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Ocean margins as a significant source of organic matter to the deep open ocean

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Continental shelves and slopes comprise less than 20% of the world ocean area, yet they are proposed to be quantitatively important sources of the organic matter that fuels respiration in the open ocean’s interior. At least certain regions of the coastal ocean produce more organic carbon than they respire, suggesting that some fraction of this non-respired, unburied organic carbon is available for export from the coastal to the open ocean. Previous studies of carbon fluxes in ocean margins have not considered the potential roles of dissolved organic carbon (DOC) and suspended particulate organic carbon (POC susp) relative to the adjacent North Atlantic and North Pacific central gyres. Mass-balance calculations suggest that DOC and POC susp inputs from ocean margins to the open ocean interior may be more than an order of magnitude greater than inputs of recently produced organic carbon derived from the surface ocean. Inputs from ocean margins may thus be one of the factors contributing to the old apparent age of organic carbon observed in the deep North Atlantic and Pacific central gyres.

The radioisotopic form of carbon, 

\(^{14}\text{C}\) (half-life, 5,730 yr), can be used as an indicator of the average age of bulk marine organic carbon pools such as DOC and POC. In addition to natural cosmogenically produced \(^{14}\text{C}\), the increase in the global inventory of \(^{14}\text{C}\) as a result of nuclear weapons testing during the late 1950s and early 1960s also allows us to use bomb-produced \(^{14}\text{C}\) to constrain the age of more recently formed (that is, over the past \(\approx 40\) years) organic carbon pools. The \(^{14}\text{C}\)-defining label \((\%_{\text{def}})\) and \(^{14}\text{C}\)-DOC values of natural marine organic carbon have been found to range from as low as \(\approx -252\)‰ (\(^{14}\text{C}\) age of \(\approx 6,000\) yr) for deep ocean DOC to as high as about \(\approx +140\)‰ for suspended POC samples containing bomb \(^{14}\text{C}\) in the mid- to late 1980s (ref. 9).

Samples for \(^{14}\text{C}\) isotope analysis of DOC and POC susp were collected from the western North Atlantic (WNA) and eastern North Pacific (ENP) continental margins. In April 1994, samples were collected from 4 depths at each of three WNA sites located over the continental slope in the Middle Atlantic Bight region between eastern Long Island, New York, and Cape Hatteras, North Carolina. The Bight is characterized by a permanent thermohaline front between continental shelf and slope waters and a net southwestward flow of slope water, of which \(\approx 50\)% is entrained across the front into slope waters and the remainder is advected offshore near Cape Hatteras. The depth of the WNA mid-slope sites ranged from \(\approx 1,100-1,500\) m. Samples were also collected from the eastern North Pacific from 1991 to 1993 at a time-series site located at the base of the continental rise (\(\approx 4,100\) m depth) at \(34^\circ 50\'\)N, \(123^\circ 00\'\)W (ref. 11), and previously in 1985 at a site in the Santa Monica basin of the California continental borderland (ref. 13). The ENP site is located \(\approx 220\) km off the coast of central California within the California current system and is influenced by spring–summer maxima in primary productivity and sinking POC fluxes as a result of seasonal upwelling.

The \(^{14}\text{C}\)-DOC values of DOC from shallow surface waters (5 m depth) of the WNA continental slope were highly variable, ranging over \(\approx 200\)‰ (Fig. 1a). In mid-depth slope waters (\(\approx 300\) m and 750 m; Fig. 1a), \(^{14}\text{C}\)-DOC values were significantly lower (that is, more negative in \(^{14}\text{C}\)) by 75 to 150‰ relative to DOC from similar depths in the central North Atlantic gyre (\(\approx 276\) to \(\approx 260\)‰ in the Sargasso Sea (SS)) (ref. 8). By 1,000 m depth, the \(^{14}\text{C}\)-DOC profiles of WNA slope water and those of SS water converged towards similar values. These data indicate the presence of \(^{14}\text{C}\)-depleted DOC at mesopelagic depths in WNA slope waters. On the basis of its \(^{13}\text{C}\) values (\(\delta^{13}\text{C}\) range: \(-21.3\) to \(-22.4\)‰; J.E.B., unpublished data), this DOC appears to be predominantly marine in origin (fully marine DOC has \(\delta^{13}\text{C}\) values ranging from \(\approx -2\) to \(-18\)‰).

