$^{14}$C constraints on the glacial-age ocean circulation and mechanism of deglacial CO$_2$ rise

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and

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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?
$^{14}\text{C}$ is cosmogenic,

\[ ^1n_0 + ^{14}\text{N}_7 \rightarrow ^{14}\text{C}_6 + ^1\text{H}_1 \]

and weakly radioactive,

\[ ^{14}\text{C}_6 \rightarrow ^{14}\text{N}_7 + \beta^- + \bar{\nu} + Q \]

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

and abundance today of

$1.176 \times 10^{-12} \ (^{14}\text{C}/\text{C})$
incorporation of $^{14}\text{C}$ into global carbon cycle

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

$^{14}\text{C}^* + \text{O}_2 \rightarrow ^{14}\text{CO} + \text{O}$

$^{14}\text{CO} + \text{OH} \rightarrow ^{14}\text{CO}_2 + \text{H}$
Basic assumption of $^{14}\text{C}$ dating:

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

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

where $\lambda = \text{decay constant or } 1/8033 \text{ yr}$

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

and

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

geomagnetic field variations ($>10^3$ yr)

greater field strength $\rightarrow$ less production

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

greater intensity $\rightarrow$ less production

redistribution amongst reservoirs
Bard et. al. ‘91 U-dated corals

is a more complete calibration likely to be “linear”? and….
what might derived “initial $^{14}C$” tell us about the Earth system?
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
initial $^{14}$C activity

$\Delta^{14}$C $\% = [(F_m e^{\lambda t}) - 1] \times 1000$

Cariaco

trees

“SWAG”

calendar age (yr BP)
$^{14}$C vs. climate

$\Delta ^{14}$C detrended (‰)

Cariaco Basin calendar age (yr BP)

YD
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:

- $P = \sim 500$ mole $^{14}$C/yr
- 500 GTC
- 1000 GTC
- 36 GTC/yr
- 38000 GTC
extended $^{14}$C calibration

having demonstrated Cariaco and Greenland climate changes synchronous, extend calibration through longer record of discontinuously laminated sediments
ODP 1002 / GISP2 correlation of Peterson et. al.

% Reflectance

1002C

GISP2

GISP2 age (cal kyr BP)

layer counts end
calibration results

Cariaco (1 sigma error)
Suigetsu varves
Bahaman speleothems
reconstructed $^{14}$C activity

- Cariaco (1 sigma error)
- Bard corals
- INTCAL/58PC
geomagnetically modulated production

$^{14}$C production (mol/yr)

NAPIS75 intensity production (error)

relative dipole strength ($I/I_0$)

$^{14}$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. $\pm 100\%$ 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

2200 GTC

1000 GTC

CaCO₃ Seds
~ 1 GTC/y

38000 GTC

36 GTC/y

GLACIAL CARBON CYCLE

< Atm 210 ppm pCO₂

< Bio/Soils

< Shallow CaCO₃ Seds

< Deep ventilation
a smaller glacial carbon cycle?
deglacial reorganization?

![Graph showing atmospheric Δ^14C (%o) over GISP2 age (yr BP). The graph has a time scale from 0 to 50,000 years before present (yr BP) and a Δ^14C axis ranging from -200 to 800‰. The graph highlights different periods labeled H0, H1, H2, H3, and H4.](image)
Broecker issues:

implies more deep ocean aging than observed
implausibly steep
ATM $^{14}$C and CO$_2$ histories similar

$^{14}$C-depleted deep ocean is source of atm. CO$_2$ rise

CO$_2$ from Monnin et. al. '01
$\delta^{18}D$ per mil vs. CO$_2$ ppmv in Antarctic climate. Monnin et al. ‘01
venting of ocean CO$_2$ thru the Southern Ocean

WOCE/JGOFS CO$_2$ survey: sDIC [μmol kg$^{-1}$]

compilation of Gruber
from Adkins ('02) pore fluid $\delta^{18}O$ and chlorinity
Southern Ocean “CO₂ window” closed during glacial

deep ocean CO₂ rises and ages (¹⁴C decay)
Pacific benthic-planktic $^{14}$C age differences

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
- $\sim$30 cm/kyr

[Graph showing depth and δ$^{18}$O over calendar age BP]
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
$\Delta^{14}\text{C}$ traces ocean’s $\text{CO}_2$ release

- very old intermediate waters during two $\text{CO}_2$ increases
- partial relaxation during Antarctic Cold Reversal
- coincides with main parts of the atmospheric $\Delta^{14}\text{C}$ 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

Fig: Toggweiler ‘99
data slides lacking citations are from the following papers:


