Sedimentation rates in the slope water of the northwest Atlantic Ocean measured directly with sediment traps

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ABSTRACT

Four sediment trap arrays were deployed in the Slope Water off the northeast United States for periods of 5.8 to 15.8 days from May to August 1976. Three traps, each a PVC cylinder 25 cm in diameter and 76 cm tall, were attached at various distances above the bottom along bottom-anchored moorings. Closure of the individual traps and release of each array from its expendable anchor was controlled by a Williams Timed Release or an AMF acoustic release. DSRV ALVIN, making observations of one array, closed those traps and released that array from the bottom.

Water depths ranged from 2200 m to 3650 m, but the traps were put as high as 518 m off bottom, as well as near bottom, to differentiate between primary pelagic sedimenting matter and resuspended material in the nepheloid zone.

Average organic carbon sedimentation rate for all traps was 12.8 mg/m^2/day, while carbonate averaged 105 mg/m^2/day. Organic carbon ranged from 3.8 to 6% of the total material caught, somewhat higher than that in bottom sediments below the traps, having concentrations of 1.2-1.3%. Size fractionation of some of the material indicated that about 20% of the organic carbon flux was carried in larger, often pelletized particles (> 63μm), with the remaining 80% being in smaller particles. Fecal pellets were larger and more abundant near bottom in the nepheloid zone than in the primary sedimenting material above it, suggesting that the fauna on and near (500 m above) bottom is consuming resuspended material and matter of recent pelagic origin before it is deposited.

Carbon budgets for the three locations, based on community metabolism, the trap measurements and carbon accumulation in the bottom, suggest that the inferred assemblage of organisms feeding just above the bottom could be utilizing a relatively large fraction of the sedimenting organic carbon.

1. Introduction

Pelagic sedimentation of particulate matter in the open ocean transfers material of biological origin and wind-blown terrestrial matter, including pollutants, to the

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deep ocean. Indirect estimates of net rates of total sedimentation are based on paleontological or radioisotope dating of sediments at specific depths in the bottom. Radioisotopes introduced by bombs or other activities of man have been useful too in restricted areas for predicting the vertical flux of matter through the deep ocean (Osterberg *et al.*, 1963, 1964a,b; Pearcy and Osterberg, 1967; Kuenzler, 1969; Lowman *et al.*, 1971; Noshkin and Bowen, 1973; Pearcy *et al.*, 1977). Although elegant theoretical (McCave, 1975) and experimental approaches have utilized particle size and the physical composition of sinking particulates to speculate on principal vertical mass transfers (Smayda, 1969; Fowler and Small, 1972; Elder and Fowler, 1977), sedimenting matter has rarely been sampled directly in the deep sea using traps (Berger and Soutar, 1967; Nishizawa and Izeki, 1975; Izeki, 1976; Wiebe *et al.*, 1976; Honjo, 1978; Spencer *et al.*, 1978). As a result little is known about magnitude, variation and composition of fluxes. Because understanding geochemical cycles in the ocean requires knowledge of sinking particle fluxes to the bottom, we are presenting a set of data gathered from deployments of traps to measure sedimentation rate directly in the deep North Atlantic.

2. Methods

Sedimentation traps (Fig. 1) were constructed of cylinders, 25 cm in diameter and 76 cm tall, of polyvinyl chloride (PVC). Oriented vertically, their tops were open and the bottoms were sealed with a circular sheet of PVC. Closing lids, pivoting on bolts through the cylinder, were placed in the lower half of each trap. The lids were held open during a deployment by a nylon line attached to a release mechanism of the type used on a Nansen bottle. A spring of latex tubing was used to close each lid at the end of a deployment. In some cases the lid release line was an integral part of a Williams Timed Release (WTR), an electrolytic timed release that works by putting a voltage through a Nickelchrome wire (Williams and Fairhurst, 1977). Most of this wire is insulated, with the exception of about 1 to 3 mm, which is exposed to seawater. The flow of current, actuated by a crystal clock, causes the wire to dissolve at the exposed section. This break releases the lid directly, or releases a messenger which trips the Nansen release, thus closing the lid.

Arrays of traps were assembled by clamping three PVC traps along a 3/16″ wire held vertically between a disposable anchor weight on the bottom and glass flotation spheres at the top of the array (Fig. 2). Williams Timed Releases dropped the anchor holding an array to the bottom or an array was released from its anchor with an AMF acoustic release. Williams Timed Releases can be attached to each trap or a single WTR can be put at the top of the array to drop a messenger.

At the end of a designated period of trapping the lids were closed and then the anchor was released, usually 2.4 hours after lid closure. The array would then ascend to the surface where it was picked up by a waiting surface vessel. At DWD

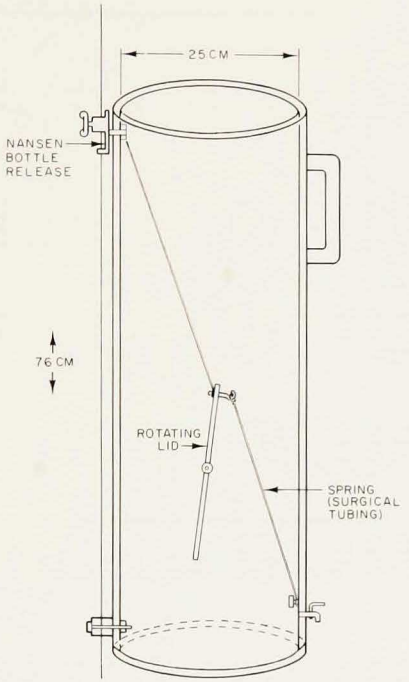

Figure 1. Sediment trap design used in this study.

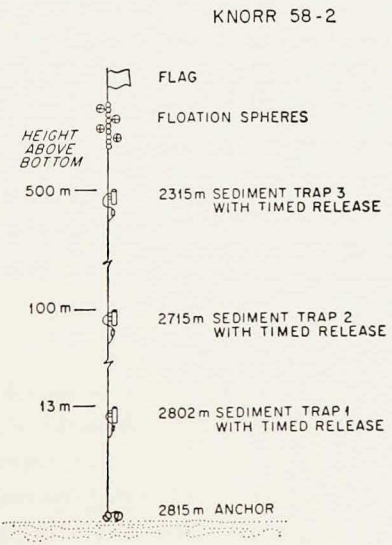

Figure 2. Typical array of traps. Flotation was approximately 20 m above top trap.

