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Distribution of Particulate Organic Carbon and Radiocarbon in the Water Column from the Upper Slope to the abyssal NE Pacific Ocean

E.R.M. Druffel[a,*], S. Griffin[a], J.E. Bauer[b], D.M. Wolgast[c], X.-C. Wang[a]

[a]*Department of Earth System Science, University of California at Irvine, Irvine, CA 92697-3100, USA*
[b]*School of Marine Sciences, College of William and Mary, Gloucester Pt, VA 23062, USA*
[c]*Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093, USA*

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Abstract

We report profiles of concentrations and radiocarbon contents of suspended particulate organic carbon (POC_{susp}) and sedimentary organic carbon from an abyssal site (Stn M) in the northeast (NE) Pacific collected in September 1994 (a period of very high flux of particulate carbon in the deep sea) and June 1995, as well as from stations on the continental rise and slope off the coast of California in June 1995. We show that during a period of anomalously high sinking POC flux to the deep sea (September 1994), $\Delta^{14}C$ of suspended POC did not decrease detectably between 85 and 1600 m depth. This is in contrast to depth profiles during low and moderate fluxes of sinking POC at this station where $\Delta^{14}C$-POC_{susp} decreased 50–60‰ in this depth range. One explanation for the constant $\Delta^{14}C$ values of POC_{susp} between 85 and 1600 m is that large quantities of sinking POC could continuously release labile, ^{14}C-enriched POC_{susp} during biological and chemical alteration of the sinking POC. The radiocarbon evidence further suggests that resuspension of organic carbon from the sediment surface, either locally or laterally transported from the slope to the deep sea, is likely, but is probably limited to depths within a few hundred meters of the bottom. Sorption of 'old' DOC by suspended particulate matter in the water column is also possible, especially at shallower depths (< 3500 m), though proof of this mechanism cannot be demonstrated at this time.

*Corresponding author. Fax: 001 714 824 3256; e-mail:edruffel@uci.edu.

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1. Introduction

Primary productivity in the euphotic zone (0–200 m depth) is the process that initiates the transport of organic carbon from the surface to the deep ocean. Both fast, sinking particles, and slower marine snow or aggregate flocs (Alldredge and Silver, 1988) are the main transport mechanisms of particles through the water column to the deep sea. Suspended particles are responsible for most of the exchange between particulate and dissolved phases in the open ocean water column (Bacon and Anderson, 1982; Clegg et al., 1991). Thus, aggregation and transport of suspended particles partially control the removal of trace elements from the water column (Shaw et al., 1998).

Radiocarbon is the rare, radioactive form of carbon that is produced by cosmic-ray secondaries in the stratosphere. It also was formed as a result of thermonuclear bomb testing in the late 1950s and early 1960s. Bomb ^{14}C is particularly useful in studies of carbon transfer between the surface and deep ocean because it serves as a transient tracer. For example, the presence of bomb ^{14}C ($\Delta^{14}C > -50‰$) in biota from the deep Pacific indicated that surface-derived organic carbon was the primary dietary source for these organisms (Williams et al., 1987).

Seasonal $\Delta^{14}C$ profiles of suspended particulate organic carbon (POC_{susp}), sinking POC (POC_{sink}), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC) at Stn M in the northeast (NE) Pacific have been reported recently (Bauer et al., 1998b; Druffel et al., 1996; Masiello et al., 1998). Druffel et al. (1996) observed a large gradient with depth in the POC_{susp} $\Delta^{14}C$ values (124–160‰) that was larger during June 1992 and July 1993 than during February and October 1992. Values of $\Delta^{14}C$ in sinking POC from deep-moored sediment trap collections (3450 m) displayed lower overall $\Delta^{14}C$ in material collected during periods of higher flux (i.e., July and September). Despite a seasonal variation in surface water DIC $\Delta^{14}C$ (20–30‰), this was not the sole source of the observed seasonality in the $\Delta^{14}C$-POC signals (Masiello et al., 1998). Overall, we speculated that two processes likely caused lower $\Delta^{14}C$ values of deep suspended and sinking POC: (1) sorption or biological incorporation of 'old' DOC onto particulate matter, and (2) lateral transport of particles that had been resuspended from the slope and rise regions.

We obtained samples from a cruise to Stn M in September 1994 and from a transect off the coast of California during June 1995 to assess the contribution of slope- and rise-derived carbon at Stn M. We wanted to test the hypothesis (Jahnke et al., 1990; Reimers et al., 1992) that inferred organic matter export off the continental shelf and upper slope from especially high organic carbon fluxes to the seafloor off the continental slope and rise off central California. They also suggested that Stn M may be affected by similar lateral processes, but by events that occurred less frequently and with lower intensity. The $\Delta^{14}C$ of sediment-derived organic matter is much lower than surface, plankton-derived carbon, and hence would be a good tracer of lateral processes. We report that the $\Delta^{14}C$ signatures and concentrations of POC_{susp} samples from the water column at the foot of the rise (3800 m depth) were similar to those at Stn M, and slightly lower than those values at the upper slope site. We report that the carbon isotopic signature of the POC_{susp} from the rise and upper slope regions of the

California coast reflects the same signature as that at the abyssal ocean site, Stn M, during June 1995. This similarity suggests that a common mechanism may be responsible for the large depth gradient of POC_{susp} $\Delta^{14}C$ observed at these different oceanic regimes, two possibilities of which are lateral transport of resuspended SOC (sedimentary organic carbon) from the shelf and slope to the abyssal plain, or sorption or biological utilization of 'old' DOC onto suspended particulate matter.

2. Sample collection and analyses

Our samples were collected at three sites (Stn M, Rise and Upper Slope) off the coast of California during 1–14 June 1995 aboard the *R/V New Horizon*. We also report results of samples collected during 13–24 September 1994 aboard the *R/V Atlantis II* to Stn M. Station M (31°50′N, 123°00′W) is located 220 km west of Point Conception, CA, at a depth of 4100 m. Sediments are composed of silty clay, and Mn nodules are abundant on the sediment surface. The southward flowing California Current System is the dominant influence on the sea surface in this region, and the seasonally-variant California Undercurrent flows north at subsurface depths ($\sim$ 200–500 m depth). Spring blooms of chlorophyll occur in surface waters (Michaelsen et al., 1988; Pelaez and McGowan, 1986; Smith et al., 1988) and vary in intensity from year to year. Generally, two maxima per year are observed in the flux of particulate organic material ($>$ 5 mg C m^{-2} yr^{-1}) at Sta M, the primary one in late spring and the secondary one in early fall (Baldwin et al., 1998).

