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Dynamics of particle export on the Northwest Atlantic margin

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ABSTRACT

The Northwest Atlantic margin is characterized by high biological productivity in shelf and slope surface waters. In addition to carbon supply to underlying sediments, the persistent, intermediate depth nepheloid layers emanating from the continental shelves, and bottom nepheloid layers maintained by strong bottom currents associated with the southward flowing Deep Western Boundary Current (DWBC), provide conduits for export of organic carbon over the margin and/or to the interior ocean. As a part of a project to understand dynamics of particulate organic carbon (POC) cycling in this region, we examined the bulk and molecular properties of time-series sediment trap samples obtained at 968 m, 1976 m, and 2938 m depths from a bottom-tethered mooring on the New England slope (water depth, 2988 m). Frequent occurrences of higher fluxes in deep relative to shallower sediment traps and low $\Delta^{14}\text{C}$ values of sinking POC together provide strong evidence for significant lateral transport of aged organic matter over the margin. Comparison of biogeochemical properties such as aluminum concentration and flux, and iron concentration between samples intercepted at different depths shows that particles collected by the deepest trap had more complex sources than the shallower ones. These data also suggest that at least two modes of lateral transport exist over the New England margin. Based on radiocarbon mass balance, about 30% ($\pm 10\%$) of sinking POC in all sediment traps is estimated to be derived from lateral transport of resuspended sediment. A strong correlation between $\Delta^{14}\text{C}$ values and aluminum concentrations suggests that the aged organic matter is associated with lithogenic particles. Our results suggest that lateral transport of organic matter, particularly that resulting from sediment resuspension, should be considered in addition to vertical supply of organic matter derived from primary production, in order to understand carbon cycling and export over continental margins.

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1. Introduction

Continental margins account for 10–20% of marine primary production and 90% of organic carbon (OC) burial globally (Hedges, 1992; Behrenfeld and Falkowski, 1997). A fraction of OC produced on the margins is exported to the open ocean (Walsh et al., 1981; Churchill et al., 1994;

Bauer and Druffel, 1998). However, the mode of transport, the magnitude of export, and the type of OC that is exported (i.e., as dissolved or particulate OC, and whether it is marine or terrestrial in origin), remain uncertain. Particulate organic carbon (POC) in both suspended and sinking form is subject to entrainment and lateral transport in prevailing currents. Of particular interest as one mode of POC transport is post-depositional redistribution of POC by resuspension of surface sediment and lateral advection as clouds of enhanced particle concentration, forming either intermediate nepheloid layers (INLs) or bottom nepheloid layers (BNLs). Resuspension-deposition cycles and

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associated redistribution of POC affects the quality of POC by further oxic-degradation in the water column (Keil et al., 2004). Redistribution of POC also causes spatio-temporal offsets in sedimentary records, complicating interpretation of paleo-environmental proxies (Ohkouchi et al., 2002).

Lateral transport of POC over continental margins has been directly observed via optical transmissometry measurements (e.g., McCave, 1983; Churchill et al., 1988; McCave et al., 2001; Karakaş et al., 2006), abrupt increase in total mass flux during a short-term deployment of near-bottom sediment traps (Bonnin et al., 2002), and differences in shallow versus deep sediment trap fluxes (e.g., Honjo et al., 1982; Biscaye et al., 1988; Freudenthal et al., 2001). Indirect evidence for lateral POC supply includes an imbalance between carbon supply and oxygen consumption in deep-sea sediments (Jahnke, 1996), “old” ^{14}C ages of suspended and sinking POC (Druffel et al., 1998; Honda et al., 2000; Hwang et al., 2004, 2008, 2009), high aluminum concentrations in suspended and sinking particles (Sherrell et al., 1998; Honda et al., 2000; Hwang et al., 2008), and the isotopic and molecular composition of deep sea sediments (Benthien and Müller, 2000; Freudenthal et al., 2001; Ohkouchi et al., 2002; Mollenhauer et al., 2006).

To understand the dynamics of particle transport over the New England slope on the NW Atlantic margin, we have initiated a project to examine sinking particles, suspended particles, and underlying sediments in this region. Previous programs such as SEEP-I (Shelf Edge Exchange Processes) showed that lateral advection of particles is prevalent on the New England shelf/slope [see Walsh et al., (1988) and a special volume (Vol. 8) in *Continental Shelf Research* for more details]. During SEEP-I, the major focus was given to export of freshly produced organic matter on the shelf to the slope, and consequently the shelf, shelf break, and upper- and middle-slope region was studied intensively. In addition to across-shelf export, several lines of evidence suggest that along-slope lateral transport over the NW Atlantic margin may be prevalent. These include: (i) Unsaturation indices and corresponding ^{14}C ages, and hydrogen isotopic compositions of alkenone lipid biomarker compounds in sediments from Bermuda Rise indicate that a large fraction of OC was produced in and transported from cooler surface waters to the north (Ohkouchi et al., 2002; Englebrecht and Sachs, 2005; Ohkouchi et al., submitted); (ii) The NW Atlantic margin is bathed by the southward flowing Deep Western Boundary Current (DWBC), whose mean flow is sufficient to resuspend and entrain fine grained sediments and particle aggregates (McCave and Tucholke, 1986). The Gulf Stream, including its warm and cold rings, also exerts an influence on the seabed, either directly or by its interaction with the DWBC, resulting in high abyssal kinetic energies (Weatherly and Kelley, 1985). In the NW Atlantic, a region of high abyssal kinetic energy extends from the Gulf Stream to the Nova Scotian margin, where it may intermittently augment the mean flow of the DWBC (Hollister and McCave, 1984). Here, frequent “benthic storms”, made famous by project HEBBLE [High Energy Benthic Boundary Layer Experiment (Hollister and Nowell,

1991)] scour the continental slope with near-bottom current velocities that often reach the threshold for resuspension of organic aggregates ($9\text{--}23\text{ cm s}^{-1}$; Lampitt, 1985; Thomsen and Gust, 2000), leading to one of the best developed BNLs in the Atlantic (Biscaye and Eitrem, 1977); (iii) Upslope and immediately adjacent to the DWBC are the highly productive waters of the Scotian shelf, Gulf of Maine, and the Middle Atlantic Bight. Organic-laden particles exiting the shelf and upper slope have the potential to be entrained in, and redistributed by, the DWBC, resulting in along-slope transport. Interactions between DWBC and the Gulf Stream create deep circulation gyres (Schmitz Jr. and McCartney, 1993) that can transport particles to the ocean interior basin (McCave and Tucholke, 1986). Accordingly, climate-driven variations in the strength and trajectory of the DWBC may influence the magnitude of carbon export.

Although the impact of the DWBC and associated currents have long been recognized to shape much of the sediment drape over the western North Atlantic Basin (McCave and Tucholke, 1986), its influence on POC export has not been examined in detail. We hypothesize that both down- and along-slope transport on the NW Atlantic margin may be an important, variable, and possibly a climatically-controlled vehicle for redistributing shelf-derived POC over varying spatial scales, ultimately sequestering it in the deep sea. We speculate that sediments are sporadically resuspended in the vicinity of the Laurentian Fan (Gardner and Sullivan, 1981; McCave, 1983; Hollister and Nowell, 1991), and are gradually transported along-slope by the prevailing southward flowing currents. During transit, the suspended material is augmented by POC exiting the shelf from the Canadian maritime provinces and the Middle Atlantic Bight as bottom and/or intermediate nepheloid layers as well as from the overlying surface waters. The advected sediment is either redeposited in areas with slower current velocity adjacent to the core of the DWBC or entrained within the recirculation gyres (Hogg et al., 1986) and deposited in the abyssal ocean (McCave, 1983). The overall magnitude of OC export and the extent to which OC is carried by these advective processes is able to survive lateral transport, remains unknown. However, evidence from the Bermuda Rise suggests that up to 80% of the POC accumulating there is margin-derived (Ohkouchi et al., 2002, submitted).