Table 1.

Trap	Depth	Meters above bottom	Total amount trapped (mg)	Total flux g/m²/day	% $CaCO_3$	% organic carbon	g $CaCO_3$ /m²/day	mg organic carbon /m²/day	Organic carbon/ nitrogen	g $CaCO_3$ /m²/yr	g Organic carbon /m²/yr
DWD 106, 22-29 June 1976 (5.8 days), 38°50′N, 72°31′W											
3	2156	36	133	0.47	48.9	3.9	.230	18.3	7.7	83.9	6.6
2	2159	33	97	0.34	43.3	4.9	.147	16.6	8.3	53.7	6.1
1	2162	30	98	0.35	50.7	5.0	.177	17.5	8.7	64.6	6.3
KN 58-1, 11-21 August 1976 (10.1 days), 38°28.2′N, 72°01.0′W											
3	2788	26	141	0.28	33.9	4.5	.094	12.6	11.9	34.3	4.6
2	2794	21	131	0.26	29.6	3.9	.077	10.1	11.0	28.1	3.7
1	2800	15	127	0.25	34.6	3.8	.087	9.5	10.4	31.8	3.5
KN 58-2, 21 August-1 September 1976 (10.7 days). 38°28.5′N, 72°02.3′W											
3	2316	500	61	0.13	33.4	5.4	.043	7.0	18.5	15.7	2.3
2	2715	100	81	0.15	—	6.0	—	9.0	16.2	—	3.4
1	2803	13	129	0.24	34.3	4.1	.082	9.8	12.1	29.9	3.7
DOS 2, 15-31 May 1976 (15.8 days), 38°19′N, 69°37′W											
2	3059	518	189	0.24	35.2	4.8	.084	11.5	9.1	30.7	4.2
1	3459	118	354	0.46	29.8	4.0	.137	18.4	9.4	50.0	6.6
Average for all traps (11)							.105	12.8		42.3*	4.6
Average of 4 arrays							.148	13.0		40.5	4.7
Average for two traps at 500 and 518 mab and all traps at DWD 106							.103	12.0		37.9	4.3

* Only 10 values.

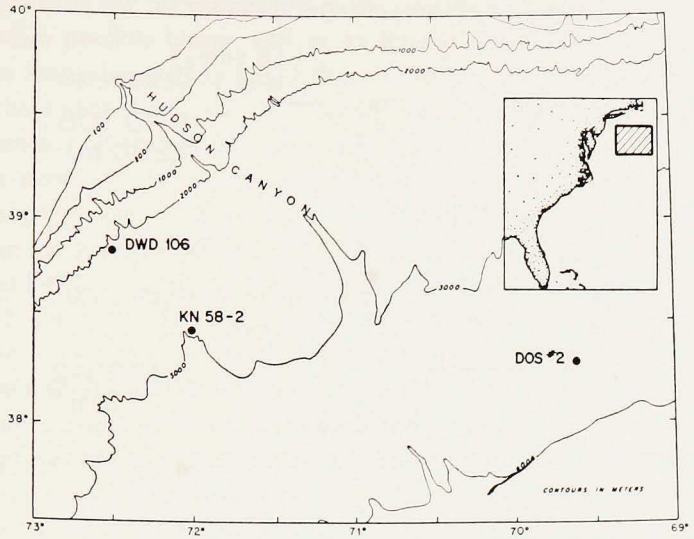

Figure 3. Locations of deployments of sediment trap arrays. KN 58-2 is also the location of deployment KN 58-1.

106 the array was inspected on bottom by DSRV ALVIN, and then ALVIN's mechanical hand was used to release the lids and the expendable anchor. There was not an absolutely tight seal when the lids of the traps were closed, but the traps to the best of our knowledge remained vertical at all times during recovery.

Four deployments were successfully made during the summer of 1976 (Table 1). They were all located in the Slope Water, from the lower continental slope to the middle continental rise off the eastern United States (Fig. 3). One deployment was made at the lower continental slope station (DWD 106), two at the intermediate site on the upper continental rise (KN 58) and another at the deep mid-rise location (DOS 2). The western North Atlantic at the latter two stations is characterized by a bottom nepheloid layer, defined as a depth zone with a high concentration of particulate matter, reaching up to as much as several hundred meters above the bottom (Biscaye and Eittreim, 1974). It is generally believed to be sediment resuspended from the bottom, although other origins are possible. Minimum concentrations of suspended matter are found just above the nepheloid zone, about 500 m above bottom at the two deeper sites and less than 100 m above bottom on the lower slope, although the layer's thickness varies in both time and space. The layer has been shown to be less pronounced in the area of the DWD 106 lower slope (shallower) deployment (Biscaye and Olsen, 1976).

The traps on two arrays were arranged so as to put traps both near bottom in the nepheloid layer and 500 m above bottom, or high enough off bottom that most of

