Ice age deep ocean circulation and atmospheric CO_2

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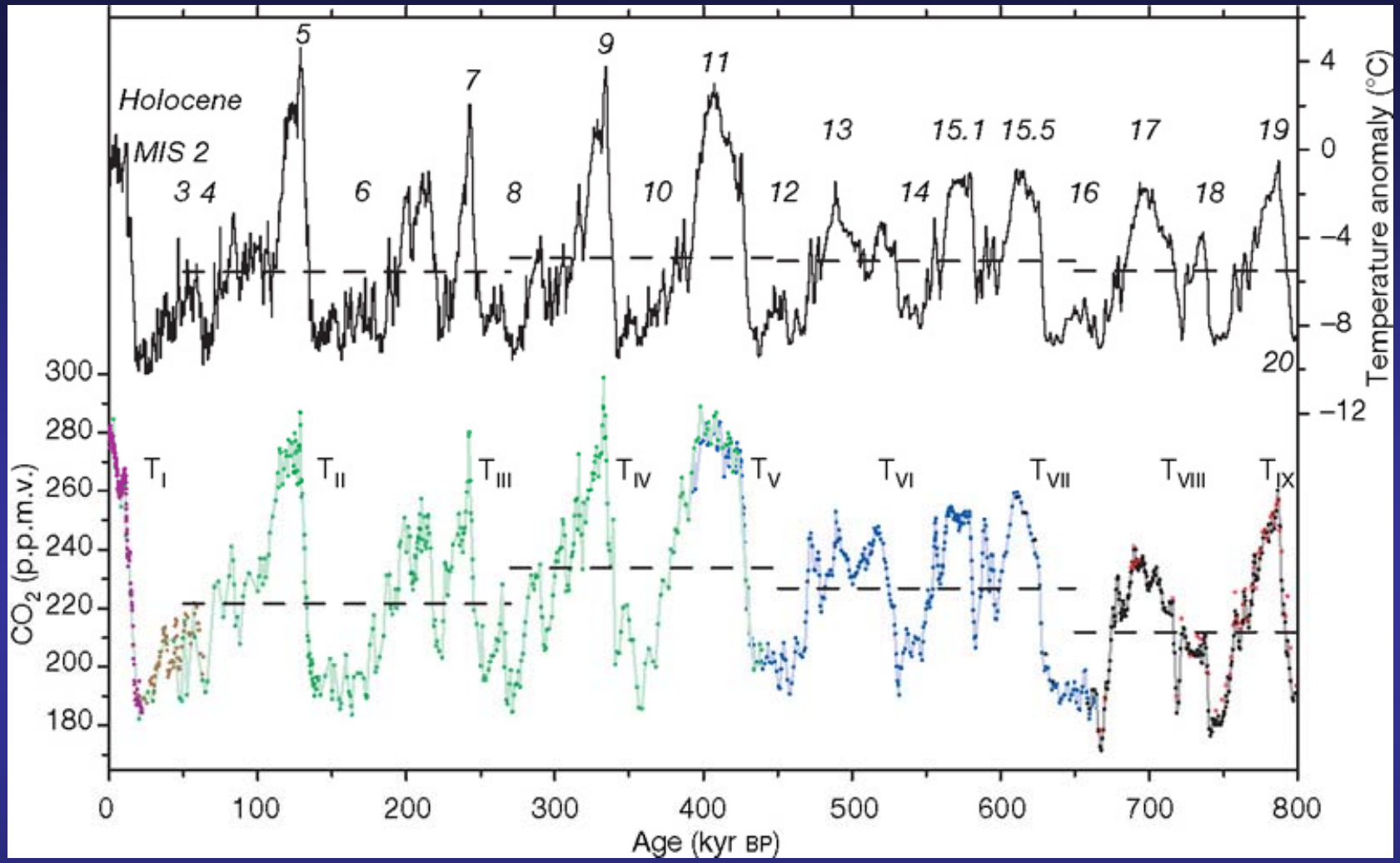


Lüthi et al. (2008) *Nature*

Atmospheric CO_2 (EPICA Dome C)

- scales closely with Antarctic temperature (and global ice volume)
- *challenge:* why do these records look so similar?
- implies a common forcing

Earth's pre-industrial carbon reservoirs

Glacial atmospheric lowering requires storage in another reservoir

("Everybody's gotta be somewhere" – Dean Martin)

smaller during LGM (source)

Atmosphere: 600 PgC

Surface ocean: 1000

Deep ocean: 38,000

Terrestrial: 2200

Seds+crust: 80,000,000?

major glacial sink

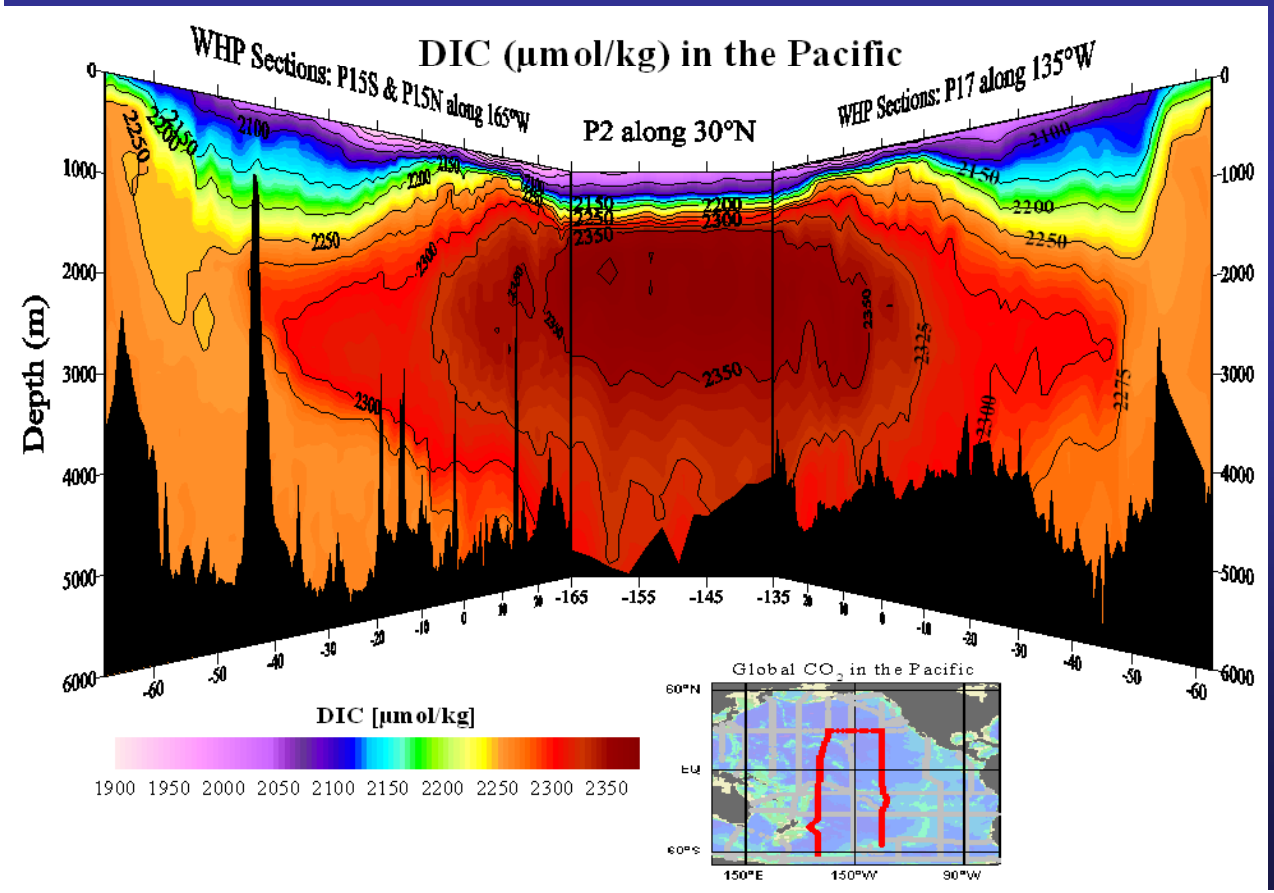
positive feedback (kyr)

