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PARTICULATE MATTER SINKING TO THE DEEP-SEA FLOOR  
AT 2000 M IN THE TONGUE OF THE OCEAN, BAHAMAS,  
WITH A DESCRIPTION OF A NEW SEDIMENTATION TRAP

by

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# Particulate matter sinking to the deep-sea floor at 2000 m in the Tongue of the Ocean, Bahamas, with a description of a new sedimentation trap

by Peter H. Wiebe<sup>1</sup>, Steven H. Boyd<sup>1</sup>, & Clifford Winget<sup>1</sup>

## ABSTRACT

A sedimentation trap for use just above the deep-sea floor was free-fallen to a depth of 2050 m in the Tongue of the Ocean canyon on January 3, 1974. On March 6, it was successfully recovered with the assistance of D.S.R.V. *Alvin*. The trap has a base 1 m square and a height of 30 cm. At the trap bottom are filters to retain falling particles. Two spring-powered sliding doors, each 1 m × 0.5 m, are used to close off the lower 2 cm of the trap during ascent to prevent disturbance of the particles collected on the filters.

Total carbon on the filters as determined by high temperature combustion averaged 2301 mgC/m<sup>2</sup> or an average on a daily basis of 36.5 mgC/m<sup>2</sup>. Similar filter aliquots were treated with cold phosphoric acid to eliminate the inorganic fraction. The resulting carbon values ( $\bar{X}$  = 5.7 mgC/m<sup>2</sup>/day) suggest 14% of the total carbon reaching the sea floor at 2000 m in this area is organic in origin. Fecal material is one readily identifiable component of the material contributing to the organic fraction. Counts of fecal pellets resulted in an estimate of an average of ~ 650 pellets/m<sup>2</sup>/day. Average pellet length was 241 μm and diameter was 109 μm. In laboratory experiments the pellets sank at rates varying from 50 m/day to 941 m/day ( $\bar{X}$  at 5°C = 159 m/day).

Comparison of the sedimentation trap estimates of organic carbon input to the sea floor in this area with benthic energy requirements indicates that rapidly sinking small particulate matter could supply approximately 14% of the metabolic requirements of the benthos.

## 1. Introduction

The "rain of particles" to the deep-sea floor has long been suggested to be a primary means by which nutritive material is supplied to organisms inhabiting the deep-sea floor (Menzies, 1962; Vinogradov, 1968; and others). Prime candidates for major components of this material are fecal pellets, crustacean carapaces, animal carcasses, large phytoplankton cells, and inorganic shells of foraminifera and pteropods with adsorbed organic matter. The utilization of detrital phytoplankton for food by bathypelagic euphausiids has been shown from measurements of phaeopigments in their stomach, intestine and fecal pellets (Nemoto, 1968; Ne-

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moto and Saijo, 1968). Euphausiid carapace sinking rates of 288 m/day (Lasker, 1966), fecal pellet sinking rates of 36-376 m/day (Osterberg, *et al.*, 1963; Smayda, 1969; Fowler and Small, 1972) and recent *in situ* measurements of surface produced fecal pellets at depths of 459 m and 4000 m (Schrader, 1971) and 1000 m (Nemoto, 1968) indicate that large organic particles can sink rather rapidly and in some cases reach great depths. In addition to the potential these fractions may hold as a major food source for deep-living animals, they also may be important as conveyors of surface introduced organophilic pollutants such as pesticides, PCBs and heavy metals into the deep-sea, or in the case of fecal pellets as a primary conveyor of phytoplankton skeletal materials.

One difficulty in sampling these particles at great depths stems from their apparently low density in the water column relative to that deep particulate organic carbon (POC) which is thought to be largely refractory and sinking at minimal rates (Menzel and Ryther, 1970; Menzel, 1974). Thus, conventional sampling techniques employing water sampling bottles or *in situ* pumps either will fail to collect rapidly sinking particles because of inadequate sample size or will find this fraction to be so small relative to the total POC collected as to be unmeasurable (see Wiebe, Remsen, and Vaccaro, 1974, for additional discussion of this point). The fragility of much of this sinking material rules out net collection of all but the most robust particles. Since evidence is circumstantial that sinking of organic matter as small particles is a major pathway to the deep-sea for food and associated elements, direct measurements are required to substantiate it.

A number of investigators have previously experimented with detrital or sedimentation collecting apparatus, for example see Moore (1931), Kleerekoper (1952), Trevallin (1967), and Brunskill (1969). However, most of the experiments employing this gear were conducted in relatively shallow water and the gear is impractical for use in the deep ocean. Newer shallow water versions are described by White and Wetzel (1973) and Fuhs (1973). The single trap design of Schick *et al.* (1968), used by Berger and Soutar (1967) below 500 m, also did not meet our basic design specifications. These specifications were that the trap should not interfere with settling particles, and that in the subsequent retrieval process particles should be quantitatively retained. We have developed a sediment trap for use above the deep-sea floor to collect settling particles. Some of the results of its use at 2050 m in the Tongue of the Ocean, Bahamas are presented.