Our study site is located northeast of the SEEP-I transect. It was chosen to align closely with the “Line W” physical oceanographic observation program that provides hydrographic context for the samples collected and also an assessment of the dynamics of the particle field in the vicinity of the DWBC on the New England slope (<http://www.whoi.edu/science/PO/linew/> accessed on July 2 2008). The major focus of our study was to answer the following questions: (1) Is the DWBC a significant conduit for along-margin transport of OC on fine-grained particles? (2) What is the source of organic matter deposited in the vicinity of the DWBC? (3) Does advective transport vary over short timescales and what is its relationship to hydrographic properties? In this paper, we focus on biogeochemical properties of sinking particles

intercepted at three depths in the water column by a sediment trap mooring on the 3000 m isobath deployed from summer 2004 to spring 2005. Sources of suspended POC constrained by molecular and isotopic properties in the study area are reported separately (Hwang et al., 2009).

2. Methods

Three conical sediment traps [McLane Mark-7, (Honjo and Doherty, 1988)] were deployed at three depths – 968 m (hereafter top trap), 1976 m (hereafter middle trap), and 2938 m (50 m above the bottom, hereafter bottom trap) – from June 27, 2004 to April 27, 2005 on the NW Atlantic margin at a water depth of 2988 m (39°28'N, 68°22'W; Fig. 1). The sediment trap carousels were programmed to open each collection cup for 23.4 days for the top trap and 14.5 days for the other two traps, resulting in total 13 samples from the top trap and 21 samples each from the middle and bottom traps. NaCl (about 5 g/L) was added to seawater that was used to fill the sampling cups. Sampling cups of the top and middle traps were filled with seawater treated with various preservatives such as HgCl₂, formalin, Lugol's solution, DMSO (dimethyl sulfoxide), and HISTOCHOICE™ for the purpose of testing their relative efficiency of DNA preservation (not discussed further in this paper; see

Table 1 for details). Sampling cups of the bottom trap were filled with seawater treated with HgCl₂ (0.3% by wt) only. Samples were stored at 4 °C until subsampling and further analyses. At Woods Hole Oceanographic Institution (WHOI), samples were separated into two size fractions, >1 mm and <1 mm. Each sample <1 mm was divided into ten equal aliquots in 40 ml vials using a wet sample splitter (WSD-10, McLane Research Laboratories, Inc.). For further chemical analyses, fractions smaller than 1 mm were used.

Samples for elemental analyses were deposited on pre-weighed 25 mm or 47 mm polycarbonate filters, rinsed with MQ water and then air-dried at 60 °C overnight. The mass of both size-fractions was determined for flux determination. Total carbon and nitrogen were analyzed using a Perkin-Elmer 2400 C-H-N analyzer. Total inorganic carbon was analyzed by coulometric titration (UIC Coloumetrics equipped with an acidification module CM5130) and organic carbon content was estimated as the difference between the total carbon and total inorganic carbon. Concentrations of elements (Al, Ca, Fe, and Si) were measured by ICP-ES (Jobin-Yvon Horiba ULTIMA2; Honjo et al., 1995). Concentrations of lithogenic particles, biogenic opal, and CaCO₃ were estimated from Al, Si, and Ca concentrations (Taylor and McLennan, 1985; Honjo et al., 1995). Briefly, lithogenic particle concentration was estimated by multiplying the Al concentration by 12.15. Organic matter was estimated by multiplying the POC

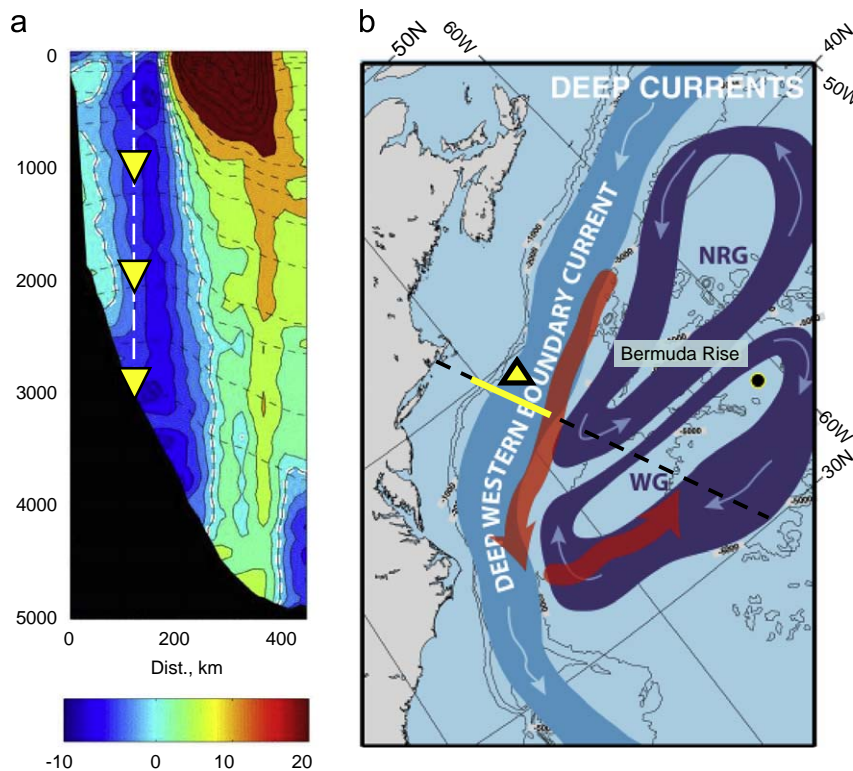


Fig. 1. a) Average normal current velocity (reproduced from Joyce et al., 2005) along a transect shown on b). The vertical dashed straight line indicates the position of the sediment trap mooring. b) A map showing sampling location (triangle) and the general current system in the NW Atlantic margin. The red arrow represents one potential mode of POC export from the margin to the deep NW Atlantic basin via deep currents. The Northern Recirculation Gyre (NRG) and the Worthington Gyre (WG) are also featured.

Table 1
Biogeochemical properties of sinking particles intercepted at three depths on the NW Atlantic margin.