The second sampling location was our Rise site (35°25′N, 122°24W) located at the foot of the continental slope at a depth of 3800 m. This site was chosen because the sediment community exhibited high O_2 consumption and it was hypothesized that it was fueled by a large lateral component to the POC flux (Jahnke, 1990). The third site was our Upper Slope site (35°40′N, 121°27′W) located at 500 m depth near site J studied by previous investigators (Reimers (1992) Jahnke (1990).

Expendable bathythermographs (XBT) were deployed at the three sites June 1995 covering the depth range of 0–1800 m. Salinity measurements were made on water samples collected using Go-flo bottles from nearly the same depths at which the in situ pumps were deployed during both cruises (June 1995 and Sept 1994).

POC_{susp} was collected using in situ Yentsch pumps (Druffel et al., 1992; 1996; Williams et al., 1980) deployed for 2–8 h (depending on expected POC concentration) on the trawl wire. During each deployment, 400–2500 l of sea water (measured using flow meters) were filtered through 0.8 μm pore-diameter, pre-combusted (550°C) quartz-fiber filters (Whatman ultra-pure QM-A, 145 mm diameter). The filters were then folded and frozen in glass jars at -20°C in the dark. The depths sampled were 25, 85, 200, 450, 700 (O_2 minimum), 1200, 1600, 2500, 3450 and 4050 m. We used a pinger deployed below the bottom pump on the trawl wire to determine the approximate height of sampling above the bottom.

The sediments at the Rise and Upper Slope sites also consisted of silty clay. Samples for SOC $\Delta^{14}C$ analyses were obtained from the Rise and Upper Slope sites (June 1995) using a 1.8-m long, gravity corer (3-in diameter core liner). At Stn M, a box core from a free vehicle grab respirometer (FVGR) (Smith et al., 1994) from Stn M was subcored for $\Delta^{14}C$ of SOC with a 3-in diameter PVC pipe (in June 1991). The cores were sectioned on board ship immediately after recovery into 1–4 cm thick layers and frozen in glass jars at $-20°C$. It appeared that there was little or no loss of sediment from the top of the gravity core from the Rise site, as the water overlying the sediment was clear and the surface floc layer appeared intact when the gravity core was brought onboard the ship. Also, the depth of the brown-green, FeIII–FeII boundary (which indicates the relative rain rate of reactive organic matter to the seafloor (Lyle et al., 1983)), was the same as that (8 cm) seen in numerous sediment samples collected using the FVGR at Stn M on many cruises. The gravity core from the Upper Slope site, however, was winnowed away near the top of the core, and it is possible that the top 5–7 cm was missing from this core.

The filters containing the POC_{susp} or 0.5–1.0 g samples of dried sediment (SOC) were acidified to $pH < 2$ with 1% H_3PO_4 for 24 h to remove the carbonates, dried under vacuum, and combusted at 850°C for 1–2 h in double quartz tubes with CuO and silver according to standard techniques (Druffel et al., 1992). The concentrations of POC_{susp} (μg/l) at each depth were determined from the manometric measurement of CO_2 gas obtained after combustion of each filter and the liters of water filtered by recording flow meters mounted on each of the Yentsch pumps. The concentrations of SOC (% dry weight, salt-corrected) were measured using a Carlo Erba 200 CHN analyzer.

The CO_2 from combusted POC_{susp} and SOC was converted to graphite targets (Vogel et al., 1987) at UCI, and ^{14}C was measured using accelerator mass spectrometry (AMS) at the Center for AMS Research at Lawrence Livermore National Laboratory by Drs. M. Kashgarian, J. Southon and colleagues. Radiocarbon measurements, reported as $\Delta^{14}C$ in per mil (Stuiver and Polach, 1977), are corrected for blank CO_2 added during combustion and during the production of graphite (Druffel et al., 1996). Statistical errors for the individual AMS $\Delta^{14}C$ measurements range from ± 4 to $\pm 9‰$. Reproducibility of POC_{susp} $\Delta^{14}C$ concentration values was determined from duplicate analyses of quartz filters from the same deployment of a given Yentsch pump to a given depth. We calculated the 1-sigma experimental uncertainty of $\Delta^{14}C$ by taking the square root of the arithmetic mean of the squares of the differences between the four data pairs. In this way, a total 1-sigma uncertainty of 15‰ for the POC_{susp} $\Delta^{14}C$ measurements was obtained; if we subtract this total uncertainty from the uncertainty from counting statistics alone (8‰), we obtain 7‰ uncertainty for machine and laboratory uncertainty (see Druffel and Griffin (1995)). Reproducibility of SOC $\Delta^{14}C$ values was equal to the statistical counting uncertainty. Stable carbon isotope results ($\delta^{13}C$) for samples in this study were performed on splits of CO_2 from the double-tube combustion step. The $\delta^{13}C$ measurements were made on a VG Micromass 602E isotope ratio mass spectrometer, were corrected for blank CO_2, and had an overall uncertainty of $\pm 0.20‰$.

3. Results

3.1. Station M – September 1994 and June 1995

The $\Delta^{14}C$ of POC_{susp} collected at Stn M during September 1994 (Pulse 22) and June 1995 (Pulse 26) are listed in Table 1 and shown in Fig. 1a. Though $\Delta^{14}C$ values were identical at 25 m and $\geqslant$3500 m for both cruises, there are significant differences inbetween these depths. During September 1994, $\Delta^{14}C$ values were constant between the depths of 85 and 1600 m, and these six values averaged $32 \pm 4‰$ (sd). In contrast, during June 1995 the $\Delta^{14}C$ values decreased from 63‰ at 85 m to 12‰ at 700 m, and values between 700 and 1600 m were constant (average $\Delta^{14}C = 9 \pm 3‰$, $n = 3$). The high flux rate of POC_{sink} during September 1994 (5–25 mg C m^{-2} d^{-1} at 50 mab (meters above bottom) (Baldwin et al., 1998) is an important clue for interpreting the isotope results observed in Fig. 1a (see Section 4).

It is interesting to note that a sample collected from 1 mab during the September 1994 cruise had a $\Delta^{14}C$ value ($-69 \pm 14‰$), which was statistically the same as that collected at 50 mab ($-80 \pm 6‰$). This indicates that the material at 1 and 50 mab is isotopically identical and that resuspension of surface-derived sediment is likely of equal magnitude, at least within 50 m of the water above the seafloor, in agreement with Beaulieu and Smith (1998).

