FLUXES, DYNAMICS, AND CHEMISTRY OF PARTICULATES IN THE OCEAN

by

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ABSTRACT

Sediment traps designed to yield quantitative data of particulate fluxes have been deployed and successfully recovered on four moorings in the deep sea. The traps were designed after extensive calibration of different shapes of containers. Further intercalibration of trap design was made in field experiments over a range of current velocities. Experiments with Niskin bottles showed that concentrations suspended particulate matter obtained with standard filtration methods were low and have to be increased by an average factor of 1.5 to correct for particles settling below the sampling spigot.

The trap arrays were designed to sample the particulate fluxes both immediately above and within the nepheloid layer. The data derived from the traps have been used to estimate vertical fluxes of particles including, for the first time, an attempt to distinguish between the flux of material settling from the upper water column (the "primary flux") and material which has been resuspended from some region of the sea floor (resuspension flux). From these data and measurements of the net nepheloid standing crop of particles one can also estimate a residence time for particles resuspended in the nepheloid layer. This residence time appears to be on the order of days to weeks in the bottom 15 m of the water column and weeks to months in the bottom 100 m.

Between 80% and 90% of the particles collected in the six traps where particle size was measured were less than 63 μm. The mean size of particles collected in the nepheloid layer was about 20 μm, and above the nepheloid layer the mean was 11 μm.

Less than 3% of the organic carbon produced in the photic zone at the trap sites was collected as primary flux 500 m above the sea floor. The primary flux measured at two sites was enough to supply 75% on the Upper Rise and 160% on the mid Rise of the organic carbon needed for respiration and for burial in the accumulating sediments.

From an intercomparison of the composition of particles falling rapidly (collected in traps), falling slowly or not at all (collected in water bottles), and resting on the sea floor (from a core top), it was determined that elements associated with biogenic matter, such as Ca, Sr, Cu, and I, were carried preferentially by the particles

falling rapidly. Once these particles reached the bottom, the concentration of those elements was decreased through decomposition, respiration, or dissolution. Dissolution appears rapid in the vicinity of the sea floor, because despite an abundance of radiolarians, diatoms and juvenile foraminifera collected in all traps, these forms were rare in core samples.

The dynamic nature of the nepheloid layer makes it possible for particles to be resuspended many times before they are finally buried. This enables sediment to be carried long distances from its origin. The recycling of particles near the sea floor may increase dissolution of silicious and carbonate matter.

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BIOGRAPHICAL NOTE

The author was born on February 16, 1947, in Salt Lake City, Utah, where he was raised and graduated from East High School in 1965. After his freshman year at the Massachusetts Institute of Technology, he served for two and a half years as a missionary in Finland for the Church of Jesus Christ of Latter-Day Saints (Mormon). Returning to MIT, he received an S. B. in Earth and Planetary Sciences in 1972. In June of that year he entered the MIT/WHOI Joint Program in Oceanography where his research interests have included experimental sediment transport in flumes, dynamics of submarine canyons and continental margins as investigated with the Navy research submersible NR-1, and the dynamics of suspended particulate matter in the ocean. The author is a member of Sigma Xi, the American Geophysical Union, and the Geological Society of America.

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CHAPTER I

INTRODUCTION

Information about the modes and rates of transport of particulate matter in the ocean is of primary importance to the understanding of many fields of oceanography. The composition and distribution of sediments are dependent upon the particulate flux. The supply of food energy derived from the flux of organic matter is a primary control of the structure and diversity of benthic communities. The chemistry of a body of water and the usefulness of any chemical species in tracing circulation are greatly affected by the formation, removal, and dissolution of particles. Additional knowledge about these processes will enable us to improve our understanding of past oceanic conditions and will allow us to make better predictions of the effects on the oceans caused by man's activities.

Nearly all particles are introduced into the ocean at the boundaries. The largest input is along the oceans' edges through rivers, which not only supply terrigenous material, but also add nutrients necessary for biological productivity. Along the eastern coast of the United States at the present time, most of this sediment remains in the estuaries (Meade, 1972), and the amount and mechanism of transport across the shelf to the deep sea is uncertain

(Swift, Duane and Pilkey, 1972). During glacial periods when sea level was lower, rivers crossed the shelf and disgorged their loads directly into the deep sea through submarine canyons. In the Antarctic and to a lesser degree the Arctic region glacially eroded material is an important source of particles. In the open ocean the input or formation of particles at the surface boundary is a result of biological activity and the atmospheric input of terrigenous dust.

Most conclusions about the mode of transport and deposition of sediments in the ocean have come from inference. Geologists sample sediments in their deposited environment, determine their mineralogical composition, measure size distribution, shape, and other physical parameters of the individual components and try to determine the source of the sediments, their mode of transport, and the environment at the time of their deposition. (Hollister, 1972; Tucholke, 1974; Hollister et al., 1974). Paleontological, paleomagnetic, and chemical relationships are used to determine the rate at which particles are deposited (Ericson et al., 1961; Ku et al., 1968). In the deep ocean these rates are averaged over time periods of thousands to millions of years.

In order to understand processes operating on shorter time scales, water bottles have been used to collect suspended particulate matter in the ocean for mass and compositional analysis (e.g. Jacobs and Ewing, 1969; Lisitzin, 1972; Spencer et al., 1976). As particles settle or are advected downward (Brewer et al., 1976) through the water column, their concentration and composition are altered by zooplankton grazing and aggregation, disaggregation, decomposition, and dissolution. Decomposition and remineralization rates are rapid above the seasonal thermocline, but continue below that depth (Menzel, 1974). If this condition continued to the sea floor the sedimentation rate could be determined by measuring or calculating the flux of suspended particulate matter just above the sediment-water interface. In a motionless ocean this material, which will be defined as the "primary flux" would consist of biogenic particles and atmospheric dust introduced at the air-sea interface. A sample of the falling particles obtained just above the sea floor could be compared with the composition of the underlying sediments, and whatever differences existed would be attributable to diagenetic processes (such as dissolution and remineralization) at or just below the sediment-water interface. The rate of these processes

could be determined by the difference between the sedimentation rate to the sea floor and the net accumulation rate measured in cores.

The ocean, however, is not tranquil, and as the sea floor is approached there is often an increase in suspended particulates to concentrations as high as those measured at the sea surface. The increased concentration of particles near the bottom (known as the nepheloid layer) complicates this picture, because the increase is attributed to sediments resuspended from the sea floor (Biscaye and Eittreim, 1977; Spencer et al., 1976). It is possible that some particles introduced into the ocean by rivers are carried over the shelf and advected into the deep sea without being deposited, but such particles would be rare, so all particles not reaching the sea floor as part of the "primary flux" will be defined as "resuspended," although they may have been resuspended far "upstream" and/or "uphill" of their site of final deposition.

Downward fluxes of suspended particles within the nepheloid layer would include a component, sometimes a very dominant component, of resuspended sediment. Because nepheloid layers are widespread in the world oceans (see for example Biscaye and Eittreim, 1977, for the Atlantic and Kolla et al., 1976 for the Indian Ocean), any

consideration of particulate fluxes and their composition must somehow discriminate the resuspended portion of the suspended particulate load from the portion which is making its first trip downward from the surface waters.

Information about rates of resuspension and transport and redeposition of sediments is important because this recycling exposes particles for additional periods of time to processes of dissolution and decomposition in near-bottom waters rather than at or just below the sediment-water interface, where those processes and rates may be different.

Because of the "resuspended" material near the sea floor, the best place to measure the "primary" flux of particles reaching the sea floor is just above the maximum height of resuspension of particles. Biscaye and Eittreim (1977) estimate that this should be near the level of minimum light scattering (nepheloid minimum or clear water) above the nepheloid layer. Decomposition or dissolution of particles falling from the nepheloid minimum to the sea floor may decrease the quantity of primary material reaching the bottom, but the decrease is not expected to be significant compared to the decrease in the surface waters provided the bottom is above the carbonate compensation depth.

Vertical fluxes within the nepheloid layer include primary and resuspended particles and can be separated by determining the primary flux. If the net standing crop of particles in suspension in the nepheloid layer is determined (Biscaye and Eittreim, 1977), gross estimates can be made for the residence time of the nepheloid layer assuming steady state and uniform deposition and erosion. This residence time is defined as the time necessary to resuspend enough sediment to create a nepheloid layer with the concentration measured at the site where resuspension fluxes are determined.

In the past attempts have been made to determine the vertical flux of particles by combining information about the size, concentration, and density of particles. The size of particles in the water column has been determined using microscopes (Bond and Meade, 1966; Eittreim and Ewing, 1972) and more recently using Coulter counters (Sheldon et al., 1967; Carder, 1970; Brun-Cotton and Ivanoff, 1971; Brun-Cotton, 1976; Gardner et al., 1976). By estimating the density of particles and calculating a Stokesian settling velocity, one can use a diffusion-advection model to calculate particulate fluxes (Eittreim and Ewing, 1972; Feely, 1975; Ichiye, 1966; Tsunogai et al., 1974; McCave, 1975). Alternatively, measurements

of radioactive isotopes associated with particulate matter (such as those in the uranium-thorium series) can be used to determine the flux of particles in the ocean (Tsunogai and Minakawa, 1974; Bacon, 1975; Bacon et al., 1976). However, the number of particles in sea water decreases exponentially with an increase in size (Bader, 1970), with the result that particles larger than 20 μm are rare (Carder et al., 1971; Sheldon et al., 1967). Yet the exponential increase with size in both mass and sinking velocity makes the larger particle sizes more important in the contribution to total mass fluxes (McCave, 1975). Because of their rarity, larger particles have a statistically low probability of being caught in standard-size water samplers. Even when large particles are caught they are seldom extracted due to the design of water samplers and methods of filtration (Gardner, 1977).

The in situ pump of Bishop and Edmond (1976) provides sampling of a larger volume of water (several cubic meters), but has been used to only 1500 m water depth. Other methods of collection of large particles and organisms include nets of numerous designs. None of these methods actually distinguishes which particles are falling or at what rate, so the same assumptions mentioned earlier are needed to arrive at a vertical particulate flux. The

problem is analagous to measuring the standing crop of plankton to determine the dynamics of a system when it is the rate of productivity which should be measured.

A means of collecting the rare, relatively large particles which gravitationally settle through the water column is needed. During the past 80 years containers of various sizes and shapes (funnels, bottles, cylinders, etc.) have been deployed to act as collectors of falling particles in lakes and shallow coastal environments (see Appendix B). Only two studies have been reported using containers beyond the continental shelf (Wiebe et al., 1976; Nishizawa and Izeki, 1975; Izeki, 1976). It is surprising, however, that while some attempts have been made to compare the flux determined with the containers (referred to as sediment traps) to accumulation rates below the traps in tranquil water, no similar experiments have been reported where currents were monitored despite the frequent use of traps in moving water.

Sediment traps appear to provide a unique method of collecting the "rain" of particles in the ocean from which we can determine the downward flux of detritus, rates of dissolution and decomposition, and compare the composition of falling particles with bottom sediments and with suspended particles too small to contribute significantly to the downward flux. Since the pioneering work

by Wiebe et al., (1976) in using traps in the deep ocean many investigators at the Woods Hole Oceanographic Institution and elsewhere have turned to sediment traps as a tool for collecting particles in transit to the sea floor.

A major contribution of this thesis was to conduct controlled experiments with sediment traps in moving water to evaluate their collection characteristics as described briefly in chapter two and in detail in appendix A. With the traps that were designed and deployed for this study, we (the author, Gilbert Rowe, and Mary Jo Richardson) have collected over 30 quantitative samples from the deep sea. Samples from half of these collections (those obtained in the Western North Atlantic) form the data base for this thesis. Most of these traps were deployed within 500 m of the bottom with the intent of measuring both primary flux and resuspended flux. A few flux measurements were obtained with traps floating near the ocean surface.

The following questions will be addressed from the analytical results of the samples collected.

(1) What is the primary flux of particles reaching the sea floor, and what is the size distribution, morphology, and chemical composition of these particles?

(2) Is the flux of organic matter to the sea floor sufficient to feed benthic communities?

(3) What are the rates of resuspension and redeposition of particles found in the ocean?

(4) How does the composition differ among (a) the primary particles falling from the upper water column, (b) the particles resuspended from the bottom, (c) surface sediments, and (d) the "standing crop" of particles which are falling very slowly and are carried with a water mass and constitute much of what is generally collected in water bottles?

(5) What is the residence time of the nepheloid layer and how long might particles be expected to be in the layer?

Before this work could be carried out it was necessary to study the collection characteristics of sediment traps to determine whether they could produce useful information. Calibration experiments were conducted in a laboratory flume and in the field and are reported in Chapter II and in more detail in Appendix A. Problems were also discovered in sampling methods using Niskin bottles and are discussed in Chapter III. Chapter IV presents the model on which this investigation was based and explains many of the procedures used. The results are presented and discussed in Chapter V and summarized in Chapter VI.

CHAPTER II

CALIBRATION OF SEDIMENT TRAPS

A. INTRODUCTION

Despite the frequent use of containers as sediment traps, it is surprising how little has been reported on observations of hydrodynamic flow around these containers or experimentation on how flow and turbulence affect their characteristics of particle collection in moving water. This chapter will provide a brief overview of the use of traps in the past and describes what the writer believes to be the first systematic laboratory experiments for the calibration of sediment traps in moving water under known conditions of sedimentation. Collection rates of calibrated traps are then compared with collection rates of larger traps in natural environments in an attempt to calibrate traps used in the open ocean. A more detailed report of the laboratory experiments can be found in Appendix A.

B. BACKGROUND

Since the work of Heim (1900) there have been over one hundred reports in the literature of various sorts of sediment traps (see Appendix B). These sediment traps can be divided into five categories: cylinders, funnels,

wide-mouthed jars, containers with bodies much wider than the mouth, and basinlike containers with width much greater than height.

About half of the published studies were conducted in lakes, where turbulence and mixing are relatively slow, while the other half were in estuaries, bays, and coastal habitats where turbulence and advection are stronger. Attempts at using sediment traps beyond the continental shelf have been rare, but their potential is being recognized and technology now makes their use in the deep sea practical (Wiebe et al., 1976; Mesecar and Carey, 1975; Nishizawa and Izeki, 1975; Izeki, 1976; Gardner et al., 1977).

1. Previous Work on Calibration of Trapping Efficiency

a. Still Water. For quantitative studies to be made with sediment traps it is necessary that the rate of deposition measured by a trap be equal to the vertical flux across the plane of the trap, or that the degree of over-accumulation or under-accumulation in the trap be known. It should also be determined whether particles are preferentially trapped according to size or density as a result of hydrodynamic differentiation. Attempts at absolute calibration of sediment traps by comparing fluxes with other methods of measuring sedimentation have been few, but significant.

When using cylindrical containers as sediment traps in tranquil lakes, the accumulation rates determined were very similar to the rates determined by independent methods (Pennington, 1974; Rigler et al., 1974). Davis (1967) reasoned that the sedimentation rate determined from traps with different size openings was correct if the amount of detritus collected were proportional to the trap opening and the extrapolation of data points intersected the origin. These conditions were met when using cylinders and wide-mouthed jars in the laboratory and in stratified lakes (Davis, 1967; Pennington, 1974) and with funnels moored in lakes (Watanabe and Hayashi, 1971), but the results of the experiments described in this chapter show that the above conclusion is not a unique interpretation.

Kirchner (1975) tested cylinders with a constant height (25 cm) and with a wide range of diameters (3.2-43.2 cm) in a lake and found no statistically significant differences in the collection rates, although in two testing periods the collection rates in different traps varied by 5-6 times in an unpredictable manner. In a laboratory experiment glass jars with openings from 1.2 to 8.4 cm generally collected pollen grains at a predictable rate (Davis, 1967). According to White and Wetzel

(1973), variations in sedimentation rates in quiet lake water among cylinders 4.8 cm, 10.3 cm and 13.3 cm wide increased slightly with trap diameter.

In comparing collection rates of cylinders and funnels, Pennington (1974) reported that the flux determined with cylinders (8 cm wide and 30 cm tall) was consistently two to three times the flux determined with a funnel 25 cm wide. Johnson and Brunkhurst (1971) compared collection rates of cylinders 5 cm and 17 cm wide with funnels 12 cm, 20 cm, and 41 cm wide. The small cylinder caught almost ten times as much as the large cylinder and funnels, which in turn varied by a factor of 2-3.

b. Moving Water. To the author's knowledge, no sediment traps have been calibrated in water known to be moving where an independent determination of the sedimentation rate was obtained. Soutar et al. (1977) deployed traps off the California coast in the Santa Barbara Basin, where varied sediments allow the sedimentation rate to be resolved on nearly a one-year time scale but current was not monitored. Their collection rate was 22% to 88% of the long term bottom sedimentation rate with the trap 100-150 m below the surface, and 66-190% of the long term rate with the trap 10 m above the bottom.

Some intercomparisons of trap sizes and shapes have been made, but generally only the trap widths are reported,

making it impossible to test for a H/W effect on the collection rate. Patten et al. (1966) observed persistence of fluorescein dye in a BOD bottle (narrow-necked bottle) placed in a channel of flowing water, but they drew no conclusions about the trapping efficiency.

Flux measurements in Cape Cod Bay by Young and Rhoads (1971) with wide-mouthed bottles of 5.3 cm and 9 cm openings were reported as showing nonsignificant differences, but no mention was made of current velocity. Johnson and Brinkhurst (1971) reported that a cylinder 5 cm wide trapped four to eight times as much material per unit area as a cylinder 17 cm wide in a bay of Lake Ontario. Nothing was mentioned about possible currents, but some movement seems likely in such a large body of water. Most inconsistencies occur when using cylinders with diameters less than 2 cm; jars less than 2 cm across caught relatively more material than wider containers in a Scottish sea lock where tidal currents are less than 5-10 cm/sec (Davies, personal communication). Cylinders 30 cm tall with diameters of 0.25, 2.54, and 5.08 cm were tested by Hoskins et al. (1975) in Reid Inlet, Glacier Bay, where currents are 1-5 cm/sec. In this case the widest cylinder collected particles at the highest rate per unit area and had the least variation in consecutive measurements.

2. Comparison with Rain and Snow Gauges

An obvious corollary to the calibration of sediment traps is the calibration of rain and snow gauges. Precipitation collectors have been used for hundreds of years (Kurtyka, 1953), but only in the last hundred years has it been realized that the collecting efficiency of rain and snow gauges decreases with an increase in wind speed (Wilson, 1954; see fig. 2.1). The primary source of error with precipitation gauges is the wind effect. Any object placed in moving fluid (air or water) is an obstruction around which the fluid must flow. A straight-walled collector creates an updraft which carries rain and snow up and over the collector opening (fig. 2.2). Encircling a collector with some version of a Nipher shield (an upward opening cone) reduces the updraft and improves the collection efficiency for rain and snow (Kurtyka, 1953).

Hydrodynamically the flow characteristics of air and water around a container are qualitatively very similar. However, due to differences in particle size and density and fluid velocity and viscosity, the path of rain drops or snow flakes around a container may be very different from the path of falling detritus in water. Raindrops of 0.5-5 mm diameters fall at 2.3-9.3 m/sec, and snow

Fig. 2.1 Collecting efficiency of rain (O) and snow (●) gauges as a function of wind speed.

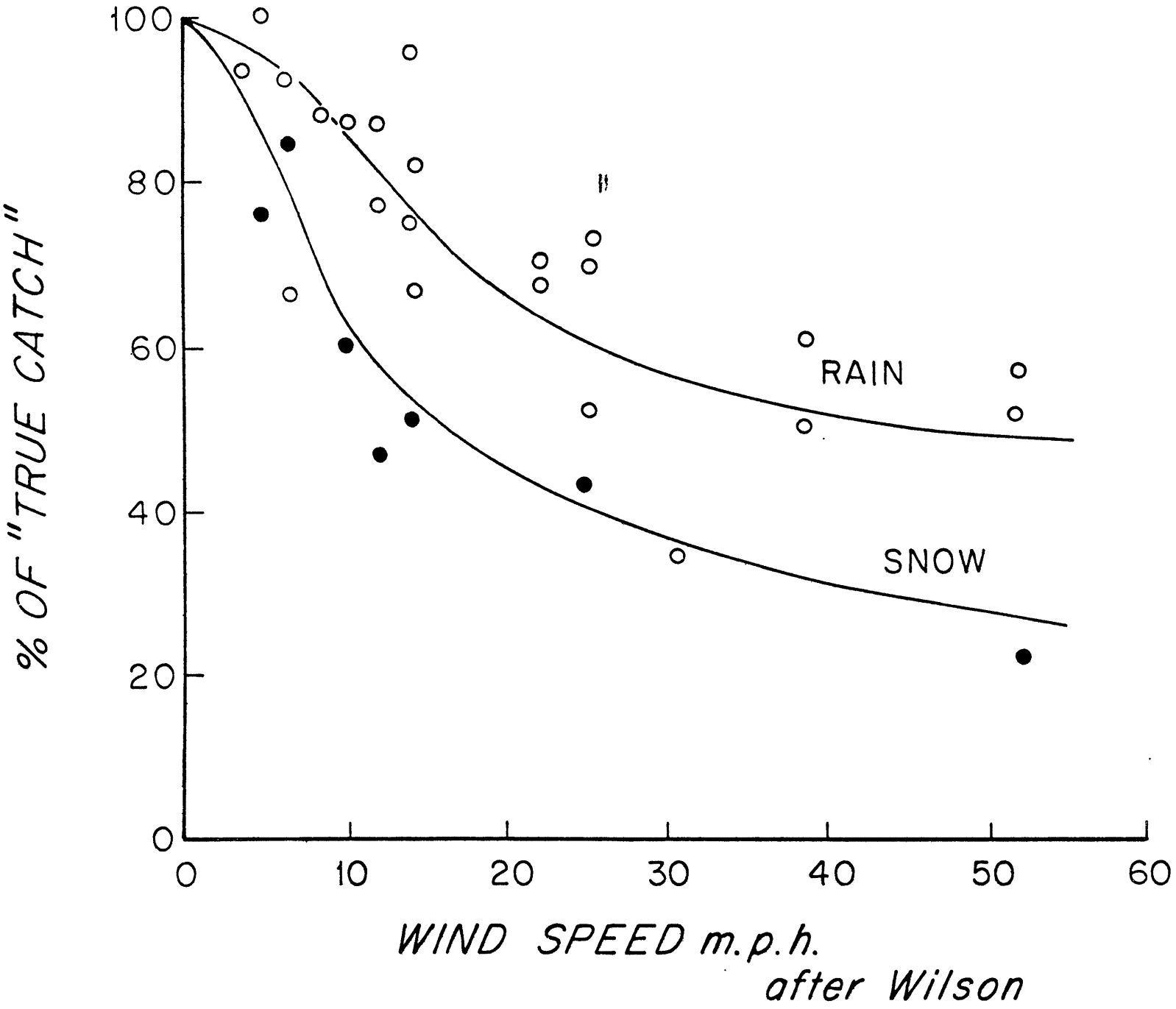
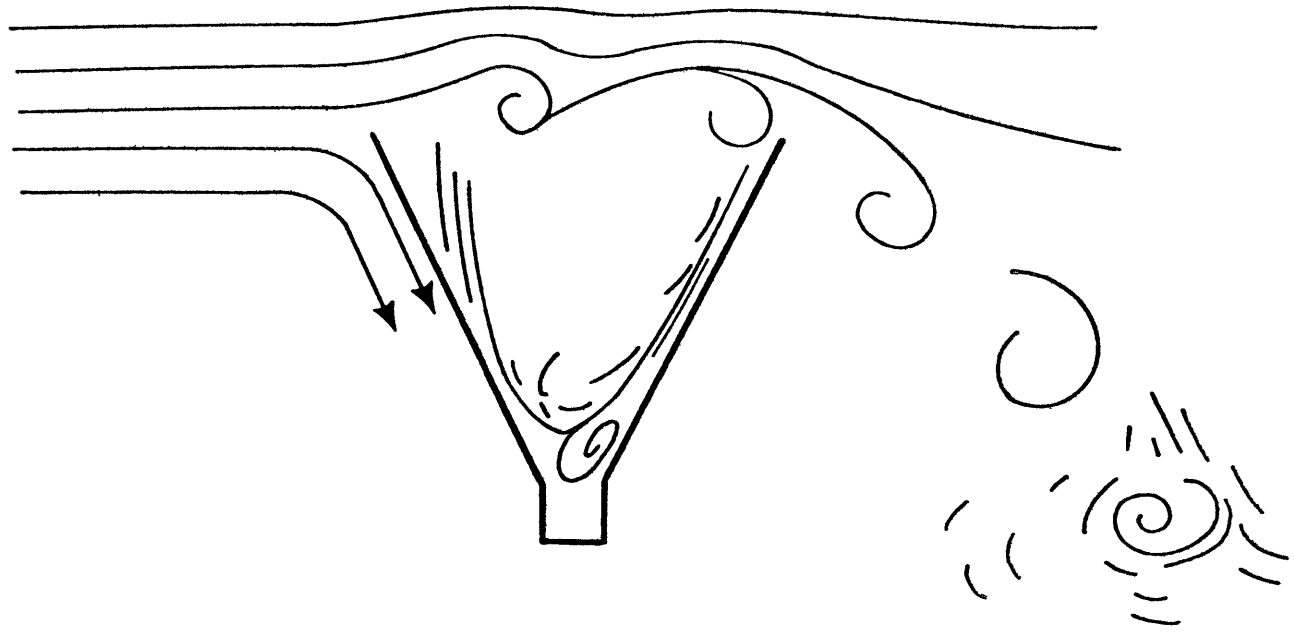
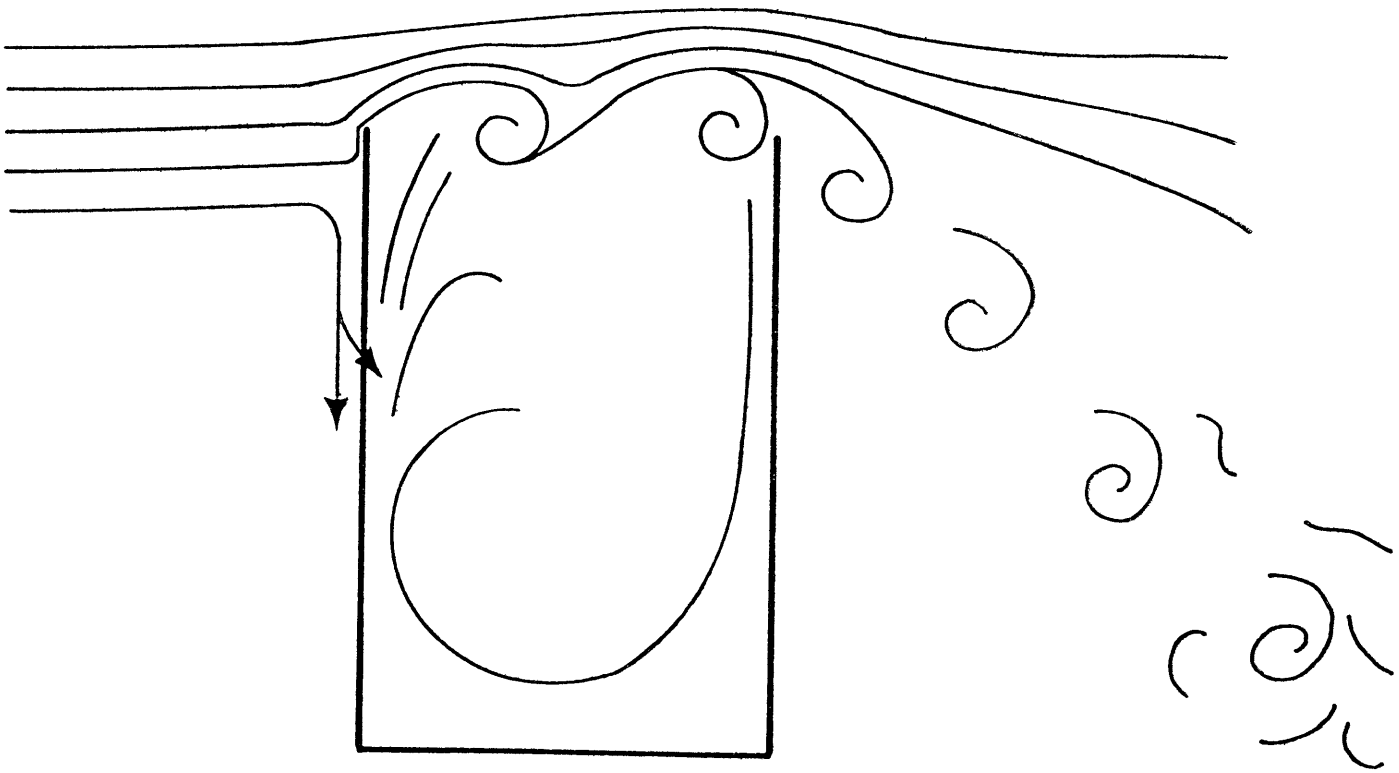

100
80
60
40
20
0
0
10
20
30
40
50
60
% OF "TRUE CATCH"
RAIN
SNOW
WIND SPEED m.p.h.
after Wilson

Fig. 2.2 Flow lines around and inside a funnel and cylinder in either air or water.





falls around 0.5 m/sec (Kurtyka, 1953). If most winds are less than 10 m/sec, then the fall velocity of rain and snow is seldom more than one order of magnitude less than the horizontal wind speed and may be one order of magnitude greater. Conversely, in the marine environment, a one-micron particle falls at about 10^{-4} cm/sec, a 40 μm particle falls at 10^{-1} cm/sec (Stokes' law for particles where $\rho<2$ g/cm^3) and fecal pellets fall at 0.04-1.0 cm/sec (Smayda, 1969; Fowler and Small, 1972), whereas current velocities are generally less than 200 cm/sec in estuarine and surface currents and less than 20 cm/sec in deep ocean water. Thus the fall velocity of most particles in water is between one and six orders of magnitude less than normal horizontal currents. Rather than descending vertically or at a slight angle, particles settling through water generally follow the fluid path lines and enter traps by being carried passively in turbulent eddies. Thus it is important to understand the flow patterns around and inside sediment traps. Some of the important variables affecting trapping efficiency are: current velocity and its variability; trap size and geometry; and size, concentration, and composition of settling particles.

C. METHODS AND INSTRUMENTATION USED IN FLUME EXPERIMENTS

Traps with a variety of geometries were exposed to steady, uniform flow in a six meter recirculating flume. Flat plates, cylinders, wide-mouthed jars, funnels, narrow-necked wide-bodied bottles (Erlenmeyer flasks and salinity bottles), and segmented basins were among the forms tested (Table A.1, Appendix A). Patterns of fluid flow around and inside the different forms were observed by using fluorescein dye as a tracer in fresh water. Three series of experiments were then made with sea water and fine-grained sediments in the same flume to evaluate the effectiveness of these containers as sediment traps.

1. Dye Experiments

Each container was placed in a recirculating flume 17 cm wide with a flow depth of 15 cm. Limited observations were also made in a flume one meter wide. Steady, uniform flow conditions were maintained over the range of 1-10 cm/sec. Fluorescein dye was released from a hypodermic needle at various heights and distances upstream of each form. Flow lines and zones of turbulence were observed, noted, and photographed. As a second means of observing the fluid exchange between the trap and the flowing water, the forms were filled with dilute fluorescein dye. The

residence time--the time required for dye inside the container to be diluted to concentrations in the flume--was compared for several configurations (Table A.2, Appendix A).

2. Sedimentation Experiments

Once the fluid motions around various geometric configurations were known, the next step was to measure the particle-collecting characteristics of the containers. Three series of experiments were made. The first experiment included a diversity of geometric forms and yielded a two-orders-of-magnitude range of trapping efficiencies between containers used. Based on the results of this experiment, a series of experiments was made using five different containers in which collection time and flow velocity were varied. The third series of experiments primarily involved funnels under various flow conditions. Two experiments were made in a fish tank to test trapping efficiency in still water.

The same six-meter recirculating flume used in the dye experiments was filled with water from the Sargasso Sea. Flow depth was 11 cm in the first experiment and 15 cm in all other experiments. Because of the author's interest in near-bottom sediment transport processes in the ocean, abyssal mud was used in all quantitative

experiments. After wet sieving, all particles were <63 μm with 95% less than 25 μm; the median grain size was 2.6 μm. Less than 10% was carbonate, and illite was the predominant clay mineral (60%). The sediment was disaggregated in 250 ml of distilled water in an ultrasonic bath for one hour, and added to the flume at the beginning of each series of experiments. The water and sediment were allowed to mix for 10-20 minutes before each experiment during which time the channel surfaces were wiped two or three times to resuspend all particles while the pump was at full discharge.

The return flow of the flume was through two-inch PVC pipe which resulted in return velocities much higher than the flume velocities, so sediment could not deposit in the return flow system. The were no dead spaces in the system where sediment could accumulate, so all sediment was assumed to be deposited on the flume bed. The flow velocity was lowered to the desired speed and the containers were positioned in the flume.

a. Determination of Sedimentation Rate on Flume Bottom. The rate of deposition in the flume was determined by measuring the concentration of suspended particles at the beginning and end of each experiment. The difference in the suspended load was assumed to have been deposited

on the flume bed. The containers were covered and removed from the flume, and the contents were washed onto a filter and the weight was corrected for particles suspended in the water inside the container (see Appendix A for details). The mass of sediment collected per square centimeter of trap opening was calculated for each container.

b. Calculation of Trap Efficiency. The trapping ratio is determined by dividing the mass/cm^2 collected in a trap by the mass/cm^2 deposited on the flume bed. The ratio is multiplied by 100 and given as the trapping efficiency. The ideal trap has an efficiency of 100%: overtrapping (catching more sediment than the sedimentation rate) yields percentages greater than 100%, and under-trapping results in percentages less than 100%.

c. Traps and Conditions Tested. The Series I experiment (Table A.3, Appendix A), included five containers: (1) a 2 oz wide-mouthed, screw-top, glass jar, (2) an identical jar with 1 mm mesh nylon screening slightly domed over the jar, (3) a domed polyethylene container, (4) a Plexiglas cylinder placed horizontally normal to the flow and containing a 0.11 cm slit parallel to the cylinder axis at the top of the cylinder, and (5) a flat Plexiglas plate.

Four experiments were conducted in Series II with five traps (Table A.4, Appendix A). Three of the containers were open Plexiglas cylinders placed vertically in the flow to test different height to width (H/W) ratios. Two of them had a 1:1 H/W ratio, but differed in their dimensions by approximately a factor of two. The third cylinder was the same width as the smaller cylinder, but had a 2:1 H/W ratio. The Plexiglas semi-model of the trap deployed by Wiebe et al. (1976) was the fourth configuration, and a dome-shaped container was the fifth trap. Flow depth, velocity, concentration of suspended sediment, and duration of each experiment in Series II are shown with the trapping efficiency in Table A.4 (Appendix A).

Series III experiments were primarily for testing funnels. The traps used, flow conditions, and concentration of suspended sediment are listed in Table A.5 (Appendix A). The effect of changing current direction was investigated in experiment no. 8 by rotating each container three times during the experiment. A clockwise rotation of 180°, 45°, and 135° was made on all traps at 3.0, 5.3, and 9.2 hours into the experiment. In experiment no. 9 the initial concentration of suspended particles was increased to 82 mg/l by adding sediment

which was mostly between 2-62 μm from the same GPC-9 core. Narrow-mouthed, wide-bodied containers were tested along with a baffled funnel and a cylinder in this experiment.

The fish-tank experiment also used sea water and the same sediment as the flume experiments. Traps tested included cylinders, a baffled funnel, a salinity bottle, and the domed trap (Table A.5, Appendix A). The first experiment left the tank uncovered, which allowed air circulation in the room to create motion within the fish tank. The fish tank was covered during the second experiment to eliminate motion induced by air circulation and allowed to equilibrate with room temperature for 24 hours to reduce thermal convection, but no attempt was made to control room temperature.

D. RESULTS OF FLUME EXPERIMENTS

The results of all the flume sedimentation experiments show that a two-order-of-magnitude range of sedimentation rates can be obtained from using different types of traps (Fig. 2.3). Tables and a detailed discussion of the data from the flume experiments as well as a discussion of the flow dynamics around traps can be found in Appendix A. The following discussion is more general.

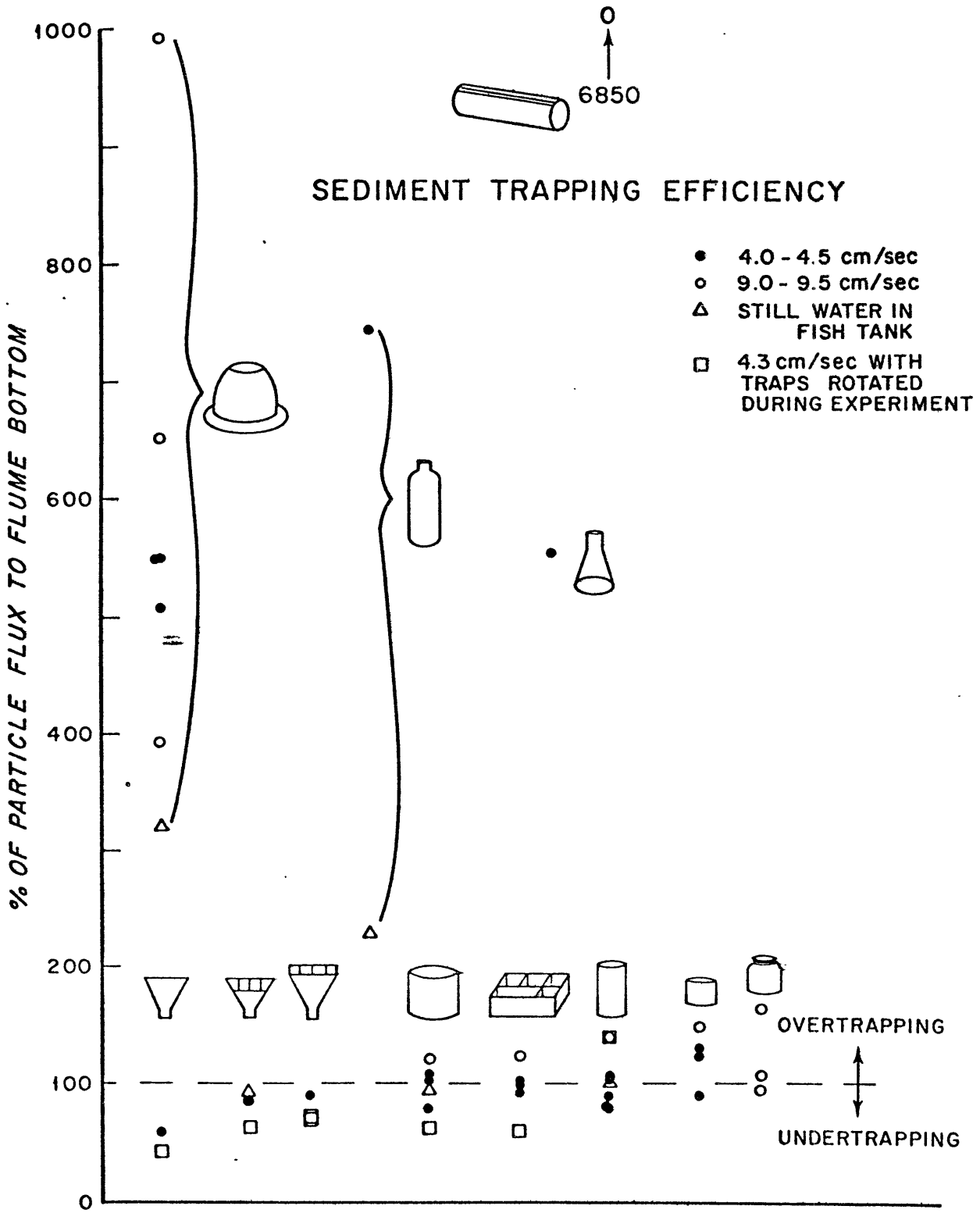
1. Evaluation of the Types of Traps Tested

a. Cylinders. The average efficiency of cylinders was closer to 100% than other configurations tested in both flowing water (4.0-9.5 cm/sec) and still water. No strong trends in trapping efficiency were evident between different sizes of cylinders, but the ranges of dimensions and velocities tested were not very great.

b. Flat Plates. A flat plate is the closest approximation to the ocean bottom, but it is a highly inefficient collector when exposed to currents. Most of the particles landing there are moved along the plate without a chance to settle permanently and with no way to be trapped. Also, recovery of such a collector without losing sediment is difficult.

c. Funnels. In still water the trapping efficiency of funnels is not substantially different than for cylinders (Table 5). In a current of 4 cm/sec the unbaffled funnel was 25% less efficient than the cylinders, whereas the funnels with baffles caught sediment at about the same rate as the cylinder. However, in these experiments the accumulation of particles has been predominantly on the inside funnel walls. It is possible that on a mooring in open water particles aggregate with time and roll down the side into the funnel neck and not be resuspended.

Fig. 2.3 A compilation of the trapping efficiency of traps tested under a variety of conditions differing in flow velocity, length of experiment, initial concentration, and orientation of the container to the flow.

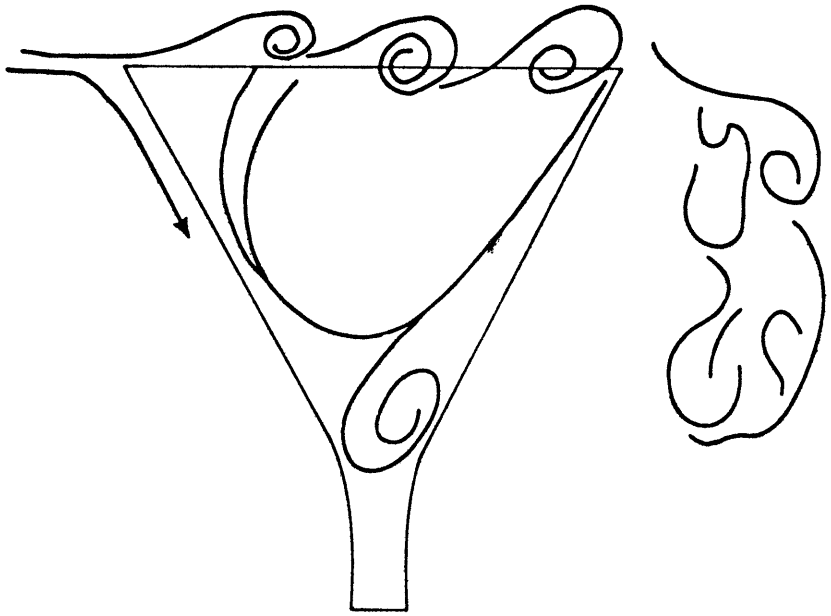

SEDIMENT TRAPPING EFFICIENCY
0
6850
4.0 - 4.5 cm/sec
9.0 - 9.5 cm/sec
STILL WATER IN FISH TANK
4.3 cm/sec WITH TRAPS ROTATED DURING EXPERIMENT
% OF PARTICLE FLUX TO FLUME BOTTOM
1000
800
600
400
200
100
0
OVERTRAPPING
UNDERTRAPPING

Brunskill (1969) reported that a minor portion of the sediment stayed on the sides of his funnels.

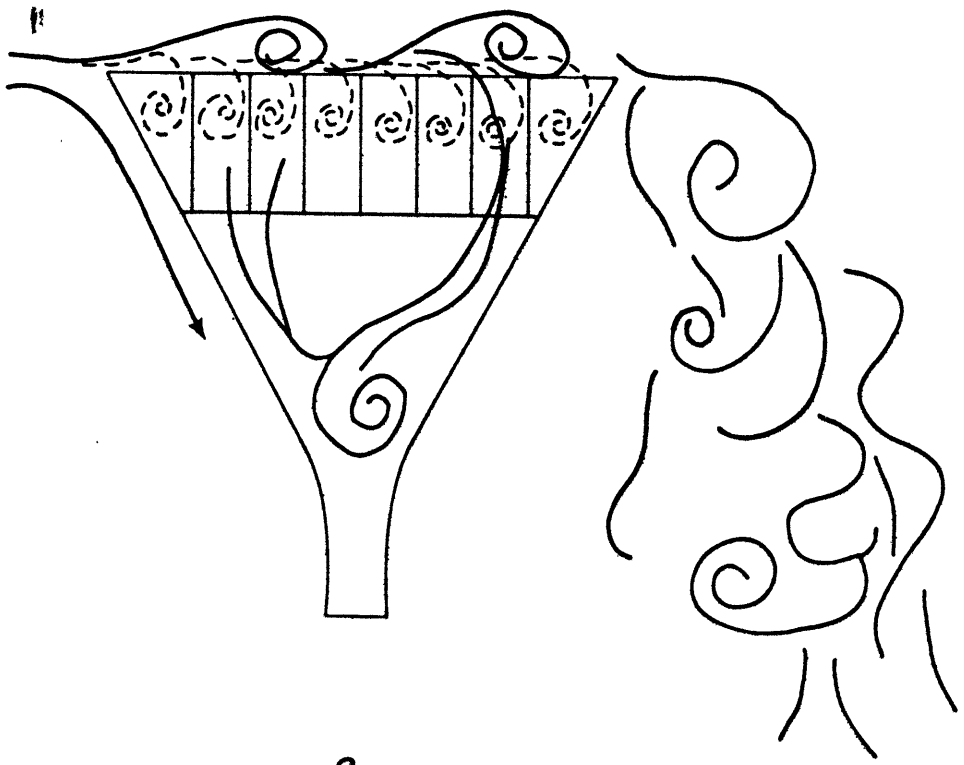
There was an insignificant difference between the efficiencies of the two funnels baffled in the manner shown in figure 2.3. The purpose of the baffle was to reduce turbulence and mixing within the funnel. The size of eddies was reduced by the baffles, but the major circulation within the funnel was not affected (figure 2.4). Most of the fluid still enters the downstream section of the funnel, descends to the bottom of the funnel, and rises out of the upstream end of the funnel. This has been observed in funnels as large as 140 cm in diameter. In a current of 7 cm/sec, plastic beads with a fall velocity of 0.8 cm sec^{-1} (690 m day^{-1}) were seen to enter the downstream end of the funnel and be carried out at the upstream end. The significance of this observation will be discussed at the end of this section.

d. Segmented Basin. Several traps have been constructed which approximate a flat basin with edges to prevent loss of collected material (Kleerekoper, 1952, 1953; Wiebe et al., 1976; Mesecar and Carey, 1975; J. Dymond, personal communication). The amount collected in different compartments in Series II and III experiments varied but the relative proportions collected in each

Figure 2.4 Flow lines around and inside a funnel (1) without a baffle and (2) with a baffle at the top. It was hoped that the baffle would reduce the scale of turbulence and create the flow lines shown by the dotted lines, but even in laminar flow with velocities as low as 4 cm/sec, the general circulation within the funnel remains unchanged [solid lines in (2)].



1



2

compartment was constant and the average efficiency for the trap was 100% at 4.4 cm/sec and 120% at 9.5 cm/sec. When the trap was rotated during the experiment, there was little variation in the relative efficiency of the different compartments, but the overall efficiency was reduced to 60%.

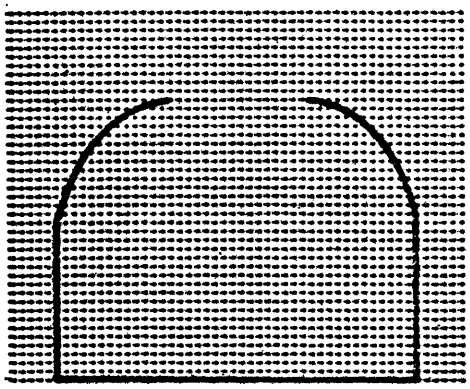
e. Narrow-necked, wide-bodied traps. Containers with bodies larger than their openings had high trapping efficiencies, even in still water. Observations in the fish tank where suspended particle concentrations ranged from 1-40 gm/l showed why (figure 2.5). Particle-laden water under an overhanging wall will soon lose particles due ~~to~~ gravitational settling. The overhanging wall prevents new particles from entering the particle-depleted water, and when sufficient particles have fallen out, the water becomes less dense than surrounding water and slowly rises in a narrow, continuous plume. These plumes were identified by the lack of backscattering of particles in the plume and by dropping tiny dye particles into the traps and watching the dyed water rise. (It was not just the dye rising because concentrated dye is slightly negatively bouyant.) The light water is replaced by water outside the container which has more particles, and the cycle is repeated. Thus, particles are pumped into

containers at a rate which depends on the particle characteristics (sinking rate, concentration) in the fluid and the proportion of overhanging wall area to trap-opening area. A plume also rose from a tall cylinder in still water (H/W = 3), but not from a short (H/W = 1) cylinder. This may be because horizontal diffusion and Brownian motion does not allow the fluid at the trap bottom to remain homogeneous, so as particles fall out at the trap bottom a less dense fluid is developed which rises.

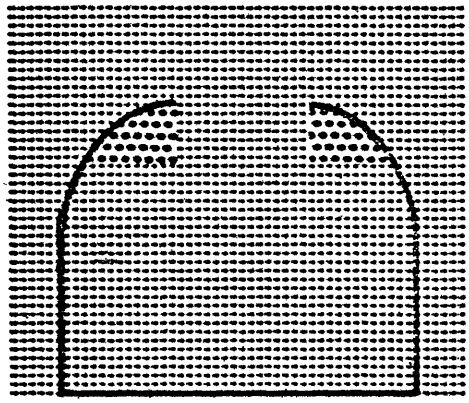
The same basic mechanism applies to these traps in moving water because the fluid is in the container long enough for some of the particles to settle out. Enough particles fall out for the fluid either to become light and rise out of the container, or to lose much of its load before an eddy penetrates deeply enough to force old fluid out.

Suspended particle concentration in the fish tank was initially 46 mg/liter, so if 75% of the particles settled out of a parcel of water, the density difference would be 34.5 ppm; this corresponds to .035°/$_{oo}$ change in salinity, which is both measurable and sufficient to cause a density instability. In the deep ocean, where concentrations of particulate matter are seldom greater

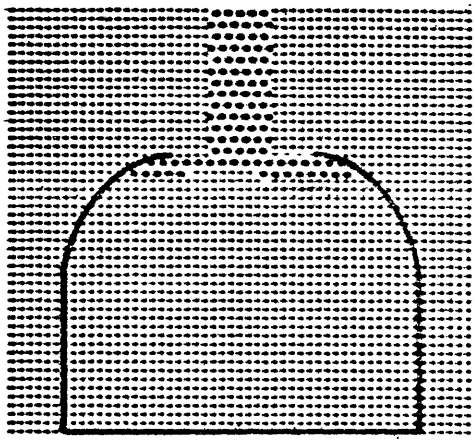
Figure 2.5 Diagram shows sequence of events causing overtrapping of particles in containers with overhanging walls. See text for explanation.



a. HOMOGENEOUS PARTICLE DISTRIBUTION



b. FORMATION OF PARTICLE-DEFICIENT WATER



c. RISING PLUME OF PARTICLE-DEFICIENT WATER

than 0.1 mg/liter, it is unlikely that any density instabilities would result if all particles settled out. The horizontal cylinder with a slit belongs in this class of traps with a narrow neck and wide body. Because this shape overcollected particles so drastically, it could prove useful in removing suspended particles for pollution control or industrial purposes.