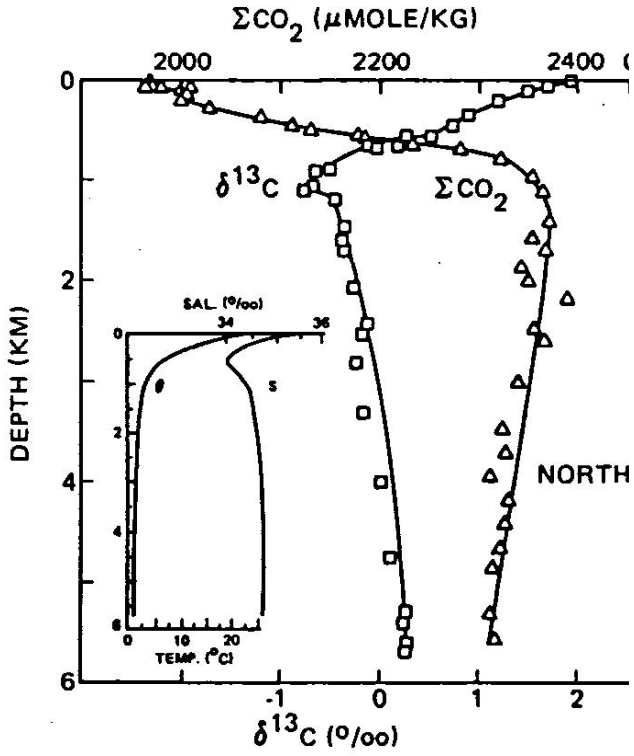
too slow (Myr)

$$pCO_2 = [CO_2(aq)] / K_0$$

Dissolved inorganic carbon stable isotopes ($\delta^{13}C$)

- biological pump depletes surface DIC, enriches deep sea
- since algae preferentially use $^{12}CO_2$, $\delta^{13}C$ follows an inverse pattern
- *air-sea exchange also enriches DIC $\delta^{13}C$*
- DIC max ($\delta^{13}C$ min) is found in modern deep North Pacific (dead end)
- deep upwelling in the Southern Ocean and productivity is limited: CO_2 leak

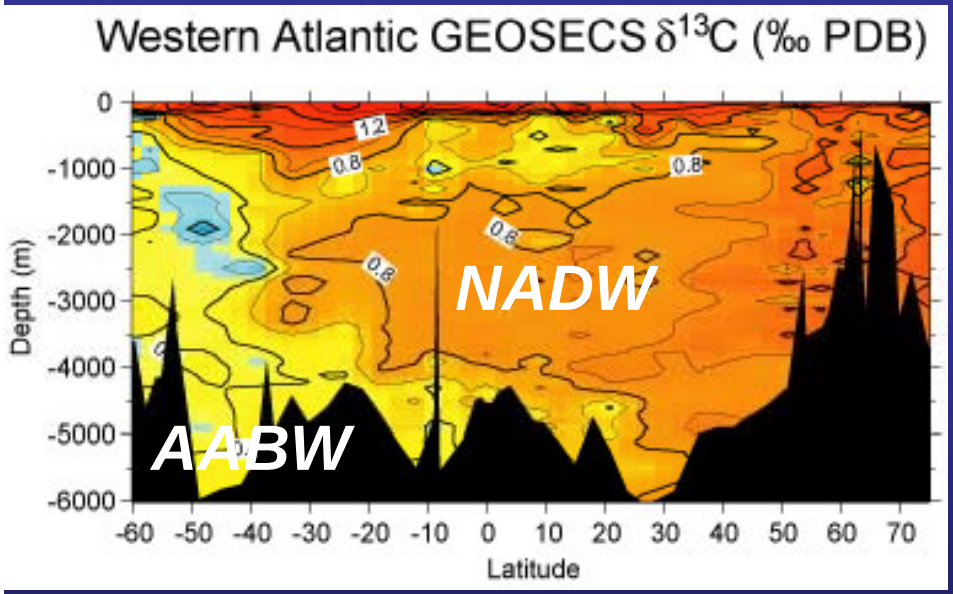


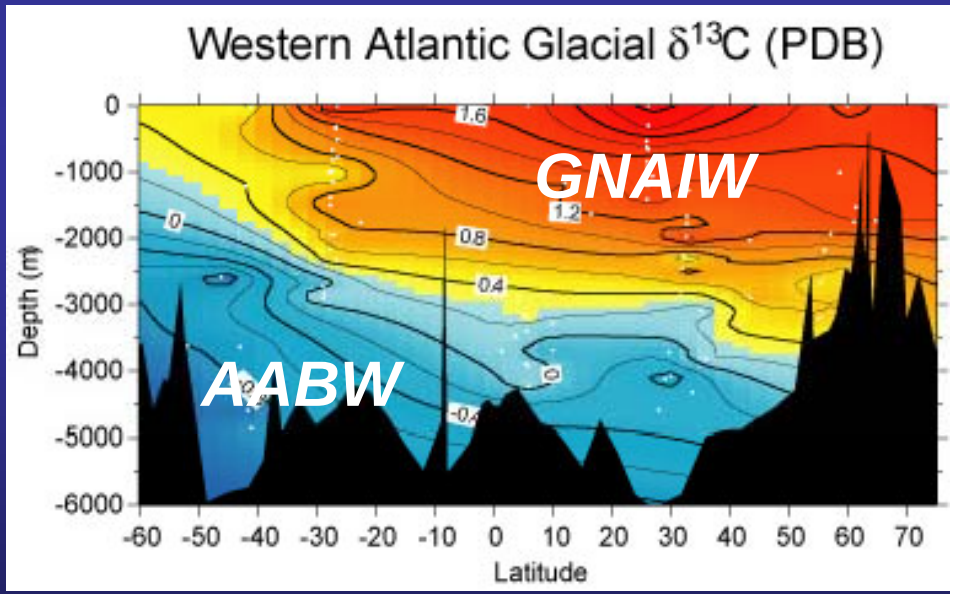


Kroopnick (1985) *DSR*

Benthic foraminiferal $\delta^{13}C$ in the Atlantic

- modern: high-$\delta^{13}C$ (low-DIC) NADW dominates
- LGM: high-$\delta^{13}C$ GNAIW overlying *very low-$\delta^{13}C$ AABW*
- Southern Ocean was most depleted water mass in LGM ocean
- implies LGM deep Southern Ocean accumulated carbon via remineralized organic matter, and/or had poor contact with the atmosphere



