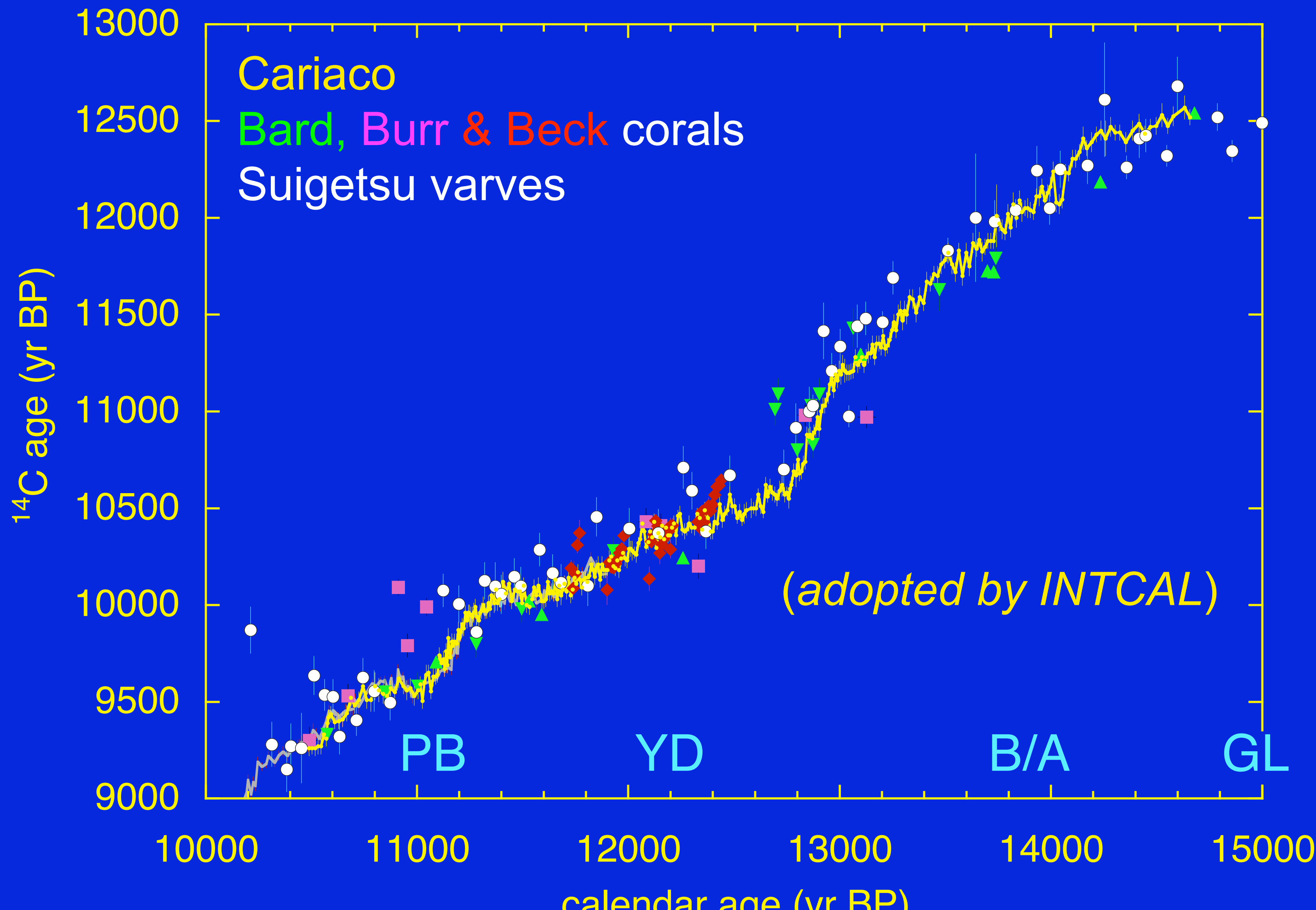


- count varves (~5500 yr floating chronology)
- ^{14}C date foraminifera (~decadal spacing)
- anchor chronology (“wiggle match” to tree ring ^{14}C)

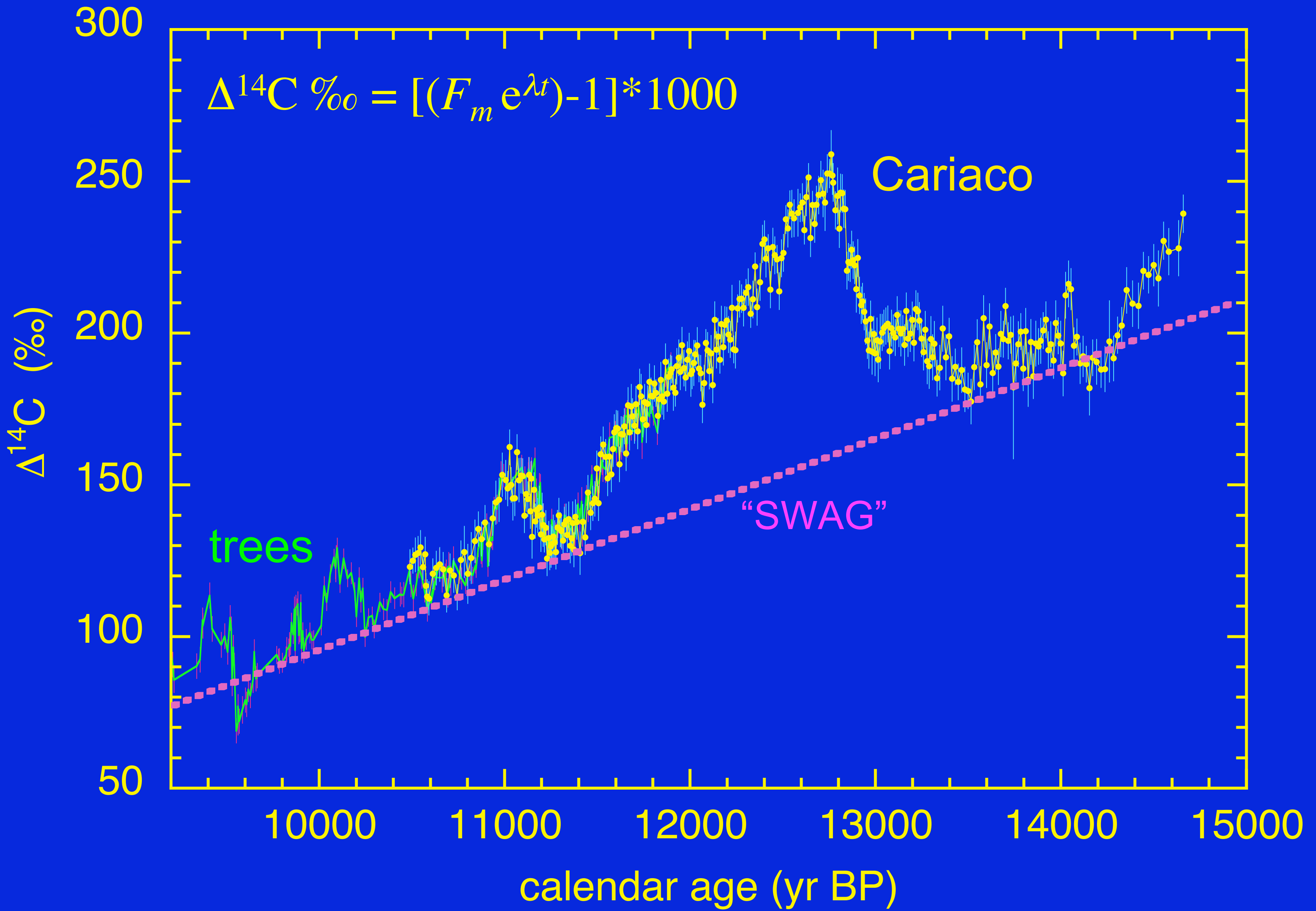
- reservoir age stable to climate
- end Cariaco YD within 5 yr of tree ring YD