2. Theoretical Collection Rate

After observing the turbulent eddies on top of sediment traps and observing that even large, fecal-pellet sized particles can be carried into and out of funnel-shaped traps when the current velocity is less than 10 cm/sec, one might wonder whether traps are effectively collecting falling particles. Although the horizontal current velocity is much greater than the fall velocity of most particles, a simple calculation will show that if all particles entering the trap stayed inside, the rate of collection would greatly exceed the accumulation rate on the flume bottom. The cylinder with H/W ratio of 2.3 has a trapping area of 11.3 cm^2. In one experiment the velocity was 4.0 cm/sec, the average concentration was 25 mg/l, and the experiment lasted 11.3 hours. If we assume fluid is entering one half of the cylinder and leaving from the other half, and only 1% of the particle mass remains inside, the mass in the

trap at the end of the experiment would be 565 mg, whereas the mass actually collected was 2.6 mg--more than two orders of magnitude lower!

After making the above calculation, it is surprising that the collection rates of cylinders and funnels match the accumulation rate of particles on the flume bed and more importantly that the results are reproducible under a variety of conditions, because only a small percentage of the particles entering the trap remain there; taking a small fraction of a large number usually causes large errors. These experiments indicate that we can design traps which collect particles at the rate of the vertical flux despite the dominant horizontal advection of particles.

3. Summary of Flume Experiments

Sufficient field and laboratory work has been done to instill confidence in the results of sediment traps deployed in tranquil waters (Davis, 1967; Pennington, 1974; Rigler et al., 1974; Kirchner, 1975; Moore, 1931; Deevey, 1964). When traps are exposed to advective currents, the velocity of flow and geometric design of the trap determine the amount of sediment trapped. Sediment traps in advective flows must not be thought of as "rain gauges" in low-velocity winds, which simply catch particles falling nearly vertically, because the fall velocity of particulate

matter in large bodies of water is so much lower than the horizontal flow velocities that most particles follow the hydrodynamic flow lines around and inside traps.

The overall performance of different shapes of sediment traps in flows up to 9 cm/sec and using sediment less than 25μ indicated that:

(1) measurements with a cylinder with a H/W ratio of 2 most accurately measured the real flux in the flume;

(2) funnels underestimate the actual flux;

(3) funnels with baffles on top of the funnel improve the trapping efficiency to 70-90%. (This is a function of the baffle design.);

(4) containers with body diameters greater than the mouth openings overtrap sediment by a factor which depends on the mouth-to-body ratio, the concentration of particulate matter, and the geometry of the trap.

Variations in velocity, current direction, suspended sediment concentration, grain-size distribution and duration of deployment showed the following relationships:

(1) The trapping efficiency of cylinders and the segmented basin trap increased only 20-35% between 4 and 9.5 cm/sec. Experiments in the fish tank showed cylinders and funnels caught particles at the rate at which they were falling in still water.

(2) Rotating the traps to simulate varying current direction reduced the trapping efficiency of a plain funnel to around 45% and the baffled funnels to around 70% (deeper baffles could improve this). Shallow containers were less efficient and the tall cylinder was more efficient when they were rotated.

(3) No variation was seen in the trapping efficiency when the initial concentration of suspended particles was varied between 12-82 mg/l.

(4) There was no apparent preferential collection of large or small particles by cylinders or the dome trap using the fine-grained sediment of the experiment (95%<25μ). The horizontal cylinder with a 1.1 mm slit trapped slightly larger flocs and particles than what was deposited on the flume bed.

(5) In the time range of 11-39 hr, the duration of the experiment had no effect on the trapping efficiency.

The containers used in these experiments are smaller than most traps used in field experiments, and the flume is much smaller than the bodies of water in which sediment traps are used. While it is possible to scale the size of traps, it is not possible to model in the flume the scale of turbulence which exists in large bodies of moving water. However, the fluid motion around and within the traps and the dynamics of particle entrapment are similar in both situations.

Additional controlled experiments are needed to extend the scope of this study. Tests need to be made at velocities above 10 cm/sec and with particles larger than 25 μm.

The next step in this study was to test traps in the natural environment where three types of calibration are possible: (1) make relative comparisons of collection rates between different types of traps; (2) compare the

collection rates of traps with an independent measure of flux in the region; and (3) deploy flume-calibrated traps with other traps to be tested and use the flume-calibrated traps as standards against which other traps are compared. The first and third approaches were used in the field experiments described in the following section.

E. METHODS AND INSTRUMENTATION FOR FIELD INTER-CALIBRATION OF TRAPS

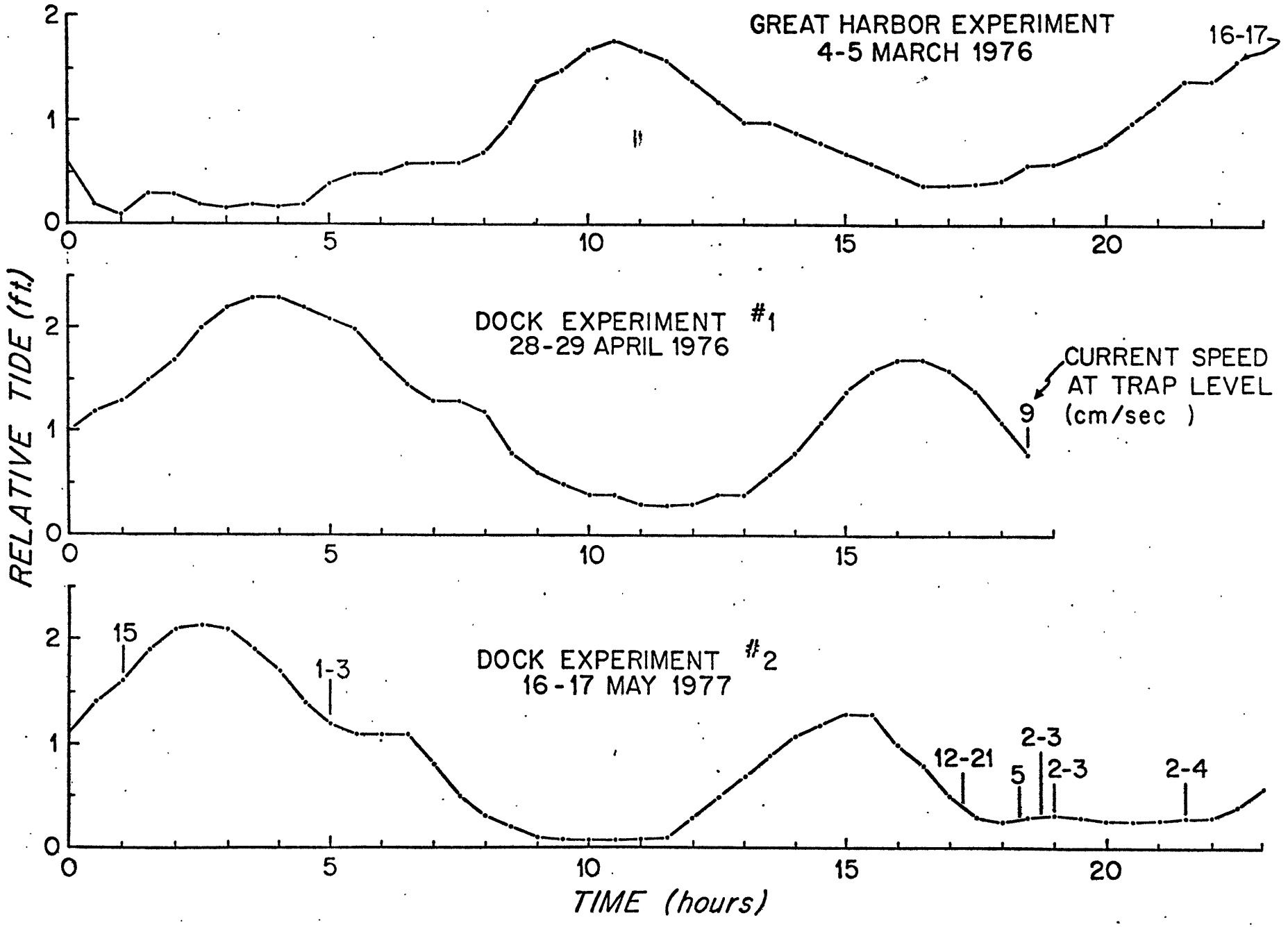
1. Sites of Field Experiments

In order to increase the velocity range of experimentation, test bigger traps, and correlate the flume results with natural depositional environments, four experiments were made near Woods Hole, Massachusetts in Oyster Pond, Great Harbor, and from the dock of the Woods Hole Oceanographic Institution. Oyster Pond is a glacial pond with a maximum depth of 6.6 m and a salinity of about 3°/$_{oo}$, and is connected by a culvert to a series of shallow ponds that are linked to Vineyard Sound and experience limited tidal exchange (Emery, 1969). Oyster Pond was chosen as a quiescent environment in which to test the traps. There was wind-driven circulation on the surface of the pond, but visual observation of dye trails in the water showed currents to be almost negligible and certainly less than 2-3 cm/sec near the traps. Due to tidal motion, current

speed and direction were highly variable both in Great Harbor and by the Woods Hole dock.

Collection periods were 22.5 hr. in Great Harbor, 18.5 hr. and 22.0 hr. by the dock, and 48 hr. in Oyster Pond, so each deployment spanned a tidal cycle. During the second dock experiment a current meter with a direct readout was lowered to the level of the traps several times to measure the velocity. Figure 2.6 shows the velocity readings superimposed on the tide-gauge record at the dock. The maximum velocity measured was 21 cm/sec, but most of the time it was below 15 cm/sec and was often below the 2-3 cm/sec threshhold of the current meter. Although the experiments were a year apart, the similarity of the tide-gauge records indicates that the velocity range was probably similar. SCUBA divers measured a current speed of 10 cm/sec while closing the traps after the first dock experiment. A current speed of 15 cm/sec was measured in Great Harbor by SCUBA divers at the end of that experiment, but experience has shown that current speeds are frequently much higher at that site than at the dock. Therefore, while there is considerable variability in the flow regime at a single site, the experiments span a range of current speeds near zero in Oyster Pond, to as high as 21 cm/sec at the dock and to an unknown maximum in Great Harbor (possibly as great as 50 cm/sec).

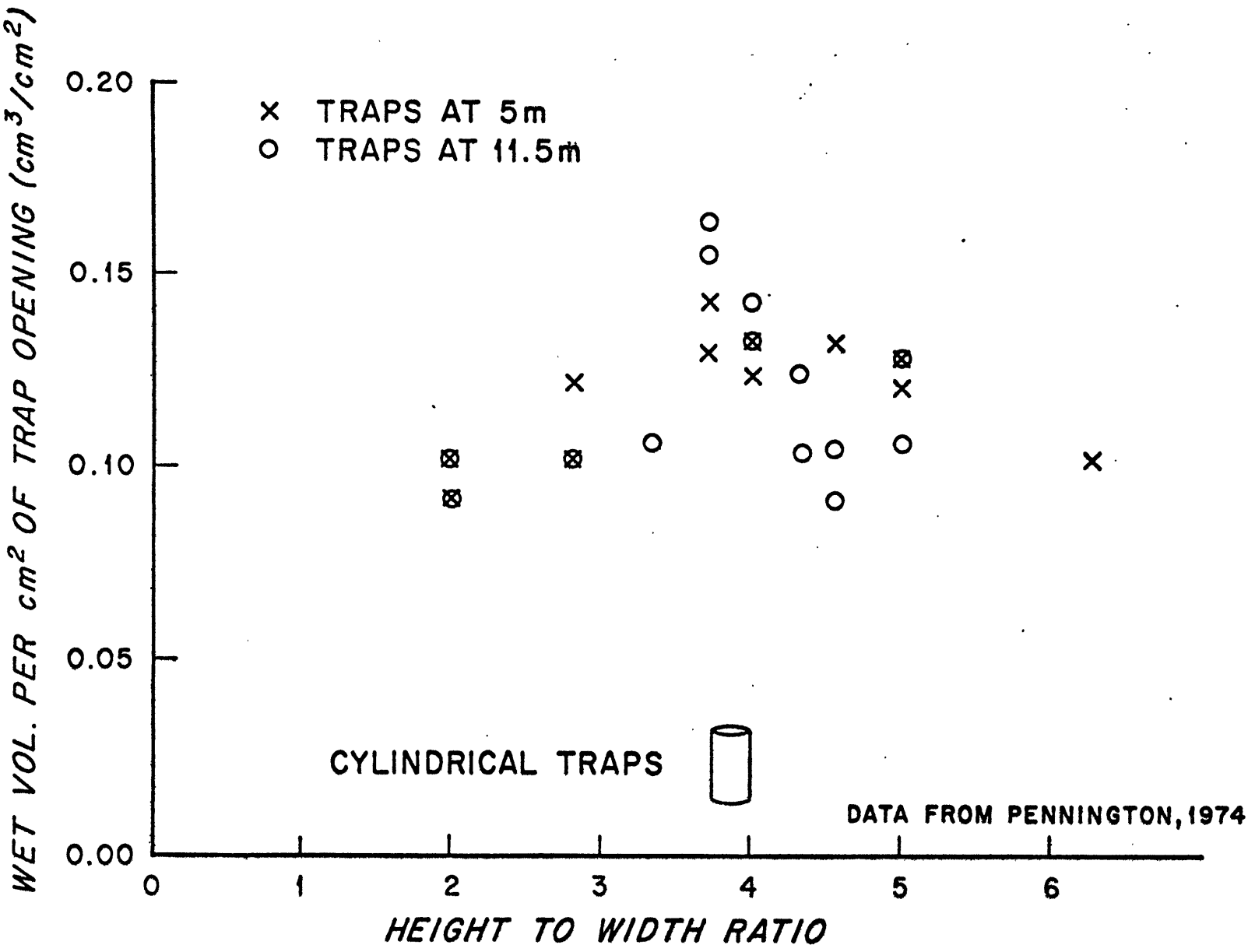
Figure 2.6 Tidal record measured at W.H.O.I. dock during sediment trap experiments. Current speeds measured at the trap level are indicated along the record when available. The highest currents were measured during flood and ebb tide. The Great Harbor experiment site was less than a mile from the W.H.O.I. dock, but the geography is such that the highest currents may not coincide with the flood and ebb tide at the dock. Currents at the Great Harbor site may reach 50 cm/sec.


GREAT HARBOR EXPERIMENT
4-5 MARCH 1976
16-17
DOCK EXPERIMENT #1
28-29 APRIL 1976
CURRENT SPEED
AT TRAP LEVEL
(cm/sec)
9
DOCK EXPERIMENT #2
16-17 MAY 1977
15
1-3
12-21
5
2-3
2-3
2-4
RELATIVE TIDE (ft.)
TIME (hours)
0
1
2
5
10
15
20

It was suggested to the writer by Klaus von Brockel (personal communication, 1975) that the height-to-width (H/W) ratio of a trap was a controlling factor in the trapping efficiency of any container. Although neither the trapping data from the flume experiments discussed earlier nor the data of other authors (Pennington, 1974; Davis, 1967; Kirchner, 1975) showed strong evidence for this (e.g. figure 2.7), analysis of the dynamics of flow within containers indicated this might be so. Therefore, PVC cylinders with diameters of 3.9 cm and 9.0 cm were constructed with H/W ratios of 1.9, 2.9, and 5.8. In addition, a PVC cylinder 25 cm wide and 76 cm tall, which was later deployed in the open ocean as a sediment trap (Gardner et al, 1977), was prepared for deployment at each site. Other small cylinders, funnels, and narrow-necked, wide-bodied containers whose trapping efficiency had been determined in the flume (section D) were simultaneously deployed to help calibrate the larger traps.

During the second dock experiment three traps designed after the description of Soutar et al. (1977) were also tested. These consisted of a 9.4 cm diameter Plexiglas cylinder filled with seven 2.5 cm diameter Plexiglas cylinders which in one case were sealed to the bottom of the large cylinder to form "closed cells" (Soutar et al., 1977) and in the other case the small inner cylinders

Figure 2.7 Volume of sediment collected in cylinders with varying height to width ratios.


WET VOL. PER cm² OF TRAP OPENING (cm³/cm²)
0.20
0.15
0.10
0.05
0.00
× TRAPS AT 5m
○ TRAPS AT 11.5m
CYLINDRICAL TRAPS
DATA FROM PENNINGTON, 1974
0
1
2
3
4
5
6
HEIGHT TO WIDTH RATIO

stopped one inch above the bottom to form "open cells". The third cylinder had no smaller cylinders inside, but may have lost a small amount of sediment during retrieval, so those data are enclosed by parentheses in figures 2.14-2.16. A large Plexiglas funnel (22.5 cm in diameter) with baffles was also moored at the dock to test for scaling factors from the 6.3 cm funnels.

3. Deployment of Traps

The large PVC cylinder was attached to a line with a Nansen bottle clamp; the other traps were secured at the ends of 1.2 m wooden crosses such that all trap tops were at the same height. In Great Harbor and Oyster Pond the moorings were held taut with subsurface floats. At the dock the moorings were tied off to beams so that no vertical motion was possible. Vertical motions cause a pumping action in the traps which can limit deposition (Pennington, 1974) or resuspend particles within the trap.

The traps were deployed at a depth of 6.6 m in Great Harbor, 6.0 m during dock experiment #1, and 6.9 m during experiment #2, and 3.3 m in Oyster Pond where the total water depths were 12, 18, 18, and 6.6 meters respectively. The concentration of particulate matter at the level of the traps at the time of deployment was 8.4, 1.3, 0.8, and

3.0 mg/liter respectively at the four sites. Before the traps were retrieved, SCUBA divers placed lids on the traps except after dock experiment #2, after which traps were slowly lifted out of the water. Sediment was lost from a few small traps, and these were discarded except in two cases where minimums are noted.

4. Sample Collection and Handling

After the collection period the contents of each container were filtered onto precombusted, preweighed glass fiber filters, then dried and reweighed. All data are in dry weight and are corrected for weight losses determined by subjecting 10 blank filters to filtration of distilled water, drying, and reweighing. Corrections were also made for the weight added by particles in the supernatant water in the traps, but this added weight was seldom over 10% of the total weight. To investigate size preference of sediment traps, the detritus collected during dock experiment #2 was wet-sieved through a 63 μm sieve and sucked onto separate filters. The high organic content caused cohesion among particles and made the process somewhat subjective, but all sieving was done by one person (the writer) to reduce operator variability.

Measurements of funnel trapping efficiencies in this and the previous section included material collected on

the inner funnel walls. In laboratory conditions a large percentage of the material remains on the inner wall, but Brunskill (1969) found that only a minor portion of the sediment stayed on the walls of his funnels in lakes. An observable but unmeasured amount of sediment stayed on the walls of the large funnel in the second dock experiment. The amount sticking to the walls decreases with increasing turbulence, but increases with the organic content of particles.

F. RESULTS OF FIELD EXPERIMENTS WITH SEDIMENT TRAPS

The mass of sediment trapped per square centimeter is plotted against the H/W ratio of each trap in figures 2.8-2.11. Containers with a variable H/W ratio are plotted on the y-axis for comparison. The most notable features of the figures are:

(1) The collection rate of cylinders is proportional to the H/W ratio.

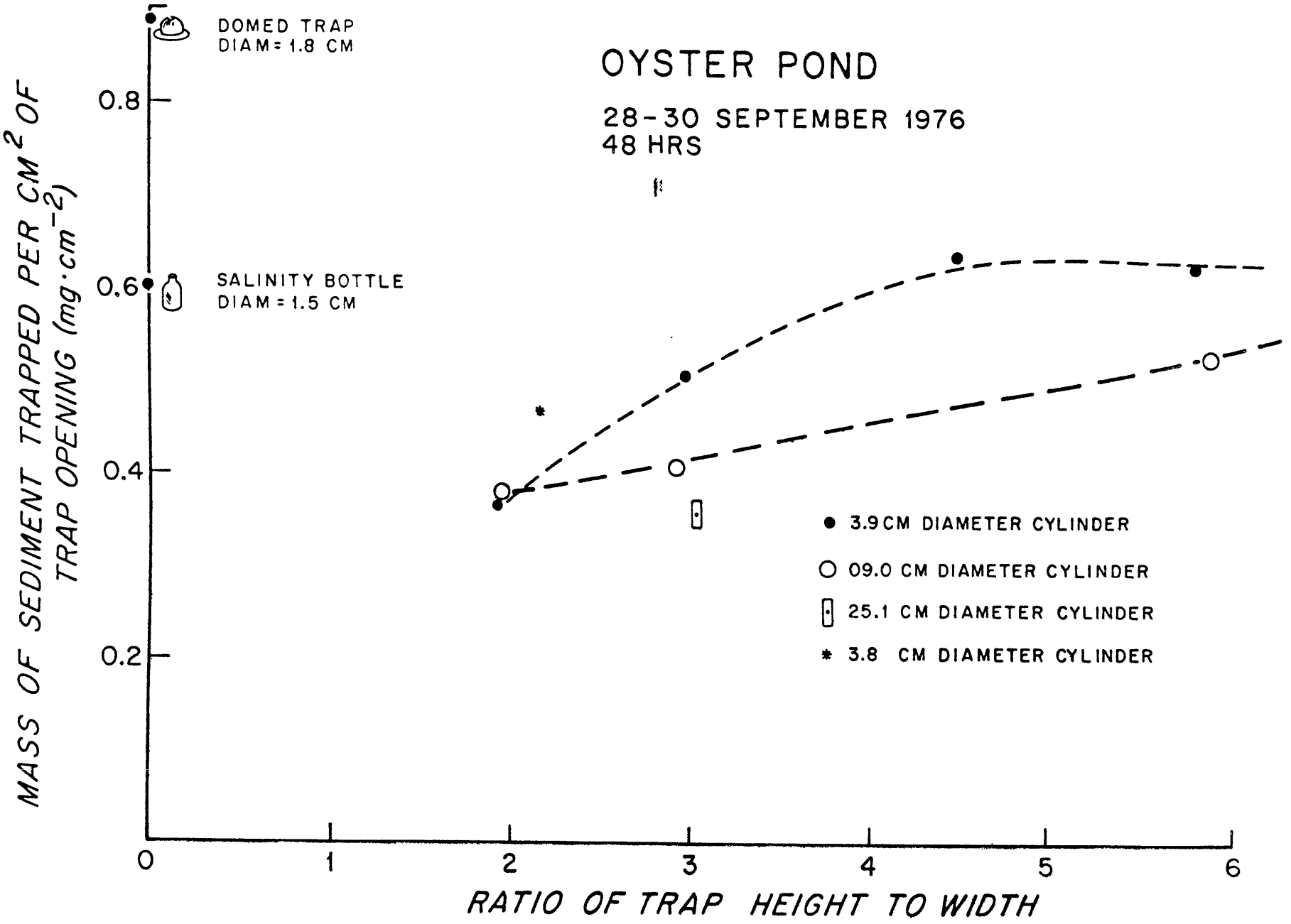
(2) The difference between collection rates of traps with high and low H/W ratios increases with current speed.

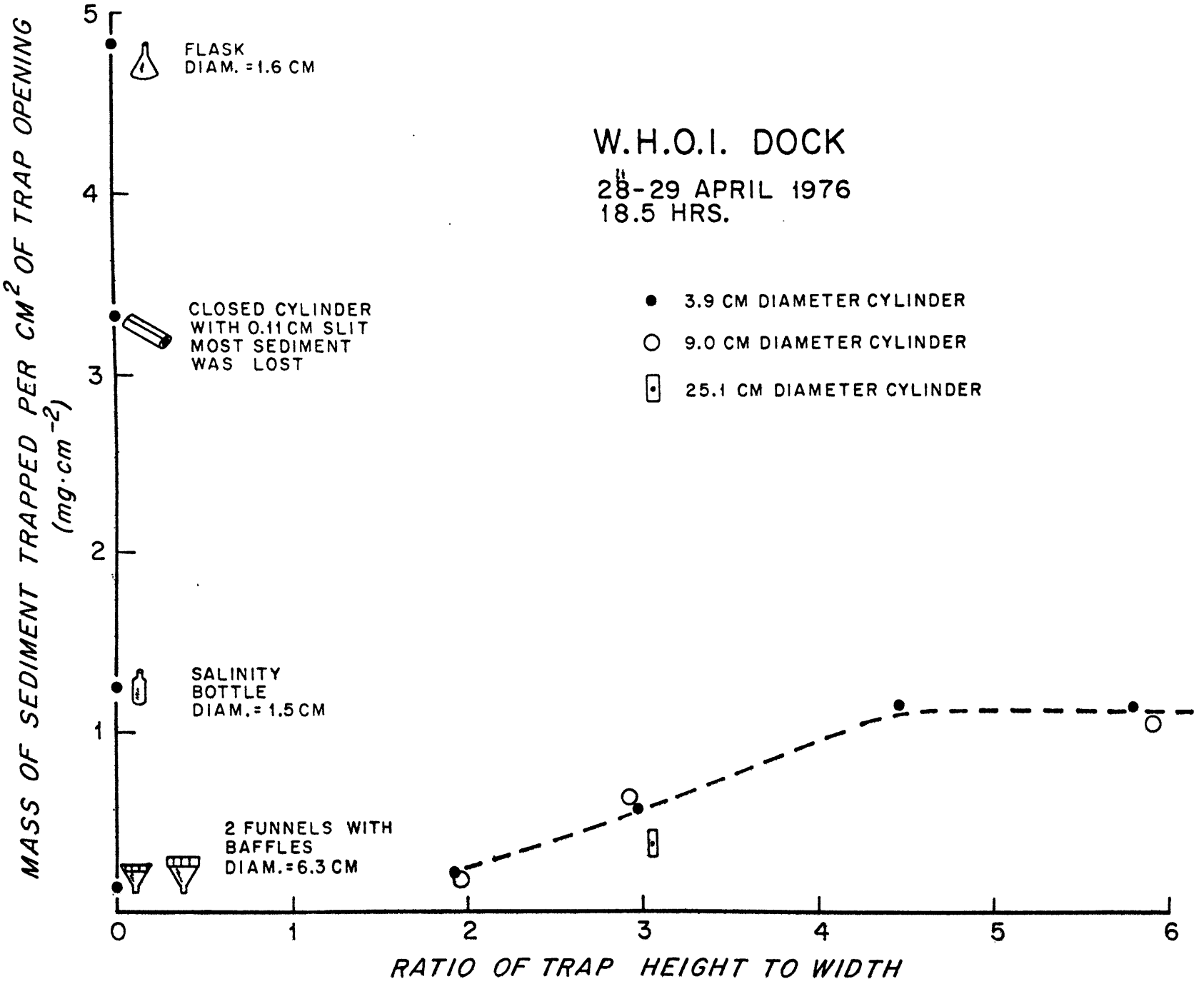
(3) Containers with small openings and large bodies collect as much as, and usually much more than, cylinders.

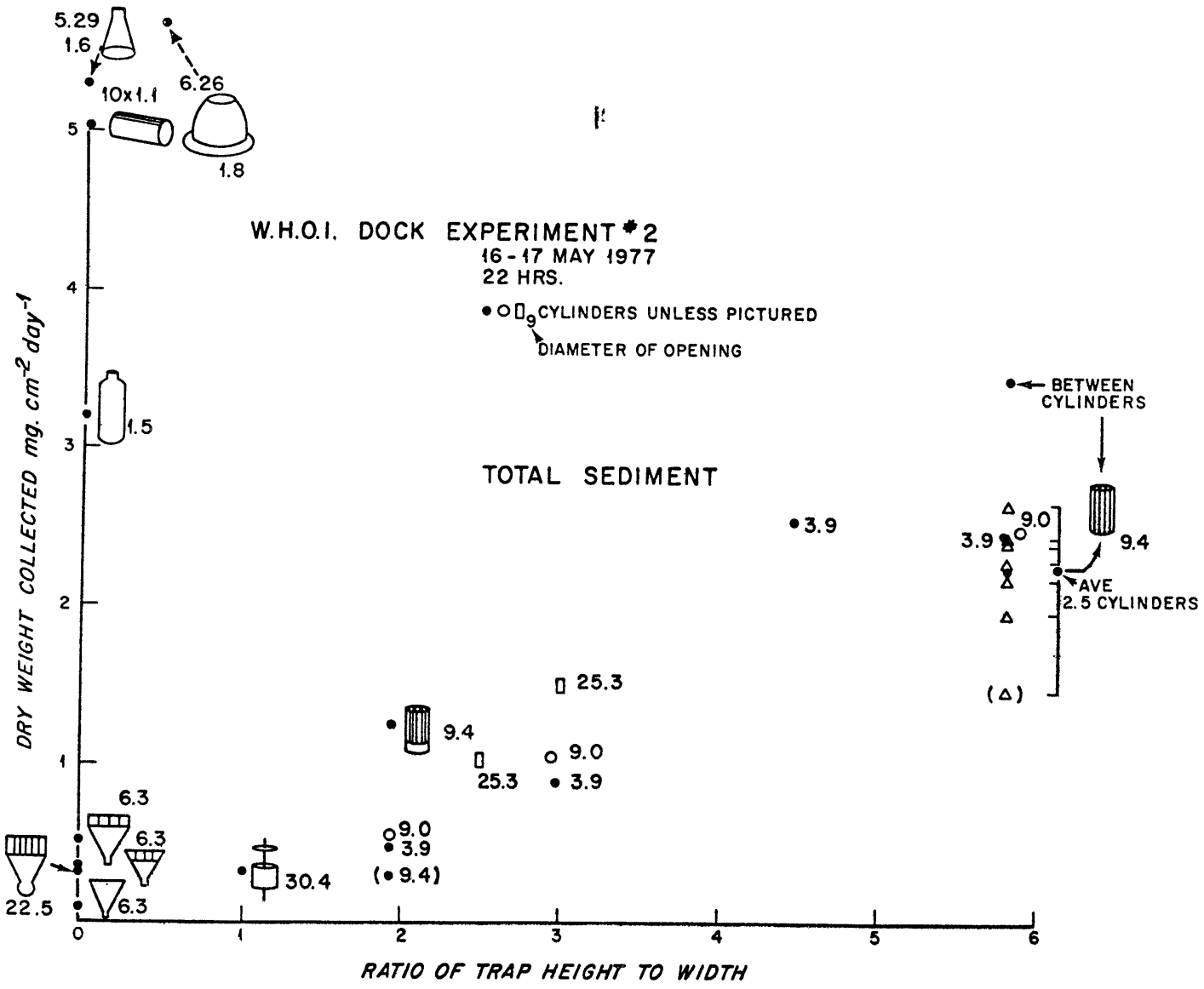
(4) Cylinders and funnels of different sizes but identical dimensional proportions will collect particles at the same rate.

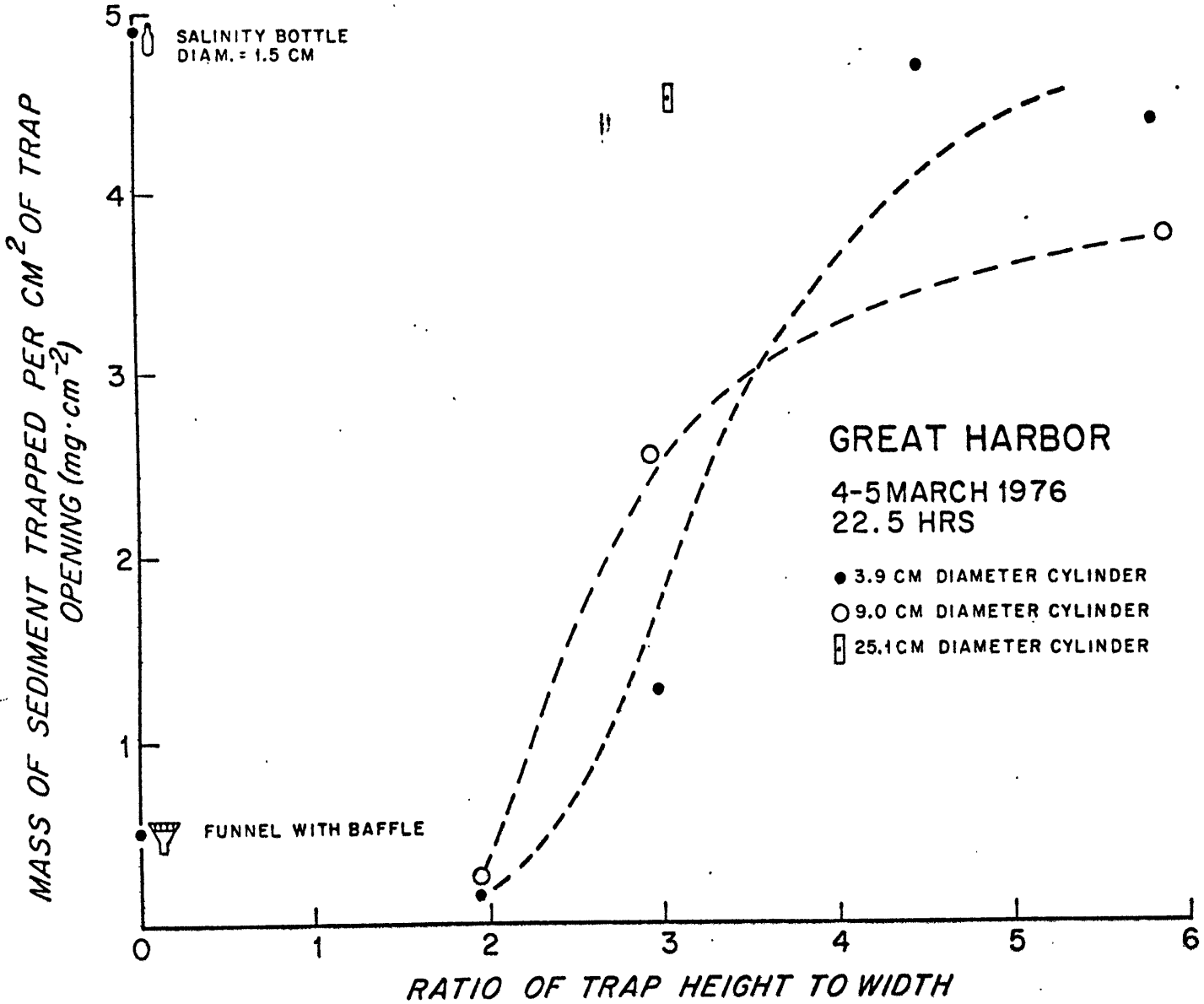
Figures 2.8 - 2.11

The mass of sediment collected per unit is shown as a function of height to width ratio for four experiments. Containers which have a variable height to width ratio are plotted along the ordinate.


OYSTER POND
28-30 SEPTEMBER 1976
48 HRS
DOMED TRAP
DIAM = 1.8 CM
SALINITY BOTTLE
DIAM = 1.5 CM
MASS OF SEDIMENT TRAPPED PER CM² OF TRAP OPENING (mg·cm⁻²)
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
RATIO OF TRAP HEIGHT TO WIDTH
3.9 CM DIAMETER CYLINDER
09.0 CM DIAMETER CYLINDER
25.1 CM DIAMETER CYLINDER
3.8 CM DIAMETER CYLINDER


W.H.O.I. DOCK
28-29 APRIL 1976
18.5 HRS.
3.9 CM DIAMETER CYLINDER
9.0 CM DIAMETER CYLINDER
25.1 CM DIAMETER CYLINDER
FLASK
DIAM. = 1.6 CM
CLOSED CYLINDER
WITH 0.11 CM SLIT
MOST SEDIMENT
WAS LOST
SALINITY
BOTTLE
DIAM. = 1.5 CM
2 FUNNELS WITH
BAFFLES
DIAM. = 6.3 CM
MASS OF SEDIMENT TRAPPED PER CM² OF TRAP OPENING
(mg·cm⁻²)
RATIO OF TRAP HEIGHT TO WIDTH
0
1
2
3
4
5
6


W.H.O.I. DOCK EXPERIMENT #2
16-17 MAY 1977
22 HRS.
CYLINDERS UNLESS PICTURED
DIAMETER OF OPENING
TOTAL SEDIMENT
BETWEEN CYLINDERS
AVE 2.5 CYLINDERS
DRY WEIGHT COLLECTED mg. cm⁻² day⁻¹
RATIO OF TRAP HEIGHT TO WIDTH
5.29
1.6
6.26
10x1.1
1.8
1.5
3.9
9.0
3.9
9.4
25.3
9.4
9.0
25.3
3.9
6.3
6.3
6.3
22.5
30.4
9.0
3.9
(9.4)
(△)
0
1
2
3
4
5
6


SALINITY BOTTLE
DIAM. = 1.5 CM
FUNNEL WITH BAFFLE
MASS OF SEDIMENT TRAPPED PER CM² OF TRAP OPENING (mg·cm⁻²)
RATIO OF TRAP HEIGHT TO WIDTH
GREAT HARBOR
4-5 MARCH 1976
22.5 HRS
● 3.9 CM DIAMETER CYLINDER
○ 9.0 CM DIAMETER CYLINDER
25.1 CM DIAMETER CYLINDER
0
1
2
3
4
5
6

(5) The dock and pond results suggest that the increase in trapping levels off when the H/W ratio reaches four or five, but the leveling-off point may be higher for larger-diameter cylinders.

These results agree with the experiments in the flume and fish tank, where flasks, domes, and narrow-necked bottles trapped more material per unit opening than cylinders and several times more than the rate of deposition in the flume or tank. One cause for this was discussed earlier in this chapter and involved particle-deficient water rising from the container and being replaced by particle-rich water due to density differences (figure 2.5).

A similar phenomenon of exchange between particle-deficient and particle-rich fluid can occur in flowing water with any particle concentration as long as a container has pockets of stagnant water where the residence time of water in the stagnant pocket is longer than the settling time of particles in the water pocket. The depth to which eddies penetrate a cylinder is a function of a Reynolds number whose length scale is the diameter of the cylinder. Therefore, the taller the cylinder, the larger the volume of stagnant water at the bottom, where particles can settle out before being replaced by new particle-rich

water. This suggests there should be no upper limit on the increase in the trapping rate as a function of H/W ratio, although there is some indication of leveling off when the ratio reaches four or five for the 3.9 cm cylinders.

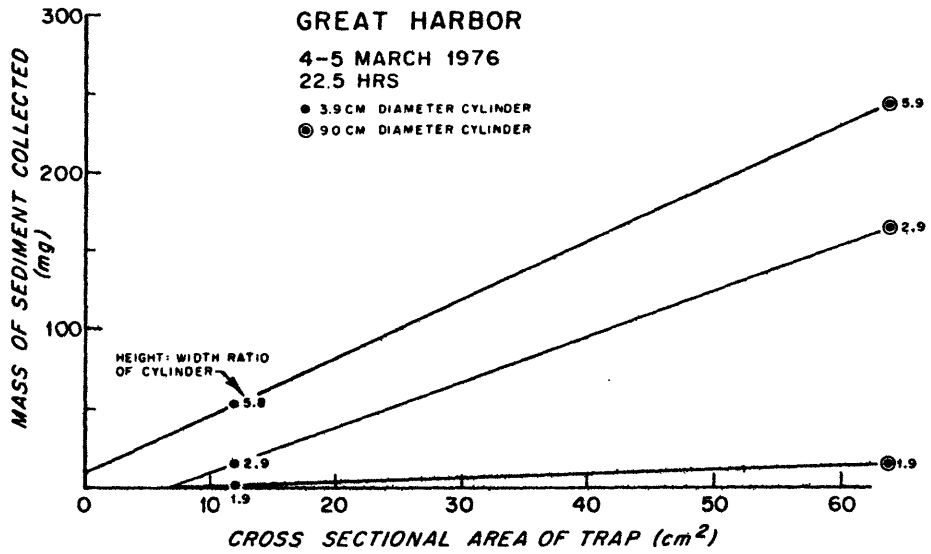
1. Influence of H/W Ratio

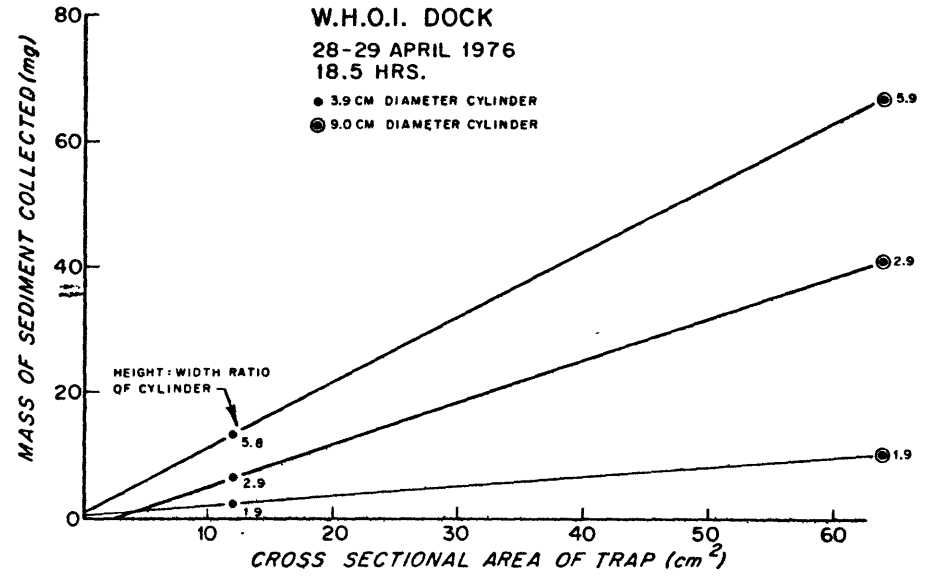
To show that traps were collecting particles at a rate equivalent to the downward flux, Davis (1967) plotted the dry weight collected as a function of trap area. The data points for any given collection period formed a line passing through the origin. She logically assumed this verified the accurate collecting ability of traps. It is possible that her traps were indeed accurate; however, it is also possible to use cylinders of different diameters and identical H/W ratios and obtain a different linear relationship for each group of traps with the same H/W ratio as shown in figures 2.12 and 2.13.

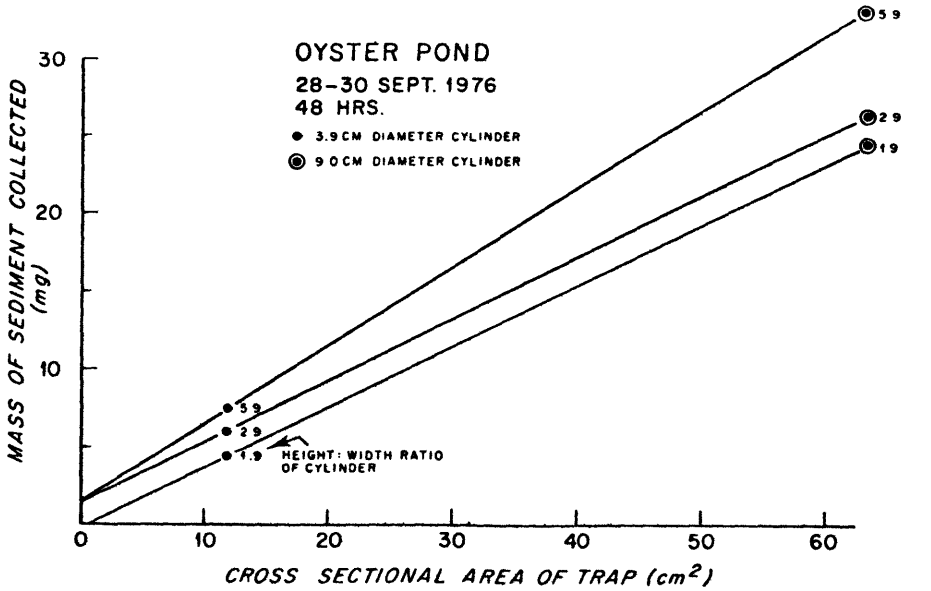
Furthermore, when the collection rate of cylinders with a H/W ratio of 5.9 is divided by the collection rate of cylinders with a H/W ratio of 1.9, the resulting ratio is directly proportional to the current velocity regime; the ratio being 1.3 in Oyster Pond, 4.4 for dock #1, 6.4 for dock #2, and 15.1 for Great Harbor. From the calibration experiments in the flume it was determined that at velocities less than 10 cm/sec cylinders with a

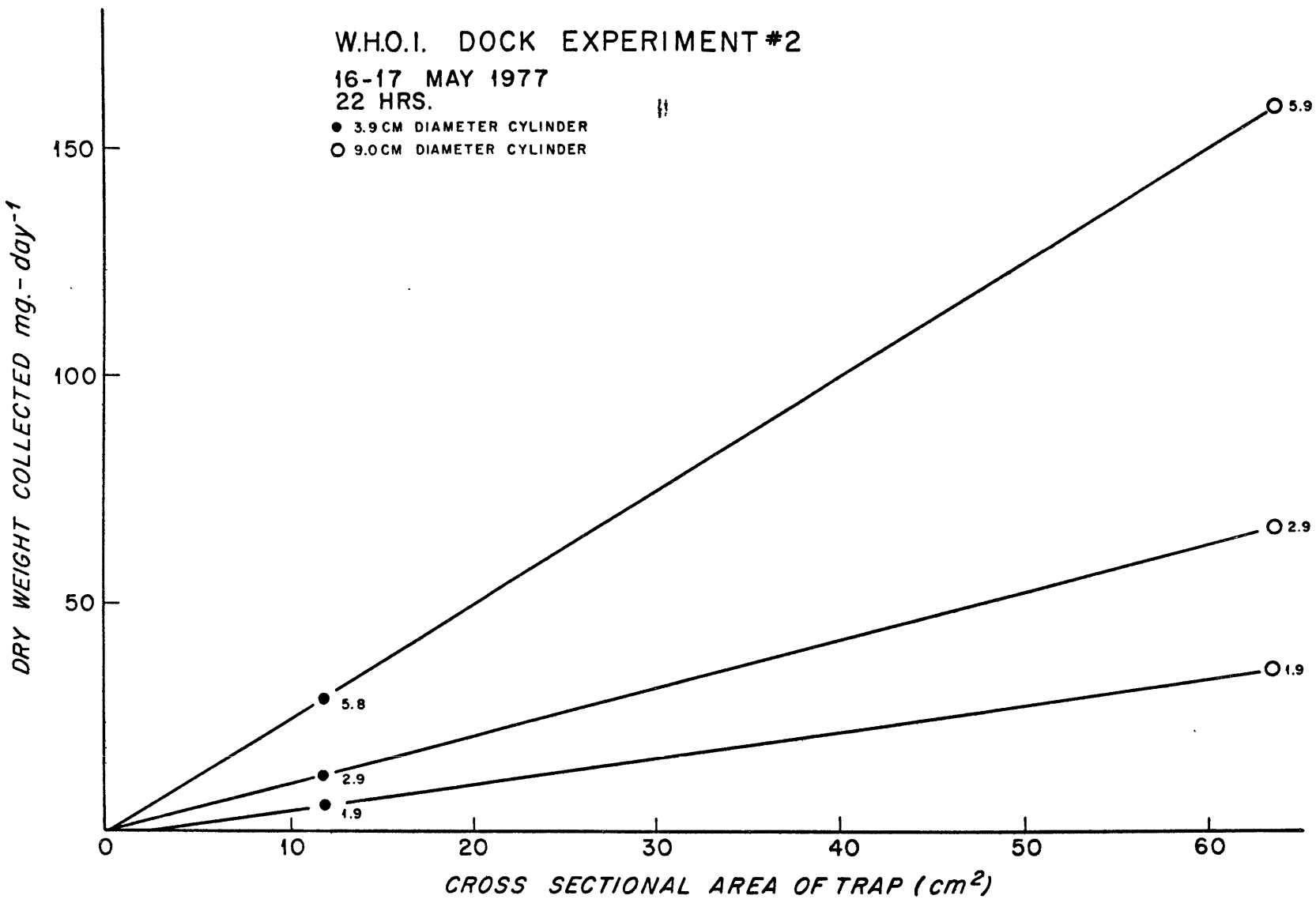
Figure 2.12 and 2.13

Mass of sediment collected in cylinders of different diameters and heights at three locations. Oyster Pond was tranquil, the dock had maximum flows of 21 cm/sec; and the harbor may have tidal currents as high as 50 cm/sec.


GREAT HARBOR
4-5 MARCH 1976
22.5 HRS
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
300
200
100
0
HEIGHT: WIDTH RATIO OF CYLINDER
5.9
2.9
1.9
5.8
2.9
1.9
10
20
30
40
50
60
CROSS SECTIONAL AREA OF TRAP (cm²)


W.H.O.I. DOCK
28-29 APRIL 1976
18.5 HRS.
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
80
60
40
20
0
HEIGHT: WIDTH RATIO OF CYLINDER
5.9
2.9
1.9
5.8
2.9
1.9
10
20
30
40
50
60
CROSS SECTIONAL AREA OF TRAP (cm²)


OYSTER POND
28-30 SEPT. 1976
48 HRS.
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
30
20
10
0
5.9
2.9
1.9
5.9
2.9
1.9
HEIGHT: WIDTH RATIO OF CYLINDER
10
20
30
40
50
60
CROSS SECTIONAL AREA OF TRAP (cm²)


W.H.O.I. DOCK EXPERIMENT #2
16-17 MAY 1977
22 HRS.
● 3.9 CM DIAMETER CYLINDER
○ 9.0 CM DIAMETER CYLINDER
DRY WEIGHT COLLECTED mg.-day⁻¹
150
100
50
0
10
20
30
40
50
60
CROSS SECTIONAL AREA OF TRAP (cm²)
5.9
2.9
1.9
5.8
2.9
1.9

H/W ratio of about two collected particles at a rate equivalent to the downward flux. The current was always below that speed in Oyster Pond, and at the dock the velocity was often below that speed, so it is hypothesized that in these experiments the containers which have sedimentation rates close to that of cylinders with a H/W ratio of about two collect particles at a rate equivalent to the downward flux. More experimentation is needed in controlled conditions above 10 cm/sec to calibrate collection rates of containers.

2. Effect of Baffles on Collection Rate of Traps

As seen in figure 2.10, a baffle on the top of a funnel increases the amount collected as in the flume studies discussed earlier. The width and depth of the neck at the funnel bottom may also affect the collection rate because it is below the level of penetration of eddies and is therefore the only area of a funnel where stagnant water exists; the volume of stagnant water in cylinders appeared to control the mass of particles collected. W. T. Edmondson (personal cummunication, 1977) made numerous collections with a long and short neck on the bottom of two inverted, one-gallon polyethylene bottles from which the bottoms were removed and found no consistent differences in collection rates; probably

because the neck volume is small compared to the volume of the bottle below the penetration depth of eddies. A similar experiment with funnels should show a positive correlation in collection rate with neck size.

