A new large volume filtration system for the sampling of oceanic particulate matter

by J. K. B. Bishop[1] and J. M. Edmond[1]

ABSTRACT

A large volume *in situ* filtration system has been developed for the extraction of material greater than one micron in diameter from several cubic meters of water. The system has worked reliably to 400 meters. The particulate matter concentrations determined in profile compare well with those found using conventional Niskin-Nuclepore techniques. By using 53μm Nitex and 1μm glass fiber filters in series, the samples are separated into two size fractions. Simple calculations show that the large size fraction contributes a significant proportion of the vertical flux of material and that this proportion increases with surface productivity.

1. Introduction

The dry weight concentration of particulate matter in the world's oceans lies between approximately 10μg/1 and several mg/1 depending on the oceanographic regime. Manheim, Hathaway, and Uchupi (1972), Copin-Montegut and Copin-Montegut (1972), Honjo, Emery, and Yamamoto (1974), Milliman and Boyle (1975) and others have demonstrated that it is mainly biogenic. The site of degradation and the mechanism of sedimentation of this material have been subjects of speculation for some time. In order to determine such basic processes as nutrient recycling and sediment formation, a knowledge of the depth dependence of particulate composition, size distribution, and morphology is necessary. Such data would also provide an important constraint on the interpretation of the distributions of dissolved nonconservative chemical tracers.

Precise methods have been developed for the sampling of particulate matter in the water column using 30 liter Niskin bottles and filtration through preweighed membrane filters, (Spencer and Sachs, 1970). However, subsequent chemical and microscopic study of the samples has been limited by the small amounts of material recovered. Larger amounts of material have been obtained using submersible or shipboard pumping devices. Beers, Stewart, and Strickland (1967), Lisitzin (1972), Lenz (1972), and Jeffrey, Fredericks, and Hiller (1973) have used pumps

1. Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, U.S.A.

to suck water from various depths through tubing for shipboard processing. This method is limited by the need to handle long lengths of large diameter tubing, necessary to minimize damage to the material sampled (Lenz, 1972).

In situ pump units are an improvement in sampling technique. In such systems, a battery powered pump is used to pull water through membrane filters; measurement of the filtered water is by flow meter. Such systems were first introduced by Laird, Jones, and Yentsch (1967) and have been proven reliable to depths as great as 5700 m by Spencer and Sachs (1970). Beer, Dauphin, and Sholes (1974) used a modified unit of this type to obtain samples of particulate matter in conjunction with nephelometer studies. The capacity of these systems is limited to volumes of several hundred liters. However from the range of particulate sizes and densities found in marine sediments it can be calculated that volumes of several cubic meters must be filtered if a valid sample of the entire range of settling material is to be obtained. A large volume *in situ* filtration system (LVFS) has therefore been developed. This system is capable of filtering tens of thousands of liters of water through large diameter one micron glass fiber filters. The system has been operated successfully on two cruises: R. V. *Atlantis II*-78 (Barbados-San Juan, October 1973) and R. V. *Chain*-115 (Dakar-Capetown, December 1973-January 1974).

2. The large volume filtration system

Fig. 1a shows the basic configuration of the large volume filtration system (LVFS). Ship's power (2.3 KW, 480VAC, 3 phase) is transmitted to the pump unit via a 400m, 1.9cm diameter, PVC-jacketed, electromechanical cable (Boston Insulated Wire and Cable Co., Boston, Mass.). The pump in the LVFS is a stock version, 3HP, 1150RPM, cast iron, Aurora Mod. 362, close-coupled centrifugal pump with bronze impeller (Aurora pump, No. Aurora, Ill.). The "D" shaped polypropylene tank (Industrial Plastic Fabricators, Norwood, Mass.) is filled with approximately 120 liters of mil-5606 oil to immerse the entire pump unit. An external bladder allows pressure equalization of the LVFS. The structural components are machined from 6061-T6 aluminum and 316 stainless steel. Other components are made from plexiglass, PVC, and polypropylene. The LVFS has been hydrostatically tested to 1400m. To date sampling has been restricted to the upper 400m, the length of cable available.

On deck, the electromechanical cable is stored on the air-motor driven tension winch. Launching and recovery of the LVFS is accomplished using the tension winch, capstan, and "A" frame controls.

Fig. 1b shows the PVC filter unit and the filtering sequence for the LVFS. Water is sucked through two 35.6 cm diameter PVC baffle plates before it passes through a 30.5 cm diameter, acid leached (0.1N HCl) 53μm Nitex prefilter. The

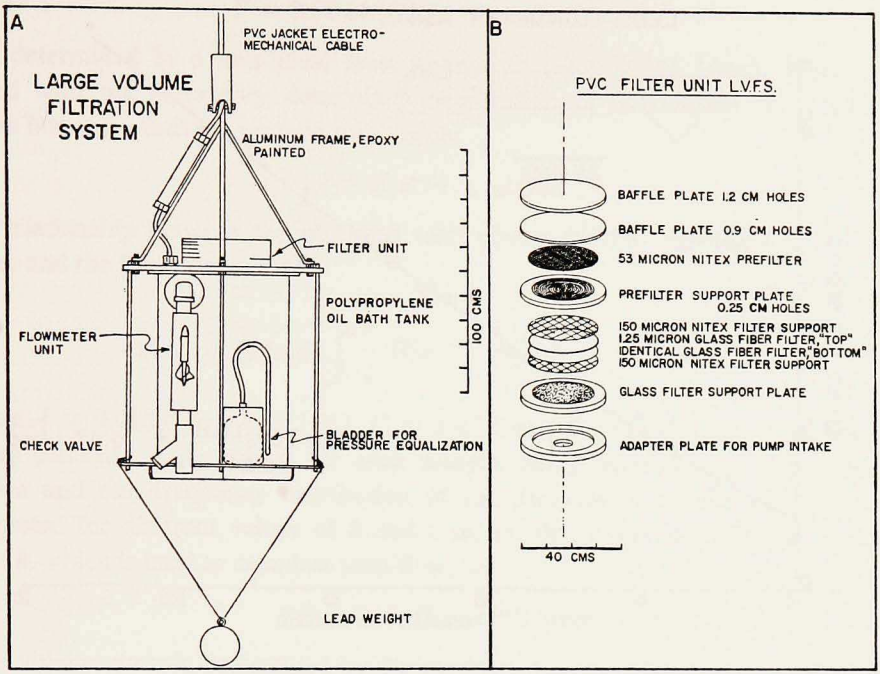
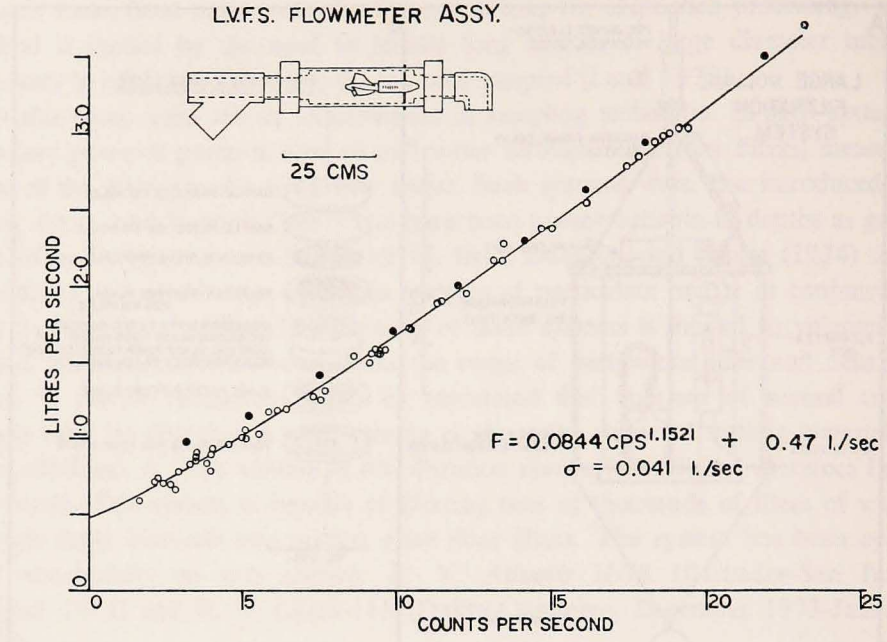