## 2. Methods and instrumentation

Our trap has a base 1 meter square and a height of 30 cm (Fig. 1). The construction materials are lucite plastic and 316 stainless steel. The interior of the trap is subdivided by vertical partitions into 16 chambers each 25 cm on a side to add structural rigidity and also to permit collection of 16 separate samples. Combusted HA (Gelman) glass fiber filters, on which sedimented material is collected, are

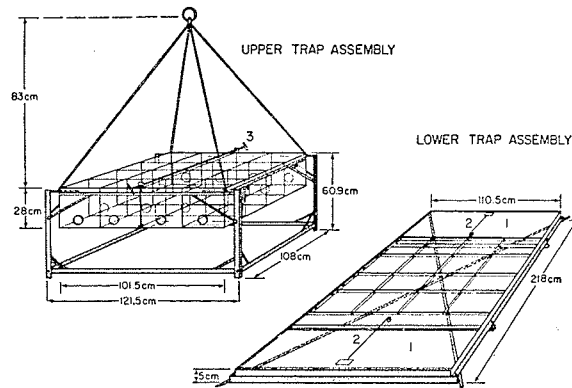


Figure 1. Detail drawing of the sedimentation trap. The lower trap assembly is attached to the upper portion by stainless steel bolts. Stippled areas are metal supports; clear areas are lucite plastic. Numbered parts are: 1 = sliding door; 2 = negator spring; 3 = door release mechanism.

placed in each 25 cm square portion of the lower trap assembly (Fig. 1). Under each filter is a perforated stainless steel plate, which with the filter is held in place by square stainless steel retaining clips formed from rods 3.2 mm (0.125 in) in diameter. These clips hold down the outside edges of the filter. The retaining square, filter and backing plate are locked into place by perpendicularly criss-crossing rods whose total length is approximately 105 cm. These rods pass the length and width of the trap through holes in the trap partitions just above the filter assembly. There are 5 drain holes ( $\frac{3}{8}$  in diameter) in the floor of the trap beneath each filter, permitting water to drain through the filters once the trap is above the sea surface. Two spring-powered sliding doors, each 1 m  $\times$  0.5 m, normally cocked in an open position during descent and collection, are used to close off the lower 2 cm of the trap during ascent to prevent turbulence from disturbing the particles collected on the filters. Portholes covered with 333  $\mu$ m plankton gauze are near the bottom of the upper trap assembly (Fig. 1), but above the track of the doors to facilitate flooding during launch and draining during recovery. The plastic portions of the trap are attached to a stainless steel angle bar and tubular supporting frame. A 333  $\mu$ m plankton gauge cap covers the top of the trap to keep large particulate matter from entering until it is in place. As presently designed both the removal of the gauze cap and the closing of the sliding doors must be accomplished by D.S.R.V. *Alvin*. The trap weighs 204 lbs in air and 120 lbs in seawater.

Although D.S.R.V. *Alvin* is presently required to open and close the trap, it is set and retrieved as a free-fall vehicle (Isaacs, 1963) and is therefore part of a larger array. In addition to the trap, the array (Fig. 2) consists of a four-ball float

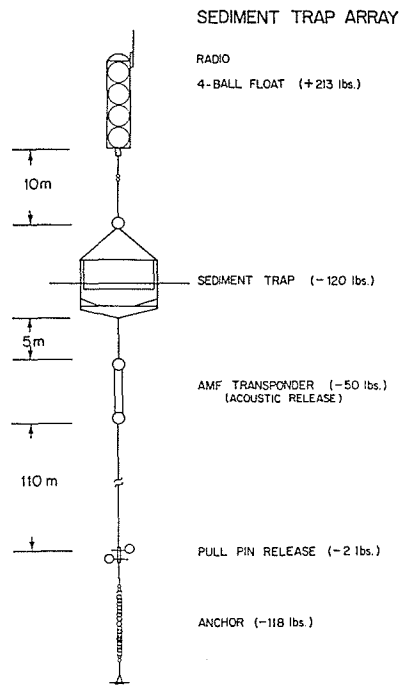


Figure 2. Schematic representation of the sedimentation trap array. Values given in parentheses are weights in seawater. The sedimentation trap weighs 92.5 kg (204 lbs) in air. All lines connecting the array units were 1.59 cm dia. (0.625 in) nylon rope. Total height of trap above sea floor is 116 meters.

assembly of glass spheres, an AMF acoustic transponder, 100 meters of nylon rope ( $\frac{5}{8}$  diameter), a pull-pin release, and an anchor (heavy chain). The AMF transponder is required to enable the surface vessel and submarine to locate the trap once it is in place on the sea floor and to recall it to the surface. The pull-pin release is a back-up release system to be used by the D.S.R.V. pilot in case the acoustic release fails.

### 3. Study areas

#### *a. Millstone, Connecticut*

Shallow water experiments were carried out to examine potential sources of trapping bias and to gain some appreciation of the catching efficiency of the trap for negatively buoyant particles released 15 to 20 m above the trap at the sea surface.

In October, 1973, the trap was anchored in a submerged quarry hole open to the sea which is presently used as an outflow pond for a nuclear power generating plant in Millstone, Connecticut. The bottom of the trap was approximately 5 m above the sediment where the water depth was approximately 20 m. A large

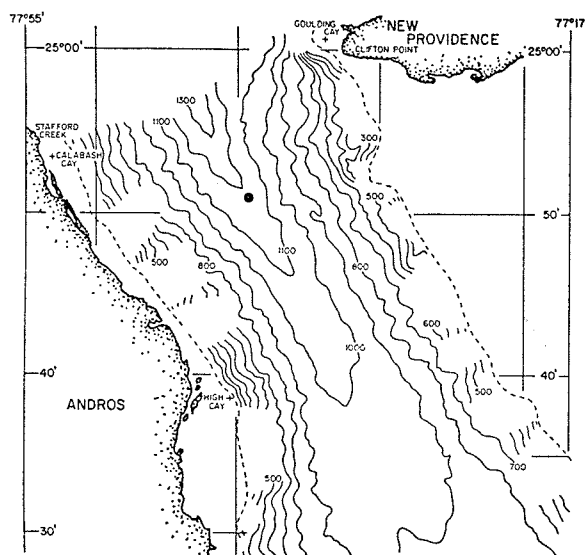


Figure 3. Bottom topography of Tongue of the Ocean, Bahamas, and location (black dot) of sedimentation trap array, January 3 to March 6, 1974. Contours in fathoms. Bottom type in most of canyon is carbonate (foraminiferal) ooze.

number ( $\sim 250,000$ ) of fluorescein dyed coffee grounds (between 0.8 and 1.4 mm in diameter) which were pre-soaked in seawater at the study site were distributed at the water surface above the trap (area of dispersal  $\sim 10$  m radius). In laboratory tests most of these particles sank at a rate of  $\sim 1.2$  m/min). After 5.75 hours the doors were closed by SCUBA divers and the trap returned to the surface. The particles were counted with the aid of an ultraviolet lamp.

#### b. Tongue of the Ocean, Bahamas

On January 3, 1974, the sediment-trap array was allowed to free-fall to a depth of 2150 m on the axis of the Tongue of the Ocean Canyon (Fig. 3). The operation involved SCUBA diver assist. The trap was lowered to the sea surface and attached to the float assembly after which it sank to a position below the float. The AMF transponder was then attached to the array by the divers. Just prior to the release of the anchor, the trap doors were opened. Although it was intended for D.S.R.V. *Alvin* to inspect the trap once it was in place and remove the gauze protective cap, this was not possible (due to operational constraints). Therefore, at approximately the same time as the anchor was released from the surface vessel, a diver removed the cap. This followed the opening of the doors. We believe the amount of contamination resulting from removing the cap prior to free-fall is small, although there is now no way to evaluate it.

After 63 days in place, the trap doors were closed by the pilot of D.S.R.V.

*Alvin* (Dive #509) and an inspection of the sediment trap array was completed prior to its recall to the surface. Film documentation of the amount of particulate matter on the trap was obtained by the Edgerton 35 mm cameras mounted outside the submersible and by hand-held 35 mm Nikon cameras from inside the submersible.

Upon the return of D.S.R.V. *Alvin* to the surface, the sediment trap array was recalled. The surface recovery operation also required SCUBA diver assist. The procedure followed was approximately the reverse of the launch procedure with several important differences. Once the AMF transponder was detached from the array and was brought to the surface, a steel cylinder of similar underwater weight was attached below the trap to act as a counter balance. Divers then installed two deflated flotation rings (modified one-man rubber rafts) under the trap. In addition, a "Port-a-lift" inflatable plastic bag attached to the top of the trap was used to raise the trap from its hanging position 10 m below the four-ball float assembly to within 3-4 m of the surface. When the flotation rings were inflated by the divers using tire inflater hoses attached to the accessory port of the SCUBA regulators, the trap floated up to a position above the sea surface and was picked up by the surface vessel. Our intention in executing this procedure was to avoid the turbulence and strain caused by the rapid vertical accelerations common to all surface vessels. However, recovery of the trap sample was marred by a temporary instability of the trap as it floated up the last 3 m to the surface, with a loss of an unknown portion of the material collected on the filters. During the process of retrieval, an underwater camera was used to photograph the sediment trap filters prior to initiation of the surface recovery.

Once on board R.V. *Lulu*, the filters were again photographed and then they were removed and allotted for various analyses. On shipboard, ten 2.54 cm diameter discs were cut from selected filters for scanning and transmission electron microscopy. These filters were immediately sealed in a stainless steel holding apparatus filled with fixative. A quarter of each of 3 filters was removed for carbon, hydrogen, and nitrogen analyses using either Hewlett Packard model No. 185B CHN analyzer or a Perkin-Elmer No. 240 CHN analyzer and detection of chlorophyll and its degradation products with a Turner fluorometer. Each quarter was further subdivided into nine subsamples and each subsample frozen in a separate vial. Seventeen 60 mm diameter circles were cut from the filters and placed in petri dishes for light microscope examination. The remaining filter material was set aside and frozen for future allotment.