Depth (m)	Cup #	Preservatives	Mid date	Mass flux > 1 mm (mg m ⁻² d ⁻¹)	Mass flux < 1 mm (mg m ⁻² d ⁻¹)	POC flux (mgCm ⁻² d ⁻¹)	Al flux (mg m ⁻² d ⁻¹)	Δ ¹⁴ C (‰)	δ ¹³ C (‰)	% long-chain FAs
968	1	HgCl ₂	07/08/04	150.7	233.4	31.4	1.1	53	-22.0	0.0
968	2	Formalin	08/01/04	7.9	154.2	9.9	2.5	22	-22.4	6.3
968	3	Lugol's	08/24/04	7.2	142.1	10.5	2.2			9.0
968	4	DMSO	09/16/04	13.7	66.2					3.9
968	5	HgCl ₂	10/10/04	19.0	212.9	15.6	4.4			6.4
968	6	Histochoice	11/02/04	16.8	397.4	32.5	10.6			2.7
968	7	HgCl ₂	11/26/04	6.6	288.9	12.7	6.9	4	-22.1	8.9
968	8	Formalin	12/19/04	14.9	191.2	10.0	4.0	7	-21.9	4.1
968	9	Lugol's	01/11/05	2.3	115.7	8.0	3.0			4.4
968	10	DMSO	02/04/05	5.3	95.7					5.7
968	11	HgCl ₂	02/27/05	2.7	287.5	13.6	11.8			5.5
968	12	Histochoice	03/22/05	9.9	253.3	17.0	3.2			1.8
968	13	HgCl ₂	04/15/05	38.9	281.8	21.5	2.0	28	-19.4	2.5
		Average		22.8	209.3	16.6	4.7	23	-21.6	4.7
		Stdev		39.6	93.8	8.5	3.6	20	1.2	2.6
1976	1	HgCl ₂	07/04/04	1.4	131.6	5.6	1.9	13	-21.9	3.2
1976	2	Formalin	07/18/04	1.0	70.8	4.0	1.2	-3	-22.0	3.4
1976	3	Lugol's	08/02/04	7.8	112.1	6.4	2.3			2.7
1976	4	DMSO	08/16/04	3.6	46.8					7.4
1976	5	HgCl ₂	08/31/04	13.0	134.5	6.8	2.4			5.0
1976	6	Histochoice	09/14/04	8.1	301.3					12.4
1976	7	HgCl ₂	09/29/04	15.5	121.8	8.7	1.9	-1	-21.8	6.0
1976	8	HgCl ₂	10/13/04	17.7	163.9	8.7	3.9	9	-21.8	10.7
1976	9	HgCl ₂	10/28/04	2.4	124.1	6.9	3.5	5	-21.4	25.2
1976	10	HgCl ₂	11/11/04	11.2	324.4	19.5	8.5	10	-21.4	7.2
1976	11	HgCl ₂	11/26/04	1.1	97.3	3.9	1.6	15	-18.5	21.1
1976	12	HgCl ₂	12/10/04	8.3	158.0	10.7	3.6	-9	-21.8	9.2
1976	13	HgCl ₂	12/24/04	2.6	88.5	5.5	1.9	-10	-21.7	7.7
1976	14	HgCl ₂	01/08/05	5.4	114.6	6.6	2.9	-14	-21.5	11.5
1976	15	HgCl ₂	01/22/05	1.8	110.9	6.6	3.0	-11	-21.9	9.6
1976	16	Formalin	02/06/05	1.9	99.9	4.1	4.0	-41	-22.6	15.2
1976	17	Lugol's	02/20/05	4.4	265.7	11.5	14.9			6.0
1976	18	DMSO	03/07/05	2.1	137.3					11.5
1976	19	HgCl ₂	03/21/05	4.3	106.5	5.5	2.0			5.8
1976	20	Histochoice	04/05/05	18.2	373.6					2.7
1976	21	HgCl ₂	04/19/05	17.2	382.5	37.4	4.8	33	-19.0	4.3
		Average		7.1	165.1	9.3	3.8	0	-21.3	8.9
		Stdev		6.0	100.1	8.2	3.3	18	1.2	5.9
2938	1	HgCl ₂	07/04/04	3.2	128.4	4.3	3.1	5	-21.8	1.1
2938	2	HgCl ₂	07/18/04	2.5	211.3	5.0	9.4	-42	-21.7	13.8
2938	3	HgCl ₂	08/02/04	5.8	151.8	6.6	4.0	-9	-21.7	13.2
2938	4	HgCl ₂	08/16/04	4.5	118.4	5.6	3.2	-18	-21.8	15.6
2938	5	HgCl ₂	08/31/04	10.0	307.3	9.8	11.0	-34	-21.6	10.4
2938	6	HgCl ₂	09/14/04	10.0	165.7	7.8	5.0	-13	-21.7	24.0
2938	7	HgCl ₂	09/29/04	13.8	139.7	7.2	3.4	15	-21.6	1.4
2938	8	HgCl ₂	10/13/04	11.2	385.0	11.6	16.5	-41	-21.6	4.2
2938	9	HgCl ₂	10/28/04	8.0	372.1	13.3	14.1	-45	-21.4	22.7
2938	10	HgCl ₂	11/11/04	6.9	262.9	11.0	9.8	-24	-21.6	21.4
2938	11	HgCl ₂	11/26/04	4.1	406.2	10.8	18.1	-52	-21.6	15.1
2938	12	HgCl ₂	12/10/04	5.9	265.0	9.4	10.9	-24	-21.6	17.1
2938	13	HgCl ₂	12/24/04	3.8	173.1	6.5	6.7	-37	-21.7	17.1
2938	14	HgCl ₂	01/08/05	7.4	182.6	6.8	6.9	-16	-21.6	16.4
2938	15	HgCl ₂	01/22/05	2.9	158.0	6.6	5.7	-15	-22.1	19.0
2938	16	HgCl ₂	02/06/05	3.3	152.2	5.7	6.5	-43	-21.9	14.5
2938	17	HgCl ₂	02/20/05	1.6	158.9	6.6	6.6	-49	-22.1	23.2
2938	18	HgCl ₂	03/07/05	1.4	151.5	6.5	5.2	-30	-21.8	15.5
2938	19	HgCl ₂	03/21/05	2.6	152.5	6.4	4.2	-14	-21.6	25.6
2938	20	HgCl ₂	04/05/05	9.8	302.7	22.2	6.6	14	-20.3	4.9
2938	21	HgCl ₂	04/19/05	26.4	399.3	39.7	6.8	30	-18.6	7.8
		Average		6.9	225.9	10.0	7.8	-21	-21.5	14.5
		Stdev		5.7	98.1	7.9	4.3	23	0.7	7.3

Table 1 (continued)