Figure 1. a) Large Volume Filtration System (LVFS) has operated *in situ* 5½ days filtering 600,000 liters to yield 60 particulate matter samples split into >53μm and <53μm size fractions. Water is sucked through filter unit and discharged through flow meter and check valve. Weight in air 430 Kgs. Design depth 5000 m. b) LVFS filter unit and filtration sequence.

prefilter is supported by a PVC plate machined with a "bullseye" pattern of grooves and drilled with holes on an equal area basis. The water is next filtered through a pair of 30.5 cm diameter, acid leached (conc. HCl), precombusted (450°C, 2.5 hr.), preweighed Mead 935-BJ glass filters supported above and below by clean 149μm Nitex mesh. The filter sandwich is supported by a PVC disk with porous polyethylene insert. The effective diameter is 25.4 cms for all filters. The whole filter unit is bolted over the pump intake using stainless steel bolts. Under normal operating conditions the maximum pressure differential across the filters is 1-1.2 bars.

2. Flow meter calibration

The flow meter (Fig. 2) calibration data (against an orifice flow meter) compares well with the General Oceanics data for a typical unit. The empirical relation between flow rate (F) and count rate (CPS):



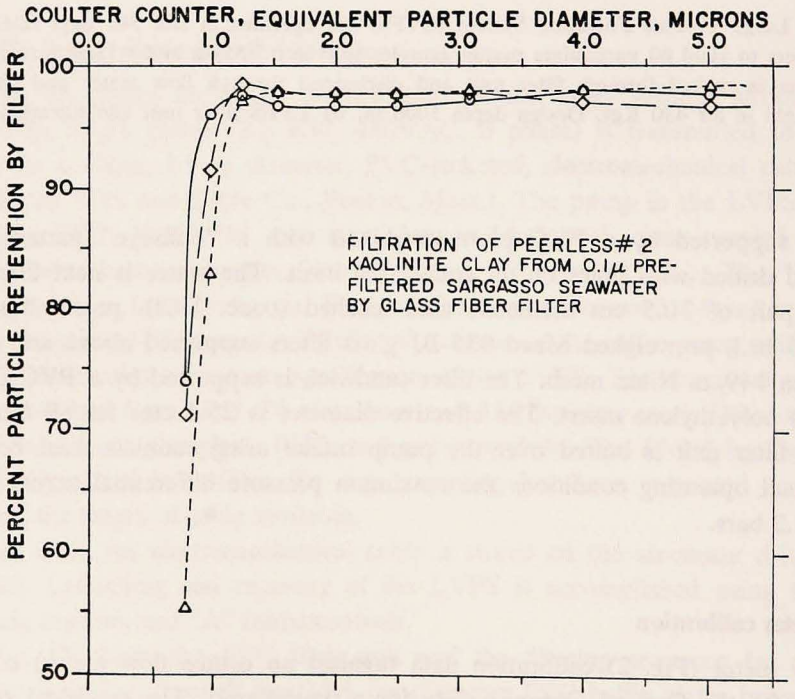


Figure 2. a) ○, LVFS flow meter calibration data; ●, General Oceanics Data, typical flow meter. Initial flow rate of water through LVFS filters is 3*l*/sec, maximum flow velocity is 6 cm/sec. b) Pore size calibration of glass fiber filter. △, one layer Mead 935-BJ; ◇, two layers Mead 935-BJ; ○, one layer Whatman GF/F (0.7μm pore size, 98% efficiency).

$$F = 0.0844\ (\text{CPS})^{1.1521} + 0.47\ l/\text{sec} \tag{1}$$

was determined by a non-linear least squares fit ($\sigma_F = 0.041\ l/\text{sec}$). When combined with the laboratory determined flow rate-time relationship for Mead *g-f* filters filtering a uniform particle suspension:

$$F = F_0 e^{-kt} \quad l/\text{sec} \tag{2}$$

the relationship between the observed total counts (ΣCPS) registered by the flow meter and the filtration time t is:

$$\Sigma\text{CPS} = (1/A)^b \int_0^t (F_0 e^{-kt} - C)^b dt \quad \text{counts} \tag{3}$$

where $A = 0.0844$, $b = 1/1.1521$, C = 0.47 l/sec, $F_0 = 2.95$ l/sec. The flow rate decay constant, k, is unique for each sample, being determined by the concentration and size frequency distribution of the particles being filtered. ΣCPS was computed for different values of k and t (secs); the observed ΣCPS and t determine k, which is used to calculate total flow, ΣF.

$$\Sigma F = F_0/k\ (1 - e^{-kt})\ \text{liters} \tag{4}$$

Flow volume error is determined by the product of σ_F and the time interval of flow measurement.