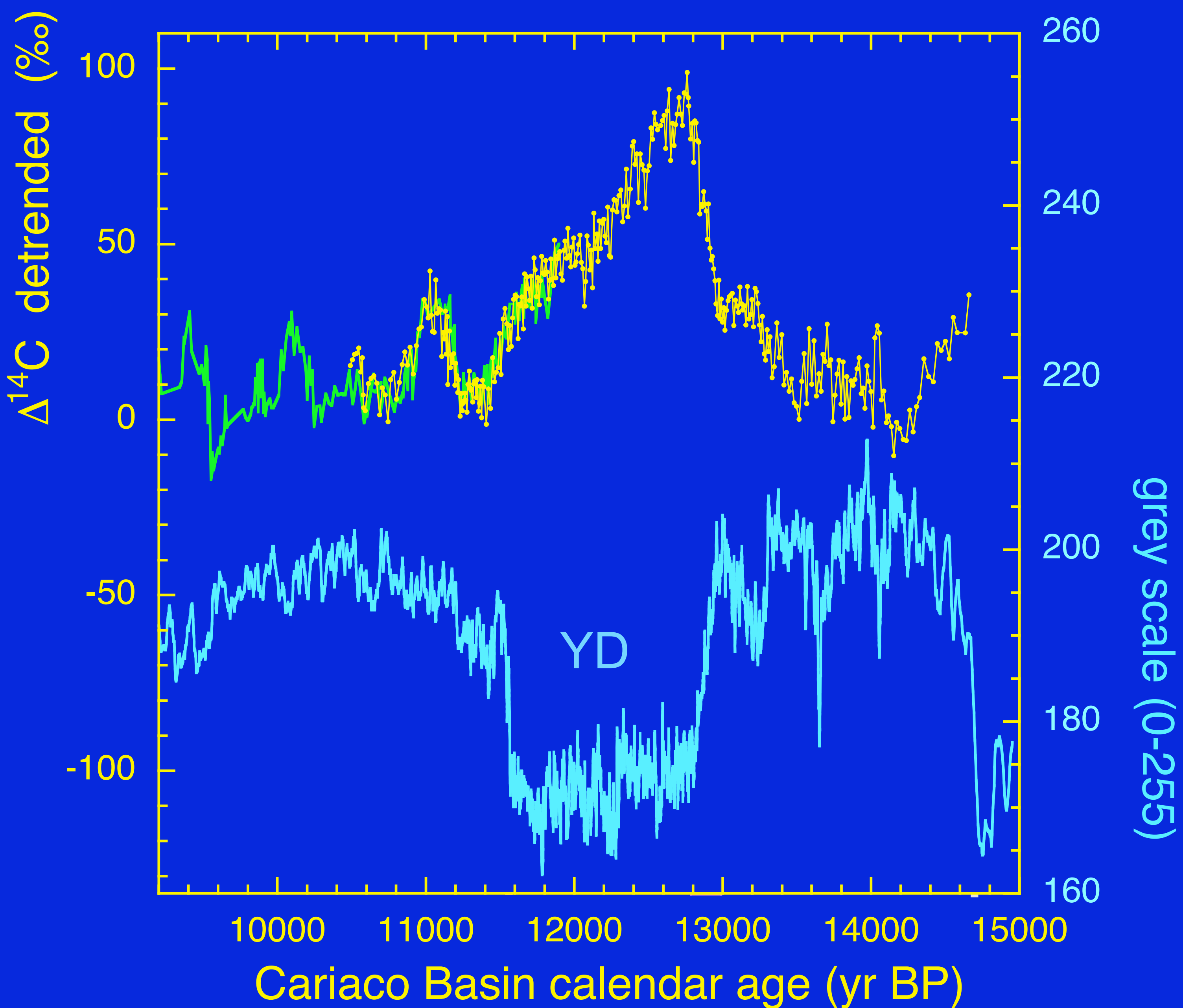
deglacial calibration results

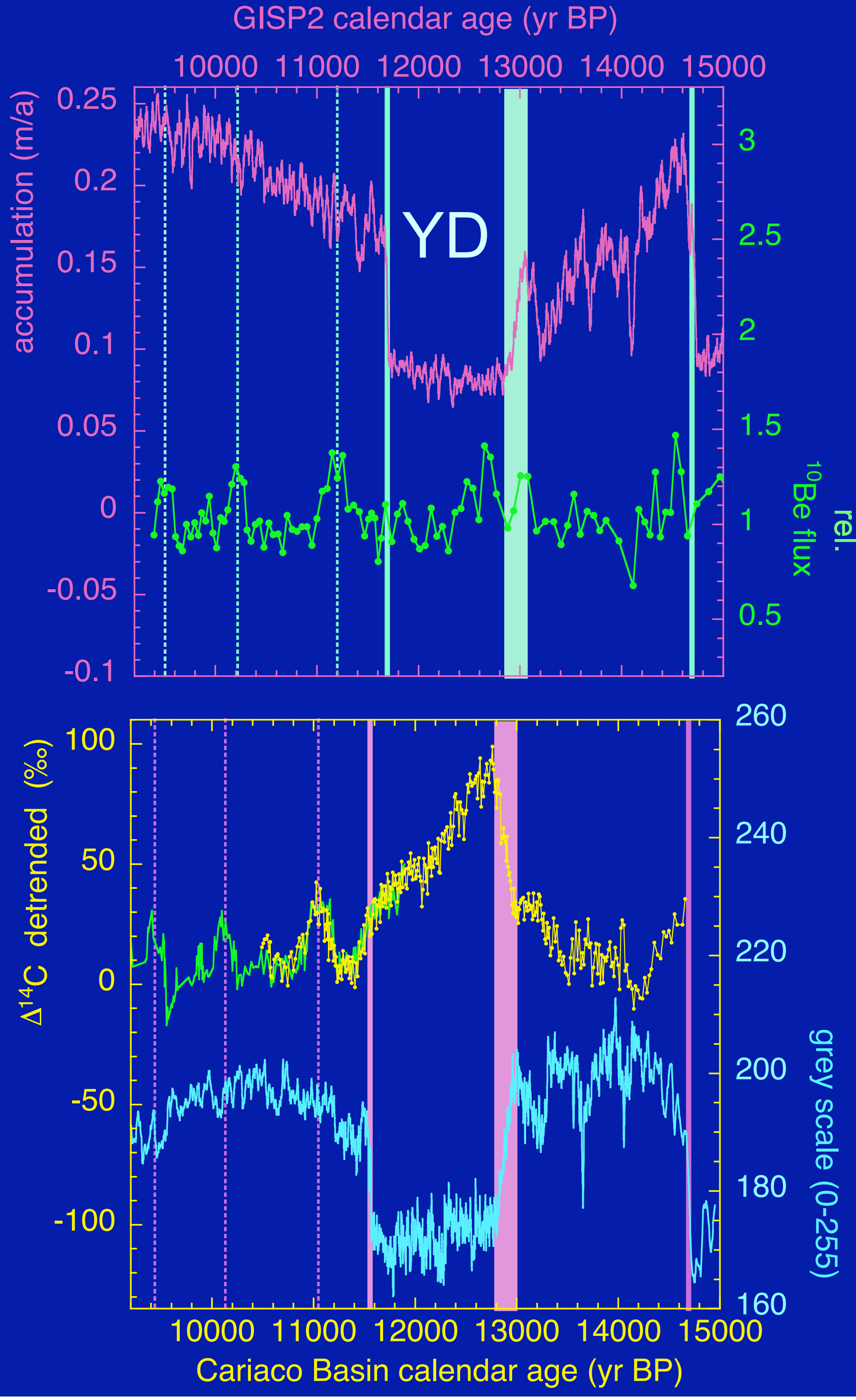


initial ^{14}C activity



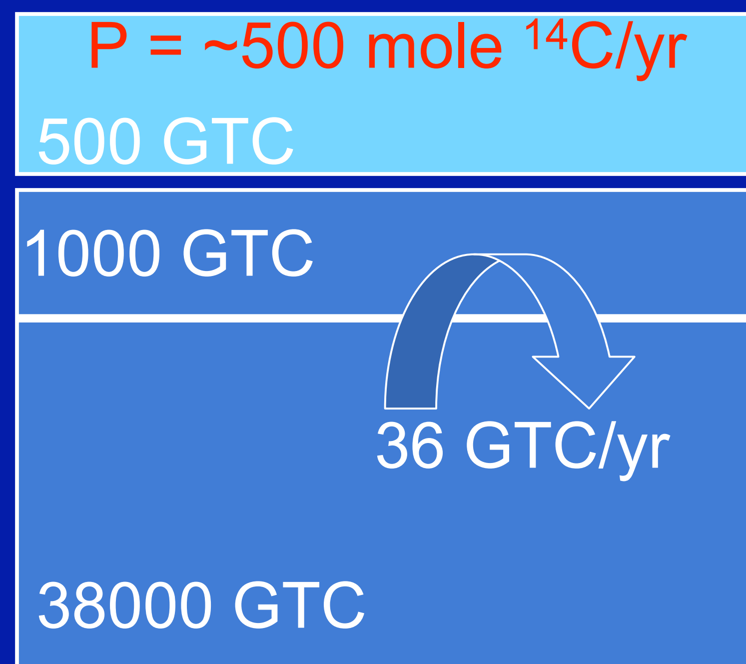
^{14}C vs. climate





- Cariaco & GISP2 chronologies agree w/in 10-100 yr

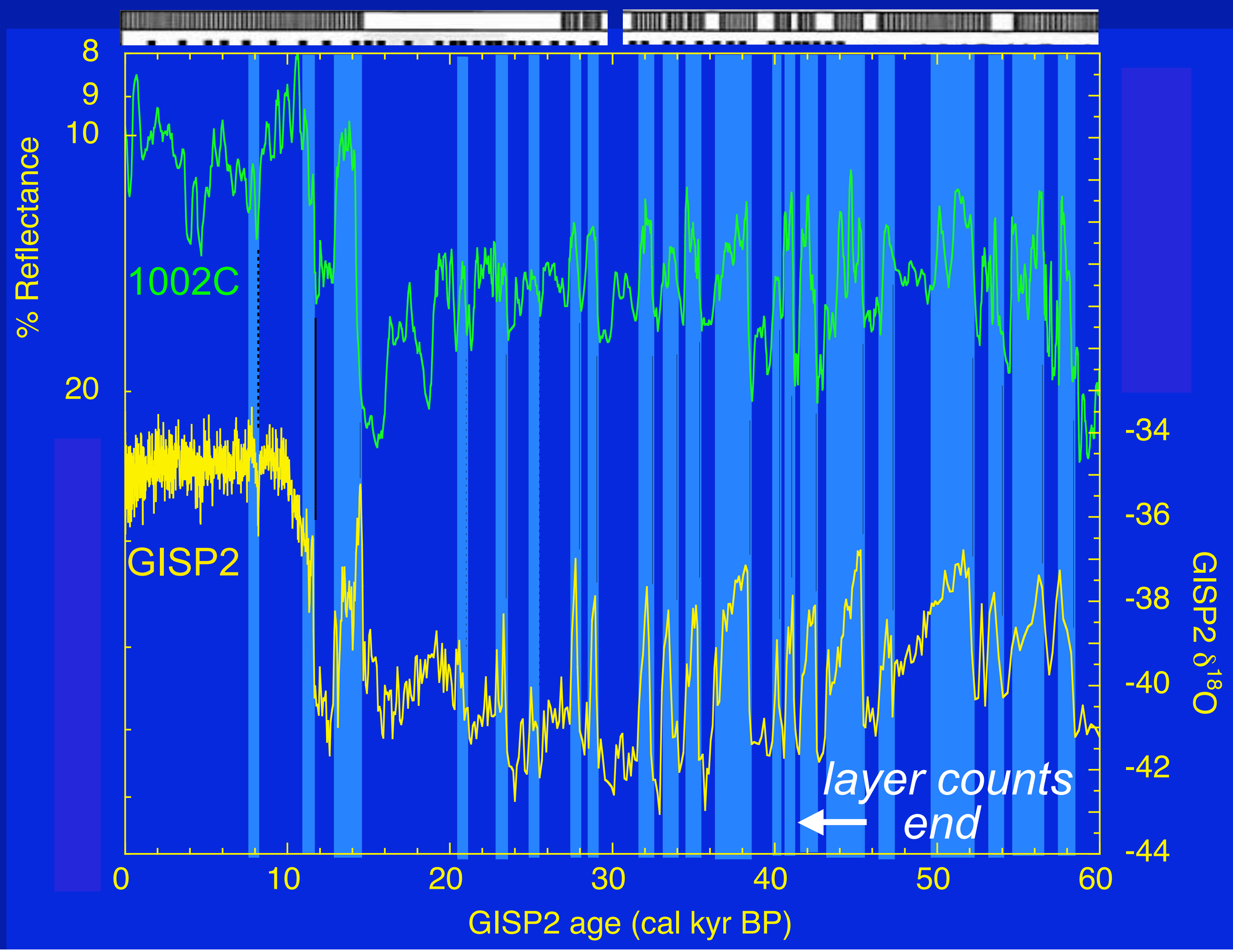
- YD ^{14}C does not scale to ^{10}Be, therefore not production, but an ocean signal:



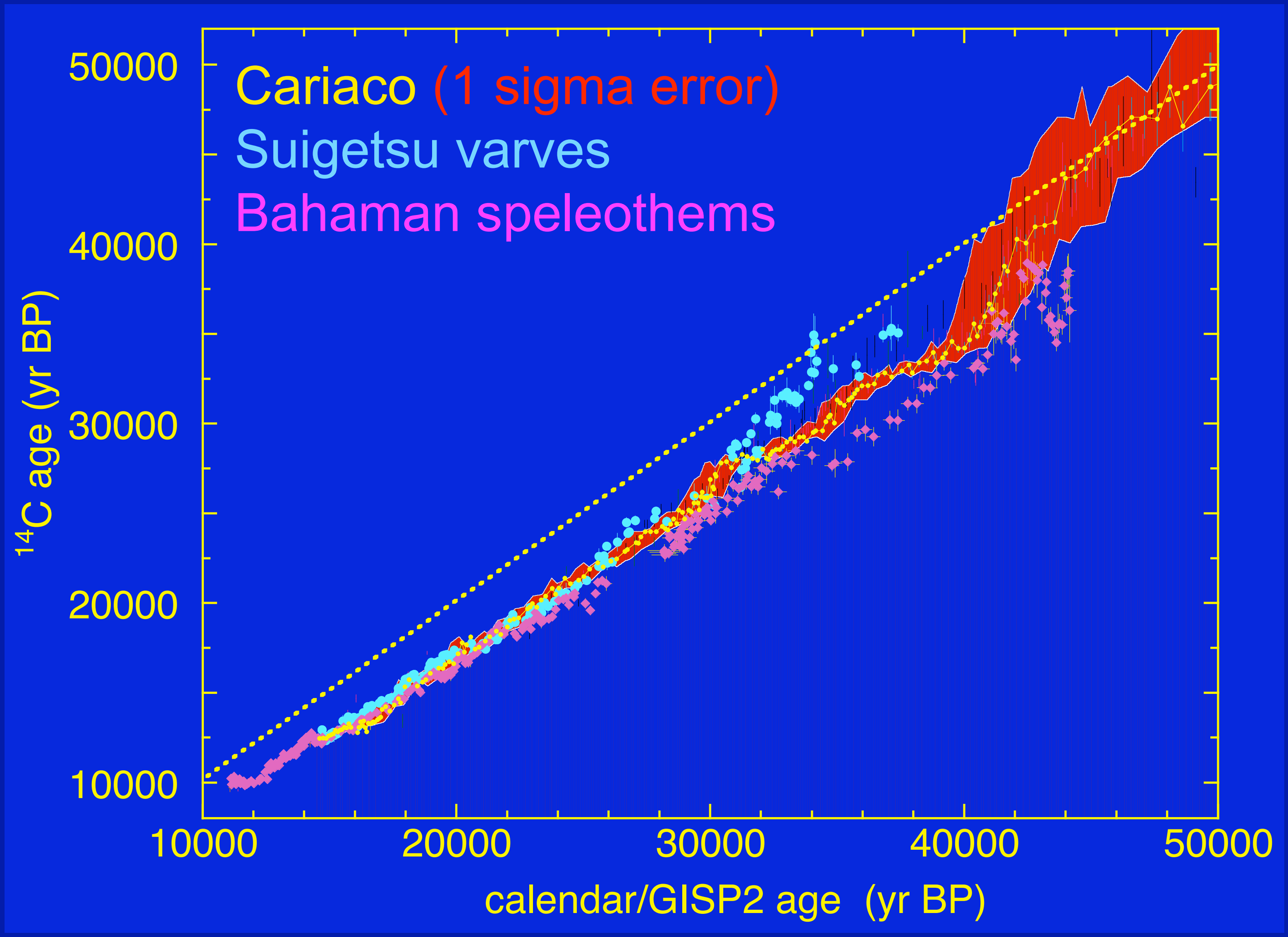
extended ^{14}C calibration

having demonstrated Cariaco and Greenland climate changes synchronous, extend calibration through longer record of dis-continuously laminated sediments

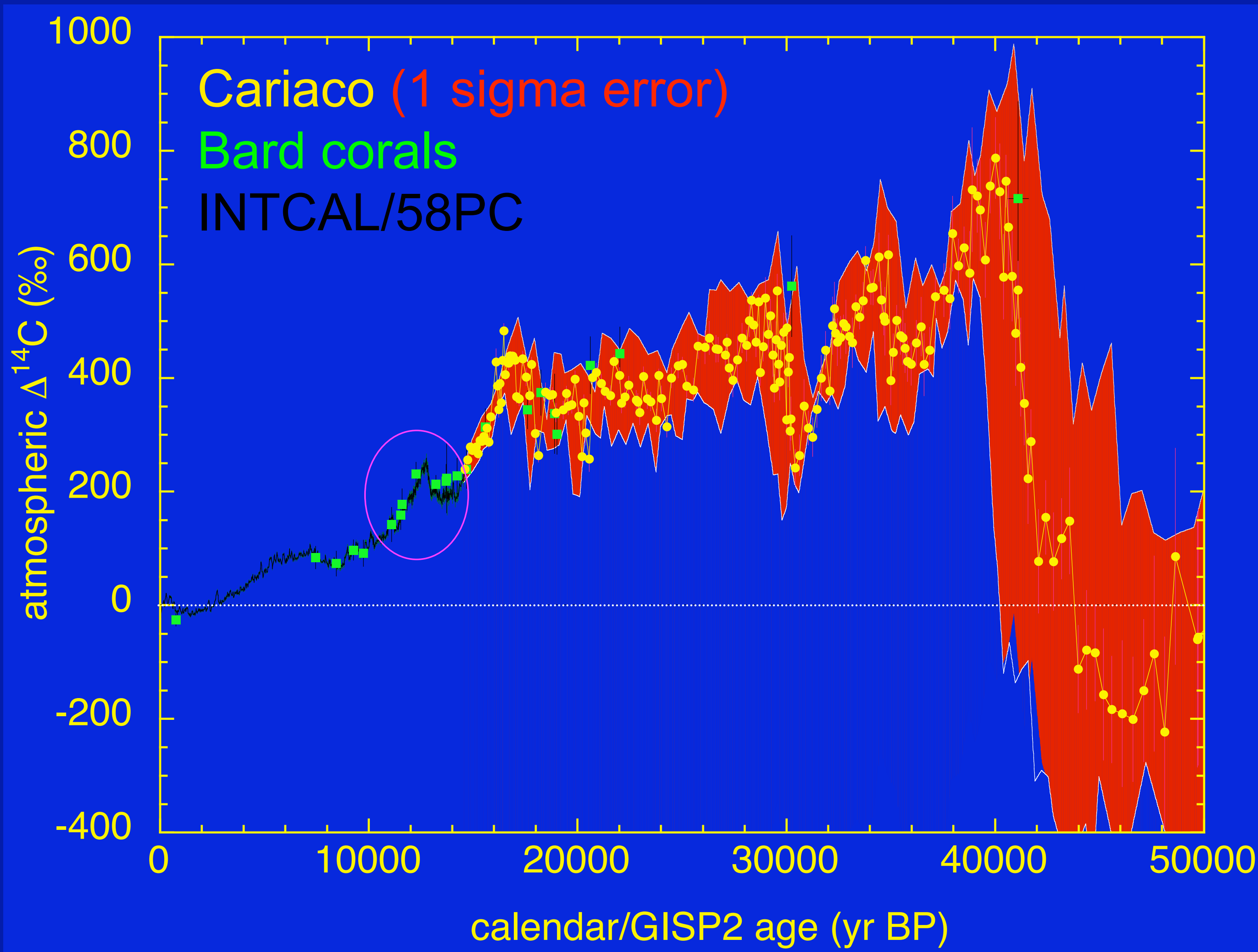
ODP 1002 / GISP2 correlation of Peterson *et. al.*