The 6.3 cm diameter funnels tested in the flume and field nearly always trapped less per unit area than cylinders in moving water, but trapped about the same as cylinders in still water.

The effect of baffles on the trapping efficiency of a cylinder depends on the baffle depth within the cylinder. In figure 2.9 the 25.1 cm cylinder actually represents two overlapping points. One cylinder had no baffle and the other had a baffle with 4 cm squares 8 cm deep. The collections were identical in weight. In dock experiment #2 the two 9.4 cm cylinders with H/W ratio of two differed by a factor of four in their collected weight. The unbaffled cylinder lost some sediment, but the 9.0 cm cylinder with H/W ratio of two still caught less than half as much as the 9.4 cm cylinder with baffles to within one inch of the bottom (design after Soutar et al., 1977). When the baffles extended to the cylinder base (i.e. formed "closed" cells), the collection rate doubled again. These points were plotted with the H/W ratio of the inner cylinders. The space between the cylinders had a larger

H/W ratio (∿15) than the cylinders, and, not surprisingly, caught sediment at a higher rate.

3. Influence of Trap Geometry on Size of Particles Collected

When the collection rates of particles greater and less than 63 μm is plotted against H/W ratio (figures 2.14 and 2.15), the same general trends appear to dominate as with the plot of total sediment. However the plot of the ratio of sediment >63 μm versus <63 μm (figure 2.16) shows that the particles trapped in most of the containers is reasonably similar. A larger percentage of coarse-grained material was collected in the short traps with a diameter of 4.0 cm than in the tall traps with the same diameters. A variable but nearly opposite trend was found for the 3.9 cm cylinders. The deeply baffled traps tended to collect a greater percentage of fines than did open cylinders. Containers that collect sediment at rapid rates, notably those with small openings and large bodies, tend to collect more fine material than other containers, reinforcing the idea that the long residence time in traps allows more particles, especially the fines, to settle out. Conversely, the rapid fluid exchange in the funnel with no baffles allowed much less fine detritus to be retained, as is indicated by the high ratio.

G. EVALUATION OF SEDIMENT TRAPS

1. Summary of Trap Collection Rates

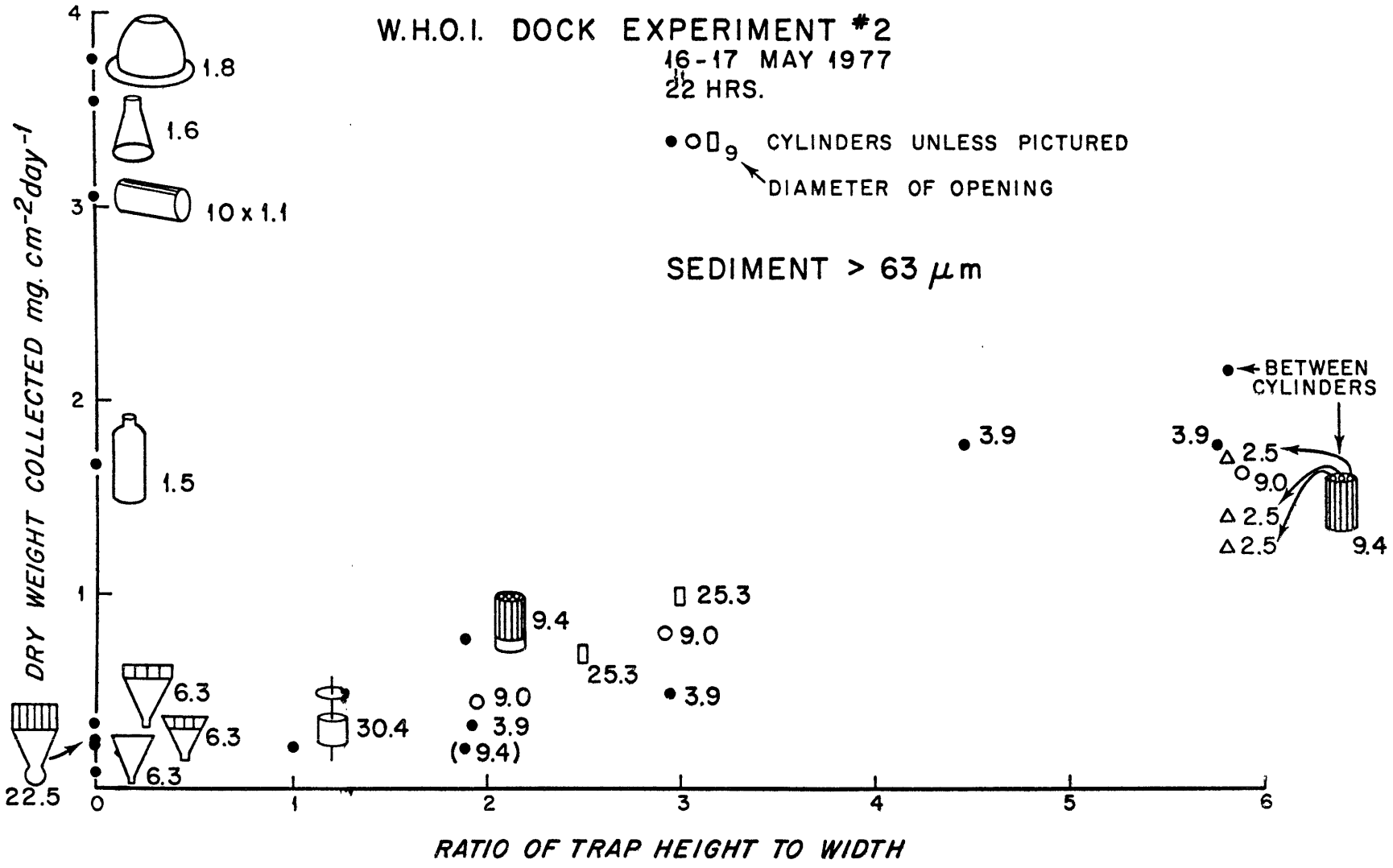
In flows with velocities below 10 cm/sec, the sedimentation rate measured with cylinders with H/W ratios of 1:1 to 2.3:1 corresponded closely to deposition rates calculated for the flume under controlled conditions and did not show a strong dependence on velocity. In Oyster Pond (quiescent conditions), larger-diameter cylinders with H/W ratios of 2:1 and 3:1 caught particles at the same ratio as the small cylinder calibrated in the flume, and taller traps collected at only slightly higher rates. At higher velocities (up to 20 cm sec^{-1} at the dock and even higher in Great Harbor) the taller cylinders collected several times more than the low-ratio cylinders, and in some cases they collected particles as rapidly as the narrow-necked containers, which were shown to overtrap. Small-mouthed, large-bodied traps consistently overtrapped fine particles.

If properly baffled, funnels can be designed so that collection rate equals deposition rate. However, more data are needed on the effect of velocity on the collection rate and degree of particle retention on the inner walls.

Conditions at higher velocities are more complicated and require further study. For instance, in currents of

Figures 2.14 and 2.15

The dry weight of particles >63 μm and <63 μm are plotted against the H/W ratio of the traps from the second dock experiment. Data from traps without easily definable H/W ratios are plotted on the ordinate axis. Data points are from cylinders unless otherwise pictured. Data from the 9.4 cm cylinder are in parentheses because some sample may have been washed out during recovery.


W.H.O.I. DOCK EXPERIMENT #2
16-17 MAY 1977
22 HRS.
CYLINDERS UNLESS PICTURED
DIAMETER OF OPENING
SEDIMENT > 63 μm
BETWEEN CYLINDERS
DRY WEIGHT COLLECTED mg. cm-2day-1
RATIO OF TRAP HEIGHT TO WIDTH
1.8
1.6
10 x 1.1
1.5
6.3
6.3
6.3
22.5
30.4
9.4
9.0
3.9
(9.4)
25.3
25.3
9.0
3.9
3.9
2.5
9.0
2.5
2.5
9.4
0
1
2
3
4
5
6

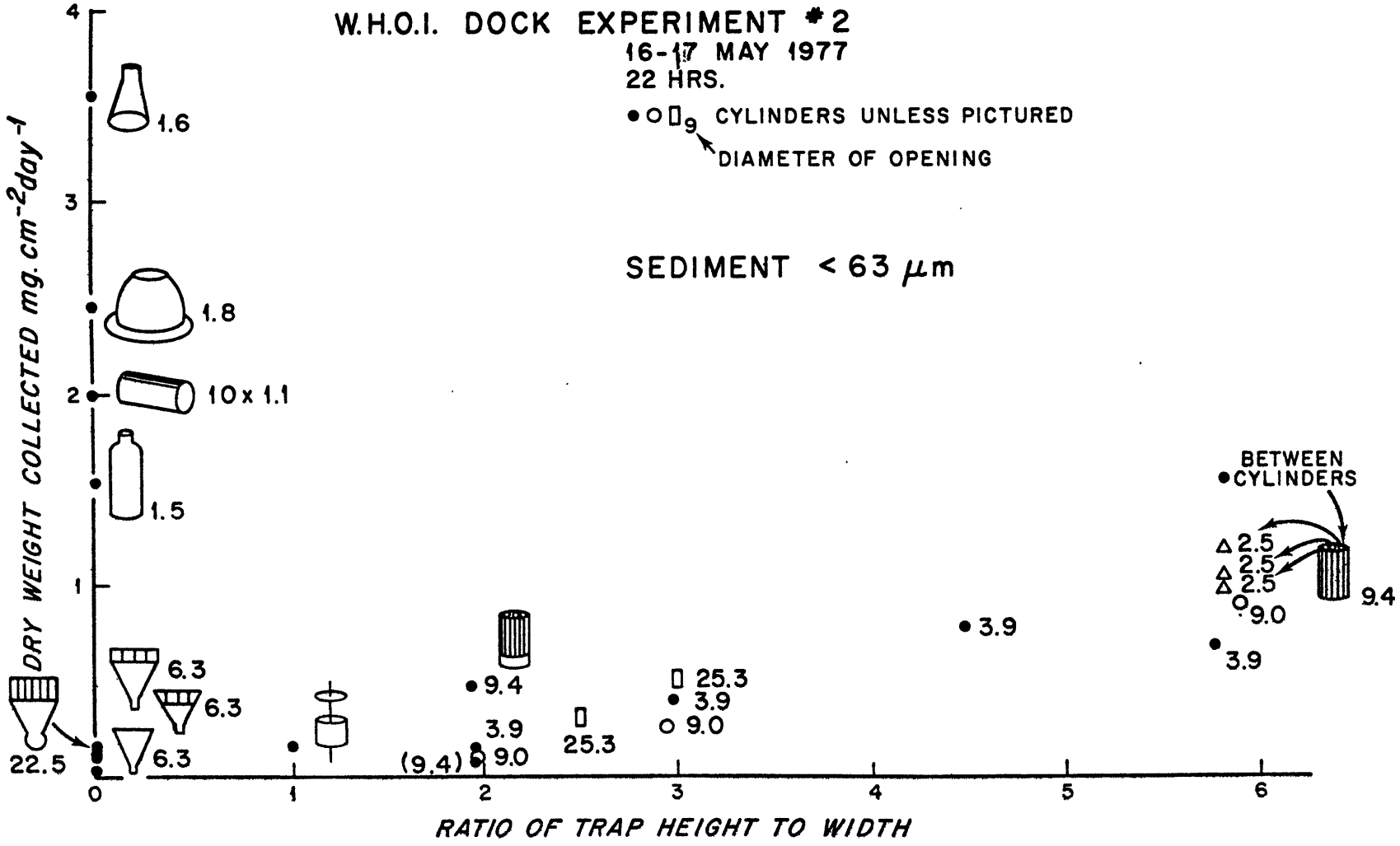
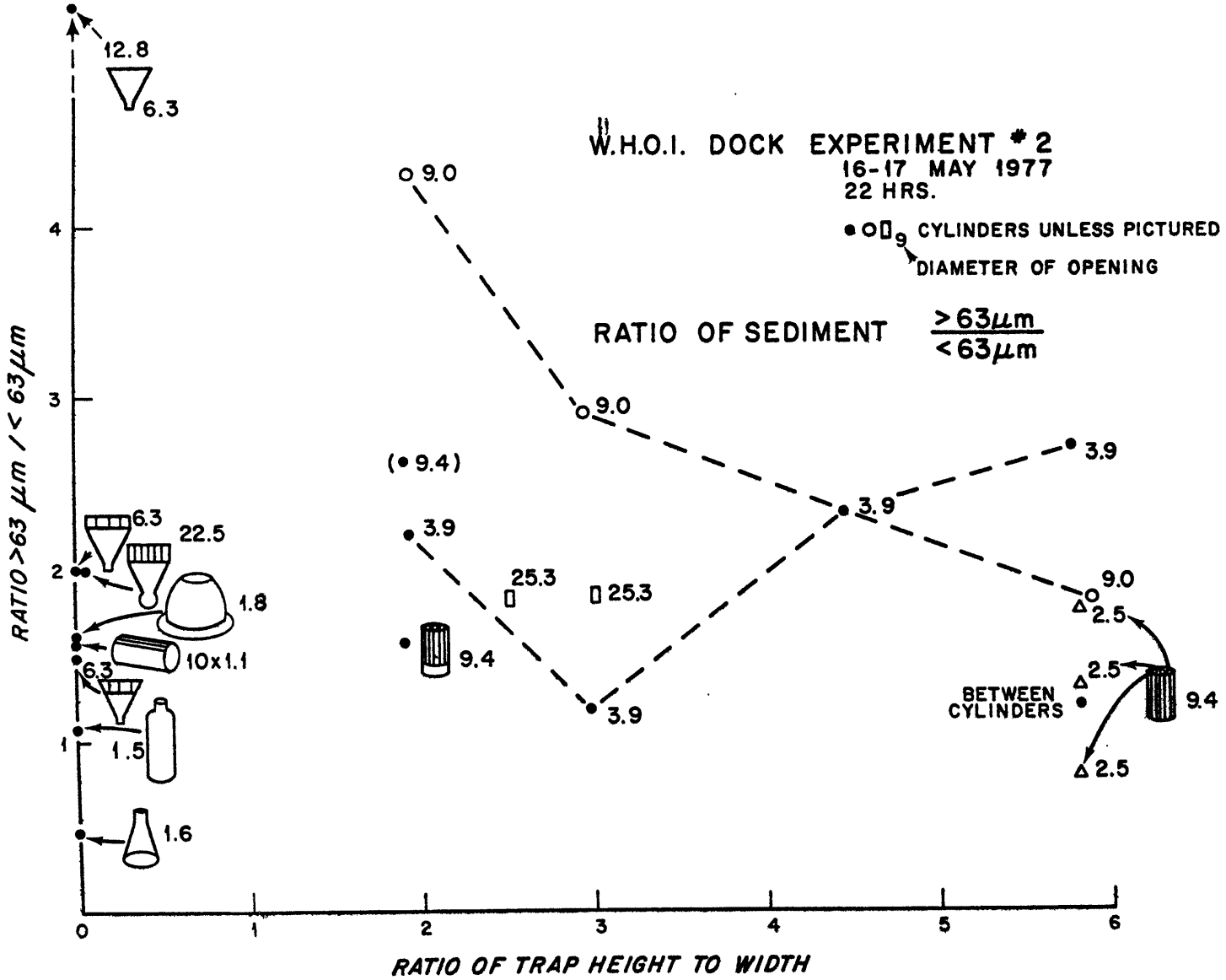

W.H.O.I. DOCK EXPERIMENT #2
16-17 MAY 1977
22 HRS.
● ○ □9 CYLINDERS UNLESS PICTURED
DIAMETER OF OPENING
SEDIMENT < 63 μm
DRY WEIGHT COLLECTED mg.cm-2day-1
RATIO OF TRAP HEIGHT TO WIDTH
1.6
1.8
10 x 1.1
1.5
6.3
6.3
6.3
22.5
9.4
3.9
9.0
(9.4)
25.3
25.3
3.9
9.0
3.9
BETWEEN CYLINDERS
△2.5
△2.5
△2.5
○9.0
9.4
3.9
0
1
2
3
4
5
6

Figure 2.16 The ratio of the weight of particles >63 μm to the weight of those <63 μm is plotted against the H/W ratio in the second dock experiment. Data points explained in caption of figures 2.14 and 2.15 and discussed in text.


W.H.O.I. DOCK EXPERIMENT # 2
16-17 MAY 1977
22 HRS.
CYLINDERS UNLESS PICTURED
DIAMETER OF OPENING
RATIO OF SEDIMENT >63μm / <63μm
RATIO >63 μm / < 63μm
RATIO OF TRAP HEIGHT TO WIDTH
12.8
6.3
22.5
1.8
10x1.1
1.5
1.6
9.0
9.0
(9.4)
3.9
3.9
3.9
25.3
25.3
9.4
3.9
9.0
2.5
2.5
BETWEEN CYLINDERS
9.4
2.5
0
1
2
3
4
5
6

about 50 cm/sec a vertical vortex circulation is set up in the bottom of tall cylinders in addition to the horizontal eddies at the top (von Brockel, personal communication). The vortex action may lift particles up and out of the trap after they have been deposited during weaker currents. Small and low-density particles would be preferentially winnowed out.

Short cylinders (H/W <1.5) are easily scoured by eddies unless they are large compared to the size of eddy produced in the trap. For instance, the collection rate of a 30 cm cylinder with H/W = 1.0 appeared reasonable (figure 2.10), whereas small 5-10 cm cylinders with the same H/W ratio were swept clean and the data were not plotted.

2. Determination of Optimum Trap

What, then, is the "ideal" trap? The answer to this question depends on what sort of sample is desired. It must be understood that the process of particle trapping is complex. It appears to be nearly coincidental rather than predictable that a container collects an amount of sediment equal to the actual flux. In reality, traps at best collect only a mass of particles equivalent to the downward flux at that level; not all the particles contributing to the downward flux which entered the trap

remain there, and it is possible that some particles which do not contribute significantly to the downward flux do remain inside the trap. This is an important point to realize when using sediment traps.

More experimentation is needed to determine whether the particles collected are representative of the following particles in terms of morphology and composition and not just equivalent in mass. The best approach for answering this question appears to be to compare the collection of particles in a moored trap in the open ocean with particles collected in a trap attached to a neutrally buoyant float. Although one is a Eularian measurement and the other Lagrangian, the neutrally buoyant trap provides the closest possible approximation to a still-water collection where differentiation of particles by size or density is less likely. If particles collected by moored traps are representative of the particles responsible for most of the vertical flux, then chemical and physical analyses of the collected particles will improve our understanding of many processes in aquatic systems.

CHAPTER III

INCOMPLETE EXTRACTION OF PARTICLES FROM WATER SAMPLERS

A. INTRODUCTION

At the sites where sediment traps were deployed, water samples from many levels in the water column were filtered to obtain suspended particulate matter. Filtration of sea water to obtain particulates is a routine analysis, but recently Bishop and Edmond (1976) compared the particulate mass filtered from 30-liter Niskin bottles and a Large Volume Filtration System (filtering tens of thousands of liters of water *in situ*) and found that particles larger than $\simeq$ 53 μm (pore size of the prefilter in their pumping system) are inadequately sampled in 30-liter Niskin bottles. Similarly, Menzel (1974) doubted the ability of present standard sampling methods to capture large particles, which, though relatively rare, may dominate the flux of matter through the water column (McCave, 1975). Considering the difference reported in the collection of large particles between standard water samplers and the *in situ* filtration system, an examination of possible bias introduced by standard sampling methodology seemed to be in order and will be described in this chapter.

The sampling spigots on Niskin bottles are generally 3 to 4 cm above the bottom of the bottle, and thus their location could prevent the extraction of particles that settle below this level. The sinking rate of many particles would allow them to fall below the sampling spigots in the time required for filtration. Within three hours (a typical time interval between sampling and filtration) particles as small as 23 μm (ρ = 1.5 g/cm^3) could settle the 90 cm length of a 30-liter Niskin bottle containing 5°C water if they fell according to Stokes' law. Larger particles, such as fecal pellets, sink at 0.04-0.44 cm/sec (Smayda, 1969) and would fall the length of a 30-liter Niskin bottle in 4-40 minutes. Draining a 30-liter Niskin bottle from the bottom in three hours lowers the water above the spigots at 0.083 cm/sec, which is equivalent to the sinking rate of a 20 μm particle. This can help move smaller particles to the bottom of the bottle where they can fall below the spigot before being extracted.

Particles enclosed in water bottles can be missed in the following three ways. (1) Leakage: If the bottom closure of a sampling bottle leaks water during retrieval, particles that have fallen to the bottom during ascent of the bottle will be lost. (2) Incomplete sampling: When

water is filtered from 30-liter Niskin bottles through spigots located above the bottom of the bottle, between 0.3 and 1.0 liter of water remains in the bottle. Due to rapid settling of large particles the residual water would be enriched in larger particles. Thus, filtering only part of the entire volume could miss the larger particles. The motion of the ship is insufficient to keep all particles in suspension, particularly when the bottle is full. (3) Inadequate filtration configuration: Pressure and vacuum filtration configurations which include transfer of unfiltered water increase the chances of shipboard contamination or particle loss due to rapid settling. Biased measurements are more likely if subsamples are taken from unmixed parent samples and if a sample or subsample is not filtered completely. The longer a sample is allowed to stand, the greater the chance of biased sampling. If the filtration apparatus requires the water to travel upward through tubes, gravity may inhibit large particles from moving with the fluid when the flow rate is low (velocity in tubes <1 cm/sec).

This chapter describes an attempt to quantify the loss and identify the components that may be missed during routine shipboard sampling of 30-liter Niskin bottles. The results are applicable to other water samplers with similar construction.

B. NISKIN BOTTLE SAMPLING

A total of 42 Niskin bottles (mostly 30-liter) have been sampled in this study (Table 3.1) in the North and western North Atlantic Ocean in areas of high and low surface productivity. Bottles from throughout the water column have been sampled, but most are from the bottom 500 meters.

Within minutes of the time the bottles were on board (10-60 minutes from tripping time of bottles) 250 ml samples were drawn for size analysis by a model TAII Coulter counter, salinity, and from three bottles, oxygen and silicate analyses. The remaining water (25-27 liters) was filtered directly through 47 mm 0.6 μm Nuclepore filters into evacuated glass bottles. When the filter for the surface bottle became clogged, the spigots were opened and the water above the spigots was rapidly drained from the bottle. The water trapped below the spigots was shaken up and poured out by lifting the bottle to the near horizontal. The portion of the water below the spigots will be referred to as the "dregs."

The particles in the dregs of the near-bottom bottle at KN 55-3, Sta. 716 and surface bottle at KN 51-3, Sta. 701 were analyzed for size distribution and volumetric concentration with the Coulter counter. The dregs from each

TABLE 3.1

Sample depth (m)	Meters above bottom	Bottle size (liters)	Water above spigots: Mass (mg)	Water above spigots: Volume filtered (liters)	Water above spigots: Concn. (µg liter^{-1})	Water below spigots: Mass in dregs (mg)	Water below spigots: Volume of dregs (liters)	Water below spigots: Dregs Concn. (µg liter^{-1})	Corrected concn. (µg liter^{-1})	Corr. Concn: uncorr. concn.
KN51-4, Sta. 716 51°41.5'N 36°05.5'W 10/1/75										
0	3,616	27	.40	4.2	95.2	.87	.48	1,813	125.7	1.32
KN51-3, Sta. 701 56°12.2'N 12°36.8'W 8/30/75										
1008	1,615	27	.31	26.2	11.8	.14	.77	182	16.7	1.41
2208	415	27	.22	25.7	8.6	.19	.78	244	15.4	1.79
2508	115	27	.36	26.9	13.4	.09	.50	180	16.5	1.23
2578	45	27	.75	25.8	29.1	.08	1.00	80	31.0	1.06
2596	27	27	.84	25.0	33.6	.09	.60	150	36.2	1.08
OC6, Sta. 704 38°49.4'N 72°30.0'W 5/11/76										
pretrip		5	.104	4.0	26.0	.087	.285	305	41.9	1.61
"		27	.320	8.8	36.4	.471	.925	509	52.6	1.44
"		27	.379	15.0	25.3	1.001	.980	1,021	61.5	2.43
" *		27	.323	7.5	43.1	.194	.685	283	49.2	1.14
OC6, Sta. 710 38°33.8'N 72°12.0'W 5/12/76										
2344	372	5	.052	4.0	13.0	.271	.7	387	65.4	5.03
pretrip		27	.059	9.8	6.0	.175	.750	233	12.3	2.05
"		27	.105	10.6	9.9	.432	.680	635	25.7	2.59
" *		27	.108	12.4	3.1	.069	.570	121	5.6	1.80
OC6, Sta. 715 38°26.7'N 72°03.2'W 5/13/76										
2419	398	5	.096	4.0	24.0	.097	.460	211	41.2	1.72
2777	40	27	.129	18.1	7.1	.182	.820	222	13.6	1.92
2787 *	30	27	.196	17.5	11.2	.154	.925	166	16.5	1.48
OC6, Sta. 718 36°34.2'N 69°41.2'W 5/14/76										
4427	58	27.2	.651	6.2	105.0	.680	.930	731	126.5	1.21
4457 *	28	27	.542	5.5	98.6	.302	.770	392	107.0	1.08
4462	23	27.6	.465	5.0	93.0	.648	.480	1,350	114.9	1.24
OC6, Sta. 721 38°17.6'N 69°36.0'W 5/15/76										
3150	501	27	.226	13.1	17.3	.151	.675	224	22.5	1.30
3550	101	27	.370	6.8	54.4	.406	1.04	390	67.3	1.24
3627 *	24	27	.566	8.8	64.3	.506	.75	675	81.3	1.26
OC6, Sta. 727 36°39.3'N 68°28.9'W 5/16/76										
4339	491	27	.282	15.1	18.7	.106	.550	193	22.2	1.19
4741	99	27	.929	13.0	71.5	.418	.510	820	85.6	1.20
4816 *	24	27	1.489	15.3	97.3	.321	.600	535	107.0	1.10

TABLE 3.1 Cont.

Sample depth (m)	Meters above bottom	Bottle size (liters)	Water above spigots: Mass (mg)	Volume filtered (liters)	Concn. (μg liter^{-1})	Water below spigots: Mass in dregs (mg)	Volume of dregs (liters)	Dregs Concn. (μg liter^{-1})	Corrected concn. (μg liter^{-1})	Corr. Concn: uncorr. concn.
OC6, Sta. 730 35°12.5'N 67°24.0'W 5/17/76										
4704	490	27	.387	26.0	14.9	.247	.925	267	23.5	1.58
5094	100	27	1.463	22.1	66.2	.717	1.08	664	90.1	1.36
5174 *	20	27	1.899	21.3	89.2	.433	.875	495	102.4	1.15
OC6, Sta. 734 34°36.8'N 68°08.3'W 5/17/76										
4747	500	27	.250	21.8	11.5	.222	.660	333	19.4	1.69
5147	100	27	1.337	17.1	78.2	.567	.750	756	97.0	1.24
5227	20	27	1.208	15.7	76.9	.976	1.00	976	110.2	1.43
OC6, Sta. 738 33°30.8'N 70°29.1'W 5/18/76										
4888	500	27.9	.248	27.1	9.2	.218	.800	287	16.8	1.82
5288	100	27	.464	20.5	22.6	.765	.750	1,020	50.3	2.23
5368 *	20	27	.737	19.7	37.4	.308	.760	385	47.8	1.28
OC6, Sta. 743 37°41.0'N 70°01.0'W 5/20/76										
3600	500	27	.369	17.5	21.1	.459	4.8	95.6	34.4	1.63
4000	100	27	.624	5.7	109.5	1.429	.975	146.6	158.5	1.45
4080 *	20	27	2.137	16.9	126.5	.877	.930	943	154.6	1.22
OC6, Sta. 750 39°45.9'N 70°35.9'W 5/21/76										
1100	500	27.5	.423	26.6	15.9	.322	.870	370	27.1	1.70
Subsig-II, Sta. 1 39°49.1'N 70°39.9'W 6/8/76										
874	40	27.6	.273	9.3	29.4	1.080	3.3	327	65.0	2.21
Dallas, Sta. 58 38°53'N 72°27'W 6/30/76										
18	2,168	8	.24	1.6	150.0	.29	.45	644	177.8	1.19
18	2,168	8	.30	2.0	150.0	.20	.5	400	165.6	1.10
1174	1,012	8	.27	2.5	108.0	.22	.5	440	128.8	1.19

bottle were filtered onto 0.6 μm Nuclepore filters. All filters were washed ten times with distilled, de-ionized water, individually sealed in petri dishes, and returned to the laboratory where they were weighed to the nearest 0.01 mg. Blank filters were similarly processed to correct for any changes in filter weight. The weighing errors involved in the procedure were estimated to be less than 5% as determined by replicate sampling of homogeneous water samples.

To identify the large particles lost during routine sampling, the scanning electron microscope and light microscope were used to compare the material filtered from above the spigots with the particles below the spigots by looking at sections of the filters from samples taken at KN 51-4, Sta. 716 at 27 m, 415 m and 1,615 m above the bottom (water depth = 2,623 m) and from the filtered surface sample at KN 51-3, Sta. 701.

Bulk chemical analysis was performed using instrumental neutron activation (Spencer et al., 1972, 1977) to check for differentiation between particles above and below the spigots. Samples analyzed were from Oc 6, Sta. 721 and Sta. 738, with preparation techniques described in Chapter 5.6, to obtain concentrations of Ca, Al, Mg, Mn, Ti, V, Ba, Sr, Cu, and I.

C. RESULTS OF ANALYSES

1. Filtration

The concentration of particulates in the dregs was from 2.8 to 64 times greater than in the water from above the spigots (Table 3.1). When the mass of dregs was integrated with the mass in the rest of the water filtered, the recalculated concentration for 30-liter bottles (37 samples) was increased by a factor of 1.06 to 2.59 with a mean of 1.50 (δ-0.39). Three 8-liter and three 5-liter bottles had similar increases except for one 5-liter bottle whose concentration increased by 5.03 times. More samples are needed to see if the concentration increase is affected by bottle size. All dregs samples caused an increase in particulate concentration.

Frequently only a few liters of water were filtered from a bottle and the remainder was rapidly drained through the spigots. Some of the dregs might have been lost during rapid drainage, particularly at KN 51-4, Sta. 716 when the ship rolled 20-30° but still the dregs were nearly twenty times as concentrated as the water above the spigots.

Dividing the water column into surface (<200 m), midwater (>200 m deep and >200 m above bottom), and bottom water (<200 mab), results in mean correction factors for

30-liter Niskin bottles of 1.2 (one sample), 1.57 (σ=0.19; 9 samples) and 1.44 (σ=0.38; 14 samples), respectively. This result implies an inverse relationship between the concentration of particulates and the correction factor to be applied, as is clearly shown in figure 3.1. A probable reason is that a few rare, large particles will constitute a larger percentage of a small weight than a large weight, thus causing larger correction factors in "clean" midwater. The actual mass of dregs collected in the near-bottom water is greater than the collection in midwater (figure 3.2), even though the correction factor is small (Table 3.1).

Six 30-liter samples were from bottles which pretripped in midwater, judging from their particulate concentrations and thermometer readings. The mean correction factor for this group of bottles (1.91; σ=0.51) was much higher than for all other midwater samples (mean of 9 samples was 1.57; σ=0.19), or any other group of samples. If this higher correction value is significant, it may mean that bottles waiting to equilibrate their thermometers lose large particles even though the drift and wave action moving the wire must cause some flushing of the bottle, whereas bottles in motion on the wire (as is likely for a pretripped bottle) are constantly being flushed with new water and capture a more representative sample.

Figure 3.1 The correction factor obtained by including the dregs in the total particulate concentration measurement is inversely proportional to concentration. Symbols are for surface water (□), mid-water from 1000 m deep to 400 m above the bottom (o), bottom water less than 400 m above the bottom (·), and samples pretripped at an unknown depth (Δ). The water in several bottles was mixed by turning the bottle upside down midway through filtration and 5-7 liters was withdrawn. Filtration was continued and the dregs withdrawn as usual, but the correction factors for these bottles was less than for other bottles in the same region. Bottles sampled in this way have the symbol (*) for the bottom 400 m, and (◇) for pretripped samples.

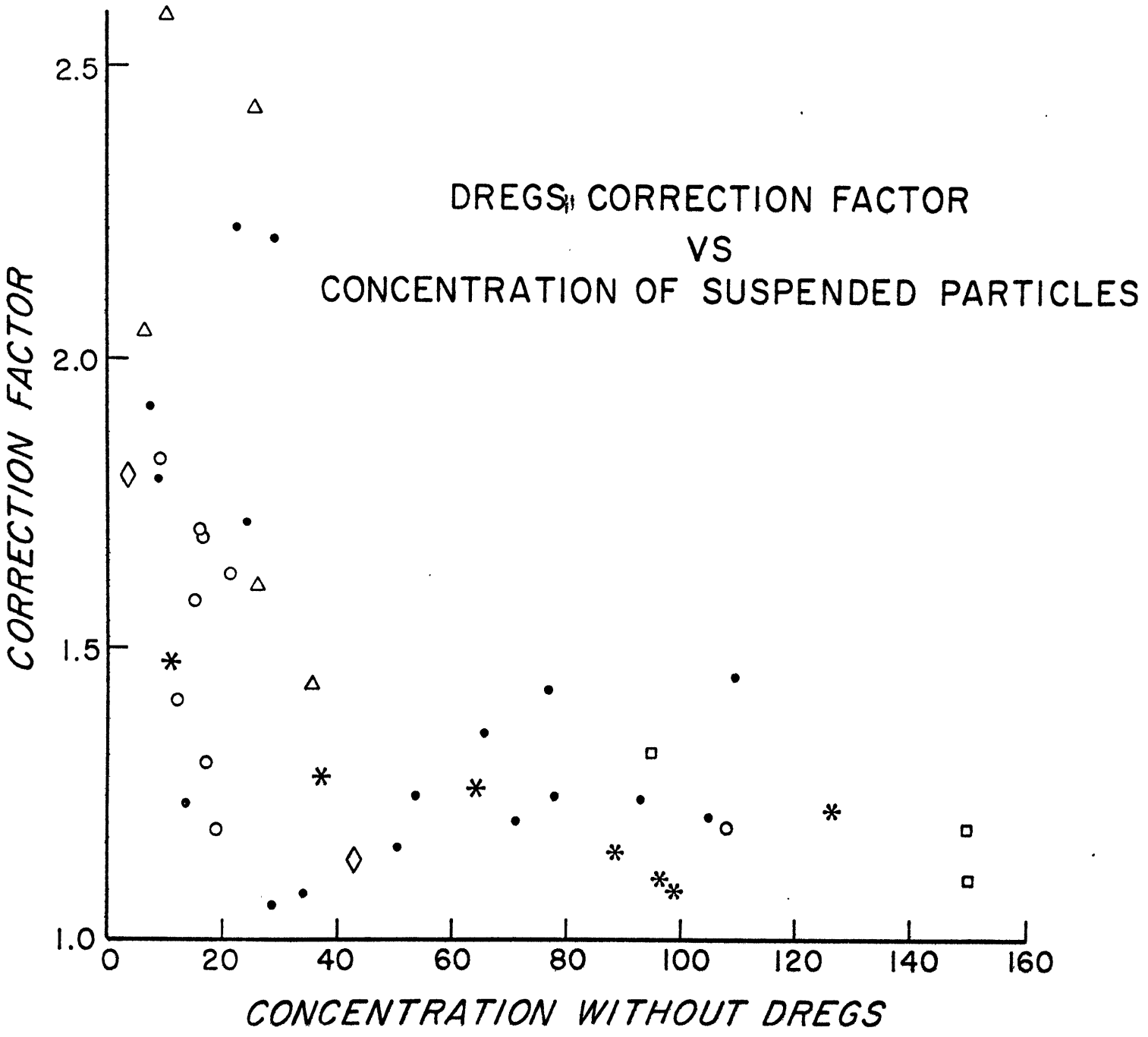
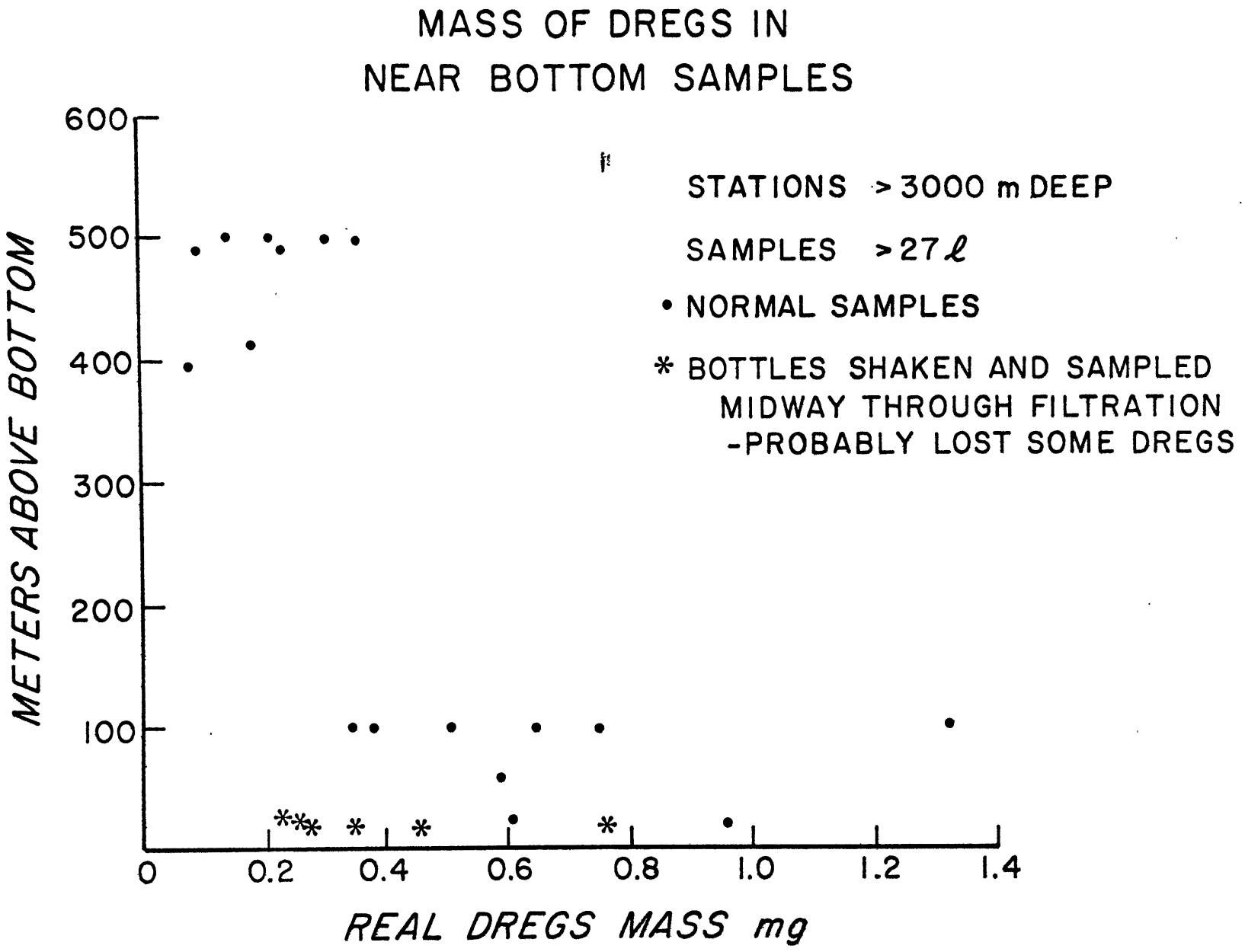

DREGS CORRECTION FACTOR
VS
CONCENTRATION OF SUSPENDED PARTICLES
CORRECTION FACTOR
2.5
2.0
1.5
1.0
0
20
40
60
80
100
120
140
160
CONCENTRATION WITHOUT DREGS

Figure 3.2 Although the correction factor is smaller for samples near the bottom than in mid-water (classified here as above the bottom 400 m, and deeper than 100 m from the surface), the particulate mass in the dregs is much greater in the bottom bottles where concentrations are higher. "Real dregs mass" refers to the mass in the water below the spigot in excess of the particle mass in the water below the spigot based on the particle concentration above the spigot.


MASS OF DREGS IN
NEAR BOTTOM SAMPLES
STATIONS > 3000 m DEEP
SAMPLES > 27 ℓ
• NORMAL SAMPLES
* BOTTLES SHAKEN AND SAMPLED
MIDWAY THROUGH FILTRATION
-PROBABLY LOST SOME DREGS
METERS ABOVE BOTTOM
600
500
400
300
200
100
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
REAL DREGS MASS mg

Shaking water bottles before filtration begins may decrease the loss of particles, but does not eliminate it. Seven 30-liter bottles which had been partially filtered (less than 5 liters) were well mixed, had 5-7 liters rapidly withdrawn for organic C and N analysis, and filtering continued. The average correction factor for these bottles from the bottom 100 m was 1.23 (σ=0.13), whereas the other eleven samples from the bottom 100 m had an average correction factor of 1.44 (σ=0.38).

2. Size Analysis

The volumetric concentration of particles was measured in the initial sample and in the dregs for the surface sample and a near-bottom sample (figures 3.3 and 3.4). The Coulter counter measures the volume of particles and then equates them to the diameters of spheres with the same volume. (See appendix C for description of changes necessary for operating a Coulter counter at sea.) Thus the calculated diameter may differ from the dimensions of particles measured optically or by Stokesian settling. The size range of particles measured in the surface sample was 2.5-64 μm, and 1.0-26 μm in the near-bottom sample. Many particles above these size ranges were observed on the filters by microscopy, but they were too rare to occur

Figure 3.3 Surface sample: comparison of the concentration and size distribution of particles in the initial sample and dregs as measured by a Coulter counter. Many particles larger than those measured in the 2.0 ml of water were seen by SEM examination.

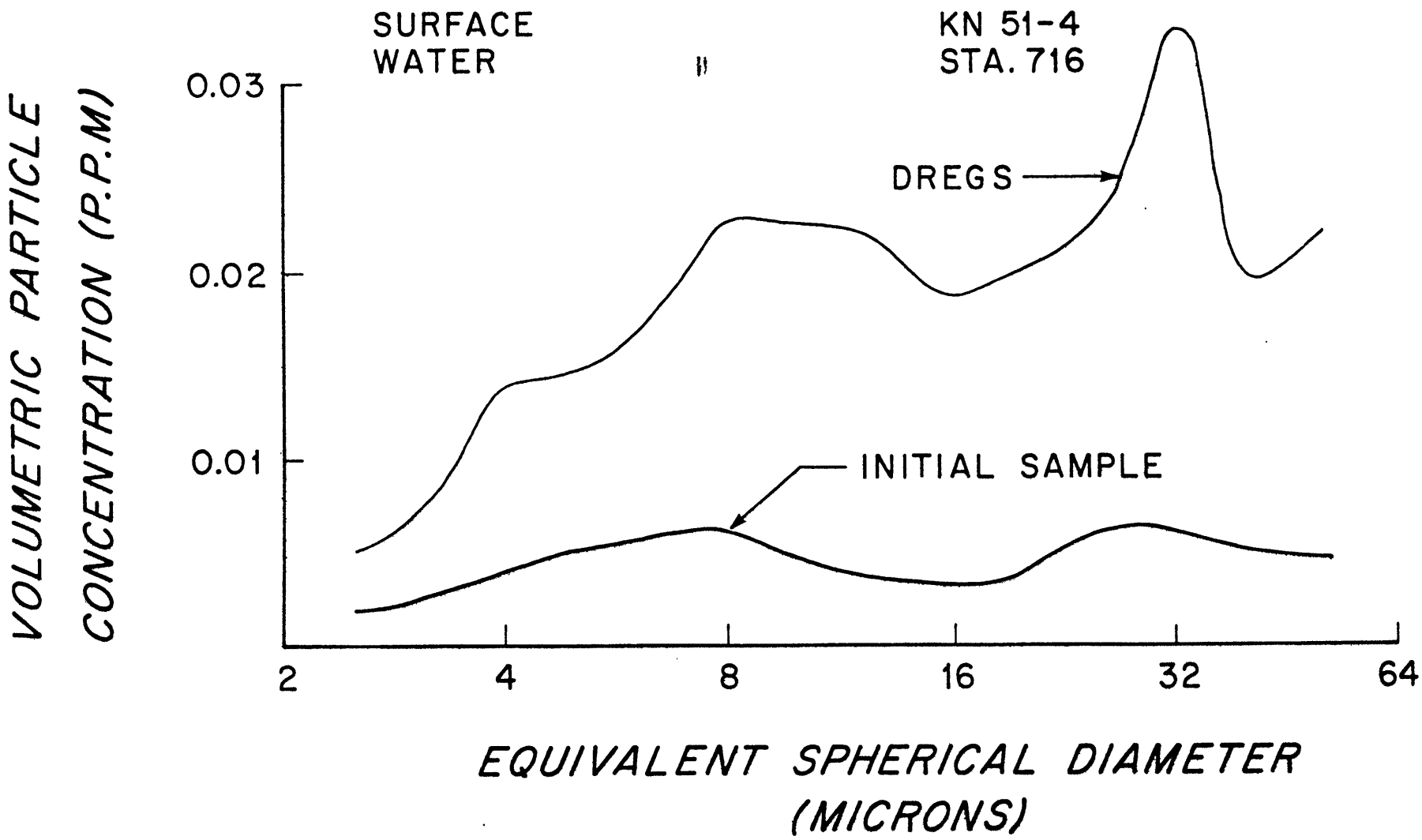
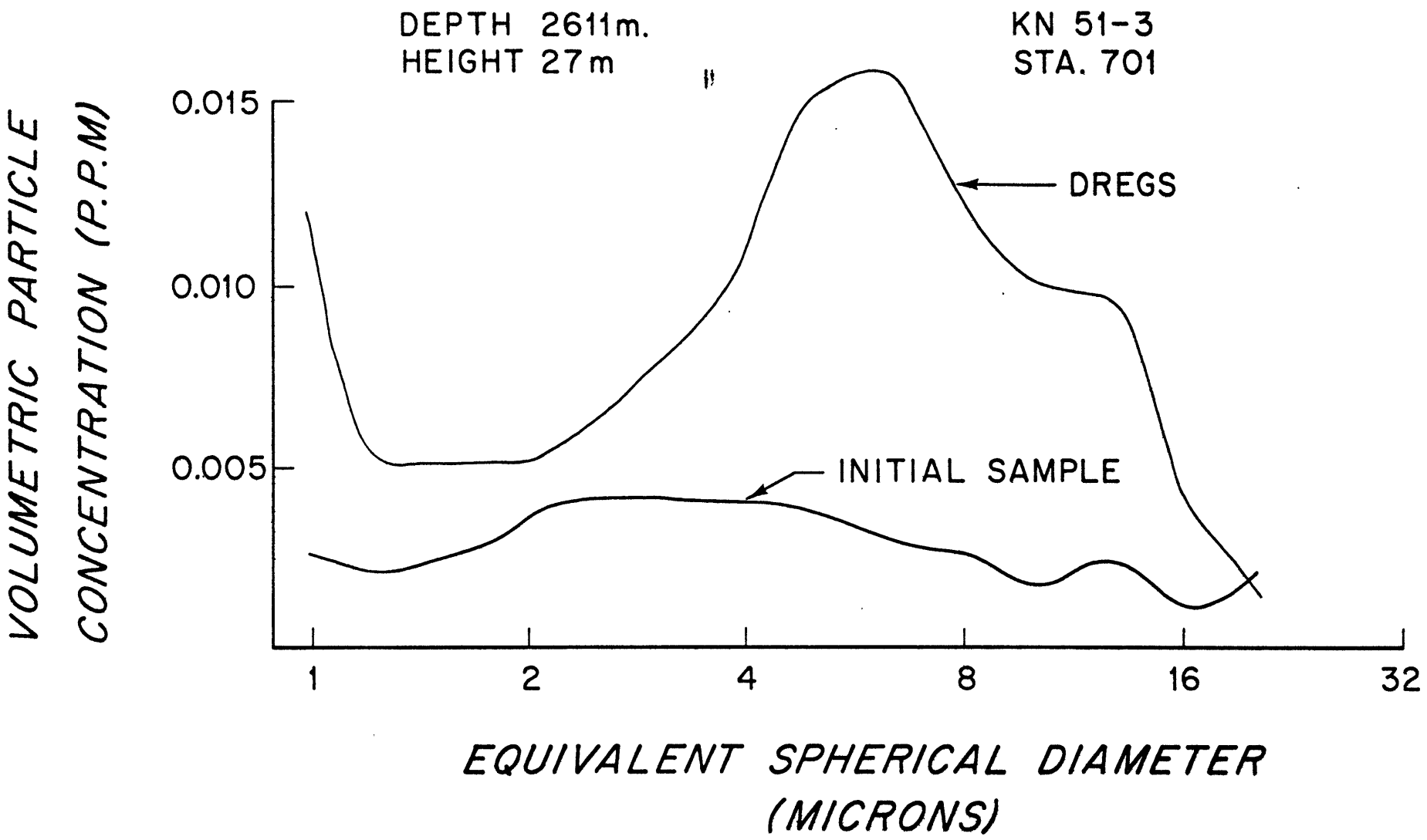

SURFACE
WATER
KN 51-4
STA. 716
0.03
0.02
0.01
DREGS
INITIAL SAMPLE
2
4
8
16
32
64
VOLUMETRIC PARTICLE CONCENTRATION (P.P.M)
EQUIVALENT SPHERICAL DIAMETER (MICRONS)

Figure 3.4 Near-bottom sample: Same parameters as Fig. 3.3. The increase in small particles at 1 micron is probably bacteria.


DEPTH 2611m.
HEIGHT 27m
KN 51-3
STA. 701
0.015
0.010
0.005
DREGS
INITIAL SAMPLE
1
2
4
8
16
32
VOLUMETRIC PARTICLE CONCENTRATION (P.P.M)
EQUIVALENT SPHERICAL DIAMETER (MICRONS)

in the 2.0 ml of water analyzed by the Coulter counter. The median size and concentration of particles increased markedly in the dregs (Table 3.2).

3. Microscopy

Filters were examined optically and with scanning electron microscopy to identify the types of particles concentrated in the dregs. Optical observations covered an entire filter, while less than 1 cm^2 segments of filters were examined with SEM.

Surface water: The concentration of *Acantharia* on the regular filter was about three $liter^{-1}$, whereas the concentration in the dregs was nearly 300 $liter^{-1}$. The individuals in the dregs were larger (up to 1,000 μm long) than in the regular samples (500-900 μm) and were usually surrounded by brown protoplasm. The overconcentration of foraminifera, dino-flagellates, and *Rhizosolenia* in the dregs was similar both in numbers and size differences. The ratio of coccospheres to coccoliths was much higher in the dregs than on the regular filter. More of the dregs filter was covered with amorphous organic matter than was the regular filter.