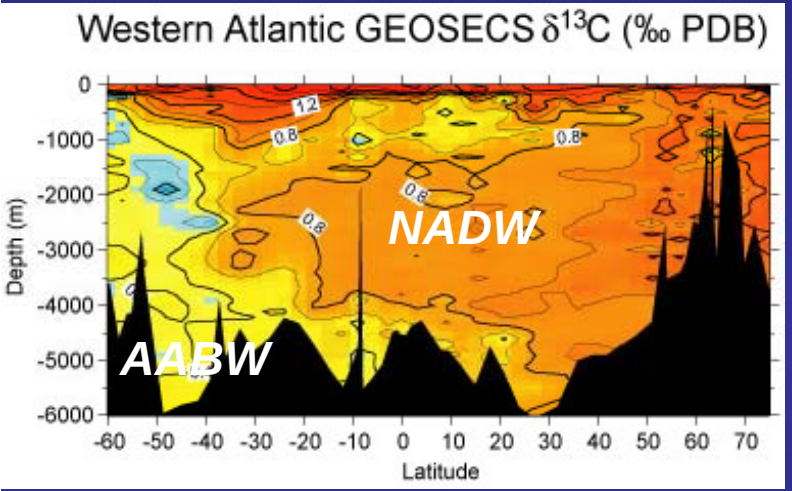


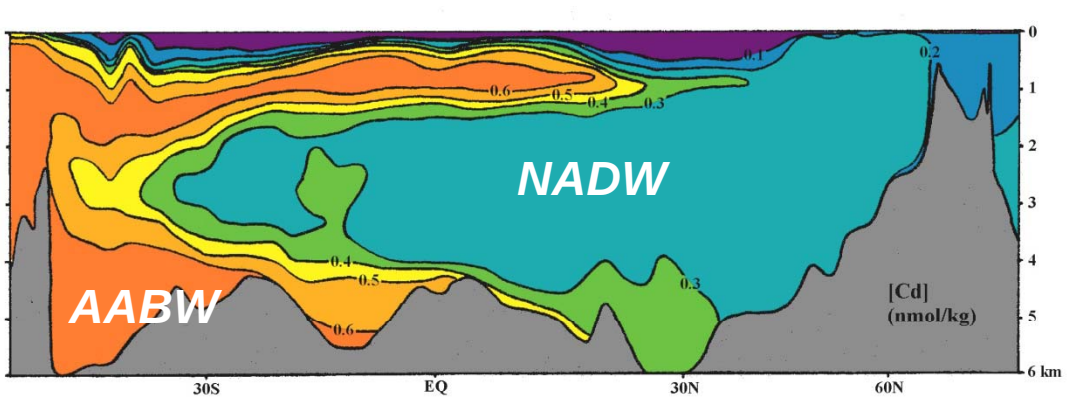
Curry and Oppo (2005) *Paleoceanography*

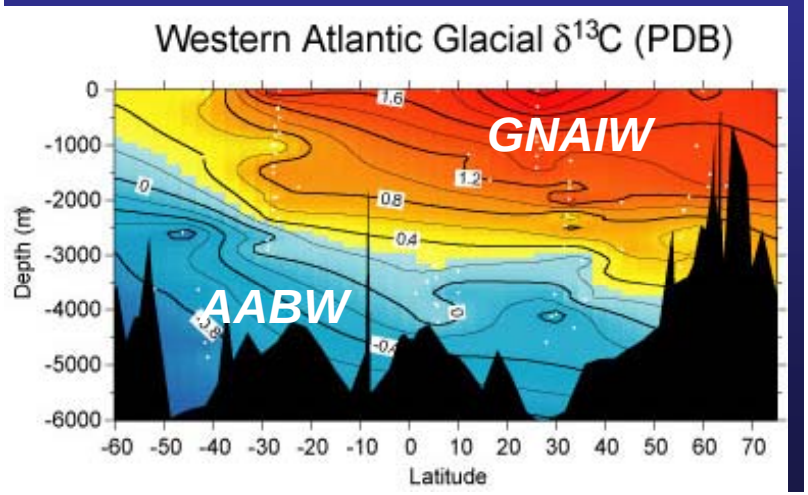
Air-sea component of $\delta^{13}C$ from comparison to Cd

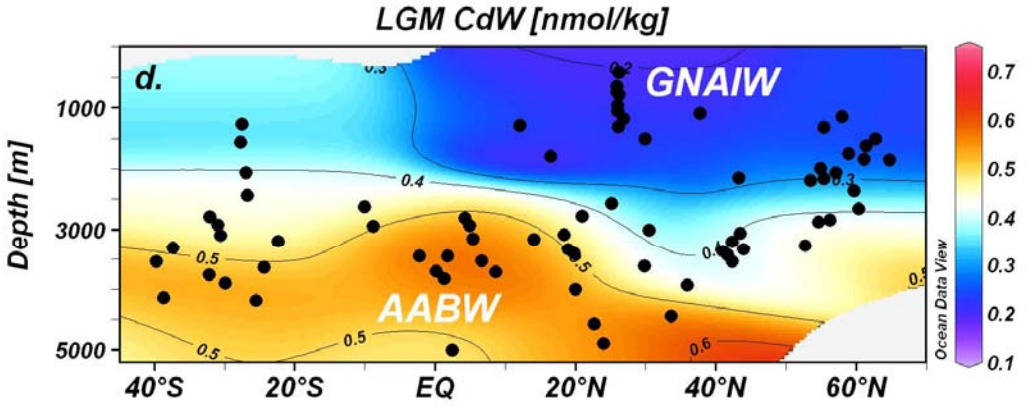
- dissolved Cd behaves like the nutrient phosphate
- should vary inversely with $\delta^{13}C$ except for air-sea exchange
- LGM Atlantic benthic Cd/Ca is broadly similar to $\delta^{13}C$