3. Pore size determination of the Mead glass fiber filter

The amount of particulate matter collected by any filtration method is dependent on the pore size of the filter used. Glass fiber filter was used because it allows higher flow rates and better loading by particles than membrane filters of similar area and pore size. The liquid filtration efficiency of Mead 935-BJ glass fiber filter (Mead Corp., South Lee, Mass.) had to be determined. A Mod. TA II Coulter Counter with population accessory and 50 micron aperture was used to study the filtration of Peerless #2 Kaolinite clay (R.T. Vanderbilt Co., N.Y.) from prefiltered Sargasso Sea water. Three experiments compared the filtration efficiency of one layer of Mead 935-BJ, two layers of the Mead filter, and one layer of Whatman GF/F (liquid filtration pore size, 0.7μm, 98% efficiency).

The experimental results (Fig. 2) showed that the Mead and Whatman filters behaved identically in their retention of particles larger than 1.25μm. Relative to Whatman GF/F, one thickness of Mead 935-BJ retained 85% of the particles counted in the 1-1.25μm size channel, and 74% of those in the 0.8-1μm channel. Similarly, two layers of Mead 935-BJ retained 95 and 96% of the particles in these two size classes respectively. This comparison of the Mead filter with the Whatman filter is more relevant than the absolute data plotted in Fig. 2 because the Coulter Counter had very high background count rates in the two smallest size

channels (600 and 700 counts/second, respectively). Thus one layer of Mead 935-BJ glass fiber filter quantitatively removes particles larger than 1.25μm; two layers behave much more efficiently, removing 95% of the particles down to 0.8μm.

The quotation of pore size of a filter is deceptive. Sheldon (1972) pointed out that the size classification of Nuclepore filters is related to their median pore size, defined as 50% removal efficiency for particles larger than the stated pore size. If the same system was used for the Mead filter, it would have a pore size much smaller than 1.2μm. Conversely, 0.4μm Nuclepore filters may have a 98% efficiency near 1μm. Sheldon (1972) has shown that heavily loaded filters retain particles much smaller than their stated pore size. Thus the only valid way of comparing two filtration methods is not from the quoted pore size of the filter but from a determination of the amount of material collected by each when sampling the same natural system. For this reason, as will be discussed below, detailed intercomparisons were made at sea with the orthodox Niskin-Nuclepore procedures.

4. Shipboard procedures

LVFS samples were taken according to temperature and nutrient data which were generated during the early part of the station. Sample depths were determined by wire out, wire angle, and 12KHz PGR which could "see" the LVFS below 100m. Pumping of the ship's bilges and sewers, and dumping of garbage was restricted during the station.

The filters used in the LVFS were stored flat in clean polyethylene bags until used at sea. After use in the LVFS, their treatment was as follows: for the *Atlantis II* cruise 78, the filters were sucked dry by vacuum. The filter unit was then unbolted from the LVFS, and carried to a clean area of the ship's main lab. There, the filters were taken from the filter unit, placed in their original polyethylene bags, and immediately stored flat and frozen until returned to the laboratory for analysis. Similar treatment was given to the samples from the first station of the *Chain* cruise. For all subsequent samples, the filters were also washed with two, 500 ml portions of double distilled deionized water while still in the filter unit mounted on the LVFS. The color of the fresh samples was classified using a Munsell soil chart.

30 liter Niskin bottles fitted with teflon coated springs were used to provide samples for particulate matter inter-calibration with the LVFS. The samples (10-20 liters) were immediately filtered (47 mm, 0.4μm Nuclepore) using a closed system (G.E.-Nuclepore 47 mm holder, tygon tubing) and evacuated glass carboys. The used filters were washed (10 times, distilled water) before being transferred (Millipore tweezers) to the Millipore petri slides for storage flat. A handling blank was run from time to time by placing an unused filter in the filter holder and repeating the washing procedure.

5. Laboratory determination of the dry weight of LVFS and Niskin filters

The filters from the LVFS were placed, still frozen, in a 60°C oven and dried for 24 hours. After drying, the top and bottom Nitex mesh supports were removed from the glass fiber filter sandwich, (Fig. 1b) and the effective filter area was cut from the filter pair using a razor blade.

The trimmed top and bottom glass fiber and Nitex filters were reweighed (Mettler B5-H26 balance). The glass fiber filter weights remained stable indefinitely; however, Nitex adsorbs water rapidly from the atmosphere. The filters were stored flat in clean poly-bags until sub-sampled for chemical analysis.

The glass fiber filter weights had to be corrected for sea salt (typically 40-50 mgs). Sodium analyses were used for this purpose as this element is discriminated against by organisms (Vinogradov, 1953; Fujita, 1971; Hughes, 1972; Martin and Knauer, 1973) unlike other major ions such as magnesium and potassium.

Invariably, the bottom glass fiber filter (originally intended as a blank) in each filter pair collected significant amounts of carbon and nitrogen in excess of the blank levels for these elements in unused glass fiber filters. Starting with Menzel (1966), an extensive literature has grown up describing this effect. His interpretation was that "surface active" dissolved organic carbon rapidly adsorbed onto the surface of the filters. Menzel (1967) noted that this effect was measurable only in the surface layer of the ocean and absent in the deep waters. Banoub and Williams (1972), and Gordon and Sutcliffe (1974), found the same effect when they used glass fiber and silver filters respectively. The adsorption of organic carbon by the Mead glass fiber filter was investigated by suspending them in surface seawater (Rockport, Mass.) for periods up to three hours; there was no uptake of carbon distinguishable from the blank values.

Sharp (1974) and Gordon and Sutcliffe (1974) preferred to interpret the presence of organic carbon on the second filter as being due to trapped colloidal organic carbon. Sharp (1973) demonstrated that as much as 20% of the total organic carbon lies in the size range 0.003-1 micron. Thus the second filter would only have to trap a small portion of this colloidal material during filtration in order to retain significant amounts of carbon.

Since the experimental work had shown that the second filter greatly increased the trapping efficiency for particles smaller than 1.25 μm, the presence of particulate material on the used bottom filter was suspected. Scanning electron microscopy showed that the bottom filter retained small particles of similar morphology to those on the top filter in the same sample. While there were occasional small particles on blank unused filters they had a different form.

The chemical composition of the material retained on the bottom filter showed it to be nitrogen-rich (C/N mole ratio of 5, $\sigma = 2$) relative to the material on the top filters (C/N ratio 7, $\sigma = 1$). Similarly, the δC-13 of the organic carbon on the top and bottom filters varied with depth in the water column in a parallel fashion.