Midwater (1,021 m): Nearly all particles were individual rather than aggregated both above and below the spigots. Roughly two-thirds of the coccospheres occurred

Table 3.2

Depth of Sample	Meters above Bottom	Median Particle Diameter (Microns)			Particle Mode Diameter (Microns)		
		Initial Samples	Half Full Bottle	Dregs	Initial Samples	Half Full Bottle	Dregs
KN51-4, STA. #716, 10/1/75							
0	3616	11.1	9.3	16.9	8.0 & 28.8	8.0 & 28.8	10.3 & 32.0
KN51-3, STA. #701, 8/30/75							
2596	27	4.1	3.2	4.6	3.3	3.2	5.7

in the dregs along with most large (up to 50 μm x 90 μm) mineral fragments. At least ten fecal pellets (100-300 μm long) were in the dregs but only one (25 μm) was seen on the regular filter.

Near-bottom (415 m and 27 m above bottom in 2,623 m of water): Aggregates of biogenic and clay particles as large as 60 μm were present on the regular filters, but the dregs filter had more aggregates and a much higher ratio of large particles (>20 μm) to small particles than the regular filter. Large particles in the dregs included carapaces (up to 200 μm), particle aggregates (up to 50 μm) mineral fragments, a patch of organic matter (>300 μm across), and at least one fecal pellet (180 μm x 85 μm).

4. Elemental Analysis

The overconcentration of elements (ng/kg of seawater) in the dregs filters relative to the regular filter confirms the previous measurements of particle loss below the spigots (Table 4.3). The ratio of element concentration (ng/mg of particles) between the dregs filter and regular filter reveals that most elements measured are slightly less concentrated in the dregs than in the regularly filtered particles. Of the major components, Ca, representing carbonate particles, is not significantly changed in concentration in the dregs or regular particles at

TABLE 3.3

HYDROCAST AND DREGS SAMPLES

p.p.m.

METERS ABOVE BOTTOM	DEPTH	WEIGHT ANALYZED (mg)	CORRECTION FACTOR*	FILTER	Ba	Ti	Sr	Mn	Mg	Cu	V	Al	Ca	I
DOS #2 (OCEANUS 6 STA.721)														
501	3150	0.221	1.30	Regular	730	2740	880	1060	21100	370	96	51900	73300	170
		0.148		Dregs	0	2220	1090	710	18700	22	53	29900	68000	140
				D/R	0	0.81	1.23	0.67	0.88	0.06	0.85	0.58	0.93	0.82
101	3550	0.361	1.24	Regular	420	3220	130	840	24800	380	120	68400	46900	60
		0.397		Dregs	490	3310	400	760	19400	330	90	46100	49800	48
				D/R	1.15	1.03	3.03	0.90	0.78	0.85	0.76	0.68	1.06	0.81
24	3627	0.553	1.26	Regular	620	4060	180	1060	29000	230	140	75200	63400	72
		0.494		Dregs	330	3500	340	1230	23000	530	90	50000	57100	100
				D/R	0.54	0.86	1.96	1.16	0.79	2.27	0.64	0.67	0.90	1.43
OCEANUS 6 STA.738														
500	4888	0.242	1.82	Regular	410	3460	370	620	13400	630	72	34200	42100	155
		0.213		Dregs	0	2580	0	220	6200	1260	22	15500	14300	48
				D/R	0	0.75	0	0.35	0.46	2.0	0.31	0.45	0.34	0.31
100	5288	0.453	2.23	Regular	510	28300	270	780	18200	610	90	47200	37800	39
		0.747		Dregs	590	23600	0	210	8260	1640	23	12300	14500	15
				D/R	1.16	0.83	0	0.27	0.45	2.70	0.26	0.26	0.38	0.37

*Ratio of corrected to uncorrected particle concentration using dregs.

DOS #2, but in deep water (Oc 6, Sta. 738), Ca is depleted in the dregs. Al, representing "clay", is depleted in all dregs samples indicating that the small clay particles are less likely to fall below the spigots than other particles. Sr is concentrated in the dregs at DOS #2 which may be the result of rapidly settling *Acantharia*, but in the deep water at Sta. 738 the Sr was undetectable in the dregs.

If most of the elements measured were depleted in the dregs sample, some unmeasured components must be concentrated in the dregs. Silica was not measured and is associated with clays, which do not settle rapidly, and diatoms and radiolarians, which, because of their large size, should settle rapidly, and based on the SEM observations, do become concentrated in the dregs. Another component which may fall below the spigots is organic matter. Of the elements analyzed, Cu and I are most often associated with organic matter. Three of the five samples show significant enrichment of Cu in the dregs, but only one sample has I enriched in the dregs. SEM examination of the surface filters showed that organic matter was highly concentrated in the dregs. Patches of organic matter were also seen in the dregs in deeper water, but further analysis is needed to determine the quantitative significance.

The only element whose concentration was not within the ranges measured by Spencer et al. (1977) by this method was Ti at 100 m above the bottom at Oc 6, Sta. 738. In both the dregs and regular sample the Ti concentration was approximately an order of magnitude higher than normal. Contamination is possible, but that the degree of contamination of Ti should be evenly distributed between the dregs and regular particles is surprising.

D. SECTION SUMMARY--NISKIN SAMPLING

Four independent methods of examining particles in sea water show that a significant portion of sampled particulate matter settles to the bottom of Niskin bottles and is not sampled with standard techniques. Inclusion of the settled mass increases the total concentrations by 1.06 to 2.59 times with a mean increase of 1.50 (σ=0.39). Although many of the unextracted particles are as small as 4 μm, the mass loss comes predominantly from the larger particles which fall through the water column relatively rapidly and are not maintained in the water mass sampled by the bottles. Because the dregs often consist of random, rare particles, their inclusion in the total concentration profiles can create anomolously high values which increases the difficulty in obtaining coherent

contours of particle concentrations. It is important to sample these particles to understand the fate and role of particulate matter, but it may be advantageous to separate the regular and dregs samples until more is understood about the differentiation which occurs in these samples, particularly with respect to organic matter.

The composition of the large particles lost varies with the portion of the water column sampled and the geographic location but includes Foraminifera, diatoms, *Acantharia*, coccospheres, dinoflagellates, organic matter, fecal material, carapaces and tightly aggregated material.

Suggestions for improved sampling methods are:

(1) Filter the entire volume of water above the spigots. The water below the spigots should be put on a separate filter. The amount of water which will conveniently pass through one filter should determine the size bottle used, or multiple filters will have to be used, and the results summed.

(2) Thoroughly mix the water in the bottom (very difficult with larger samplers), quickly draw a subsample, and filter the whole subsample, taking care that places for particles to be trapped and lost do not exist.

(3) Redesign large volume samplers to allow for complete extraction of the water. Salinity, oxygen, and

other samples which are not affected by particulates should be drawn from a spigot which does not extract the large particles which rapidly fall to the bottom.

(4) Extra care must be taken during retrieval to avoid loss of water (and large particles) through the bottom of the sampler. Bottom closures must be tight, winch movements should be smooth, and bottle handling careful.

CHAPTER IV

DEPLOYMENT OF SEDIMENT TRAPS

A. INTRODUCTION

The previous two chapters described the tests and analyses made to determine the optimum sediment trap and water sampling techniques to be used during this study. This chapter contains an explanation of the model for ocean sedimentation used in deciding where in the water column to locate traps and a description of the traps, moorings, and methods of sample treatment.

B. WORKING MODEL FOR OCEAN SEDIMENTATION USED IN TRAP DEPLOYMENT

Most particles are introduced into the ocean at the boundaries and are carried by rivers, wind, and glaciers, or are produced biologically at the sea surface, or deeper in the water column as part of the food chain. Away from land masses the main source of particles in the surface waters is biological production. Terrigenous dust is also found in surface waters (Folger, 1970; Stoner, 1974; Krishnaswami and Sarin, 1976), and locally is an important source of particles (Delany et al, 1967; Chester et al, 1972; Emery et al, 1974; Nichols and Rowe, 1977). The concentration of particles decreases rapidly in the top

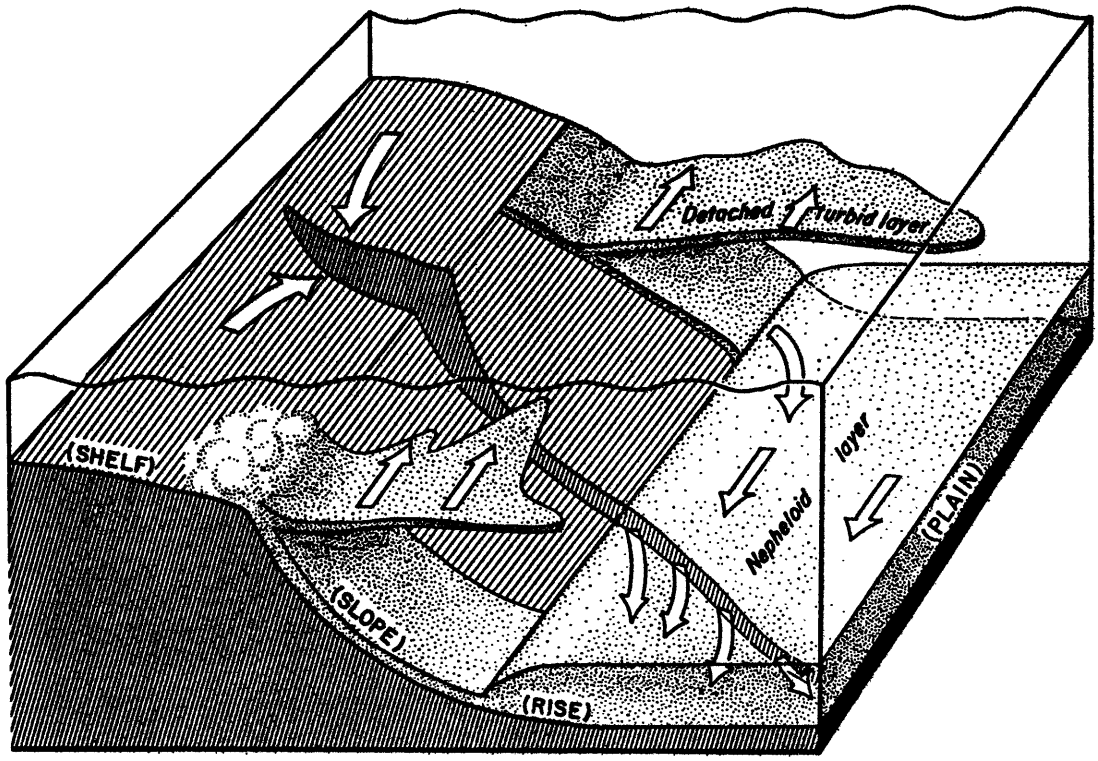
100 m of the ocean due to remineralization of biogenic particles (Gordon, 1970; Menzel, 1974), which occurs almost entirely above the thermocline (Riley and Chester, 1971) and is most rapid in the near-surface waters (Menzel and Ryther, 1970), and by the aggregation of small particles into fecal material, which is rapidly removed from the surface water by accelerated sinking rates (Marshall and Orr, 1955; Osterberg et al, 1963; Smayda, 1969, 1970, 1971; Schrader, 1971; Manheim et al, 1972; Fowler and Small, 1972; Honjo, 1975; Cherry et al, 1975). Terrigenous particles remain largely unaltered as they move through the water column, but they are commonly agglomerated with organic material (Johnson, 1974; Wiebe and Pomeroy, 1972).

Low concentrations of suspended particles are generally found throughout the water column, but a gradual increase in particulates is commonly found as much as 500-1700 meters above the bottom, and a very large particulate increase in the bottom 50-200 (Jerlov, 1953; Ewing and Thorndike, 1965; Eittreim et al, 1969, 1972; Eittreim and Ewing, 1972; Jacobs et al, 1973; Spencer et al, 1976). The zone of increased particulate concentration near the bottom is termed the nepheloid layer

(Ewing and Thorndike, 1965). In a review of suspended sediments Pierce (1976) lists and documents from the literature possible sources of terrigenous particles in the nepheloid layer as outward diffusion of fluvial discharge, low-density flows down submarine canyons, turbidity currents, resuspension of bottom sediments, introduction of glacial or glaciofluvial sediments at high latitudes (particularly important near areas of bottom-water formation), and particles that have settled through the entire water column - having been introduced into the surface layers by eolian transport.

Organic material from continents, or from biological production in the ocean, can also enter the nepheloid layer in the same way. Figure 4.1 is a cartoon showing some of these processes along a continental boundary. Armi (1977) suggests that well-mixed bottom layers may move away from a slope, retain some of their particulate load, and penetrate horizontally into a basin while maintaining their temperature-salinity-particle characteristics. However, the complexity of oceanic circulation--including many scales of turbulent mixing in the form of internal waves, large-scale eddies, and intensified boundary flows--makes it seem unlikely that the layers of turbid waters in

Fig. 4.1 Particulate matter from the continents may reach the deep sea via turbidity currents, low-density flows down canyons, resuspension of bottom sediments, or outward diffusion of fluvial discharge and be incorporated in the nepheloid layer. After Pierce (1976).


Detached Turbid layer
(SHELF)
(SLOPE)
(RISE)
Nepheloid layer
(PLAIN)

the midwater column (Figure 4.1) maintain their distinction for large distances from their origin.

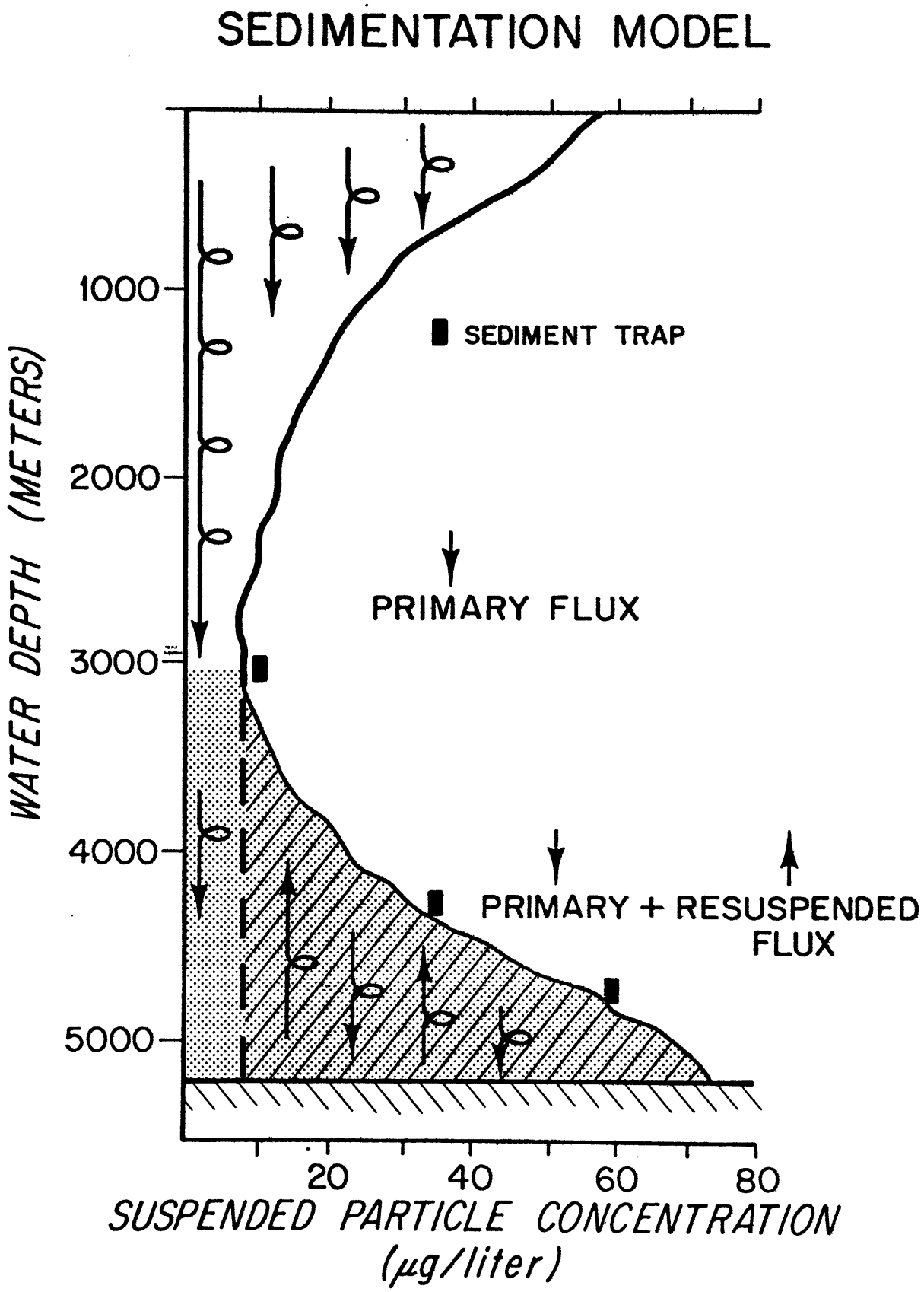
Terrigenous material is a major source of sediment in the ocean and its movement is predominantly along the sea floor where turbidity currents have formed thick deposits in the deep ocean and created extensive abyssal plains (Heezen and Laughton, 1963), and deep ocean currents may have shaped the continental rise and created massive ridge-like deposits (Heezen et al., 1966; Jones et al., 1970; Hollister and Heezen, 1972). The pelagic rain of particles from the surface layers of the ocean (from biological production and atmospheric dust) forms the other major source of particles that become deep-sea sediments. It was the intent of this study to deploy sediment traps in such a manner as to delineate particles from the two sources, determine their rate of input, and compare and contrast the morphology and composition of particles from the two sources. Further comparisons were made among the falling particles collected in traps, particles collected in water bottles, and surface sediment.

As a first-order approach, the model of Biscaye and Eittreim (1977) was used in deciding where in the water column to make collections of falling particles

(Figure 4.2). They suggested that at the depth of minimum light scattering (or particle concentration) just above the nepheloid layer, which they refer to as the "clear-water" minimum, the suspended particulate load reflects the downward transport of particles from the surface waters, whereas below the clear-water minimum the increase in particles results from the resuspension, vertical mixing, and advection of sediments at the sea floor. Injection of particles into the nepheloid layer may occur "upstream" and "upslope" a long distance from the site being analyzed and accounts for nepheloid layers hundreds of meters thick; a height well above the frictional influence of the sea floor (Wimbush and Munk, 1970; Weatherly, 1972). The layer of intense light scattering near the sea floor often corresponds with isothermal or well-mixed layers and is believed to be a region of strong vertical mixing (Biscaye and Eittreim, 1974; Eittreim et al., 1975; Armi and Millard, 1976), so the resuspended particulate load in such layers is more likely to be of local origin.

Following this model, the author chose the clear-water minimum as the best level at which to collect the flux of particles from the surface waters which will accumulate on the sea floor, and called this portion

Figure 4.2 (After Figure 2 of Biscaye and Eittreim, 1977) Typical nephelometer profile from an area with a strong nepheloid layer. The minimum in light scattering (suspended particulate concentration), which is at the top of the stippled area, is called the "clear-water minimum." The clear-water minimum is defined as the upper limit of the nepheloid layer and all suspended matter below it as the Gross Particulate Standing Crop in units of g/cm^2 (stippled area). The model shown here schematically assumes that all particles falling from above the clear water minimum have come from the surface layers. (The curlicue arrows represent the fact that downward settling is not presumed to be a strictly one-dimensional process and that horizontal advective processes affect the particles also.) The suspended matter below clear water which is in excess of the clear water concentrations is defined as the Net Particulate Standing Crop (diagonally barred area) and it is assumed that this represents particles mixed upward or injected "upstream" and/or "upslope" (curlicue arrows upward). The primary flux (F_p) represents the remnant of the surface water particulate load during its downward transit. The best measurement of the primary flux reaching the sea floor should be obtained at the clear water minimum, assuming that some particles in the nepheloid layer below clear water have been subject to resuspension. The resuspended flux ($F_R(z)$) is the flux of particles resuspended from the bottom to a height, z, above the bottom. The total flux ($F_T(z)$) measured at any level below clear water is the sum of primary and resuspension fluxes. Particles are resuspended from the sea floor ($F_R(0)$) at a rate equivalent to the net depositional rate of particles in the nepheloid layer under the assumption of steady state.


SEDIMENTATION MODEL
1000
2000
3000
4000
5000
WATER DEPTH (METERS)
SEDIMENT TRAP
PRIMARY FLUX
PRIMARY + RESUSPENDED FLUX
20
40
60
80
SUSPENDED PARTICLE CONCENTRATION
(μg/liter)

the "primary flux". The processes of decomposition and dissolution that cause a decrease in particulate concentration from the surface to the clear-water minimum (Figure 4.2) continue to operate below that level. However, the rate of decrease with depth just above the clear-water minimum in most profiles is sufficiently low that one readily speculates that most of the decomposition/dissolution that occurs has taken place by midwater and that additional changes below that level are small until the depth exceeds the lysocline. Whatever the validity of that conjecture, a trap at the clear-water minimum is the lowest level at which the primary flux (F_p; Figure 4.2) can be directly measured and a sample obtained for compositional analysis uncontaminated by particles resuspended from the bottom.

Analysis of the particles in the traps at the clear-water minimum indicated that some bottom-derived sediment may be present even at this level, so in this study the primary flux will refer to the downward flux at the clear-water minimum.

Traps deployed below clear water and above any existing intense near-bottom nepheloid layer will collect both the primary-flux particles and particles

resuspended some distance away, while traps within an intense nepheloid layer will also collect particles resuspended "locally". The resuspended particles, whether resuspended locally or far away, will be referred to as the "resuspension flux".

C. RESIDENCE TIME OF PARTICLES IN THE NEPHELOID LAYER

In order to better understand processes of sediment transport and diagenesis, it is desirable to know the rate at which particles are being resuspended from the sea floor and the period of time they are in a state of resuspension and in a state of primary flux. This would help determine the proportion of transportation, decomposition, or dissolution that occurs during the initial transit time through the water column versus that which occurs during resuspension. While it would be difficult to determine the duration of resuspension for individual particles, a rate of turnover - or mean residence time - could be determined for particles by making the simplifying assumption that the dynamics of the nepheloid layer are in steady state and uniform over the region of resuspension and deposition.

Under these conditions the upward flux of particles at any level within the nepheloid layer is equal to the

downward flux at that level after the primary flux (F_p) is subtracted. Assuming that traps capture only settling particles, a trap below the clear-water minimum will capture particles both falling from the surface (F_p) and those which have been resuspended to the height (z) of the trap above the bottom.

Thus $F_T(z) = F_p + F_R(z)$

where $F_T(z)$ = the total flux directly measured at height z above bottom within the nepheloid layer

F_p = the primary flux directly measured at the clear-water minimum, and

$F_R(z)$ = the resuspended flux calculated by difference at height z above the bottom.

The resuspension flux at a trap height z is then divided into the total concentration of resuspended particles (the "net nepheloid-layer standing crop" of Biscaye and Eittreim, 1977) below z to arrive at a mean residence time of particles in the nepheloid layer (fig. 4.2). The concept of residence time here refers to the time required to establish or deplete a nepheloid layer knowing the rate of input or outflow, or

$$\frac{\text{Reservoir} \quad (ML^{-2})}{\text{Flux in or out} \quad (ML^{-2}T^{-1})} \leftarrow \frac{\text{Water Bottle Data}}{\text{Trap Data}} = \tau(t)$$

The residence time, τ, of resuspended particles up to a height z is defined by

$$\tau(z) = \frac{SC(z)}{F_R(z)}$$

where SC(z) = the net standing crop of resuspended particles below z, or $\int_{z=o}^{z} (C_z - C_{\text{clear-water minimum}})\, dz$

and $F_R(z) = F_t(z) - F_p$

as defined above.

This F_R overestimates the residence time below z because more particles may be resuspended to a lesser height and contribute to the net nepheloid standing crop but not be measured by the traps. One could also use $F_R(z)$ as an estimate of what is falling out of the net nepheloid standing crop above z, and derive an estimate of minimum residence time for the nepheloid layer above z.

Calculating residence times by dividing water-bottle concentrations by sediment-trap fluxes may underestimate the mean residence time of particles in the nepheloid layer because water bottles are generally thought to miss sampling the rare large particles found in the trap. However, the calculations made in chapter 3 indicate that when all the particles collected in water bottles are extracted (above and below the spigots), the concentrations are similar to those made by filtering thousands of liters of water (Bishop and Edmond, 1976), so the residence times

may not be grossly affected by this consideration.

A factor which may cause the residence times calculated in this study to be overestimated is that the total concentration of resuspended particles was determined from water bottles which collect not only the rapidly falling particles, but also the small particles which presumably contribute little to the downward mass flux. Arguments will be made in chapter 5 that residence times in this study may be high by a factor of two.

The assumption that the nepheloid layer is in steady state is open to some criticism in that there are known to be temporal variations in turbidity and standing crop at a given location (Biscaye and Eittreim, 1974; Feely, 1975). Within ocean basins on a time scale of years, however, the nepheloid layer appears to be a stable phenomenon. This is at least implied by the fact that the data comprising the maps of gross and net nepheloid-layer standing crop drawn by Biscaye and Eittreim (1977) represent measurements made over the course of almost a decade. Their internal consistency, despite possible variability between adjacent stations made at different times, results in a contouring pattern compatible with our understanding of general

ocean circulation and sediment sources. These are obviously not conclusive validations of the steady state assumption but, by making it, we can calculate a first-order approximation of the residence time of resuspended particles in the nepheloid layer.

In presenting the concept of a nepheloid-layer residence time it is also necessary to consider the spatial uniformity of resuspension and deposition, because we are dealing with a three-dimensional problem. The consistency of concentration of standing crop of the nepheloid layer should be related to the uniformity of resuspension and deposition. The compilations of the Lamont nephelometer work clearly show geographic variations on a basin-wide scale in the nepheloid layer, indicating a non-uniform situation, so particles could be resuspended in an area of erosion and be deposited in a more tranquil environment "downstream". However, when time and distance scales are considered, we find that all particles >20μm (ρ=1.5 g/cm^3) could fall through 100 meters of nepheloid layer in about 20 days. With a mean transport rate of 5 cm/sec the horizontal distance carried would be less than 100 kilometers. It seems reasonable to assume that the cycle of resuspension and deposition could remain con-

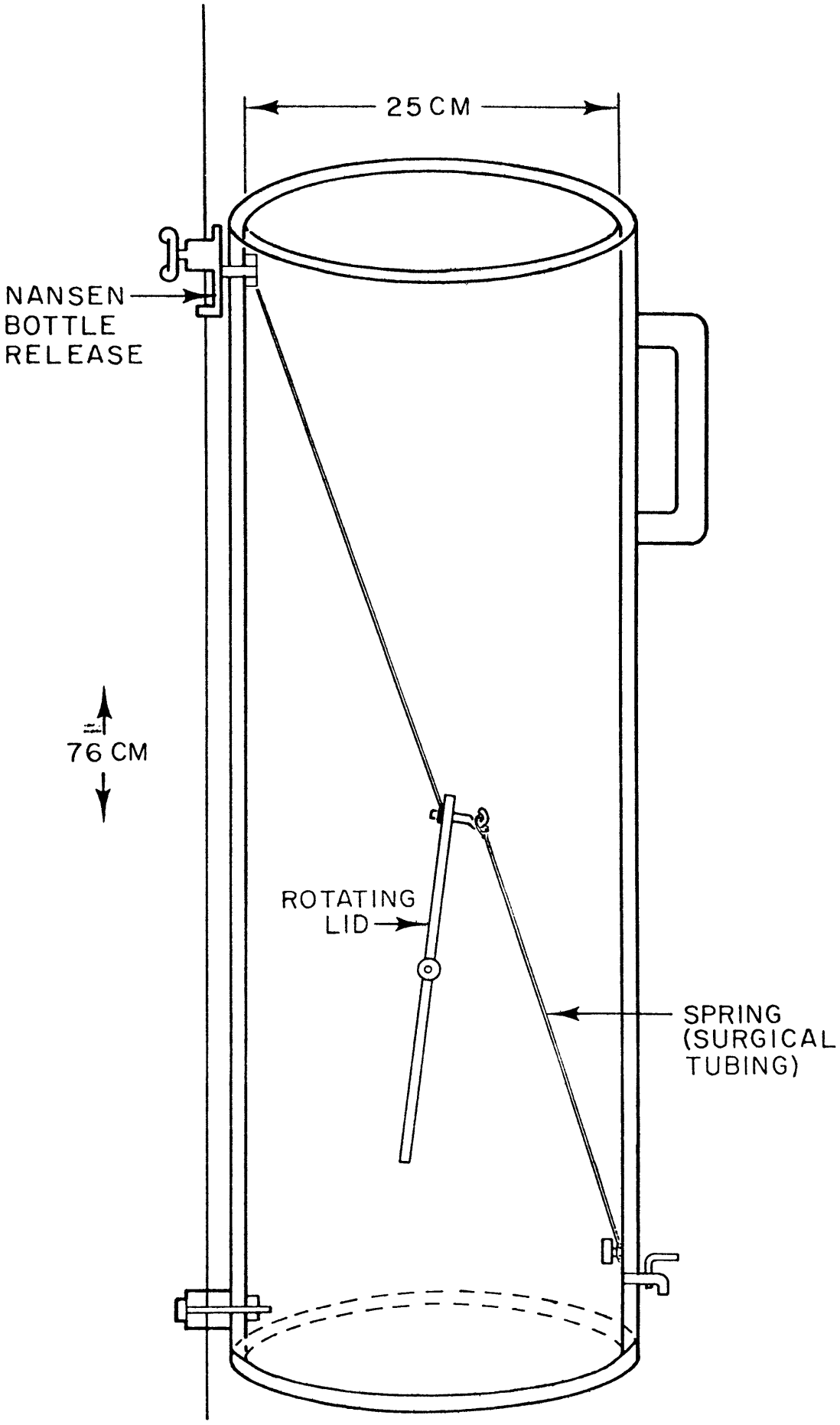
stant over a distance of this scale or several times that distance.

In dealing with the effect of horizontal advection and vertical settling of particulates, it would be better to create a two-dimensional box model in which the inputs and outputs are known at each side of the box (M.J. Richardson, personal communication; I.N. McCave, personal communication). This would require elaborate and extensive instrumentation and was not possible with the experiment conducted.

D. TRAP DESIGN AND DEPLOYMENT

Based on the flume and field experiments with sediment traps (Chapter 2), cylindrical traps were designed in a joint project with Dr. G.T. Rowe for use on moorings in the open ocean. To minimize contamination of the sample the traps were constructed principally from PVC (Dexter, 1974), a material which is also easy to machine. The body of the trap is 76 cm tall with 25 cm inside diameter and wall thickness of 1.9 cm (Fig. 4.3). The PVC bottom is 1.3 cm thick and is securely fastened with cement and machine screws. To isolate the collected material after a preset period of time, a circular disc is held inside the trap in a nearly vertical position with 100-lb.-test nylon

Figure 4.3 The trap used to collect sediment for analysis in this report is a PVC cylinder with an internal lid which rotates and isolates the trapped sediment. The lid can be closed by a timed release, weighted messenger, or the manipulator arm of a submersible.


25 CM
NANSEN
BOTTLE
RELEASE
76 CM
ROTATING
LID
SPRING
(SURGICAL
TUBING)

monofilament line connected to a release mechanism. When the release is activated, the lid rotates into the closed position by the spring action of surgical or rubber tubing. A stainless steel bolt or short PVC dowel provides a ridge to stop the lid once it reaches the horizontal position.

The trap is attached to the mooring line with a Nansen bottle release clamp at the top of the trap and a PVC clamp at the bottom. The Nansen release allows the trap to be closed with a messenger from above, or a burn wire can be used to close the lid directly. Care must be taken to prevent electrolytic reaction of metal parts even in short deployment. One stainless steel pin in the Nansen release nearly corroded through in ten days.

Our traps were generally closed in the above manner by a burned wire triggered by a quartz-crystal-timed release designed and built by A.J. Williams of W.H.O.I. This release can be set at one-day increments from one to 256 days from the time it is initialized. It can also be equipped with 12 kHz and 37 kHz pingers. With or without pingers, the release performs the following functions: twelve hours after the release is initialized, a command is given to burn a nichrome

wire. This was designed to open the trap lids after the traps were deployed, but was not used. If the release has pingers, they begin pinging at a one-second repetition interval one day before the preset time of release. One tenth of a day before the release time another wire is burned and can be used to close the lid, drop a messenger, or perform any other function. A final wire is burned at the preset time to release the anchor weight. A release hook is used to multiply the tensile strength of the burn wire in holding the anchor weight.

The mooring line was 3/8" wire or polypropylene rope (table 4.1). Glass spheres with plastic hard hats were located at the top of each array to keep the mooring line taut so the traps remained vertical during the collection period. The flotation spheres were balanced with iron-chain anchors to create 100-150 pounds negative buoyancy after the anchor was released. Positive buoyancy of 50-70 pounds allowed the array to rise at about 40 m/min. Visual observation from ALVIN of a 30-meter array at 2200 m (DWD 106) showed the mooring to be taut and motionless. A computer simulation of the 500-meter arrays showed the maximum tilt of any trap would be 1.2° in a 5 cm/sec current and 4.9° in a 10 cm/sec current.

TABLE 4.1

Array	Mooring Line	Method of Lid Closure	Anchor Release	Deployment Time	Collection Period
DWD #106	3/16" wire	arm of ALVIN	AMF acoustic transponder	23-29 June 1976	5.8 d
KN-58-1	3/8" polypropylene rope	messenger from Williams release	Williams timed release	11-21 Aug. 1976	10.1 d
KN-58-2	3/16" wire	burn wire activated by Williams timed release below each trap	Williams timed release	21 Aug.-1 Sept. 1976	10.7 d
DOS #2	3/16" wire	messenger from Williams timed release	AMF acoustic transponder	15-31 May 1976	15.8 d

The model and rationale used for the vertical arrangement of traps on the mooring was detailed in the previous section. One trap intended to measure the primary flux was moored at the level of the clear-water minimum as determined from previous neighboring LDGO nephelometer profiles. Because of logistical limitations in two (of four) instances we were not able to emplace a trap at the clear-water minimum. One to three traps were located within the nepheloid layer at each site to measure the total downward flux of primary and resuspended particles.

During the summer of 1976, four arrays of traps were successfully deployed and recovered at three sites in the western North Atlantic (Figure 4.4). The array deployed at the Deep-Water Dumpsite #106 (DWD 106) was in conjunction with a cruise designed to investigate the biological effects of dumping industrial wastes in the open ocean. The site is on the continental slope (2200 m) where the regional contours are irregular. The bathymetry of the area was surveyed and the array was deployed on the outer edge of a large-scale knoll (Fig. 4.5). Observations of the trap array and region

Figure 4.4 Trap arrays have been deployed and recovered at DOS #2 and DWD #106 and two arrays were deployed and recovered at KN-58. Lamont nephelometer lowerings nearest the trap sites were used to estimate the nepheloid layer structure for planning the vertical spacing of traps on the mooring. Trap array spacing at DOS #2 and at KN-58 was based on those estimates. Hydrocasts were made at each site to determine the nepheloid layer structure, concentration and standing crop at each station at the time of deployment. Surface sediment samples were obtained at each site with a gravity core or from RSRV ALVIN.

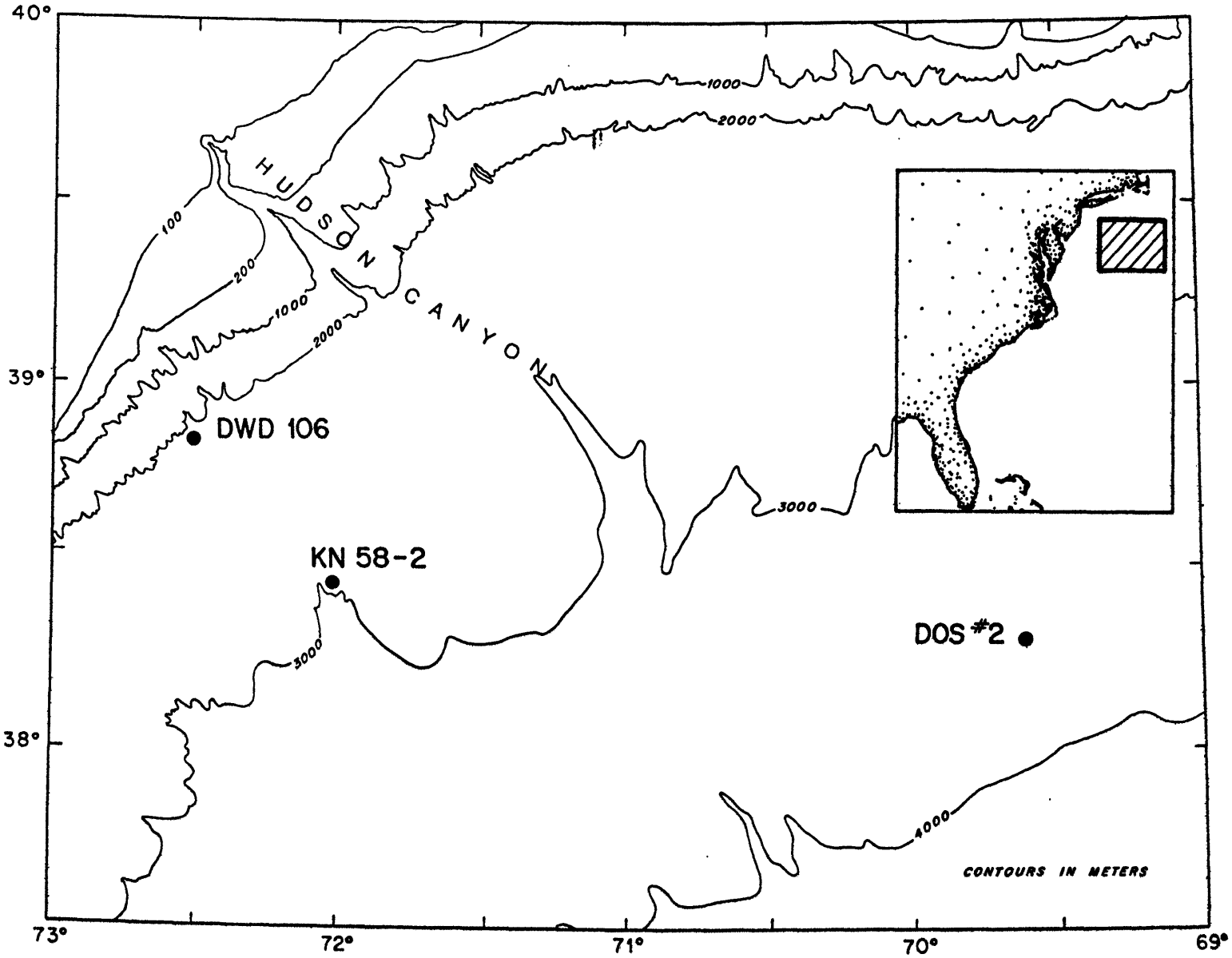
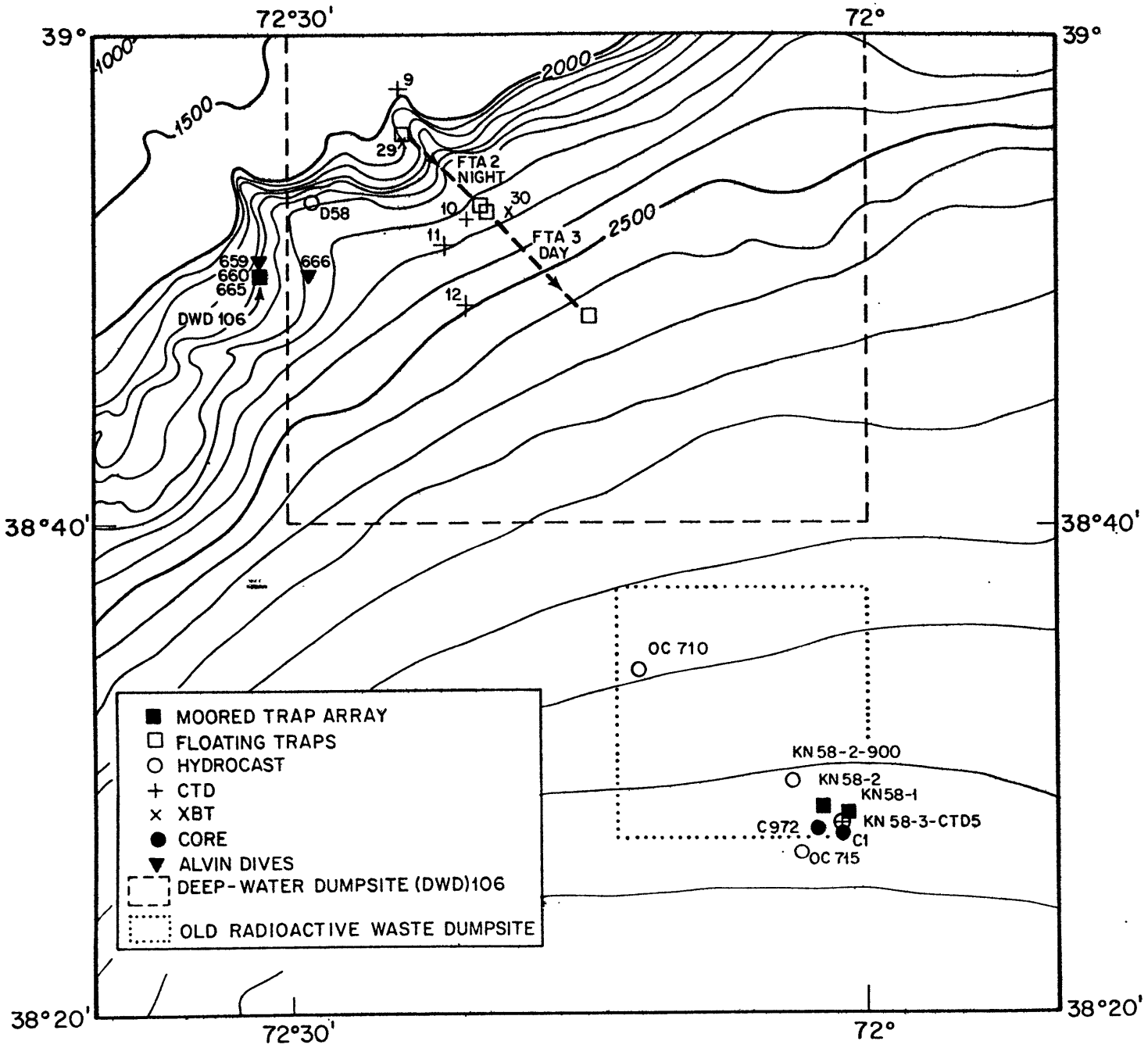

40°
39°
38°
73°
72°
71°
70°
69°
HUDSON CANYON
100
200
1000
2000
3000
4000
DWD 106
KN 58-2
DOS #2
CONTOURS IN METERS

Figure 4.5 A more detailed map reveals the topography and sampling density in the vicinity of DWD #106 and KN-58. Locations on the slope and rise with minimally rough topography were sought for the moored arrays. The floating trap arrays were deployed in a warm core ring which had very low productivity based on collections in plankton nets and low suspended particulate concentrations.


72°30'
72°
39°
38°40'
38°20'
1000
1500
2000
2500
9
29
FTA 2
NIGHT
10
30
D58
11
FTA 3
DAY
12
659
660
665
666
DWD 106
OC 710
KN 58-2-900
KN 58-2
KN58-1
KN 58-3-CTD5
C972
C1
OC 715
MOORED TRAP ARRAY
FLOATING TRAPS
HYDROCAST
CTD
XBT
CORE
ALVIN DIVES
DEEP-WATER DUMPSITE (DWD)106
OLD RADIOACTIVE WASTE DUMPSITE

of deployment were made from DSRV ALVIN and showed outcrops of semi-lithified sediments one to ten meters high.

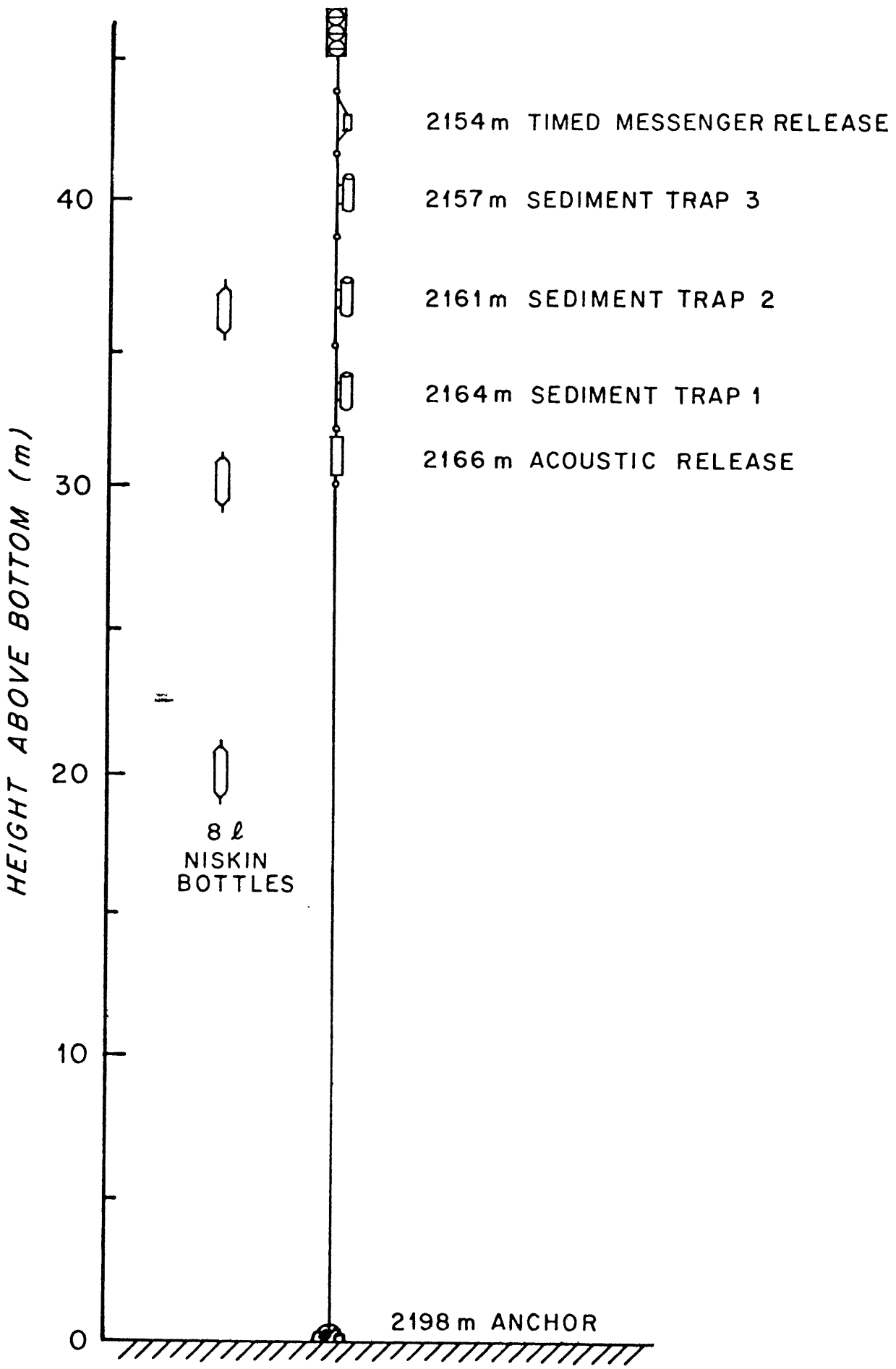
A site on the upper continental rise of intermediate depth (2800 m) between the other two arrays was chosen for the last two arrays (KN-58-1 and 2), which were deployed for two consecutive ten-day periods. Echo sounding (12 kHz) in the area showed the bottom to be gently sloping regionally with no rough topography, which would have showed up on the echo-sounding records as hyperbolic echoes (Hollister and Heezen, 1972).

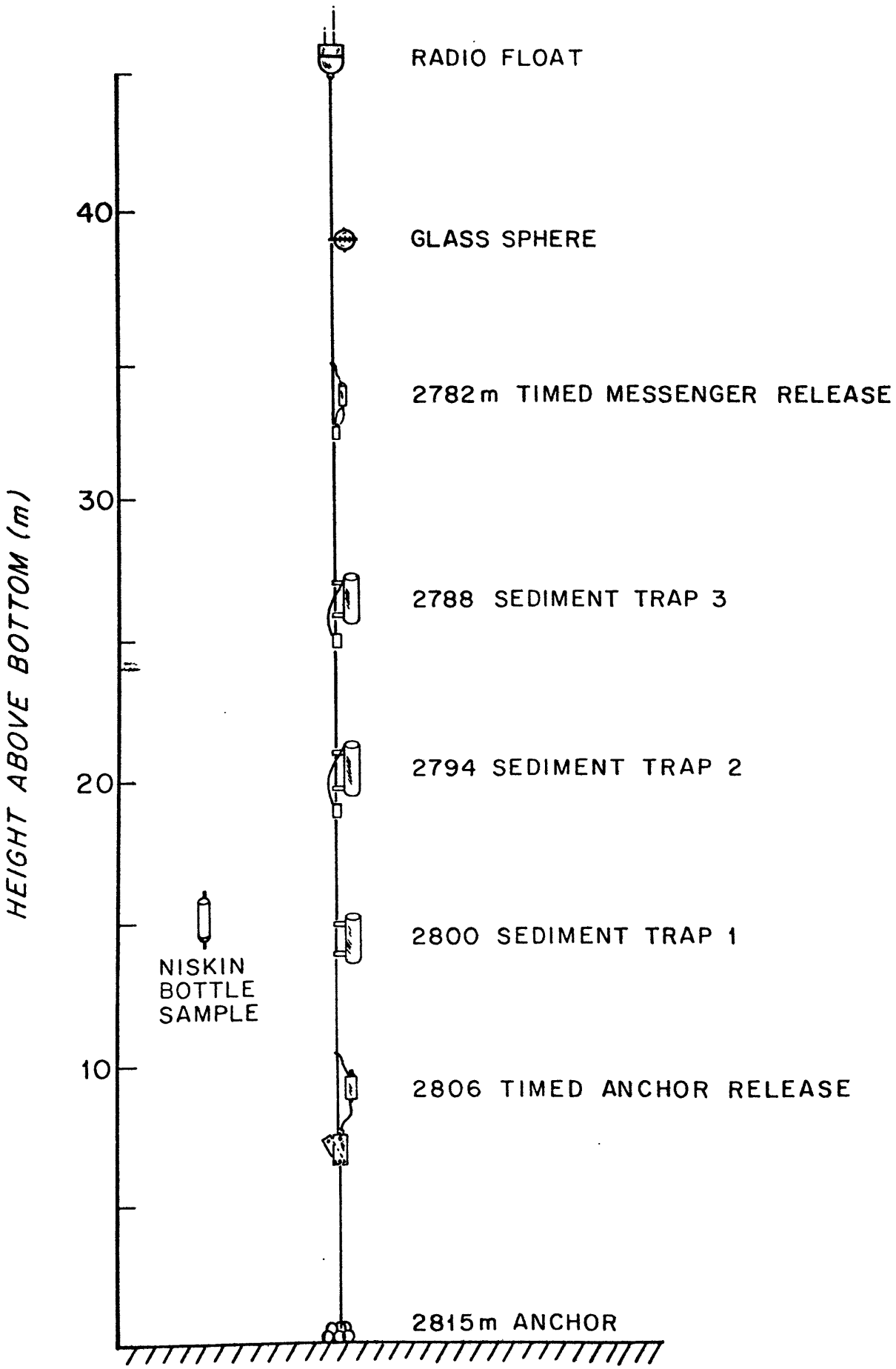
The array at Deep Ocean Station #2 (DOS #2) was on the Continental Rise (3600 m) and is at the upper edge of the Western Boundary Undercurrent (Hollister and Heezen, 1972). The regional contours in the area are very uniform and observations during ALVIN dives in the area show only a gently sloping topography with low relief.