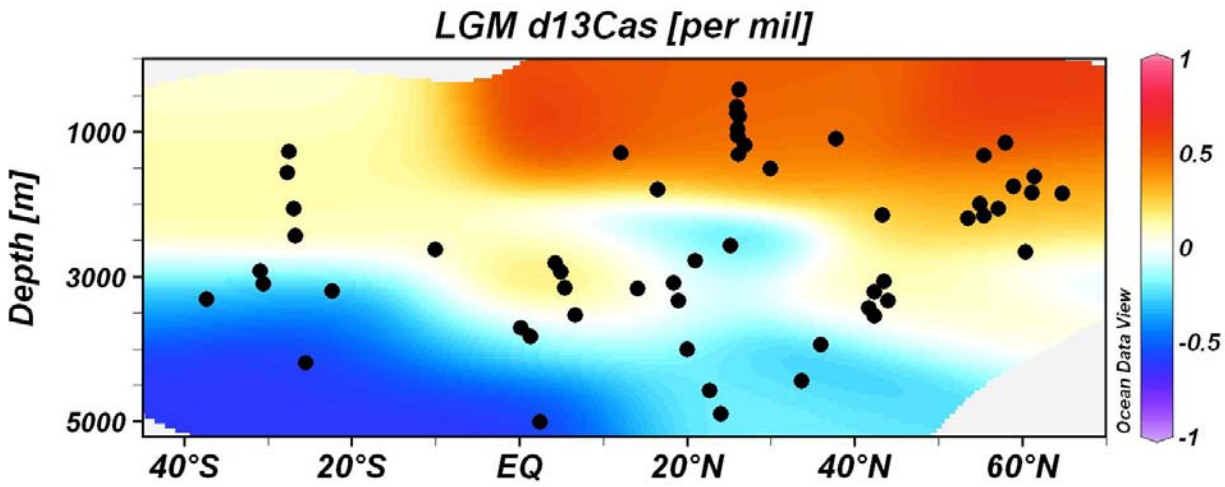
Marchitto and Broecker (2006)







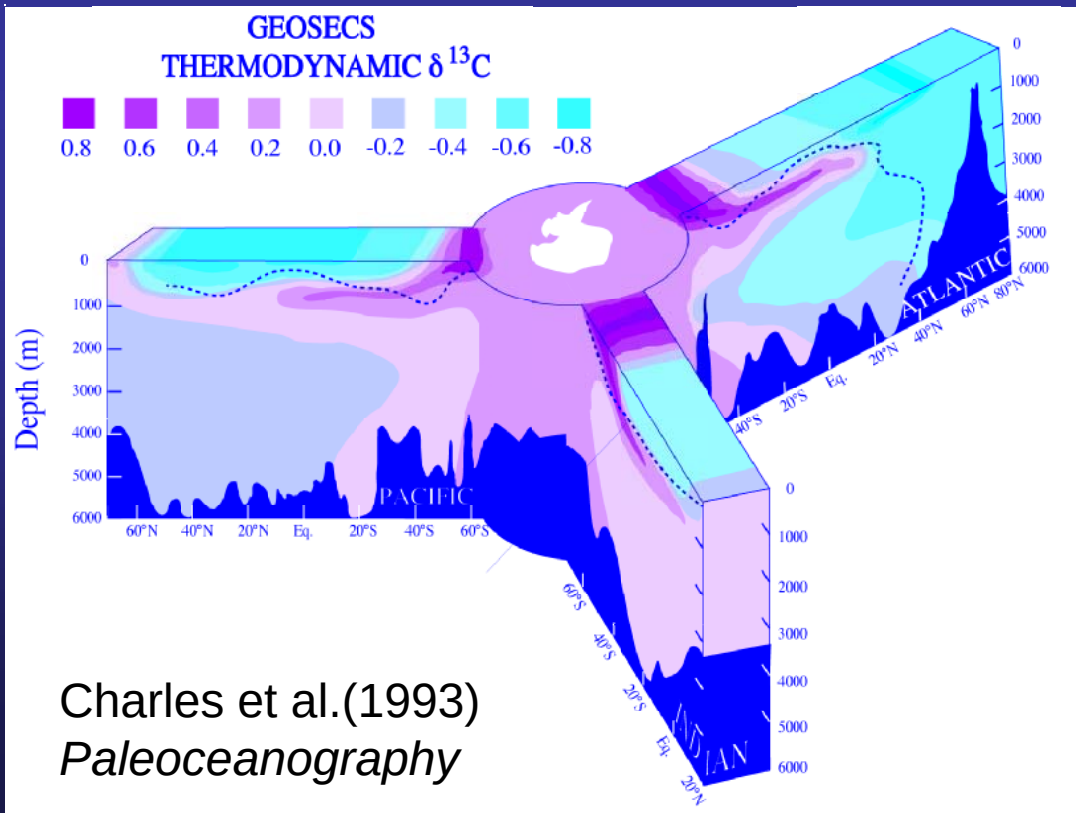




Marchitto and Broecker (2006) *G-Cubed*

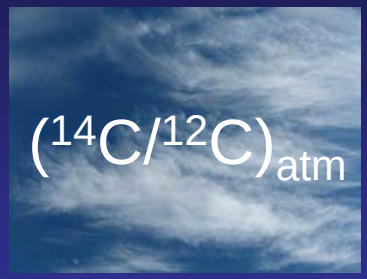
- LGM AABW: lower $\delta^{13}C$ than expected from Cd: low $\delta^{13}C_{as}$
- modern AABW: high $\delta^{13}C_{as}$
- suggests poorer air-sea contact during LGM

- what can we learn from ^{14}C?