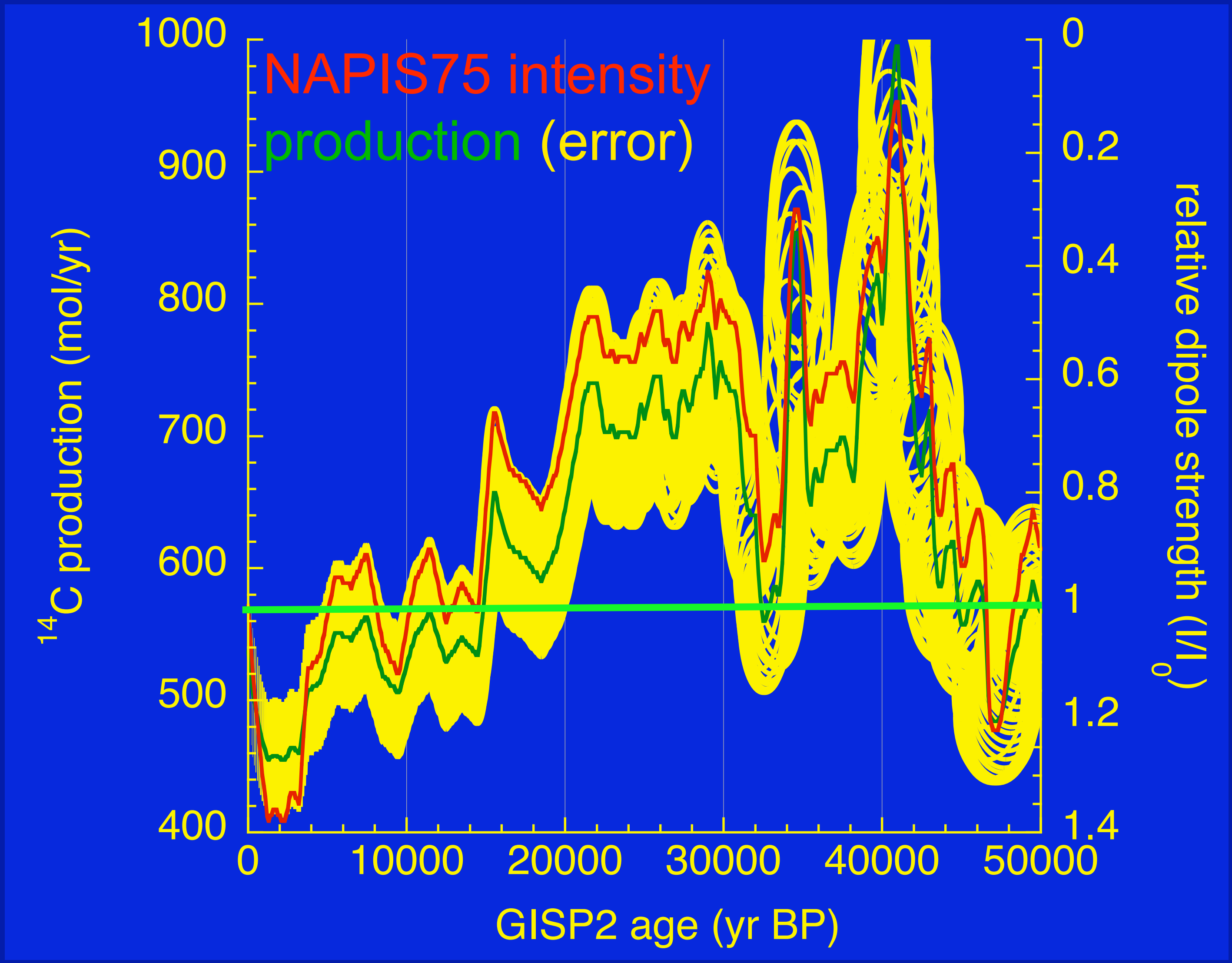
calibration results



reconstructed ^{14}C activity

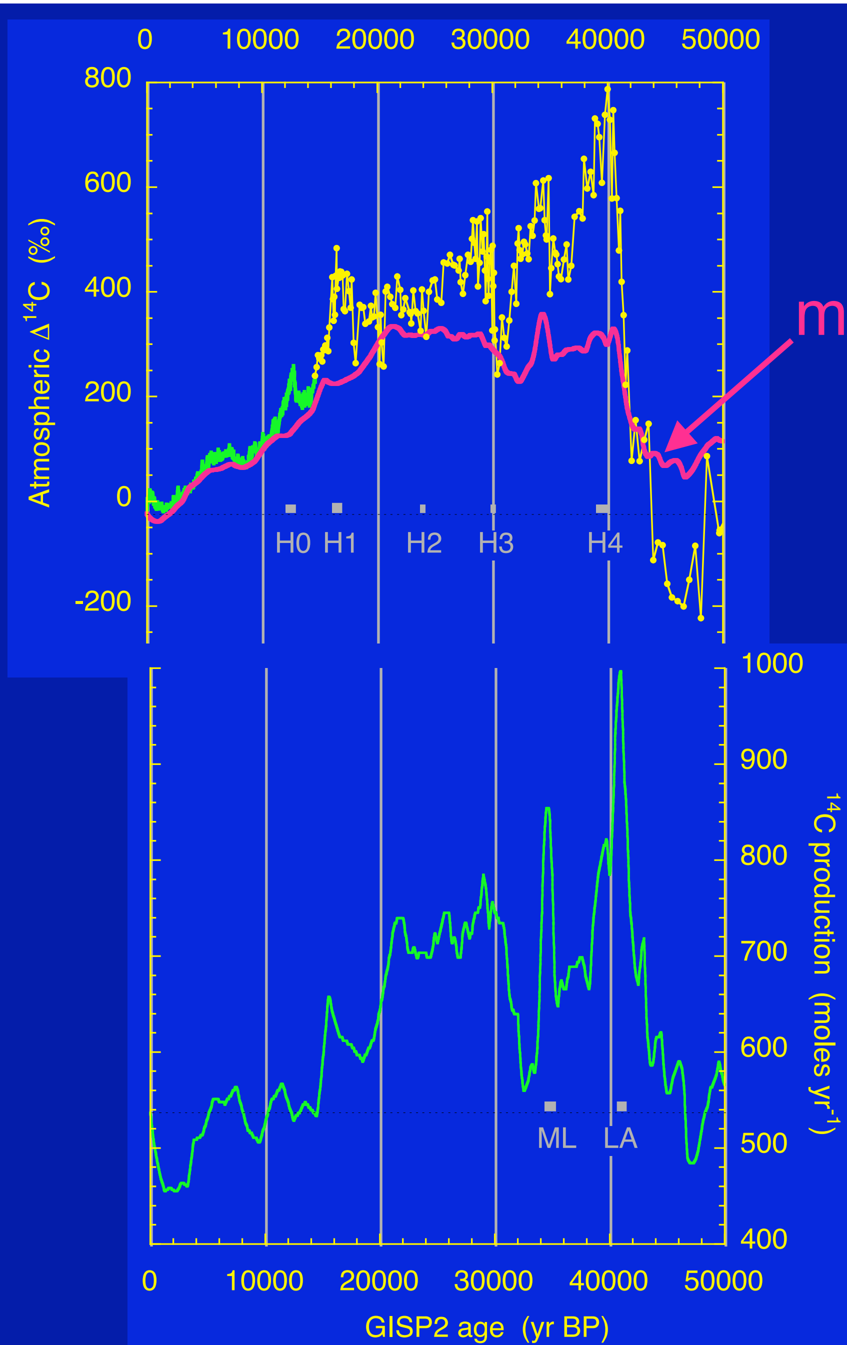


geomagnetically modulated production



^{14}C prod. v. I/I_0 from Masarik & Beer '99

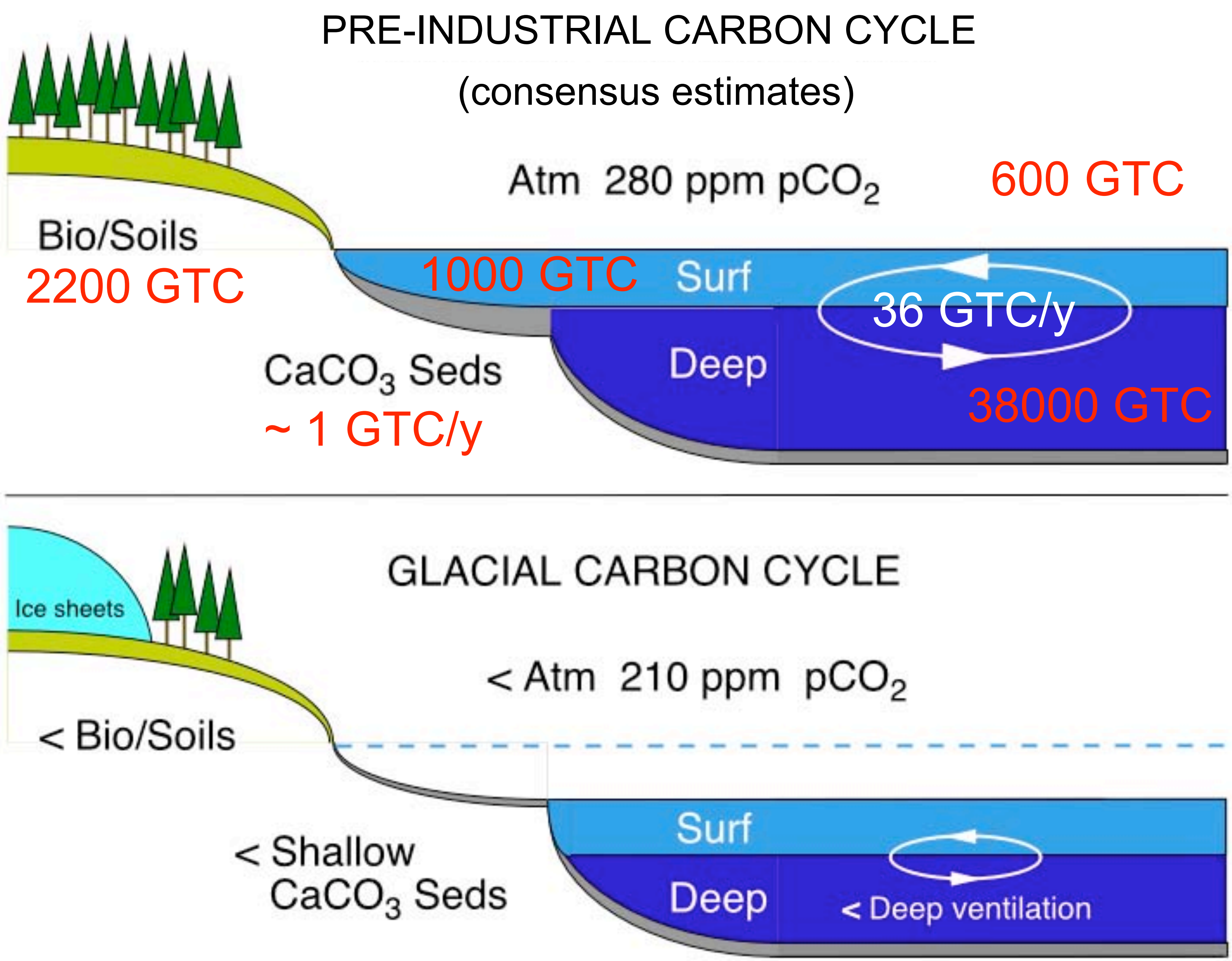
simulated vs. observed $\Delta^{14}C$



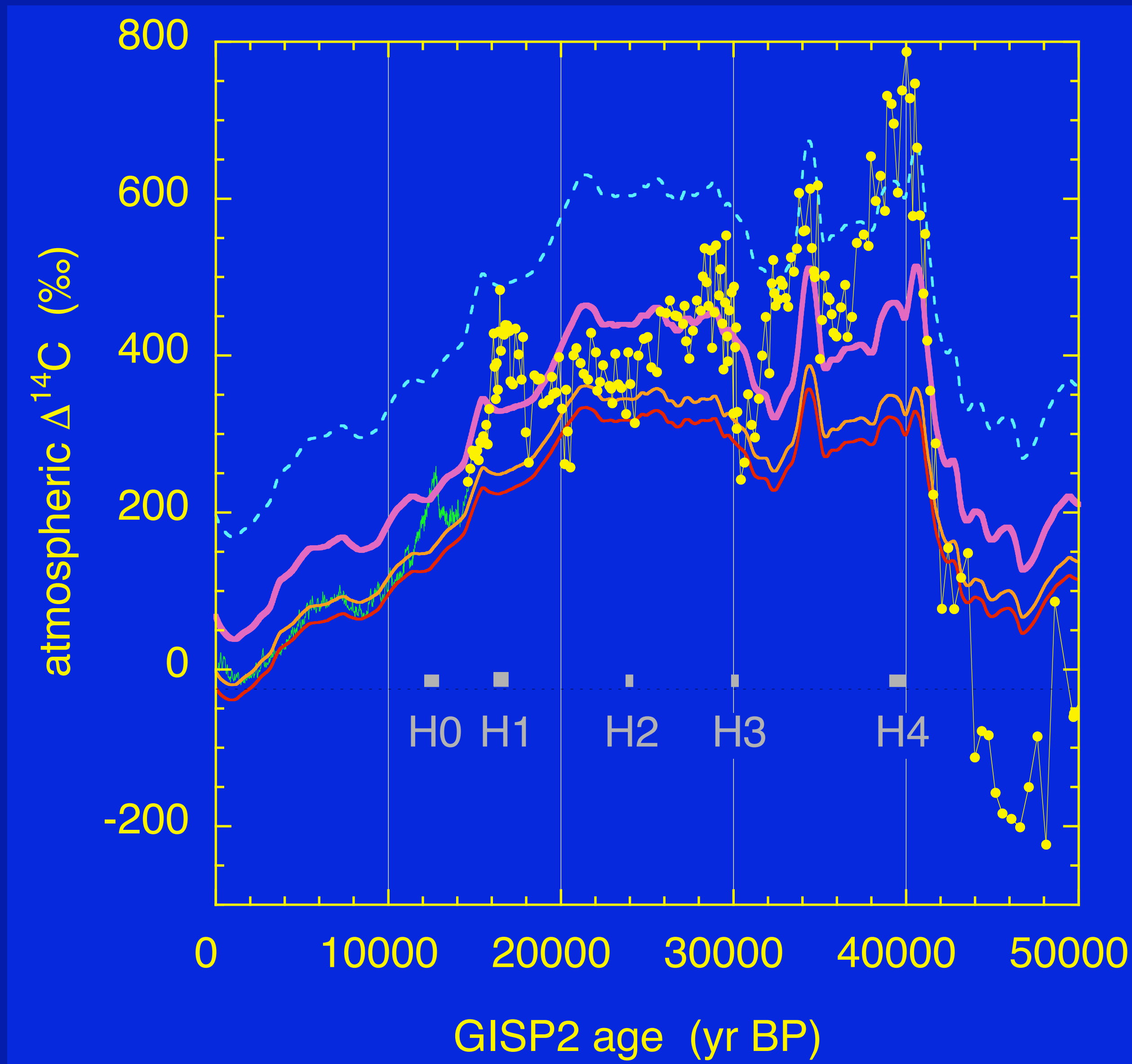
model:

for contemporary carbon inventories and exchange terms, variable production (approx. ± 100‰ errors not shown)

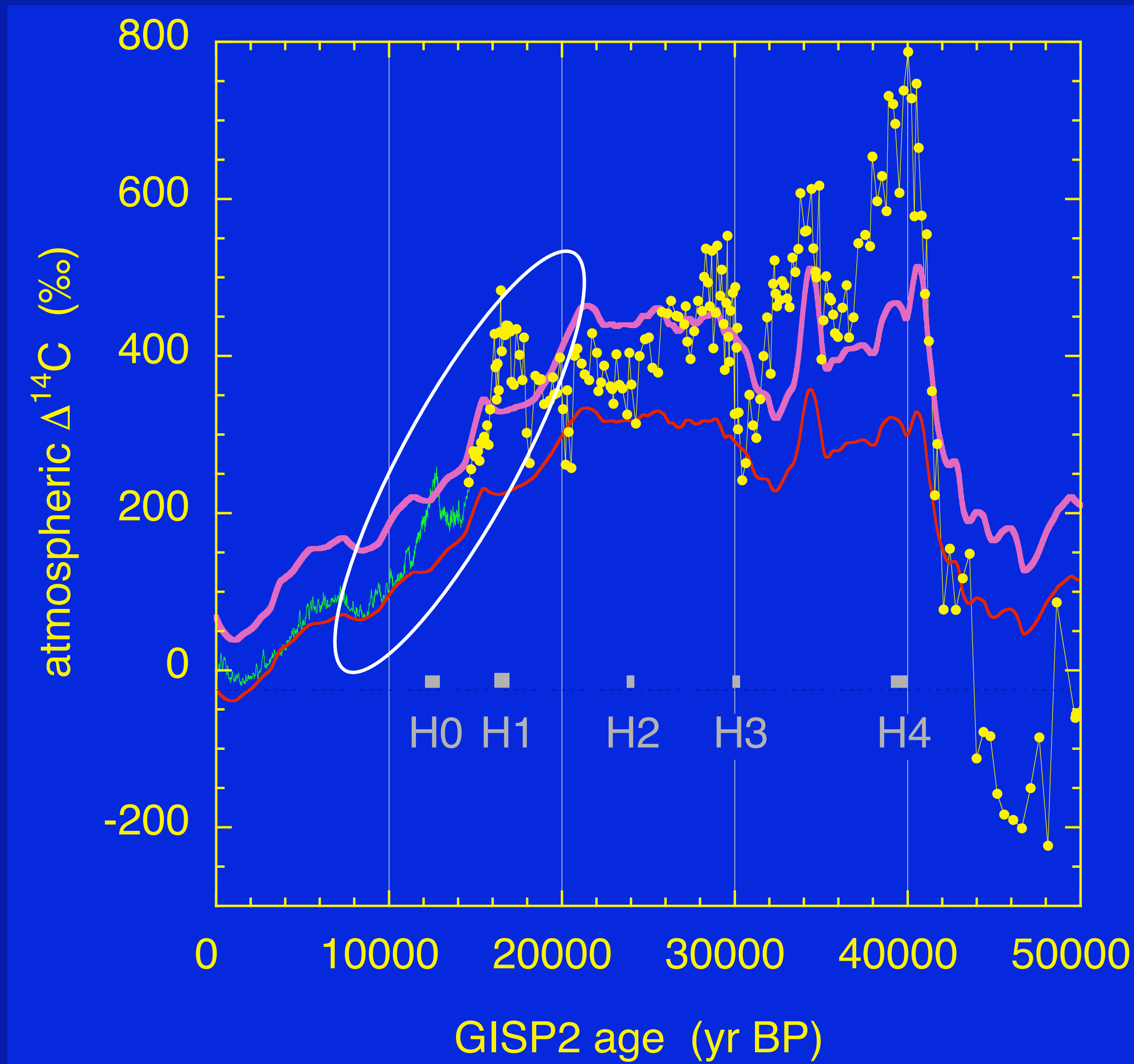
glacial data look like estimated production with small C-cycle


PRE-INDUSTRIAL CARBON CYCLE
(consensus estimates)
Atm 280 ppm pCO2
600 GTC
Bio/Soils
2200 GTC
1000 GTC
Surf
36 GTC/y
Deep
CaCO3 Seds
~ 1 GTC/y
38000 GTC
GLACIAL CARBON CYCLE
Ice sheets
< Atm 210 ppm pCO2
< Bio/Soils
Surf
< Shallow
CaCO3 Seds
Deep
< Deep ventilation

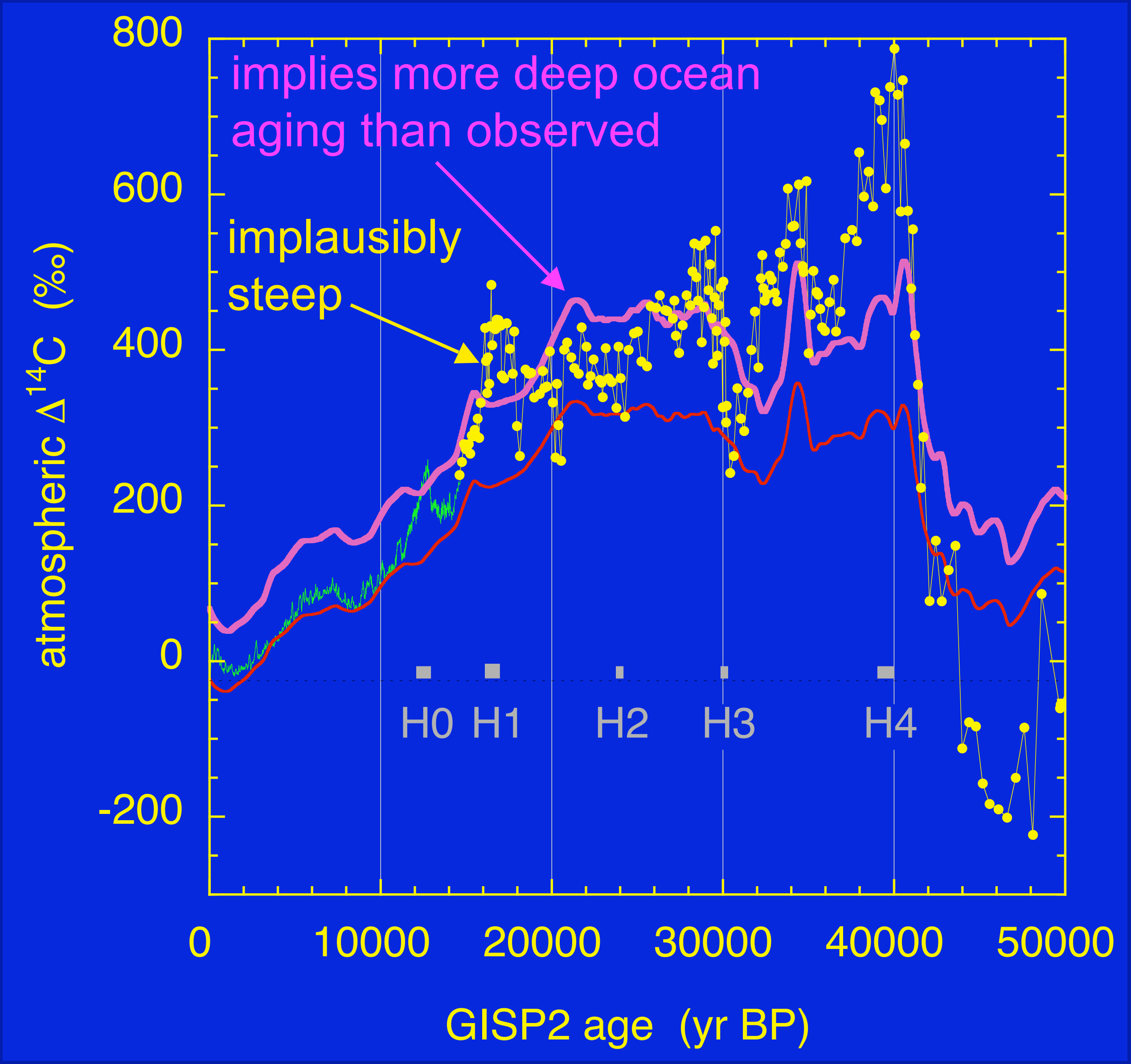
a smaller glacial carbon cycle?