Depth m	Cup #	TC %	TN %	PIC %	POC %	OC/ TN molar	Al %	Ca %	Si %	Fe %	POM %	CaCO ₃ %	OPAL %	Lithogenic %	Molar biogenic Si/Ca
968	1	17.7	1.9	4.2	13.5	8.3	0.5	14.3	5.1	0.2	33.7	35.1	8.2	5.8	0.3
968	2	12.6	0.8	6.2	6.4	8.8	1.6	21.4	12.6	0.8	16.0	51.5	16.9	19.4	0.5
968	3	13.7	1.0	6.3	7.4	8.7	1.6	21.8	11.2	0.8	18.4	52.5	13.8	18.8	0.4
968	4	17.3	2.2												
968	5	13.1	1.0	5.7	7.3	8.9	2.1	20.2	11.5	1.1	18.3	47.9	10.2	25.2	0.3
968	6	11.8	1.1	3.7	8.2	8.4	2.7	13.5	14.1	1.3	20.4	30.5	11.5	32.3	0.6
968	7	10.0	0.7	5.6	4.4	6.9	2.4	19.8	16.4	1.0	11.0	46.6	19.2	29.2	0.6
968	8	11.5	0.8	6.3	5.2	7.3	2.1	22.0	14.6	1.1	13.1	52.4	17.5	25.3	0.5
968	9	10.9	0.9	4.0	6.9	9.1	2.6	14.5	13.7	1.2	17.2	33.0	10.9	31.9	0.5
968	10	7.7	1.1												
968	11	7.5	0.6	2.7	4.7	8.9	4.1	11.2	24.4	2.5	11.8	22.8	24.0	49.9	1.6
968	12	9.3	0.9	2.6	6.7	8.5	1.3	9.1	19.4	0.6	16.8	21.3	35.9	15.4	2.5
968	13	10.8	1.0	3.2	7.6	8.9	0.7	11.1	16.9	0.4	19.0	26.9	34.4	8.8	1.9
	Average	11.8	1.1	4.6	7.1	8.4	2.0	16.3	14.5	1.0	17.8	38.2	18.4	23.8	0.9
	Stdev	3.1	0.4	1.5	2.4	0.7	1.0	4.9	4.9	0.6	6.1	12.2	9.4	12.3	0.8
1976	1	10.8	0.6	6.5	4.3	8.9	1.5	22.4	12.8	0.8	10.7	54.2	18.6	17.7	0.5
1976	2	11.2	0.5	5.6	5.7	12.2	1.7	19.3	9.8	0.8	14.2	46.3	9.5	20.3	0.3
1976	3	10.5	0.6	4.8	5.7	11.6	2.0	16.9	12.3	0.9	14.3	39.8	12.4	24.7	0.5
1976	4	9.8	1.2												
1976	5	11.7	0.7	6.6	5.1	8.9	1.8	22.9	10.8	0.9	12.6	55.1	11.0	21.7	0.3
1976	6	12.1	3.1												0.3
1976	7	12.4	0.7	5.3	7.1	11.4	1.5	18.4	8.5	0.8	17.8	44.1	7.7	18.5	0.3
1976	8	11.2	0.6	5.9	5.3	9.6	2.4	20.8	11.9	1.2	13.2	49.1	8.8	28.6	0.3
1976	9	9.9	0.6	4.3	5.6	11.5	2.8	15.7	11.8	1.3	13.9	35.7	4.7	34.2	0.2
1976	10	9.9	0.6	3.9	6.0	11.1	2.6	14.4	12.8	1.3	15.0	32.7	8.7	31.7	0.4
1976	11	10.9	0.6	6.9	4.0	8.5	1.6	23.7	10.3	0.9	10.1	57.3	11.1	19.9	0.3
1976	12	10.4	0.7	3.7	6.8	10.8	2.3	13.3	12.7	1.2	16.9	30.4	11.1	28.0	0.5
1976	13	10.5	0.6	4.3	6.2	12.8	2.1	15.3	10.9	1.1	15.5	35.7	8.3	25.9	0.3
1976	14	10.1	0.6	4.4	5.7	11.7	2.5	15.9	11.7	1.3	14.3	36.5	7.2	30.3	0.3
1976	15	9.8	0.7	3.9	5.9	10.6	2.7	14.2	12.7	1.4	14.8	32.2	7.6	33.0	0.4
1976	16	8.9	0.6	4.8	4.1	8.1	4.0	18.0	22.2	2.8	10.3	40.0	19.9	48.4	0.7
1976	17	7.0	0.6	2.6	4.3	8.9	5.6	11.5	24.0	3.4	10.9	21.7	10.3	68.3	0.7
1976	18	5.4	0.7												
1976	19	9.3	0.6	4.2	5.1	10.8	1.9	15.0	12.6	1.0	12.8	35.1	14.3	23.2	0.6
1976	20	11.1	2.3												1.3
1976	21	12.8	1.2	3.0	9.8	9.6	1.2	10.6	19.0	0.7	24.4	24.8	35.0	15.2	2.1
	Average	10.3	0.9	4.7	5.7	10.4	2.4	17.0	13.3	1.3	14.2	39.4	12.1	28.8	0.5
	Stdev	1.7	0.7	1.2	1.4	1.4	1.1	3.9	4.3	0.7	3.4	10.3	7.1	12.9	0.5
2938	1	9.0	0.3	5.6	3.4	12.4	2.4	20.0	12.8	1.4	8.4	46.9	10.4	29.3	0.3
2938	2	6.8	0.3	4.4	2.4	9.9	4.5	17.0	18.8	2.6	5.9	36.9	7.6	54.3	0.3
2938	3	8.4	0.4	4.1	4.4	13.2	2.7	14.9	13.6	1.4	10.9	33.9	10.2	32.3	0.5
2938	4	8.6	0.5	3.8	4.8	12.0	2.7	14.1	13.6	1.5	11.9	31.8	10.2	32.5	0.5
2938	5	7.3	0.4	4.1	3.2	10.5	3.6	15.6	14.5	2.0	8.0	34.5	4.8	43.5	0.2
2938	6	8.4	0.4	3.7	4.7	13.2	3.0	13.8	12.8	1.7	11.8	30.6	5.4	36.6	0.3
2938	7	9.4	0.5	4.3	5.1	12.2	2.4	15.5	11.3	1.4	12.8	35.6	6.5	29.8	0.3
2938	8	6.9	0.4	3.9	3.0	9.8	4.3	15.2	16.7	2.5	7.5	32.5	4.1	52.2	0.2
2938	9	6.5	0.3	2.9	3.6	12.6	3.8	11.6	15.4	2.2	8.9	24.2	5.2	46.0	0.3
2938	10	7.4	0.4	3.2	4.2	11.9	3.7	12.4	15.5	2.3	10.5	26.3	5.9	45.3	0.3
2938	11	6.5	0.3	3.9	2.7	10.9	4.5	15.1	17.0	2.6	6.7	32.3	3.4	54.2	0.2
2938	12	6.9	0.4	3.3	3.5	10.8	4.1	13.1	15.8	2.5	8.9	27.7	3.3	50.1	0.2
2938	13	7.2	0.3	3.4	3.8	12.7	3.9	13.4	16.2	2.4	9.4	28.6	6.4	46.9	0.3
2938	14	7.5	0.4	3.8	3.7	11.2	3.8	14.5	15.9	2.2	9.4	31.5	6.7	45.6	0.3
2938	15	7.9	0.4	3.7	4.1	11.5	3.6	14.2	15.4	2.0	10.4	30.9	6.7	43.8	0.3
2938	16	7.2	0.4	3.4	3.7	10.4	4.3	13.6	17.2	2.5	9.3	28.6	5.4	52.0	0.3
2938	17	6.8	0.4	2.6	4.1	11.5	4.2	10.9	15.6	2.6	10.3	22.1	2.6	50.4	0.2
2938	18	7.5	0.5	3.2	4.3	10.9	3.4	12.4	14.7	2.2	10.8	26.8	6.4	41.9	0.4
2938	19	8.1	0.4	3.9	4.2	11.3	2.7	14.4	14.5	1.7	10.5	32.6	11.8	33.3	0.5
2938	20	10.4	0.9	3.1	7.3	9.9	2.2	11.3	17.2	1.3	18.4	25.5	23.0	26.5	1.3
2938	21	12.4	1.1	2.4	10.0	10.5	1.7	8.9	16.2	1.0	24.9	20.2	24.7	20.5	1.8
	Average	8.0	0.4	3.7	4.3	11.4	3.4	13.9	15.3	2.0	10.7	30.5	8.1	41.3	0.4
	Stdev	1.4	0.2	0.7	1.7	1.1	0.8	2.3	1.8	0.5	4.1	5.8	5.8	10.0	0.4

concentration by 2.5. Opal concentration was estimated by multiplying the biogenic Si concentration by 2.4 (the latter is calculated as the difference between total Si and lithogenic Si = $3.5 \times \text{Al}$). Biogenic CaCO₃ was estimated by

multiplying the biogenic Ca concentration by 2.5 (the latter is calculated as the difference between total Ca and lithogenic Ca = $0.5 \times \text{Al}$). The samples in the top and middle traps treated with DMSO and Histochoice gave

unusually low values for Ca, and for Al, Si, and Ca, respectively. These six samples were therefore disregarded.

Only samples poisoned with HgCl₂ or formalin were used for carbon isotope measurements. Fractions smaller than 1 mm were used except for 5 samples that were subsampled before size-fractionation (top trap samples #1, 5, 13; bottom trap samples #5, 11). Supernatant seawater was removed from the vials and the residues were then freeze-dried. Samples treated with formalin were rinsed with MQ water three times before freeze-drying to remove formaldehyde. After rinsing with MQ water and freeze-drying, the effect of any residual formaldehyde on ¹⁴C determination appears negligible. Dried samples were spread on petri-dishes and exposed to concentrated HCl vapor in a desiccator for ~12 hours to remove inorganic carbon (Hedges and Stern, 1984). Each HCl-fumed sample was packed in doubled quartz tubes with CuO and silver wires, evacuated, flame-sealed, then combusted at 850 °C for 5 hours. Produced CO₂ gas was cryogenically purified. Carbon isotope ratios were measured at the National Ocean Sciences AMS facility at WHOI (McNichol et al., 1994). Two duplicate radiocarbon analyses yielded Δ¹⁴C values that agreed within ±3%. Empirical precision for sinking POC is considered smaller than ±10%.