The POC_{susp} concentration values during June 1995 (Fig. 1b, Table 1) are within the observed range of that from four other cruises to Stn M as reported previously (Druffel et al., 1996). Values decreased with depth from the surface to 2500 m. In contrast, POC_{susp} abundances during the high flux period of September 1994 display two minima, one at 700 m and a second at 650 mab and a deep maximum between 1200 m and 2500 m. These features are significant considering the uncertainty of $\pm 10\%$ in the individual abundance values. The minima in POC_{susp} concentrations did not correlate with any significant concomitant offsets in $\Delta^{14}C$-POC_{susp} (Fig. 1a). The contrasting trends of POC_{susp} abundances at Stn M during the two cruises are also likely related to the vastly different sinking flux rates of POC_{sink} measured in the deep sea during the two time periods (see Section 4).

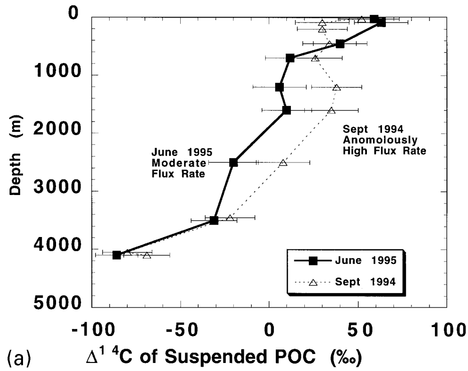
3.2. Slope-to-Stn M Transect – June 1995

The XBT results from the June 1995 cruise illustrated a greater stratification of the surface waters with increased distance from the coast. Specifically, there was an isothermal mixed layer at Stn M, with a depth of about 70 ± 10 m and a temperature of 13.6°C. The mixed layer at the Rise site was shallower and less defined; temperatures gradually decreased from 13.2°C at 1 m to 11°C at 80 m. The Upper Slope site had a lower mixed layer temperature (10.0–10.5°C) than the other sites, with a depth of about 80 m. The density (sigma-t) (Bauer et al., 1998a) at 25 m on the Upper Slope (sigma-t = 25.68) was greater than those at the Rise (sigma-θ = 25.04) or Stn M (sigma-t 24.61) sites. This demonstrates the stronger influence of wind-driven upwelling near the California coast.

Table 1
Isotope and concentration data of POC_{susp} collected during September 1994 and June 1995 at Stn M, and the Rise and Upper Slope sites. The reported total uncertainties of the $\Delta^{14}C$ values are counting statistics plus 7‰ (see text for detail)

Depth (m)	UCID No.	CAMS No.	Sta No.	POCsusp Δ14C‰	± ‰	δ13C ‰	[POC] (μgC/l)
Stn M	P-22	1994 Sept					
25	523	17667	2204	52	13	− 24.7	77.49
85	758	21809	2204	30	15	− 24.7	14.32
200	760	21811	2211	30	14	− 22.6	6.35
450	814	21408	2211	34	15	− 20.1	1.86
700	521	17666	2222	26	15	− 20.6	1.02
1200	815	21409	2222	38	14	− 21.9	2.25
1600	506	17429	2206	35	15	− 20.9	2.74
2500	1509	29678	2206	8	15	− 21.4	1.83
3450	505	17671	2217	− 22	14	− 21.7	1.14
4050	759	21810	2217	− 80	14	− 21.3	2.07
4099	524	17668	2228	− 69	13	− 21.1	2.30
Stn M	P-26	1995 June					
25	1394	27812	2603	59	14	− 22.9	44.15
85	1415	27821	2603	63	15	− 25.1	17.29
450	1416	27822	2608	40	15	− 21.8	3.70
700	1395	27813	2608	12	14	− 21.5	2.44
1200	1417	27823	2626	6	15	− 21.5	2.04
1600	1396	27814	2626	10	14	− 21.6	2.06
2500	1418	27824	2626	− 20	14	− 21.8	1.28
3500	1397	27815	2614	− 31	13	− 21.8	1.67
4050	1425	27828	2614	− 86	12	− 21.5	1.73
Rise	P-26	1995 June					
25	1398	27818	2632	35	14	− 23.2	42.98
200	1419	27825	2632	41	15	− 20.7	9.30
700	1420	27826	2632	7	13	− 21.2	3.51
1600	1421	27827	2645	4	13	− 21.5	1.98
2600	1426	27829	2639	− 16	13	− 21.0	1.63
3400	1399	27817	2639	− 23	14	− 21.3	1.65
3750	1427	27830	2639	− 65	13	− 21.1	1.86
U Slope	P-26	1995 June					
25	1400	27816	2647	38	14	− 23.5	30.11
100	1428	27831	2651	47	15	− 19.9	5.52
250	1401	27819	2647	40	15	− 19.7	7.11
400	1402	27820	2651	− 48	14	− 20.3	10.30
450	1429	27832	2647	− 62	13	− 20.5	10.35

The $\Delta^{14}C$ measurements of POC_{susp} collected along the June 1995 transect are shown in Fig. 2a and listed in Table 1. Near-surface (25 and 85 m) values (59‰ and 63‰, respectively) at Stn M, were higher than those at either the Rise (35‰ at 25 m, 41‰ at 200 m) or Upper Slope (38‰ at 25 m, 47‰ at 100 m) sites. This offshore gradient reflects the differences in the surface (25 m) DIC $\Delta^{14}C$ values between the



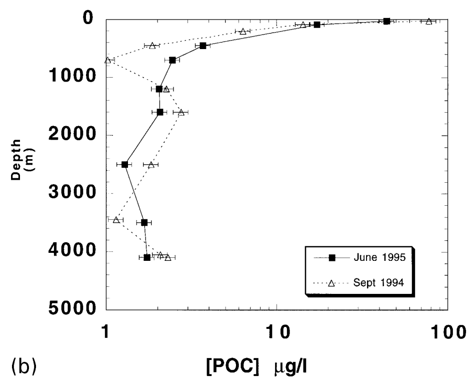


Fig. 1. (a) $\Delta^{14}C$ (in ‰) and (b) concentration (on a log-linear scale)(in μg/l) of POC_{susp} samples collected in situ using Yentsch pumps at Stn M during September 1994 and June 1995. Error bars in (a) are $\pm$ 1 sigma total uncertainty of the AMS $\Delta^{14}C$ measurements (see Table 1), and in (b) are $\pm$ 10% of the measured values.

Upper Slope (44‰) and Rise (45‰) sites and Stn M (68‰) (Masiello et al., 1998). Below 450 m, the $\Delta^{14}C$-POC_{susp} values (Fig. 2a) and $\Delta^{14}C$-DIC values were indistinguishable at the Rise and Stn M sites (Bauer, 1998). $\Delta^{14}C$ values for the near-bottom samples (50 and 100 mab) from the Upper Slope site (− 48 to − 62‰, respectively) are not distinguishable from that at 50 mab at the Rise site (− 65‰), but are not as low as the value at 50 mab at the Stn M site (− 86‰). The surface-to-deep gradient in $\Delta^{14}C$ for Stn M in June 1995 was 90‰, excluding the 50 mab sample that was clearly influenced by resuspended sediment. The surface to deep gradient for the Rise and Upper Slope sites were 58‰ and 86‰, respectively, also excluding the 50 mab depths.