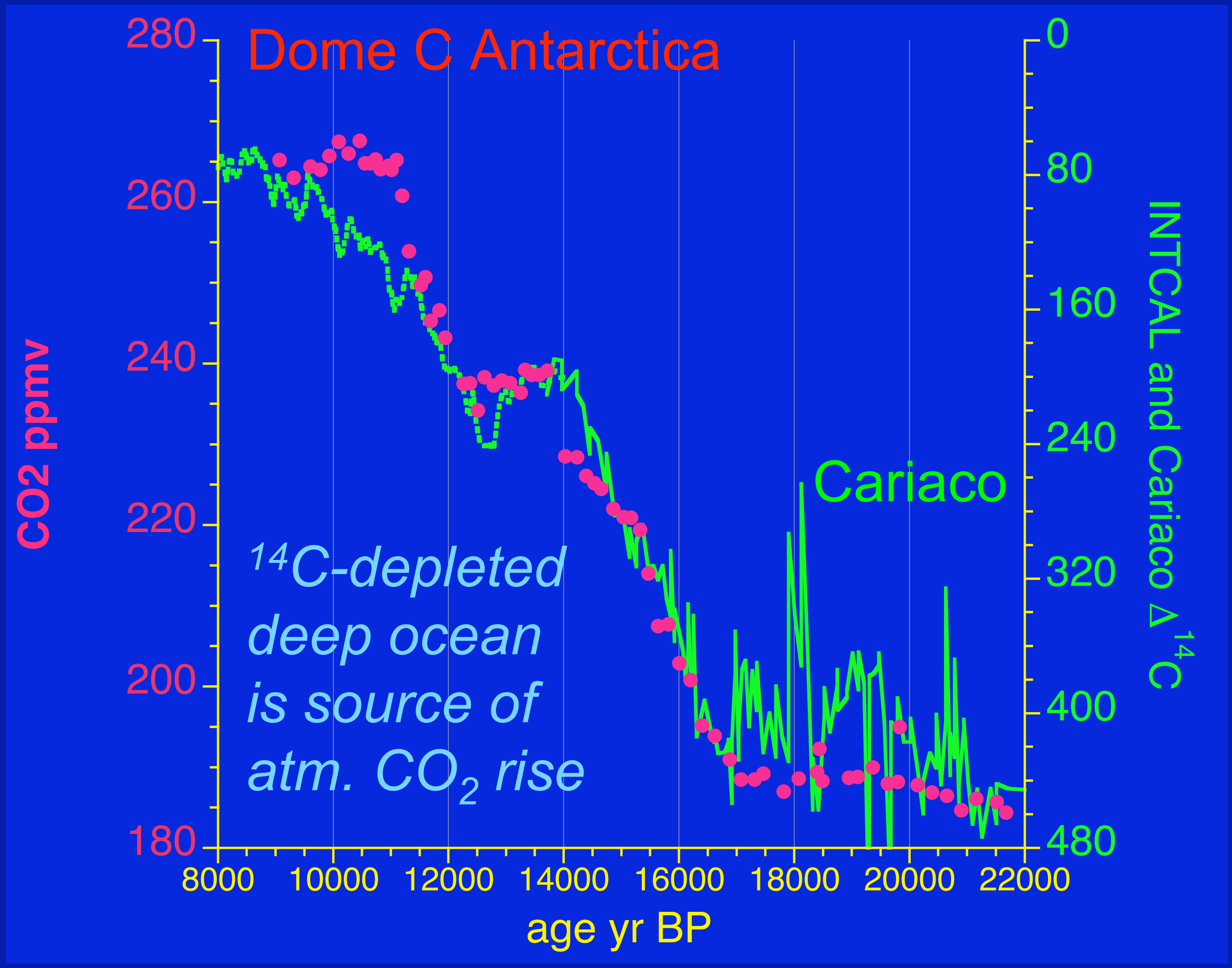
deglacial reorganization?



Broecker issues:

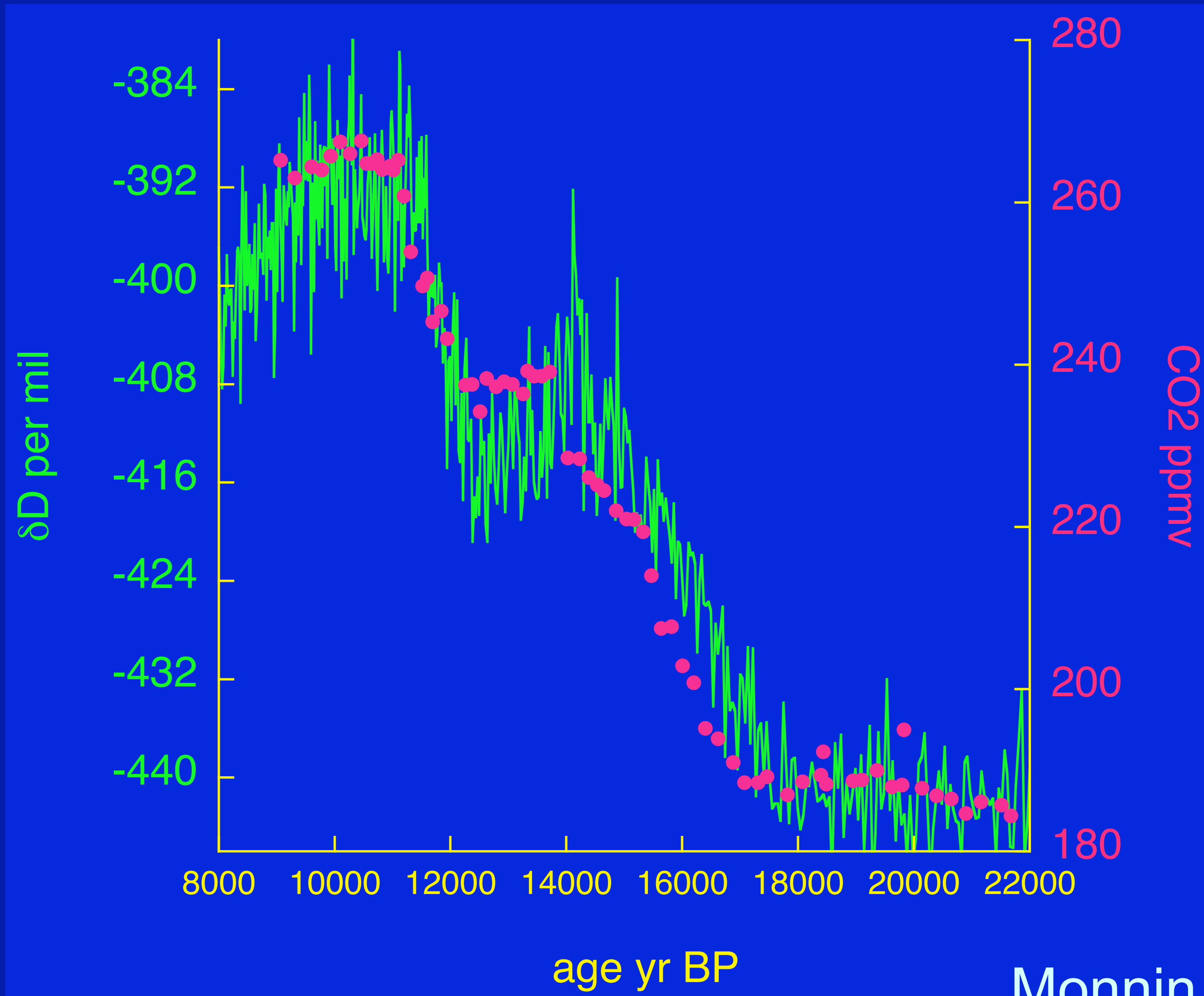


ATM ^{14}C and CO_2 histories similar



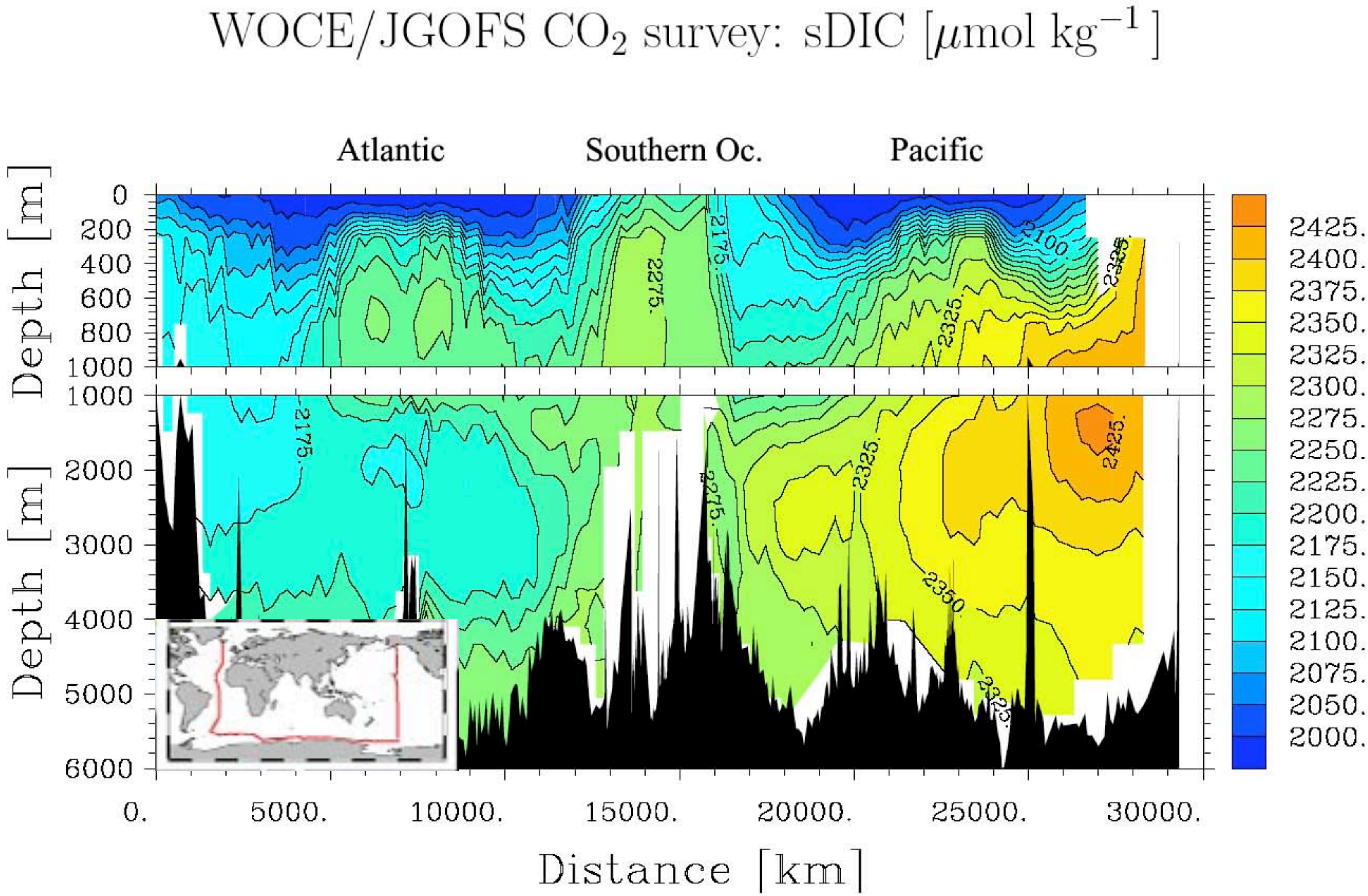
CO_2 from Monnin et. al. ‘01

CO_2 linear in Antarctic climate



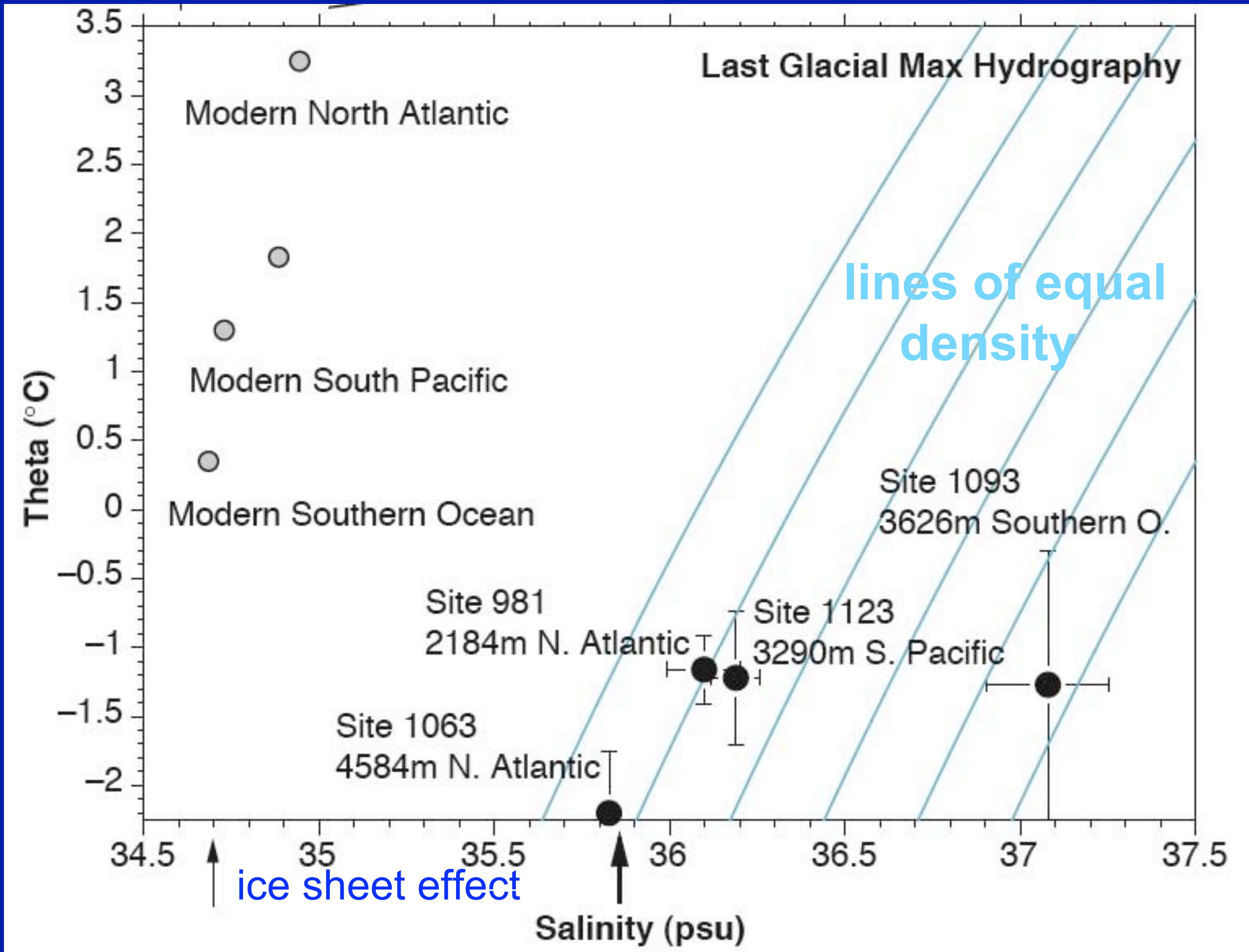
Monnin et al. '01

venting of ocean CO_2 thru the Southern Ocean

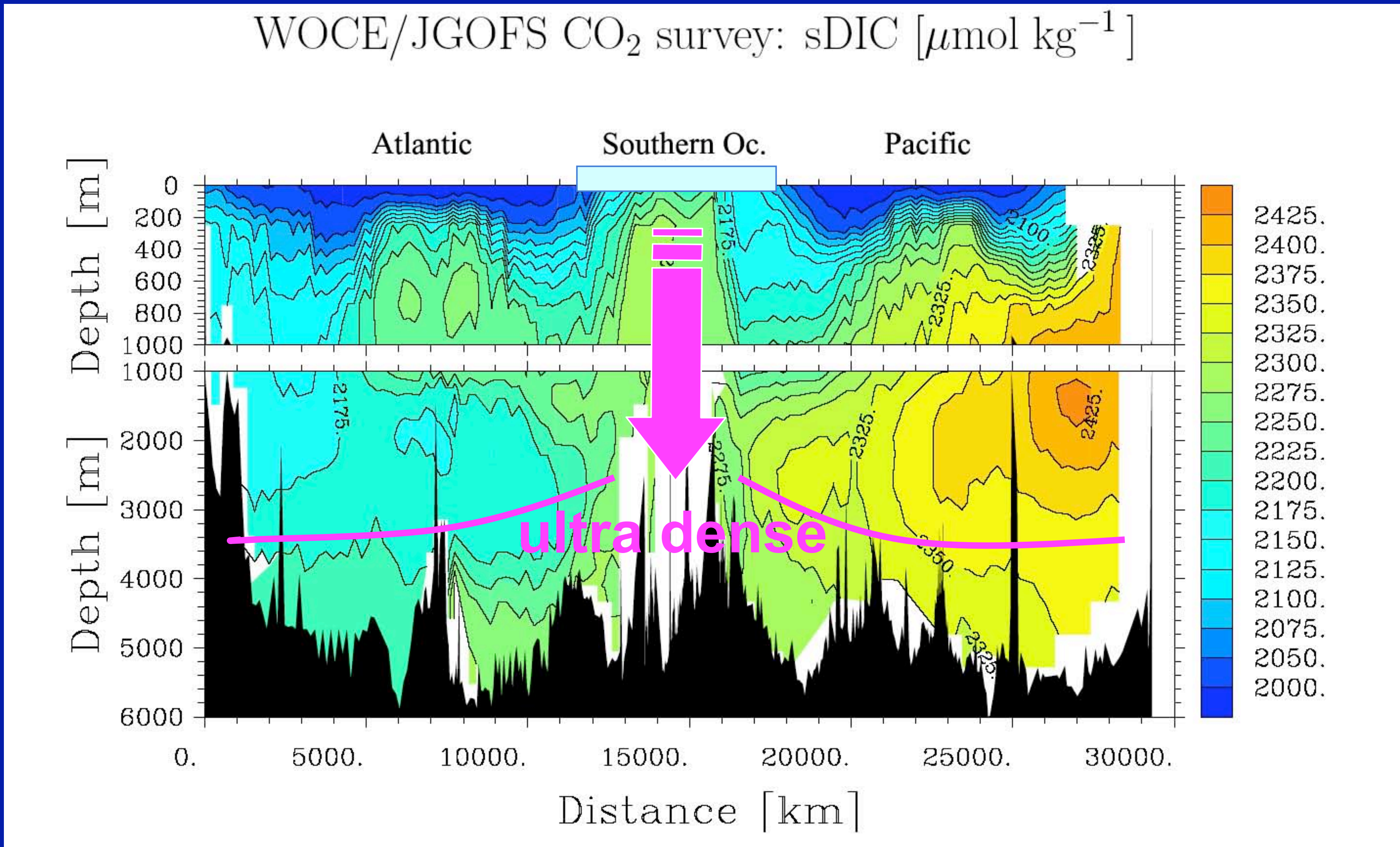


compilation of Gruber

from Adkins ('02) pore fluid $\delta^{18}O$ and chlorinity