About 10 to 350 mg freeze-dried samples were used for *n*-alkanoic acid analysis. Total lipid extracts were obtained using a mixture of methylene chloride and methanol (93:7 by volume) in an accelerated solvent extraction system (DIONEX ASE 200). Total lipid extracts were saponified in ~10 ml of 6% KOH in methanol at 80 °C for 2 hours. A neutral lipid fraction was obtained by liquid-liquid extraction with hexane. Following the isolation of the neutral fraction from each saponified sample, the aqueous phase was acidified (pH <1) with concentrated HCl and an acidic fraction was obtained by partitioning into hexane: methylene chloride (4:1 by volume, at least 3 times). The acidic fraction was methylated in 5% HCl/methanol at 70 °C for about 12 hours (or overnight). Fatty acids (FAs) were then quantified via flame ionization detection (FID) as their corresponding fatty acid methyl esters (FAMES) with a gas chromatograph (GC) equipped with a 30 m capillary column (Varian, CP-SIL 5CB, 30 m × 0.25 mm ID × 0.25 μm film thickness). The FAMES were identified using a Supelco FAME standard (catalog number 18918-1AMP). Although the concentrations of FAMES were not converted to those of FAs, this causes <7% error which is within the uncertainty range for this analysis. A chain-length index (% long-chain FAs) was derived as the percentage of saturated even-numbered long-chain FAs (24 ≤ carbon number ≤ 30) relative to total saturated even-numbered FAs (14 ≤ carbon number ≤ 30) (Bourbonniere and Meyers, 1996). Recovery efficiencies of the extraction process (by addition of an internal standard) were not determined because of potential subsequent use of the samples for carbon isotopic analysis. However, % long-chain FAs, a relative property, has a much smaller uncertainty than the concentration because of the high degree of internal GC reproducibility.

3. Results

3.1. Mass flux

Over the duration of the sediment trap mooring deployment, the flux of particles smaller than 1 mm ranged between 50 and 406 mg m⁻² d⁻¹ (Fig. 2a). In general, mass flux was highest from October to early December, and in March and April. Variability in the flux to the top trap appears to be smaller than those to the other two traps, in spite of the fact that each sample in the top trap integrated over longer time intervals (23 days compared to 14.5 days). The flux for the top trap appears to be bimodal with high values at the beginning and the end of the sampling period and one maximum in October/November. In contrast, the middle and bottom traps exhibited sporadic peaks that lasted for a single sampling interval (i.e., 14.5 days). With the exception of the peaks in April, intervals of high flux at each trap depth were also temporally decoupled. This decoupling in fluxes is most apparent between the middle trap and the bottom trap. Average mass flux was the lowest to the middle trap (165 ± 100 mg m⁻² d⁻¹), whereas those of the top and the bottom traps were similar in magnitude (209 ± 94 and 226 ± 198, respectively). These mass fluxes to meso and bathypelagic waters on the New England slope are among the highest values observed at corresponding water depths globally (Honjo et al., 2008).

The flux of particles larger than 1 mm was low throughout the sampling period (average <23 mg m⁻² d⁻¹) except for the first and the last samples in the top trap where it accounted for 39% and 12% of the total flux, respectively (Table 1). On average, the flux of particles larger than 1 mm accounted for 9 ± 10% (6 ± 5% when the first sample is excluded—see discussion below), 4 ± 3%, and 3 ± 2% of the total flux to the top, middle, and bottom traps, respectively.

3.2. POC flux and Concentration (%POC)

The average POC flux was 16.6 ± 9 mgC m⁻² d⁻¹ at 968 m and was lower at greater depths (9 ± 8, and 10 ± 8 mgC m⁻² d⁻¹ at 1976 m and 2938 m, respectively) (Fig. 2b). The POC flux at 2938 m (3.65 g m⁻² yr⁻¹) ranks among the highest for the bathypelagic zone of the open ocean [global average = 1.0 g m⁻² yr⁻¹, (Honjo et al., 2008)]. Primary production on the New England slope estimated from SeaWiFS chlorophyll concentration is about 1000 mgC m⁻² d⁻¹ (Mouw and Yoder, 2005) and new production in the 30 m-thick mixed layer estimated from nitrate profiles is about 70 mgC m⁻² d⁻¹ (Bisagni, 2003). The observed POC flux at 968 m therefore corresponds to ~25% of the new production. The POC flux showed a different pattern from that of total mass flux in several respects. First, temporal variation of POC flux was much smaller than that of mass flux, especially for the bottom trap. POC flux was lower than 15 mgC m⁻² d⁻¹ except for a few distinctly higher values at the beginning and at the end of the study period, and in October/November. High sinking particle flux peaks observed in

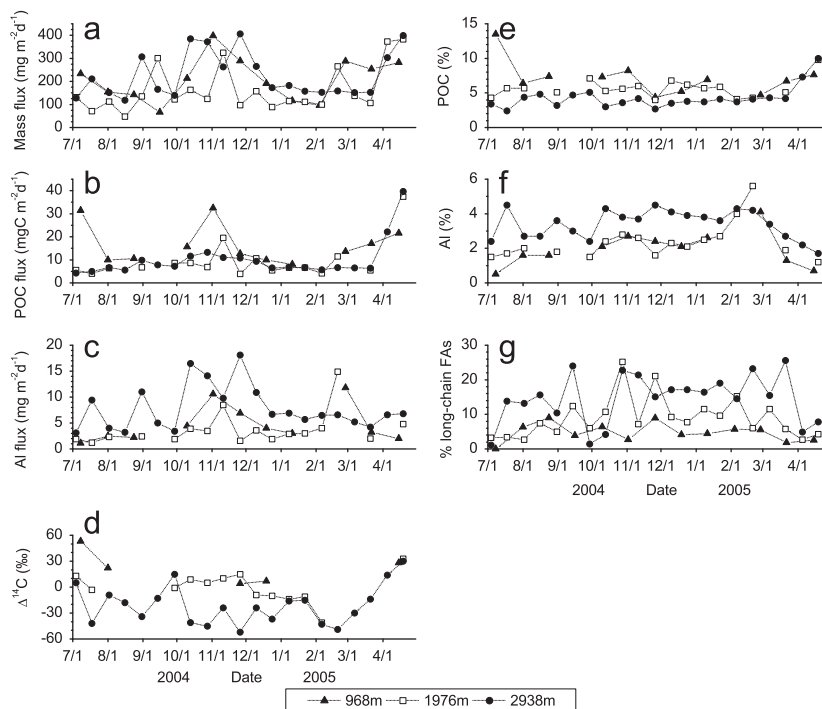


Fig. 2. Biogeochemical properties of sinking particles intercepted at three depths, 968 m, 1976 m, and 2938 m, from June 27, 2004 to April 27, 2005. The bottom trap was 50 m above the bottom. Biogeochemical properties were measured on the particles smaller than 1 mm. a) mass flux ($\text{mg m}^{-2} \text{d}^{-1}$), b) POC flux ($\text{mgC m}^{-2} \text{d}^{-1}$), c) aluminum flux ($\text{mg m}^{-2} \text{d}^{-1}$), d) $\Delta^{14}\text{C}$ values (‰), e) POC concentration (%), f) aluminum concentration (%), and g) proportions of long-chain fatty acids (%).

October/November in the bottom trap were noticeably muted for corresponding POC flux because of low %POC for those samples. Second, the average POC flux was the highest for the top trap, whereas the mass flux was the highest for the bottom trap.

