

timescale-controlled sea-level data with rebound predictions based on ice models linked to the ^{14}C scale. Yet this is what Bard *et al.* do.

A second difficulty with the conclusion of Bard *et al.* is the sea level during the last glacial maximum. Around 18,000–20,000 years ago, sea levels are generally believed to have been at about 130 m below their present level (although this depth will be regionally variable) and the Barbados coral data support this: the minimum depths at this time of the corals are about 120 m below present sea level. Ice models for the Laurentide and Fennoscandia that produce rebound at the centres of these ice sheets that are consistent with these observations of sea-level change within and near the ice-sheet margins contain only enough ice to raise sea level by 60–80 m (refs 5,7). Increasing the volumes in these ice sheets results only in implausible predictions of rebound at these sites unless the melting was initially very rapid. The Barbados sea-level curve from 18,000 to 6,000 years before present, however, argues against this, so it has been suggested that

this missing melt water has to come from other areas such as the Barents–Kara ice sheet in Antarctica, or possibly from eastern Siberia^{4–6}. Rather than negate the previously drawn conclusions about the importance of these centres of deglaciation, the Barbados results reinforce them.

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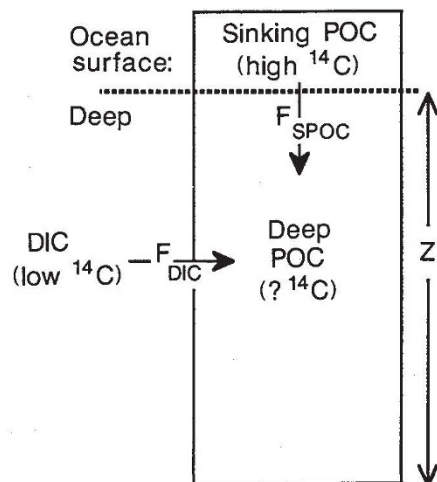
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Another recipe for bomb ^{14}C dilution

SIR — As recently pointed out by Druffel and Williams¹ and Toggweiler², the relatively low amount of atom-bomb-derived ^{14}C in deep-ocean particulate organic carbon (POC) has significant implications for the way carbon is cycled in the ocean's interior. Druffel and Williams conclude that the low $\Delta^{14}\text{C}$ found



Model of deep-ocean POC formation from dissolved inorganic carbon (DIC) and sinking POC sources. Within the deep ocean, sinking and suspended POC are not differentiated. F_{SPOC} , areal flux rate of sinking POC through the surface/deep ocean boundary; F_{DIC} , areal flux rate (uptake) of deep DIC into POC.

in POC suspended in the deep ocean is probably the result of dilution by incorporation of ^{14}C -depleted dissolved organic carbon (DOC) into deep POC. As well as DOC→POC transformations, I wish to point out that dissolved inorganic carbon (DIC) is another large carbon source for such

dilution, and that the conversion rate of DIC to POC in the deep sea is quantitatively, and therefore isotopically, important.

Let us assume that the only source of non-bomb carbon in the deep ocean is DIC, and that deep POC must therefore originate from some combination of this source and ^{14}C -rich sinking POC (see figure). If we know the fluxes and $\Delta^{14}\text{C}$ of these sources, the $\Delta^{14}\text{C}$ in POC resident in the deep ocean can be calculated. Although it has been assumed¹ that uptake of DIC into POC is negligible in the deep sea, Sorokin reported³ uptake rates ranging from 0.5 to 3 $\mu\text{g C m}^{-3} \text{d}^{-1}$ at depths greater than 1 km in the central Pacific Ocean. Such rates are indeed minuscule when compared to those in surface waters, but they become significant when integrated over depth and compared with the sinking POC flux into the deep ocean. Using a mean deep-ocean DIC uptake rate of 2 $\mu\text{g C m}^{-3} \text{d}^{-1}$, the estimated areal flux rate of DIC into POC (10 $\text{mg C m}^{-2} \text{d}^{-1}$) equals the sinking POC flux into deep water in the north central Pacific Ocean (see table). This yields an estimated deep POC $\Delta^{14}\text{C}$ of -52‰ (see table), even more depleted in bomb ^{14}C than actually observed¹ ($> 43\text{‰}$), indicating the potential importance of the DIC → POC pathway in effecting ^{14}C dilution in the deep sea.

In the Santa Monica Basin, a greater flux (30 $\text{mg C m}^{-2} \text{d}^{-1}$) of POC sinking into a shallower aphotic zone could be viewed as less advantageous for dilution of bomb ^{14}C in deep POC. But aphotic DIC→POC conversion in such basin environments ranges from < 1 to 24 $\text{mg C m}^{-3} \text{d}^{-1}$ (refs 4–7), at least several orders of magnitude greater than those observed³ in the open ocean. Assuming a conservative mean rate estimate for this site of 1 $\text{mg C m}^{-3} \text{d}^{-1}$, depth-integrated uptake of deep DIC is calculated to be 800 mg C

$\text{m}^{-2} \text{d}^{-1}$ or more than 20 times the flux entering aphotic waters via sinking POC. This again yields an estimated deep POC $\Delta^{14}\text{C}$ value that is much lower than that of POC sinking from surface waters (see table).

A further example of the magnitude of such a process is provided by Tuttle and Jannasch⁵, who reported that DIC uptake in waters above the Cariaco trench is at least 17–58 % as great as photosynthetic inorganic carbon assimilation in overlying surface waters. The above observations again lead to the conclusion that bomb ^{14}C in

FLUXES AND $\Delta^{14}\text{C}$ RELEVANT TO DEEP POC FORMATION

Site	Z (m)	Fluxes ($\text{mg C m}^{-2} \text{d}^{-1}$)		$\Delta^{14}\text{C}$ (‰)	
		SPOC	DIC	SPOC	DIC
NCP	4,760	10	10	+136	-240
SMB	800	30	800	+86	-50
Ref.	1	8,9	3–7	1	1

(This report)

SPOC, sinking POC at surface/deep ocean boundary; DPOC, deep POC (both sinking and suspended); NCP, north central Pacific Ocean site²; SMB, Santa Monica Basin site². The DIC flux (F_{DIC}) is derived by multiplying the mean per-volume rate estimates (2 $\mu\text{g C m}^{-3} \text{d}^{-1}$ (ref. 3) and 1 $\text{mg C m}^{-3} \text{d}^{-1}$ (refs 4–7) for NCP and SMB, respectively) times the respective deep-ocean water column depth, Z. The surface/deep ocean boundary is arbitrarily chosen to be at a depth of 1,000 m at the NCP site and at 100 m at the SMB site. $\text{DPOC } \Delta^{14}\text{C} = ((F_{\text{SPOC}}/F_{\text{DIC}}) \times \text{SPOC } \Delta^{14}\text{C}) + ((F_{\text{DIC}}/F_{\text{DIC}}) \times \text{DIC } \Delta^{14}\text{C})$ where $F_{\text{DIC}} = F_{\text{SPOC}} + F_{\text{DIC}}$ (ref. 1) in units of parts per thousand (‰).

resident deep-ocean POC can be substantially diluted by DIC uptake, independent of DOC incorporation or other mechanisms¹.

Thus, as previously noted¹⁰, DIC uptake should not be ignored in interpreting the paucity of ^{14}C in some deep-sea organisms and POC pools. It would therefore be premature to ascribe such ^{14}C depletion to DOC incorporation alone. Clearly, further rate and isotope measurements are needed better to characterize this important piece of the global carbon cycle.

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