In the examination of the trapped material with a binocular scope, the fecal pellets were counted, their length and width were measured, and some were removed for electron microscopy and sinking rate determinations. Sinking rate measurements were done in a volumetric cylinder filled with seawater (salinity between 35 and 36‰). In the first series of measurements the water was at 22.7°C;

in the second series, it was between 4 and 5°C. Fecal pellets were picked off frozen filter aliquots, thawed to temperature of experiment, and then placed slightly below the seawater surface. Time to sink a known distance was recorded after the pellets reached terminal velocity. The methodology is similar to that employed by Fowler and Small (1972).

#### 4. Results

##### a. Millstone, Connecticut

Field testing of the sedimentation trap at the Millstone Quarry using marked particles resulted in an average of 13.4 marked particles occurring on a filter (25 cm × 25 cm, range 8 to 17). The variability about the mean did not deviate from a random expectation ( $0.70 > P > 0.50$ ). Without current flow past the trap, 50 (800/m<sup>2</sup>) were expected to land on each filter. However, there was significant horizontal flow observed during the experiment. The trap was lowered a second time and remained in place for 16 hours. Just prior to closing the doors, a diver placed 25 marked particles on one of the filters. The doors were then closed and the trap floated to the surface. None of the particles were lost during the process of ascent to the surface or draining of the trap. This latter experiment was conducted on two previous occasions (in Buzzards Bay in August, 1971, depth of water 16 m and beside the Woods Hole Oceanographic Institution dock in August, 1971, depth of water 21 m) in less quantitative form with similar results. In all cases, surface conditions did not interfere with the passage of the trap through the air-sea interface. Our results, which suggest that the trap is providing an unbiased estimate of the downward flux of sinking material, are supported by recent work evaluating sediment traps (Kirchner, 1975; Pennington, 1974, and Rigler *et al.*, 1974).

##### b. Tongue of the Ocean, Bahamas

*In situ* observations of the sediment trap at 2050 m from D.S.R.V. *Alvin* revealed that the filters were overlain by a rich coating of brown particulate material. Most of the material was too small to be identifiable; however, four pieces of unidentified sea grass 2-3" long were observed on two of the filters. The brown particulate material on the trap was visually similar to the material observed at the sediment water interface. After its ascent, visual inspection of the trap at 10 m indicated little change in the amount of material on the filters.

As noted previously, some of the material on the filter was lost while bringing the trap through the air-sea interface. As a result, the estimates presented here we consider minima.

Total carbon (inorganic and organic) on 18 untreated filter aliquots averaged 2301 mgC/m<sup>2</sup>. This amount averages on a daily basis 36.5 mgC/m<sup>2</sup> (range: 11.8-



Table 1. Summary of analysis for carbon retained on sediment trap filters.

Filter Area (cm <sup>2</sup> )	Date of Analysis	N	MgC/m <sup>2</sup> /Day	
			$\bar{x}$	Range
0.77	March 1974	7	37.9	(11.8-83.5)
1.76	April 1974	8	24.7	(19.0-29.0)
1.76*	April 1974	4	6.4	( 4.4-11.3)
1.64	December 1975	3	64.5	(55.2-75.5)
1.64*	December 1975	3	4.7	( 0 -13.3)

\* Treated with 10% cold phosphoric acid (see text for details).

83.5, Table 1). In two separate experiments (April, 1974; December, 1975) replicates of the filter aliquots analyzed for total carbon were set on the surface of a solution of 10% cold phosphoric acid for approximately 24 hours to eliminate the inorganic fraction. (Sharp, 1974, p. 987 discusses some aspects of this treatment.) These replicates were then analyzed for carbon. In the first set, the values averaged 6.4 mgC/m<sup>2</sup>/day and in the second, they averaged 4.7 mgC/m<sup>2</sup>/day (Table 1). The values suggest that on the average between 7% and 25% of the total carbon reaching the sea floor in this area is organic in origin. Much of the remaining carbon was in the form of calcium carbonate. Although quantitative counts have not been attempted, tremendous numbers of foraminifera tests and thecosomatous pteropod shells were present on the filters and contributed significantly to the total carbon.

Fecal pellets were one readily identifiable component of the material contributing to the organic fraction on the filters. Counts of pellets on filter aliquots (Table 2) suggest an average of 658 pellets/m<sup>2</sup>/day reached the trap (range 456 to 916/m<sup>2</sup>/day). These counts may be as much as one order of magnitude too small not only because of the material lost in trap recovery, but also because some of

Table 2. Fecal pellet statistics.

Aliquot No.	Aliquot Size	No. Fecal Pellets	No. Pellets /m <sup>2</sup> /day	Pellet length ( $\mu$ m)		Pellet width ( $\mu$ m)	
				$\bar{x}$	range	$\bar{x}$	range
1	8.7	25	456	192	( 92-385)	—	—
2	8.7	50	912	—	—	—	—
3	8.7	28	511	190	(108-339)	—	—
4	8.7	29	592	150	( 92-277)	64	(31-123)
5	8.7	45	821	257	(139-847)	100	(46-262)
6	†	33	—	277	(123-770)	—	—
7	†	12	—	241	(184-308)	91	(46-123)
8	†	11	—	259	(185-570)	140	(77-231)
means			658	224		93	

† Not quantitative. Numbers measured were not total numbers present.