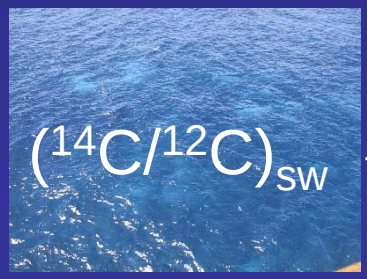
Charles et al.(1993) *Paleoceanography*

Reconstructing past $\Delta^{14}C$ distributions


$(^{14}C/^{12}C)_{atm} \rightarrow$

$(^{14}C/^{12}C)_0 \rightarrow$ time $\rightarrow$

$(^{14}C/^{12}C)_{meas}$


$(^{14}C/^{12}C)_{sw} \rightarrow$

$(^{14}C/^{12}C)_0 \rightarrow$ time $\rightarrow$

$(^{14}C/^{12}C)_{meas}$

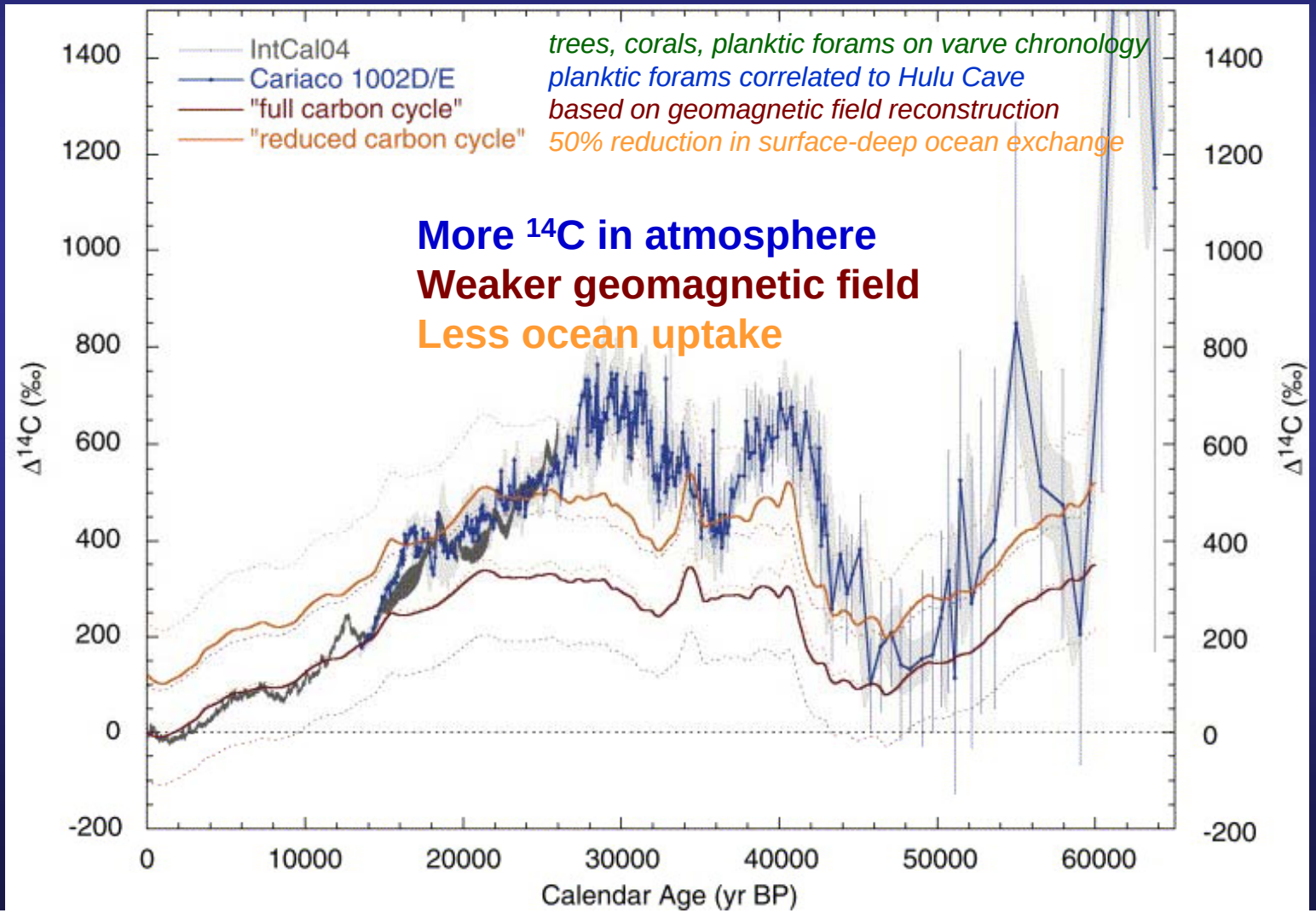
- ^{14}C beta decays with half life of 5730 yr (Godwin, 1962)
- decay equation: $(^{14}C/^{12}C)_{meas} = (^{14}C/^{12}C)_0 e^{-\lambda t}$

- *dating:* solve for t using an assumed value for $(^{14}C/^{12}C)_0$

- *tracer:* if t is known independently, can solve for $(^{14}C/^{12}C)_0$
- can use this method to reconstruct paleo-$\Delta^{14}C$ of the atmosphere or ocean

Atmospheric $\Delta^{14}C$ reconstruction

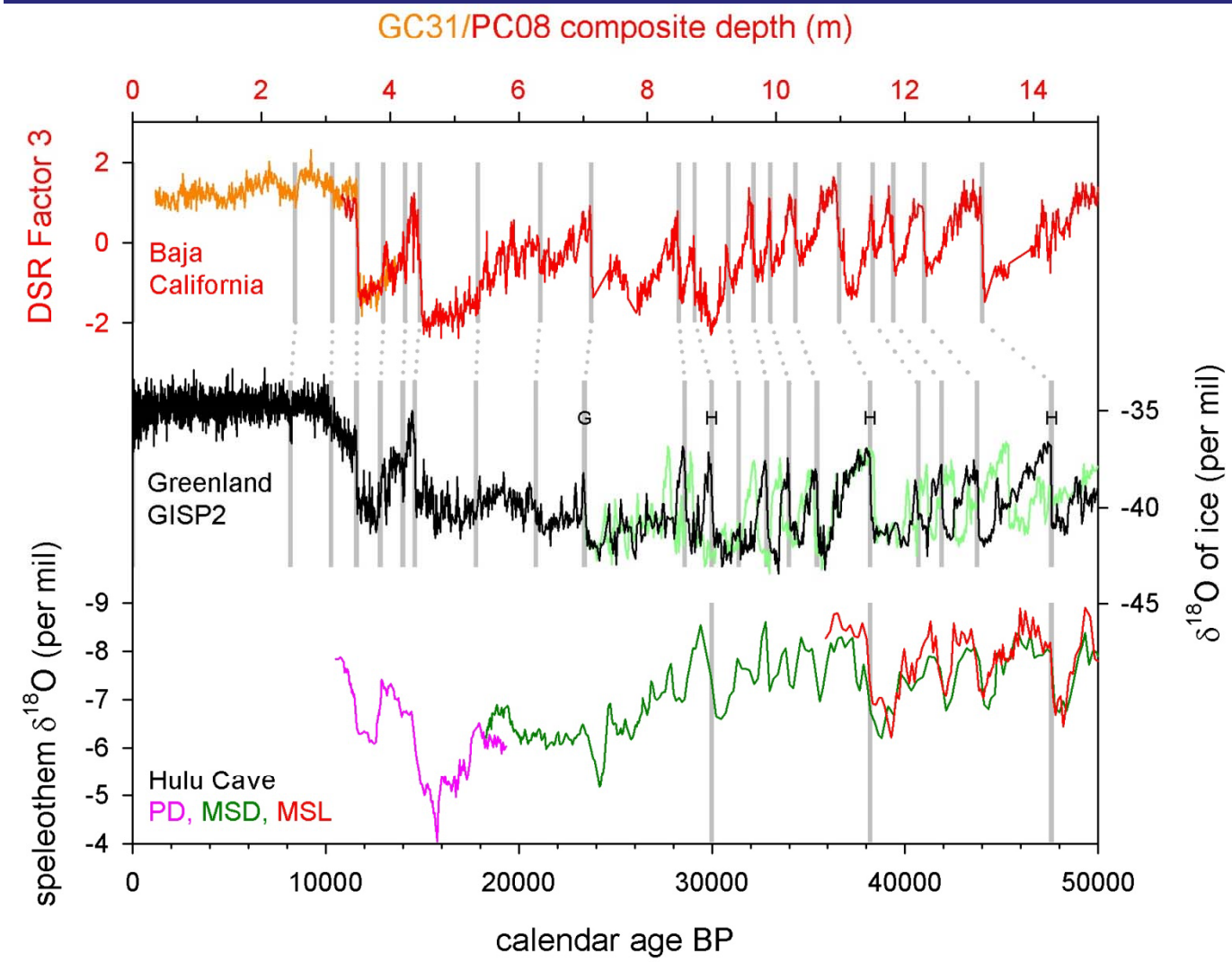
- glacial $\Delta^{14}C$ was higher than predicted from a weaker geomagnetic field
- necessitates a “smaller” carbon cycle (less ocean uptake)
- requires $\Delta^{14}C$ depletion in the deep ocean *(elusive)*