Small particles therefore account for some fraction of the excess carbon and nitrogen on the bottom filters but the magnitude is still unconstrained by experiment. Whatever the form of this material, adsorbed or particulate, it is related in chemical composition to the material on the top filter and for this reason, should be included in the loosely defined category of "particulate matter".

Particulate mass, Δ P.M., is calculated using:

$$\Delta \text{ P.M.} = (W_{Tf} - S_T + C_B) - R\,(W_{Ti}) \text{ grams} \tag{5}$$

where R is the ratio of trimmed to original bottom filter weights after correction for salt and carbon. W_{Tf} and W_{Ti} are the used-trimmed and unused-untrimmed top filter weights; S_T is the salt content of the top filter; and C_B is the organic content of the bottom filter (as CH_2O + N). The major source of error to this calculation was the fact that the area ratios varied by 0.2% (σ). This led to an error of 0.013 gms (σ) in the calculation of dry weight. One filter pair, which was used in the LVFS at 5 m for 15 min. at *Chain* 115, LVFS stn. 8 without filtering any seawater, gave a particulate mass blank of −.011 gms, using the calculation scheme above.

The mass of material collected by the Nitex 53μm prefilters was determined by correcting the final oven dried weights for salt and subtracting the mean of the oven dried weights of ten unused Nitex disks from the same batch. The error was 0.026 gms (σ).

Washing glass fiber filters with distilled water may result in the loss of organic material due to lysis. The worst case was determined by measurements of carbon lost from the thawed wet filters from the R. V. *Atlantis II*-78 cruise after rinsing in the laboratory with approximately 1 liter of distilled water using a suction filtration apparatus. The carbon in the filtrate was measured using the persulfate oxidation technique of Menzel and Vaccaro (1964), and compared to the analysis of the filters using a Perkin Elmer CHN analyzer. Approximately 15% of the total carbon was lost from samples shallower than 150 m at *AII*-78 LVFS Station 1, and 5% below this depth. This would result in the dry weight concentration being 15% and 3% low for the samples above and below 150 m respectively. Rewashing a dried LVFS sample from 25 m at *Chain* 115 LVFS station 6 showed no significant loss of either C or N from the filters as determined by CHN analysis before and after washing. Quickly washing the fresh filters at sea with 1 liter of distilled water probably results in least loss of sample.

The 0.4μm Nuclepore filters were returned to the GEOSECS balance room at W.H.O.I. and weighed several weeks later (Mettler M5 microbalance). Unfortunately, the method blanks showed that the filters were contaminated with as much as 1 mg of sea salt from the seawater retained in the slots of the G.E. Nuclepore filter holder. The filters had to be rewashed. In the light of the above discussion, there was probably little mass lost from the filters when rewashed. The

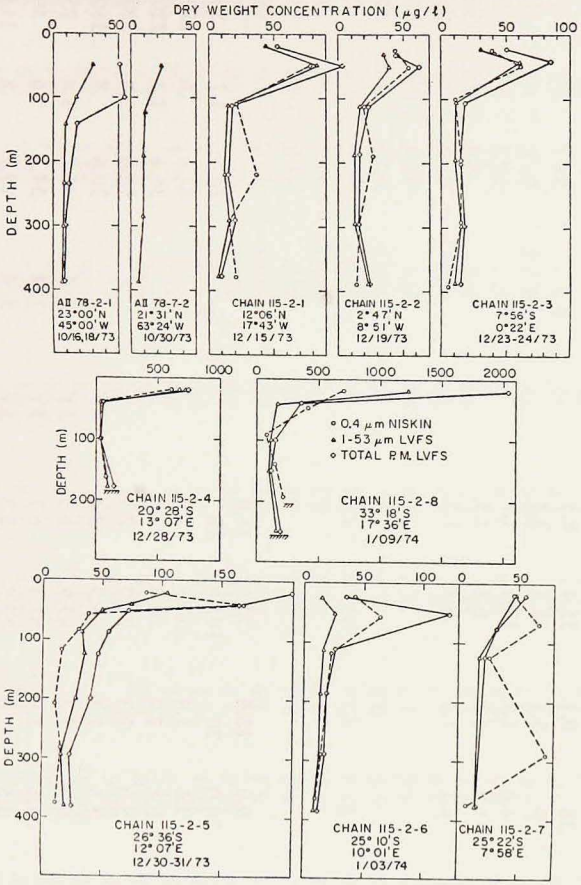


Figure 3. Particulate matter, dry weight concentration profiles, *Atlantis II* 78-2 LVFS stations 1 and 2; *Chain* 115-2 LVFS stations 1 to 8.
○, 0.4μm Nuclepore filter, 30*l* Niskin bottle
△, <53μm particulate matter, LVFS
◇, total particulate matter, LVFS

weighing error of the Niskin method was determined from the weights of unused and handling blanks before and after the *Chain* cruise; this was 16μg (σ).

6. Results

The "particulate" dry weight concentrations were determined for each method using the dry weight calculations and the flow volume data discussed previously. The errors were determined by the errors in flow volume and dry weight. Station positions, depths, suspended mass concentrations, and errors are summarized in Table 1. The suspended mass profiles determined by each method are shown in Fig. 3. The close agreement of the shapes of the profiles of dry weight concen-

Table 1. Particulate mass data: LVFS-NISKIN intercalibration.