The \(^{14}\text{C}\)-values of POC susp from the WNA ranged from \(\approx 190\) to \(+80\)‰ and were significantly lower than \(^{14}\text{C}\)-POC susp from the SS (Fig. 1b). \(^{14}\text{C}\)-values more positive than about \(-70\) to \(-40\)‰ are considered to be post-bomb (that is, later than early 1950s to early 1960s) thermocline carbon testing) because the pre-bomb \(^{14}\text{C}\)-of the temperate and tropical surface ocean was in this range (ref. 5). The \(\delta^{13}\text{C}\) values in POC susp (range: \(-22.9\) to \(-24.9\)‰; J.E.B., unpublished data) suggest that terrestrial carbon (with an assumed average \(\delta^{13}\text{C}\) \(\approx -27\)‰) may have contributed slightly more to POC susp than to DOC in WNA slope waters. The similar offsets in \(^{14}\text{C}\) for both DOC and POC susp between the WNA and the SS (Fig. 1a, b) suggest that the same or related mechanisms may control inputs of \(^{14}\text{C}\)-depleted DOC and POC susp to WNA slope waters.

Similar to the WNA, profiles from the ENP also indicate a net depletion in \(^{14}\text{C}\) (that is, more negative \(^{14}\text{C}\) values) of both DOC and POC susp relative to the central North Pacific (CNP) gyre (Fig. 1c, d). The lowest \(^{14}\text{C}\)-DOC values in the ENP occurred, also like the WNA, at shallow to intermediate depths (\(0-700\) m), and \(^{14}\text{C}\)-DOC values in the ENP were lower than in the CNP at all depths samples (Fig. 1c). The \(^{14}\text{C}\)-DOC values in Santa Monica basin were also, with the exception of the single 850-m sample, lower than values in the CNP (Fig. 1c). Significantly lower \(^{14}\text{C}\)-values of POC susp were likewise observed at all depths in both the ENP and Santa Monica Basin relative to the CNP gyre (Fig. 1d). The average difference in \(^{14}\text{C}\)-DOC between WNA and SS waters was greater than the corresponding margin-central gyre difference in the North Pacific (compare Fig 1a, c); the margin-central gyre offset in \(^{14}\text{C}\)-DOC was also greater overall in the North Atlantic (compare Fig. 1b, d). The corresponding \(\delta^{13}\text{C}\) values for DOC (range: \(-20.5\) to \(-21.7\) (ref. 12)) and POC susp (range: \(-20.0\) to \(-22.9\)‰ (ref. 11)) in ENP waters were greater (more positive) as a whole than for DOC and POC susp from the WNA.
Concentrations of DOC were greatest in shallow (0 to ~100 m) WNA (J.E.B., unpublished data) and ENP in slope and rise waters and decreased with increasing depth. With the exception of ~300 m depth in the WNA and 0 to 700 m depth in the ENP, DOC in slope and rise waters exceeded by 4–9 μM those concentrations measured previously in North Atlantic and Pacific central gyres waters2–5 (Table 1). Suspended POC concentrations were up to an order of magnitude higher in surface waters of the slope and rise than in surface waters of both the SS (J.E.B., unpublished data; ref. 9) and CNP. At depths ≥~500 m, POC susp concentrations in slope and rise waters were in all cases ~2–3 times (2–3 μg C l-1) greater than in the deep SS and CNP, where POC susp concentrations were ~0.6–1 μg C l-1 (Table 1).