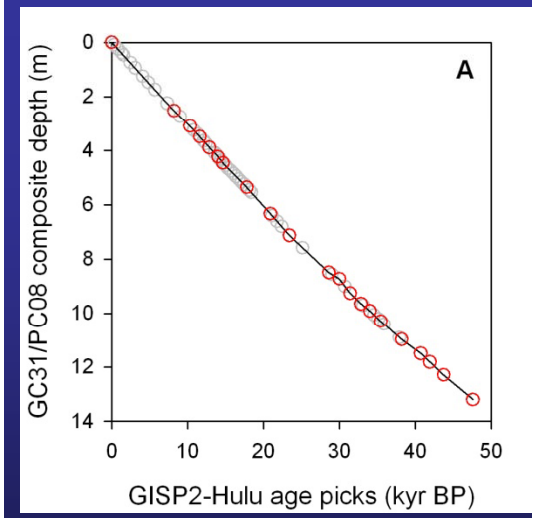


Hughen et al. (2006) *QSR*

Intermediate-depth (Baja Calif.) $\Delta^{14}C$ reconstruction

- like other low-latitude records, reflectance displays clear "Greenland pattern"
- t established through 21 tie points to GISP2 $\delta^{18}O$ record
- aided by a high and very constant sedimentation rate (30 cm/kyr)