Station	LVFS volume filtered (m^3)	σ_v	LVFS z (m)	LVFS <53μm (μg/l)	σ	LVFS >53μm (μg/l)	σ	LVFS total (μg/l)	σ	Munsell color <53μm		Niskin [P.m.] (μg/l)	σ	Niskin z (m)
AII 78-2-1	2.80	.22	50	30.5	5.2	21	14.3	51.5	15.0					
23°N	5.04	.30	100	17.4	2.8	38	8.1	55.4	8.5					
45°W	12.7	.4	143	9.5	1.1	9	3.1	18.5	3.3					
10/16,18/73	21.6	.4	235	8.4	0.6	4.6	1.8	13.0	1.9					
	26.8	.6	299	7.8	0.5	1.9	1.5	9.7	1.5					
	27.5	.6	387	7.3	0.5	2.1	1.4	9.4	1.5					
AII 78-2-2														
21°31′N	3.23	.15	50	23.0	4.1									
63°24′W	8.97	.30	125	10.7	1.5									
10/30/73	15.9	.4	192	9.3	.9									
	23.4	.5	285	9.7	.6									
	31.3	.6	383	6.2	.4									
CH 115-2-1	3.10	.15	20	43.8	4.7	9.0	12.6	52.8	13.4			—		—
12°06′N	1.95	.13	50	83.4	8.7	20.0	20	103.4	22			78.4	1.7	50
17°43′W	11.6	.30	113	14.5	1.2	3.4	3.4	17.9	3.6			22.2	.8	110
12/15/73	14.5	.4	221	12.0	1.0	2.4	2.7	14.4	2.9			36.4	1.3	220
	17.1	.6	291	15.6	.9	5.0	2.3	20.0	2.5			16.6	.8	290
	17.1	.6	378	7.7	.8	1.5	2.3	9.3	2.4			20.6	.8	380
CH 115-2-2	4.57	.15	32	34.7	3.1	9.2	5.7	43.9	6.5	5Y	8/4	43.7	1.4	25
02°47′N	4.47	.15	50	38.9	3.2	23.5	5.9	62.4	6.7	5Y	7/4	54.3	1.6	50
08°51′W	12.8	.3	113	17.0	1.1	5.5	2.0	22.5	2.3	5Y	5/4	19.9	.8	113
12/19/73	17.8	.4	188	12.5	0.8	3.4	1.5	15.9	1.7	2.5Y	5/4	26.4	.9	190
	21.1	.6	294	12.9	0.7	3.0	1.2	15.9	1.4	5Y	4/3	15.7	.8	294
	23.7	.6	388	22.8	0.4	.8	1.1	23.6	1.4	2.5Y	5/4	14.3	.8	388
CH 115-2-3	3.06	.15	23	30.5	4.5	20.5	8.6	51.0	9.7	5Y	8/3	39.7	1.5	25
07°56′S	2.53	.15	42	60.9	6.3	24.7	10.4	85.7	12.1	5Y	6/6	62.1	1.2	50
00°22′E	10.14	.30	105	10.8	1.3	7.3	2.6	18.1	2.9	5Y	6/3	10.8	.8	100

12/23-24/73	18.5	.44	196	11.5	0.8	3.1	1.4	14.7	1.6	2.5Y	5/2	15.8	.8	200
	19.0	.6	296	16.0	0.8	1.9	1.4	18.0	1.6	5Y	4/4	15.4	.8	290
	21.0	.6	386	11.3	0.7	3.9	1.2	15.2	1.4	2.5Y	4/4	5.6	.8	390
CH 115-2-4	.35	.025	20	723	64	—	—	—	—	10YR	6/4	61.3	11.2	19
21°28′S	.42	.034	20	673	62	68.2	61.4	741	87.2	10YR	5.5/8	61.3	11.2	19
13°07′E	4.51	.15	42	39.6	3.2	20.0	5.8	59.6	6.6	2.5Y	6/4	48.7	1.1	48
12/28/73	6.55	.30	100	40.4	2.7	4.7	4.0	45.1	4.8	5Y	5.5/3	42.4	0.9	97
	3.70	.26	177-188	96.5	7.6	47.6	7.8	144.1	10.9	2.5Y	5/6	78.5	1.5	165
CH 115-2-5	1.59	.11	20	105.2	11.0	103.8	18.	209	21.	5Y	7/6	86.4	1.9	20
22°36′S	2.28	.15	40	74.0	7.5	90.6	13.	164.6	15.	5Y	7/4	166.4	4.4	40
12°07′E	4.38	.15	50	42.3	3.3	30.0	6.0	72.3	6.9	5Y	6/6	38.8	1.1	56
12/30,31/73	7.10	.30	88	32.9	2.3	22.9	3.8	55.8	4.4	5Y	6/4	30.1	1.0	84
	8.40	.30	124	34.9	2.0	12.1	3.1	47.0	3.7	5Y	6.5/3	16.5	0.9	117
	11.43	.30	199	28.3	1.4	12.6	2.3	40.9	2.7	5Y	6/3	10.7	1.0	206
	15.00	.6	294	16.8	1.1	6.5	1.8	23.3	2.1	5Y	6/3.5	15.2	0.9	280
	12.88	.6	379	18.9	1.3	6.3	2.0	25.2	2.4	5Y	6/3	11.6	0.8	374
CH 115-2-6	3.37	.15	26	14.0	3.9	19.0	7.8	33.0	8.7	5Y	8/1.5	40.1	1.6	24
25°10′S	2.40	.15	52	25.8	5.6	95.4	12.4	121.2	13.6	5Y	8/4	62.4	1.3	58
10°01′E	9.47	.30	113	16.2	1.5	9.2	2.8	25.4	3.1	5Y	7/4.5	21.5	0.8	121
1/03/74	15.54	.44	187	13.3	0.9	5.4	1.7	18.7	1.9	5Y	7/4	17.8	0.8	193
	20.2	.6	289	13.2	0.8	3.9	1.3	17.1	1.5	5Y	6/3	14.4	0.8	289
	22.0	.6	386	8.8	0.6	3.2	1.2	12.0	1.3	5Y	6/3	9.6	0.8	366
CH 115-2-7	2.41	.15	20	47.3	6.1	9.3	10.8	56.6	12.4	5Y	8/1	46.7	1.7	20
25°22′S	2.69	.15	75	31.6	5.1	−4.8	9.7	26.8	10.4	5Y	8/2.5	67.6	1.8	69
7°58′E	8.30	.19	124	17.4	1.6	4.7	3.1	22.1	3.5	5Y	6.5/4	25.2	0.8	125
1/05/74	22.2	.6	377	15.0	.7	1.4	1.2	16.4	1.4	5Y	6/3	7.8	0.7	385
CH 115-2-8	.30	.03	20	1225.	130.	820.	120.	2045.	176.	5Y	6/8	709	7.1	19
33°18′S	1.37	.10	42	167.	15.4	196.	23.8	363.	28.3	2.5Y	5/6	420	2.1	47
17°36′E	2.14	.15	100	111.	10.	38.6	12.4	150	15.9	5Y	6/3	87	1.1	93
1/09/74	2.57	.15	150	103.	7.8	17.	10.2	120.3	12.8	5Y	5.5/3	141	1.2	141
	2.25	.16	251	160.	12.8	31.4	11.8	192	17.4	5Y	5.5/3	215	1.3	196