The Upper Slope waters generally contained lower POC_{susp} concentrations compared to those at similar depths at the Rise and Stn M sites, except in the two samples nearest the bottom where they were greater (Fig. 2b). At 700 m and deeper, the Rise site contained the same or higher (by 8–43%) POC_{susp} concentration values as those at Stn M during June 1995. Results of transmissometry casts made at both the Rise

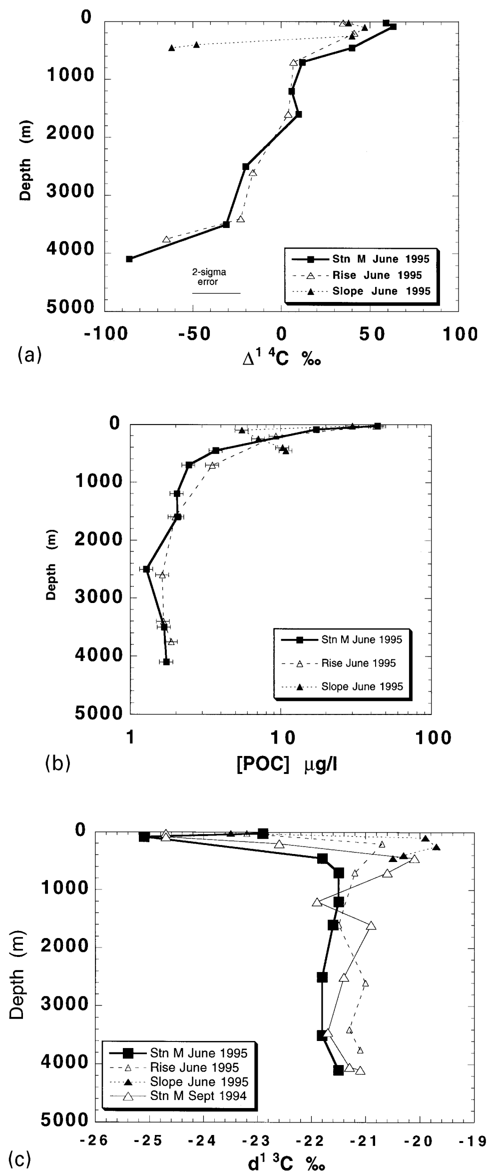


Fig. 2. (a) $\Delta^{14}C$, (b) concentration, and (c) $\delta^{13}C$ of POC_{susp} samples collected during June 1995. (c) also includes Pulse 22 (September 1994) samples.

and Stn M sites during the June 1995 cruise (Baldwin et al., 1998) show identical values at all depths except between 2300 and 2800 m where the Rise site values were slightly higher (0.2% light transmission units) than those at Stn M which is consistent with the higher POC_{susp} concentration values at the Rise site at 2500 m.

The $\delta^{13}C$ values for POC_{susp} spanned a 5‰ range in the upper water column (Fig. 2c), but had only about a 1‰ range below 1000 m depth. Minima in $\delta^{13}C$-POC_{susp} profiles at Stn M in both September 1994 and June 1995 corresponded to the approximate depth (85 m) of the chlorophyll maximum (Bianchi et al., 1998). During June 1995, Stn M $\delta^{13}C$ values were lower than those at the Rise or Upper Slope sites except at 1600 m where Stn M and Rise values were the same (as were their POC abundances at this depth, see Fig. 2b). This suggests the presence of a fraction of additional organic carbon, with higher $\delta^{13}C$ values, at the Rise and Upper Slope sites. In September 1994, $\delta^{13}C$ values at Stn M were 0.2–1.7‰ higher than those during June 1995 (except at 1200 m where they were 0.4‰ lower). These data were similar to those found for previous occupations of Stn M, which showed that below 700 m, $\delta^{13}C$ values increased with time over the calendar year (from February to October 1992) as did POC abundance (Druffel et al., 1996). Overall, $\delta^{13}C$ values during September 1994 and June 1995 were slightly lower than those found for the earlier Pulse cruises (Druffel et al., 1996). Whether this offset is due to El Nino conditions that predominated during the collection of the earlier data cannot be determined at this time.

Sedimentary organic carbon (SOC) $\Delta^{14}C$ results are shown in Table 2 and Fig. 3. The uppermost layer of sediment (0–1 cm) from the Rise and Upper Slope cores had SOC $\Delta^{14}C$ values of $-265 \pm 5‰$ and $-249 \pm 4‰$, respectively. These $\Delta^{14}C$ values are lower limits, as loss of surficial sediment and mixing of the upper few cm are

Table 2
Isotopic and concentrations data of SOC collected during June 1991 at Stn M ($\Delta^{14}C$ data were published in graphical form in Fig. 1 of Bauer et al. (1995) and during June 1995 at the Rise and Upper Slope sites.

Depth (cm)	UCID No.	CAMS No.	SOC Δ14C‰	± ‰	δ13C ‰	% Org Carbon
Stn M	P-7	1991 June				
0–0.25	357	5010	− 236	8	− 21.8	1.4
0.25–0.5	358	5022	− 243	6	–	1.4
0.5–0.75	359	5023	− 241	9	–	1.4
0.75–1	360	5024	− 244	9	–	1.4
1–1.25	361	5011	− 244	10	–	1.4
1.25–1.5	362	5025	− 238	5	–	1.4
2.5–3	363	5014	− 227	6	− 21.8	1.5
5.0–6.0	364	5026	− 206	8	− 21.8	1.4
9.0–10.0	365	5027	− 347	5	− 21.9	1.1
Rise	P-26	1995 June				
0.0–1.0	1472	29682	− 265	5	− 22.9	3.0
4.0–5.0	1474	29683	− 237	5	− 21.8	2.4
9.0–13.0	1476a	29684	− 313	4	− 21.6	2.1
9.0–13.0	1476b	29685	− 313	5	− 21.6	
Upper Slope P-26		1995 June				
0.0–1.0	1478	29686	− 249	4	− 22.1	1.5
4.0–5.0	1480	29687	− 273	5	− 21.7	1.7
9.0–13.0	1482	29688	− 287	4	− 21.9	1.6

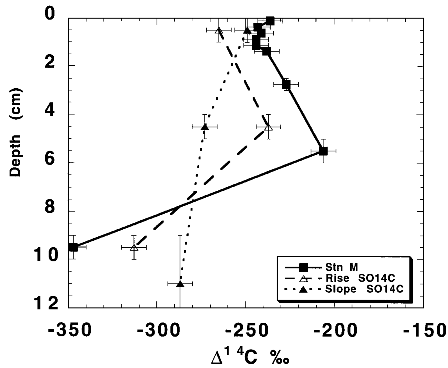


Fig. 3. $\Delta^{14}C$ of SOC from cores collected during June 1995 (Rise and Upper Slope) and June 1991 (Stn M) (data from Bauer et al., 1995).

common with gravity cores. We suspect that these effects are small in the Rise gravity core (see Section 2). These values are similar to those from Stn M surface sediment collected using a box core (FVGR, (Smith et al., 1994)) during June 1991 (Fig. 3). The three cores differed by 70‰ or less in the samples analyzed for this study.