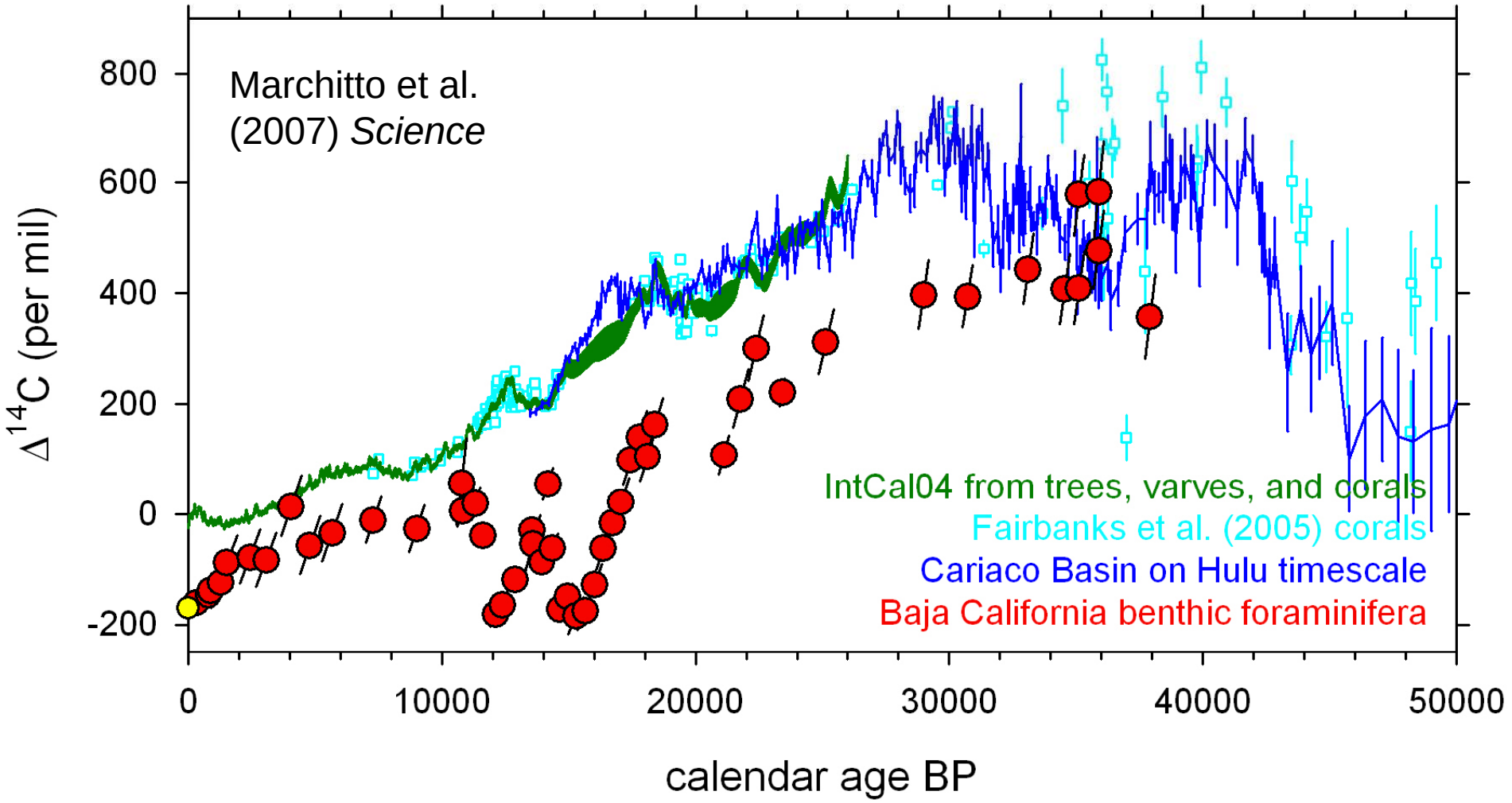




Marchitto et al. (2007) *Science*

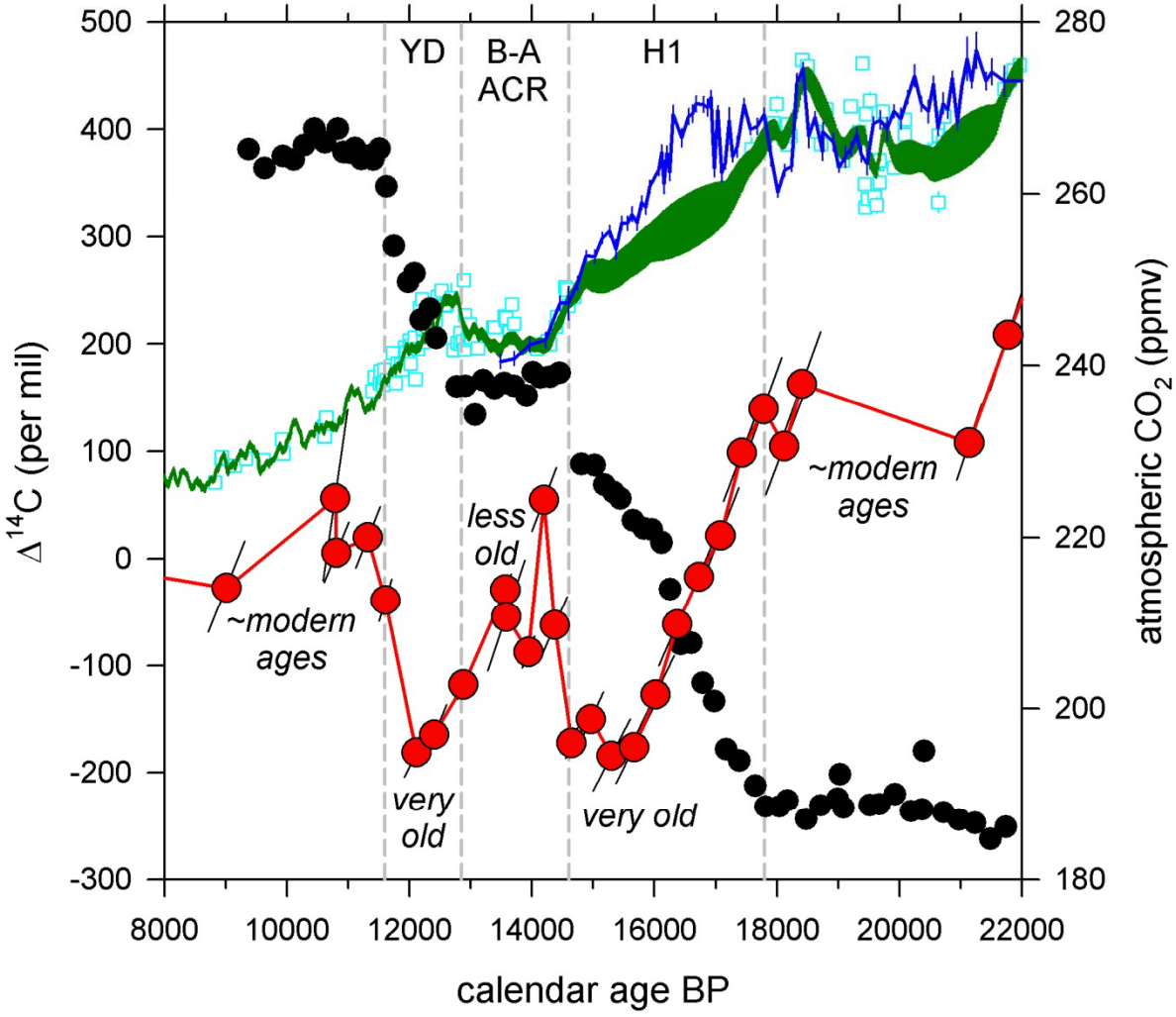
Results: Baja California intermediate water $\Delta^{14}C$

- 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



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

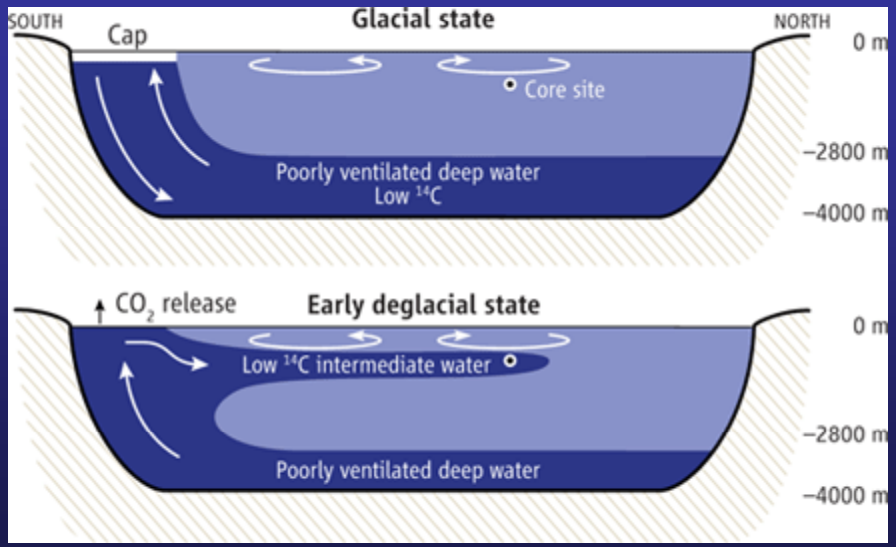
- very old intermediate waters during two CO_2 increases
- partial relaxation during Antarctic Cold Reversal
- coincides with main parts of the atmospheric $\Delta^{14}C$ drop