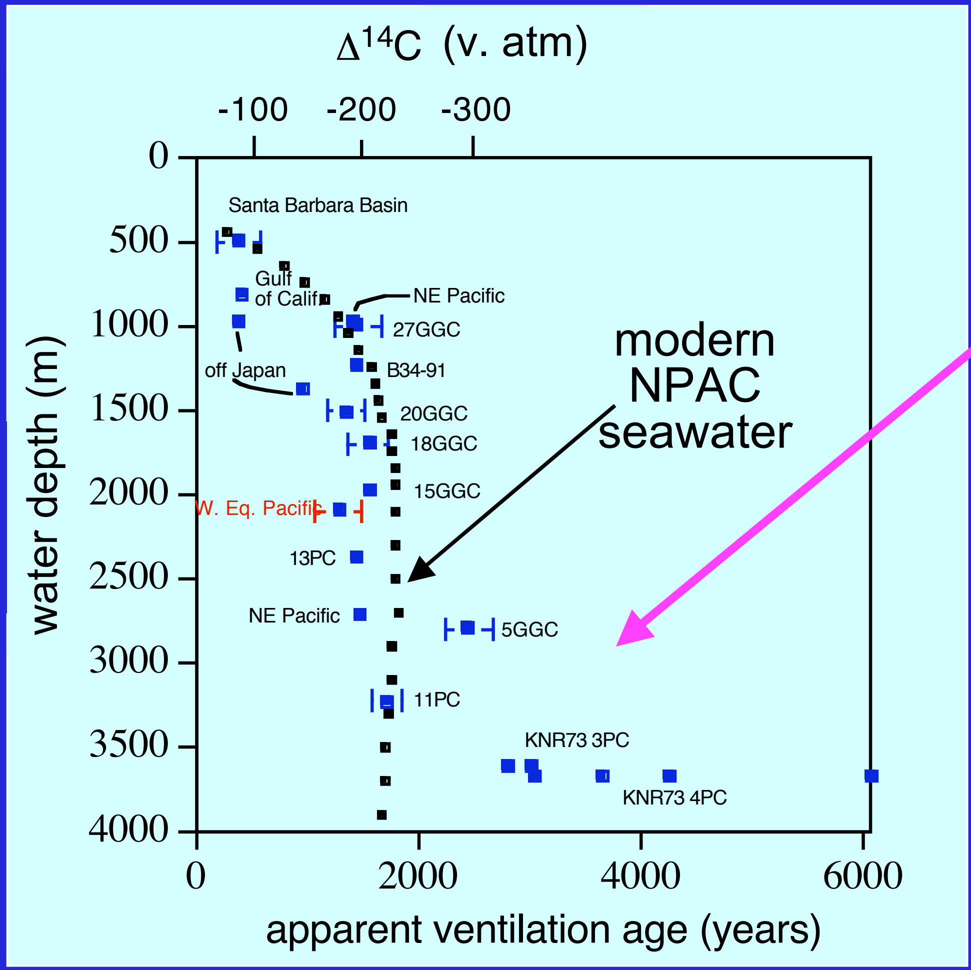


Southern Ocean "CO_2 window" closed during glacial



deep ocean CO_2 rises and ages (^{14}C decay)

Pacific benthic-planktic ^{14}C age differences

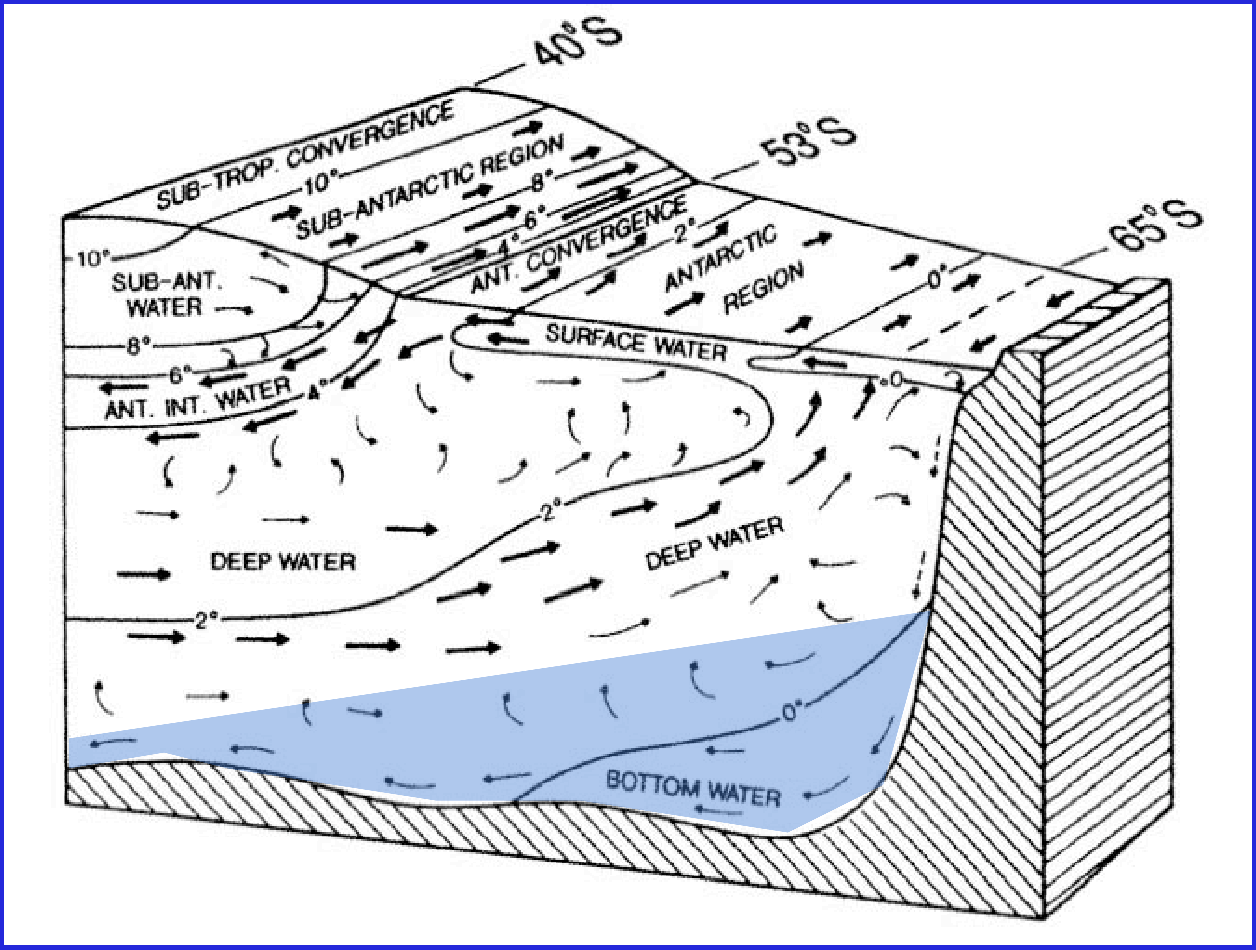


glacial ocean deep ^{14}C divide

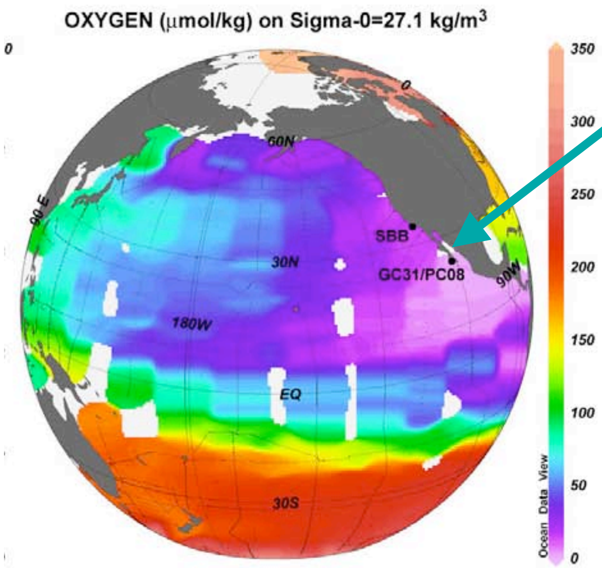
Keigwin, Lehman, Cook (unpub.)

deglacial mechanics

radiometrically old, isolated AABW mixed up to SO surface and into AAIW?