4. Discussion

4.1. Relation of POC_{sink} flux rate to POC_{susp} $\Delta^{14}C$ signatures

Comparisons of POC_{susp} $\Delta^{14}C$ results obtained from Stn M in June 1995 with the seasonal profiles obtained previously for February, June and October 1992 and July 1993 (Druffel et al., 1996) are shown in Fig. 4a. In general, the June 1995 POC_{susp} $\Delta^{14}C$ profile resembles those from June 1992 and July 1993 (solid symbols in Fig. 4a). At most depths, the $\Delta^{14}C$ values for June 1995 are 20–30‰ lower than those from other times of the year (February and October 1992). Druffel et al. (1996) surmised that the small, but significant decrease in POC_{susp} $\Delta^{14}C$ with depth seasonally was likely due to either lateral transport of resuspended sediment from the continental shelf and slope during early summer or increased sorption of 'old' DOC onto POC_{susp} during the high flux time of the year (May–June). This was consistent with their observation of lower $\Delta^{14}C$ values in POC_{sink} during high flux periods ($>5\,mg\,C\,m^{-2}\,d^{-1}$) as well.

The preceding scenario does not appear to support the consistently high POC_{susp} $\Delta^{14}C$ values during September 1994 (Fig. 1a). One may have predicted $\Delta^{14}C$ values during September 1994 to have been low, as was observed for the early summers of 1992, 1993 and 1995 (Fig. 4a). In contrast, the $\Delta^{14}C$ values during September 1994 remained virtually unchanged from 85 m to 1600 m depth (Fig. 1a). There was an anomalously large flux of POC to the deep sea during July through September 1994 (5–25 mg C m^{-2} d^{-1} at 50 mab), whereas that during April through June 1995 was moderate in comparison (2–6 mg C m^{-2} d^{-1}) (Baldwin et al., 1998). In fact, the flux during summer 1994 was so high that the 600 and 650 mab traps were suspected to have been clogged with aggregate marine snow, preventing any material from collecting in the trap cups (Baldwin et al., 1998). As September 1994 was a period of anomalously high flux, the constant $\Delta^{14}C$ signature may have been due to a greater

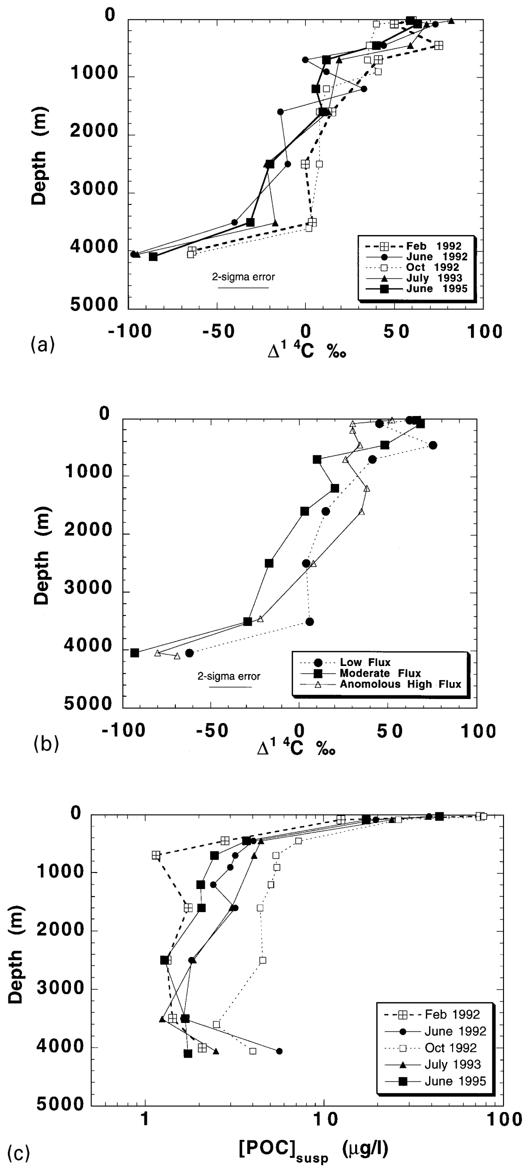


Fig. 4. (Continued).

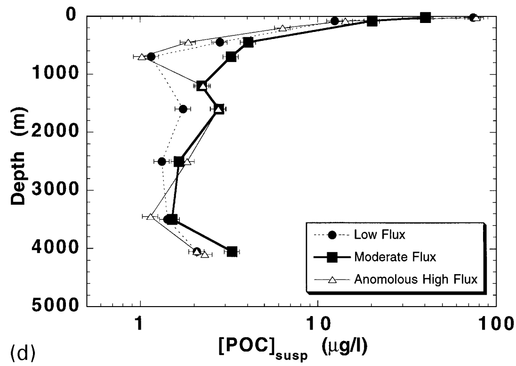


Fig. 4. (a) $\Delta^{14}C$ of POC_{susp} samples collected at Stn M during June 1995 and previously reported data by Druffel et al. (1996) from February 1992, June 1992, Oct 1992, and July 1993; (b) Average $\Delta^{14}C$ of POC_{susp} collected during periods of low flux (February 1992), moderate flux (averages of June 1992, July 1993, June 1995) and anomalously high flux (September 1994). The 2-sigma error bar represents the average uncertainty of individual values for each depth from a given category. (c) Concentration of POC (in μg/l) in samples described in (a). (d) Concentration of POC (in μg/l) in samples described in (b).

amount of surface-derived POC_{sink} having been transported downward where it disaggregated into 'young' POC_{susp}.