%POC ranged mostly between 2% and 8%, except for the first and the last samples (Fig. 2e). For the top trap, %POC varied between 4% and 8% with the exception of the extremely high value of sample #1 (13.5%). This high value appears decoupled from the middle and bottom trap samples from the same time interval. Cup #1 of the top trap was filled with macro-zooplankton and the HgCl_2 poison appeared to have been overwhelmed judging from the odor of decomposing organic matter. Breakdown of these organisms to particles smaller than 1 mm may be the cause of the temporally decoupled high POC value for this sample. In comparison, the high values for the last samples occurred at all trap depths. Average %POC was $7 \pm 2\%$, $6 \pm 2\%$, and $4 \pm 2\%$ for the top, middle, and bottom traps, respectively, decreasing with increasing depth.

3.3. Aluminum flux and concentration (< 1 mm)

Temporal variation in Al flux (Fig. 2c) resembled that of mass flux. In general, Al fluxes for the top and middle traps were similar to each other in both magnitude and temporal variation. There were two discernible, temporally coinciding peaks for the top and middle traps in October/November and in February/March. However, the bottom trap showed different variability than the other

two traps: there were four prominent peaks prior to December but no peaks afterwards. Al flux was the highest for the bottom trap ($7.8 \pm 4.3 \text{ mg m}^{-2} \text{d}^{-1}$), then the top trap (4.7 ± 3.6), and the lowest for the middle trap (3.8 ± 3.3).

Aluminum accounted for up to ~6% of particle mass (Fig. 2f). In general, Al concentrations were the highest in the bottom trap with the exception of samples in February/March when the values at the top and middle traps were higher. Al concentrations for the top and middle traps were similar and co-varied temporally. Al concentration was significantly higher for the bottom trap than for the other traps during October through December.

3.4. $\Delta^{14}\text{C}$ values

Organic carbon in samples poisoned with HgCl_2 or formalin were analyzed for ^{14}C content (expressed as $\Delta^{14}\text{C}$ values). Two samples that were positioned immediately adjacent to sample cups treated with DMSO turned out to be contaminated, most likely by carryover of DMSO from the next sampling cup. Both $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ values were unusually low (-120% and -25% for $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$, respectively), and were therefore disregarded.

The $\Delta^{14}\text{C}$ values ranged between 53‰ and -52% (Fig. 2d). These values were all lower than the $\Delta^{14}\text{C}$ value observed for suspended POC in the surface water in summer 2005 (67‰). For the top trap, the $\Delta^{14}\text{C}$ values were slightly higher in July and April than the other two

samples in November/December. The lowest value for the middle trap was observed in February and the highest value in April. For the bottom trap, $\Delta^{14}\text{C}$ values were negative throughout the sampling period except for four samples. In some cases, the variability between consecutive samples for the bottom trap samples was substantial, with the largest difference being 56‰. In April, $\Delta^{14}\text{C}$ values for all traps were similar and high.

The average $\Delta^{14}\text{C}$ values were $23 \pm 20\%$, $0 \pm 18\%$, and $-21 \pm 23\%$ and POC flux-weighted average $\Delta^{14}\text{C}$ values were 30‰, 9‰, and -12% for the top, middle, and the bottom traps, respectively, clearly showing a decreasing trend with increasing depth. However, it should be noted that the average value for the top and middle traps are likely to be biased toward higher values because of a lack of data, especially when low $\Delta^{14}\text{C}$ values were expected considering the high Al concentration (see discussion for the relationship between $\Delta^{14}\text{C}$ values and Al concentrations and estimation of new flux-weighted average based on this relationship).

3.5. C/N molar ratio

C/N molar ratio varied between 7 and 13 during the sampling period (Table 1, not shown). The ratio for the top trap (8 ± 1) was significantly different from those for the middle (10 ± 2) and bottom (11 ± 1) traps. In general, C/N ratio increased with increasing trap depth. There are not any statistically meaningful correlations between C/N ratio and other properties such as POC and Al.

3.6. Distribution of *n*-alkanoic acids (FAs)

FA 16:0 (saturated *n*-fatty acid with 16 carbons) was the most dominant (ave. 64%, 61%, and 55% for the top, middle, and bottom traps, respectively) among the even-numbered FAs followed by 14:0 and 18:0. Long-chain even-numbered FAs ($24 \leq \text{carbon number} \leq 30$) were a significant fraction (up to 26%) of total even-numbered FAs ($14 \leq \text{carbon number} \leq 30$) for all samples except for the first sample of the top trap (Fig. 2(g)). The proportion of long-chain FAs (% long-chain FAs) shows an increasing trend with increasing trap depth (5 ± 3 , 9 ± 6 , and $14 \pm 7\%$ for the top, middle, and bottom traps, respectively).

4. Discussion

4.1. Biogenic and lithogenic particle flux

The four components – organic matter, CaCO_3 , biogenic opal, and lithogenic particles – accounted for $98 \pm 9\%$, $95 \pm 10\%$, and $91 \pm 5\%$ of the total mass for the top, middle, and the bottom traps, respectively (Fig. 3 and Table 1). Biogenic particulate material accounted for $74 \pm 10\%$, $66 \pm 11\%$, and $49 \pm 9\%$ of the total mass for the top, middle, and the bottom traps, respectively, showing a clear decreasing trend with increasing depth. Notably, even the top trap samples contained over 20% of lithogenic particles. This value increased to 41% in the deep trap.

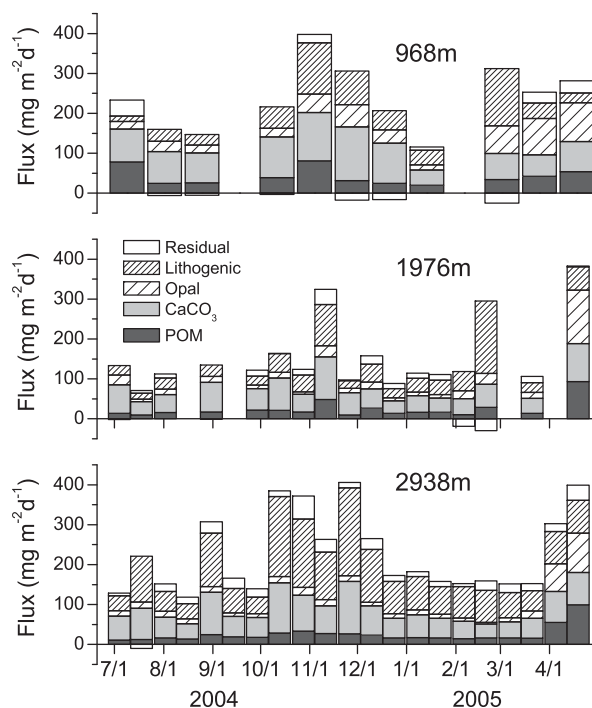


Fig. 3. Fluxes of lithogenic and biogenic components of sinking particles intercepted at three depths. Contributions of lithogenic material, organic matter, biogenic opal, biogenic calcium carbonate were estimated from Al, POC, Si, Ca concentrations (see text for more details). The residual (either positive or negative particle flux) is the difference between the sum of the estimated fractions and the measured particle flux.

The molar ratio of biogenic Si/Ca, an index for relative importance of siliceous and calcareous shell-forming organisms, was lower than 0.5 and co-varied at all three depths during the first half of the study period, but was higher and more variable in the second half of the study period (Table 1, not shown). Near the end of the sampling period, the ratio increased dramatically (up to 2.5) suggesting a bloom by siliceous phytoplankton (Biscaye et al., 1988; Falkowski et al., 1988). The spring bloom determined by sinking particle flux during SEEP-I in this area was reported to occur from March to July (Biscaye et al., 1988; Rowe et al., 1988). Our trap deployment (from July to May) may not have fully captured the spring bloom. The first sample of the top trap may have caught the tail end of a bloom event as well. The $\Delta^{14}\text{C}$ value and POC concentration for this sample was the highest among those analyzed. There is an event in October/November when mass flux and POC concentration at the top and middle traps were high and the biogenic Si/Ca ratio was slightly elevated. However, high Al concentrations suggests that particle flux in this bloom event was augmented by input of allochthonous particles.