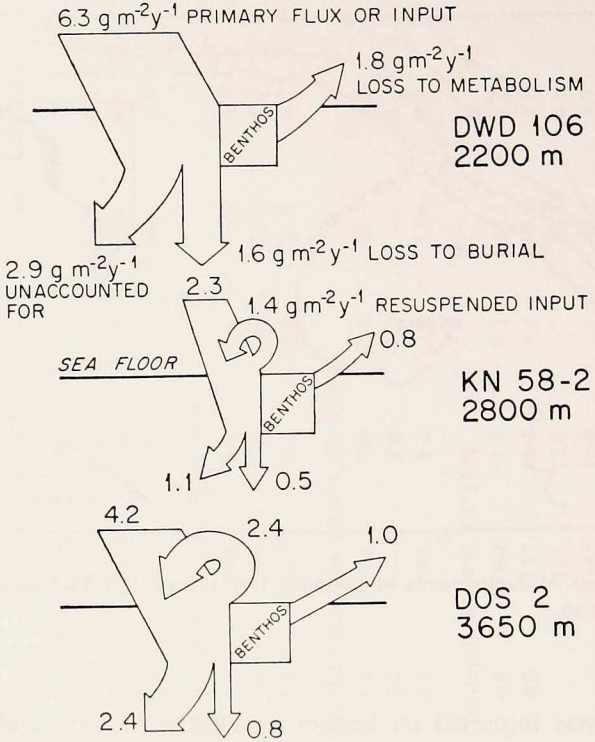

Figure 4. Flow diagram of organ carbon flux at each location, in grams organic carbon per meter square per year. Data are from top trap (500 meters off bottom) at KN 58-2 and DOS 2 and the average of all traps at DWD 106. Resuspension estimates are total in bottom trap minus total in top trap. No resuspension is considered to occur at DWD 106 (see text and Table V). Metabolism conversions to organic carbon rates are based on the work of Smith (1978), but do not include denitrification rates discussed in the Discussion, published by Smith *et al.* (1978).

the material caught was not resuspended, but of pelagic origin. We refer to material captured in the 500 m traps as primary material (Fig. 4) as opposed to the lower traps which caught both primary pelagic material and material from the nepheloid layer, assumed to be resuspended. At DWD 106 and at one deployment on the continental rise (KN 58) all the traps were relatively close to the bottom. Deployments lasted from 5.8 to 15.8 days (Table 1).

The turbulence around and in stationary traps in flowing water may bias catching rates. Any biases encountered should logically be related to trap size and shape, current velocity and the sinking velocity, a function of size and density, of the particles trapped. Our use of a cylinder with a height three times its diameter was decided on after extensive testing of various shapes in a flume (Gardner, 1977; Gardner, submitted ms. a) and a field calibration of different moored traps (Gardner, 1977;

Gardner, submitted ms. b). Staresinic *et al.*, (1978) proposed using free drifting traps to aleviate possible biases, and in an intercomparison between moored and drifting traps Staresinic (1978) found that the drifting traps consistently captured more than those that were moored, although such differences are probably quite variable depending on currents and trap design.

Our traps may have been exposed to relatively strong currents. According to numerous long-term current meter records in the mid-Atlantic bight, deep currents are sometimes as great as 30 cm/sec (Luyten, 1977) at the two deeper locations (KN58-2 and DOS 2) on the continental rise. We believe currents were never more than about 5 cm/sec at DWD106, based on our observations there with DSRV ALVIN. The traps used in our study should therefore collect material with little bias at the nearshore site (DWD 106), and if the other data are biased, we might expect they underestimate the average flux due to winnowing.

No attempt was made to retard microbial activity in the traps during deployments, and although microbial activity at great depths might be slight (Jannasch *et al.*, 1971), at least relative to shallower water, we believe this may also contribute to an underestimate of the flux of organic matter.

On the surface and once aboard ship, the water overlying the lid of each trap was carefully siphoned off and discarded. The water below the lid was split into several fractions for various chemical, physical or visual analyses. These included a size analysis by wet sieving and counting the fine particles with a Coulter Counter, loss on acidification to estimate calcium carbonate content, scanning electron microscopy, light microscopy, and elemental analyses of both the combustible (organic carbon and nitrogen) and noncombustible elements, the latter by neutron activation. We report here the results of the analyses for organic carbon and nitrogen and percent $CaCO_3$ loss on acidification, by weight.

Each sample was filtered under gravity through a precombusted, preweighed glass fiber filter. Each filter was then dried to constant weight at 60°C, and acidified with a dilute solution of phosphoric acid until no evolution of gas from the residue could be detected, assuring that all carbonate had been dissolved. The filters were then rewashed with distilled water, redried and reweighed to provide a measure of the carbonate lost from the filter. The filters were then combusted in a Perkin Elmer #240 elemental analyzer to determine percent organic carbon and nitrogen. From these we derived our flux estimates of organic matter.

Precise fractions of each total sample were obtained with a plankton splitter before filtering for several of the analyses. Standard deviations for the splits ranged from 0-10% of the mean and the average was 4.7% on samples with a mean size of 7 to 97 mg dry weight. This variation does not affect the C, N and $CaCO_3$ estimates because all the fractions were filtered, dried and weighed.

Two one-quarter fractions from KN 58-1 and KN 58-2 were gently washed through 125, 63 and 20 μm sieves. One fraction of each size was sucked onto

separate Nuclepore or glass fiber filters. It is possible that the sieving process broke fragile particles, but it did not appear that the distilled water wash used after sieving carried additional material through the 125 or 63 μm sieves. A few drops of the portion of the samples going through the 20 μm sieves were analyzed using a model TA II Coulter Counter (Sheldon and Parson, 1967), soon after trap recovery. The 20 μm mesh screen was a 55 mm square piece of etched nickel micro-mesh that was set on a Millipore glass funnel filtering stand, separated from the filter below it with rubber gaskets. When the pore openings became clogged, the material was resuspended before it was finally washed onto the filter reserved for the 20-63 μm fraction. This was repeated two to three times before all of the subsample was processed with the 20 μm screen. This treatment might have broken fragile particles less than 63 μm, so the 20 μm separation may not be as accurate as we might hope it could be.

One set of size-separated samples put on glass fiber filters from the KN58-1 trap 15 m above bottom (mab)[3] was combusted in the Perkin Elmer #240 elemental analyzer for percent carbon and nitrogen, again after acidification to remove the carbonate.

At DWD 106 and DOS 2 DSRV ALVIN was used to take short cores of the bottom sediment for comparison with the trap samples. A short gravity corer without a catcher was used to take undisturbed surface sediment at the KN 58-2 site. Treatment of a sample from each core top was identical with the samples from the traps for grain size analysis, carbonate content and percent organic matter. A thorough description of these and other North Atlantic short cores is available (Rowe and Clifford, 1978).