after Sverdrup et al. 1942

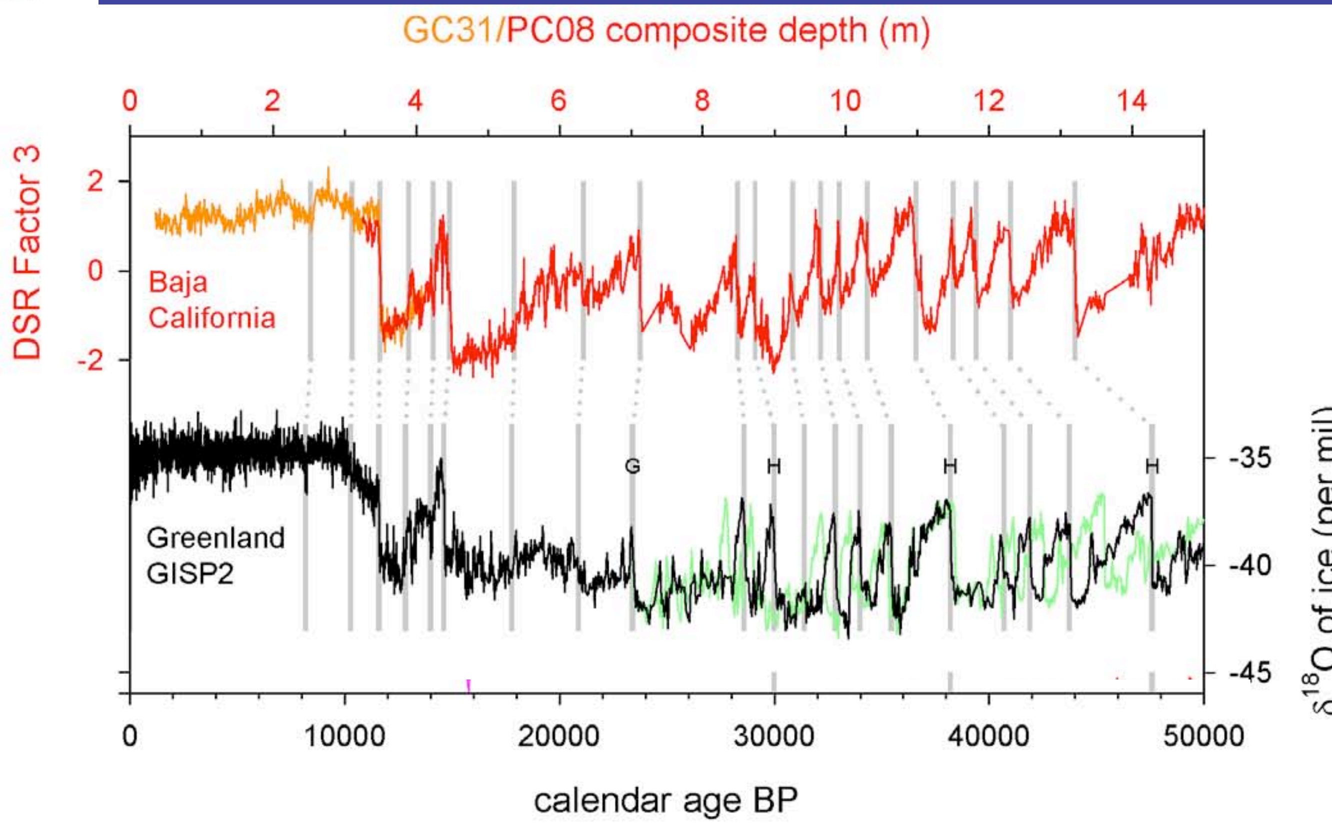


Baja CA core GC31/PC08 (705 mwd)

Baja sediments can be placed on "Greenland" timescale and benthic (i.e. bottom water) $\Delta^{14}C$ estimated

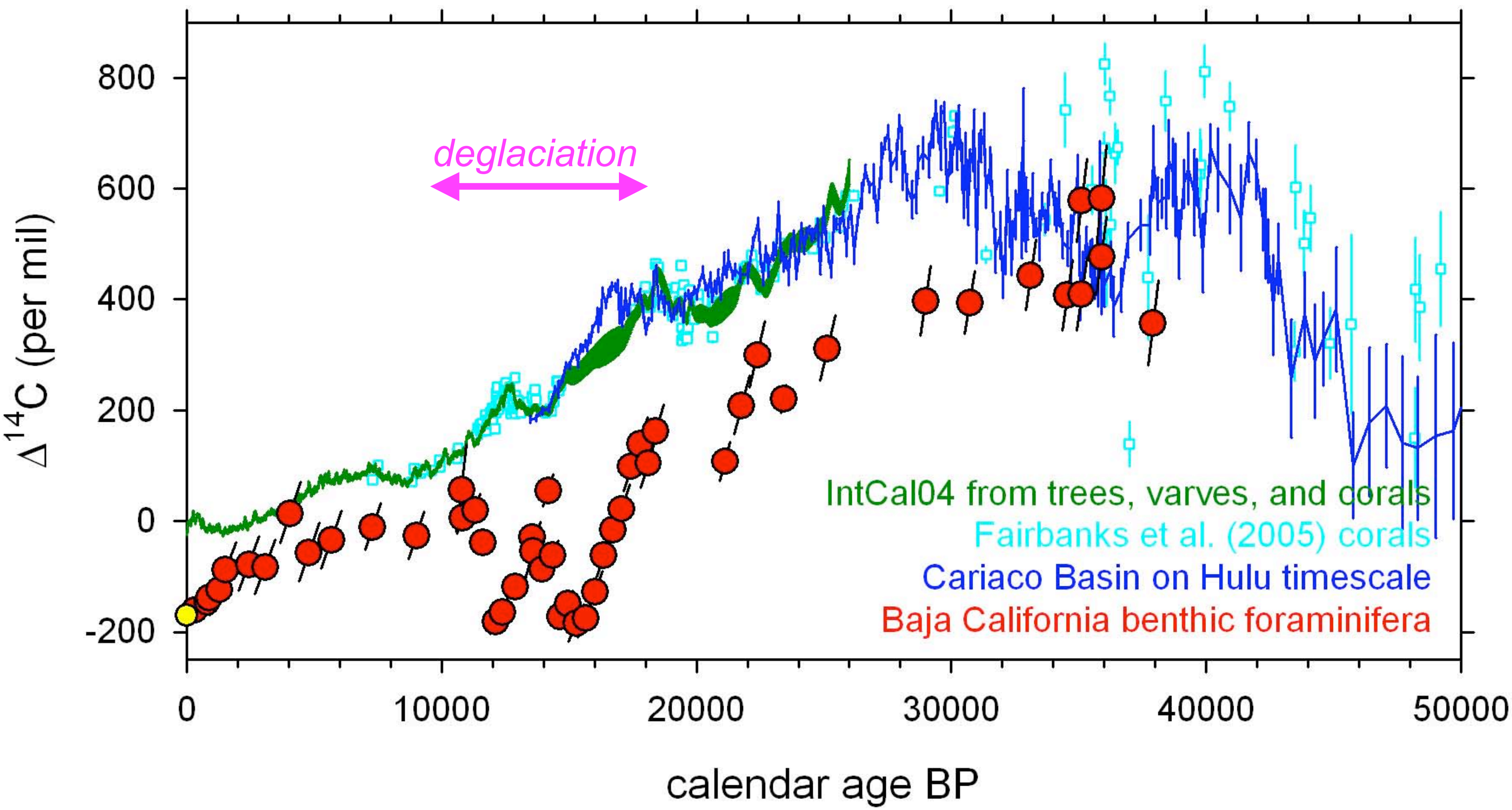
(similar to Cariaco planktic strategy)

- 23.5°N, 111.6°W
- 705 m water depth
- open margin
- O_2 minimum zone
- ~30 cm/kyr



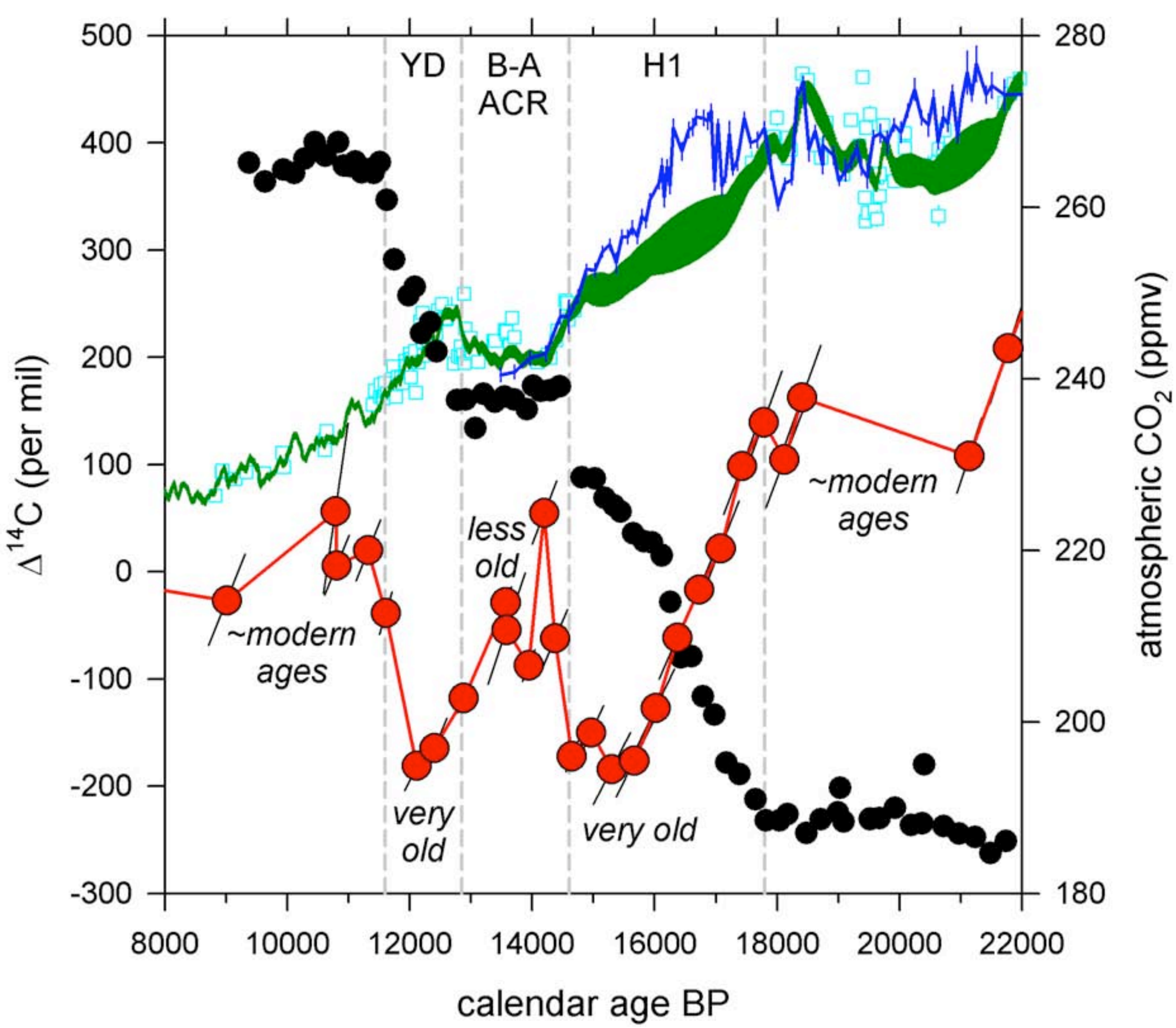
Baja California intermediate water $\Delta^{14}C$ v. "ATM"

- extremely ^{14}C-depleted waters during *deglaciation*
- up to 4 kyr old if projected back to atmosphere along decay curve
- similar to age of presumed deep, old reservoir



$\Delta^{14}C$ traces ocean's CO_2 release

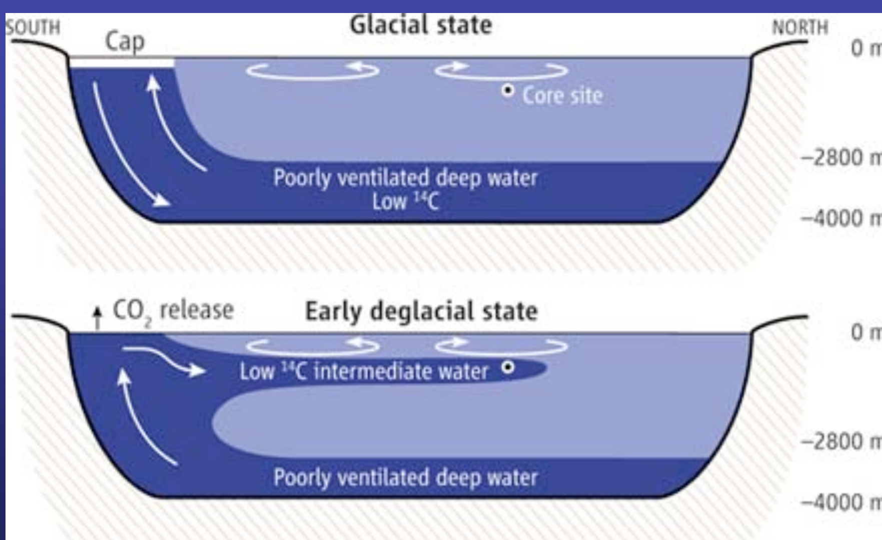
- very old intermediate waters during two CO_2 increases
- partial relaxation during Antarctic Cold Reversal
- coincides with main parts of the atmospheric $\Delta^{14}C$ drop