The elevated DOC and POC susp concentrations in slope (in the WNA) and rise (in the ENP) waters, together with lower Δ14C values in both pools, indicate that organic matter older than that in the North Atlantic and Pacific central gyres is present in ocean margins and that it is potentially available for export to the open ocean. The origin(s) of this old, 14C-depleted carbon to continental slope and rise waters is (are) not known, but several possibilities may be considered. In the WNA, the reintroduction to the water column of old sedimentary organic carbon (both as DOC and POC susp) from weathered shelf and upper slope sediments16–17 may contribute to the highly 14C-depleted (Δ14C as low as about ~700‰) colloidal and dissolved organic carbon observed in near-bottom waters in the Middle Atlantic Bight18 as well as to the 14C-depleted POC susp (Fig. 1b). The WNA may also at times be influenced by upwelled Antarctic Intermediate Water19 which could impart lower-than-average Δ14C values to the DOC pool (but less likely so to the POC susp pool) of the ENP compared with areas remote from seepage (such as the CNP). Thus, the older DOC and POC susp in these two ocean margin systems may arise from multiple system-specific sources or from a common source such as weathered shelf and slope sediments.

The DOC of surface open ocean waters can be shown conceptually to consist of a mixture of both old, conservative material that has aged in the deep ocean and of young labile material recently which was significantly greater. All POC susp samples from the WNA slope were significantly depleted in Δ14C relative to the Sargasso Sea Δ14C-POC susp profile, with the exception of the single 750-m sample, which was not significantly different. c. Values of Δ14C of DOC (open circles) with solid line-of-best-fit added, and d. POC susp (filled circles) from the eastern North Pacific (ENP) including a continental rise site off central California at 34°50’N, 123°00’W and Santa Monica basin (star symbols) in the southern California continental borderland20. Symbols for Δ14C of DOC in the ENP (open circles) represent individual samples measured on six separate occasions between July 1991 and July 1993. Symbols for Δ14C of POC susp in the ENP (solid circles) represent mean values (±1σ) from four profiles measured between February 1992 and July 1993 (ref. 11). Also shown are profiles of Δ14C-DOC and Δ14C-POC susp (both dashed lines) determined previously for the central North Pacific (CNP)21. Errors associated with 14C AMS analyses of both DOC and POC susp are smaller than symbols and averaged ±6‰ (±1σ) for DOC susp in the CNP; single profiles measured in 1985 and 1987 showed minimal differences from each other21; the average standard deviation of these Δ14C-DOC profiles in the upper 1,000 m was 12‰, equivalent to the 2σ measurement error. All DOC and POC susp samples from both eastern North Pacific sites were significantly depleted in Δ14C relative to the corresponding central N. Pacific profiles, with the exception of the 900-m Santa Monica basin DOC sample which was not significantly greater. Note the differences in Δ14C scales between all panels and in depth scales between WNA (in a and b) and ENP (in c and d) profiles. Stippled area under WNA and ENP profiles indicates approximate depth of the sea floor at these sites.