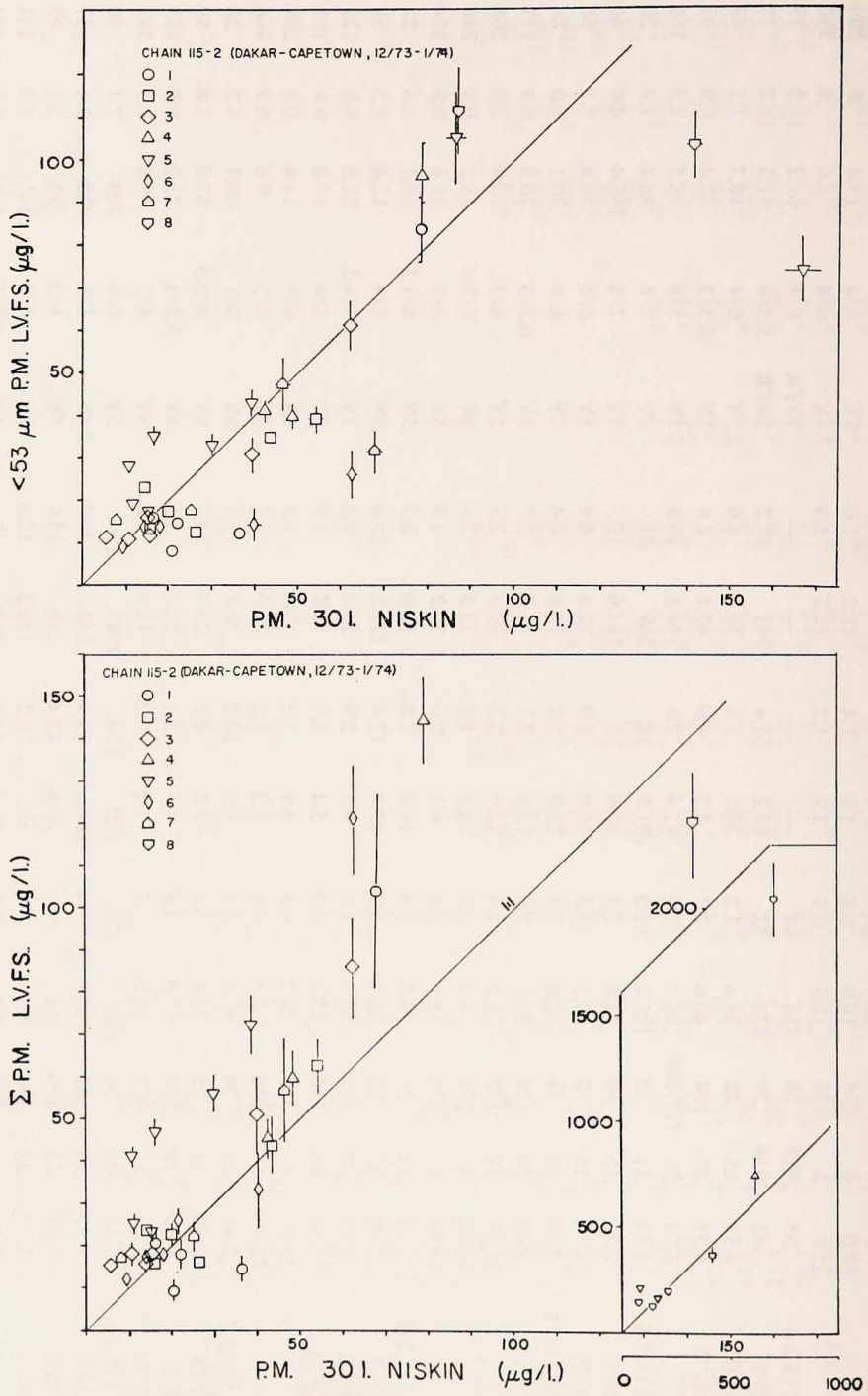


Figure 4. Dry weight concentration intercalibration, LVFS and 30*l* Niskin.

tration from the LVFS and the 30*l* Niskins demonstrates that these methods describe the bulk of the suspended mass distribution equally well. Frequently the profiles show the base of the mixed layer to be the depth of maximum particle concentration. Below this depth, the particle concentrations drop sharply to levels of 20μg/l in areas of high biological productivity, 10-15μg/l in moderately productive waters, and less than 10μg/l in the waters of the tropical central north Atlantic. The particle concentration varies consistently with the surface biological productivity. The sharp mass concentration gradient below the particle maximum is probably maintained by the grazing activity of filter feeding organisms. It is in this small depth interval that the major change occurs in the distribution and color of particulate matter.

Fig. 4a shows the correlation of the LVFS dry weight concentration of the <53μm size fraction with the Niskin dry weight concentrations. Error bars are shown where the standard deviation of the data exceeds the size of the data point. Most points scatter slightly below a one to one correlation line, indicating that the 30*l* Niskin method sampled particles up to 53μm in size. The plot of *total* LVFS suspended mass concentration against that of the Niskin method (Fig 4b) shows improved correlation; the slope is greater than 1 indicating the LVFS sampled more material than Niskin bottles. The fact that points fall in the same trend up to 1 mg/l dry weight concentration (see inset in Fig. 4b) leads us to place confidence in the flow meter calibration and flow volume calculation for the LVFS.

Intercalibration results from *Chain* 115-2 LVFS Stn. 5 showed large disagreement (Figs. 3 and 4). This station was 230 Km due west of Walvis Bay. The basic differences of the two methods are illustrated by Fig. 5. The LVFS profile provides a space-time average of the particulate matter distribution over the period of one day and an area of several tens of square kilometers. In contrast, the Niskin bottles sampled instantaneously, providing a snapshot of the particulate matter distribution at a discrete geographical location.

The PGR record for the station revealed an intense surface-ward migration of the deep scattering layer at sunset and a similar downward migration at sunrise. Since these organisms derive their food from the plankton near the surface, it would not be surprising to see their feeding activities mirrored in the composition and distribution of the larger-sized particulate matter in the water column. The migration of the deep scattering layer was observed at every station and hence is not the primary cause for the apparent time variations of the fine particulate matter concentrations.