3. Results

The total amount of sediment captured (Table 1) during the four deployments ranged from 61-354 mg. Converted to fluxes, this range was 0.13-1.47 g/m^2/day. We expected a decrease in total flux with distance from land, but this was not observed. To the contrary, lowest mean values of all parameters were found at the intermediate locale and not at the deepest most-distant-from-shore station. Highest mean values for arrays were nearshore (.39 g/m^2/d), with lower values at the intermediate location (.26 and .17 g/m^2/d). At the two deployments in which traps were put above the nepheloid zone (DOS 2 and KN 58-2), values were much higher near bottom than at 500 m above it. The material above the nepheloid layer can be considered the "primary" material of pelagic origin, whereas that matter caught in the nepheloid layer is thought to be composed both of recently sedimented and resuspended sediments. The difference between the quantity caught by a lower trap and

3. mab = meters above bottom.

Table 2. Surface sediment at sediment trap locations.

	% $CaCO_3$	% Organic carbon	C/N
DWD 106	28.0	1.3	7.5
KN 58-1	26.2	1.2	14.3
KN 58-2	31.6	1.2	10.6
DOS #2	22.8	1.29	13.6

a trap at 500 mab is a relative estimate of resuspension, if the nepheloid layer is assumed to be in a quasi-steady state.

The range of all values of organic carbon was low (7.0-18.4 mg C/m²/day), compared to the range of total amount caught and the range of the flux of total material. Overall mean flux of organic carbon at all traps was 12.8 mg/m²/day. Percent organic carbon decreased from the top traps to bottom traps at the two locales where traps were put 500 m above bottom. The KN 58-1 setting had a similar gradient, although all traps were near bottom, but the reverse was observed at DWD 106, the nearshore station.

$CaCO_3$ flux ranged from 43-230 mg $CaCO_3$/m²/d, with highest values again at the nearshore station (DWD 106). Lowest values were at the intermediate site and intermediate values again were at the offshore site. The overall mean flux was 105.3 mg/m²/d, or about 8 times the organic fraction flux. Primary flux of $CaCO_3$ from the two traps 500 m above bottom averaged 63.5 mg/m²/d, about 7 times greater than the primary organic carbon flux.

Carbon to nitrogen ratios tended to be inversely related to material flux rates. They were lowest nearshore, highest at intermediate sites, and of intermediate values offshore (Table 1).

Bottom sediments, taken with the cores at the same locations (Table 2), contained carbonates which were somewhat less than what was caught in the traps, with the greatest differences being nearshore at DWD 106 (28% vs. 48%). Percent organic carbon values from the cores of the bottom were very similar at the three locations, but the mean percent organic carbon of all traps (4.6%) was 3.7 times that on the bottom, reflecting utilization on the bottom by heterotrophic organisms.

The separation of trapped material by size indicated that most of the flux was in the < 20 μm and 20-63 μm fractions, not in the larger fraction. The larger particles (greater than 63 μm), which includes fecal pellets, accounted for only about 20% of the flux in the traps where material was analyzed by size fraction. In the cores (Table 2) this fraction was 25%, but this included numerous Foraminifera. In the single trap where the size fractions were analyzed for organic carbon and nitrogen, the highest percentage of organic carbon was found in the 63-125 μm and >125 μm fractions (6.9 and 9%), compared to 4.2% for the smaller fractions. The larger particles had lower C:N ratios. Even though the concentration of organic matter

Table 3. Percent by particle size of material in traps and core.

Depth (m)	Meters above bottom	Size fraction (microns)	Weight on nuclepore filter (mg)	Weight on glass fiber filter (mg)	Average (mg)	Average (%)	Average flux ($g/m^2/yr$)	% Organic carbon	Organic carbon flux	C:N
					KN 58-2					
2315	500	>125	0.73	0.93	0.83	7.3	03.1			
		63-125	0.65	0.69	0.67	5.9	02.5			
		20-63	3.19	2.78	2.99	26.3	11.1			
		<20	6.42	7.35	6.89	60.5	25.4			
2715	100	>125	1.20	2.75	1.98	13.3	07.5			
		63-125	0.97	1.21	1.09	7.3	04.1			
		20-63	6.06	3.74	4.90	33.0	18.6			
		<20	5.63	8.16	6.90	46.4	26.1			
	13	>125	1.47	1.83	1.65	6.4	05.7			
		63-125	1.42	0.75	1.09	4.3	03.8			
		20-63	17.76	9.59	13.68	53.3	47.5			
		<20	6.49	11.96	9.23	36.0	32.1			

					KN 58-1					
2788	27	>125	4.90	4.59	4.75	14.1	14.5			
		63-125	3.07	2.02	2.55	7.5	07.7			
		20-63	15.28	12.09	13.69	40.5	41.8			
		<20	11.29	14.33	12.81	37.9	39.1			
2794	21	>125		2.78		9.0	08.6			
		63-125		1.76		5.7	05.5			
		20-63		8.35		27.0	25.9			
		<20		18.01		58.3	55.9			
2800	15	(>500)*		(1.46)*		(4.7)*	4.2	2.7	.11	2.3
		>125		4.08		13.2	7.9	9.0	.71	7.3
		63-125		2.34		7.6	7.4	6.9	.51	4.9
		20-63		12.04		39.1	36.2	4.2	1.51	8.2
		<20		12.33		40.1	37.2	4.1	1.53	8.7
2822	Core 1	>125	15.69	11.25	13.47	18.8				
		63-125	4.71	4.06	4.39	6.1				
		20-63	31.57	21.20	26.39	36.9				
		<20	22.42	32.10	27.26	38.1				

* Calculated separately, but included in the >125 micron fraction. Consisted primarily of radiolarion tests and included *no* fecal pellets.

Table 4. Identification of particles >125 μm, Station KN 58-2.

Particle type	Primary flux no/m²/day 2315 m depth 500 mab	Primary and resuspended flux no/m²/day 2802 m depth 13 mab
% by weight > 125 μm	7.3%	6.4%
Radiolarians	770	1690
Diatoms		
Centric	636	1084
Pennate	127	643
	763	1727
Fecal Pellets		
Well-formed	112	237
Broken	359	680
Flattened	127	613
	598	1540
Pteropods		
Coiled	142	389
Straight	135	404
	277	793
Foraminifera	232	964
Identity unknown	142	232
Tintinnids	127	179
Ostracods	No data	52
Zooplankton carapaces	No data	30
Unidentified fragments	No data	389

was higher in the larger fractions, the apparent flux in the smaller fractions was still almost four times greater than that in the larger fractions.