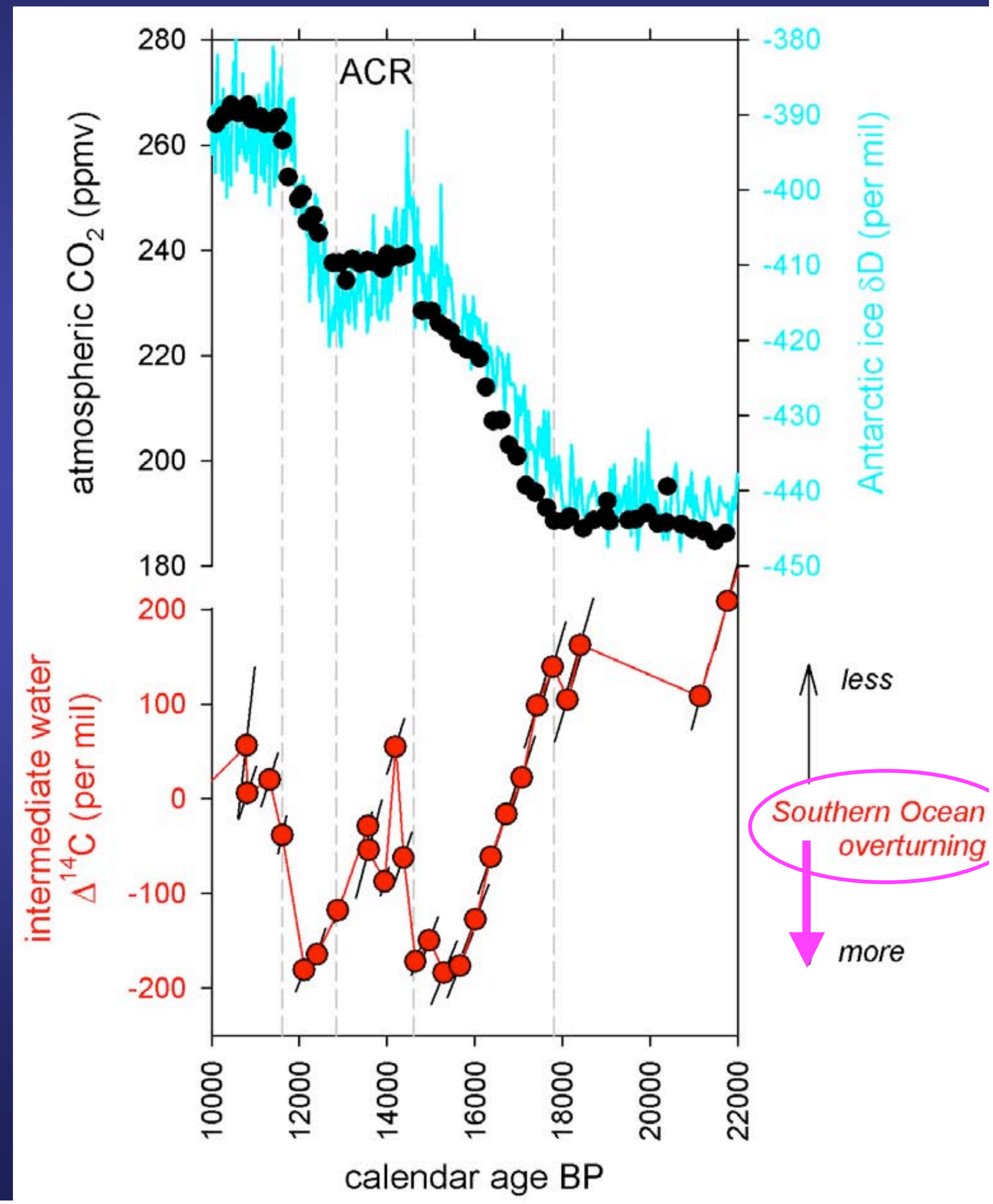
link with Southern Ocean deep convection

- LGM: expanded sea ice, poor ventilation, CO_2 'leak' capped

- deglaciation: sea ice retreat, deep convection/upwelling
- simultaneous warming and release of CO_2
- temporarily interrupted by Antarctic Cold Reversal



Keeling (2007) *Science* Perspective

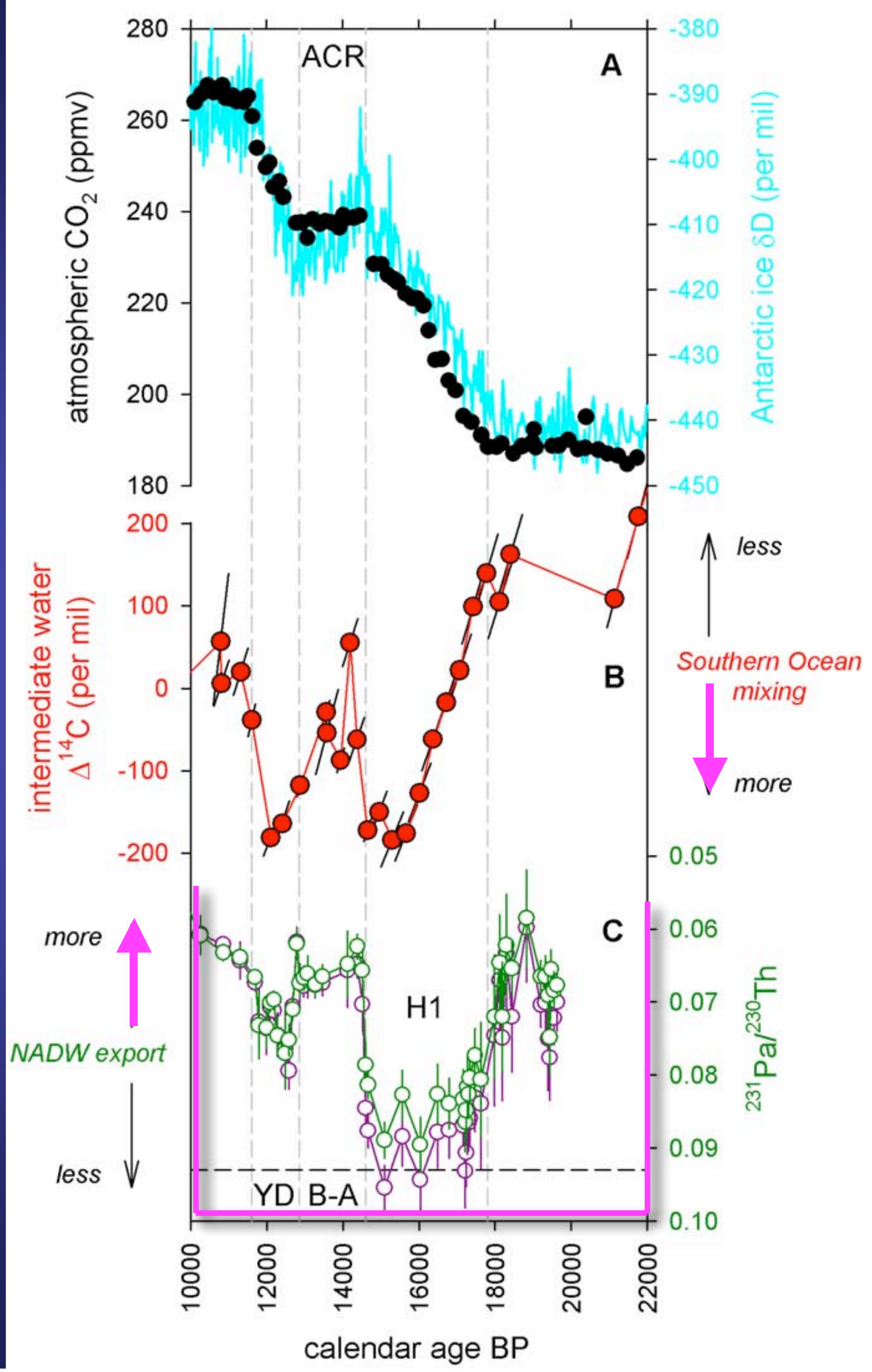


link with North Atlantic Deep Water export

- NADW ‘shutdown’ inferred from $^{231}Pa/^{230}Th$ (during *Heinrich event 1*; reduction during *Younger Dryas*)
- CO_2 release / increased Southern Ocean ventilation correspond closely w/ NADW reductions

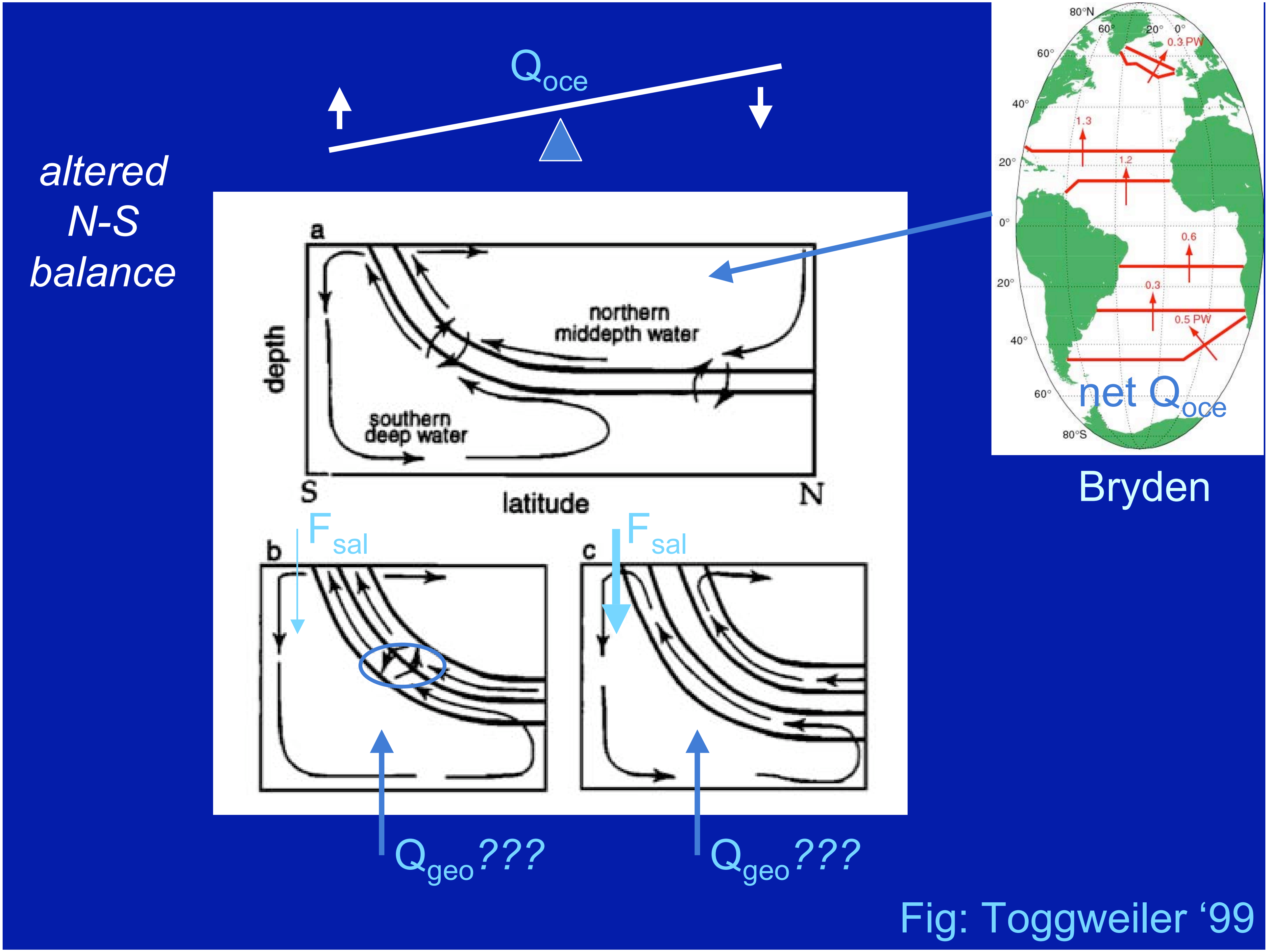
- tight N-S coupling
- ↑overturning in Southern Ocean as *response* to reduced NADW?
- bipolar seesaw warming, sea ice retreat?
- deep water formation required to balance global deep upwelling?

Pa/Th from McManus et al. (2004) *Nature*



conclusions

- atmosphere and intermediate water $\Delta^{14}C$ reconstructions *require* substantially reduced ventilation of deepest ocean during glacial
- deglacial atmospheric CO_2 and $\Delta^{14}CO_2$ change is likely associated w/ improved ventilation of the Southern Ocean (6x according to some geo-chemical model constraints)
- ventilation histories of Southern Ocean and North Atlantic are inversely (and v. tightly) coupled
- and….


altered N-S balance
Q_{oce}
a
depth
northern middepth water
southern deep water
S
latitude
N
b
c
F_{sal}
F_{sal}
Q_{geo}???
Q_{geo}???
80°N
60°
20°
0°
0.3 PW
40°
1.3
1.2
0.6
0.3
0.5 PW
80°S
net Q_{oce}
Bryden
Fig: Toggweiler '99

data slides lacking citations are from the following papers:

Marchitto, T.M.*, Lehman S, J.*, Ortiz, J.D., Flueckiger, J., & A. van Geen. (2007). Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO_2 rise. Science 316: 1456-1459.

Hughen, K., Southon, J., Lehman, S.J., C. Bertrand, and J. Turnbull (2006). Updated Cariaco Basin ^{14}C Calibration and Activity Record of the Past 50,000 Years. Quaternary Science Reviews, doi:10/1016/j.quascirev.2006.03.014.

Hughen, K.A., Lehman, S.J., Southon, J.R., Turnbull, J., Marchal, O. and J.T. Overpeck (2004). ^{14}C activity and carbon cycle changes over the past 50,000 years. Science 303: 202-7.

Hughen, K.A., Southon, J.R., Lehman, S.J., and J.T. Overpeck (2000). Synchronous radiocarbon and climate shifts during deglaciation. Science 290: 1951-54.

Hughen, K., Overpeck, J., Lehman, S.J., Kashgarian, M., Peterson, L.C., Alley, R. and D.M. Sigman (1998). Deglacial changes in ocean circulation from an extended ^{14}C calibration. Nature 391: 65-68.