Figure 1 Δ14C values of DOC and POC in North Atlantic and North Pacific waters. a. Values of Δ14C (deviation in parts per thousand from the 14C activity of nineteenth century wood) of DOC (open symbols with solid line-of-best-fit added), and b. POC susp (solid symbols with solid line-of-best-fit added) from 3 stations between 35°39.06’ N, 74°36.78’ W and 39°37.72’ N, 71°37.78’ W (circles, northern slope station; triangles, central slope station; squares, southern slope station) along the Middle Atlantic Bight continental slope in the western North Atlantic (WNA). Also shown are Δ14C-DOC and Δ14C-POCsusp profiles determined previously for the Sargasso Sea (SS, dashed lines)21. DOC and POC susp collection and sample-processing techniques are given in refs 9 and 12. Briefly, DOC samples (650 ml of 0.7-μm-filtered sea water) were oxidized to CO2 by high-energy (2,400 W) ultraviolet irradiation for 2 h. POC susp samples were collected from up to several thousand litres of sea water using in situ pumps with 0.7-μm quartz-fibre filters followed by sealed-tube combustion of sample filters to produce CO2. Procedures for conversion of sample CO2 to graphite and subsequent 14C analysis by accelerator mass spectrometry (AMS) are presented in ref. 30. All 14C data are corrected for sample 14C (data not shown) and are reported using the conventions of Stuiver and Pollach22. Errors associated with 14C AMS analysis are smaller than the symbols and averaged ±6‰. Errors due to blank corrections for Δ14C-POCsusp samples from the WNA only (filled symbols) are as follows: 5-m samples, ~1%; 300–1,000-m samples, ~40–60‰, with the exception of one 300-m sample (~171‰), which had an error of ~80‰. All DOC samples from the WNA slope were significantly depleted in Δ14C relative to the SS Δ14C-DOC profile, with the exception of the single 1,000-m sample (Δ14C = ~408‰) which has not significantly different, and the single 5-m sample (Δ14C = ~107‰) which was significantly greater. All POC susp samples from the WNA slope were significantly depleted in Δ14C relative to the Sargasso Sea Δ14C-POC susp profile, with the exception of the single 750-m sample, which was not significantly different. c. Values of Δ14C of DOC (open circles) with solid line-of-best-fit added, and d. POC susp (filled circles) from the eastern North Pacific (ENP) including a continental rise site off central California at 34°50’N, 123°00’W and Santa Monica basin (star symbols) in the southern California continental borderland20. Symbols for Δ14C of DOC in the ENP (open circles) represent individual samples measured on six separate occasions between July 1991 and July 1993. Symbols for Δ14C of POC susp in the ENP (solid circles) represent mean values (±1σ) from four profiles measured between February 1992 and July 1993 (ref. 11). Also shown are profiles of Δ14C-DOC and Δ14C-POC susp (both dashed lines) determined previously for the central North Pacific (CNP)21. Errors associated with Δ14C AMS analyses of both DOC and POC susp are smaller than symbols and averaged ±6‰ (±1σ). For Δ14C-DOC in the CNP, single profiles measured in 1985 and 1987 showed minimal differences from each other21; the average standard deviation of these Δ14C-DOC profiles in the upper 1,000 m was 12‰, equivalent to the 2σ measurement error. All DOC and POC susp samples from both eastern North Pacific sites were significantly depleted in Δ14C relative to the corresponding central N. Pacific profiles, with the exception of the 900-m Santa Monica basin DOC sample which was not significantly greater. Note the differences in Δ14C scales between all panels and in depth scales between WNA (in a and b) and ENP (in c and d) profiles. Stippled area under WNA and ENP profiles indicates approximate depth of the sea floor at these sites.
produced in the photic zone. Using a mass-balance approach, it has been calculated that surface seawater $\Delta^{14}C$-DOC values for the central North Pacific and North Atlantic Oceans are $-155$‰ and $-214$‰, respectively, which agree well with measured values of $-153$‰ and $-210$‰, respectively. A similar calculation is made here for surface (5 m) slope water of the central WNA, which has the highest $\Delta^{14}C$-DOC value ($-170$‰, Fig. 1a) of all WNA slope waters examined. The background DOC from deeper (300–1,000 m) waters of the central WNA slope has a mean concentration of 52 µM (J.E.B., unpublished data) and a mean $\Delta^{14}C$ of $-421$‰ (Fig. 1a). The DOC concentration of surface slope water is $-91$ µM (J.E.B., unpublished data), giving a calculated $\Delta^{14}C$ of the ‘excess’ surface DOC component (with a concentration of $91$ µM minus 52 µM, or $39$ µM) of $+311$‰. This $\Delta^{14}C$ value is high and similar to previous measurements of humic substances in Amazon river water made in 1984 ($\Delta^{14}C = +230$‰) and reflects the input of post-bomb, terrestrial carbon to shallow central WNA slope waters which are influenced by inputs from rivers and estuaries.