The biotic composition of particles greater than 125 μm in the 500 mab and 13 mab traps (at KN 58-2, 2800 m depth) were counted using a light microscope (Table 4). The number of all particles greater than 125 μm was much greater in the 13 mab trap than in the 500 mab trap, even though this relative proportion by weight of this particle size to the total trapped was about the same or less close to the bottom. Numerically, no single particle type was overwhelmingly dominant, although radiolarians, diatoms and fecal pellets were most abundant. The fecal pellets were uniform in color and texture, except for a few pellets that were black and possibly not feces at all but oil droplets. No difference in color or shape was detected in the fecal pellets after leaching carbonate from them with phosphoric acid. The flux of pellets in the 500 mab trap was not very different from that estimated by Wiebe *et al.* (1976) in the Tongue of the Ocean. In both these areas, very different in climate and hydrography, the portion of material (and the apparent flux)

identifiable as fecal pellets, was small, although Wiebe *et al.* did not state this explicitly.

Fecal pellets on the glass fiber and Nuclepore filters at Kn 58-2 appeared larger at 13 mab than at 500 mab. As an attempt to measure this difference we removed these pellets from the filters after drying and placed them on a preweighed filter. Eleven pellets from the 500 mab sample weighed approximately 17 μg or 1.55 μg per pellet, whereas 39 fecal pellets from the 13 mab sample weighed 104 μg, or 2.67 μg per pellet, suggesting that the near-bottom pellets were larger than those relatively high above the bottom. (The precision of the balance we used, in an atmosphere-controlled weighing room, approaches $\pm$ 5 μg for Nuclepore filters at equilibrium with the room.) Additional studies using neutron activation to determine the elemental composition of these pellets supports our contention that the pellets captured 13 meters above bottom were larger; these results will be reported elsewhere by Gardner.

4. Discussion

The sedimentation of pelagic organic matter, sometimes called a "rain of dead organisms", has long been presumed to be the major source of food for deep-sea organisms (Maury, 1965; Agassiz, 1888), and it is surprising that attempts to measure this flux directly were not made until recently. The abundance and biomass of the deep-sea benthos decline exponentially with depth and from this decline it has been inferred that food supplies to the deep-sea decrease with depth (Rowe and Menzel, 1971; Rowe, 1971; Rowe *et al.*, 1974). Although we found highest fluxes nearshore at DWD 106, an offshore or depth gradient was not observed in our set of samples.

It was expected that most of the flux would be found in larger sized particles, in accord with the predictions of McCave (1975), and numerous suggestions in the literature concerning the role of zooplankton fecal pellets in the transport of matter to the deep-sea (Marshall and Orr, 1955; Osterberg *et al.*, 1963; Smayda, 1969, 1970, 1971; Schrader, 1971; Manheim *et al.*, 1972; Fowler and Small, 1972; Honjo, 1976; Wiebe *op cit.*, and Cherry *et al.*, 1975), but our results suggested otherwise (Table 3). There are several possible explanations for this contradiction. First, our techniques could have damaged very fragile pellets and particle aggregates. We believe sample processing itself caused little damage because we observed (visually) no destruction of pellets during sample splitting or sample filtering. Size separation by wet sieving could have been responsible for some destruction of pellets in those two samples processed in that manner, but not in all the samples. Residence in the traps could have subjected fragile pellets to biological processes that caused their destruction. One explanation is that some of the material might have left near-surface depths as pellets, but in transit to the bottom the coherence of the pellets was destroyed by pellet-eating (coprophagic) organisms and microbial activity.

We expected that resuspended material in the nepheloid layer would be encountered in the traps near the bottom. The size distribution of the resuspended material in the near-bottom water however was not what we expected. Instead of finding more fine particles, with little increase in pelletized material, we encountered more pellets near bottom as well. The pellets were not only more abundant, but appeared to be larger on the average than those caught above the nepheloid zone. This leads us to suggest that these pellets were not produced near the surface, but originated on the bottom or in the bottom nepheloid zone. Our attempt in our discussion below at a mass balance of organic matter input and fate indirectly suggests that a near-bottom assemblage exists that utilizes a large fraction of the primary input. Qualitative observations of this community are extensive (Grice and Hulseman, 1970; Vinogradov, 1968; Hessler *et al.*, 1972; Haedrich and Henderson, 1974; Pearcy and Ambler, 1974, and Haedrich, 1974), but its significance is unknown. Spencer *et al.* (1978) found two types of fecal pellets in the sample from a large cone-shaped trap 200 m off bottom in water 5369 m deep (Honjo, 1978). Reddish fecal pellets were presumed to originate in the near-bottom nepheloid zone, whereas green pellets were presumed to come from higher up in the water column.

Studies of the growth of microbial populations on matter caught in traps set off Peru (Watson and Hobbie, pers. comm.) and in the Baltic Sea (Iturriaga, in prep.) suggest microbial activity in shallow water is very great. We suspect that large alterations in matter might occur, based on the circumstantial evidence we have summarized. More extensive studies need to be conducted on the processes to which material in the water column is subjected in transit to the bottom.

The organic matter deposited on the bottom can be utilized by the biota or it can be buried. Recent measurements of bottom sediment oxygen uptake, a measure of community metabolism, have been used by Smith (1978) as an indirect measure of organic carbon utilization. He compared carbon utilization to the organic carbon sedimentation flux we measured and primary production at the surface. We can extend an analysis of this kind to include burial using a flow diagram which compares pelagic input and resuspension for each station to losses by metabolic conversion to carbon dioxide (from Smith *op. cit.*), and burial. [All the data are extrapolated to grams carbon per square meter per year ($g/m^2/yr$) (Table 5 and Fig. 4).] Burial rate was derived from noncombustible input (clay and $CaCO_3$) to the traps minus the difference in the organic fraction in the traps and on the bottom. This approach agrees well with radiocarbon dating done 15 n. mi. from DOS 2 (Turekian, 1965, sedimentation rate equals 6-7 $gm/cm^2/1000$ yrs).

