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

James E. Bauer* & Ellen R. M. Druffel†

* School of Marine Science, College of William and Mary, Gloucester Point, Virginia 23062, USA
† Department of Earth System Science, University of California, Irvine, California 92697, USA

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) inputs, even though both pools are quantitatively larger than sinking POC. Here we report natural radiocarbon (14C) abundance measurements that reveal continental slope and rise waters to contain both DOC and POC that are concurrently older and in higher concentrations than DOC and POC from the adjacent North Atlantic and North Pacific central gyres. Mass-balance calculations suggest that DOC and POC 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 radiocarbon age of carbon, 14C (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 14C, the increase in the global inventory of 14C as a result of nuclear weapons testing during the late 1950s and early 1960s also allows us to use bomb-produced 14C to constrain the age of more recently formed (over the past ∼40 years) organic carbon pools. The Δ14C (defined as the deviation in parts per thousand (‰) from the 14C activity of nineteenth century wood) values of natural marine organic carbon have been found to range from as low as around −525‰ (14C age of ∼6,000 yr) for deep ocean DOC to as high as about +140‰ for suspended POC samples containing bomb 14C in the mid- to late 1980s (ref. 9).

Samples for 14C isotope analysis of DOC and POC 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 thermocline front between continental shelf and slope waters and a net southward flow of slope water, of which ∼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 ∼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 (∼4,100 m depth) at 34° 50′ N, 123° 00′ W11,12, and previously in 1985 at a site in the Santa Monica basin of the California continental borderland. The ENP site is located ∼220 km off the coast of central California within the California current system and is influenced by spring–summer maximum in primary productivity and sinking DOC fluxes as a result of seasonal upwelling.14

The Δ14C values of DOC from shallow surface waters (5 m depth) of the WNA continental slope were highly variable, ranging over ±200‰ (Fig. 1a). In mid-depth slope waters (∼300 m and 750 m; Fig. 1a), Δ14C-DOC values were significantly lower (that is, more negative in Δ14C) by 75 to 150‰ relative to DOC from similar depths in the central north Atlantic gyre (−276 to −260‰ in the Sargasso Sea (SS)8). By 1,000 m depth, the Δ14C-DOC profiles of WNA slope water and those of SS water converged towards similar values. These data indicate the presence of 14C-depleted DOC at mesoscale depths in WNA slope waters. On the basis of its δ13C values (δ13C range: −21.3 to −22.4‰; J.E.B., unpublished data), this DOC appears to be predominantly marine in origin (fully marine DOC has δ13C values ranging from about −22 to −18‰).

The Δ14C values of POC from the WNA ranged from −190 to +80‰ and were significantly lower than Δ14C of POC from the SS (Fig. 1b). Δ14C values more positive than about −70 to −40‰ are considered to be post-bomb (that is, later than early 1950s to early 1960s thermonuclear weapons testing) because the pre-bomb Δ14C of the temperate and tropical surface ocean was in this range.5 The δ13C values in POC (range: −22.9 to −24.9‰; J.E.B., unpublished data) suggest that terrestrial carbon (with an assumed average δ13C ≈ −27‰) may have contributed slightly more to POC than to DOC in WNA slope waters. The similar offsets in Δ14C for both DOC and POC between the WNA and the SS (Fig. 1a, b) suggest that the same or related mechanisms may control inputs of 14C-depleted DOC and POC to WNA slope waters.

Similar to the WNA, profiles from the ENP also indicate a net depletion in 14C (that is, more negative Δ14C values) of both DOC and POC relative to the central North Pacific (CNP) gyre (Fig. 1c, d). The lowest Δ14C-DOC values in the ENP occurred, also like the WNA, at shallow to intermediate depths (0–700 m), and Δ14C-DOC values in the ENP were lower than in the CNP at all depths (Fig. 1c). The Δ14C-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 Δ14C values of POC 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 Δ14C-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 Δ14C of POC was also greater overall in the North Atlantic (compare Fig. 1b, d). The corresponding δ13C values for DOC (range: −20.5 to −21.7 (ref. 12)) and POC (range: −20.0 to −22.9‰ (ref. 11)) in ENP waters were greater (more positive) as a whole than for DOC and POC from the WNA.
Concentrations of DOC were greatest in shallow (0 to ~100 m) WNA (J.E.B., unpublished data) and ENP12 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 waters10–12 (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 CNP9. 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 borderland12. 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) of four profiles measured between February 1992 and July 1993 (ref. 11). Also shown are profiles of Δ14C-DOC and Δ14C-POCsusp (both dashed lines) determined previously for the central North Pacific (CNP)12. 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 other20; 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 C. Nature © Macmillan Publishers Ltd 1998
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 $-155\%_0$ and $-214\%_0$, respectively, which agree well with measured values of $-153\%_0$ and $-210\%_0$, 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 ($-107\%_0$, 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 $\mu$M (J.E.B., unpublished data) and a mean $\Delta^{14}$C of $-421\%_0$ (Fig. 1a). The DOC concentration of surface slope water is $-91\%_0$ (J.E.B., unpublished data), giving a calculated $\Delta^{14}$C of the ‘excess’ surface DOC component (with a concentration of 91 $\mu$M minus 52 $\mu$M, or 39 $\mu$M) of $+311\%_0$. 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 = $+230\%_0$) 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 surface waters yields a different conclusion. Using a deep, background mean DOC concentration of 51 $\mu$M (J.E.B., unpublished data) and a $\Delta^{14}$C-DOC value of $-435\%_0$ (Fig. 1a) and a DOC concentration and $\Delta^{14}$C-DOC value in shallow slope waters of 83 $\mu$M (J.E.B., unpublished data) and $-306\%_0$ (Fig. 1a), respectively, then the $\Delta^{14}$C of the ‘excess’ surface DOC component (with a concentration of 83 $\mu$M minus 51 $\mu$M, or 32 $\mu$M) is calculated to be $-100\%_0$. 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 POCsusp using this simple model are not justified because of the ~10-fold greater concentrations of POCsusp 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 POCsusp to the deep central gyres (Table 1). We can estimate by $\Delta^{14}$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 POCsusp (refs 7–9); (2) the two dominant sources of DOC and POCsusp to the deep central gyres are lateral inputs of $\Delta^{14}$C-depleted material derived from the margins and vertical inputs of ‘modern’, $\Delta^{14}$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 POCsusp, 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.