Our study site adjacent to Line W is in close proximity to the transect studied during SEEP-I and we compare our results to those of that study (Biscaye et al., 1988). The particle flux at our site is in many ways similar to those observed on the SEEP-I moorings along $70^\circ 55' \text{W}$. Both the magnitude and the amplitude of variability in particle flux

in both studies were similar. With respect to the latter, the flux was affected by processes occurring with a time-frame of 2–3 weeks (one sampling interval), indicating marked short-term variability. At the seaward-most mooring sites (6 and 7) of SEEP-I, the flux decreased to minimum values in the upper 1000 m layer then increased with depth to the bottom. Although our site showed a similar feature qualitatively, the depth of minimum particle flux was greater (1976 m). The magnitude of the particle flux at our site was significantly greater than those observed at SEEP mooring 7 on the 2750 m isobath, but similar to those at mooring 6 on the 2300 m isobath. Also the maximum flux, about $400 \text{ mg m}^{-2} \text{ d}^{-1}$ at mooring 6 (at 850 m, 1750 m, and 2250 m), was similar to the maximum value at our site. Along the SEEP-I transect, the particle flux showed a clear decrease seaward over the slope and rise. It is not clear whether the higher particle fluxes at the present study site on the 3000 m isobath than at 2750 m during SEEP-I was caused by temporal (interannual) or spatial variability, or whether lateral transport is more prevalent at one location than another. Further research is needed to distinguish the modes of supply and transport over the New England margin.

4.2. Lateral supply of POC

Several observations indicate the lateral supply of particulate matter and associated OC in the water column at our study site. These include: 1) Mass fluxes for the middle and bottom traps often exceeded that of the upper trap. 2) High mass flux episodes in the traps occurred as sporadic pulses on a time scale shorter than the single sample interval (roughly two weeks). 3) Variations in mass fluxes at different depths are temporally decoupled, even considering the uncertainties in sinking velocities. 4) The concentration of lithogenic (non-biogenic) particles was high and co-varied with mass flux (with April being the exception). 5) $\Delta^{14}\text{C}$ values were lower than the value observed for POC in the surface water.

Percent long-chain FAs also supports significant influence from lateral transport of resuspended sediment. Marine organisms almost exclusively produce short-chain (carbon number ≤ 22) FAs whereas terrestrial higher plants also produce long-chain (carbon number ≥ 24) FAs (Eglinton and Hamilton, 1967; Killops and Killops, 2004). Because of supply from the continents and selective preservation of long chain FAs in the marine environment (e.g., Camacho-Ibar et al., 2003), sediments proximal to the continents contain high proportions of long-chain FAs (Meyers, 1997; Waterson and Canuel, 2008). Percent long-chain FAs in the core-top sediments near the study site ranged between 57% and 79%, whereas the lowest value observed for sinking POC was $< 1\%$. In this sense, relative contribution of long-chain FAs can be used as a tracer of particulate matter that has been subject to significant alteration, notably margin-derived resuspended sediment. The % long-chain FAs of the first sample of the top trap was almost zero, consistent with its highest

$\Delta^{14}\text{C}$ value. Overall, % long-chain FAs and $\Delta^{14}\text{C}$ were weakly negatively correlated ($R^2 = 0.32$). The average index value increased with increasing trap depth (5 ± 3 , 9 ± 6 , 14 ± 7 at 968 m, 1976 m, and 2938 m, respectively), also indicating increasing contribution of resuspended sediment particles.

Judging from the Al flux data (4.7, 3.8, and $7.8 \text{ mg m}^{-2} \text{ day}^{-1}$ for the top, middle, and bottom traps, respectively), the middle trap samples contain the least amount of resuspended sediment. This observation is seemingly inconsistent with the trend of decreasing average $\Delta^{14}\text{C}$ values with increasing depth. There may be two reasons for this discrepancy: 1) The average $\Delta^{14}\text{C}$ value for the top trap was not representative of the actual $\Delta^{14}\text{C}$ values because most available samples were collected when biological particles dominated the mass flux (i.e., smaller relative contribution from resuspended sediment). When $\Delta^{14}\text{C}$ values of 968 m and 1976 m samples were estimated using the correlation between $\Delta^{14}\text{C}$ and Al concentrations (Fig. 4) the flux-weighted average $\Delta^{14}\text{C}$ values at 968 m and 1976 m were 12‰ and 2‰, which are lower than the values obtained from available data only (30‰ and 9‰, respectively). 2) The small amount of resuspended sediment more strongly influenced $\Delta^{14}\text{C}$ values for 1976 m samples than 968 m samples because of the difference in POC concentration.

4.2.1. Modes of lateral transport of particles

Transmissometry surveys from CTD hydrocasts performed previously in this region and during the Line W physical oceanographic program showed that the thickness and degree of beam attenuation increase with increasing bottom depth toward the Gulf Stream region along the transect (J. Toole, unpublished data, 2007; http://oceanz.tamu.edu/~pdgroup/SMP_prj/DataDir/HTML_Files/WBEX1b_section.htm accessed on August 27 2008). In addition to the BNLS, strong INLS were also observed between 500m and 1000m (Hwang et al., 2009). These nepheloid layers appear to be a persistent feature in this region (Biscaye et al., 1988; J. Toole, unpublished data, 2007) and are expected to contribute to particles intercepted in each trap, and especially in the top trap.

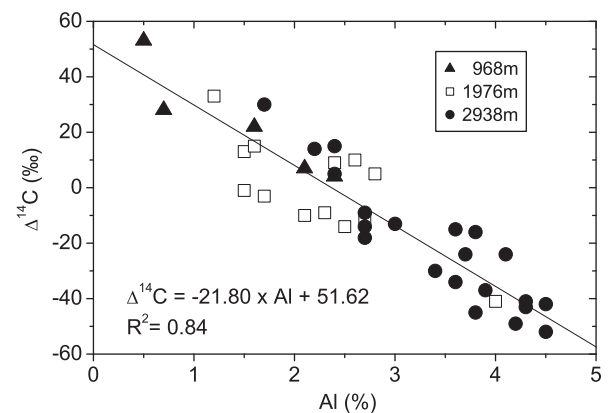


Fig. 4. Correlation between $\Delta^{14}\text{C}$ of POC and Al concentration of sinking particles.

The bottom trap was within the BNL (Hwang et al., 2009) and hence affected by both local resuspension and longer-range lateral advection of allochthonous particles, whereas lateral inputs to the upper and middle traps are likely to be derived only from the INLs in the overlying water column. Properties such as Al concentration and flux, Fe concentration (Table 1, not shown) for the top and middle trap samples were generally similar to each other but distinct from those for the bottom trap samples. These observations suggest that the bottom trap samples had an additional particle source or sources. Overall, these observations suggest that there are at least two modes of lateral particle transport: one through the INLs affecting the top and middle traps and the other through the BNLs affecting mostly the bottom trap.

The somewhat lower $\Delta^{14}\text{C}$ values observed for the samples in the top trap suggest that the particles in the INLs contain a component of aged organic matter: i.e., a fraction of the particles in the INLs originate from sediment resuspension (Karakas et al., 2006). However, the provenance of the particles in the INLs remains uncertain. One potential mode of supply is via across-margin transport from the shelf-slope break off New England (Butman, 1988) and/or transport off the Nova Scotian shelf and further entrainment into the net southward flowing Slope Water Current (Flagg et al., 2006). Suspended particles emanating from the shelf can be entrained into warm core rings and further transported southwest (Bishop and Joyce, 1986). Across-shelf transport of resuspended sediments was observed from transmitter moorings on the New England shelf (Churchill et al., 1988), and processes resulting in detachment of benthic boundary layers from the New England shelf break (Pickart, 2000) are likely to inject resuspended sediments basinward at intermediate depths.