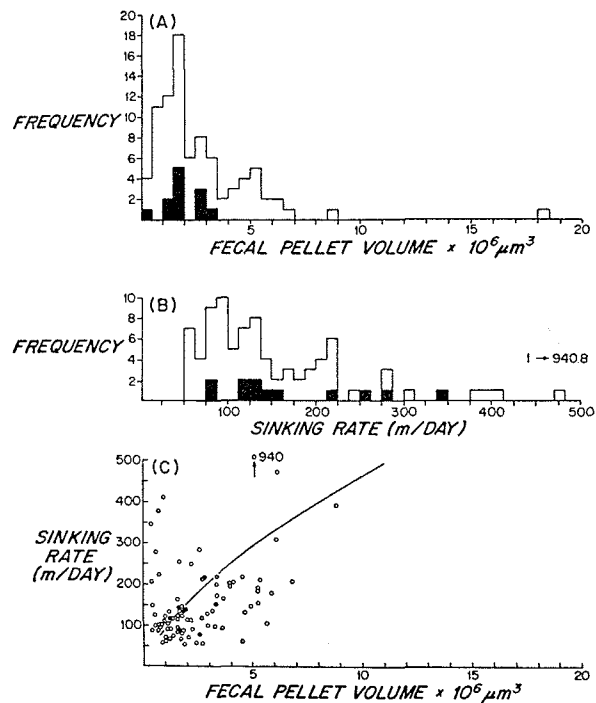


Figure 4. A. Fecal pellet volume histogram. Pellets used in sinking experiment at 5°C are clear and at 21.7°C are blacked.

B. Fecal pellet sinking rate histogram. Population differentials as in A, (see text for detailed description of this experiment).

C. Relationship between fecal pellet volume and sinking rate. Fecal pellets sinking in 5°C seawater, open circles; in 21.7°C seawater, solid dots. Curve based on Stoke's law for a sinking body in a viscous medium (see text).

the fecal pellets, being extremely soft, lost their form and could no longer be positively identified as pellets. These questionable pellets were not counted. In addition, many of the fecal pellets were "buried" in the accumulations of the sedimented material on the filters and could not be accurately counted.

Generally, pellets were cyclindrically shaped with tapered ends. They averaged 224  $\mu\text{m}$  in length and 93  $\mu\text{m}$  in width (Table 2). The 86 pellets used in the sinking rate experiments were of similar size ( $\bar{X}$  length = 241  $\mu\text{m}$ ;  $\bar{X}$  width = 109  $\mu\text{m}$ ) and the volume-frequency distribution (Fig. 4A) is similar to that obtained for the pellets counted on filter aliquots. In determination of fecal pellet volume, we have assumed a cylindrical shape even though some of the pellets were more ellipsoidal. The resulting volume is at most a 30% overestimate of the true volume. However, the overall bias is less because most pellets had a shape intermediate between a cylinder and an ellipsoid.

Most fecal pellets sank at a rate between 50 and 225 m per day with a small number (10% of the total) sinking faster, up to 941 m per day (Fig. 4B). The data on sinking rates at the two temperatures ( $\bar{X}$  rate at 21.7°C = 171 m per day;  $\bar{X}$  rate at 5°C = 159 m per day) indicate that the fecal pellets are slowed in their descent by the increased viscosity ( $\mu$ ) at colder temperatures ( $\mu = .0105$  poise at 21.7°C;  $\mu = .0161$  poise at 5°C; Sverdrup, Johnson, and Fleming, 1942, p. 69). This viscosity effect is in fact greater than indicated by the average difference between sinking rates at the two temperatures because the average pellet volume ( $2.72 \times 10^6 \mu\text{m}^3$ ) in the 5°C runs was larger than the volume ( $1.90 \times 10^6 \mu\text{m}^3$ ) in the 21.7°C runs. The average sinking rates of these data sets fit Stoke's law for a sinking body in a viscous liquid. (Hutchinson, 1969, p. 258, Equation 16) and they therefore can be used to indirectly estimate the average density of the fecal pellets. This value ( $1.222 \text{ gm/cm}^3$ ) was used to calculate the expected sinking rate curve given in Fig. 4C. The scatter about the line is wide, partly as a result of variability in the density of the pellets (Fig. 4C). We have not attempted to measure the density of fecal pellets directly, but light and electron microscopy revealed considerable variation in their compositional structure and compactness.

Small amounts of chlorophyll *a* and phaeophytin were detected on four filter aliquots. The quantities (total pigment) ranged from 3.0 to 5.0  $\mu\text{g/m}^2/\text{day}$ . Much of this material was probably in the fecal pellets as electron micrographs revealed the presence of phytoplankton cellular membranes and chloroplasts in some pellets and whole coccospheres of coccolithophores as well as numerous coccoliths in others (Honjo and Wiebe, unpublished data). About a tenth of the total pigment was estimated to be chlorophyll *a*. This estimate must, however, be viewed with caution because the analysis was run on filters which were frozen for approximately ten weeks following trap retrieval.