The dynamics of upwelling may account for the time variability in the particulate matter distributions observed at this station. Jones (1971), Bang (1971), and Calvert and Price (1971) have demonstrated time variability in hydrography near this area. Therefore one would not expect a steady state distribution of the suspended matter due to the variable intrusion rates of open ocean water with low

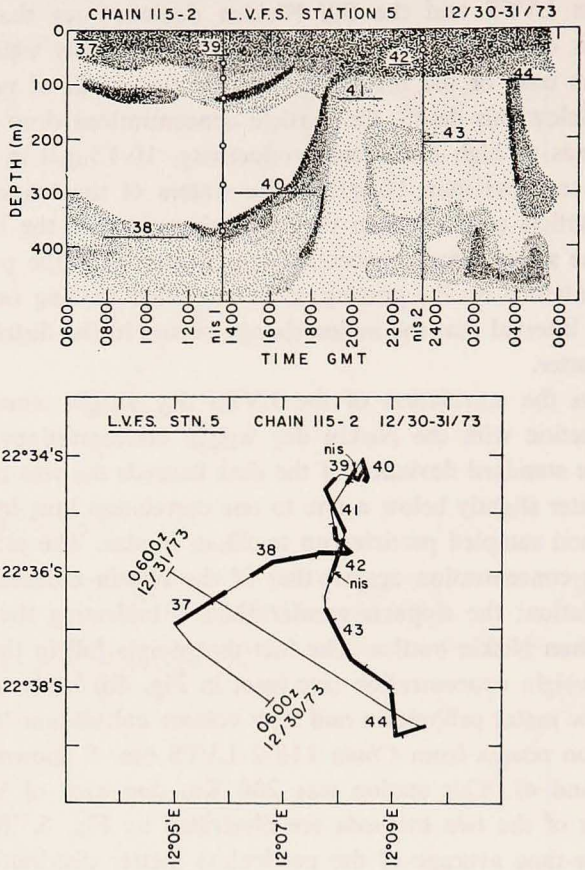


Figure 5. *Chain* 115-2 LVFS station 5. Upper: 12 KHz PGR record showing the migration of the deep scattering layer, LVFS and Niskin depths as a function of time. Lower: ship's position during the station showing location of LVFS and Niskin samples.

particulate concentrations. Thus dynamics, both physical and biological, contribute to the scatter of the correlation of the LVFS and Niskin methods at stations near upwelling areas. Stations 4, 5, and 8 fall into this category.

7. Large particle flux

One of the major reasons for studying particulate matter is to evaluate the vertical sinking rates of chemical elements, and of material known to be reactive with the water column. Rates of degradation, dissolution, adsorption and aggregation of the material may be calculated by knowing the sinking rates as a function of depth. Chemical and microscopic study of the LVFS samples will provide size, composition and morphological information which will be used in a sinking model to calculate the vertical mass flux of chemical elements in particulate matter.

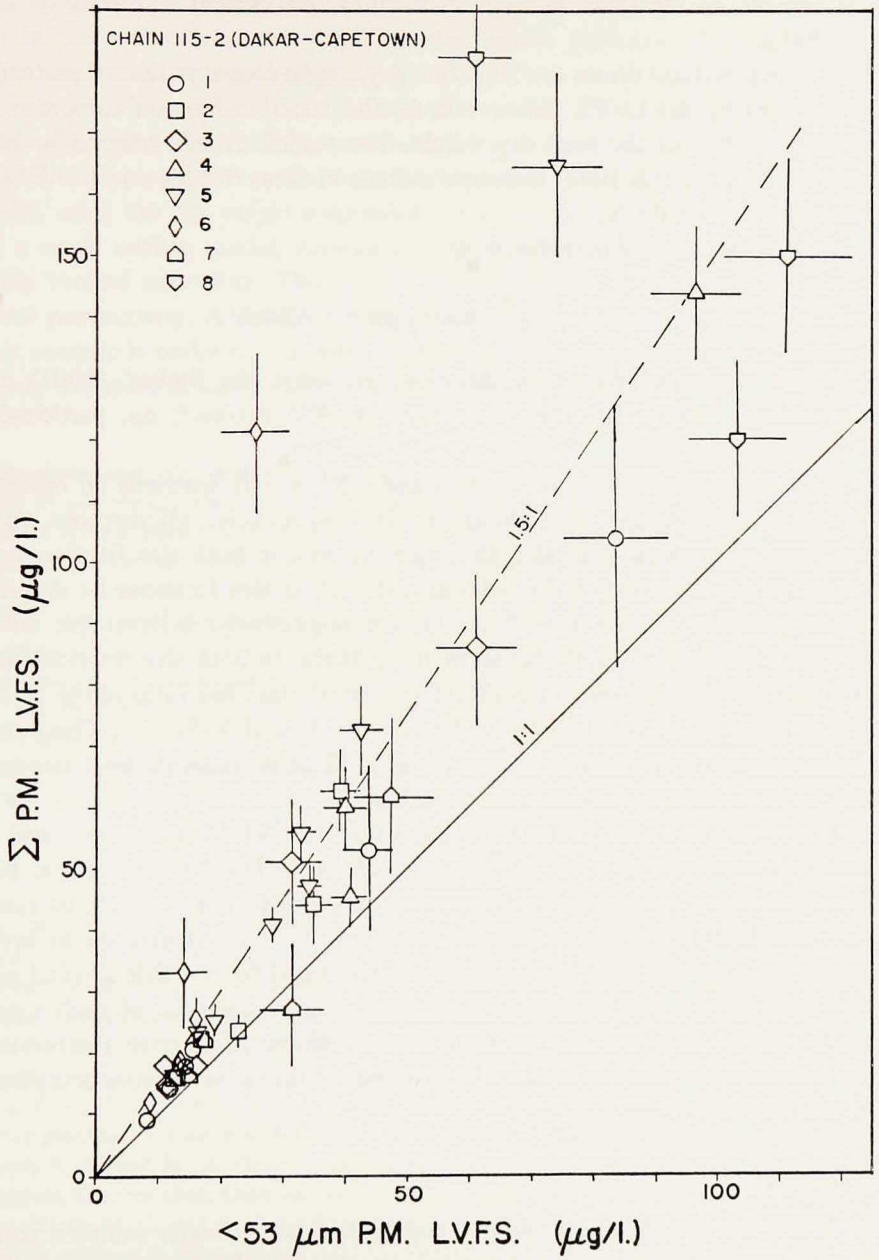


Figure 6. LVFS dry weight concentration data: total dry weight concentration vs. <53μm dry weight concentration.

Until this study is complete, a simple model is used to evaluate crudely the relative importance of the large particle fraction to the vertical transport of mass through 400 m.

Fig. 6 shows the total versus the 53 $</\mu$m dry weight concentration of particulate matter sampled by the LVFS. Below 100 m, the $>$ 53μm fraction comprises between 10 and 30% of the total dry weight. For station 5, this fraction is 30%, whereas for station 7 it is 10%; these are stations in areas of high and low biological productivity respectively.

The vertical mass flux of particles, Φ_d is:

$$\Phi_d = m_d \left(\frac{g}{18\eta} \Delta\rho d^2 \right) \text{gm cm}^{-2} \text{ sec}^{-1} \tag{6}$$

which is the suspended mass concentration, m_d times the Stokes' (1901) Law particle settling velocity; (η, fluid viscosity; g = 980 cm/sec^2; $\Delta\rho$, particle-fluid density).