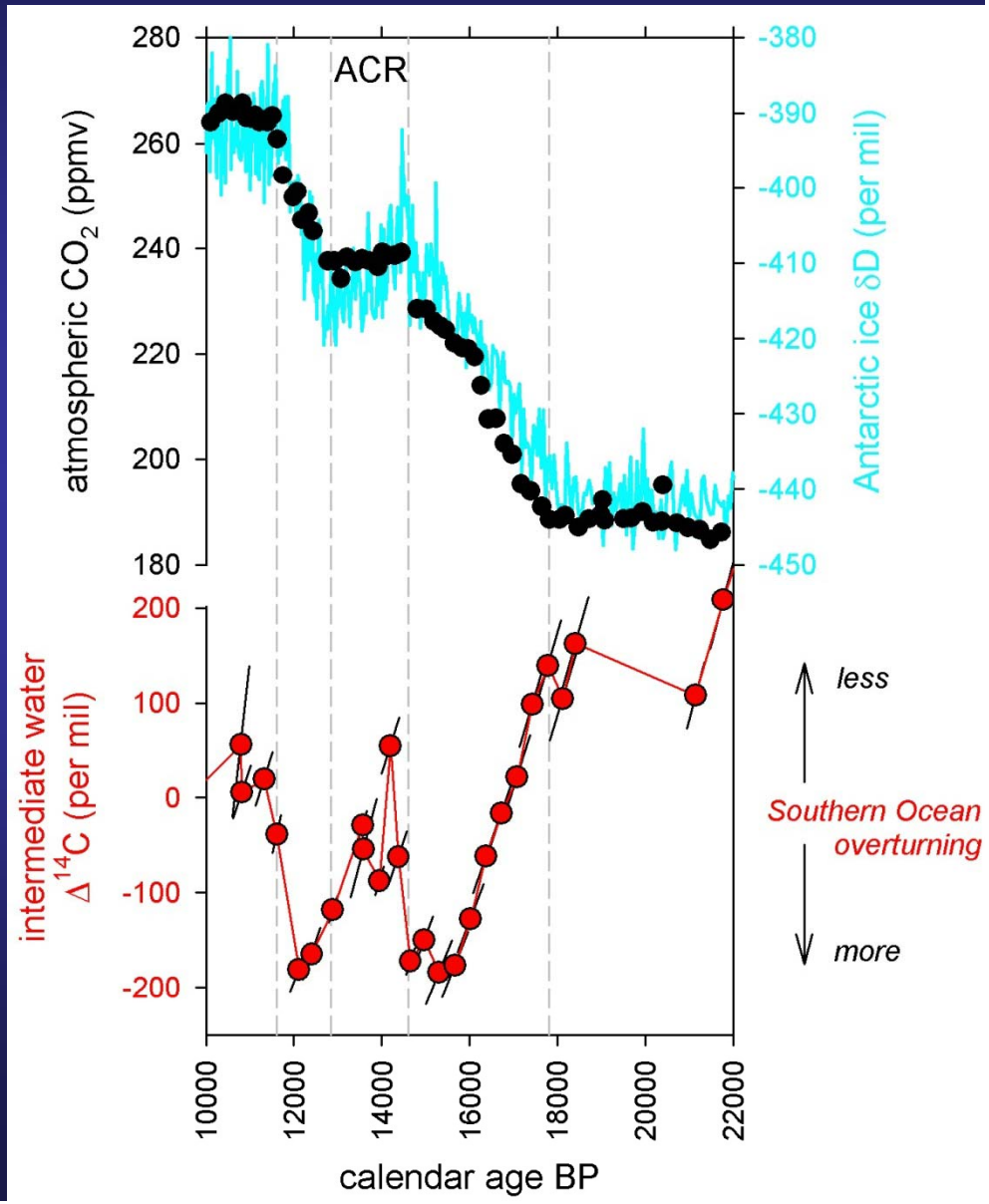
Marchitto et al. (2007) *Science*

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 old CO_2
- temporarily interrupted by Antarctic Cold Reversal



Keeling (2007) *Science* Perspective

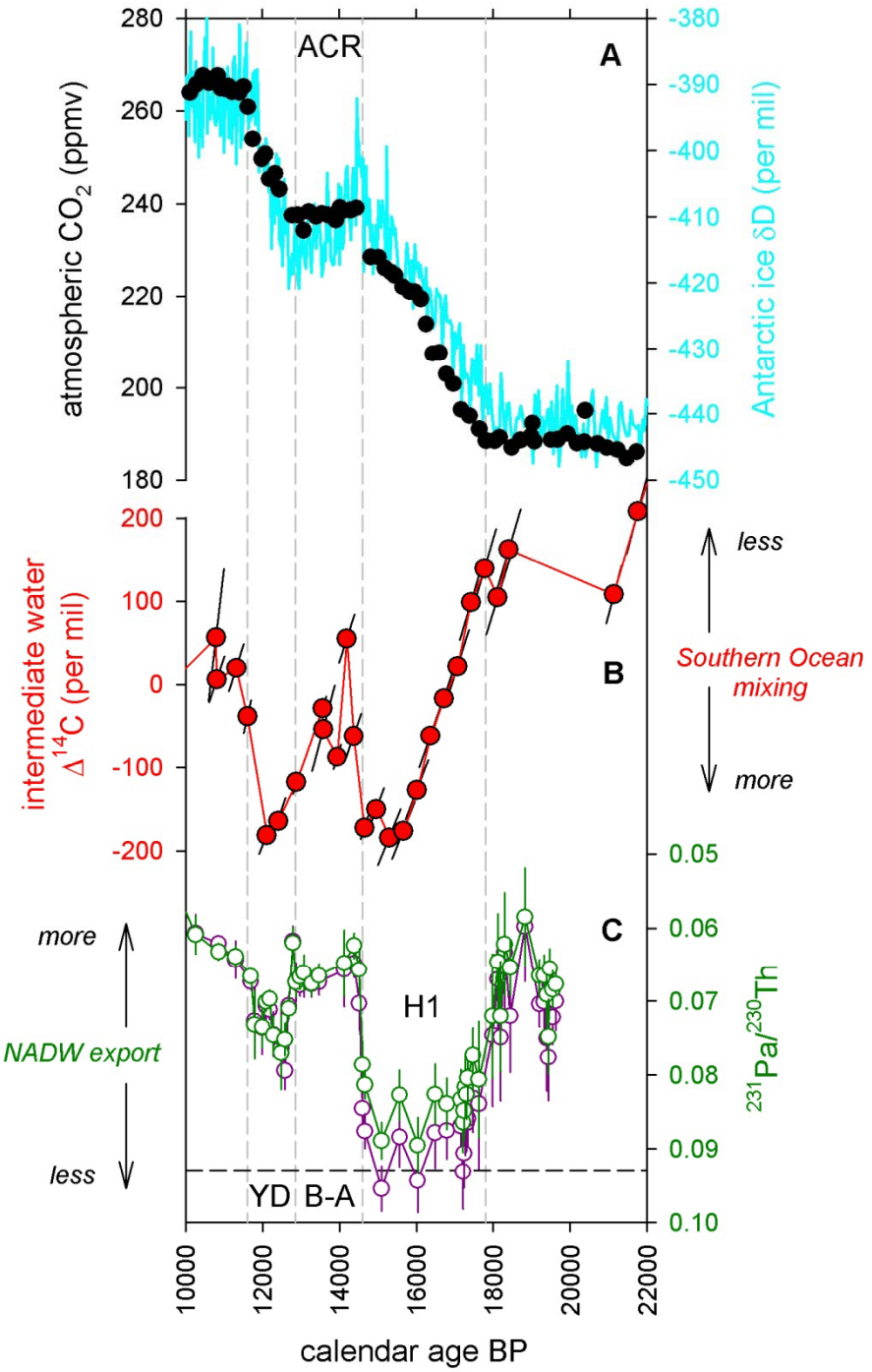


Link with North Atlantic deep convection

- NADW 'shutdown' inferred from $^{231}Pa/^{230}Th$ during Heinrich event 1; reduction during Younger Dryas
- old CO_2 releases closely correspond to NADW reductions

- overturning in Southern Ocean as *response* to reduced NADW?
- bipolar seesaw warming, sea ice retreat, westerly contraction?
- deep water formation required to balance global deep upwelling?

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



Two take-home points

- ^{13}C and Cd/Ca suggest the ice age deep ocean was more poorly ventilated, especially around Antarctica

- ^{14}C depletion of intermediate waters during deglaciation appears to track the release of ‘old’ carbon sequestered in the deep sea, possibly triggered from the North Atlantic

Challenges

- map the deglacial ^{14}C events using other intermediate depth cores: Arabian Sea, southern Chile

- find the old, deep glacial reservoir

- better incorporate biogeochemical tracers into numerical models