The same calculation when applied to shallow WNA waters yields a different conclusion. Using a deep, background mean DOC concentration of 51 µM (J.E.B., unpublished data) and a $\Delta^{14}C$-DOC value of $-435$‰ (Fig. 1a), and a DOC concentration and $\Delta^{14}C$-DOC value in shallow slope waters of 83 µM (J.E.B., unpublished data) and $-306$‰ (Fig. 1a), respectively, then the $\Delta^{14}C$ of the ‘excess’ surface DOC component (with a concentration of 83 µM minus 51 µM, or 32 µM) is calculated to be $-100$‰. This $\Delta^{14}C$-depleted component of excess DOC added to southern WNA surface slope water (about 400‰ lower than the ‘excess’ component in central WNA slope surface waters) is reflective of an older source of carbon to the surface DOC pool, perhaps originating from shelf and slope porewaters and sediments that are advected seaward. Similar calculations for POC$_{\text{surf}}$ using this simple model are not justified because of the $-10$-fold greater concentrations of POC$_{\text{surf}}$ in surface compared with deeper waters. For DOC, however, it is clear that sources having highly disparate $\Delta^{14}C$ may contribute to the surface ocean pool, leading to the high degree of variability observed in the WNA.

The existence of positive concentration gradients between the margins and deep open ocean and between the surface and deep open oceans indicates that both margins and the surface ocean may serve as sources of DOC and POC$_{\text{surf}}$ to the deep central gyres (Table 1). We can estimate by $^{14}$C mass balance the relative potential contributions of each of these sources to the deep North Atlantic and Pacific using the following simplifying assumptions: (1) the deep central North Atlantic and Pacific are in steady state with respect to $\Delta^{14}C$ values and concentrations of DOC and POC$_{\text{surf}}$ (refs 7–9); (2) the two dominant sources of DOC and POC$_{\text{surf}}$ to the deep central gyres are lateral inputs of $^{14}$C-depleted material derived from the margins and vertical inputs of ‘modern’, $^{14}$C-enriched material derived from surface ocean production; and (3) the margin-to-deep open ocean and surface-to-deep open ocean gradients observed in these studies are representative of the North Atlantic and Pacific as a whole. We find that in order to maintain the observed average DOC $\Delta^{14}C$ values in the deep central gyres, the input of DOC from the margins is calculated to be as much as 25–100 times that of modern, surface ocean-derived carbon; for POC$_{\text{surf}}$, the contribution from margins is smaller than that for DOC but still 5–19 times greater than the contribution of material from the surface (Table 1). These estimates of margin and surface contributions to the deep open ocean have two principal implications: (1) inputs of ‘aged’ organic carbon from the margins to the deep open ocean may surpass inputs derived from recent surface ocean production, and (2) in view of the much larger surface-to-deep than margin-to-deep concentration gradients, most young, surface-derived material must be degraded, allowing a smaller but more highly refractory margin component to contribute proportionally more to the deep central gyres.

Table 1 Relative contributions of margin and surface ocean organic carbon to the deep central gyres

<table>
<thead>
<tr>
<th>Dissolved organic carbon</th>
<th>Margin component</th>
<th>Modern surface component</th>
<th>Margin fraction</th>
<th>Surface fraction</th>
<th>Margin: surface ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Atlantic</td>
<td>$\Delta^{14}C_{\text{DOCsurf}}$</td>
<td>$\Delta^{14}C_{\text{DOC}}$</td>
<td>$\Delta^{14}C_{\text{DOCsurf}}$</td>
<td>$\Delta^{14}C_{\text{DOC}}$</td>
<td></td>
</tr>
<tr>
<td>North Atlantic</td>
<td>$-78$‰</td>
<td>9 µM</td>
<td>$+520$‰</td>
<td>34 µM</td>
<td>0.06</td>
</tr>
<tr>
<td>North Pacific</td>
<td>$-39$‰</td>
<td>4 µM</td>
<td>$+665$‰</td>
<td>23 µM</td>
<td>0.99</td>
</tr>
</tbody>
</table>

| Suspended particulate organic carbon | $\Delta^{14}C_{\text{POCsurf}}$ | $\Delta^{14}C_{\text{POC}}$ | $\Delta^{14}C_{\text{POCsurf}}$ | $\Delta^{14}C_{\text{POC}}$ |                          |
|------------------------------------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|                          |
| North Atlantic                     | $-217$‰                     | 3 µg L$^{-1}$              | $+93$‰                      | 28 µg L$^{-1}$              | 0.84                | 0.16                | 5.2              |
| North Pacific                      | $-83$‰                      | 2 µg L$^{-1}$              | $+94$‰                      | 31 µg L$^{-1}$              | 0.96                | 0.05                | 19               |