Near-bottom measurements at DWD 106 have been assumed to represent mostly pelagic input, with little resuspension, because our observations there with DSRV ALVIN found currents to be less than 5 cm/sec (one meter off bottom) and exposed sedimentary rock surfaces were draped with a thin veneer of fine sediments. This is also an area where the bottom nepheloid layer is most poorly developed. If our

Table 5. Carbon mass balance (see text and fig. 3, all units in grams carbon per square meter per year, unless otherwise noted).

Station	Depth (m)	Oxygen demand[1] ($LO_2/m^2/yr$)	CO_2 conversion[1] (g $C/m^2/yr$)	Organic carbon primary flux ($g/m^2/yr$)†	Organic carbon resuspension‡	Loss to sediments
DWD 106	2200	4.03	1.84	6.3	0	1.6*
KN 58-2	2800	1.75**	0.80	2.3	1.4	0.45*
DOS 2	3650	2.10	0.96	4.2	2.4	0.8***

1. from Smith (1978).

† Top trap or, at DWD 106 with minimal nepheloid layer (Biscay and Olsen, 1976), average of three traps.

‡ Bottom trap minus top trap, probably underestimated because of distance of lower traps off bottom.

* Based on totals from traps, less the difference in organic matter in the traps and on the bottom (Table 2).

** Assumed equivalent of Smith's (1978) Sta. HH, 3000 m, on the Massachusetts to Bermuda transect.

*** Sedimentation rate of 6 to 7 gm $cm^2/1000/yr$, from Turekian 1965, from a core *ca.* 15 n. mi. from DOS 2. This rate multiplied by percent carbon (organic) gives loss to burial assuming no diagenetic losses after burial and constant rate over time.

assumptions are wrong the pelagic input could be considerably smaller than indicated on Figure 4.

Each diagram of carbon flow (Fig. 4) presents a somewhat similar pattern. The greater the input, the greater the losses to both metabolism and burial. Theoretically, total input should equal losses to the biota and to burial. There is, however, in each set of data, a large fraction of the input that has not been accounted for. The "lost" fraction is about half the pelagic input. Between the different locations we see that pelagic input varies by a factor of about 3, whereas loss to burial varies by a factor of 4 and metabolic loss varies by a factor of 2. The unaccounted for fraction at the nearshore site is three times that at the intermediate site, but an overestimate of the pelagic input at the nearshore site, due to our assumptions of little resuspension there, could account for this wide difference.

There are a number of possible explanations for the apparent imbalance between input and losses. The bell jar or grab respirometers measure the heterotrophic metabolism of small infaunal aerobic organisms. Absent from such measurements are the epibenthic organisms which are important components of deep assemblages (Haedrich and Rowe, 1977) and could be utilizing a lot of the organic matter well up into the water column. Likewise, anaerobic heterotrophic metabolism may be of some importance. While this might seem unlikely because no abiotic oxygen uptake was measured by Smith (*op. cit.*) at these depths and the sediments were not characterized by a redox discontinuity, Smith *et al.* (1978) did measure nitrate loss to the sediments at the nearshore station and at a location, 135 km to the east of our KN 58 stations. At the nearshore site they measured a loss of .95 μmoles m^{-2} hr^{-1}

of NO_3 to the bottom, which would be equivalent to approximately .116 gm N m^{-2} hr^{-1} loss. Assuming about 1.5 moles of carbon are oxidized to CO_2 for every mole of NO_3 used, we can estimate that 150 mg C m^{-2} yr^{-2} were oxidized by denitrification. At the intermediate site, by using Smith *et al's.* nitrate loss of .8 μmoles m^{-2} hr^{-1} from their station of similar depth we can estimate an additional utilization of 126 mg C m^{-2} yr^{-1}. These are only small fractions of the unaccounted for material.

A third possibility is that the traps catch more than is actually sedimenting out. An over-estimation of particle sinking or mass flux could result from the alteration of natural turbulence caused by our design of moored trap (Gardner, 1977; Staresinic *et al.*, 1978). Trap biases are difficult to evaluate, but as we observed slowest currents (< 5 cm sec^{-1}) and negligible resuspension (at DWD 106) where rates of flux were highest, we believe alteration of the flow field by moored traps does not result in overtrapping. Staresinic (*op. cit.*) has conducted an intercomparison of moored versus free drifting traps off Peru and his data suggest that moored traps, if anything, will suffer from undertrapping.

Another potential error in each budget is in the estimate of burial. We made these estimates by multiplying total net rate times percent organic carbon in the sediment. The net rate for DOS II came from values in the literature (Turekian, 1965) for the western North Atlantic, in grams (cm^{-2} 1000 yr^{-1}), and the percent organic carbon values were our own measurements. We have also estimated total rates from the amount captured in the traps, and at DOS II the value in the literature (6-7 gm $cm^{-2}10^{3}y^{-1}$) is close to the trap estimate (8.8 gm $cm^{-2}10^{3}yr^{-1}$). If considerable material is deposited at any of these sites from nearbottom transport from lesser depths moved as near-bottom resuspended material, this could cause over or underestimates in our budget, depending on the amount of organic matter that sediment contained.

Our measurements were made over periods of days in separate deployments from May through August 1976. If the seasonal variations in primary production known to exist in the surface waters (Ryther, 1963) are reflected in the transport down through the water column, our measurements would be somewhat higher than the yearly average, thus accounting for some of the imbalance in the budget. Based on our limited information we believe the fraction of organic matter for which we cannot account is partially a result of a seasonal bias in sampling, but that some of the unaccounted for organic matter is being used by organisms living on or just above bottom. Resolution of the problem will require some method of estimating the metabolism and secondary production of this assemblage and setting traps at other seasons.