## 5. Discussion

In assessing present knowledge about the cycling of organic matter in the oceans, Menzel (1974, p. 675) states that ". . . virtually nothing is known of the mechanisms by which organic matter is transported to depths and how the energy requirements of the deep-sea are met." It is his opinion that this ". . . is the single most important unresolved problem in the fields of marine biology and chemistry . . .". The problem is unresolved because of the paucity of data regarding the energy requirements of deep-sea organisms and the lack of direct measurements of energy inputs to the deep-sea environment. While possible pathways of energy flux to the deep ocean have been discussed (Menzies, 1962; Vinogradov, 1968; Wiebe, Remsen, and Vaccaro, 1974), few attempts have been made to evaluate them. In the deep ocean, sedimentation traps would appear to possess unique capabilities for collecting small particles which are rapidly sinking to the sea floor

without inclusion of the quantitatively dominant particulate matter which is essentially uniform in distribution below approximately 400 m in all oceans and largely refractory. Such traps ought to provide quantitative data on the importance of such particles in the energy flux to deep-sea communities.

If sedimentation trap data are to be meaningful the possibility must be minimized of contamination by resuspended particles previously deposited on the bottom or by organisms which come to use the trap as a substrate or feeding area. Placement of our trap at least 100 m above the sea floor appears to have obviated both possible problems. Based on the inspection of the array with D.S.R.V. *Alvin*, we found no evidence that organisms had colonized the trap and were living on or in it at the time of recovery. Large nekton or zooplankton interaction with or aggregation around the trap appeared minimal.

Two lines of evidence indicate that particles resuspended from the sea floor were not a significant contaminant. First, current meters suspended within 10 m of the sea floor less than a mile from the sedimentation trap array recorded horizontal current velocities no greater than 28 cm/sec during the 63 days the trap was in place. The highest velocity (28 cm/sec) recorded only lasted a maximum of approximately 10 hours and then declined to much lower values (<5-10 cm/sec, R. Ballard, pers. comm.) These would have been insufficient to move the type of particles caught by the trap to an elevation of 100 m. However, there is the possibility that material from the sides of the canyon at shallower depths may have been transported to a position over the trap by downwelling density currents. Second, some of the fecal pellets examined by electron microscopy were composed in part of undigested plant material produced in the photic zone. It seems unlikely this material could also undergo secondary digestion by benthic organisms and remain recognizable although we lack specific information to support this contention.

As noted above, evaluation of the importance of an energy flow pathway linking primary producers to deep-sea benthic consumers requires information about benthic energy requirements as well as the energy input rate. Total respiration of the benthos (megafauna, microfauna, and microbial components) has been used as one measure of metabolic activity (Smith and Teal, 1973) and such values can be converted to average carbon content of the food required to sustain the activity assuming  $1 \text{ ml O}_2 = 4.83 \text{ gm cal}$  and  $9 \text{ gm cal} = 1 \text{ mg C}$ . Six *in situ* bell jar total oxygen uptake measurements (benthos and chemical oxygen demand) of the bottom at 2000 m in the vicinity of the sedimentation trap were made by K. L. Smith, Jr. (pers. comm., unpublished data). Four values ( $\bar{X} = 3.2 \pm .03 \text{ ml O}_2/\text{m}^2/\text{hr}$ ) were determined by bell jars operated from D.S.R.V. *Alvin* and two values ( $3.0 \pm .05 \text{ ml O}_2/\text{m}^2/\text{hr}$ ) were determined by respirometers attached to a free-fall tripod system. Application of the conversion factors provides estimates of 38 to 42 mgC/m<sup>2</sup>/day as the total benthic energy requirement. Comparison with our minimum estimate of organic material settling on the trap which averaged 5.7 mgC/

$\text{m}^2/\text{day}$  (range 0 to  $13.3 \text{ mgC}/\text{m}^2/\text{day}$ ) indicates that rapidly sinking small particulate matter could supply approximately 14% of the benthic requirements in this area. It is important to note that there is at least one other important source of energy for the benthos in this area. Large quantities of turtle grass and other macroscopic plant materials were observed on a number of the dives by D.S.R.V. *Alvin* to the Tongue of the Ocean canyon floor to depths as great as 3050 m. Although quantitative estimates of the amount of this material and its input rate have not been made, the ubiquity in distribution of such plant material in this canyon environment indicates that it is an important energy source. Menzies, Zaneveld, and Pratt (1967) and Schoener and Rowe (1970) have made similar suggestions regarding macroscopic grasses and seaweeds observed on the deep-sea floor off North Carolina.