There appear to be three distinct POC_{susp} $\Delta^{14}C$ profiles (see Figs 4b): (1) a low flux period profile (February) that decreases from $40 \pm 20‰$ at 700 m to about 0‰ at 3450 m; (2) a moderate flux period profile of June–July which is relatively constant (10‰) between 700 to 1600 m and then decreases to $-30‰$ by 3450 m; and (3) an anomalously high flux period profile (i.e. September 1994) that is constant (32‰) between 85 and 1600 m and then decreases to $-25‰$ by 3450 m. There is considerable overlap among these three profiles, though significant differences ($>$ 2 sigma) are found at the following: (a) at 1600 m, during the anomolous high flux period, the $\Delta^{14}C$ value is 32‰ higher than the moderate flux profile at this depth; (b) at 2500, $\Delta^{14}C$ is 23–25‰ lower during moderate flux times than during other times of the year; and (c) at 3450 m $\Delta^{14}C$ is significantly higher (by 28–35‰) during the low flux period than at other times.

These differences could relate to the DIC cycle at Stn M given the $\Delta^{14}C$ variability that was present in the surface waters. Masiello et al. (1998) observed a 20‰ change in DIC $\Delta^{14}C$ that could be explained by seasonal changes in the mixed layer depth at Stn M as caused by changes in wind speed. The average of 11 DIC $\Delta^{14}C$ values in 25 m water from 10 cruises to Stn M was $70 \pm 8‰$, and the average of 7 POC $\Delta^{14}C$ values from the same depth from 7 cruises was $62 \pm 10‰$. At the 85 m depth, there is no obvious offset between the DIC and POC_{susp} $\Delta^{14}C$ values; the averages of the DIC $\Delta^{14}C$ values for 9 cruises is $56 \pm 17‰$ and of POC_{susp} $\Delta^{14}C$ values for 6 cruises is $54 \pm 17‰$. The POC_{susp} $\Delta^{14}C$ averages for both depths (25 and 85 m) are similar and are closer to the deeper DIC $\Delta^{14}C$ average, though both are within 2 sigma. This suggests that the POC_{susp} $\Delta^{14}C$ signature is derived from DIC closer to 85 m depth than that at 25 m. This establishes a general depth range from where the particle matter originates during photosynthesis, and represents the origin of its isotopic ratio.

The flux of sinking particles and exchange between POC_{sink} and POC_{susp} pools likely influenced the observed $\Delta^{14}C$ profiles of POC_{susp}. During the anomolously high flux period of September 1994, presumed high production in the surface water resulted in larger amounts of ^{14}C-enriched POM that sank through the water column. POC_{sink} likely broke down by biological (grazing) and chemical (dissolution) alteration at depth, and produced POC_{susp} that was more labile than that already present at depth. The high flux of a large portion of young POC_{sink} to mid-depths (1600 m) and continuous release of POC_{susp} could have resulted in a constant, high $\Delta^{14}C$ value (equal to that at the depth of origin, 85 m) for the POC_{susp}. In contrast, during normal and low flux periods, most POC produced in the surface water likely remineralizes to CO_2 in the upper ocean, and the POC_{susp} released reflects a less labile, more decomposed (and possibly lower $\Delta^{14}C$) organic material (Martin et al., 1987).

4.2. Seasonal variability of POC_{susp} abundance

The concentration of POC varied dramatically in the water column as a function of season (Fig. 4c). The POC concentration values in the deep water (> 700 m) increased over the course of 1992 by a factor of three (Druffel et al., 1996), and then decreased once again by February 1993 (Druffel, unpublished data). By July 1993, POC concentrations had increased to about the same range as that present in June 1992. In June 1995, POC concentrations were again in the same range as those that had been present during June–July of 1992 and 1993. The abundance of POC_{susp} during September 1994 was anomalous (Fig. 1b), in that it was very low in the upper water column (85–700 m) and increased to a maximum at 1600 m, even though the $\Delta^{14}C$ signature of all samples from 1600 m and shallower (to 85 m) were not significantly different. Average POC_{susp} abundance values are plotted for the three June/July sampling periods (moderate flux), along with those from September 1994 (Anomolous high flux), and February (low flux) (see Fig. 4d). Despite the factor of 3 difference between the abundance of POC_{susp} during October and February 1992, the $\Delta^{14}C$ values are virtually the same (Fig. 4a, c). This imperviousness of the POC_{susp} $\Delta^{14}C$ signature to its concentration indicates that the relative abundance of ‘old’ organic matter incorporated in the POC_{susp} is the same, regardless of standing stock of POC_{susp} (Druffel et al., 1996).

4.3. Comparison of slope – Stn M with Santa Monica Basin data

The POC_{susp} $\Delta^{14}C$ values obtained from our slope-rise-Stn M transect are compared with the only other coastal California values available, a site in the Santa Monica Basin (SMB, 33°50′N, 118°50′W) occupied during the California Basin Study CABS11 cruise in October 1986. The SMB values ranged from 110‰ in the surface (75 m depth) to − 50‰ at 700 m depth, and rose to 8‰ at 50 mab (900 m bottom depth) (Fig. 5). The upper two SMB values were 60–70‰ higher than our Upper Slope values. Twenty-four per mil of this difference can be accounted for from the lowering

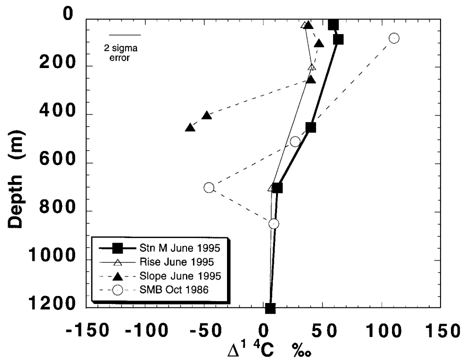


Fig. 5. $\Delta^{14}C$ of POC_{susp} collected from Stn M, Rise and Upper Slope sites during June 1995 (this work) and from the center of the Santa Monica Basin in October 1986 (data from Williams et al., 1992).

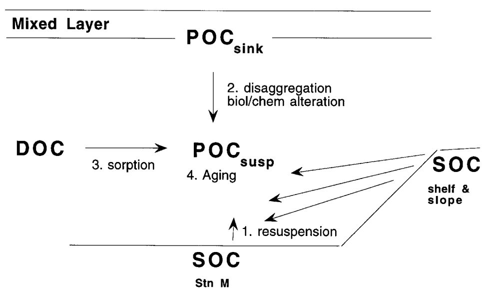


Fig. 6. Schematic showing four processes that can contribute to controlling the $\Delta^{14}C$ of POC_{susp} at Stn M.

of the DIC $\Delta^{14}C$ in the surface ocean between 1986 (94‰ at 5m (Williams et al., 1992) and 1995 (70‰ at 25 m; (Masiello et al., 1998)). The rest of the offset likely owes to resuspension of sediments that contain vastly different $\Delta^{14}C$ signatures (− 10 to − 35‰ and anaerobic in 0–1.25 cm depth at Santa Monica Basin, and − 242 ± 4‰ and aerobic in 0–1 cm depth at Upper Slope station) (Bauer et al., 1995; Williams et al., 1992).