The global carbon cycle is of considerable importance because the increasing anthropogenic CO_2 in the atmosphere, resulting from fossil fuel consumption, could alter climatic patterns and terrestrial primary production. The role of the ocean in this cycle is not clearly known, although the ocean is usually featured as an important

sink in simplified global models (Eriksson and Welander, 1955; Craig, 1957; Bolin and Eriksson, 1959; Pleset and Dugas, 1967; Cramer and Myers, 1972; Machta, 1973; Oesenger *et al.*, 1974; Gowdy *et al.*, 1975). The great age of the deep-sea carbon pool and the age of the deep water suggest that the rate at which organic matter and carbonate enter the deep water is relatively slow, implying the deep-sea is not a sink for carbon on short time scales. Rapidly sinking biogenic particles, however, could transport carbon directly to the bottom, as an important fate of carbon produced in surface waters. Our data cannot be used to estimate whether sinking particulate carbon can be of significance on a global scale because we sampled only the lower continental slope and upper rise of the North Atlantic and we sampled only in the summer. The deep ocean could be acting as a sink for carbon on a global scale, but as so few measurements of this kind have been made, there is no way yet of determining how rates will compare elsewhere and whether the sedimentation of particulate carbon is increasing.

REFERENCES

Agassiz, A. 1888. Three cruises of the BLAKE. Bull. Mus. Comp. Zool., *14,* 1.

Berger, W. and A. Soutar. 1967. Planktonic foraminifera: field experiment on production rate. Science, *156,* 1495–1497.

Biscaye, P. E. and S. L. Eittreim. 1974. Variations in benthic boundary layer phenomena: nepheloid layer in the North American Basin, *in* Suspended Solids in Water, R. J. Gibbs, Ed. Plenum Publishing Corp., New York.

Biscaye, P. E. and C. R. Olsen. 1976. Suspended particulate concentrations and compositions in the New York Bight, *in* Symposium on the Mid-Atlantic Continental Shelf and New York Bight, M. G. Gross, Ed. New York. Limnol. Oceanogr. Soc. Amer., Lawrence, 441 pp.

Bolin, B. and E. Eriksson. 1959. Changes in the carbon content of the atmosphere and sea due to fossil fuel combustion, *in* The Atmosphere and the Sea in Motion. The Rockefeller Institute Press, New York, 509 pp.

Cherry, R. D., S. W. Fowler, T. M. Beasley, and M. Heyroud. 1975. Polonium^{210} and its vertical oceanic transport by zooplankton metabolic activity. Mar. Chem., *3,* 105–110.

Craig, H. 1957. The natural distribution of radio-carbon and the exchange time of carbon dioxide between atmosphere and sea. Tellus, *9,* 1–17.

Cramer, J. and A. L. Myers. 1972. Rate of increase of atmospheric carbon dioxide. Atmos. Environ., *6,* 563–573.

Elder, D. L. and S. W. Fowler. 1977. Polychlorinated biphenyls: penetration into the deep ocean by zooplankton fecal pellet transport. Science, *197,* 459–461.

Eriksson, E. and P. Welander. 1955. On a mathematical model of the carbon cycle in nature. Tellus, *8,* 155–175.

Fowler, S. W. and L. F. Small. 1972. Sinking rates of euphausiid fecal pellets. Limnol. Oceanogr., *17,* 293–296.

Gardner, W. D. 1977. Fluxes, dynamics and chemistry of particulates in the ocean. Ph.D. Thesis, Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography. 405 pp.

—— Submitted. Sediment trap dynamics and calibration: a laboratory evaluation.

—— Submitted. Field calibration of sediment traps.

Gowdy, C. M., R. J. Mulholland, and W. B. Emanuel. 1975. Modeling the global carbon cycle. Int. J. Systems Sci., *6,* 965–976.

Grice, G. D. and K. Hulsemann. 1970. New species of bottom-living calanoid copepods collected in deep water by the DSVR ALVIN. Bull. Mus. Comp. Zool. Harvard, *139,* 185–227.

Haedrich, R. L. 1974. Pelagic capture of the epibenthic rattail *Coryphaenoides rupestris.* Deep-Sea Res., *21,* 977–979.

Haedrich, R. L. and N. R. Henderson. 1974. The pelagic food of *Coryphaenoides armatus,* a deep benthic rattail. Deep-Sea Res., *21,* 739–744.

Haedrich, R. L. and G. T. Rowe. 1977. Megafaunal biomass in the deep sea. Nature, *269,* 141–142.

Hessler, R. R., J. Isaacs, E. Mills. 1972. Giant amphipod from the abyssal Pacific Ocean. Science, *175,* 636–637.

Honjo, S. 1976. Coccoliths: production, transportation and sedimentation. Mar. Micropaleontology, *1,* 65–79.

—— 1978. Sedimentation of materials in the Sargasso Sea at 5,367 m deep station. J. Mar. Res., *36,* 469–492.

Iturriaga, R. Unpublished manuscript. Bacterial activity related to sedimenting particulate matter.

Izeki, K. 1976. *In situ* measurement of the vertical flux of particles by a newly designed collector. Chem. Ocean. Soc. Dept. Fish., Tohoku Univ. Preprint Collection No. 3, 18–25.

Jannasch, H. W., K. Eimhjellen, C. O. Wirsen, and A. Farmanfarmaian. 1971. Microbial degradation of organic matter in the deep sea. Science, *171,* 672–675.

Kuenzler, E. J. 1969. Elimination and transport of cobalt by marine zooplankton, *in* National Symposium (2nd) Radioecology NTIS Conference 670503, 783 pp.

Lowman, F. G., T. R. Rice, and F. A. Richards. 1971. Accumulation and redistribution of radionuclides by marine organisms, *in* Radioactivity in the Marine Environment, NAS-NRC, 272 pp.

Luyten, J. 1977. Scales of motion in the deep Gulf Stream and across the continental rise. J. Mar. Res., *35,* 49–74.

Machta, L. 1973. Prediction of CO_2 in the atmosphere, *in* Carbon and the Biosphere. G. M. Woodwell and E. V. Pecan, Eds. Washington, D.C., 392 pp.

Manheim, F. T., J. C. Hathaway, and E. Uchupi. 1972. Suspended matter in surface waters of the northern Gulf of Mexico. Limnol. Oceanogr., *17,* 17–27.

Marshall, S. and A. P. Orr. 1955. The Biology of a Marine Copepod. Oliver and Boyd. Edinburgh, 188 pp.