Two of the arrays (DOS #2 and KN-58-2) had a primary-flux trap at the clear-water minimum and two traps in the nepheloid layer (only one of which worked successfully in DOS #2 (Fig. 4.6d and c). One of the arrays (KN-58-1) had three traps within the nepheloid

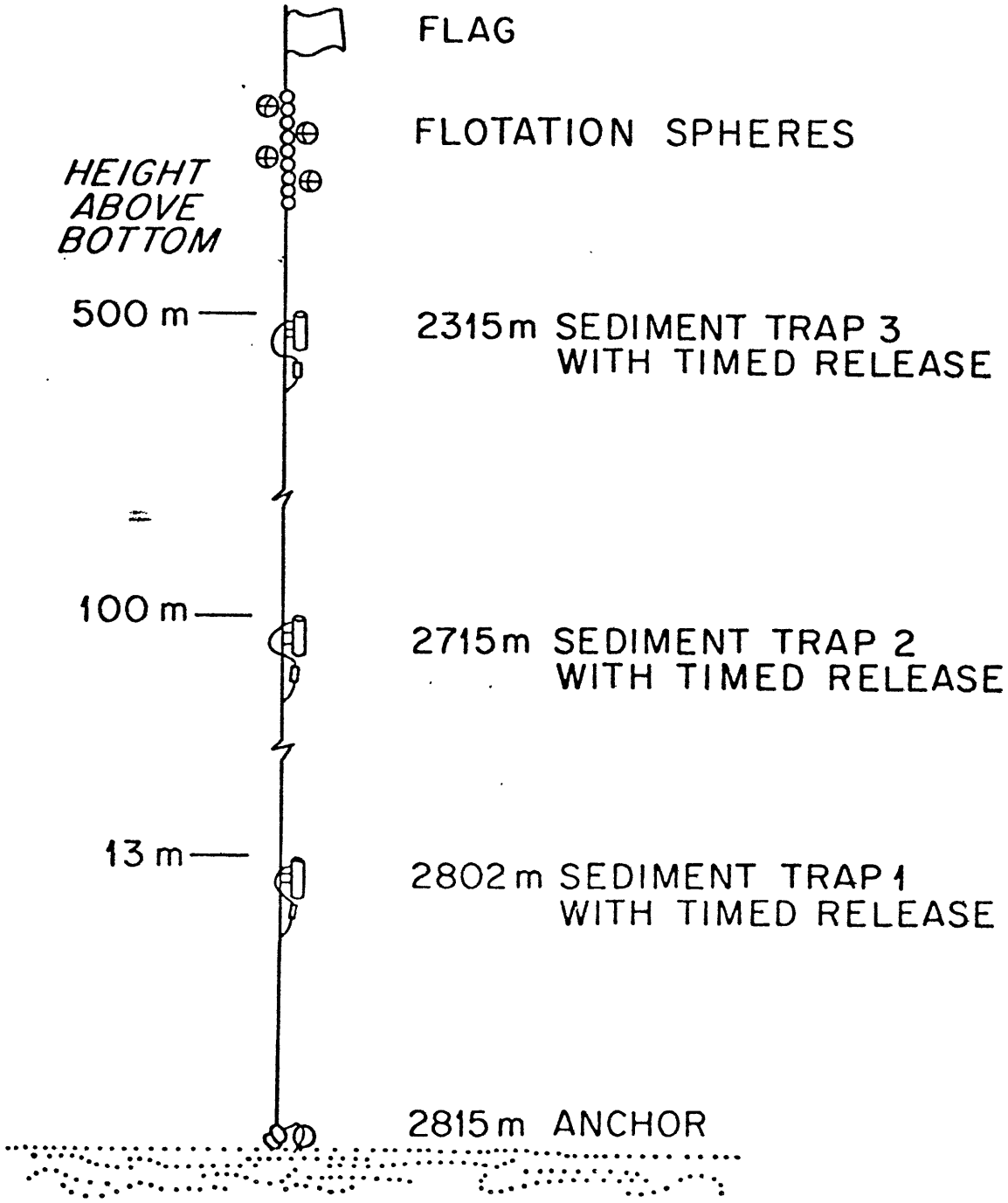
Fig. 4.6 a-d

The moorings used at the trap sites had glass balls for flotation and were recovered twice with an acoustic release and twice with a timed release designed and built by A. J. Williams at W.H.O.I. The location for water samples taken are also indicated for DWD #106 and KN 58-1. Water samples were taken near the trap depths at the other two sites.

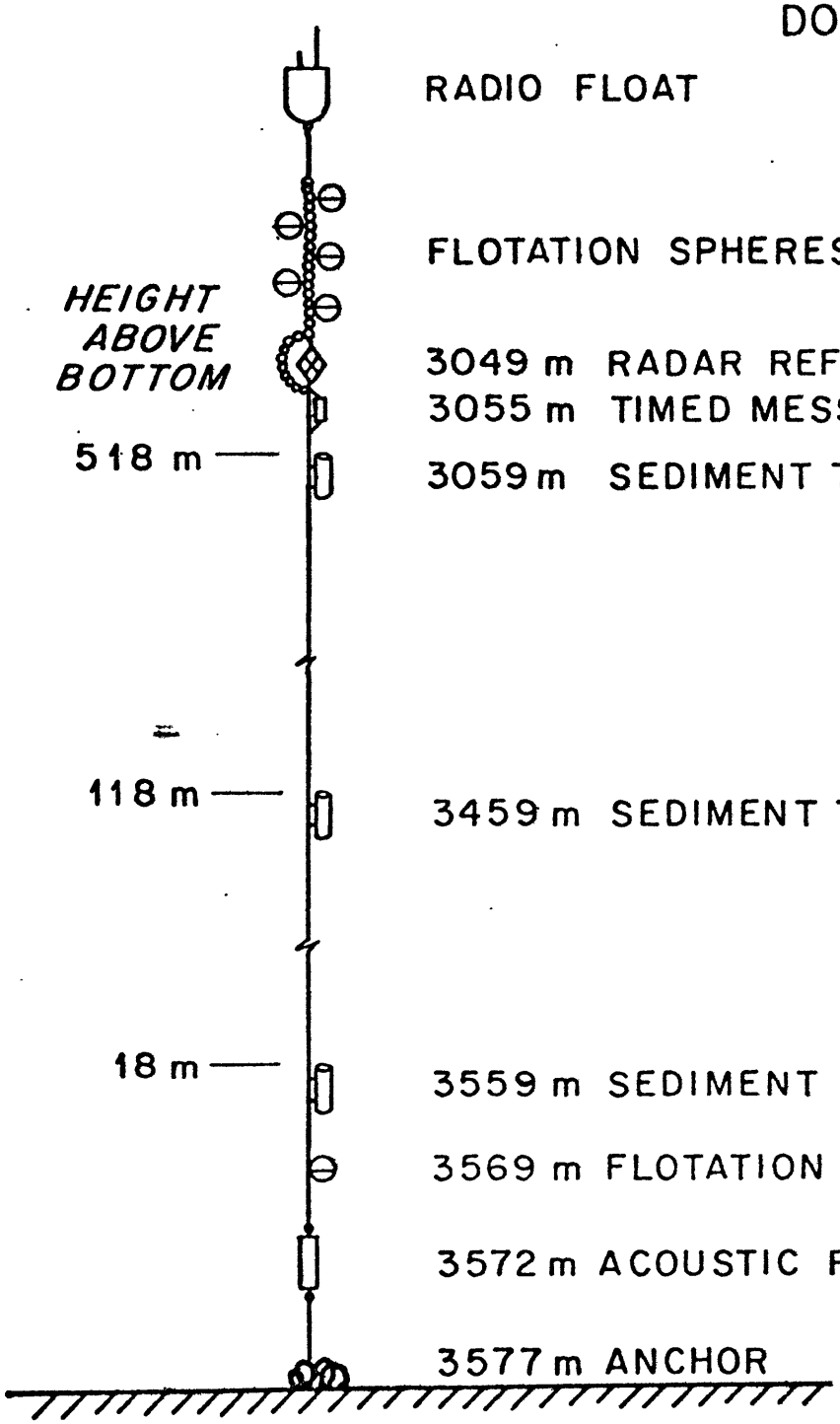

DWD 106
2154 m TIMED MESSENGER RELEASE
2157 m SEDIMENT TRAP 3
2161 m SEDIMENT TRAP 2
2164 m SEDIMENT TRAP 1
2166 m ACOUSTIC RELEASE
8 ℓ
NISKIN
BOTTLES
2198 m ANCHOR
HEIGHT ABOVE BOTTOM (m)
40
30
20
10
0


KNORR 58-1
RADIO FLOAT
GLASS SPHERE
2782m TIMED MESSENGER RELEASE
2788 SEDIMENT TRAP 3
2794 SEDIMENT TRAP 2
2800 SEDIMENT TRAP 1
2806 TIMED ANCHOR RELEASE
2815m ANCHOR
NISKIN BOTTLE SAMPLE
HEIGHT ABOVE BOTTOM (m)
40
30
20
10

KNORR 58-2


FLAG
FLOTATION SPHERES
HEIGHT ABOVE BOTTOM
500 m
2315m SEDIMENT TRAP 3
WITH TIMED RELEASE
100 m
2715m SEDIMENT TRAP 2
WITH TIMED RELEASE
13 m
2802m SEDIMENT TRAP 1
WITH TIMED RELEASE
2815m ANCHOR

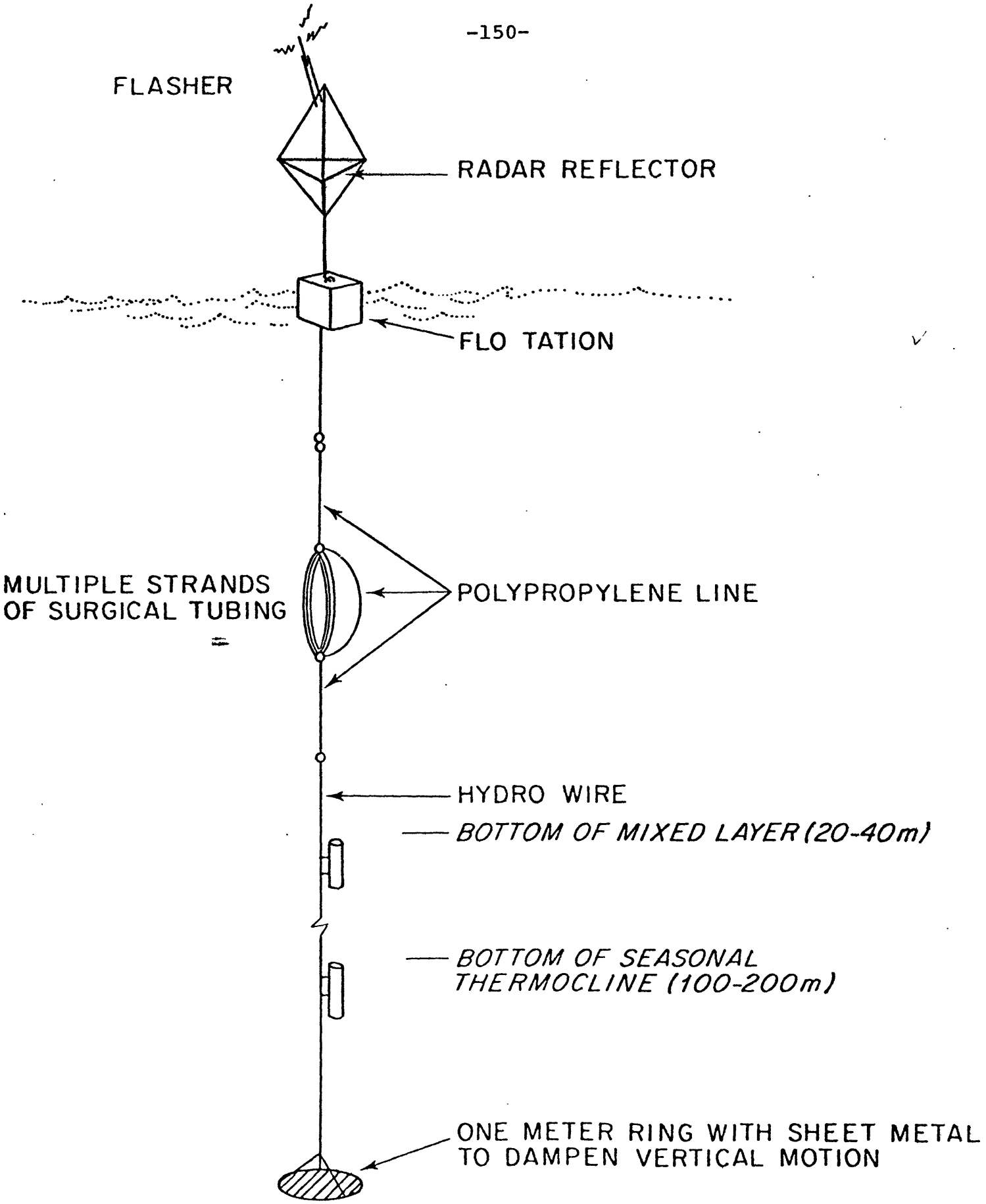
DOS # 2


RADIO FLOAT
FLOTATION SPHERES
HEIGHT ABOVE BOTTOM
3049 m RADAR REFLECTOR
3055 m TIMED MESSENGER RELEASE
518 m
3059 m SEDIMENT TRAP 3
118 m
3459 m SEDIMENT TRAP 2
18 m
3559 m SEDIMENT TRAP 1
3569 m FLOTATION SPHERE
3572 m ACOUSTIC RELEASE
3577 m ANCHOR

layer designed to look for any near-bottom gradient in the total particulate flux (fig. 4.6). The fourth array (DWD #106) had three traps within or near the top of the nepheloid layer; because of logistical limitations, they were spaced very close together on the mooring (fig. 4.6a).

Floating sediment traps were deployed for 12 hours at night and during the day northeast of the DWD 106 site at the base of the mixed layer (40 m) and near the base of the seasonal thermocline (100 m) to collect particles immediately below the regions of particle production and remineralization. Traps moored from the sea floor to this level would make poor collectors because of large vertical excursions on such long arrays. As long as the wave motion can be damped out, floating traps are much more effective near the sea surface than moored arrays. Furthermore, traps moving with a water mass have less turbulent mixing inside to bias particle collections. To attenuate the vertical wave energy transferred to the traps a section of highly elastic surgical tubing was used as part of the mooring line near the surface. A one-meter ring was covered with sheet metal and hung below the bottom trap to reduce vertical motion of the array (fig. 4.7).

Fig. 4.7 Two deployments of floating traps were made for about 12 hours each during the day and night to sample the particulate flux at the base of the mixed layer (40 meters in both deployments) and near the bottom of the seasonal thermocline (100 meters in both deployments. To diminish the vertical motion of the traps caused by surface waves, a section of surgical tubing was inserted in the line above the traps and a damper was connected below the traps. By discharging dye from hypodermic needles while SCUBA diving on a one hundred foot version of this array it was possible to observe the motion of the trap relative to the surrounding water. Most of the relative motion was eliminated, but further coupling of the trap motion with the surrounding water may be accomplished by putting traps at only one level and putting drogues closer to the traps (Staresinic, et al., 1977).


FLASHER
RADAR REFLECTOR
FLO TATION
MULTIPLE STRANDS
OF SURGICAL TUBING
POLYPROPYLENE LINE
HYDRO WIRE
BOTTOM OF MIXED LAYER (20-40m)
BOTTOM OF SEASONAL
THERMOCLINE (100-200m)
ONE METER RING WITH SHEET METAL
TO DAMPEN VERTICAL MOTION

Whenever sediment traps were deployed, a hydrocast and a one-meter gravity core were taken to obtain suspended and deposited particles for comparison with particles caught by the traps. Hydrocasts were taken at nine other stations in the western Atlantic Ocean (fig. 4.8) to obtain a more widespread picture of the height and intensity of nepheloid layers and the size and state of aggregation of suspended particles.

E. TREATMENT OF SEDIMENT TRAP SAMPLES TAKEN FROM THE WESTERN NORTH ATLANTIC

A standard procedure developed for handling the water and sediment from the traps is as follows (see fig. 4.9 for a flow diagram). Upon recovery of the traps, water above the lids is immediately siphoned off. By rotating the lids at this point and looking at the bottom of the trap, one can see that most of the sediment is at the bottom of the trap despite constant motion during recovery. Even so, the traps are allowed to sit for one hour so that any sediment stirred up during the recovery procedure can settle back to the bottom.

Particles tend to collect in the spigot, so the first 50 ml of water drawn from the spigot is separated and put on a separate filter or added to the whole sample during splitting. The water between the lid and spigot is sucked

Fig. 4.8 Location of hydrocasts (solid dots), moored trap arrays (solid squares) and floating trap arrays (open circle) in the Western North Atlantic. Stations were taken from the SUB SIG II (SS), USS DALLAS (D), R/V KNORR (KN), and R/V OCEANUS (numbers only). See figures 5.1-2 for profile of suspended particulate concentration and Appendix D for data from these hydrocasts.

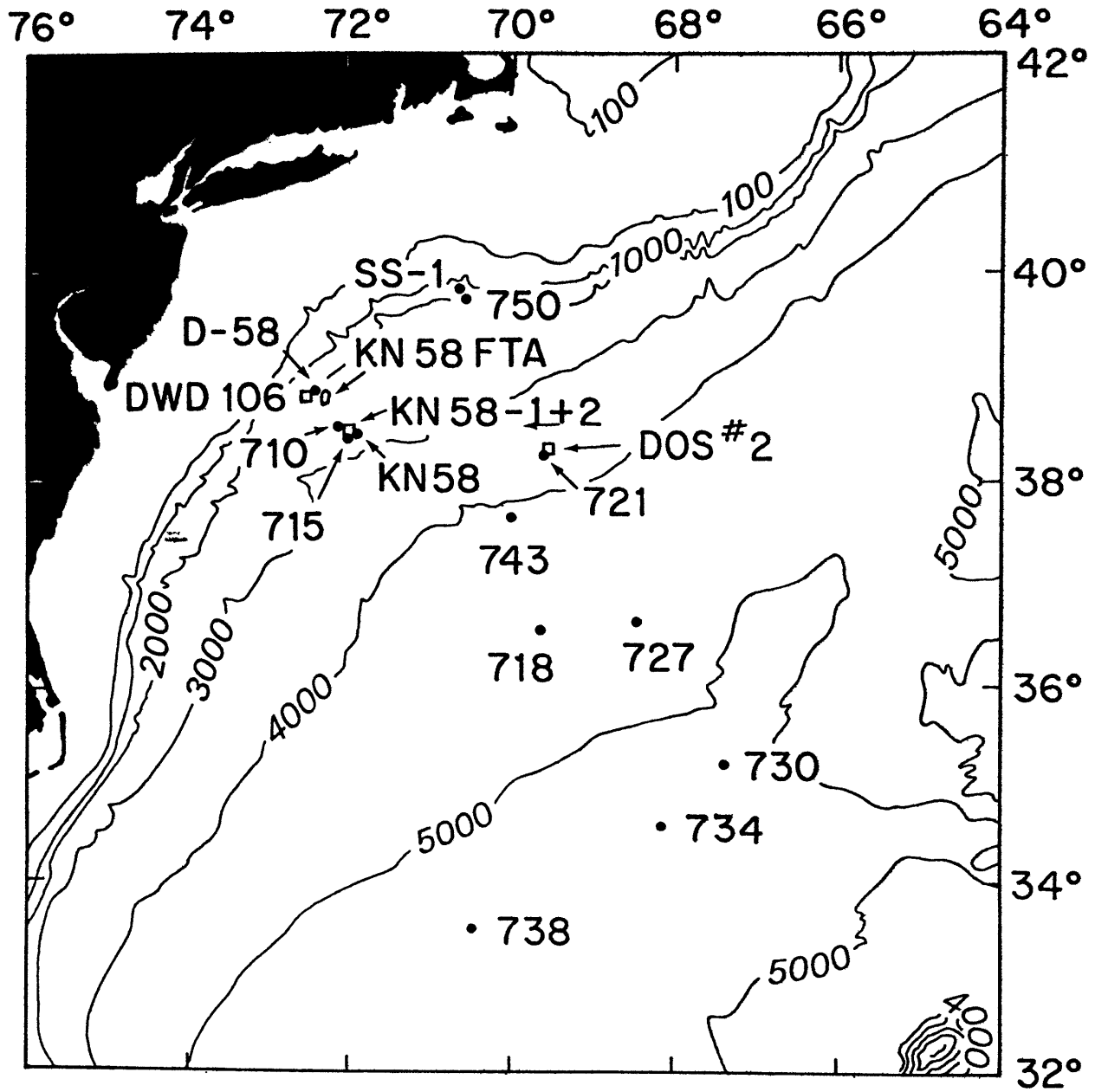
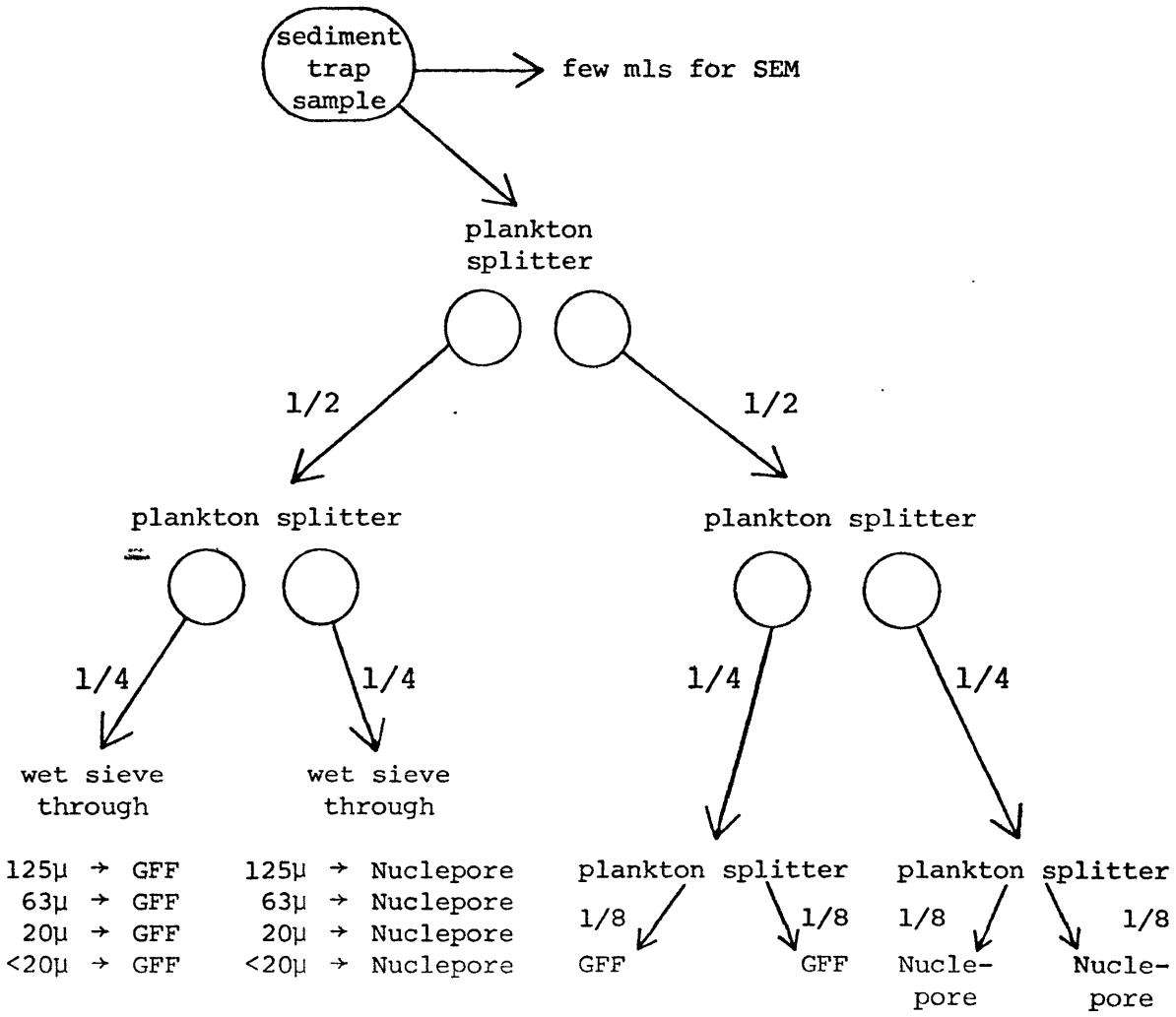

76°
74°
72°
70°
68°
66°
64°
42°
40°
38°
36°
34°
32°
100
100
1000
SS-1
750
D-58
KN 58 FTA
DWD 106
KN 58-1+2
710
DOS #2
KN58
721
715
743
718
727
730
734
738
2000
3000
4000
5000
5000
5000
4000

Figure 4.9

FLOW DIAGRAM OF HANDLING PROCEDURE USED FOR SEDIMENT TRAP SAMPLES



directly from the spigot through a precombusted and preweighed glass-fiber filter. The remaining sediment and water (about 4 liters) is gently poured into a clean PVC bucket. After gently stirring the water to homogenize the sediment, a 2-4 ml sample is taken with a pipette and filtered under low vacuum (5-10 psi) through a 0.6 μm Nuclepore filter for examination with scanning electron microscope (SEM). The water is then poured into a two-part plankton splitter and separated in several steps into two samples, each containing one-quarter of the total sediment, and four samples, each containing one-eighth of the total trapped sediment. Two of these eighths are filtered onto separate precombusted, preweighed, glass-fiber filters (GFF) for analysis for organic matter (CHN), and the other two eighths are filtered onto two preweighed Nuclepore filters for microscope, x-ray diffraction and chemical analyses. The one-quarter samples are carefully washed through 125, 63, and 20 μm sieves and each fraction is then sucked onto separate filters, one each set onto glass fiber and the other set onto Nuclepore filters for weighing and analysis of each size fraction. It is possible that the sieving process breaks up fragile particles, but it was noted that, after the sample had been poured through the sieve, the distilled water wash did not carry many additional particles through the 125 or 63 μm sieves.

The 20 μm screen was a 55 mm square piece of etched nickel micro-mesh (Buckmee Mears) that was used with a Millipore glass funnel filtering setup and separated from the Nuclepore or glass-fiber filter below it with rubber gaskets. Because of the small pore opening the screen became clogged easily. The material was resuspended twice and allowed to settle down again before it was washed onto the filter reserved for the 20-63 μm fraction. This process was repeated two or three times before all of the subsample was sucked through the 20 μm screen. Because of this extensive treatment, fragile particles smaller than 63 μm could have been broken up, so the accuracy of the 20 μm separation is suspect, but it does give us for the first time a first-order approximation of the size distribution of particles in transit down through water column. In the future a 20 μm sieve with a 3 inch diameter will be used to improve the accuracy of the separation.

To determine the size distribution of the <20 μm fraction, a few drops of sample were collected after passing through the 20 μm sieve and diluted with filtered sea water to a suitable concentration for size analysis with a model TA II Coulter counter (Sheldon and Parsons, 1967). These samples were run on board ship soon after trap recovery.

The water and sediment from each trap were covered and refrigerated at 4°C until they could be processed, usually within a few hours of retrieval. All filters were rinsed 10 times with filtered, distilled water, frozen, and upon return to the laboratory were oven dried at 50°C for 24 hours. After another 24 hours in a humidity-controlled room they were reweighed. Blank Nuclepore and glass fiber filters were treated with the same washing, drying and weighing procedures to correct for any changes. Nuclepore filters seldom need any correction, but glass-fiber filter weights are unstable, mostly because of the loss of glass fibers when the filter is wet.

Washing samples with distilled water has the potential of lysing cells and losing some of the organic compounds. However, this is mostly a problem with living cells, and the likelihood that cells caught in traps are still living or whole decreases rapidly with depth. Therefore, the problem of lysing particles in trap samples is not believed to be severe, though no tests were made.

A system was implemented for poisoning the material in the trap at 18 m at DOS #2 to preclude bacterial decay during deployment. A glass bottle containing mercuric chloride crystals was cemented to the bottom of the trap.

The bottle was covered with a fine mesh screen that allowed slow diffusion into the trap. Solid crystals were still left in the bottle after recovery. The effect of the poison is unknown because there was no control sample for comparison. This particular trap lost an unknown amount of material through a crack at the trap bottom.

An experiment by Johnson and Brinkhurst (1971) in a lake suggested that 15-25% of the organic material in their trap was consumed over a period of six days. However, this percentage difference is within the range of variation of replicate samples (Hargrave, et al., 1976; Webster et al., 1975). Furthermore, rates of microbial decay are much slower in the deep ocean than in shallow depths (Jannasch et al., 1971). The material reaching the sea floor is also likely to be the more refractory organic components (Menzel, 1974).

The above method of sample treatment evolved in time for use with the KN-58 arrays after earlier methods proved unsatisfactory on the first two arrays. For DOS #2 the water between the lid and the spigot was drained through the spigot into clean glass carboys and later filtered through 0.6 μm Nuclepore or glass-fiber filters. The water below the spigot was gently poured into a clean PVC bucket, a 4 ml sample drawn for SEM examination, and a

10 ml sample taken for analysis of the size distribution with a Coulter counter. The concentrated sample was then centrifuged in 50 ml tubes at 3000 RPM for ten minutes. The supernatant liquid was poured off, and to prevent any loss of particulates, was filtered through 0.6 μm Nuclepore filters, washed ten times with filtered, distilled water, dried and weighed. Each transfer of sample from one tube to another necessitated washing with distilled water, so that by the time the sample was concentrated into one tube most of the salt had been removed, but the tube was filled with distilled water and centrifuged two or three more times. After washing the sample into a pre-weighed glass vial, it was dried at 60°C, cooled in a desiccator and weighed.

This method does not allow size-fractionation measurements of the sample because once the sample has dried in the vial its state is completely changed. Only the samples taken for SEM could be used to determine particle morphology. Chemical analyses could be adequately performed by grinding the sample to homogenize it and take subsamples for replicates and different analyses. However, to separate some of the large organisms and obtain subsamples similar to those from KN-58-1 and 2, the samples were resuspended in distilled water and treated in the manner of the KN-58 samples.

After the samples from DWD #106 were poured from the traps, subsamples of about 50 ml were taken for examination with SEM. The rest of the water below the spigots was filtered onto glass fiber filters, each filter being used until it became clogged. Because of possible size fractionation during pouring, each filter may not have a totally representative sample of what was caught in the trap. Thus, it was necessary to use a section of each filter from the trap when doing quantitative analyses.

F. CARBONATE, ORGANIC CARBON AND ORGANIC NITROGEN ANALYSIS

Carbonate content was assumed equivalent to the fraction of weight loss after several tens of milliliters of phosphoric acid were passed by gravity through the precombusted glass-fiber filters containing samples. Sample weights of 5-35 mg were used to calculate weight changes ranging from 20-70%. The organic carbon and nitrogen were determined by combustion in a CHN analyzer and corrected by blank filters containing no sample, but exposed to the same procedure.

The three traps on the mooring on the continental slope (DWD #106) were so close together (all within 6 m at 33 m above the bottom) it may be possible to treat them as replicate samples. Otherwise, there were no duplicate trap samples available from the deep-sea moorings to determine reproducibility. This problem was discussed in Chapter II.

G. ELEMENTAL ANALYSIS

Analysis was made for ten elements (Ba, Ti, Sr, Mn, Mg, Cu, V, Al, Ca, and I) using a method of instrumental neutron activation developed by Peter Brewer and Derek Spencer (W.H.O.I.). Samples analyzed included particles from traps, water bottles, and cores. Details of the method will be given in the next chapter.

CHAPTER V

RESULTS AND ANALYSIS OF SAMPLES COLLECTED

The sediment trap program has proven very successful. Eleven of the twelve traps recovered functioned properly and this has enabled us to calculate fluxes in the open ocean for the first time using calibrated traps. Sufficiently large samples were obtained to perform chemical and morphological analyses that will be described in this chapter.

A. SEDIMENT TRAP DATA AND PARTICULATE FLUXES

Following the model described in Chapter IV, the primary flux measured at the clear-water particle minimum is an approximation of the rate of pelagic sedimentation to the sea floor. Total sedimentation on the seafloor probably includes some sediment advected in horizontally. Therefore, the primary flux represents a minimum sedimentation rate and the total flux measured by a near-bottom trap represents a maximum sedimentation rate. As will be discussed in section H of this chapter, the atmospheric input of aluminum was lower than the aluminum flux at clear water suggesting that the particles collected at clear water included some resuspended material and resulted in overestimates of the primary flux. However,

because the atmospheric aluminum flux was not monitored during this experiment, calculations made in this chapter will assume the flux at the clear-water particle minimum is composed only of primary particles.

A regional picture of the concentration of suspended particulate matter from the slope to the abyssal plain is obtained from figures 5.1 and 5.2. These profiles cut through the sediment trap sites. Suspended particle concentrations were obtained by filtering water from Niskin bottles as described in Chapter III. The concentrations shown include the dregs at the bottom of the bottle which accounts for the values being higher than normally reported. See appendix D for data on these profiles.

The primary fluxes measured at the clear-water particle minimum (fig. 5.3) on the upper and mid-continental rise (KN 58-2 and DOS #2) were 4.2 and 8.8 $g/cm^2/1000$ y, and represent the minimum flux to the bottom at these sites. The total fluxes measured in the nepheloid layer were about twice those values (table 5.1). One way of evaluating whether these fluxes are realistic is to compare the sedimentation rate determined from sediment traps with the accumulation rate determined from cores. The accumulation rate differs from the sedimentation rate

Fig. 5.1 Cross-sectional profile of suspended particulate matter through trap arrays DWD 106 on continental slope and KN 58-1 and 2 on Upper Rise. Concentrations have been corrected for "dregs" (see Chapter III). Data appears in Appendix D.

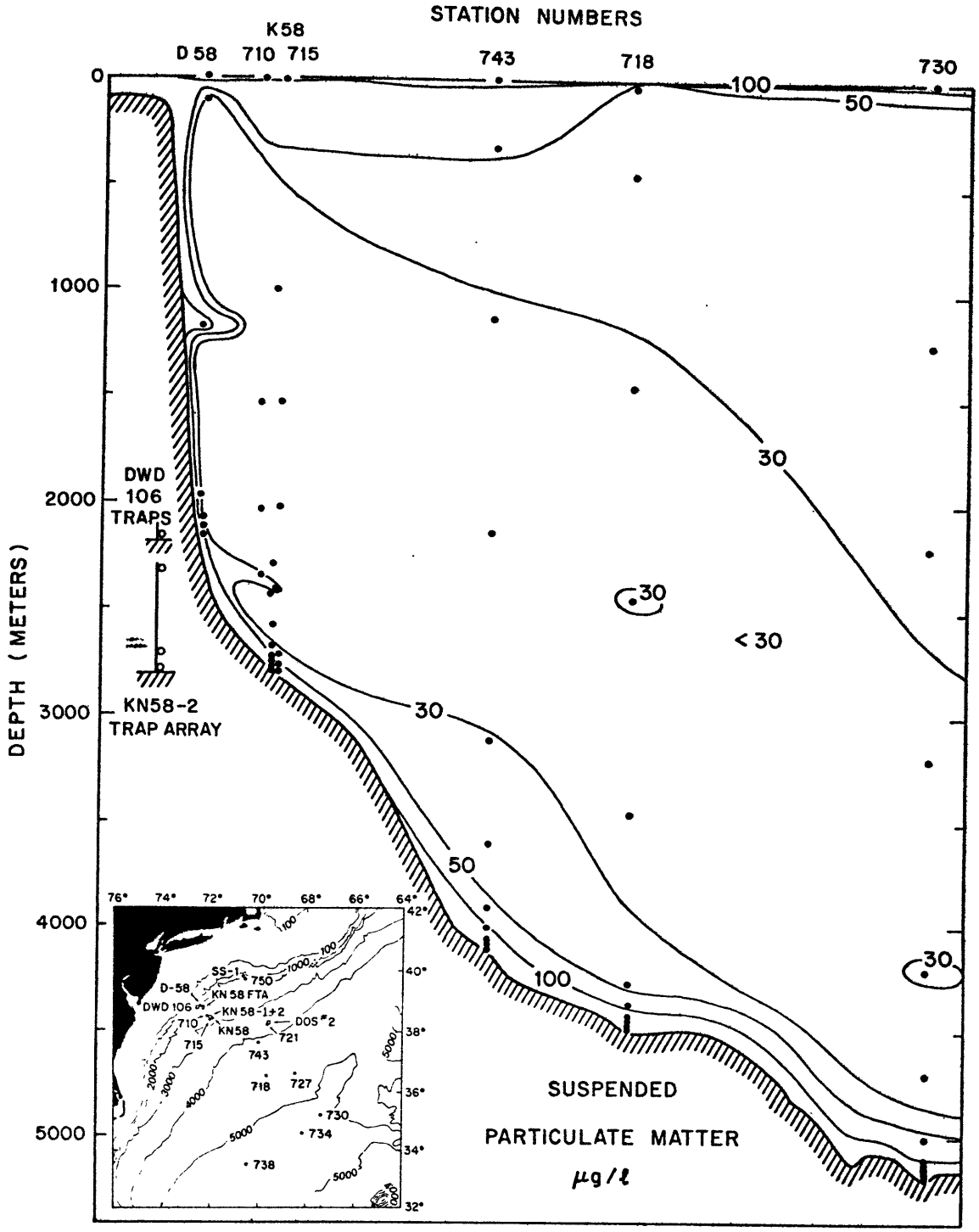

STATION NUMBERS
K58
D 58
710
715
743
718
730
0
1000
2000
3000
4000
5000
DEPTH (METERS)
100
50
30
< 30
DWD
106
TRAPS
KN58-2
TRAP ARRAY
SUSPENDED
PARTICULATE MATTER
µg/l
D-58
KN 58 FTA
DWD 106
KN 58-1+2
DOS #2
KN58
721
727
734
738

Fig. 5.2 Cross-sectional profile of suspended particulate matter through trap array DOS #2 on mid-Rise. Concentrations have been corrected for "dregs" (see Chapter III). Data appears in Appendix D.

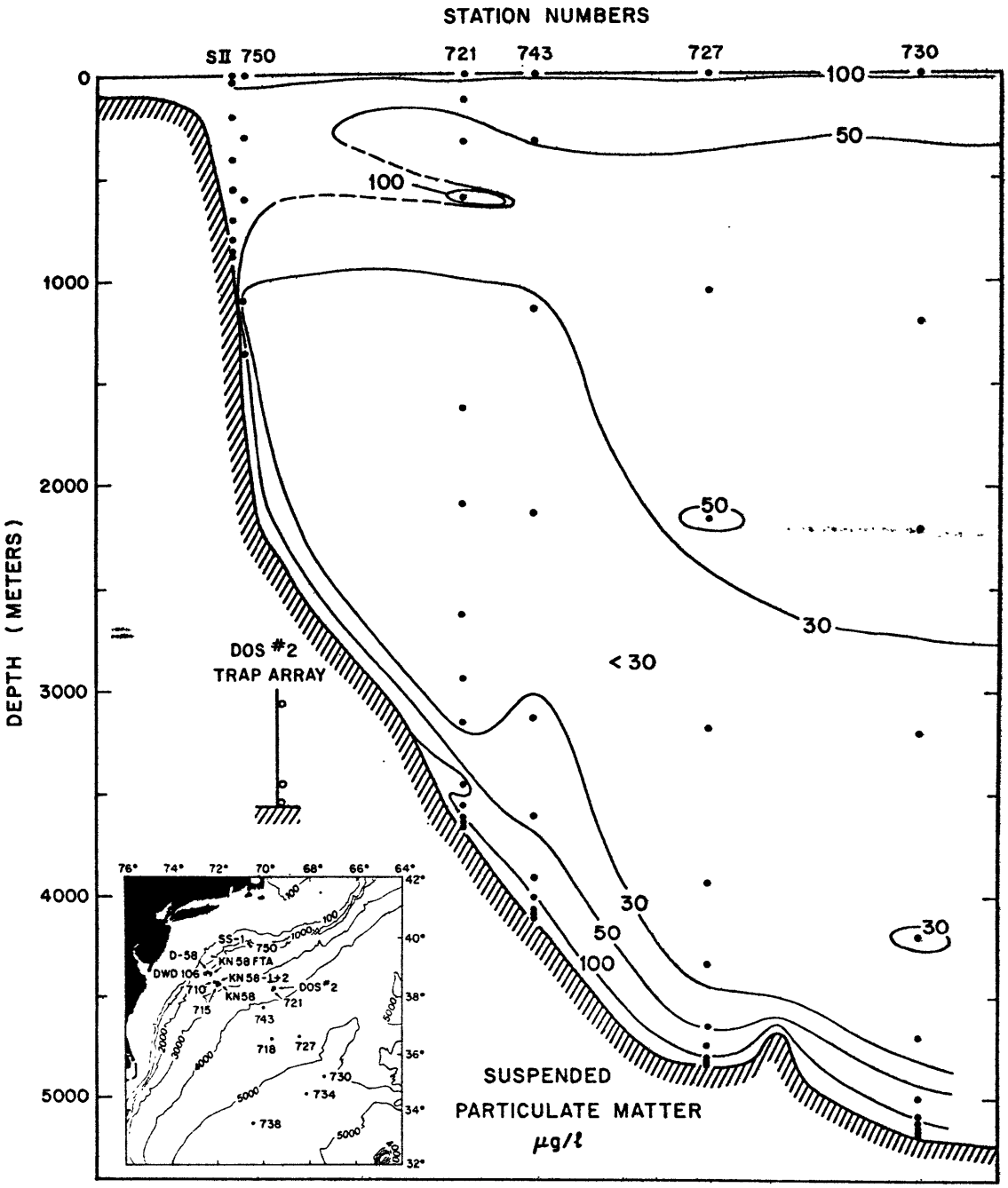

STATION NUMBERS
SII 750
721
743
727
730
0
1000
2000
3000
4000
5000
DEPTH (METERS)
100
50
100
50
30
< 30
30
50
100
30
DOS #2
TRAP ARRAY
SUSPENDED
PARTICULATE MATTER
µg/l
76°
74°
72°
70°
68°
66°
64°
42°
40°
38°
36°
34°
32°
SS-1
750
D-58
KN 58 FTA
DWD 106
KN 58-1+2
DOS #2
710
KN58
721
715
743
718
727
730
734
738
2000
3000
4000
5000

Fig. 5.3 Profile of suspended particulate matter at trap site DOS #2 on the mid-Rise. Nearby nephelometer profile taken eight years earlier is also shown. Rectangles indicate levels where traps were deployed.

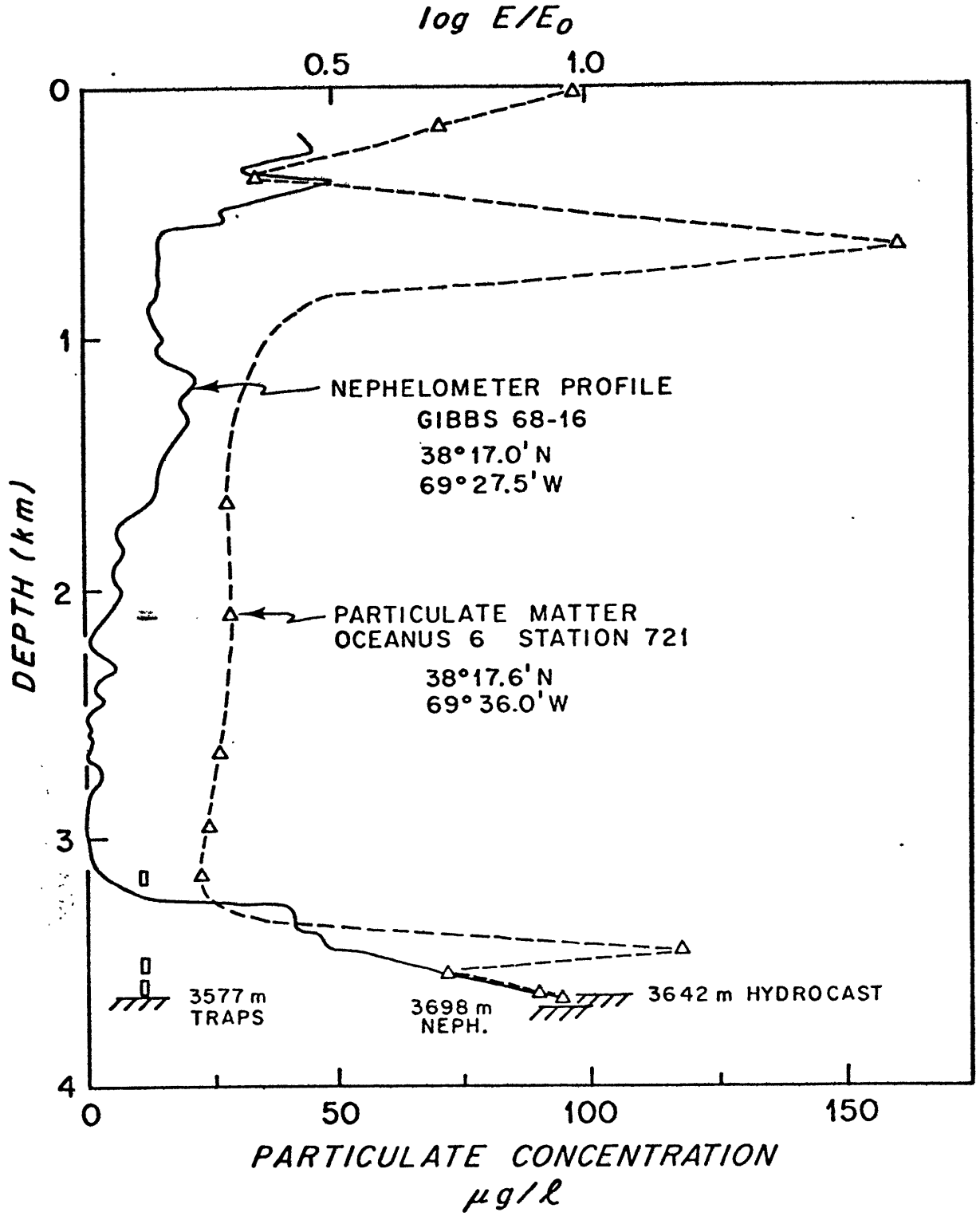

log E/E0
0.5
1.0
0
1
2
3
4
DEPTH (km)
NEPHELOMETER PROFILE
GIBBS 68-16
38°17.0'N
69°27.5'W
PARTICULATE MATTER
OCEANUS 6 STATION 721
38°17.6'N
69°36.0'W
3577 m
TRAPS
3698 m
NEPH.
3642 m HYDROCAST
0
50
100
150
PARTICULATE CONCENTRATION
μg/ℓ

TABLE 5.1

COLLECTIONS AND FLUXES FOR MOORED SEDIMENT TRAPS

TRAP	DEPTH (M)	METERS ABOVE BOTTOM (M)	TOTAL WT. TRAPPED (mg)	TOTAL FLUX CALCULATED *g cm^{-2} $1000y^{-1}$ ($g\ m^{-2}\ d^{-1}$)	PRIMARY FLUX (F_P) *g cm^{-2} $1000y^{-1}$ ($g\ m^{-2}\ d^{-1}$)	RESUSPENSION FLUX (F_{RZ}) *g cm^{-2} $1000y^{-1}$ ($g\ m^{-2}\ d^{-1}$)
DWD 106 23-29 June 1976 (5.8d) 38°50'N 72°31'W						
3	2156	36	133	16.9 (0.47)	-	-
2	2159	33	97	12.4 (0.34)	-	-
1	2162	30	98	12.5 (0.35)	-	-
KN 58-1 11-21 August 1976 (10.1d) 38°28.2'N 72°01.0'W						
3	2788	27	141	10.3 (0.28)	-	-
2	2794	21	131	9.58 (0.26)	-	-
1	2800	15	127	9.29 (0.25)	-	-
KN 58-2 21 August -- 1 September 1976 (10.7d) 38°28.5'N 72°02.3'W						
3	2316	500	61	4.20 (0.11)	4.2 (0.11)	-
2	2715	100	81	5.62 (0.15)	-	1.4 (0.033)
1	2803	13	129	8.92 (0.24)	-	4.7 (0.13)
DOS #2 15-31 May 1976 (15.8d) 38°19'N 69°37'W						
3	3059	518	189	8.84 (0.24)	8.8 (0.24)	-
2	3459	118	354	16.6 (0.46)	-	7.8 (0.21)
1	3559	18	166**		-	?