4.4. Sources of old organic carbon to the POC_{susp} pool

What factors are responsible for the differences in the average POC_{susp} $\Delta^{14}C$ profiles shown in Fig. 4b? Fig. 6 shows a schematic representation of four mechanisms that are important for determining the $\Delta^{14}C$ of POC_{susp}. First, the magnitude and timing of input from resuspended sediment either locally or from the slope likely play significant roles in transporting old POC to the abyssal plain. Washburn et al. (1993) observed a turbidity layer between 200 and 260 m depth within an anticyclonic eddy off the coast of northern California during June and July of 1988 and concluded that it was the result of advection of resuspended sediments from the continental shelf into the deep ocean. They estimated that this cross-shelf sediment mass flux was a dominant feature during summer. This may be the coastal manifestation of an event similar to that which could provide resuspended sediment to Stn M.

Second, biological and chemical alteration and disaggregation of sinking particles to smaller, suspended particles is an important process that occurs in the open-ocean water column (McCave, 1984; Simpson, 1982). Wakeham and Canuel (1988) showed two, distinct, large sinking particle pools that are sampled separately by traps and situ pumps; one is dominated by zooplankton-derived compounds carried to the deep sea via fecal pellets (that fall into traps); the second is a phytoplankton-dominated source that sinks to the deep sea as marine snow and disaggregates to suspended particles, and is collected by in situ pumps. Smith et al. (1998) also observed increases in flocculent aggregate flux with no simultaneous increase in particulate fluxes in deep sediment traps at Stn M.

Third, the most abundant organic carbon fraction present in seawater is DOC (dissolved organic carbon), which is the material that passes a 1 μm filter. Its concentration in seawater ranges from 35–100 μM, compared to the concentration range for suspended POC of 0.5–10 μM. It has been hypothesized that the incorporation of DOC (7% of the POC_{susp} at 450 m and 12% of the POC_{susp} at 3450 m; Druffel et al., 1996), either by biological processes or physical, sorptive processes, could be a contributing factor in lowering the $\Delta^{14}C$ signature of POC in the deep sea (Druffel et al., 1992; 1996; Druffel and Williams, 1990). This hypothesis has not been proven, however.

Fourth, age of the particles is likely not a factor in changing the $\Delta^{14}C$ of suspended POC. Bacon and Anderson (1982) determined that the residence time of suspended particles in the open ocean is about 5–10 years, based on modeling of natural radionuclide distributions. Sherrell et al. (1998) observed significant seasonal variability in suspended particles at Stn M, and concluded that the residence time of suspended particles in this higher flux region is less than a year.

It is important to note that similar surface-to-deep gradients of POC_{susp} $\Delta^{14}C$ have been observed at two other open-ocean sites, where lateral input from the shelves is likely to be small (Druffel and Williams, 1990; Druffel et al., 1992, 1998). These gradients indicate that a vertical process is responsible for a large part of the surface-to-deep $\Delta^{14}C$ gradient at these mid-gyre sites in the North Pacific and North Atlantic, as well as at our near-continental site (Stn M).

In an effort to identify the true sources of the old carbon in the POC_{susp} pool, we plot $\Delta^{14}C$ vs POC_{susp} concentration for all of the profiles we have obtained to date at Stn M (Fig. 7a). Virtually all of the samples that were high in concentration (>4 μgC/l) also had high, post-bomb $\Delta^{14}C$ values ($\geqslant 10‰$). Four exceptions were the 50 mab samples taken from Stn M in June 1992 and October 1992, and the 50 and 100 mab samples from the Upper Slope site in June 1995 (see Fig. 7a). These four samples had very low $\Delta^{14}C$ values, between $-48‰$ and $-97‰$, and almost certainly contained resuspended material from the surface sediment. The samples containing less POC_{susp} (<3 μgC/l) and low $\Delta^{14}C$ values ($< -50‰$)(see Fig. 7a, lower left-hand points) are all from $\leqslant 100$ mab and likely contain resuspended surface sediment as well.

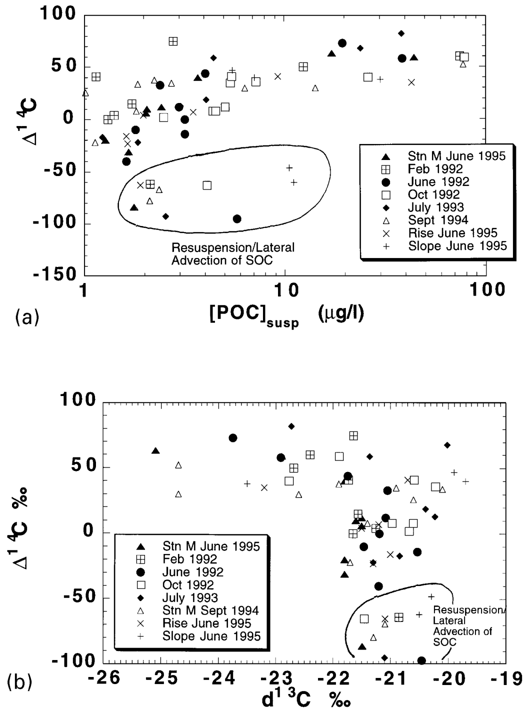


Fig. 7. (a) POC_{susp} $\Delta^{14}C$ values versus concentration on log scale. Values circled likely represent samples influenced by SOC resuspended or laterally advected from the continental slope; all are from depths $\leqslant$ 100 mab. (b) POC_{susp} $\Delta^{14}C$ vs. $\delta^{13}C$. Circled values likely represent samples influenced by SOC resuspended or laterally advected from the continental slope; all are from $\leqslant$ 100 mab.

Samples likely to be affected by resuspension are both high in $\delta^{13}C$ and low in $\Delta^{14}C$ (see circled points in Fig. 7b, all of which are from 1–100 mab). From this analysis, it appears that significant resuspension of SOC is localized to within a few hundred meters off the bottom. POC_{susp} collected from shallower depths all have higher $\Delta^{14}C$ values, suggesting surface-derived organic carbon as the primary source to shallower depths. This conclusion agrees with that of Bianchi et al. (1998) who found significant quantities of pyrophaeophorbide-a, a degradation product of chl a contained mainly in sediments, in samples that revealed low values POC_{susp} $\Delta^{14}C$ values (Fig. 7a).