Input of resuspended POC appears to occur sporadically. For example, variations in POC concentration for the bottom trap appear to be controlled by sporadic increases in Al flux. When Al flux peaked for samples #2, 5, 8, and 11, %POC fell below 3% and then returned to higher values until the next peak of Al flux occurred (Fig. 2). The relationship between Al concentration and %POC appears robust ($R^2 = 0.54$) suggesting that %POC is controlled mainly by dilution from particles rich in lithogenic material but poor in POC. Although these pulses, manifested as peaks in Al flux, occur throughout the study period, they appear more intense during the winter (October to February). These features bear similarities to the characteristics of the “benthic storms” observed in the HEBBLE project study area (39–43°N, 59–66°W) on the Nova Scotia slope and rise (Hollister and Nowell, 1991). The HEBBLE project revealed that duration of these turbidity events was between 2 and 20 days, typically 3–5 days, and the frequency was 8–10 storms per year. These “benthic storm” events in the HEBBLE area occurring throughout the study period (September 1985–July 1986) consisted of clouds of fine-grained suspended material advected into the region, in addition to inputs from local sediment erosion (Gross and Williams, 1991). Peak particle concentrations immediately followed the peak in current velocity, but deposition of fine particles

stemming from these events was observed to persist for several weeks.

4.2.2. Estimation of the contribution of aged POC in sinking POC

Comparison of $\Delta^{14}\text{C}$ values and Al concentrations reveals that these properties are tightly coupled (Fig. 4), and suggests mixing between two end members: fresh POC from primary production and aged OC associated with lithogenic particles. The y-intercept ($52 \pm 5\%$) can be interpreted as the fresh POC end member value and is similar to observed $\Delta^{14}\text{C}$ values for suspended POC in the surface water ($60 \pm 10\%$, $n = 4$; Hwang et al., 2009). The samples from different traps fall on the continuum of a single mixing line. This apparent continuum in the $\Delta^{14}\text{C}$ and Al concentration relationship implies inputs across all trap depths and would argue against local sediment resuspension as the primary source. Assuming there is more than one source of aged organic matter (i.e., INLs and BNLs), this relationship suggests that the mode of association of aged organic matter in the lithogenic particles, and transport mechanisms are similar for both sources.

We estimated the proportion of laterally supplied (allochthonous) OC based on ^{14}C isotopic mass balance. It should be noted that this ^{14}C -based estimate only accounts for lateral supply of aged OC (resuspended sediment), not the entire fraction that is laterally supplied which may include freshly produced POC (Mollenhauer et al., 2006). Hence the actual fraction that is supplied laterally is likely larger than our ^{14}C -based estimate. We used the average of the observed $\Delta^{14}\text{C}$ values ($60 \pm 10\%$, $n = 4$) for suspended POC in surface water at our site to define the “fresh” (autochthonous) OC end member. The end member for resuspended sediment is harder to determine because the source(s) of this POC is not well known. As discussed above, core-top sediment may represent a plausible end member. However, it should be noted that unconsolidated fluffy material at the sediment-water interface is more likely to be resuspended than the 0–1 cm sediment typically recovered and measured as core-top. These detrital aggregates and sediment floccs have higher $\Delta^{14}\text{C}$ values than those of “bulk” OC in core-top sediments (Wang et al., 1996). Hence, using the former values to derive an end member will likely provide the minimum estimate of the allochthonous fraction contained in sinking POC. We assumed that the top and middle trap samples were influenced mostly by resuspended particles emanating as INLs from the shelf-break. Because we do not have $\Delta^{14}\text{C}$ data for every sample from the top and middle traps, we used $\Delta^{14}\text{C}$ values estimated from the measured Al concentration and Al- $\Delta^{14}\text{C}$ correlation as discussed earlier. The resulting flux-weighted $\Delta^{14}\text{C}$ values are 12‰ and 2‰ for 968 m and 1976 m, respectively, instead of 30‰ and 9‰ calculated from existing data. From the correlation between the water depth and $\Delta^{14}\text{C}$ values of core-top sediments on the north Atlantic margin (Hwang and Eglinton, unpublished data, 2007), $-140 \pm 50\%$ was used for the representative $\Delta^{14}\text{C}$ value of resuspended particles from the shelf. The uncertainty of $\pm 50\%$ reflects the scatter in $\Delta^{14}\text{C}$ values. The resulting

estimates for the contribution of allochthonous POC are $24 \pm 9\%$, $29 \pm 10\%$ for the top and middle trap samples, respectively.

Since the bottom trap was likely also to receive resuspended sediment from the BNL, we estimated this component of the POC flux to be the difference ($0.7 \text{ mgC m}^{-2} \text{ day}^{-1}$) between the fluxes at 1976 m ($9.3 \text{ mgC m}^{-2} \text{ day}^{-1}$) and 2938 m ($10.0 \text{ mgC m}^{-2} \text{ day}^{-1}$) assuming that loss of POC by degradation between these two depths is minimal (Martin et al., 1987). From the increase in POC flux and decrease in $\Delta^{14}\text{C}$, we estimated the $\Delta^{14}\text{C}$ value of the additional component of resuspended POC in the BNL. The estimated $\Delta^{14}\text{C}$ value, -198% , is lower than that of the shelf sediment, implying that the resuspended sediment in the BNL originated from the slope or a mixture of the shelf and slope sediments. The resulting estimate for the fraction of allochthonous POC supplied to the bottom trap was $34\% [(9.3 \times 0.29 + 0.7)/10.0]$. This isotopic mass balance estimate therefore shows increasing inputs of resuspended sedimentary OC to sinking POC (24%, 29%, and 34% at 968 m, 1976 m, and 2938 m, respectively). Overall, these values are similar to the estimate for the allochthonous particle input on the slope based on ^{210}Pb during the SEEP-I study ($0.44 \text{ dpm cm}^{-2} \text{ y}^{-1}/1.44 \text{ dpm cm}^{-2} \text{ y}^{-1} = \sim 30\%$; Biscaye et al., 1988).

5. Conclusions

As for all continental margin systems, the dynamics of POC cycling over the New England slope is complex and challenging to characterize. Our results show that horizontal input of aged POC from sediment resuspension and lateral transport is a significant source of carbon in addition to primary production and vertical supply from the overlying water column. This process must therefore be considered in assessment of carbon export over the margin. Multiple lines of evidence will clearly be required to accurately deconvolute and quantify these various inputs. The present study of sinking particle samples intercepted at three depths on the New England slope in the NW Atlantic Ocean, revealed several key aspects of particle transport in this region.

- Biogeochemical properties including $\Delta^{14}\text{C}$, Al concentration, and proportions of long-chain FAs are consistent with an input of allochthonous POC from laterally transported resuspended sediment particles.
- At least two modes of lateral particle transport exist over the New England margin. INLs and BNLs are both prominent features and the decoupled mass fluxes at different trap depths indicates that they exert a significant influence on particle dynamics and biogeochemistry.
- $\Delta^{14}\text{C}$ values of sinking POC at all depths indicated the existence of aged allochthonous POC, with the proportion of the latter increasing with increasing trap depth.
- Comparison between $\Delta^{14}\text{C}$ values and Al concentrations reveals that these properties are tightly coupled, suggesting that sinking POC represents a mixture between two dominant end members – fresh POC

from primary production and aged OC associated with lithogenic particles.

- Lateral advection of particles near the bottom occurs as relatively brief (< 2 weeks) turbidity pulses immediately followed by relaxation and sedimentation spanning about a month.
- Based on measured $\Delta^{14}\text{C}$ values of POC in surface ocean and OC in sediments, we estimate that between 24 and 34% of POC intercepted by the traps is derived from lateral advection of resuspended shelf and slope sediment.

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