The occurrence on the sedimentation trap filters of fecal pellets composed of phytoplankton remains provides direct evidence that surface formed pellets reach bathyal depths in large numbers and underscores their importance as a means of transfer for food and other materials as documented in the introduction. Our data on their size range and sinking rates, which agree with those presented by Smayda (1969, 1971) and Fowler and Small (1972), indicate that most pellets were in transit from the surface to the trap (2050 m) between 9 and 40 days. Intact phytoplankton cells within some fecal pellets, coupled with rapid sinking rates, lead us to believe that the phytoplankton cells observed by Malone *et al.* (1973) to bloom when North Atlantic red clay sediments from 6150 m were brought to the surface and incubated, were transported to the bottom in fecal pellets.

Crustacean exoskeletons are one element of particulate organic matter which we did not find on the filters. Clearly our very limited sampling is inadequate to do more than note their absence, but it is curious since a body of circumstantial evidence exists which suggests that some carapaces should reach the sea floor (for example, Lasker, 1966; Fowler and Small, 1967, 1972; Wheeler, 1967; Martin, 1970). In support of our finding, Steele and Baird (1972) recently reported the lack of exoskeletons in shallow sedimentation trap collections from the North Sea.

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## REFERENCES

- Berger, W. H., and A. Soutar. 1967. Planktonic foraminifera: field experiment on production rate. *Science*, 156, 1495-1497.
- Brunskill, G. J. 1969. Fayetteville Green Lake, New York. II. Precipitation and sedimentation of calcite in a meromictic lake with laminated sediments. *Limnol. Oceanogr.*, 14, 830-847.
- Fowler, S. W., and L. F. Small. 1967. Moulting of *Euphausia pacifica* as a possible mechanism for vertical transport of zinc-65 in the sea. *International Journal of Oceanol. Limnol.*, 16, 293-296.
- . 1972. Sinking rates of euphausiid fecal pellets. *Limnol. Oceanogr.*, 17, 293-296.
- Fuhs, W. 1973. Improved device for collection of sedimenting matter. *Limnol. Oceanogr.*, 18, 989-993.
- Hutchinson, G. E. 1967. A Treatise on Limnology. II. Introduction to lake biology and the limnoplankton. New York, John Wiley and Sons. 1115 pp.
- Isaacs, J. D. 1963. Deep-sea anchoring and mooring, in *The Sea*, Vol. 2, M. N. Hill, ed., New York, Interscience Publishers, 516-527.
- Kirchner, W. B. 1975. An evaluation of sediment trap methodology. *Limnol. Oceanogr.*, 20, 657-660.
- Kleerekoper, H. 1952. A new apparatus for the study of sedimentation in lakes. *Canadian J. of Zoology*, 30, 185-190.
- Lasker, R. 1966. Feeding, growth, respiration, and carbon utilization of a euphausiid crustacean. *J. Fish. Res. Bd. Can.*, 23, 1291-1317.
- Malone, T. C., C. Garside, R. Anderson, and O. A. Roels. 1973. The possible occurrence of photosynthetic microorganisms in deep-sea sediments of the North Atlantic. *J. Phycology*, 9, 492-498.
- Martin, J. H. 1970. The possible transport of trace metals via moulted copepod exoskeletons. *Limnol. Oceanogr.*, 15, 756-761.
- Menzel, D. W. 1974. Primary productivity, dissolved and particulate organic matter, and the sites of oxidation of organic matter, in *The Sea*, Vol. 5, E. D. Goldberg, ed., New York, John Wiley and Sons, 659-678.
- Menzel, D. W., and J. H. Ryther. 1970. Distribution and cycling of organic matter in the oceans, in *Organic Matter in Natural Waters*, D. W. Hood, ed., occasional publication, Inst. of Marine Science University of Alaska, 1, 31-54.
- Menzies, R. J. 1962. On the food and feeding habits of abyssal organisms as exemplified by the Isopoda. *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, 47, 339-358.
- Menzies, R. J., J. S. Zanefeld, and R. M. Pratt. 1967. Transported turtle grass as a source of organic enrichment of abyssal sediment off North Carolina. *Deep-Sea Res.*, 14, 111-112.
- Moore, H. B. 1931. Muds of the Clyde Sea Area III. *J. of the Marine Biological Association, United Kingdom*, 14, 325-358.
- Nemoto, T. 1968. Chlorophyll pigments in the stomachs of euphausiids. *J. of Oceanographical Society, Japan*, 24, 253-260.
- Nemoto, T., and Y. Saijo. 1968. Trace chlorophyll pigments in stomachs of deep-sea zooplankton. *J. of the Oceanographical Society, Japan*, 24, 1276-1277.
- Osterberg, C., A. G. Carey, and H. Curl. 1963. Acceleration of sinking rates of radionuclides in the ocean. *Nature, London*, 200, 1276-1277.
- Pennington, W. 1974. Seston and sediment formation in five district lakes. *J. Ecol.*, 62, 215-251.
- Rigler, F. H., M. E. MacCallum, and J. C. Roff. 1974. Production of zooplankton in Char Lake. *J. Fish. Res. Bd. Can.*, 31, 637-646.