4.5. Lateral transport of POC_{susp} from continental slope to abyssal ocean

The similarities of the Stn M and Rise POC_{susp} $\Delta^{14}C$ and POC concentration profiles (Fig. 2a and b) suggest that the suspended POC pool does not vary dramatically with distance from the continental rise to the abyssal ocean in the NE Pacific, though these two sites are only about 60 km apart. This could mean one of two things. First, it could indicate that lateral mixing of suspended POC is relatively rapid and thus important off this coast. Alternatively, a minimal lateral gradient in the abundance of suspended POC with distance from the coast could suggest that there was no concentrated source of slope particles to the abyssal ocean during June 1995. It is difficult to discern the relative importance of the lateral mixing component because we have data from only one time period.

There is, however, a lateral gradient in POC abundance near the bottom between the Upper Slope and Rise sites, indicating possible transport of POC_{susp} along the slope over a limited (i.e., near-bottom) depth range. More sites need to be occupied to assess the magnitude of this transport. Fig. 7a supports the contribution of resuspended sediment to the Upper Slope site and other sites. According to the property-to-property plots of Fig. 7, the transport of resuspended sediments appears to have been limited to depths within a few hundred meters of the bottom. It also seems unlikely that sediments would have been resuspended further up into the water column.

We conclude that, during June 1995, the evidence supports significant resuspension of organic carbon from the sediment surface, either locally near Stn M or from the slope to the deep-sea, at depths deeper than 3500 m. More observations during other seasons (i.e., fall, winter) are needed to determine the magnitude of this transport.

4.6. Sorption of DOC onto POC

As a surface-to-deep gradient of POC_{susp} $\Delta^{14}C$, similar in magnitude to that observed at Stn M, exists even in mid-gyre ocean locations (Druffel and Williams, 1990; Druffel et al., 1992, 1998), it is reasonable to assume that at least some of the lowering of $\Delta^{14}C$ is due to processes other than lateral transport of resuspended POC from the shelf and slope. We suggest that a plausible mechanism is sorption or biological incorporation of 'old' DOC onto POC_{susp}, though data do not presently exist to show the magnitude of this process toward lowering POC_{susp} $\Delta^{14}C$.

Smith et al. (1998) report the existence of detrital aggregates on the sediment surface at Stn M that are normally present from July through November. Beaulieu and Smith (1998) distinguish between discrete aggregates that are likely pteropod webs or larvacean houses that entrain suspended particles as they fall to the bottom, and 'rad mat' aggregates that are a conglomeration of floc material that has been on the bottom for days to weeks with new, freshly deposited material. Wang et al. (1996) reported $\Delta^{14}C$ measurements for two 'rad mat' detrital aggregates collected from Stn M during September 1994. The $\Delta^{14}C$ values of bulk organic carbon were $-170‰$ and $-200‰$ which are lower than sinking POC from a 650 mab sediment trap at Stn M (0–80‰) (Druffel et al., 1996) or the suspended POC during September 1994 ($-69‰$ at 1 mab, see Table 1), and higher than the top 5 mm of sediment ($-235‰$; (Bauer et al., 1995)). The low $\Delta^{14}C$ values of the detrital aggregates likely are explained by the incorporation of both sedimentary organic carbon on the ocean bottom, and DOC that sorbed onto the aggregate material during its transit through the water column. Shaw et al. (1998) report similar excess ^{234}Th activities (on a per mass basis) for both sinking particle matter and 'rad mat' detrital aggregates that originated from marine snow. This demonstrates that both of these particulate phases (sinking POC and detrital aggregates) contain fresh material from the euphotic zone (Th data), but the low $\Delta^{14}C$ values of the detrital aggregates indicate that an old carbon source is present as well, perhaps as SOC or DOC.

We hypothesize that the lowering of POC_{susp} $\Delta^{14}C$ values at Stn M during the 1994–1995 sampling periods is from two sources. First, the upper part (80–90%) of the water column at Stn M contains POC_{susp} that has been sorbed primarily with 'old' DOC. Second, POC_{susp} in the bottom part of the water column contains both the POC that had been sorbed with DOC in the upper water column, plus the resuspended sediment from local and/or shelf and slope sources.

4.7. *Estimates of relative fractions of 'old' carbon sources to suspended POC*

Estimates of the relative amounts of 'old' DOC sorbed onto POC_{susp} that originates in the upper 25–85 m ($\Delta^{14}C = 60‰$) are made based on the average $\Delta^{14}C$ values for POC_{susp} during early summer at three depths in the upper water column (50‰ at 450 m, 20‰ at 1600 m, and −20‰ at 2500 m, from Fig. 4b) and the average $\Delta^{14}C$ values for DOC at each of these depths (−450‰ at 450 m and −550‰ at 1600, and 2500 m; (Bauer et al., 1998a, b). The percentages of 'old' DOC on POC_{susp} at 450, 1600 and 2500 m depth needed to lower POC_{susp} $\Delta^{14}C$ to the observed values are 2, 7 and 13%, respectively. We assume that a constant 13% DOC is sorbed onto POC_{susp} in the lower part of the water column. We also assume that the average $\Delta^{14}C$ values for POC_{susp} during early summer are −31‰ at 3450 m, and −96‰ at 4050 m (from Fig. 4b) and that the average $\Delta^{14}C$ of resuspended sediment is −250‰ near Stn M. We calculate that the percentages of resuspended sediment organic carbon at 3450 and 4050 m depth needed to lower POC_{susp} $\Delta^{14}C$ to the observed values are 5 and 33%, respectively. The higher fraction of SOC in the suspended POC at 50 mab is in agreement with observations of higher particle flux at this depth as compared to that at 600 mab (Baldwin et al., 1998; Smith et al., 1994).

In summary, several co-occurring factors are probably operating at any point in time to give the observed POC_{susp} $\Delta^{14}C$ profiles. One explanation for the constant $\Delta^{14}C$ values of POC_{susp} between 85 and 1600 m in September 1994 is that large quantities of sinking POC could continuously release labile, ^{14}C-enriched POC_{susp} during biological and chemical alteration of the sinking POC. The radiocarbon evidence further suggests that the resuspension of organic carbon from the sediment surface, either locally or laterally transported from the slope to the deep sea is likely occurring, but is probably limited to depths deeper than 2500 m. We feel that sorption of 'old' DOC by suspended particulate matter in the water column is probably occurring, especially at shallower depths (< 3500 m), though proof of this mechanism cannot be demonstrated at this time.

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