* Multiply these values by 10 to obtain units of g m^{-2} y^{-1}

** Unknown amount of particulate matter lost due to crack in trap.

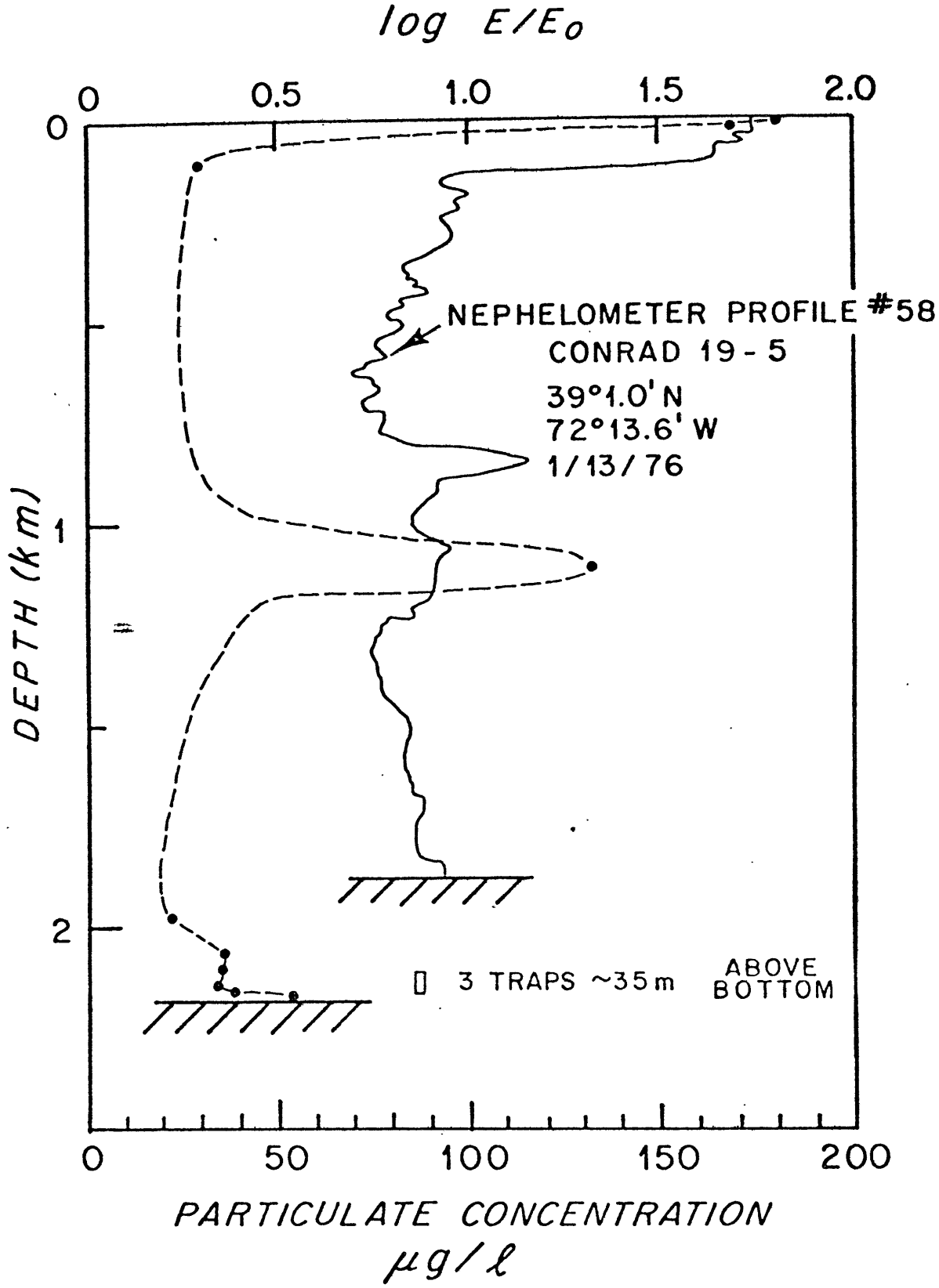
in that the former represents the sediment remaining after the completion of diagenetic changes such as oxidation or consumption of organic matter, dissolution of carbonate and silicate, and cation exchange in buried sediments.

An extrapolation of processes measured over a period of days versus thousands of years is admittedly large and does not take into account seasonal variations. Nevertheless, it allows us for the first time to compare trap fluxes with accumulations rates in the ocean determined from cores, and the correlation is remarkably good. One core less than fifteen miles from DOS #2 has a post-glacial sedimentation rate between 6 and 7 $g/cm^2/1000$ y (Turekian, 1965), compared with the primary flux of 8.8 $g/cm^2/1000$ y and total flux measured 118 m above bottom of 16.6 $g/cm^2/1000$ y. Values calculated from averages over the last 18,000 years in the area are in the same range or higher than that of Turekian (Biscaye, unpublished CLIMAP data). Emery et al. (1970) calculated sedimentation rates on the lower slope and upper rise to be greater than 6 cm/1000 yr on the East Coast of North America.

The traps on the slope array (DWD 106) were very close together (3 m separations), and they caught approximately the same amount of sediment. The percentage variation among the three traps (30%) was no greater than the

variation among four traps moored at the same level in a bay (Hargrave et al., 1976). Nearby nephelometer lowerings and a hydrocast at the trap site showed only a slight increase in particles near the bottom, and the traps were above the strongest gradient (fig. 5.4). A regional study by Biscaye and Olsen (1976) showed this portion of the slope to be a zone of relatively low near-bottom concentrations of suspended sediment. During an ALVIN dive made near the trap array with Dr. Gilbert T. Rowe, we observed no evidence of any recent strong current activity such as ripples, scour marks, or preferential deposition around rocks. Currents never exceeded 5 cm/sec while ALVIN was near the bottom during four dives. Outcrops of white chalk up to 10 m high were abundant, indicating erosion in the past, but rocks and World War II munitions boxes on the bottom all had a slight draping of sediment (<1 cm) suggesting very tranquil conditions for at least tens of years. Therefore, even though the traps were not totally above the weak nepheloid layer, they were probably not collecting a significant amount of locally resuspended material. However, it is difficult to monitor the primary flux over the continental slope because the slope is so steep that it takes very little horizontal movement of resuspended particles to enter traps moored

Fig. 5.4 All three traps on the continental slope at DWD 106 were clustered within 6 meters centered around 35 meters above the bottom. All traps were above the two water samples showing the highest concentrations of suspended particulates. No traps were moored at the clear water minimum. The nephelometer profile was taken 32 kilometers away on the slope a few months before the trap was deployed.


log E/E₀
0
0.5
1.0
1.5
2.0
NEPHELOMETER PROFILE #58
CONRAD 19-5
39°1.0' N
72°13.6' W
1/13/76
DEPTH (km)
1
2
3 TRAPS ~35m ABOVE BOTTOM
0
50
100
150
200
PARTICULATE CONCENTRATION
μg/ℓ

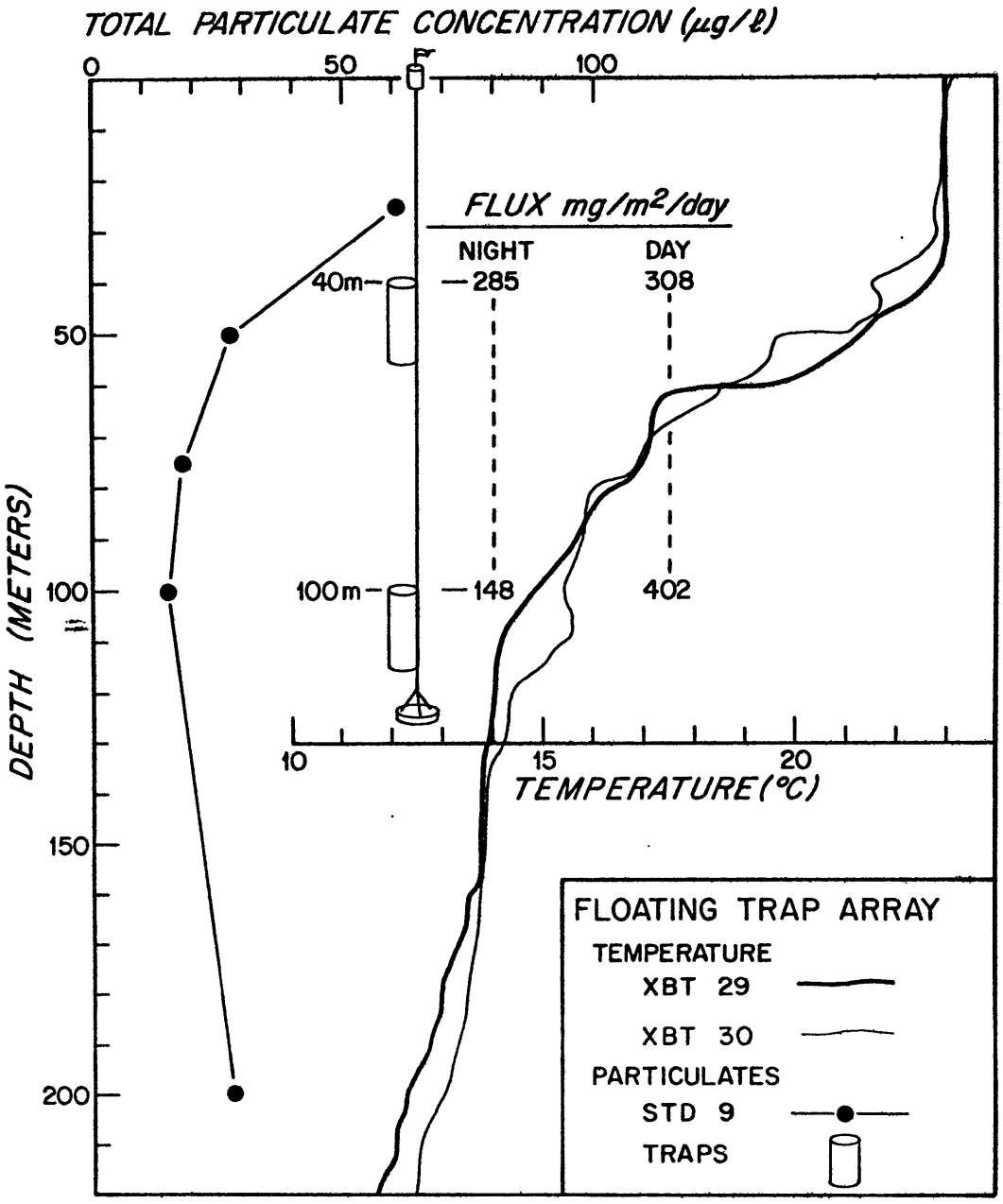
hundreds of meters above the bottom from a position down slope. The average flux of 13.3 g/cm^2/1000 y determined for the three traps on the slope is therefore a maximum.

B. FLOATING SEDIMENT TRAPS

In order to collect particles falling from the photic zone, sediment traps were located at the base of the mixed layer and at the base of the seasonal thermocline. This was possible only by using floating sediment traps as described in Chapter IV and by Staresinic et al. (1977). A daytime and a nighttime deployment were made while the moored array was on the upper slope (KN 58-2; see fig 4.5 for location). An XBT was launched before each deployment of floating traps to determine the thermal structure (fig. 5.5).

During the nighttime deployment, the trap at 40 m collected nearly twice the total matter collected at 100 m, probably reflecting grazing and defecation by zooplankton and fish in the neuston. The resulting detritus was collected at 40 m, but was more decomposed by the time it reached 100 m. The daytime collection was 30% greater at 100 m than 40 m. This may be because maximum productivity usually occurs below 40 m, although the single profile of suspended particulate matter does not show a maximum below that level at that time.

Fig. 5.5 Floating traps deployed in slope water between DWD 106 and KN 58 were placed at the base of the mixed layer and near the bottom of the seasonal thermocline. Deployment was made in early September. The temperature structure as well as concentration of suspended particulates are shown along with the fluxes measured at two depths.


TOTAL PARTICULATE CONCENTRATION (µg/ℓ)
0
50
100
FLUX mg/m²/day
NIGHT
DAY
40m
285
308
100m
148
402
50
100
150
200
DEPTH (METERS)
10
15
20
TEMPERATURE (°C)
FLOATING TRAP ARRAY
TEMPERATURE
XBT 29
XBT 30
PARTICULATES
STD 9
TRAPS

The total flux measured by the floating traps is not significantly higher than the primary flux measured at clear water over 2000 m deeper. Although Menzel and Ryther (1970) stated that nearly all recycling of organic matter occurred in relatively shallow surface waters, another explanation of the low flux comes from net tows and physical oceanographic data obtained on the same cruise. The temperature and salinity data from numerous CTD lowerings, the tracks of free-drifting drogues, and satellite photos indicated the floating traps were in an old warm core ring from the Gulf Stream. Collections of zooplankton made with the 3 m by 4 m net of Wiebe et al. (1976) were much smaller within the warm core ring than outside of it (S. Boyd and J. Craddock, personal communication).

C. LARGE PARTICLE FLUX AND SIZE DISTRIBUTION OF COLLECTED PARTICLES

One of the primary goals of this study was to determine the morphological state in which particles settled through the water column and the size of particles responsible for the flux of material in the oceans.

1. Source of Large Particles

Long ago it was observed that deep-sea sediments reflected the composition of the phytoplankton in overlying waters (Murray and Renard, 1891). However,

individual phytoplankton are so small that they could be carried thousands of kilometers before they reach the bottom if they fall individually according to Stokes Law (see figs. 5.6 and 5.7). Many authors (Marshall and Orr, 1955; Osterberg et al., 1963; Smayda, 1969, 1970, 1971; Schrader, 1971; Manheim et al., 1972; Fowler and Small, 1972; Honjo, 1975; Cherry et al., 1975) have therefore suggested that zooplankton feeding and subsequent transport in fecal pellets enable the phytoplankton to rapidly reach the bottom before they become dispersed geographically or, in the case of siliceous and carbonate organisms, dissolved when in contact with water undersaturated in those ions. The rapid exponential decrease in the concentration of particles below the photic zone also suggests rapid removal by decomposition, dissolution, or aggregation into large particles followed by rapid gravitational settling.

2. Predicted Size Distribution of Particles Responsible for Flux

Studies of particle size distributions in oceanic waters have indicated that the mean particle size is 3-6 μm (Sheldon et al., 1972; Carder et al., 1971; McCave, 1975; Gardner, unpublished data). These samples are taken from water bottles that do not usually catch the rare, large particles, and (as discussed in Chapter III) when they are caught, they are seldom extracted from the bottle.

Fig. 5.6 The settling velocity of small particles in still water is best described by Stokes' law, and is plotted here assuming different densities and water temperatures (which alter the viscosity). By measuring particle sizes and measuring density (a difficult task), one can estimate the fall velocity. A range of empirically derived fall velocities are shown for several biological particles based on compilations from Smayda (1970), and Fowler and Small (1972). The size range of these particles are not shown, but can be inferred.

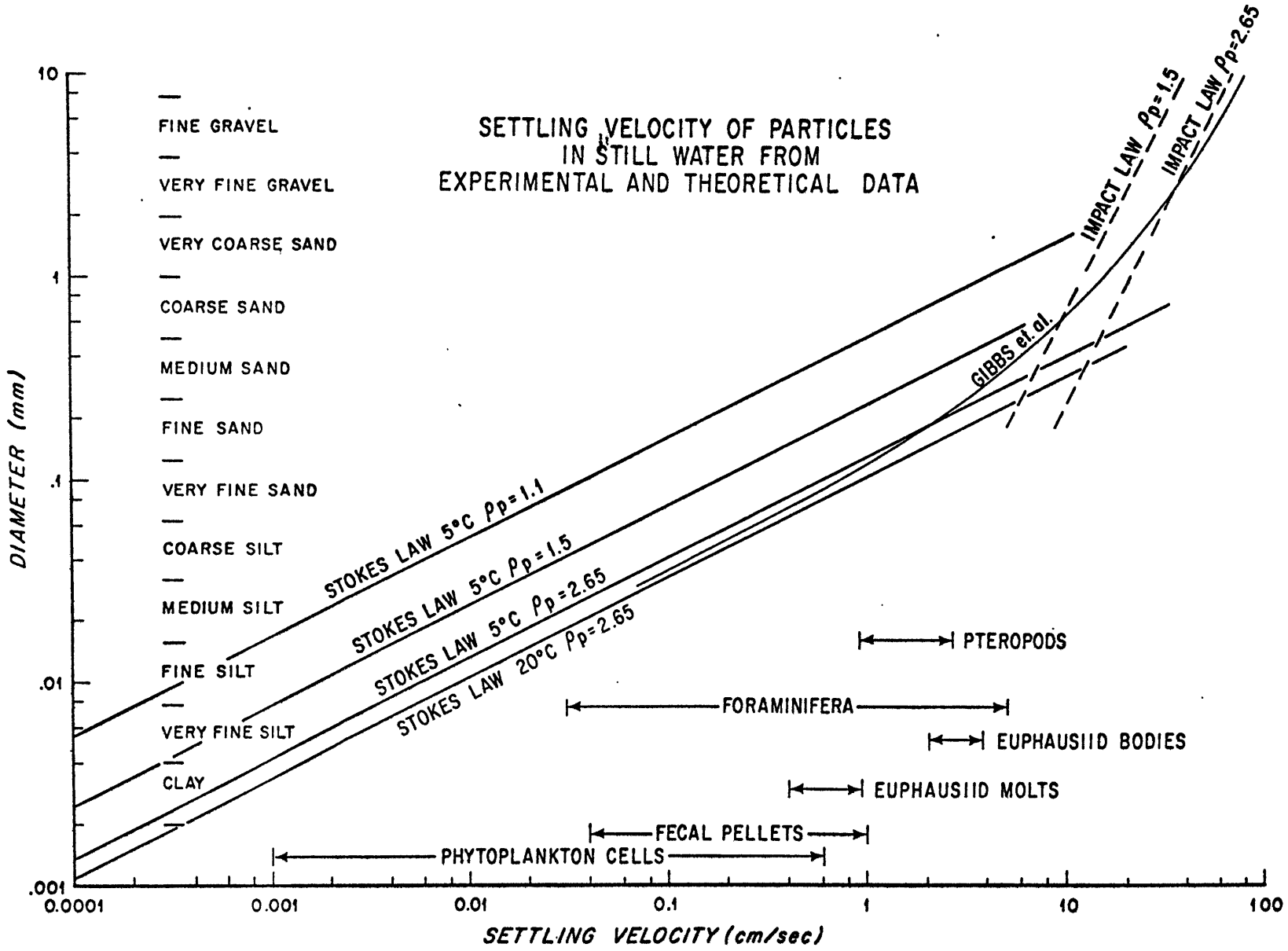
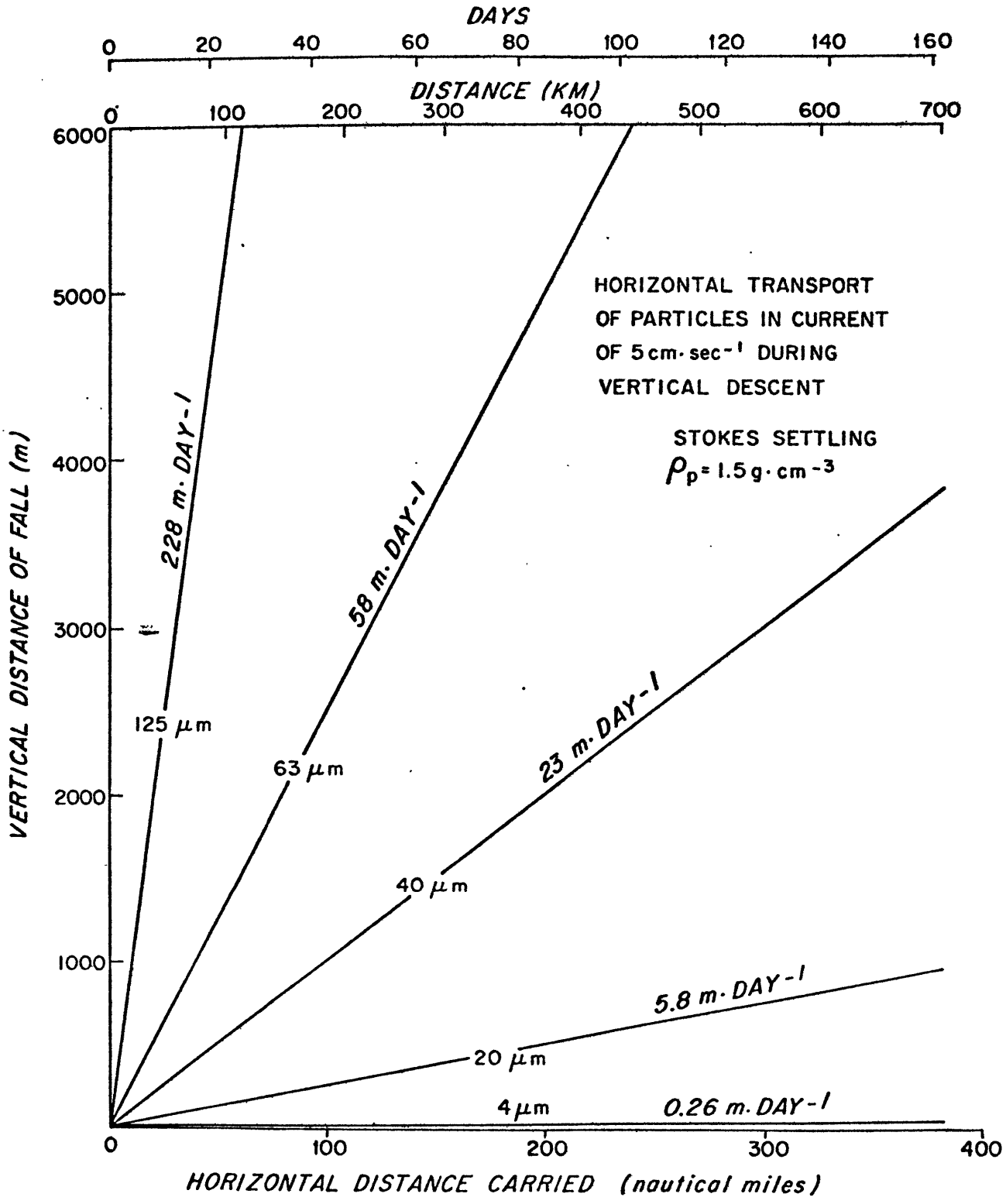

SETTLING VELOCITY OF PARTICLES
IN STILL WATER FROM
EXPERIMENTAL AND THEORETICAL DATA
DIAMETER (mm)
SETTLING VELOCITY (cm/sec)
10
1
.1
.01
.001
0.0001
0.001
0.01
0.1
1
10
100
FINE GRAVEL
VERY FINE GRAVEL
VERY COARSE SAND
COARSE SAND
MEDIUM SAND
FINE SAND
VERY FINE SAND
COARSE SILT
MEDIUM SILT
FINE SILT
VERY FINE SILT
CLAY
STOKES LAW 5°C ρp=1.1
STOKES LAW 5°C ρp=1.5
STOKES LAW 5°C ρp=2.65
STOKES LAW 20°C ρp=2.65
GIBBS et al.
IMPACT LAW ρp=1.5
IMPACT LAW ρp=2.65
PTEROPODS
FORAMINIFERA
EUPHAUSIID BODIES
EUPHAUSIID MOLTS
FECAL PELLETS
PHYTOPLANKTON CELLS

Fig. 5.7 Horizontal advection may be important when considering the source of particles collected by sediment traps. Most currents in the ocean are neither steady nor uniform in speed or direction, but the 5 cm/sec current velocity used for calculations here allow an estimate of the distance particles of different fall velocities might be carried as they sink through the water column.


DAYS
0 20 40 60 80 100 120 140 160
DISTANCE (KM)
0 100 200 300 400 500 600 700
6000
5000
4000
3000
2000
1000
VERTICAL DISTANCE OF FALL (m)
HORIZONTAL TRANSPORT
OF PARTICLES IN CURRENT
OF 5 cm·sec⁻¹ DURING
VERTICAL DESCENT
STOKES SETTLING
ρ_p = 1.5 g·cm⁻³
228 m·DAY⁻¹
58 m·DAY⁻¹
23 m·DAY⁻¹
5.8 m·DAY⁻¹
0.26 m·DAY⁻¹
125 μm
63 μm
40 μm
20 μm
4 μm
0 100 200 300 400
HORIZONTAL DISTANCE CARRIED (nautical miles)

McCave (1975) has eloquently pointed out that in calculating the downward flux of particles it is not the particle number concentrations which determine the total flux of detritus, but the product of the mass of particles and their settling velocities. It is difficult, however, to accurately determine either the size concentration or the settling velocity of particles (a function of size and density) by taking water samples even as large as hundreds of liters. First, we do not know to what degree the sampling methods break up the loosely aggregated "marine snow" commonly seen from submersibles. Nor has anyone precisely shown what part of a flocculated particle is actually "seen" by electro-sensing counters--the commonly used method of sizing particles. And finally, no method has been devised to measure the density of each particle as well as its size.

Nevertheless McCave (1975) has modeled the flux of particles based on a range of reported and extrapolated size distributions and particle densities. The size distribution of suspended particles in sea water generally follows a hyperbolic distribution described by the equation $N = ad^{-m}$, where N is the number of particles larger than a given diameter d, a is the total number

of particles, and m is a constant describing the distribution (Junge, 1963; Bader, 1970; Brun-Cottan, 1971; Sheldon et al., 1962, 1972; Carder et al., 1971). For $m = 3$ the total volume of particles in all sizes is equal. For $m < 3$, more volume is in the larger particles and for $m > 3$, more volume is in the smaller particles.

McCave combines the size distribution of suspended particles with a density range which decreases with increasing particle size to obtain a Stokesian settling velocity for each size range. The flux for each size interval is obtained using the equation

$$\vec{F} = c\omega_s - E_s \frac{\partial c}{\partial z}$$

where c is concentration, ω_s is settling velocity, and E_s is the particle eddy diffusivity, which he assumes is equal to the vertical eddy diffusivity of water and negligible away from boundaries. Even though a surprisingly low density is assumed for the two coarsest grade sizes (1.068 = 1.057 g cm^{-3} for 128-512 μm particles), the calculations indicate that they contribute 47-89% of the flux while only making up 0.37% to 28% of the mass concentration.

3. Measured Particle Size Distribution from Traps

Sediment traps offer a new approach to measuring fluxes and size distributions because they hopefully allow collection of the particles that are actually falling and therefore constitute the flux of particles across a horizontal plane during a given time. If the material collected in a sediment trap is the material in downward flux, the size distribution of the material in the trap is the size distribution of the particles which constitute the downward flux of particles. It must be acknowledged that once particles have entered a trap, settled to the bottom, and come into contact with other particles, it becomes impossible to determine the actual morphology of the particles which originally entered the trap. Nevertheless, it is important to make a first-order approximation of the size distribution of the trapped material to see how the data observations correspond with theory.

The size-distribution analyses made here are especially important because despite the numerous studies using sediment traps (Chapter II), these are the first direct size measurements made on collected material and the results differ significantly from the theoretical estimates by McCave (1975) of which particle sizes are responsible for the downward flux in the ocean.

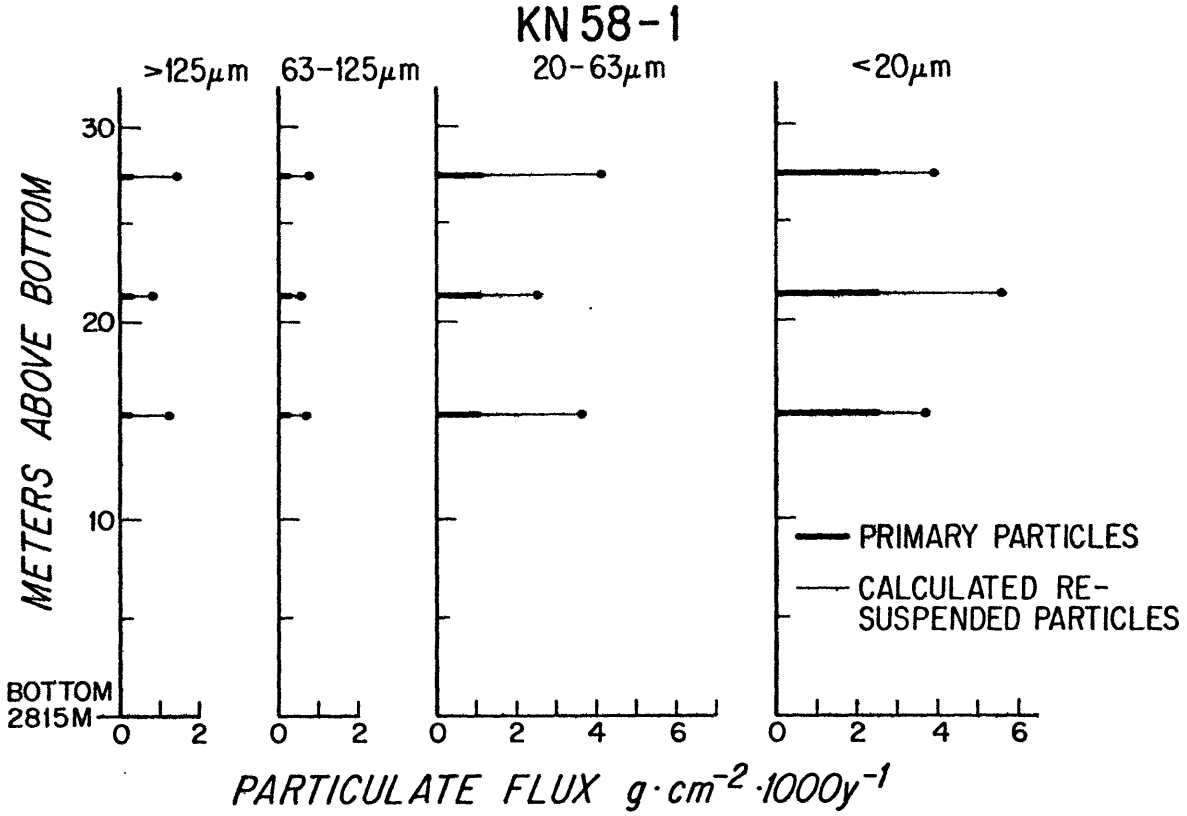
Particles from the traps and core tops were analyzed for size using a process of wet sieving down to 20 μm, as described in section 4-A. The Coulter counter size analysis of the 20 μm fraction was included, and the mean and median particle sizes of the material in each trap were computed.

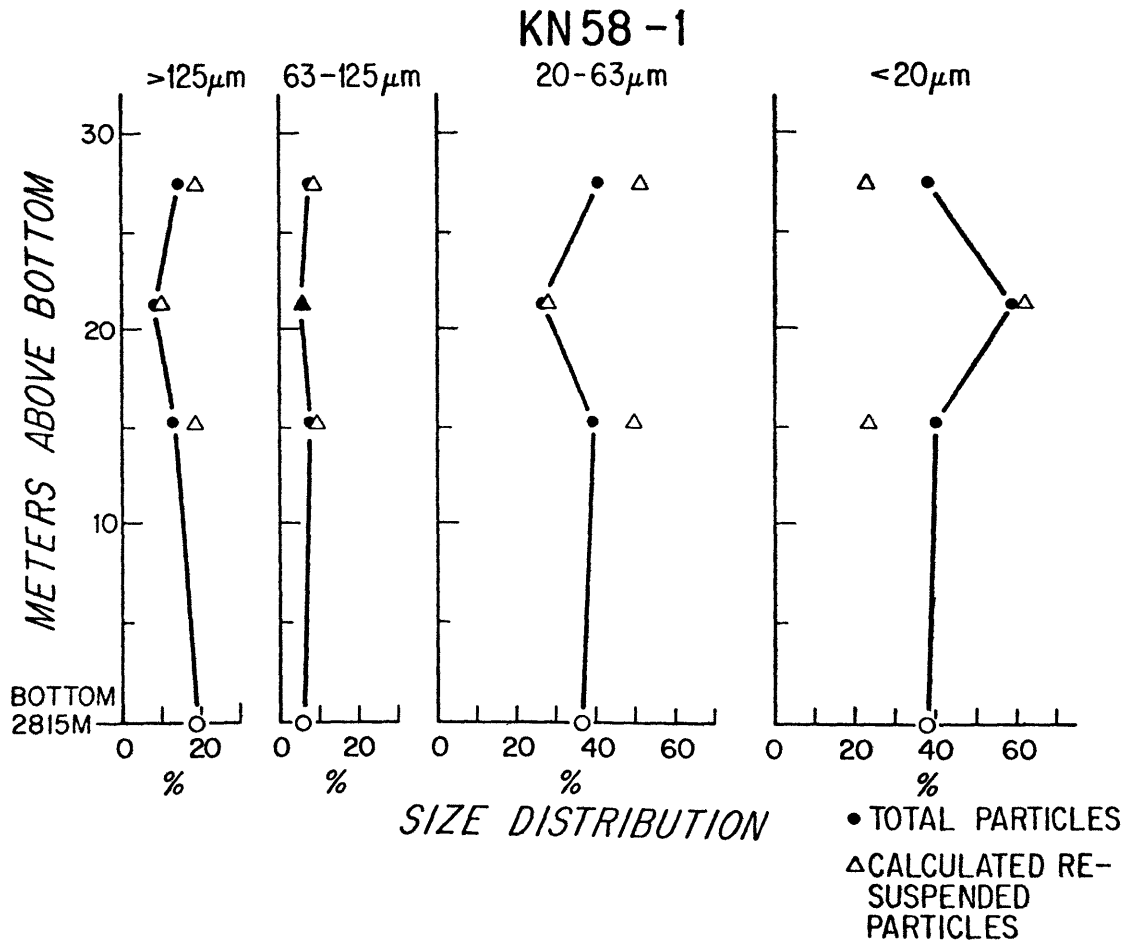
Because of McCave's theoretical calculations, it is most surprising that in the traps where particles were analyzed for size, over 80% of the material was less than 63 μm (figs. 5.8 and 5.9). Instead of the predicted 47-89% of the particles being greater than 125 μm, only 5-10% were above that size. This result was consistent in the six traps analyzed in this manner (table 5.2).

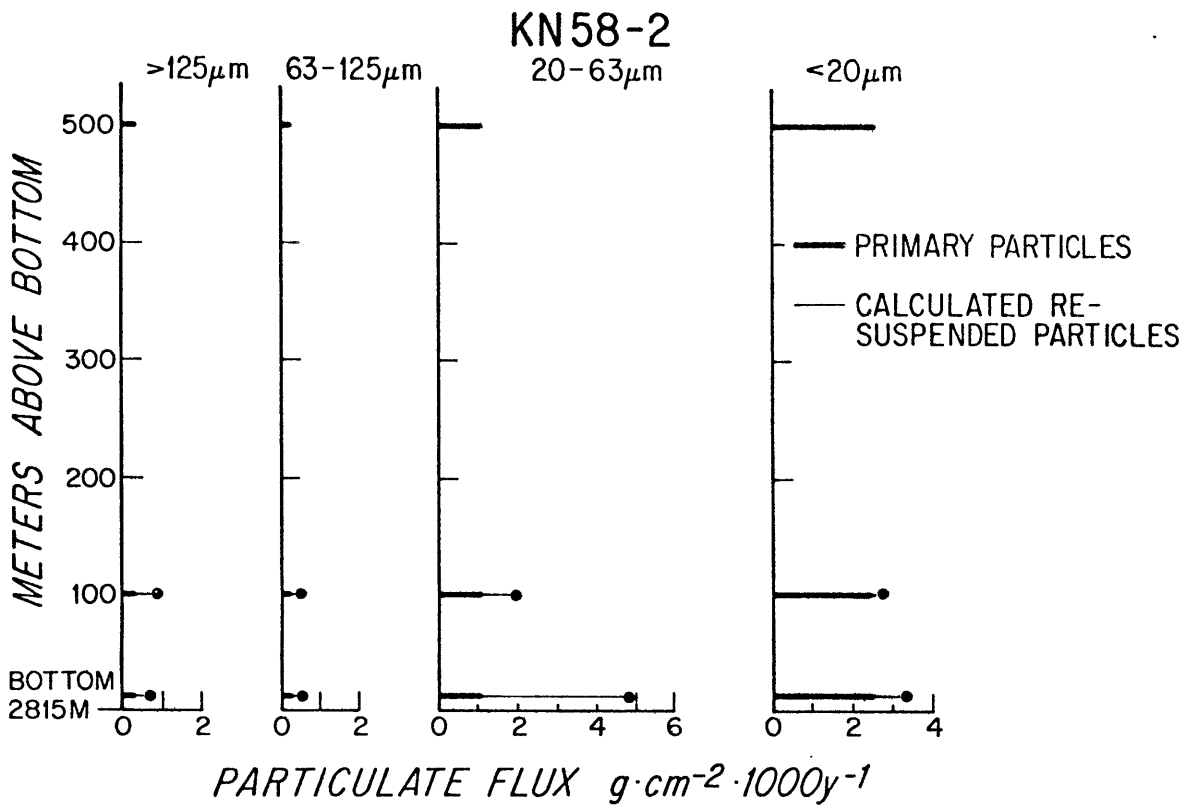
The mean size of particles in the primary flux was only 11 μm and was no greater than 22 μm in any of the traps in the nepheloid layer (figs. 5.10 and

Fig. 5.8 and 5.9

Sub-samples from the traps were separated according to size by wet filtration immediately after recovery. The flux and size distribution of the trap 500 mab was taken as the primary component and this was subtracted from the total collected in other traps for both KN 58-1 and 2 to obtain the resuspended component.


KN 58-1
>125μm
63-125μm
20-63μm
<20μm
METERS ABOVE BOTTOM
30
20
10
BOTTOM
2815M
0 2
0 2
0 2 4 6
0 2 4 6
PRIMARY PARTICLES
CALCULATED RE-SUSPENDED PARTICLES
PARTICULATE FLUX g·cm⁻²·1000y⁻¹


KN 58-1
>125μm
63-125μm
20-63μm
<20μm
METERS ABOVE BOTTOM
30
20
10
BOTTOM
2815M
0 20
0 20
0 20 40 60
0 20 40 60
%
%
%
%
SIZE DISTRIBUTION
• TOTAL PARTICLES
△CALCULATED RE-SUSPENDED PARTICLES


KN58-2
>125μm
63-125μm
20-63μm
<20μm
METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
2815M
0 2
0 2
0 2 4 6
0 2 4
PRIMARY PARTICLES
CALCULATED RE-SUSPENDED PARTICLES
PARTICULATE FLUX g·cm⁻²·1000y⁻¹

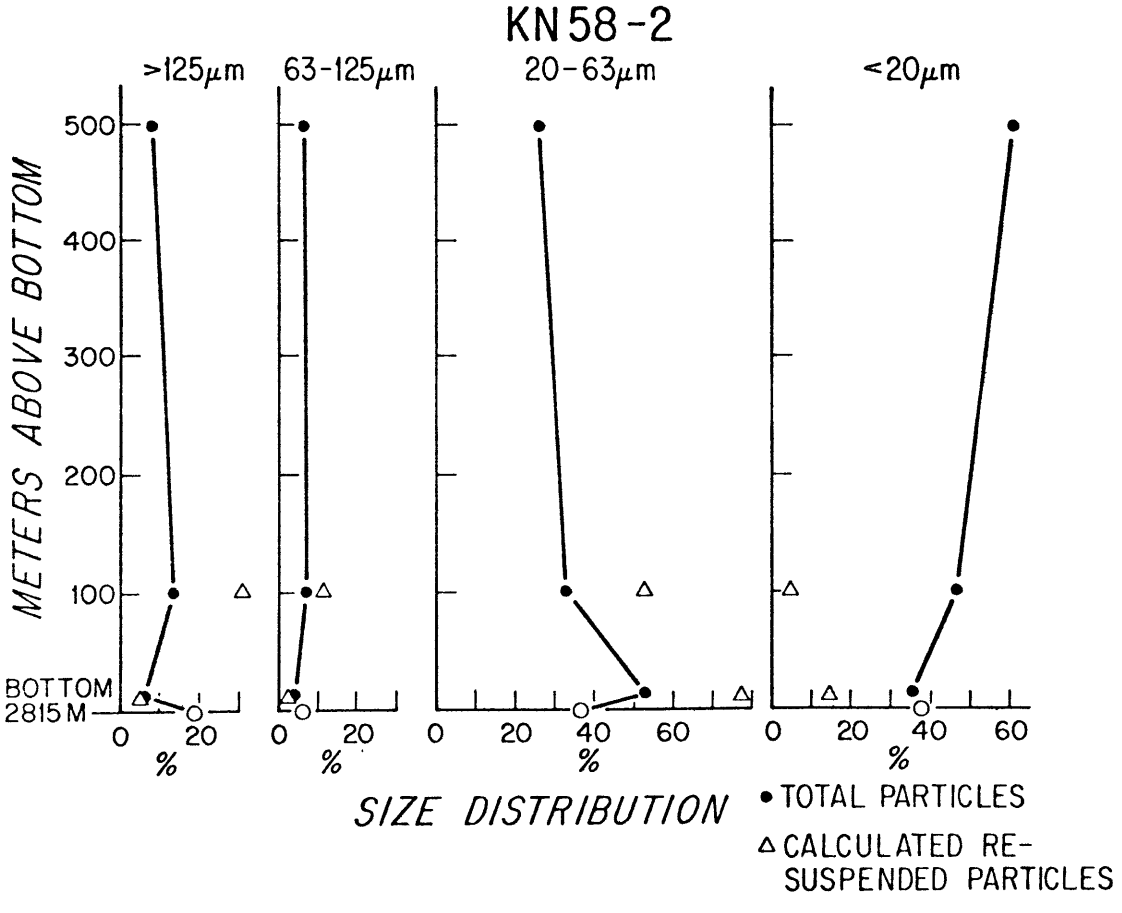
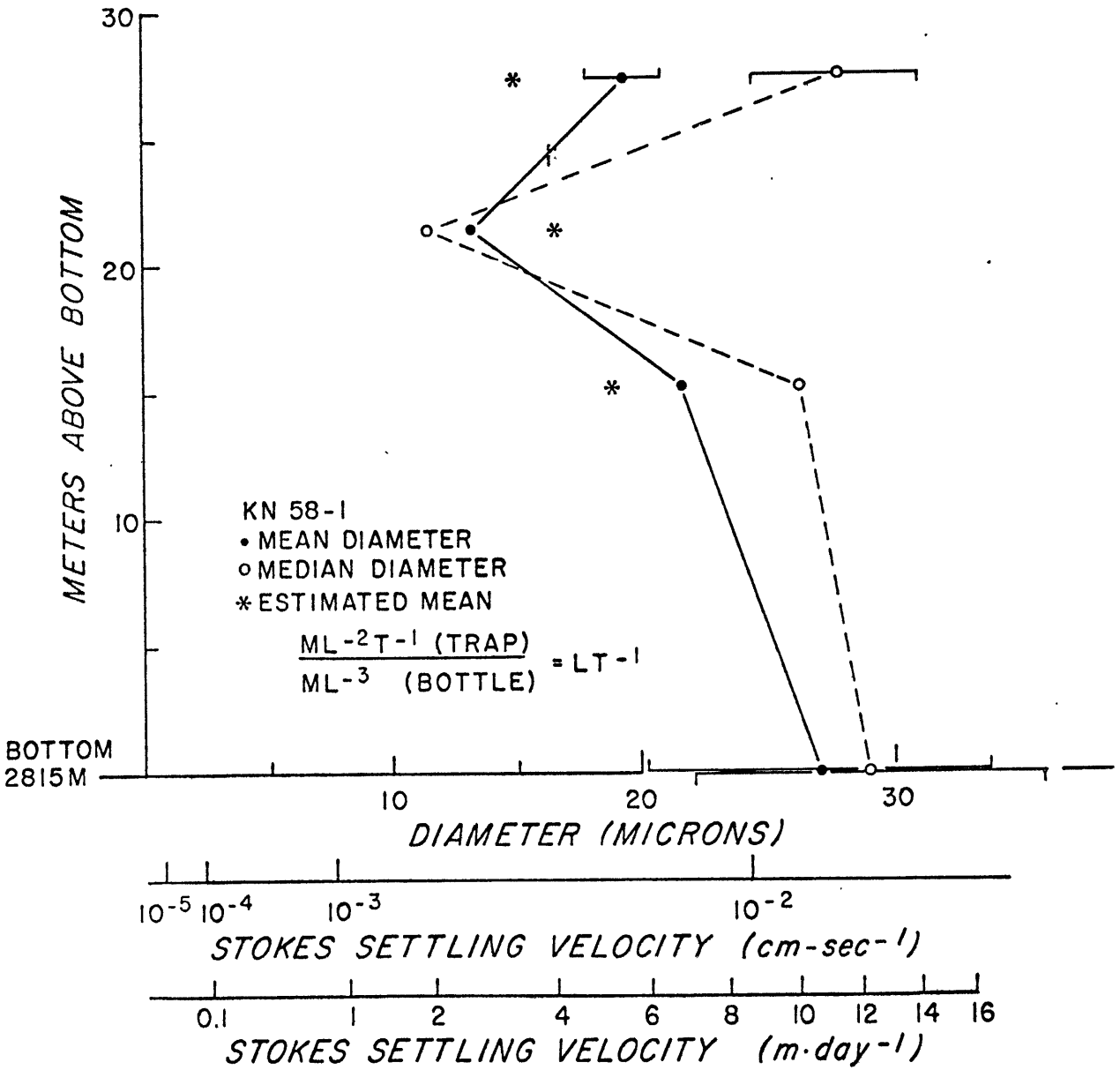
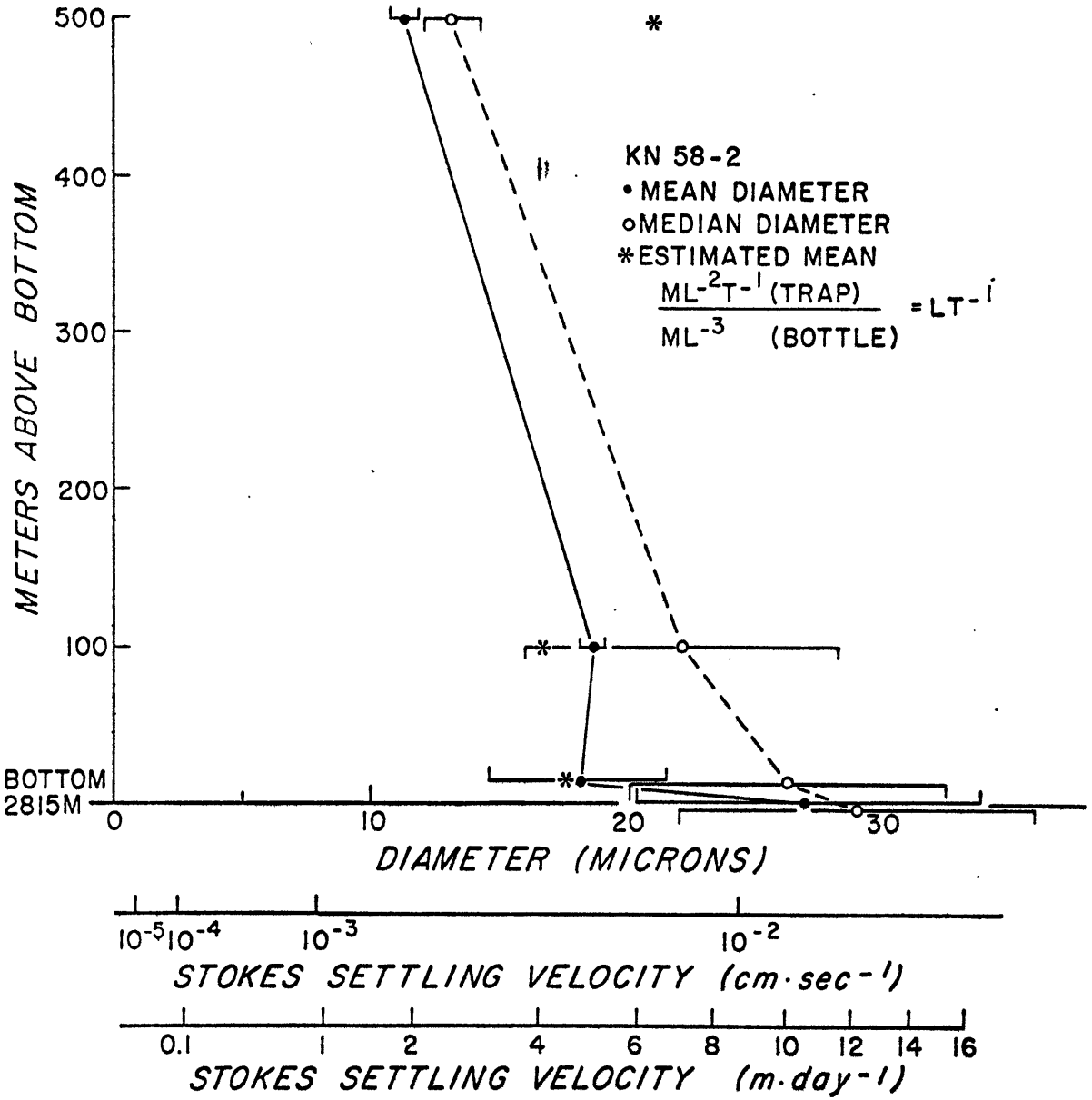

KN58-2
>125μm
63-125μm
20-63μm
<20μm
METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
2815M
0 20
0 20
0 20 40 60
0 20 40 60
%
SIZE DISTRIBUTION
• TOTAL PARTICLES
△ CALCULATED RE-SUSPENDED PARTICLES

Fig. 5.10 and 5.11

The data from wet sieving trap samples was combined with Coulter counter analysis of the <20 μm fraction to obtain mean and median particle sizes. The averages of two samples are plotted as data and the ends of the bars mark the real data points. The estimated mean settling velocity (*), and corresponding particle size is derived by dividing the flux measured at the trap level by the concentration of suspended particles at that level.


30
20
10
METERS ABOVE BOTTOM
KN 58-1
• MEAN DIAMETER
o MEDIAN DIAMETER
* ESTIMATED MEAN
ML-2T-1 (TRAP) / ML-3 (BOTTLE) = LT-1
BOTTOM
2815M
10
20
30
DIAMETER (MICRONS)
10-5 10-4 10-3 10-2
STOKES SETTLING VELOCITY (cm-sec-1)
0.1 1 2 4 6 8 10 12 14 16
STOKES SETTLING VELOCITY (m·day-1)


500
400
300
200
100
BOTTOM
2815M
METERS ABOVE BOTTOM
KN 58-2
• MEAN DIAMETER
o MEDIAN DIAMETER
* ESTIMATED MEAN
ML-2T-1 (TRAP) / ML-3 (BOTTLE) = LT-1
0
10
20
30
DIAMETER (MICRONS)
10-5 10-4
10-3
10-2
STOKES SETTLING VELOCITY (cm·sec-1)
0.1
1
2
4
6
8
10
12
14
16
STOKES SETTLING VELOCITY (m·day-1)

5.11). The larger mean diameter of the core sample (20-35 microns) was a result of an abundance of Foraminifera in one core.

4. Reasons for Discrepancy between Theory and Data

How can we account for the unexpected preponderance of flux in the smaller particles? Possible solutions are:

1. Particles are broken up either during collection or wet sieving.

2. Sediment traps preferentially collect small particles or discriminate against large particles.

3. This is an accurate measurement of a real phenomenon, and by the time particles reach the seafloor there are fewer large particles than expected.

Regarding the first point, it was noticed that once the particle suspension from the trap was poured through sieves, very little of the sediment resting on the 63 μm and 125 μm sieves went through the screen upon gentle washing. Furthermore, samples gently extracted from the trap for microscope work and not sieved appeared to have a similar size distribution when examined qualitatively. It is, of course, impossible to know the size of particles when they first entered the trap. Most of the size measurements shown in figures 5.8 and 5.9 are averages of

two sets of samples; one sucked onto glass fiber filters and the other onto Nuclepore filters (see table 5.2 for available data). The bars shown in figures 5.10 and 5.11 represent the end numbers and are not error bars.