Lateral transport of organic matter from margins to pelagic and abyssal environments has been invoked previously to help explain carbon and oxygen imbalances in the deep ocean. Transport of $\Delta^{14}$C-depleted DOC and even POCsusp from ocean margins to the central gyres may be facilitated by isopycnal (that is, lateral) eddy diffusion, which can be $10^5$–$10^6$ times greater than vertical eddy diffusive transport. Although vertical transport of recently produced surface material to the central gyres may also be enhanced by such processes as seasonal thermocline breakdown and rapidly sinking organic particles, we would expect this younger organic carbon to be relatively more susceptible to microbial remineralization and older margin-derived material. Thus, although the open ocean undoubtedly receives inputs from both its margins and surface production, the $\Delta^{14}$C and concentration profiles of DOC and POCsusp in the deep central gyres may be maintained by greater relative inputs from the margins than from recent surface production.

<table>
<thead>
<tr>
<th>Dissolved organic carbon</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 $\Delta^{14}$C-DOC</td>
<td>$-78%_0$</td>
<td>9 $\mu$M</td>
<td>$+520%_0$</td>
<td>34 $\mu$M</td>
</tr>
<tr>
<td>North Pacific $\Delta^{14}$C-DOC</td>
<td>$-39%_0$</td>
<td>4 $\mu$M</td>
<td>$+665%_0$</td>
<td>23 $\mu$M</td>
</tr>
<tr>
<td>Suspended particulate organic carbon $\Delta^{14}$C-POC</td>
<td>$-167%_0$</td>
<td>3 $\mu$g$^{-1}$</td>
<td>$+93%_0$</td>
<td>28 $\mu$g$^{-1}$</td>
</tr>
<tr>
<td>North Pacific $\Delta^{14}$C-POC</td>
<td>$-63%_0$</td>
<td>2 $\mu$g$^{-1}$</td>
<td>$+84%_0$</td>
<td>31 $\mu$g$^{-1}$</td>
</tr>
</tbody>
</table>

Estimates of the relative contributions of margin and surface ocean carbon to the deep central gyres. Shown are DOC and suspended POC, with margins providing $\Delta^{14}$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.

* 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 (here shown for DOC): $\Delta^{14}$C of DOC in deep central gyre $= \Delta^{14}$C of DOC in margins + $\Delta^{14}$C of DOC in surface ocean, where $\Delta^{14}$C of DOC in surface ocean is $\Delta^{14}$C of DOC in shelf margins + $\Delta^{14}$C of DOC in shelf seas.

** Estimates used for DOC in surface ocean are for the Sargasso Sea and central North Pacific, respectively.

* Mean observed gradients in concentrations of DOC and POC between margins and deep central gyres.

† Mean observed gradients in concentrations of DOC and POC between surface and deep central gyres.

‡ Mean observed gradients in $\Delta^{14}$C values of DOC and POC derived from recent photosynthetically fixed surface ocean organic 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 $+120\%_0$ and $+140\%_0$ for the Sargasso Sea and central North Pacific, respectively.

§ Mean observed gradients in $\Delta^{14}$C values of DOC and POC derived from recent photosynthetically fixed surface ocean organic 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 $+120\%_0$ and $+140\%_0$ for the Sargasso Sea and central North Pacific, respectively.

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Excludes shallower depths sampled where concentrations were up to 30 times greater in margins.
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 POC_{susp} seaward of the shelf-slope front. The isotope signatures of DOC and POC_{susp} at the coastal–open ocean boundaries (that is, slope and rise) indicate that here 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 ocean.

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Correspondence and requests for materials should be addressed to J.E.B. (e-mail: bauer@vims.edu).