Estimates of the relative contributions of margin and surface ocean-DOC derived DOC and suspended POC to the deep central North Atlantic and Pacific gyres. Shown are DOC and suspended POC, $\Delta^{14}C$ and concentration gradients between the deep open North Atlantic and North Pacific Oceans, their respective margins (WNA and ENP, respectively), and modern surface ocean organic carbon. Also shown are the fractions of margin and surface ocean DOC and POC required to maintain the observed steady-state $\Delta^{14}C$ profiles of DOC and suspended POC in the deep North Atlantic and Pacific central gyres.

1 Relative contributions of margin and surface-derived DOC and POC required to maintain the observed average $\Delta^{14}C$ values of DOC and POC in the deep central North Atlantic and Pacific gyres. The contribution of each component is described by the mass balance equation (hence shown for DOC): $\Delta^{14}C_{\text{DOCsurf}} = (x) \cdot \Delta^{14}C_{\text{DOCsurf}} + (y) \cdot \Delta^{14}C_{\text{DOCsurf}}$, where $x$ is the margin component, $y$ is the surface component, and $x + y = 1$. Note that by definition $\Delta^{14}C_{\text{DOCsurf}} = 0$. For calculating the margin and surface-derived suspended POC component, POC values were normalized for DOC values in the above equation. Average values used for $(\Delta^{14}C_{\text{DOCsurf}} - \Delta^{14}C_{\text{DOCsurf}})_{\text{SS}}$ were 43 and 35 µM for the SS and CNP, respectively; the average value used for $(\Delta^{14}C_{\text{POCsurf}} - \Delta^{14}C_{\text{POCsurf}})_{\text{SS}}$ was 0.72 µg L$^{-1}$ for both the SS and CNP.

2 Mean observed gradients in $\Delta^{14}C$ values of DOC and POC between margins and deep central gyres.

3 Mean mean observed gradients in $\Delta^{14}C$ values of DOC and POC derived from recent surface ocean carbon and that present in deep central gyres. The average $\Delta^{14}C$ values of surface-derived, photosynthetically fixed carbon measured at the time each central gyre site was sampled were +120‰ and +140‰ for the Sargasso Sea and central North Pacific, respectively.

4 Excludes observed gradients in $\Delta^{14}C$ values of DOC and POC between margins and deep central gyres.

5 Mean observed gradients in $\Delta^{14}C$ values of DOC derived from recent surface ocean carbon and that present in deep central gyres. The average $\Delta^{14}C$ values of surface-derived, photosynthetically fixed carbon measured at the time each central gyre site was sampled were +120‰ and +140‰ for the Sargasso Sea and central North Pacific, respectively.

6 Mean observed gradients in $\Delta^{14}C$ values of DOC and POC between margins and deep central gyres.

7 Mean observed gradients in $\Delta^{14}C$ values of DOC and POC derived from recent surface ocean carbon and that present in deep central gyres. The average $\Delta^{14}C$ values of surface-derived, photosynthetically fixed carbon measured at the time each central gyre site was sampled were +120‰ and +140‰ for the Sargasso Sea and central North Pacific, respectively.
Shallow continental shelf and slope waters may also act as low-salinity conduits of younger terrestrial organic matter (J.E.B., unpublished data, and ref. 18), where margins are affected significantly by rivers and estuaries. However, most of this material must also be degraded in nearshore waters or sequestered in sediments as it does not appear to comprise a significant component of open ocean DOC and POCsuspended seaward of the shelf-slope front. The isotope signatures of DOC and POCsuspended at the coastal–open ocean boundaries (that is, slope and rise) here indicate that this carbon has mainly a non-recent marine origin and is older than organic carbon from the North Atlantic and central Pacific gyres. If this material propagates seaward, possibly along isopycnal surfaces, it may represent a source of old DOC and POC to intermediate and deep waters of the interior ocean4.

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