The second and third possible solutions for the discrepancy with theory will be addressed simultaneously by briefly reviewing the collection process of traps. When water moves past a sediment trap there is a continuous exchange of water within the trap in the form of turbulent eddies. Particles are carried into the trap within a turbulent eddy, and if not deposited on the bottom, can easily be carried out again. Thus a trap does not necessarily collect all the particles above a certain size, nor does it reject all particles smaller than a certain size. The intention is to at least collect a mass of particles equivalent to the flux of particles down through the water column. The question is whether the size distribution of particles collected is representative of the particles responsible for the vertical flux.

Because of the large flow of water and particles in and out of the trap, one might then ask if a sediment trap does not just collect the "horizontal" flux. A simple calculation will help answer this question. As a first approximation, what is the mass of particles moving

through an area equal to the trap opening?

Mass = Flux x Time

= Area x Velocity x Concentration x Time

At the KN 58-2 trap site, the trap area was 0.05 m^2, deployment time was 10.7 days, and we will assume a current speed of 5 cm/sec. The data for this array are then

Trap height	500 m	100 m	13 m
In situ concentration (from Niskin bottle)	17 µg/l	55 µg/l	75 µg/l
Mass passing through trap	39 x 10^6mg	125 x 10^6mg	172 x 10^6mg
Mass acctually collected	61 mg	81 mg	129 mg

The mass calculated to have moved through the trap was six orders of magnitude greater than what was actually collected. Even assuming only 25% of the trap area has a flow into the trap at a given time and only 10% of the particles in the water settle in the trap, the calculated masses are still more than four orders of magnitude higher than what was actually collected. Thus, the mass collected is orders of magnitude closer to the vertical flux than the horizontal flux.

Even if the total flux is correct, the trap could be collecting more small particles than it should and not retaining enough large particles. In the flume experiments,

using sediment with 95% less than 25 μm, the particles collected in cylinders had the same size distribution as those accumulating on the flume bed when analyzed with a Coulter counter. Experiments described earlier (Chapter II) showed that the percentage of particles >63 μm retained in the trap was related to the trap design. More experimentation is needed to answer this question satisfactorily. An excellent approach would be to compare the size distributions and fluxes of particles collected in a moored trap with those found in traps attached to neutrally buoyant floats. This would best be done in the open ocean where there is less variability in productivity and terrigenous sources of particles in a given area than in coastal environments.

5. Resuspended Particles

In an attempt to determine the characteristics of the resuspended particles, the flux of the primary particles was subtracted from the total flux determined from the traps in the nepheloid layer. The remaining flux was presumed to be resuspended particles. Since the first Upper Rise array (KN 58-1) had no trap above the nepheloid layer, the primary flux calculated from the second Upper Rise array (KN 58-2) during the ten days following deployment of the first array was subtracted from each trap to

determine the size distribution of the resuspended material. Based on this calculation, very little of the resuspended material collected in the traps is less than 20 μm! For array KN 58-2 (fig. 5.9), 50-80% of the resuspended material is between 20 and 63 μm. This does not mean that smaller particles are not resuspended, only that they do not contribute significantly to the vertical flux. Studies by Feely (1976) and Gardner et al. (1976) indicate that particles within the nepheloid layer are more likely to be aggregated than those found above the nepheloid layer. Aggregation probably occurs on the sea floor, where particles are abundant, and then aggregates are resuspended.

A simple mixing model for particle concentration and size distribution would balance gravitational settling with vertical eddy diffusion. The result would be a decrease away from the bottom in both concentration and particle size. This holds true on the Upper Rise (KN 58-2) for concentration (fig. 5.14) and mean particle size (fig. 5.11). One problem however is that particles greater than 125 μm are unlikely to be resuspended 100 m off the bottom, where they are twice as abundant as at 500 m off the bottom. A possible mechanism for this result will be discussed after the morphology and composition of particles has been examined.

D. RESIDENCE TIME OF RESUSPENDED PARTICLES IN THE NEPHELOID LAYER

As explained in Chapter IV, the residence time of particles in a nepheloid layer is defined as the time required to create a nepheloid layer of a measured concentration when supplied with particles at the rate of resuspension calculated at a given trap level. This concept is based on an assumption of a steady-state model with uniform conditions of resuspension and deposition. Support for these assumptions was sought in Chapter IV from the regionally similar nephelometer profiles, which could have concentrations contoured in a manner consistent with hypotheses about abyssal circulation.

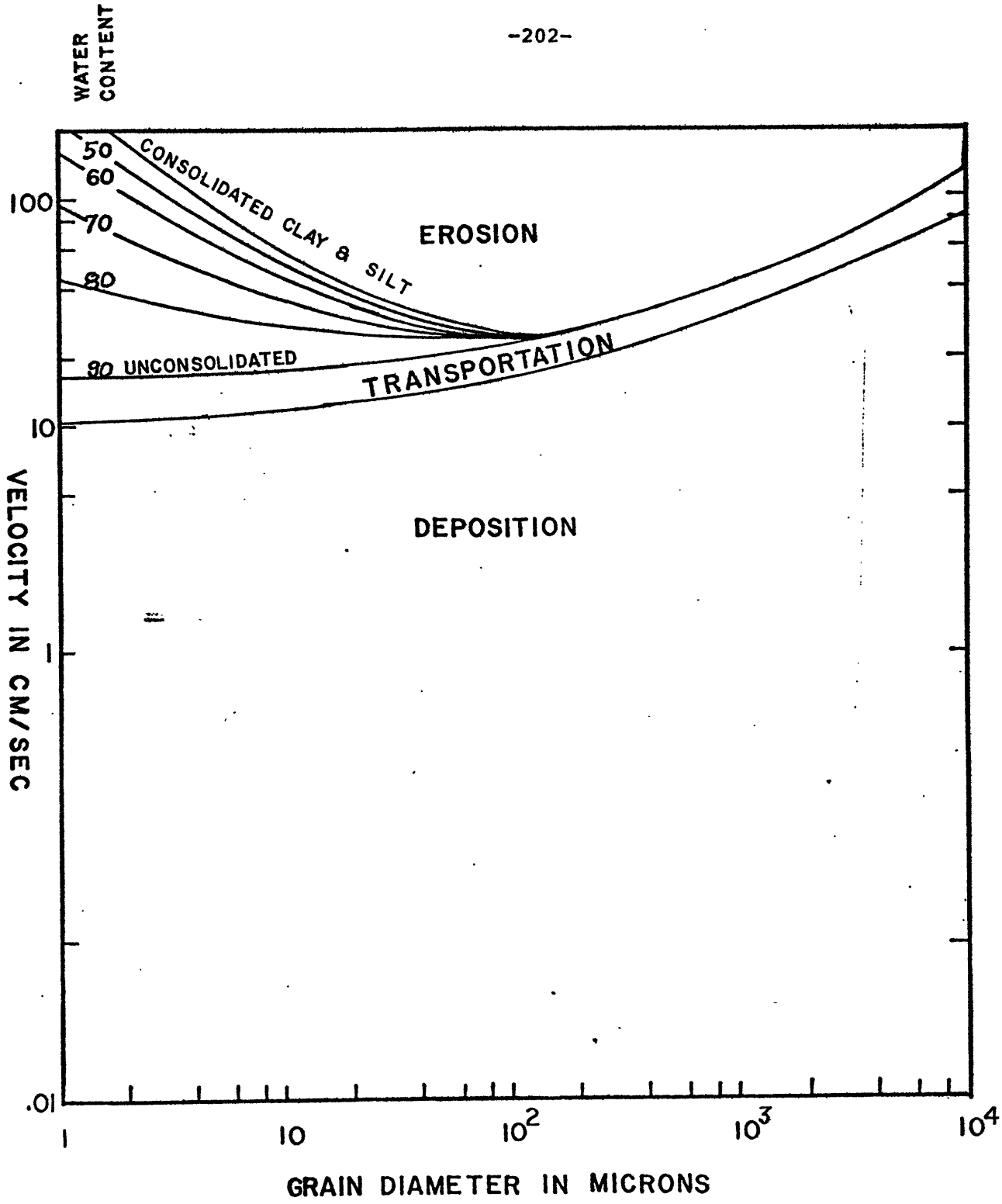
An additional (short-term) piece of evidence in favor of the steady-state assumption is that the fluxes measured in traps moored at 13 and 15 mab on the Upper Rise (KN 58) during two consecutive ten-day periods were nearly identical (25 and 24 $\mu g/cm^2/day$, respectively).

A steady-state assumption also implies that erosion and deposition could be occurring simultaneously, which is consistent with the flume studies of Krone (1962). One must then determine what constitutes an erosional or depositional regime. Bottom sediments are composed of a range of particle sizes, each with its own resuspension threshold. Once in suspension, a given current may be

competent to carry the smaller sizes of particles, but the larger ones will be deposited. Thus, under most conditions in the deep ocean large particles such as fecal pellets will settle to the bottom and are less likely to be resuspended by current shear than smaller particles in unconsolidated sediments (see fig. 5.12). However, deposited particles could be broken down mechanically or biologically and thus be more susceptible to resuspension. Furthermore, currents not strong enough to resuspend particles of a particular size may be competent enough to maintain particles of that size in suspension if they are resuspended by another means, such as organisms feeding on the bottom, injecting the material into the current as part of their filtering process, or ingesting mud on the bottom and swimming off the bottom before they defecate.

When discussing nepheloid layer residence times one must also consider to what size particles the model applies. The traps, from which the flux is determined, are intended to collect the large, rapidly falling particles, whereas water bottles, from which the nepheloid standing-crop concentration is determined, collect both falling and "background" particles. If water bottles do not adequately sample the rare large particles, an underestimate of the

Fig. 5.12 Postma (1967), using the data of Sundborg (1956) and his own observations, defined the above regions of erosion, transportation, and deposition as a function of current velocity and grain diameter. Velocity was measured 15 cm above the bed. Also see Miller et al. (1977).


WATER CONTENT
50
60
70
80
90 UNCONSOLIDATED
CONSOLIDATED CLAY & SILT
EROSION
TRANSPORTATION
DEPOSITION
100
10
1
.01
VELOCITY IN CM/SEC
1
10
10^2
10^3
10^4
GRAIN DIAMETER IN MICRONS

residence time may result. Conversely, the fact that water bottles collect the background particles, which presumably are not sampled by traps, leads to an overestimate of the residence time. What, then, are the upper and lower size cutoffs for both sampling methods?

The smallest size particles sampled from water bottles is determined by the pore size of the filter, which in this study was 0.6 μm, and while there is no upper size limit, only about 50% of the particles (by volume) are greater than 4-6 μm. By using a pre-filter with their in situ pump, Bishop and Edmond (1976) found that roughly 20% of the suspended particles they collected in the upper 400 m were greater than 53 μm when thousands of liters were filtered, and the total concentrations of particles were higher than those determined from filtering 30-liter Niskin bottles. The measurements of suspended particle concentration made at the trap sites in this study included the "dregs" in the water bottles (see Chapter III), which resulted in corrections comparable to those found by Bishop and Edmond. Therefore, if Niskin bottles are sampled correctly, the large-particle population can be measured adequately.

The upper size limit of particles collected in traps was the diameter of the trap opening. Of the collections

made less than 25% of the dry weight was in particles larger than 63 μm (see table 5.2). Between 36% and 61% of the particles collected were less than 20 μm, but at least 80% of the particles were larger than 4 μm.

If we assume that if the dregs are included when calculating the concentration of suspended particles, the large-particle population is adequately sampled, and that 50% of the particle mass collected by filtering water bottles is not available for collection in the traps, then calculations of the residence time of particles in the nepheloid layer are high by a factor of two when using total particulate concentrations, as done in this study.

Despite the assumptions and limitations discussed above it is useful to make a first-order approximation of the residence time (τ) of the nepheloid layer, as has been done in figures 5.13 and 5.14 for the mid and upper Rise. The times shown are accurate only to the point of indicating that the residence time of a nepheloid layer is on the order of weeks to months rather than years to tens of years, though it is conceivable that individual particles may indeed stay in suspension for long periods of time. These relatively short residence times indicate a rapid exchange between the surface sediment and the

TABLE 5.2

DRY WEIGHT AND PERCENT BY PARTICLE SIZE OF
PRIMARY, TOTAL, AND CALCULATED RESUSPENDED MATERIAL
IN TRAPS AND CORE

Depth (m)	Meters Above Bottom (m)	Size Fraction (microns)	Wt. on Nuclepore Filter (mg)	Wt. on Glass Fiber Filter (mg)	Ave. (mg)	Ave. (%)	Ave. Flux (g $cm^{-2}1000y^{-1}$)	Resusp. Flux (g $cm^{-2}1000y^{-1}$)	% of Resusp. Material
KN58-2									
2315	500	>125	0.73	0.93	0.83	7.3	0.31		
		63-125	0.65	0.69	0.67	5.9	0.25		
		20-63	3.19	2.78	2.99	26.3	1.11		
		< 20	6.42	7.35	6.89	60.5	2.54		
2715	100	>125	1.20	2.75	1.98	13.3	0.75	0.44	31.0
		63-125	0.97	1.21	1.09	7.3	0.41	0.16	11.3
		20-63	6.06	3.74	4.90	33.0	1.86	0.75	52.8
		< 20	5.63	8.16	6.90	46.4	2.61	0.07	4.9
	13	>125	1.47	1.83	1.65	6.4	0.57	0.26	5.5
		63-125	1.42	0.75	1.09	4.3	0.38	0.13	2.8
		20-63	17.76	9.59	13.68	53.3	4.75	3.64	77.5
		< 20	6.49	11.96	9.23	36.0	3.21	0.67	14.3
KN58-1 (using primary flux determined at 500 mab during KN58-2)									
2788	27	>125	4.90	4.59	4.75	14.1	1.45	1.14	18.7
		63-125	3.07	2.02	2.55	7.5	0.77	0.52	8.5
		20-63	15.28	12.09	13.69	40.5	4.18	3.07	50.3
		< 20	11.29	14.33	12.81	37.9	3.91	1.37	22.5
2794	21	>125		2.78		9.0	0.86	0.55	10.2
		63-125		1.76		5.7	0.55	0.30	5.6
		20-63		8.35		27.0	2.59	1.48	27.5
		< 20		18.01		58.3	5.59	3.05	56.7
2800	15	(>500)*		(1.46)		(4.7)	(0.44)		
		>125		4.08		13.2	1.23	0.92	18.1
		63-125		2.34		7.6	0.71	0.46	9.0
		20-63		12.04		39.1	3.63	2.52	49.5
		< 20		12.33		40.1	3.73	1.19	23.4
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.

Fig. 5.13 Based on the model in Fig. 4.2, the concentration of suspended particles is shown for the bottom 500 m on the mid-Rise (DOS #2). The net particulate standing crop is the area with diagonal bars. The total flux for each trap (F_T) is shown on the left. The resuspension flux, F_R and residence times, T_R, are shown on the right. With the steady state assumption the residence time at a given height can be viewed as the rate at which the nepheloid layer below the trap is "filling up" or the rate at which the nepheloid layer above the trap is "emptying". The residence time shown is for the entire nepheloid layer below the indicated depth.

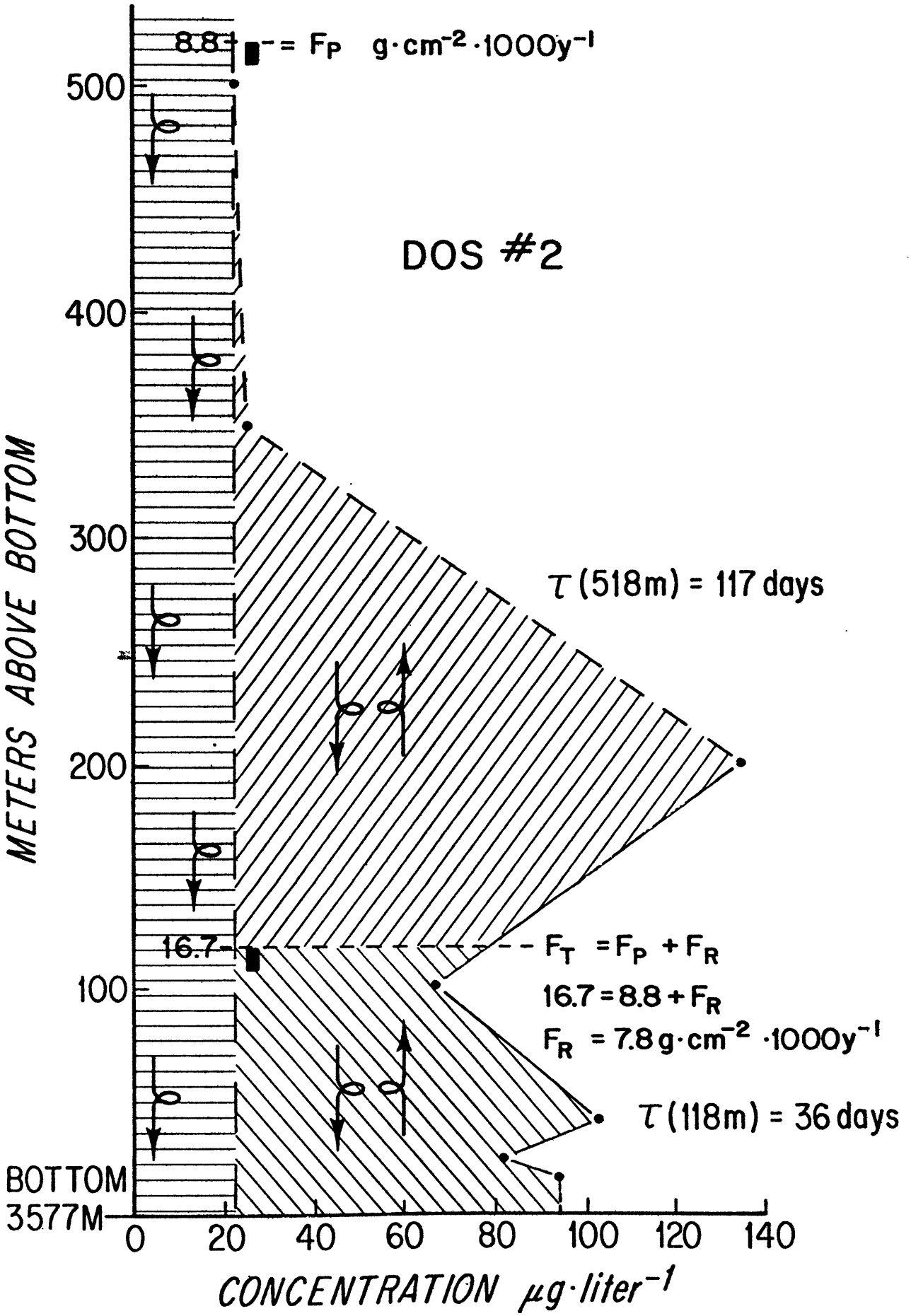
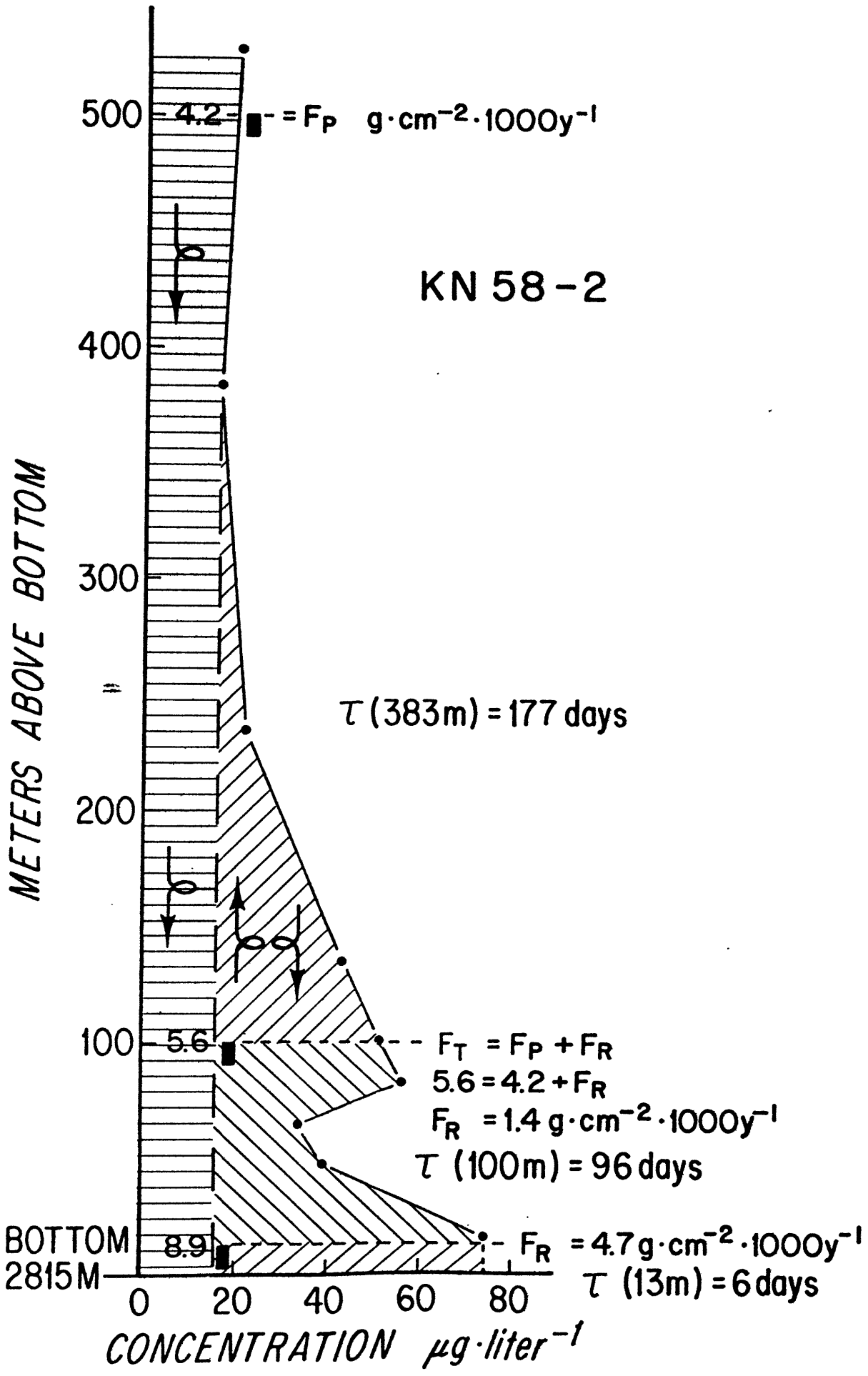

8.8
= F_P g·cm^{-2}·1000y^{-1}
500
400
300
200
100
BOTTOM
3577M
DOS #2
τ (518m) = 117 days
16.7
$F_T = F_P + F_R$
16.7 = 8.8 + F_R
F_R = 7.8 g·cm^{-2} ·1000y^{-1}
τ (118m) = 36 days
METERS ABOVE BOTTOM
0
20
40
60
80
100
120
140
CONCENTRATION μg·liter^{-1}

Fig. 5.14 The data for KN 58-2 is shown as based on the model in fig. 4.2 and further explained in figure caption 5.13.


500
400
300
200
100
BOTTOM
2815M
4.2
F_P g·cm^{-2}·1000y^{-1}
KN 58-2
τ (383m) = 177 days
5.6
$F_T = F_P + F_R$
$5.6 = 4.2 + F_R$
F_R = 1.4 g·cm^{-2}·1000y^{-1}
τ (100m) = 96 days
8.9
F_R = 4.7 g·cm^{-2}·1000y^{-1}
τ (13m) = 6 days
0
20
40
60
80
METERS ABOVE BOTTOM
CONCENTRATION μg·liter^{-1}

nepheloid layer, so for particles to be carried long distances in the nepheloid layer they will frequently be deposited on the bottom and then resuspended, as opposed to being carried long distances during a single stay in the nepheloid layer.

The short residence times shown in figures 5.13 and 5.14, also indicate that particles could be resuspended numerous times before final burial. If particles are resuspended several times before final burial, they are likely to spend more time in a resuspended state than was required for original transit to the sea floor. Resuspension may therefore play a significant role in the dissolution of carbonate and silicate particles.

Could the resuspension of sediment be a significant mechanism for mixing sediment? The sediment thickness required to be eroded to equal the resuspension flux measured by the near-bottom traps is on the order of a few tens of microns per year. This is insignificant when compared with biological reworking (Berger and Heath, 1968).

A practical benefit of the rapid recycling of particles in the nepheloid layer may exist. Since the feasibility of burying radioactive waste beneath the sea floor is being discussed (Bishop and Hollister, 1974; Anderson

et al., 1976), it is important to consider all physical and chemical processes which might act as barriers to the dispersal of any material not retained below the sediment. The cation exchange characteristics of clay minerals may enable them to scavenge metal or transuranic ions which may have escaped into the water column (Grimwood, 1977).

E. COEFFICIENT OF VERTICAL EDDY DIFFUSION DERIVED FROM PARTICLE FLUX

Coefficients of eddy diffusion are an indication of small scale mixing rates and are derived from measurements of gradients of properties of sea water or concentrations of a dissolved or suspended species in the sea water. Calculations of diffusion coefficients are easiest when conservative properties such as salinity or temperature are used (Stommel, 1958; Munk, 1966; Veronis, 1969), but if sufficient information is available about the chemical reactivity and rates of supply or depletion of a particular substance, it can also be used to calculate diffusion coefficients. For instance measurements of radon and radium have been used to derive coefficients of vertical eddy diffusion in the deep ocean (Broecker, 1965; Broecker et al., 1968; Biscaye and Eittreim, 1974), and more recently Sarmiento et al. (1976) have established an apparent

relationship between vertical eddy diffusion and the inverse buoyancy gradient, which is derived from the density gradient with depth. Eittreim and Ewing (1972) estimated the coefficient of vertical eddy diffusion by measuring the concentration gradient of suspended particles from nephelometer data and using the equation

$$F = cw_s - E_s \frac{dc}{dz} .$$

Assuming a balance between the upward diffusion flux and downward gravitational flux (i.e. steady state), they set the net flux equal to zero and obtained the solution

$$\frac{w}{E_s} = \frac{1}{c} \frac{dc}{dz} = \frac{d(\ln c)}{dz}$$

Using this equation requires that we know, or can accurately estimate both the concentration and settling velocity of all particles.

The advantage of the measurements made in this thesis is that the flux of particles (cw_s) is measured directly at different levels. If the model portrayed in figure 4.2 is valid, it is possible to separate the downward flux across the clear-water particle minimum from the upward resuspension flux. By assuming a steady state and subtracting the primary flux from each trap below the clear water minimum, the net flux in the nepheloid layer is zero, so that

$$F = o = cw_s - E_s \frac{\partial c}{\partial z} \quad \text{or} \quad cw_s = E_s \frac{\partial c}{\partial z}$$

Thus, the settling of particles is balanced by vertical eddy diffusion carrying particles upward. The resuspension flux, $F_R(z)$, determined at each trap level by taking the difference between the total and primary fluxes, is a direct measurement of the settling flux of particles cw_s, at that level so

$$cw_s = F_R(z) = E_s \frac{\partial c}{\partial z}$$

If the vertical concentration gradient near each trap is measured sufficiently well, an estimate of the vertical eddy diffusivity E_s for particles can be derived from the concentration gradient and the resuspension flux using the above equation. The assumption that the profiles of suspended particles at the trap locations represent an equilibrium situation may be a dangerous one, as has been pointed out above. The fact that there is a change in sign of dc/dz in the nepheloid layer at DOS #2 and KN 58 indicates that the balance between the upward diffusion flux and the downward gravitational settling is not a simple two-dimensional steady-state phenomenon. However, if several profiles at each site were combined, the average concentration gradient could probably be used to derive a representative coefficient of vertical eddy diffusion.

Only one profile is available at each site, but it appeared worthwhile to approximate the vertical eddy diffusion from the available data shown in fig. 5.13 and 5.14 and table 5.1. The gradient dc/dz on the mid-Rise (DOS #2) was erratic, so the gradient used for the 118 m trap was the gradient between 100 m and 16 m. On the Upper Rise (KN 58-2) gradients were determined in the close vicinity of the trap and as an average between 16 m and 230 m. Using the average gradient on the Upper Rise (KN 58-2) produced larger diffusivities, which decreased away from the bottom. The diffusivity was greater on the mid-Rise than on the Upper Rise (table 5.3), again suggesting more activity at the mid-Rise site.

From the data available it is possible to compare the coefficients of vertical eddy diffusion derived from the above method with other methods. The method of Eittreim and Ewing (1972) described earlier was applied using the concentration gradients from this study and the particle fall velocity of the mean particle size measured in the traps (22 μm) in the nepheloid layer on the Upper Rise. Coefficients were at least twice as large using this method (table 5.3), but still lower than the E_s of 300 cm^2/sec averaged for the New York Region for 20 μm particles (Eittreim and Ewing, 1972).

TABLE 5.3

VERTICAL EDDY DIFFUSIVITIES DERIVED
BY DIFFERENT METHODS

TRAP	HEIGHT ABOVE BOTTOM (m)	VERTICAL EDDY DIFFUSIVITY E_s cm^2/sec				
		Eittreim & Ewing (1972)		Sarmiento et al. (1976)	This Study	
		near trap	ave. in nepheloid layer		near trap	ave. in nepheloid layer
DOS #2						
3	518	-			-	-
2	118	211		131-177	80	-
1	18	-			-	-
KN 58-2						
3	500	-	-		-	-
2	100	130	145	131-177	15	19
1	13	38	145		22	109

However, they felt that based on their data, a mean particle diameter of 12 μm was the preferred value, which would suggest an E_s of 108 cm^2/sec for the bottom 800 m of the water column; a higher value than is obtained using the author's method.

No radon measurements have been made at these sites, but many CTD profiles are available nearby and can be used to derive the buoyancy gradient $(g/\rho)(\partial\rho_{pot}/\partial z)$, which is the square of the Brunt-Väisälä frequency where g is gravity and ρ_{pot} is potential density (Phillips, 1966). Sarmiento et al. (1976) compared the buoyancy gradient with coefficients of vertical eddy diffusion obtained from profiles of excess ^{222}Rn and ^{228}Ra and estimated a constant of proportionality of 4×10^{-6} cm^2/sec^3. After examining one profile on the Upper Rise (Peter Hendrichs, unpublished data) and several profiles on the mid-Rise (Robert Millard, unpublished data) the range of buoyancy gradients was $2.25 - 3.06 \times 10^{-8}$ sec^{-2} which results in a range for E_s of 131-177 cm^2/sec. Measurements made in the Atlantic by Sarmiento et al. (1976) were between 5 cm^2/sec and 128 cm^2/sec with one very high value of 440 cm^2/sec.

The value commonly cited for vertical eddy diffusivity in the deep ocean is 1 cm^2/sec. It is possible that the values shown in table 5.3 are real, or is the mixing implied by these numbers a result of other processes, such as horizontal advection? The flux equation used at the beginning of this section can be modified to include horizontal advection in one direction to obtain

$$u \frac{\partial c}{\partial x} = E_s \frac{\partial^2 c}{\partial z^2} + \omega_s \frac{\partial c}{\partial z}$$

where u is velocity in the x direction. Assuming that the fall velocity of particles (ω_s) is much smaller than the first two terms, let us compare the importance of horizontal advection and vertical diffusion. Then

$$\frac{u \frac{\partial c}{\partial x}}{E_s \frac{\partial^2 c}{\partial z^2}} = \frac{\frac{uc}{L}}{E_s \frac{c}{H^2}} = \frac{uH^2}{E_s L}$$

where L is the horizontal distance needed to find a significant change in particle concentration and H is the thickness to which E_s is being applied. For u = 5 cm/sec, L = 200 km, H = thickness of nepheloid layer = 1000 m, and E_s = 100 cm^2/sec as implied in table 5.3, the above ratio is 25, or horizontal advection is 25 times greater than vertical diffusion. However, if we consider the region of the intense nepheloid layer

in the bottom 100 m, which often corresponds with a well-mixed bottom layer, the ratio becomes 0.25, or vertical diffusion is four times greater than horizontal advection. These numbers are, of course, rough estimates, but they are important in that they suggest that while horizontal advection may be important in developing and maintaining the thick nepheloid layers (up to 1500 m) reported by Eittreim and Ewing (1972), Biscaye and Eittreim (1977) and others, in the intense nepheloid layer of the benthic boundary layer, vertical diffusion may play an important and even a dominant role in mixing resuspended particles upward in the water column. This adds validity to the concept of nepheloid layer residence time discussed earlier.

F. MORPHOLOGICAL EXAMINATION OF PARTICLES BY MICROSCOPE

Morphological studies have been made on particles retained after filtration of water samples (Bond and Meade, 1966; Jacobs and Ewing, 1969; Manheim et al., 1972; Honjo et al., 1974; Eittreim and Ewing, 1972; Feely, 1976), but as was reported for the first time in Gardner (1977) and Chapter III of this thesis, many particles escape extraction and therefore examination when using water bottles. Furthermore, it was important to collect and examine the particles responsible for

the downward mass flux in the ocean and to determine not only their size, but also their origin; i.e. fecal pellets, individual tests of phytoplankton, zooplankton carapaces, organic aggregates, etc. A morphological description has been made of fecal pellets collected by Wiebe et al. (1976) by those authors and by Honjo (1976), but little was said about the rest of the particles, which constituted most of the mass. In the present study, samples were available from more than one depth in the water column, so an examination was made to determine the morphology and origin of particles at different depths. This information would also aid the interpretation of chemical analyses of the samples.

A qualitative examination was made of all filters which contained samples from the moored and floating traps using a binocular microscope with magnification between 7 and 75 times under reflecting light. Several filters were also examined with transmitted light under 10-100 times magnification. The particles larger than 125 μm were counted on the glass fiber filters from the traps collecting the primary flux (500 mab) and the primary plus resuspended flux (13 mab) for the Upper Rise station (KN 58-2). The filters contained one quarter of the fraction >125 μm and were examined under a combination of reflected and transmitted light.

From the data on the flux of particles per square meter per day (table 5.4) for the Upper Rise (KN 58-2), one can see that numerically, no single particle type is dominant, although Radiolarians, diatoms, and fecal pellets are most abundant. Since fecal pellets are generally "solid" particles rather than empty shells, their mass contribution is greater than their numerical percentage. Fecal pellets were counted in categories of "well-formed", "broken", and "flattened". Many of the fecal pellets survived the wet-sieving, but, as is critical with many particles, once water was sucked from them during filtration, they lost their integrity and were sucked flat. Most of the fecal pellets on the filters were not flattened, but maintained their shape very well, although more of them appeared broken in some way rather than in a whole form. Perhaps some pellets appeared broken because they were a more continuous fecal excrement rather than discrete pellets, but most appeared to be discrete. The fecal pellets were very uniform in color and texture except for a few black pellets which were possibly oil droplets rather than fecal pellets. The fecal pellets were re-examined after they had been leached with phosphoric acid to remove the carbonate fraction. No difference in the color or shape of the pellet was noticeable with reflected light microscopy.

TABLE 5.4

IDENTIFICATION OF PARTICLES >125 μm
Upper Rise (KN 58-2)

Particle Type	Primary Flux #/m^2/day 2315 m depth 500 mab	Primary and Resuspended Flux #/m^2/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	247
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 carapces	No data	30
Unidentified fragments	No data	389

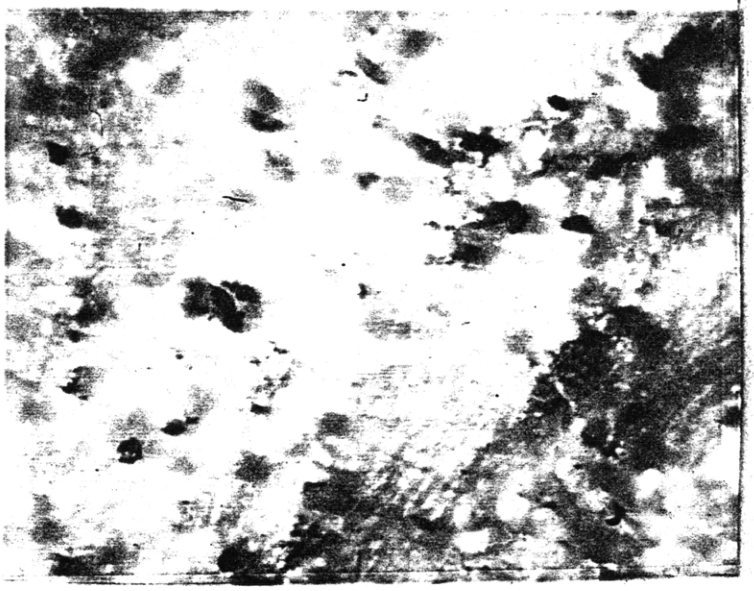
Fig. 5.15 The particles shown came from the trap 13 m above the bottom on the Upper Rise (KN 58-2). The magnification of each of the photographs was the same.

A. (all sizes) One eighth of the trap sample was filtered onto a Nuclepore filter without any sieving. There appeared to be no more large particles when the sample was filtered directly than when they were sieved and filtered.

B. (63-125 μm) The juvenile forams in the sieved fraction between 63 μm and 125 μm were more abundant than the fecal pellets.

C. (>125 μm) Many fecal pellets remained well-formed throughout the filtration process, while others were flattened when the water was sucked from them. Although fecal pellets were less numerous than diatoms or radiolarians in this fraction, the mass of fecal pellets was probably dominant.

A



B

C

The largest well-formed and broken fecal pellets from the glass fiber and Nuclepore filters were removed and weighed prior to elemental analysis. Eleven fecal pellets from 500 mab weighed a total of 17 µg or 1.55 µg per pellet. Thirty-nine fecal pellets from 13 mab weighed 104 µg, or 2.67 µg per pellet. If all fecal pellets counted from these traps weighed as much as the average of the largest fecal pellets, they would comprise 13% by weight of the primary flux >125 µm (500 mab), and 30% by weight of the total flux >125 µm 13 meters above the bottom.

It was curious that none of the four floating traps contained any well-formed fecal pellets. No poisons were used in the traps to prevent microbial decay, but the exposure time was less than 12 hours, and while the upper trap (40 m) was in 23°C water, the lower trap (100 m) was in 15°C water, which should have been cold enough to inhibit degradation of fecal pellets.

No significant abundances of radiolarians have been reported for the Western North Atlantic, so it was surprising that numerically they were the most abundant particles in the trap samples. The surface sediments at these sites were examined and radiolarians were rarely found. Another observation which differed from what might have been expected based on historical data was that

pteropods were as abundant as foraminifera, and because the coiled pteropods were much larger than most forams, they contributed more to the vertical flux during the time the traps were deployed.

In the fraction of particles 63-125 μm, juvenile forms of planktonic foraminifera were extremely abundant in all traps and were dominant numerically and possibly in terms of mass.

Interesting, but anomalous, collections made in the traps on the mid-Rise (DOS #2) include:

1. a cluster of three asteroids and an ostracod tangled in a mat of fiberous-looking material several hundred microns in diameter; 518 mab,

2. three or four droplets of oil a few millimeters in diameter; 518 and 18 mab,

3. a well preserved, 4 cm decapod which was not alive, but was frozen immediately and is to be analyzed for gut content; 118 mab.

Over 80% of the material collected in most traps was less than 63 μm in diameter, assuming that large particles were not broken down significantly during processing. Under reflected light it was not possible to determine the origin of these particles. This will have to await further examination with scanning electron

microscopy. Examining the data on particles 125 μm in table 5.4 can therefore be misleading if previous assumptions about sediment traps are correct, because the data includes less than 10% of the total flux. However, the analysis gives us information about the relative importance of different types of large particles in transit through the water column for the time and place of deployment.

Fecal pellets are probably important as a vehicle for transporting small particles from surface waters to the deep ocean, but in terms of total carbonate and silica flux, it appears that the individual tests of radiolarians, diatoms, pteropods, and foraminifera are equally, if not more important. The total number of pellets falling as part of the primary flux each day was very close to the flux of fecal pellets measured by Wiebe et al. (1976). However, the absence of well-formed fecal pellets in the floating traps is curious, despite the estimate for low zooplankton abundance during the trap deployment. Fecal pellets could be advected in horizontally from a more productive area to account for the many fecal pellets in the moored traps, but a more likely explanation is that many of the fecal pellets which reach the sea floor are formed by migrating zooplankton

and are defecated below the surface waters. Retaining a full gut would also enable zooplankton to descend more rapidly as the light of day approached. Elemental analysis of fecal pellets supports the idea that fecal pellets reaching the sea floor did not come solely from scavenging at the surface (see section 5.H).

The flux of fecal pellets and other types of particles 13 mab is two to three times their flux at 500 mab, and this increase is attributed in earlier sections to resuspension by currents or biological activity. It is noteworthy, however, that not only the flux, but also the size of fecal pellets is larger 13 mab than 500 mab. It thus seems necessary to find another mechanism to account for the large near-bottom fecal pellets, and the most likely source is the hypo-benthic community, as will be discussed more in section 5.H.

G. COMPOSITION AND FLUXES OF CARBONATE, ORGANIC CARBON, AND NON-COMBUSTIBLE MATERIAL

Marine sediments can be divided into the major categories of carbonate, silicious, organic, and lithogenous matter. There are abundant data on the influx of these components by rivers (Livingstone, 1963; Garrels and MacKenzie, 1971), wind (Delaney et al., 1967; Folger, 1970), and glaciers (Garrels and MacKenzie, 1971), and many measurements have been made on the biological

productivity of the surface waters of the ocean (Ryther, 1963). Likewise, there have been numerous studies of the rates of accumulation of these components from deep sea cores. The present work, however, is one of the first attempts to directly collect particles in vertical transit to the deep ocean and determine contemporaneous sedimentation rates of these components and look for changes in the composition of the particles as they pass through the water column on their way to becoming tomorrow's deep-sea sediments. The composition of resuspended material will also be calculated from trap data to see if any particle types are preferentially resuspended. This could have a major effect on dissolution rates of carbonates and silicates.

This study was made with Dr. G. T. Rowe of WHOI, whose primary interest was to investigate the transport of organic matter to the deep sea to study how the energy requirements of deep sea benthic organisms are met. This remains one of the most important unresolved questions of marine biology and chemistry (Menzel, 1974). Theories about this problem range from having the organic matter supplied by the slow "rain" of particles from the surface waters (Agassiz, 1888), to food being conveyed by overlapping zones of verticaly migrating plankters (Riley, 1951; Vinogradov, 1962; Wickstead, 1962), to accretion of

dissolved organic matter into usable particulate organic matter. Views also differ on the relative importance of large carcasses (squids, shrimp, fishes) in providing food in the deep sea (Isaacs, 1969; Dayton and Hessler, 1972) versus the fine detritus falling from surface waters and the effect on benthic communities (Grassle and Sanders, 1973).

From the model discussed for sedimentation (Chapter IV) most of the decomposition of organic matter is believed to occur in the surface waters above the thermocline (Menzel and Ryther, 1970). Dissolution of biogenous silica begins in surface waters because it is undersaturated in sea water at all depths (summarized by Krauskopf, 1959), but carbonate forms do not begin rapid dissolution until falling below the lysocline (1000-2500 m for aragonite and 4000-5000 m for calcium carbonate, Li et al., 1969). No rapid diagenetic changes are known to occur in the lithogenous fraction with depth. In this study the samples were divided into categories of carbonate, organic carbon, and non-combustible material. The non-combustible component includes silicious organisms such as diatoms and radiolarians as well as mineral grains. All of the traps deployed were above the carbonate compensation depth, but below or near the compensation depth for aragonite, so a

decrease in the carbonate component could be due partially to dissolution. Changes in the carbonate content or flux could also result from patchiness in the "rain" of carbonate particles, or could come from resuspension of bottom sediments. If bottom sediments have a smaller percentage of carbonate than the primary flux of particles, the addition of resuspended sediment will decrease the carbonate content, whereas the decrease could otherwise be attributed to dissolution of carbonate.

1. Floating Traps

Because only small amounts of material were collected during the half-day deployments, only total flux and organic carbon and nitrogen flux were measured. The sample collected from 40 m at night included two zooplankters, so the organic carbon flux and percentage are high for that sample. Otherwise, it appears that both the flux and percent composition of organic carbon is less at 100 m than at 40 m during the day and night (table 5.5).

2. Variations in Flux and Composition with Depth

The flux of all components in the traps moored in the nepheloid layer is greater than the primary flux (fig. 5.16-5.19 and table 5.6). The percentage of carbonate in the traps does not vary significantly until

TABLE 5.5

ORGANIC CARBON CONTENT OF MATERIAL IN FLOATING TRAPS

Flux Units in $mg/m^2/day$

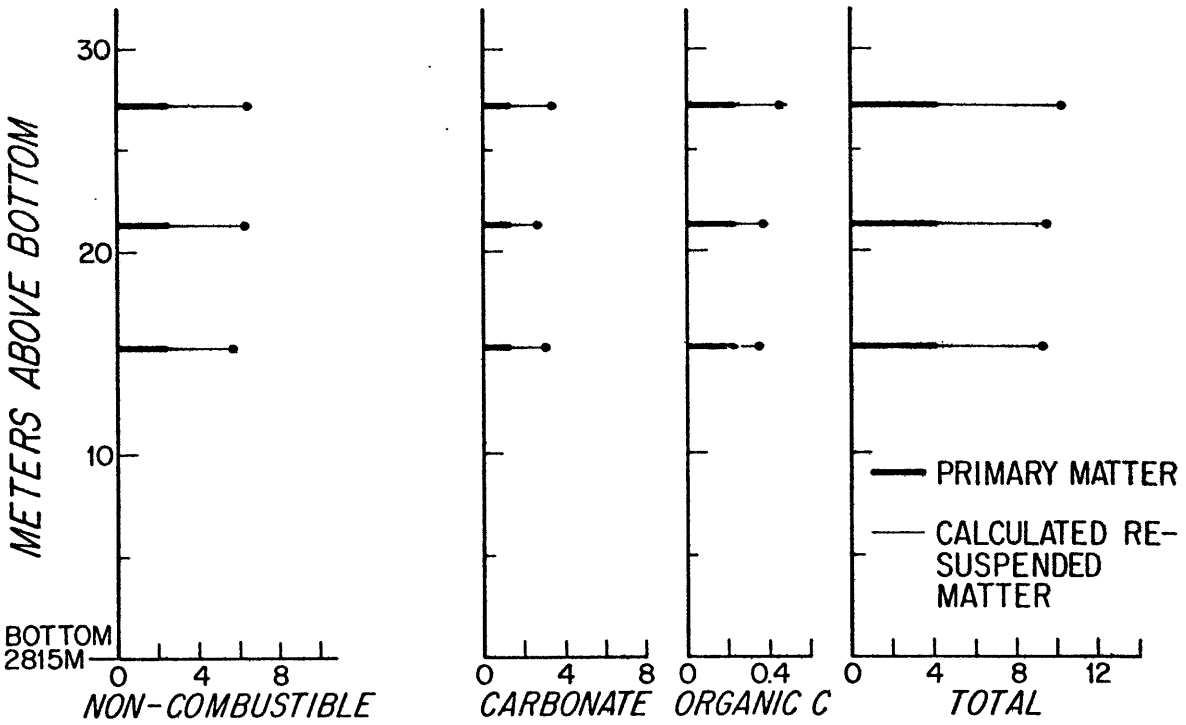
	Depth (m)	Total Dry Wt. (mg)	Total Flux	Organic Carbon Flux	%	C:N
Night	40	7.33	285	*157	55	4.6
	100	3.82	148	21	14	8.1
Day	40	5.93	308	62	20	9.6
	100	7.74	402	53	13	11.5

* includes 2 anomalous zooplankters

Figs. 5.16-5.19

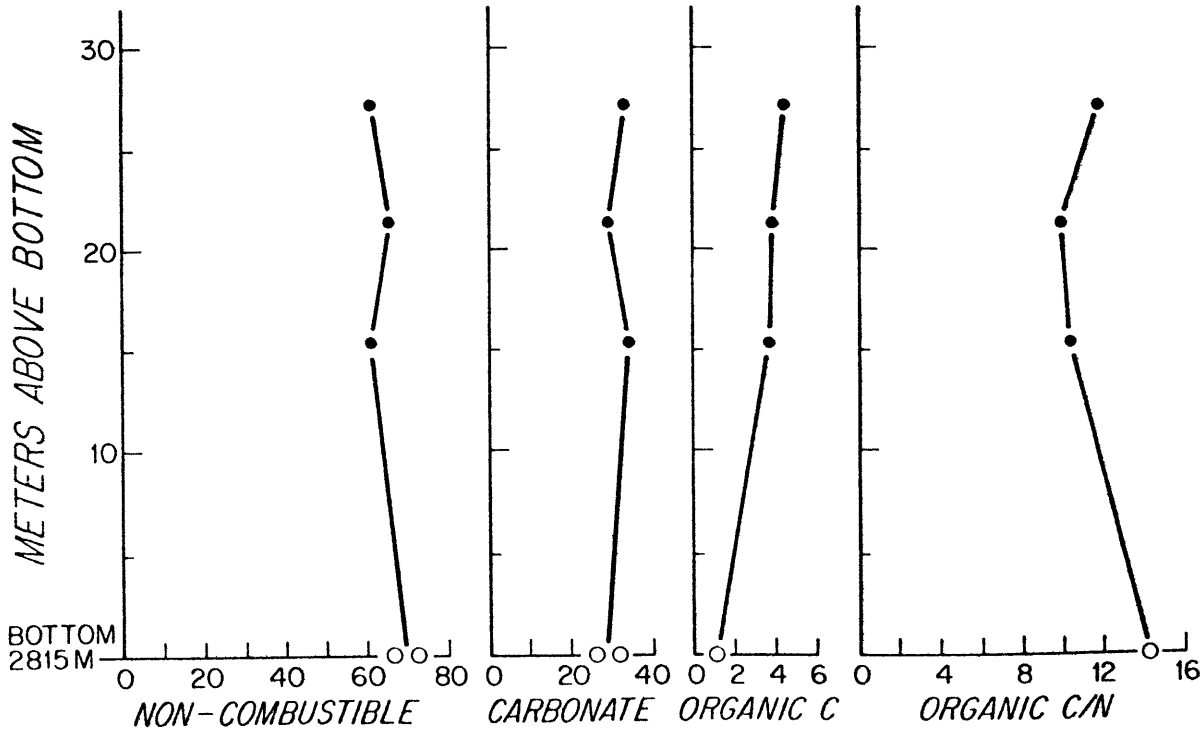
The material collected in the traps was categorized as carbonate, organic carbon, or non-combustible and plotted as the flux and percent composition of each component. No correction was made for non-carbon organic matter lost during combustion in the CHN analyzer, so the non-combustible category should be reduced by the percentage of organic carbon, assuming organic matter equals two times organic carbon. The primary flux of each component (thick bar) was subtracted from the total flux in the lower traps to calculate the resuspended flux (narrow portion of bar). No primary flux measurement was made at DWD 106 and the primary flux at KN 58-2 was used in calculation for KN 58-1. The composition of the total trap sample was indicated with a solid dot in the lower graph and the composition of the calculated resuspended matter was indicated with an open triangle. The open circles are core top analyses at each site.