Let the sinking behavior of the <53μm and >53μm size fractions be described equally by particles 20μm and 100μm in size respectively. Microscopic studies support these assumptions and also show the material in both size fraction to be

Let the sinking behavior of the >53μm and <53μm size fractions be described equally by particles 100μm and 20μm in size respectively. Microscopic studies support these assumptions and also show the material in both size fractions to be biogenic and therefore of similar density. The vertical mass flux ratio of the >53μm to <53μm size fraction is calculated to be 12 (Stn. 5) and 3 (Stn. 7). These crude calculations demonstrate the importance of the >53μm particles in the transport of material to the sediments.

Light microscopy of the particles retained on the LVFS prefilters showed the presence of Acantharia, Radiolaria, diatoms, silicoflagellates, Foraminifera, dinoflagellates, chitinous exoskeletal and appendage materials from a variety of macroinvertebrates, loosely aggregated organic particles, and fecal pellets up to several mm in size. In polarized light, the aggregate material and fecal pellets showed many small mineral particles in association with them. The importance of each type of particle to vertical transport of elements contained within must await the results of detailed microscopic examination now in progress; at that time, a more complicated model will be justified.

8. Conclusions

The LVFS has been used routinely to collect particulate matter samples, several tenths of a gram in weight, from the open ocean in the upper 400 m in areas of widely varying particulate matter concentration. It has proved to be highly reliable and efficient in its operation. It samples *in situ,* and without appreciable mechanical damage, the particles too small for plankton nets and too rare for Niskin bot-

tles to sample reliably. The intercalibration of the LVFS method with the Niskin method shows that both give the same basic picture of particulate matter distribution in the water column except for the largest particles. Differences between the two methods of sampling near upwelling areas can be explained in terms of physical and biological dynamics rather than by differences in methodological approach. Using 53μm Nitex screen and 1μm glass fiber filters in series it is possible to separate the particles into a large and small size fraction. Preliminary results, using the dry weight suspended mass concentrations in both size fractions and a crude settling model, demonstrate the relative importance of large particles to the vertical mass flux. This importance is perhaps a function of surface biological productivity. A detailed analysis of the size, morphology and chemistry of these samples is under way in order to evaluate the general importance of the large particle transport as well as to study the recycling of many elements.

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REFERENCES

Bang, N. D. 1971. The southern Benguela Current region in February, 1966: part 2, Bathythermography and air-sea interactions. Deep-Sea Res., *18:* p. 209–224.

Banoub, M. W. and P. J. leB. Williams. 1972. Measurements of the microbial activity and organic material in the western Mediterranean Sea. Deep-Sea Res., *19:* p. 433–444.

Beer, R. M., J. P. Dauphin and T. S. Sholes. 1974. A deep-sea *in situ* suspended sediment sampling system. Marine Geol., *17:* p. M35–M44.

Beers, J. R., G. L. Stewart and J. D. H. Strickland. 1967. A pumping system for sampling small plankton. J. Fish. Res. Bd. Canada, *24:* p. 1811–1818.

Clavert, S. E. and N. B. Price. 1971. Upwelling and nutrient regeneration in the Benguela Current, October 1968. Deep-Sea Res. *18:* p. 505–523.

Copin-Montegut, C. and G. Copin-Montegut. 1972. Chemical analysis of suspended particulate matter collected in the northeast Atlantic. Deep-Sea Res., *19:* p. 445–452.

Fujita, T. 1971. The concentration of major chemical elements in marine plankton. Geochem. J., *4:* p. 143–156.

Gordon, D. C., Jr. and W. H. Sutcliffe, Jr. 1974. Filtration of sea water using silver filters for particulate nitrogen and carbon analysis. Limnol. Oceanog., *19:* p. 989–993.

Honjo, S., K. O. Emery and S. Yamamoto. 1974. Non-combustible suspended matter in surface waters off eastern Asia. Sedimentology, *21:* p. 555–575.

Hughes, M. N. 1972. The inorganic chemistry of biological processes. New York. Wiley, 304 pp.

Jeffrey, L. M., A. D. Fredericks and E. Hiller. 1973. An inexpensive deep-sea pumping system. Limnol. Oceanog., *18:* p. 336–340.

Jones, P. G. W. 1971. The southern Benguela Current region in February 1966: Part I, Chemical observations with particular reference to upwelling. Deep-Sea Res., *18:* p. 193–208.

Laird, J. C., D. P. Jones and C. S. Yentsch. 1967. A submersible batch filtering unit. Deep-Sea Res., *14:* p. 251–252.

Lenz, J. 1972. A new type of plankton pump on the vacuum principle. Deep-Sea Res., *19:* p. 453–461.

Lisitzin, A. P. 1972. Sedimentation in the World Ocean, S.E.P.M. Spec. Publ. 17, 218 pp.

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

Martin, J. H. and G. A. Knauer. 1973. The elemental composition of plankton. Geochim. Cosmochim. Acta., *37:* p. 1639–1655.

Menzel, D. W. and R. F. Vaccaro. 1964. The measurement of dissolved organic and particulate carbon in seawater. Limnol. Oceanog., *9:* p. 138–142.

Menzel, D. W. 1966. Bubbling of sea water and the production of organic particles: a re-evaluation. Deep-Sea Res., *13:* p. 963–966.

—— 1967. Particulate organic carbon in the deep sea. Deep-Sea Res., *14:* p. 229–238.

Milliman, J. and E. Boyle. 1975. Biological uptake of dissolved silica, Amazon River Estuary. Science, *189:* p. 995–997.

Sharp, J. H. 1973. Size classes of organic carbon in seawater. Limnol. Oceanog., *18:* p. 441–447.

—— 1974. Improved analysis for 'particulate' organic carbon and nitrogen from seawater. Limnol. Oceanog., *19:* p. 984–989.

Sheldon, R. W. 1972. Size separation of marine seston by membrane and glass fiber filters. Limnol. Oceanog., *17:* p. 494–498.

Spencer, D. W. and P. L. Sachs. 1970. Some aspects of the distribution, chemistry and mineralogy of suspended matter in the Gulf of Maine. Marine Geol., *9:* p. 117–136.

Stokes, G. G. 1901. Mathematical and Physical Papers, Vol. III, Cambridge Univ. Press, 413 pp.

Vinogradov, A. P. 1953. The elementary composition of marine organisms. Sears Foundation of Marine Research, Memoir II, New Haven, Conn. Yale University, 647 pp.

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