- Schick, G. B., J. D. Isaacs, and M. H. Sessions. 1968. Autonomous instruments in oceanographic research, in *Marine Sciences Instrumentation*, Vol. 4, F. Alt, ed., New York, Plenum Press. (Proceedings of the Fourth National ISA Marine Sciences Instrumentation Symposium, January 22-26, 1968, Cocoa Beach, Florida.) 203-230.
- Schoener, A. and G. T. Rowe. 1970. Pelagic Sargassum and its presence among the deep-sea benthos. *Deep-Sea Res.*, 17, 923-925.
- Schrader, H. J. 1971. Fecal pellets: role in sedimentation of pelagic diatoms. *Science*, 174, 55-57.
- Sharp, J. H. 1974. Improved Analysis for "Particulate" organic carbon and nitrogen from seawater. *Limnol. Oceanogr.*, 19, 984-989.
- Smayda, T. J. 1969. Some measurements of the sinking rate of fecal pellets. *Limnol. Oceanogr.*, 14, 621-625.
- 1971. Normal and accelerated sinking of phytoplankton in the sea. *Mar. Geology*, 11, 105-122.
- Smith, K. L., Jr., and J. M. Teal. 1973. Deep-sea benthic community respiration: an *in situ* study at 1850 meters. *Science*, 179, 282-283.
- Steele, J. H., and I. E. Baird. 1972. Sedimentation of organic matter in a Scottish Loch. *Mem. Ist. Ital. Idrobiol.*, 29, Suppl. 72-88.
- Sverdrup, H. U., M. Johnson, and R. Fleming. 1942. *The Oceans*. Englewood Cliffs, N.J., Prentice-Hall, 1087 pp.
- Trevallion, A. 1967. An investigation of detritus in Southampton water. *J. Mar. Biol. Assoc., U.K.*, 47, 523-532.
- Vinogradov, M. E. 1968. Vertical distribution of oceanic zooplankton. (In Russian). *Isdatel'stvo "Nauka"*, Moskva, 319 pp. Israel Programme for Scientific Translations, 1970, 339 pp.
- White, W. S., and R. G. Wetzel. 1973. A modified sediment trap. *Limnol. Oceanogr.*, 18, 986-988.
- Wheeler, E. H., Jr. 1967. Copepod detritus in the deep-sea. *Limnol. Oceanogr.*, 12, 697-702.
- Wiebe, P. H., C. C. Remsen, and R. F. Vaccaro. 1974. *Halosphaera viridis* in the Mediterranean Sea: size range, vertical distribution, and potential energy source for deep-sea benthos. *Deep-Sea Res.*, 21, 657-667.

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<p>Woods Hole Oceanographic Institution WHOI-76-85</p> <p>PARTICULATE MATTER SINKING TO THE DEEP-SEA FLOOR AT 2000 M IN THE TONGUE OF THE DEEP-OCEAN, BAHAMAS, WITH A DESCRIPTION OF A NEW SEDIMENTATION TRAP by Peter H. Wiebe, Steven H. Boyd and Clifford Winget. 14 pages. Reprinted from "The Journal of Marine Research, 1976, Volume 34, No. 3," September 1976. Prepared for the Office of Naval Research under Contract N00014-66-C-0241; NR 083-004 and the Atlantic Foundation.</p> <p>A sedimentation trap for use just above the deep-sea floor was free-fallen to a depth of 2050 m in the Tongue of the Ocean canyon on January 3, 1974. On March 6, it was successfully recovered with the assistance of D.S.R.V. Alvin. The trap has a base 1 m square and a height of 30 cm. At the trap bottom are filters to retain falling particles. Two spring-powered sliding doors, each 1 m x 0.5 m, are used to close off the lower 2 cm of the trap during ascent to prevent disturbance of the particles collected on the filters.</p> <p>Total carbon on the filters as determined by high temperature combustion averaged 2301 mgC/m<sup>2</sup> or an average on a daily basis of 36.5 mgC/m<sup>2</sup>. Similar filter aliquots were treated with cold phosphoric acid to eliminate the inorganic fraction. The resulting carbon values (<math>\bar{X}</math> = 5.7 mgC/m<sup>2</sup>/day) suggest 14% of the total carbon reaching the sea floor at 2000 m in this area is organic in origin. Fecal material is one readily identifiable component of the material contributing to the organic fraction. Counts of fecal pellets resulted in an estimate of an average of ~ 650 pellets/m<sup>2</sup>/day. Average pellet length was 241 μm and diameter was 109 μm. In laboratory experiments the pellets sank at rates varying from 30 m/day to 941 m/day (<math>\bar{X}</math> at 5°C = 159 m/day).</p> <p>Comparison of the sedimentation trap estimates of organic carbon input to the sea floor in this area with benthic energy requirements indicates that rapidly sinking small particulate matter could supply approximately 14% of the metabolic requirements of the benthos.</p>	<p>1. Sedimentation Trap 2. Fecal Pellets 3. Particulate Flux</p> <p>I. Wiebe, Peter H. II. Boyd, Steven H. III. Winget, Clifford IV. N00014-66-C-0241; NR 083-004</p> <p>V. Atlantic Foundation</p> <p>This card is UNCLASSIFIED</p>
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