Maury, M. F. 1965. The Physical Geography of the Sea and Its Meteorology. 8th Edition, 1861 (reprinted 1963, The Belknap Press of Harvard University Press, Cambridge, Mass.), 293 pp.

McCave, I. N. 1975. Vertical flux of particles in the ocean. Deep-Sea Res., *22,* 491–502.

Nishizawa, S. and H. Izeki. 1975. Sediment trap applied in Bering Sea suspended sediment, Seminar Rec. Ocean Res. Inst. Tokyo.

Noshkin, V. E. and V. T. Bowen. 1973. Concentrations and distributions of long-lived fallout radionuclides in open ocean sediments, *in* Radioactive Contamination of the Marine Environment. International Atomic Energy Agency, Vienna, 786 pp.

Oesenger, H., V. Siegenthaler, V. Schotterer, and A. Guyelmann. 1974. A box diffusion model to study the carbon dioxide exchange in nature. Tellus, *27,* 168–192.

Osterberg, C., A. G. Carey, and M. Curl. 1963. Acceleration of sinking rates of radionuclides in the ocean. Nature, *200,* 1276–1277.

Osterberg, C., H. C. Curl, Jr., and W. G. Pearcy. 1964a. Radioactivity and its relationships to oceanic food chains. J. Mar. Res., *22,* 2–12.

Osterberg, C., J. Pattullo, and W. G. Pearcy. 1964b. Zinc-65 in euphausids as related to the Columbia River water off the Oregon coast. Limnol. Oceanogr. *9,* 249–257.

Pearcy, W. G., E. E. Krygier, R. Mesecar, and F. Ramsey. 1977. Vertical distribution and migration of oceanic micronekton off Oregon. Deep-Sea Res., *24,* 223–245.

Pearcy, W. G. and J. W. Ambler. 1974. Food habits of deep-sea macrourid fishes off the Oregon coast. Deep-Sea Res., *21,* 745–759.

Pearcy, W. G. and C. L. Osterberg. 1967. Depth, diel, seasonal, and geographic variations in zinc-65 of midwater animals off Oregon. Int. J. Oceanol. Limnol., *1,* 103–116.

Pleset, M. S. and D. J. Dugas. 1967. Decay of a disturbance of carbon 14. J. Geophys. Res., *72,* 4131–4137.

Rowe, G. T. 1971. Benthic biomass and surface productivity, *in* Fertility of the Sea, J. D. Costlow, Jr., Ed. Gordon and Breach, New York, 622 pp.

Rowe, G. T. and D. W. Menzel. 1971. Quantitative benthic samples from the deep Gulf of Mexico with some comments on the measurement of deep-sea biomass. Bull. Mar. Sci., *21,* 556–566.

Rowe, G. T. and C. H. Clifford. 1978. Sediment data from short cores taken in the northwest Atlantic Ocean. W.H.O.I. Technical Rept. 78-46. 55 pp. Unpublished manuscript.

Rowe, G. T., P. T. Polloni, and S. G. Hornor. 1974. Benthic biomass estimates from the northwestern Atlantic Ocean and the northern Gulf of Mexico. Deep-Sea Res., *21,* 641–650.

Ryther, J. H. 1963. Geographic variations in productivity, *in* The Sea, Vol. 2, M. N. Hill, Ed. Wiley-Interscience, New York, 554 pp.

Schrader, T. J. 1971. Fecal pellets: role in sedimentation of pelagic diatoms. Science, *174,* 55–57.

Sheldon, R. W. and T. R. Parson. 1967. A practical manual on the use of the Coulter Counter in marine science. Coulter Electronics, Toronto. 66 pp.

Smayda, T. J. 1969. Some measurements of the sinking rate of fecal pellets. Limnol. Oceanogr., *14,* 621–625.

—— 1970. The suspension and sinking of phytoplankton in the sea. Oceanogr. Mar. Biol. Ann. Rev., *8,* 353–414.

—— 1971. Normal and accelerated sinking of phytoplankton in the sea. Mar. Geol., *11,* 105–122.

Smith, K. L., Jr. 1978. Benthic community respiration in the N. W. Atlantic: *in situ* measurements from 40 to 5200 meters. Marine Biology, *47,* 337–347.

Smith, K. L., Jr., G. A. White, M. B. Laver and J. A. Haugsness. 1978. Nutrient exchange and oxygen consumption by deep-sea benthic communities: Preliminary *in situ* measurements. Limnol. Oceanogr., *23,* 997–1005.

Spencer, D., P. Brewer, A. Fleer, S. Honjo, S. Krishnaswami and Y. Nozaki. 1978. Chemical fluxes from a sediment trap experiment in the deep Sargasso Sea. J. Mar. Res., *36,* 493–523.

Staresinic, N., G. T. Rowe, D. Shaughnessey, and A. J. Williams, III. 1977. Measurement of the vertical flux of particulate organic matter with a free-drifting sediment trap. Limnol. Oceanogr., *23,* 559–563.

Staresinic, N. 1978. The vertical flux of particulate organic matter in the Peruvian coastal upwelling as measured with a free drifting sediment trap. Ph.D. thesis. Woods Hole-M.I.T. Joint Program in Biological Oceanography.

Turekian, K. K. 1965. Some aspects of the geochemistry of marine sediments, *in* Chemical Oceanography. J. P. Riley and G. Skirrow, Eds. Academic Press, New York, 508 pp.

Vinogradov, M. E. 1968. Vertical Distribution of the Oceanic Zooplankton. Academy of Sciences of the USSR, Inst. of Oceanography, Moscow. 339 pp.

Wiebe, P. H., S. H. Boyd, and C. Winget. 1976. Particulate matter sinking to the deep-sea floor at 2000 meters in the Tongue of the Ocean, Bahamas with a description of a new sedimentation trap. J. Mar. Res., *34,* 341–354.

Williams, A. J., III and K. Fairhurst. 1977. Two oceanographic releases. Ocean Engineering, pp. 205–210.

Woodwell, G. M., R. H. Whittaker, W. A. Reiners, G. E. Likens, C. A. S. Hall, C. C. Delwiche and D. B. Bodkin. 1978. The biota and the world carbon budget. Science, *199,* 141–146.

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