KN58-1

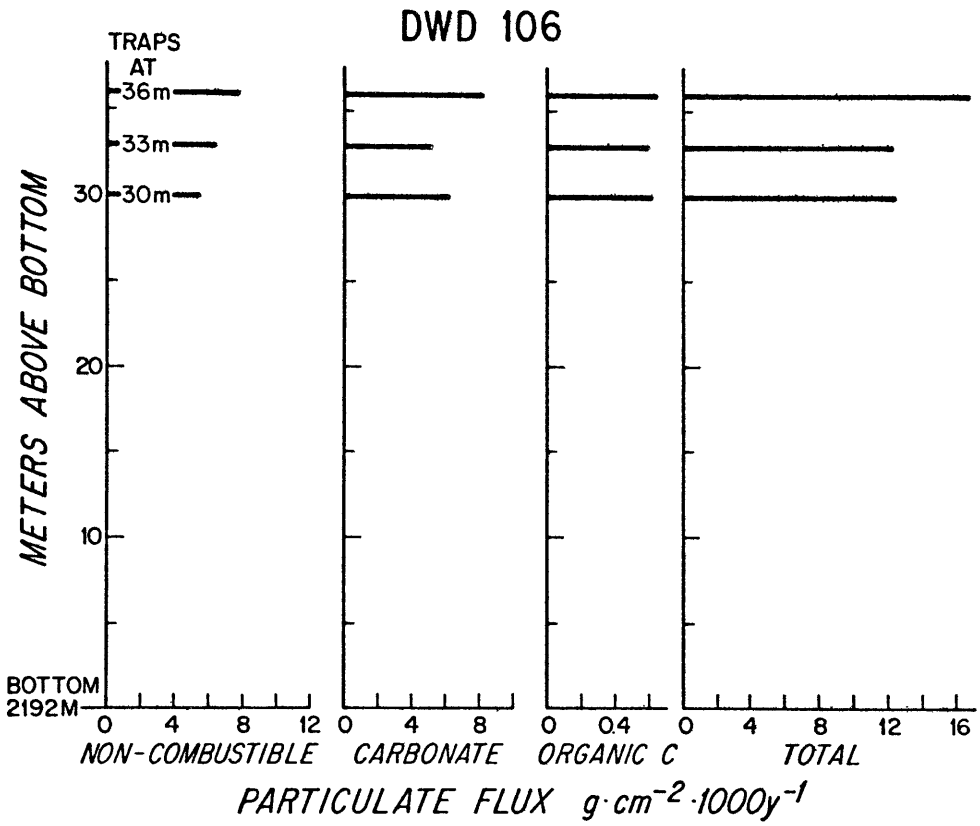


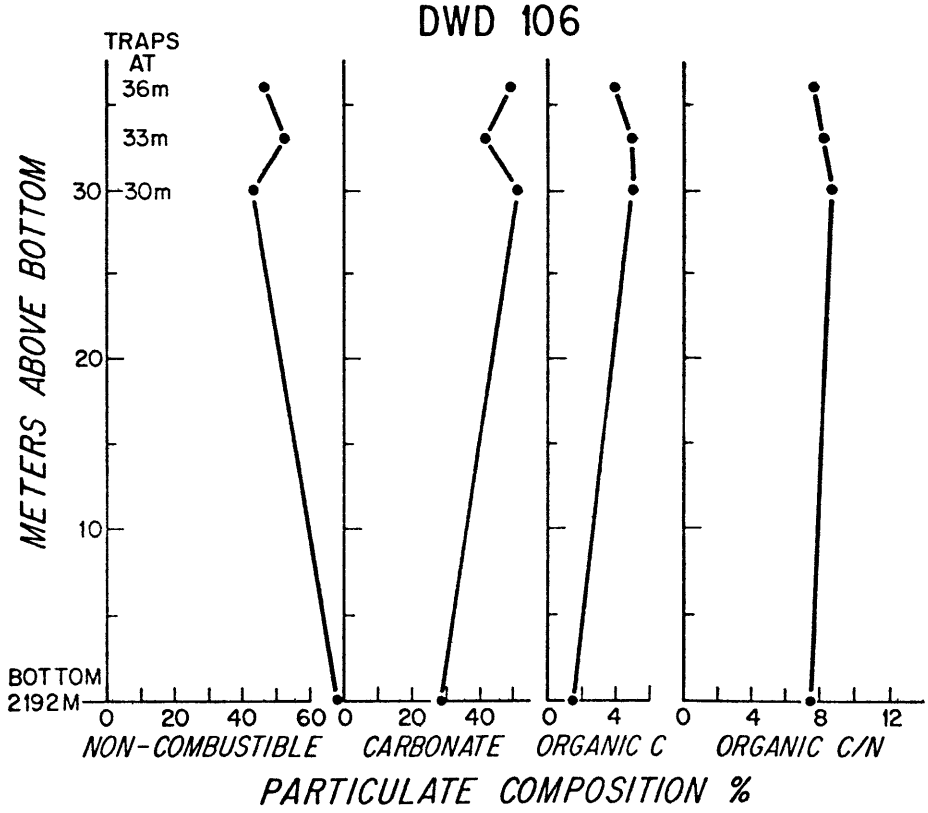
PARTICULATE FLUX $g \cdot cm^{-2} \cdot 1000y^{-1}$

KN58-1

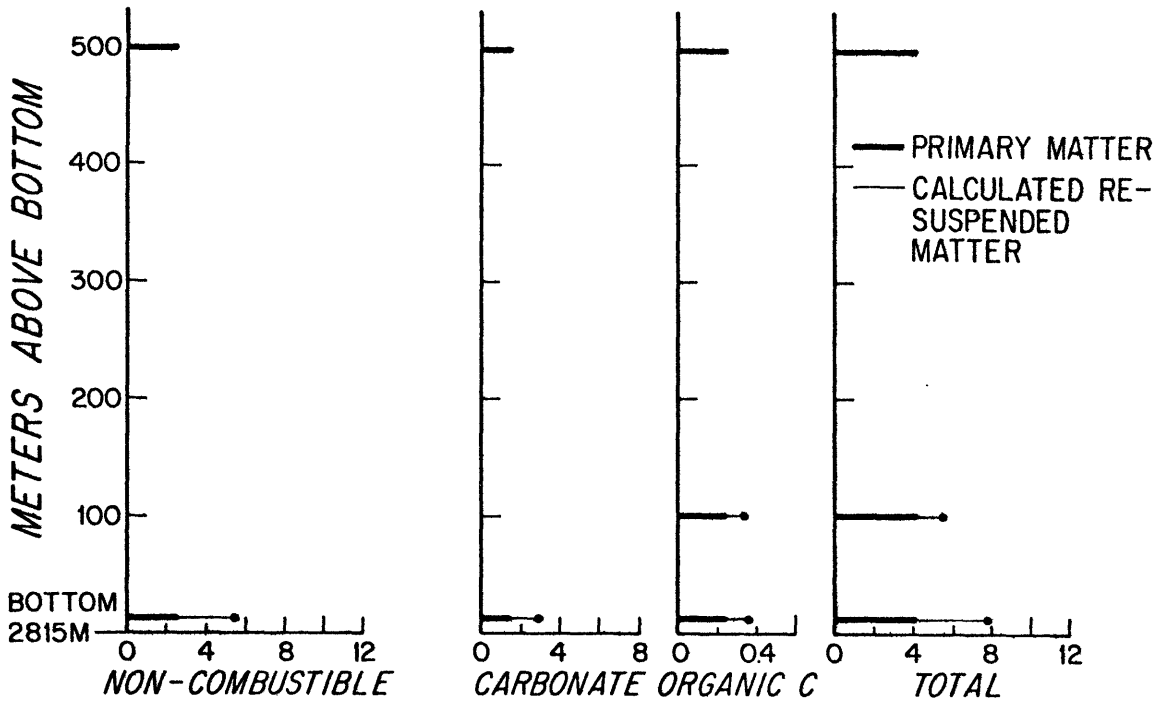


PARTICULATE COMPOSITION %

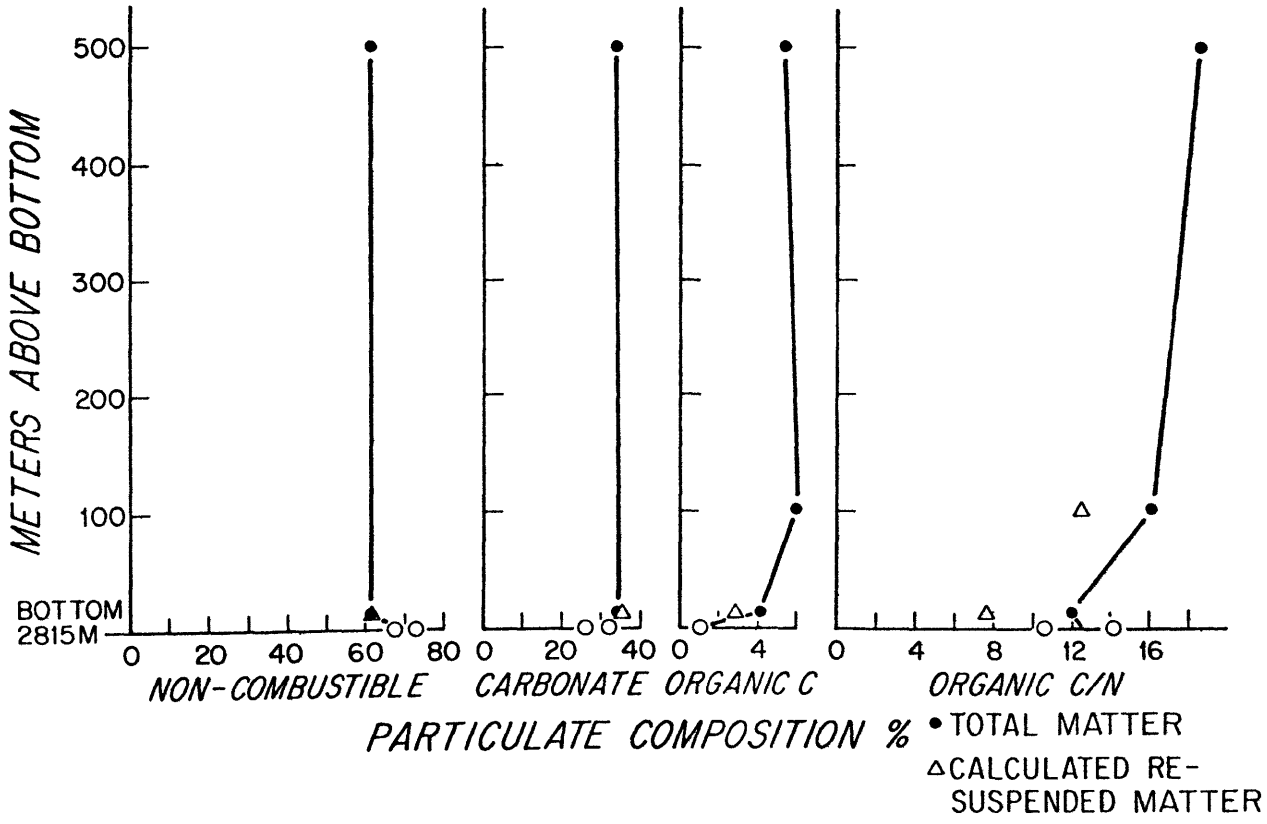

DWD 106
TRAPS AT
36m
33m
30m
METERS ABOVE BOTTOM
30
20
10
BOTTOM 2192M
0 4 8 12
0 4 8
0 0.4
0 4 8 12 16
NON-COMBUSTIBLE
CARBONATE
ORGANIC C
TOTAL
PARTICULATE FLUX g·cm⁻²·1000y⁻¹


DWD 106
TRAPS AT
36m
33m
30m
METERS ABOVE BOTTOM
30
20
10
BOTTOM 2192M
0 20 40 60
0 20 40
0 4
0 4 8 12
NON-COMBUSTIBLE
CARBONATE
ORGANIC C
ORGANIC C/N
PARTICULATE COMPOSITION %

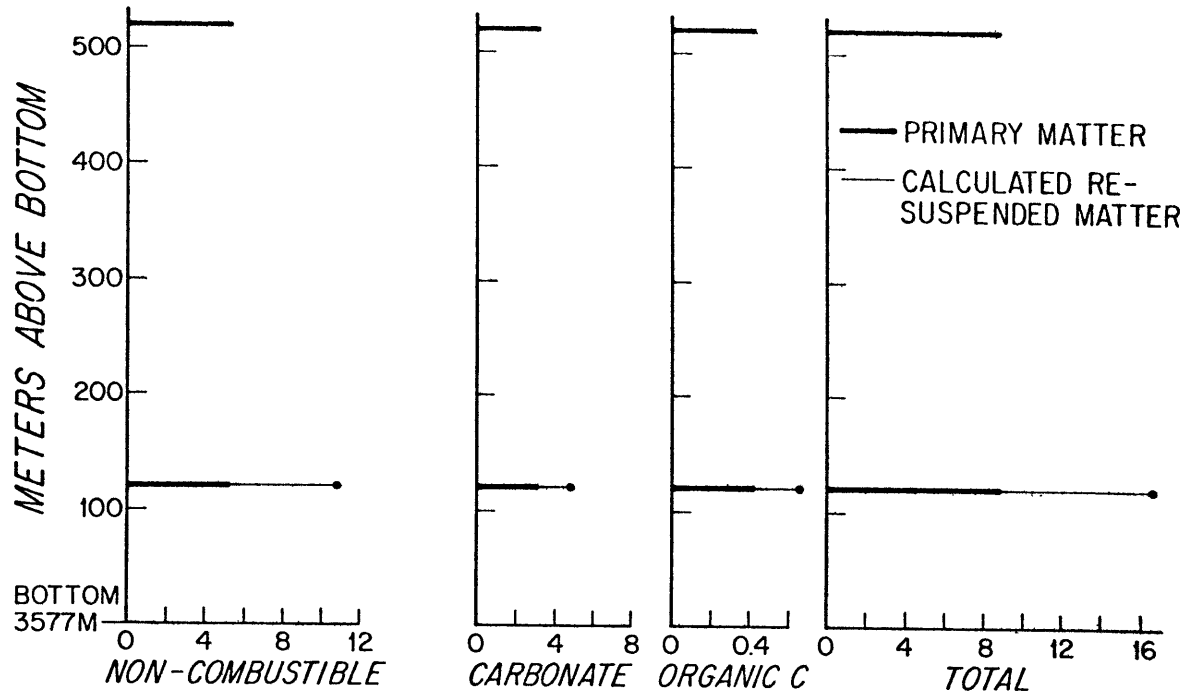
KN58-2


METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
2815M
0 4 8 12
NON-COMBUSTIBLE
0 4 8
CARBONATE
0 0.4
ORGANIC C
0 4 8 12
TOTAL
PRIMARY MATTER
CALCULATED RE-SUSPENDED MATTER
PARTICULATE FLUX g·cm⁻²·1000y⁻¹

KN58-2


METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
2815M
0 20 40 60 80
NON-COMBUSTIBLE
0 20 40
CARBONATE
0 4
ORGANIC C
0 4 8 12 16
ORGANIC C/N
PARTICULATE COMPOSITION %
• TOTAL MATTER
△ CALCULATED RE-SUSPENDED MATTER

DOS #2


METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
3577M
PRIMARY MATTER
CALCULATED RE-SUSPENDED MATTER
0 4 8 12
NON-COMBUSTIBLE
0 4 8
CARBONATE
0 0.4
ORGANIC C
0 4 8 12 16
TOTAL
PARTICULATE FLUX g·cm⁻²·1000y⁻¹

DOS #2

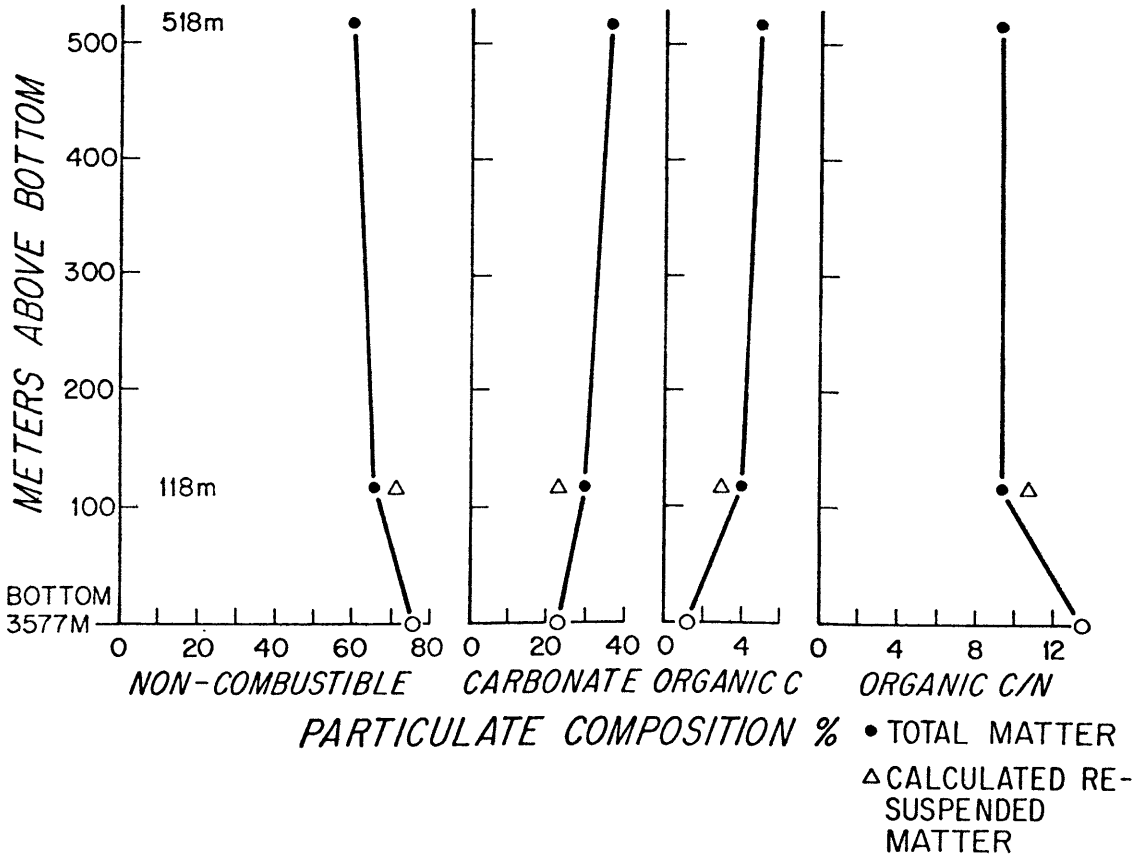

METERS ABOVE BOTTOM
518m
500
400
300
200
118m
100
BOTTOM
3577M
0 20 40 60 80
NON-COMBUSTIBLE
0 20 40
CARBONATE
0 4
ORGANIC C
0 4 8 12
ORGANIC C/N
PARTICULATE COMPOSITION %
• TOTAL MATTER
△ CALCULATED RE-SUSPENDED MATTER

TABLE 5.6

COMPOSITION OF TRAP MATERIAL AND CORE TOPS
*FLUX UNITS IN g cm^{-2} $1000y^{-1}$

DEPTH (M)	METERS ABOVE BOTTOM	TOTAL DRY WT. (mg)	TOTAL FLUX	†NON-COMBUSTIBLE FLUX**	(%)	CARBONATE FLUX	(%)	ORGANIC CARBON FLUX**	(%)	ORGANIC NITROGEN FLUX	C:N
DWD 106											
2156	36	133	16.9	7.88	(46.6)	8.26	(48.9)	0.66	(3.9)	0.08	7.65
2159	33	97	12.4	6.47	(52.2)	5.25	(43.3)	0.61	(4.9)	0.07	8.27
2162	30	98	12.5	5.46	(43.7)	6.34	(50.7)	0.63	(5.0)	0.08	8.73
2192	Core				(70.5		(28.0)		(1.3)		7.47
KN58-1											
2788	27	141	10.31	6.35	(61.6)	3.50	(33.9)	0.46	(4.5)	0.039	11.9
2794	21	131	9.58	6.32	(66.0)	2.84	(29.6)	0.37	(3.9)	0.037	11.0
2800	15	127	9.29	5.69	(61.3)	3.21	(34.6)	0.35	(3.8)	0.03	10.4
2822	Core 1				(67.1)		(31.6)		(1.2)		10.6
2813	Core 972				(72.5)		(26.2)		(1.2)		14.3
KN58-2											
2315	500	61	4.20	2.56	(60.9)	1.40	(33.4)	0.23	(5.4)	0.013	18.5
2715	100	81	5.62					0.34	(6.0)	0.021	16.2
2802	13	129	8.92	5.47	(61.3)	3.06	(34.3)	0.37	(4.1)	0.030	12.1
2822	Core 1				(67.1)		(31.6)		(1.2)		10.6
2813	Core 972				(72.5)		(26.2)		(1.2)		14.3
DOS #2											
3059	518	189	8.84	5.26	(59.5)	3.11	(35.2)	0.42	(4.8)	1.2	9.07
3459	118	354	16.55	10.89	(65.8)	4.93	(29.8)	0.66	(4.0)	.066	9.39
	Core				(75.8)		(22.8)		(1.29)		13.6

* Multiply these values by 10 to obtain units of g m^{-2} y^{-1}
** Not corrected for non-carbon organic material lost during combustion
† Includes silicious frustules

the sediment surface is reached, where there is a slight decrease. Some of the decrease may be due to slow dissolution, although it is also possible that there is a near-bottom transport of terrigenous sediment into the region.

The most noticeable compositional gradient occurs in the organic carbon content. The total flux of organic carbon increases 50% between 500 m and 13 m above the bottom, but the percentage of material that is organic carbon decreases by 50% over that interval and by as much as 500% when compared with the surface sediment.

3. Composition of Resuspended Material

In order to investigate the composition of resuspended material, the primary flux of each component was subtracted from the total flux in the nepheloid layer. On the Upper Rise (KN 58-2) the calculated composition of resuspended material did not vary more than a few percent from the composition of the total flux in carbonate or noncombustible content even though the surface sediment below the traps contained 10% less carbonate than the total flux material. The organic carbon content decreased by a factor of 25%, but was still richer in organic carbon than surface sediments (fig. 5.18). The resuspended material on the mid-Rise (DOS #2) decreased

by a factor of 30% in carbonate content to a similar composition as the surface sediment (fig. 5.19). The organic carbon decreased by the same factor, but still had a higher content than surface sediment (John Farrington, unpublished data).

4. Comparison of Organic Carbon Flux with Benthic Respiration Rates.

Smith and Teal (1973) have measured respiration rates of the benthic community by monitoring the oxygen uptake in an enclosed bell jar. Oxygen is utilized both in respiration and in the oxidation of organic matter, but this was corrected for in their measurements. Respiration rates decreased about two orders of magnitude from coastal waters (47-53 $ml/m^2/hr$) to the continental slope at 1850 meters (0.5 $ml/m^2/hr$). To convert oxygen consumption to the average carbon content of the food required to sustain the measured activity, it is assumed that 1 ml O_2 = 4.83 gm cal and 9 gm cal = 1 mg C (Wiebe et al., 1976). This means that the respiration rate measured at 1850 meters, 2.37 g $C/m^2/y$ are required.

The primary fluxes of organic carbon measured on the mid and Upper Rise were 4.2 g $C/m^2/y$ and 2.3 g $C/m^2/y$. This is 177%-97% of the organic carbon required for respiration. However, some organic carbon is buried with the sediments. Using the sedimentation rate of

60 g/m^2/y (Turekian, 1965) and the organic carbon content of the surface sediment, 0.72 g C/m^2/y are required for burial. This means that 159%-74% of the total organic carbon required is provided by the "rain" of particulate matter.

The flux of organic carbon measured 36 m above the sea floor on the slope (DWD 106) was 6.3 g C/m^2/y, but may have included some resuspended material. Assuming all the material is primary, 266% of the organic carbon necessary for respiration is provided by the particulate flux and 209% of the flux for both respiration and burial is available.

5. Primary Production Compared with Organic Carbon Flux: Moored and Floating Traps

During the time when the floating traps were deployed, primary production was measured to be 125 g C/m^2/y (344 mg C/m^2/day) by Ortner (1977), although the region generally had a slightly higher productivity. Based on that measurement, the percentage of primary production of organic carbon collected by the traps floating at 100 m was 6% during the night and 15% during the day, indicating that most of the primary production was utilized or regenerated within the photic zone.

The organic carbon flux measured 500 m above the bottom near this site (KN 58-2) was only 1.8% of the primary production, and was 12-30% of the flux measured 100 m below the sea surface. The mid-Rise traps (DOS #2) were moored in May some 200 km from the floating traps, which were deployed in September, so comparisons there are not applicable. However, Ortner's (1977) measurements of primary production in that area averaged 160-180 g $C/m^2/y$, and only 2.3-2.6% of that amount was collected at the level of primary flux measurements. This confirms previous reports (Menzel and Ryther, 1970) that most recycling of organic matter occurs in the surface waters and very little reaches the sea floor.

6. Correlation Between Particle Size and Content of Organic Carbon

The percent of organic carbon was determined for each size fraction in the trap 15 m above bottom on the Upper Rise (KN 58-1). The fractions between 63-500 μm showed a much higher content of organic carbon than other fractions (table 5.7). Most of the fecal pellets collected were also in that size range, suggesting that fecal pellets play a significant role in the transport of organic matter.

TABLE 5.7

ORGANIC CARBON CONTENT IN EACH SIZE FRACTION

Flux Units in $g/cm^2/1000$ y

	Depth (m)	Meters Above Bottom (m)	Total Dry Wt.	Total Flux	Organic Carbon Flux	%	C:N
KN 58-1	2800	15					
	Size Fraction						
	>500 µm		6.4	0.42	0.011	2.7	2.3
	125-500 µm		11.4	0.79	0.071	9.0	7.3
	63-125 µm		10.2	0.74	0.051	6.9	4.9
	20-63 µm		49.5	3.62	0.151	4.2	8.2
	<20 µm		50.8	3.72	0.153	4.1	6.7
	Total		127	9.29	0.437	4.7	

H. ELEMENT COMPOSITION AND FLUXES

Using techniques of carbonate dissolution and CHN analysis, it was possible in the last section to look at the general composition of the material collected in traps and compare it with surface sediments below the traps. However, the trap sites were all shallower than the calcium carbonate compensation depth, so little change in overall composition could be expected due to carbonate dissolution except in the aragonite phase. To determine if any other diagenetic changes were occurring during the time the particles were falling through the water column, resuspended in the benthic boundary layer, or on the sea floor, elemental analyses were made and will be reported in this section.

There have been a few attempts to compare the composition (mostly mineralogy) between suspended particles and sea floor sediments (Lisitzin, 1972; Tucholke, 1974; Rupke and Stanley, 1974; Pierce and Stanley, 1975), but never before have comparisons been made among bottom sediments, suspended sediments (from water bottles), and the particulates in transit to the bottom (from sediment traps) in the deep ocean, as will be presented here.

The traps at the clear-water minimum were located to collect the primary flux of particles from the upper water

column and the traps in the nepheloid layer were to collect both primary and resuspended material. The difference in the flux is presumed to be resuspended material (see Chapter IV) and the composition of this material can then be calculated. From the analysis of composition by size we can see which elements are concentrated in the large or small particles and determine which particle sizes are predominantly responsible for the flux of each element. Finally, we can make the first direct comparisons of the flux of these elements with long-term fluxes determined from deep-sea cores. In making this comparison it must be realized that traps were deployed for only days to weeks, and accumulation rates in cores are measured on time scales of thousands of years. Nevertheless this information should help improve models of particle and elemental fluxes in the ocean and processes of chemical cycling.

1. Methods

The instrumental neutron activation technique used here was developed and described by Spencer et al. (1972, 1977). The handling procedure for the trap and core material was described in Chapter IV-E. The hydrocast samples were drawn from ten-liter or 30-liter Niskin bottles through 47 mm pre-weighed Nuclepore filters

(0.6 μm pore size) into an evacuated glass carboy. After ten rinsings with filtered distilled water, the filters were stored in individual plastic dishes and returned to the laboratory for reweighing. The precision of the measurement of particulate weight per liter of sea water was ±5 μg, but is complicated by the "dregs" problem discussed in Chapter III.

This particular neutron activation method was designed to analyze the very small quantities (sometimes <100 μg) of material collected by filtering sea water. Many of the trap and core samples were too concentrated on individual Nuclepore filters to analyze all the material on a filter with this method. To reduce the weight analyzed the filters containing particles 63-125 μm and greater than 125 μm were weighed, cut in half with a razor blade and reweighed to determine the sample weight. The material was not always evenly distributed, and led to the greatest inaccuracies for the samples where one half of the filter was analyzed. On most filters only a few percent of the material was needed. Furthermore, I wished to preserve a small portion of the regular and dregs filters for SEM examination. Both of these needs were satisfied by using an acetone-cleaned single-hole paper punch to remove a sample dot for activation or SEM

observation. Forceps were used to place a Nuclepore filter separator paper above and below the filter to minimize contamination. Two blank filters were punched three times to determine the uniformity of the dot weight which proved to be 1.86% ± 0.02% of the total filter weight in one case and 1.85% ± 0.08% in the other. The dot area was 3.16% of the filtered area when a Millipore filter base and funnel were used and 2.32% of the filtered area when using the in-line filter holder. These percentages were used to correct for the material removed for SEM examination and water volumes used in concentration calculations. Sample dots taken from trap and core filters were individually weighed and the sample weight was determined by subtracting 1.855% of the original filter weight. Two samples consisted of fecal pellets picked from the upper Continental Rise traps (KN 58-2) at 13 and 500 meters above the bottom.

The sample dots were placed on a blank Nuclepore filter and all samples were individually pelletized to minimize geometry problems and to increase resistance to irradiation damage and fragmentation during analysis (Spencer et al., 1972). Whole filter blanks and blanks punched with dots were treated identically and used to correct the samples. The blank values never contained

more than a few percent of any element analyzed, and no contamination was detectable from the paper punch. Pelletized samples were irradiated for 10 minutes at the Rhode Island Nuclear Science Center research reactor. After 5 minutes of cooling, the samples were counted with a 24% Ge (Li) detector and analyzed with a Canberra pulse height analyzer. The spectra were recorded on magnetic tape and peak areas determined with the computer program, GAMANL. The elements analyzed were Al, Ca, Mg, Mn, Sr, Ti, Ba, V, Cu, and I.[1]

Samples analyzed came from trap sites on the Upper Rise (KN 58-2) and mid-Rise (DOS #2) and a hydrocast on the Hatteras Abyssal Plain (OC 738). A subsample from each trap was analyzed as well as samples from one core top from the mid-Rise (DOS #2) and the tops of two cores from the Upper Rise (KN 58-2). The Niskin bottle sample closest to the level of each trap was also analyzed. A subsample of each size fraction (>125 μm, 63-125 μm, 20-63 μm and <20 μm) from the 500 meter and 13 meter traps on the Upper Rise (KN 58-2) were analyzed along with the three finer size fractions of one core top. Hydrocast samples taken at the Upper Rise site (KN 58) had the entire bottle contents, including the dregs,

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[1]A more complete analysis of the sediment could be made if concentrations of silica and iron were known. Analysis for these elements will be made in the future.

filtered onto a single filter. At the mid-Rise site (DOS #2), 30-liter bottles were used and the "dregs" were placed on separate filters. Both the normal and dregs were placed on separate filters. Both the normal and dregs samples were analyzed for comparison with the trap samples and to further evaluate the fractionation occurring in the dregs. For this latter purpose a normal and dregs sample were also analyzed from 30-liter bottles 100 and 500 meters above the bottom in 5388 meters of water--depths below the CCD.

2. Source and Role of Elements Analyzed

Aluminum is derived from inorganic sources and is one of the basic building blocks of alumiosilicates; in the ocean the most abundant of which are the various forms of clay minerals brought in by wind and water. The relative abundance of aluminosilicates ("clays") can be obtained by multiplying the aluminum content of the sample by 10 (Arrhenius, 1963). Particulate titanium (Ti) and vanadium (V) are primarily associated with the aluminum (Riley and Chester, 1971, p. 394; Chester, 1965, p. 52), although both are concentrated in ferro-manganese deposits relative to pelagic clays.

Calcium most commonly occurs in a carbonate form of calcite, magnesium calcite, or aragonite and is biologically precipitated to form the skeletons of

foraminifera, coccolithophorids, or pteropods. Most of this production occurs at the sea surface where the water is oversaturated in calcium carbonate. As the organisms sink in the water column, either individually, or after being injested by filter-feeding zooplankton and compacted into fecal pellets, they encounter water which, due to increased pressure and decreased temperature has become undersaturated with carbonate. Once the depth known as the carbonate compensation depth is reached, rapid dissolution removes the particulate carbonate forms. In the western North Atlantic, this depth is between 1000-2500 m for aragonite, and 4,000-5,000 m for calcite (Li et al., 1969). Magnesium is associated with both organic and inorganic constituents as magnesium calcite, organic matter, clay, and other silicate minerals (Drever, 1974).

The major carrier of strontium in surface waters is the phytoplankter Acantharia, containing a test of strontium sulphate (Bottazzi, Schreiber, and Bowen, 1971; Brass and Turekian, 1974), although strontium is also present in foraminifera and coccoliths (Emiliani, 1955; Krinsley, 1960; Thompson and Bowen, 1969; Kilborne and Sen Gupta, 1973; Bender et al., 1975). Acantharia are highly soluble in sea water after their organic coating

is removed and only a few percent of the Acantharia observed in the upper 100 meters were found below that depth in a vertical profile by Bishop et al. (1977).

Manganese is associated with the aluminosilicates in the water column but is enriched in the surface sediments as manganese oxide and can form coatings on organic and inorganic particles as well as forming nodules. Barium is associated with biogenous products (Chan et al., 1977), but its carrier is uncertain as no barium is found in the phytoplankton frustules (Chester, 1965, p. 65). Chesselet et al. (1976 AGU) have observed barium sulphate particles on filters which they believe to be of biogenic origin. Two elements analyzed--Cu and I--are indicative of the presence of organic matter (Goldschmidt, 1954; Wong et al., 1976).

3. Concentration of Measured Elements

The data are tabulated in parts per million for the upper Continental Rise site (KN 58-2) and middle Continental Rise site (DOS #2) in table 5.8 and 5.9. When these data are plotted on a semi-log scale (fig. 5.20) the associations of elements becomes more apparent. Elements such as Al, Ti, and V are related in abundance in the material in the traps and core as is indicated by similar slopes between each depth. Mn appears related to Al between 500 and 100 m

TABLE 5.8 NEUTRON ACTIVATION DATA FOR KN58-2

METERS ABOVE BOTTOM	WEIGHT ANALYZED (mg)	FILTER #	SIZE FRACT. (μm)	p.p.m. Ba	Ti	Sr	Mn	Mg	Cu	V	Al	Ca	I
Composition (ppm) of Trap and Core Material													
500	0.176	1975-2	All	710	1960	1170	900	13700	1210	72	33200	162000	390
100	0.145	1965-2	All	920	2602	1270	1220	21700	420	93	44400	168000	440
13	0.298	1958-2	All	530	3180	1370	1990	19400	370	102	50900	152000	350
Core 972	0.395	1982	All	520	3350	350	3480	16200	270	140	53200	96000	190
Core 1	1.307	1772	All	360	2970	610	3720	15100	150	90	46900	135000	120
Composition (ppm) of Size Fractions of Trap and Core Material													
500	0.30	1970	>125	500	930	420	430	6480	820	26	11500	80000	360
13	0.55	1953	>125	370	1130	840	500	6270	190	31	14500	95000	230
500	0.27	1969	63-125	500	1170	740	500	6680	860	40	17100	110000	270
13	0.65	1952	63-125	360	1240	830	720	7700	1270	43	20200	120000	200
Core 1	0.058	1775	63-125	0	2060	0	2060	9840	42	110	32100	80000	360
500	0.108	1968	20-63	680	1420	1450	600	10700	700	54	25400	119000	310
13	0.388	1951	20-63	440	2920	860	1890	16600	380	83	43900	122000	280
Core 1	0.898	1778	20-63	380	3000	520	5200	19800	380	105	53700	90500	140
500	0.184	1967	<20	680	1860	1160	900	12700	620	69	31600	138000	320
13	0.196	1950-2	<20	830	3200	1630	1770	21100	300	110	50300	149000	440
Core 1	0.631	1779	<20	390	3580	650	3460	19200	220	110	57800	84600	140
Composition (ppm) of Fecal Pellets													
500	0.017	2033	>125	0	910	1190	790	0	310	59	22600	87100	260
13	0.104	2032	>125	1014	1800	830	980	7650	200	67	28800	113000	330
Composition (ppm) of Hydrocast Particulates													
533	0.149	1943	Total	790	1870	360	700	16700	270	55	21300	56100	240
82	0.338	1948	Total	450	2840	470	750	17300	1020	41	23000	42400	180
16	0.549	1941	Total	610	3360	350	1620	19000	400	90	47800	73100	140
Concentration of Hydrocast Particulates (ng/kg of seawater)													
533	7.3	1943	Total	16	38	7	14	340	5	1.1	432	1140	5
82	6.0	1948	Total	25	160	27	42	970	57	2.3	1290	2390	10
16	7.4	1941	Total	45	250	260	120	1410	30	6.5	3550	5430	11
Flux from Trap Data (mg $m^{-2}y^{-1}$) (divide by 10^{-4} for g $cm^{-2}1000y^{-1}$)													
500			All	30	82	49	38	580	51	3.0	1400	6780	16
100			All	51	146	71	68	1210	24	5.2	2490	9400	25
13			All	47	283	122	177	1720	33	9.1	4530	13500	31
Flux by Size Fraction mg $m^{-2}y^{-1}$													
500			>125	1.6	2.9	1.3	1.3	20	2.5	0.08	35	250	1.1
13			>125	2.1	6.5	4.8	2.8	36	1.1	0.18	83	540	1.3
500			63-125	1.2	2.9	1.8	1.3	17	2.1	0.10	42	270	0.66
13			63-125	1.4	4.6	3.1	2.7	29	4.8	0.16	75	450	0.73
500			20-63	7.5	16	16	6.7	120	7.7	0.6	280	1310	3.4
13			20-63	21	140	41	90	790	18	3.9	2100	5800	13.3
500			<20	18	47	29	23	320	16	1.8	810	3520	8.1
13			<20	27	102	52	57	680	9.6	3.5	1600	4780	140
Sum of Flux by Size Fractions (mg $m^{-2}y^{-1}$)													
500			All	28	69	49	32	480	28	2.5	1160	5350	13
13			All	51	250	100	150	1530	34	7.8	3860	11800	29

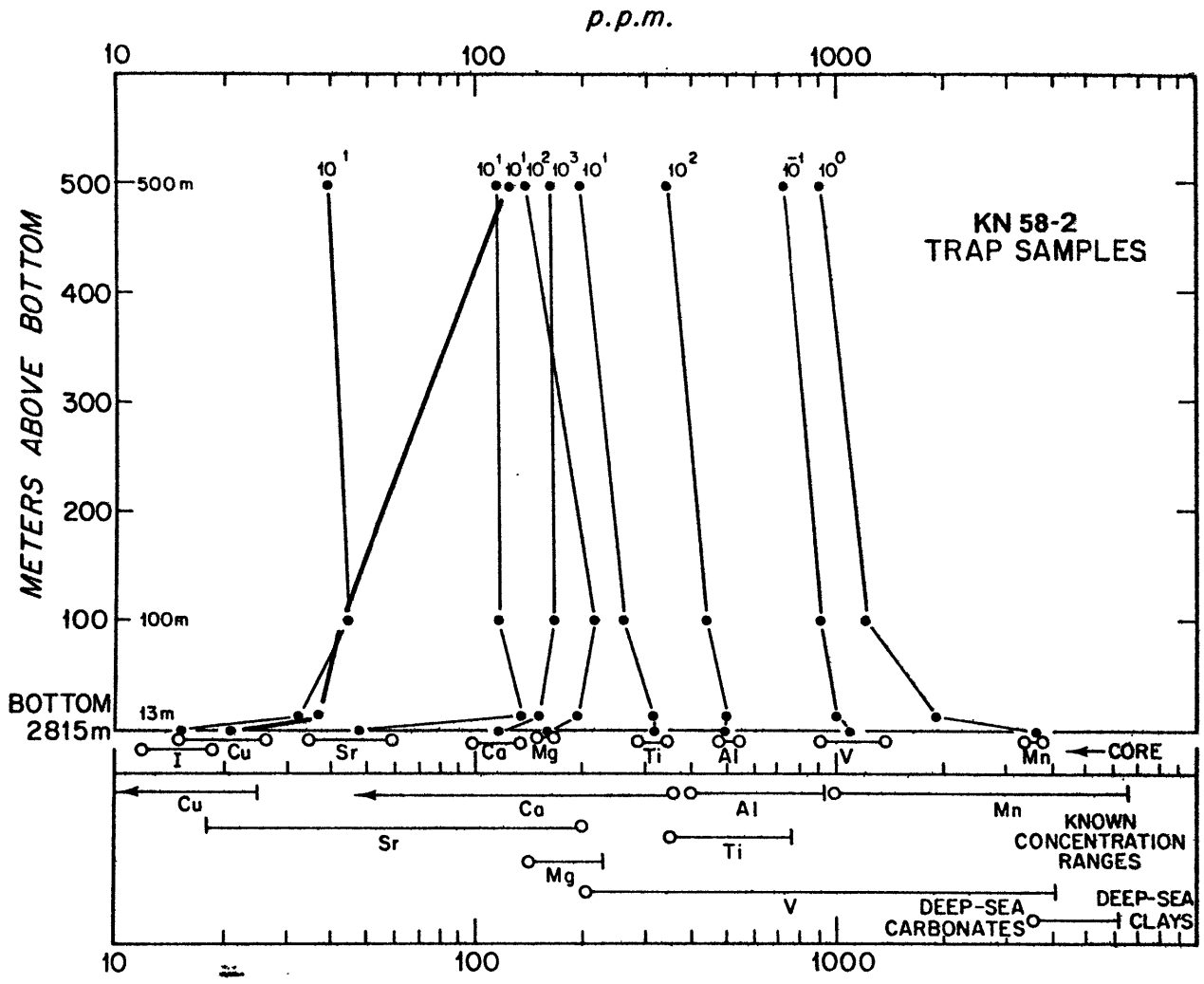
TABLE 5.9

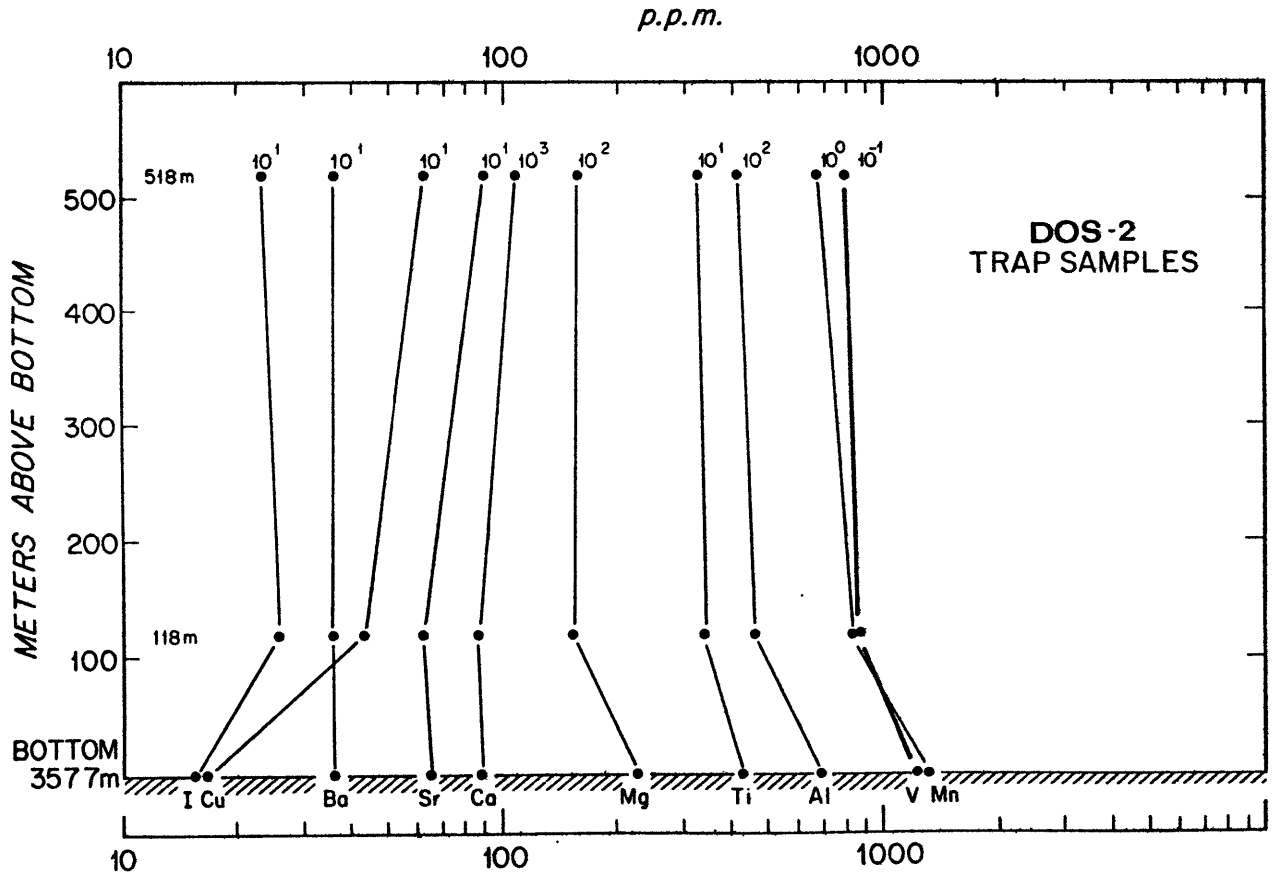
NEUTRON ACTIVATION DATA FOR DOS #2

p.p.m.

METERS ABOVE BOTTOM	WEIGHT ANALYZED (mg)	FILTER #	SIZE FRACT. (μm)	Ba	Ti	Sr	Mn	Mg	Cu	V	Al	Ca	I
Composition (ppm) of Trap and Core Material													
518	0.538	2025	All	360	3280	900	670	15700	610	82	42100	107500	240
118	0.545	1763	All	360	3340	610	820	15100	420	86	45400	85100	250
Core	0.286	2034	All	360	4270	650	1290	22300	170	130	69200	87900	160
Composition (ppm) of Hydrocast Particulates													
501	0.221	1575	Regular	730	2740	880	1060	21100	370	100	51900	73300	170
101	0.361	1576	Regular	420	3220	130	840	24800	380	120	68400	46900	60
24	0.533	1577	Regular	620	4060	180	1060	29000	230	140	75200	63400	72
Concentration (ng/kg of seawater) of Hydrocast Particulates													
501	12.8 l	1575	Regular	13	47	15	18	370	7	2	900	1270	3.0
101	6.6 l	1576	Regular	23	160	7	46	1360	21	7	3740	2570	3.2
24	8.6 l	1577	Regular	40	260	11	68	1870	15	90	4830	4080	4.6
Flux Calculated from Traps (mg m^{-2} y^{-1}) (divide by 10^4 for g $cm^{-2}1000^{-1}$)													
518			All	32	290	79	59	1380	54	7	3710	9460	21
118			All	59	550	100	140	2510	70	14	7540	14120	42

Fig. 5.20 The concentration of elements is shown for samples collected in sediment traps and for surface sediment below the traps. Element identification is indicated at the bottom of each graph and the concentration is obtained by multiplying the number at the top of each profile times the scale at the top of the graph (e.x., the concentration of Mn 500 mab at KN 58-2 is 10° x 900 = 900 ppm). Two core tops were sampled and analyzed at KN 58-2 to obtain the two values shown for the core. The ranges of known concentrations of these elements in deep-sea clays (—|) and deep-sea carbonates (o—) are reported in Turekian (1965), Chester (1965), and Riley and Chester (1971).


p.p.m.
10
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
500m
100m
BOTTOM
2815m
13m
KN 58-2
TRAP SAMPLES
I
Cu
Sr
Ca
Mg
Ti
Al
V
Mn
CORE
KNOWN
CONCENTRATION
RANGES
DEEP-SEA
CARBONATES
DEEP-SEA
CLAYS


p.p.m.
10
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
518m
118m
BOTTOM
3577m
DOS-2
TRAP SAMPLES
I
Cu
Ba
Sr
Ca
Mg
Ti
Al
V
Mn

on the Upper Rise (KN 58), but the near-bottom suspended particulates and surface sediments are greatly enriched in Mn. This enrichment does not occur at the mid-Rise site (DOS #2). Based on submersible dives near and at KN 58-2 in R/S ALVIN by Heezen and Dyer (1977) and Rowe and myself, this is a tranquil area with currents probably less than 5 cm/sec most of the time, whereas the mid-Rise site (DOS #2) experiences far more energetic currents (Luyten, 1977) and greater resuspension; a process (see fig. 5.13 and 5.14), that apparently inhibits the accumulation of reduced Mn in the surface sediments.

All of the elements related to biological processes (Ca, Mg, Sr, Cu, and I) showed a decrease near the bottom on the Upper Rise (KN 58-2). The Cu and I are probably consumed with organic matter and released in solution (Wong et al., 1976). The decrease in Ca near the bottom is not likely to result from dissolution of calcite since the depth is only 2800 m, but some Ca may be lost by dissolution of aragonite at this depth. Otherwise it is most likely that the concentration of Ca in the falling detritus during this ten day period in August is higher than the average input of Ca to the seafloor in this region. Terrigenous material might also be brought in through horizontal transport to dilute the Ca in the sediments.

Concentration gradients for the biogenic elements I, Sr, and Ca as well as Mn at DOS #2 are not as large as at KN 58-2, but the gradient is steeper for the "clay" related elements Al, Ti, and V between the primary particles collected at 518 mab, particles collected at 118 mab, and the surface sediment. Again, it is difficult to assess the importance of seasonality and resuspension in these differences.

For comparison with previously measured surface sediment concentrations in the North Atlantic, values compiled from many sources by Riley and Chester (1971), Turekian (1965), and Chester (1965) are shown at the bottom of figure 5.20. All of the measurements made at the two sites fall within the range of concentrations in the literature.

The only major components not measured were silica and iron. It is possible to estimate the contribution these components might have by adding up the organic matter, "clay", and carbonate to see what percent of material is unaccounted for. Making the assumptions that organic matter is twice the organic carbon, "clay" is ten times the Al (Arrhenius, 1963), and carbonate is 2.5 times the Ca, we find that at KN 58-2 15% of the material is unaccounted for at 500 meters, 2% at 100 meters,

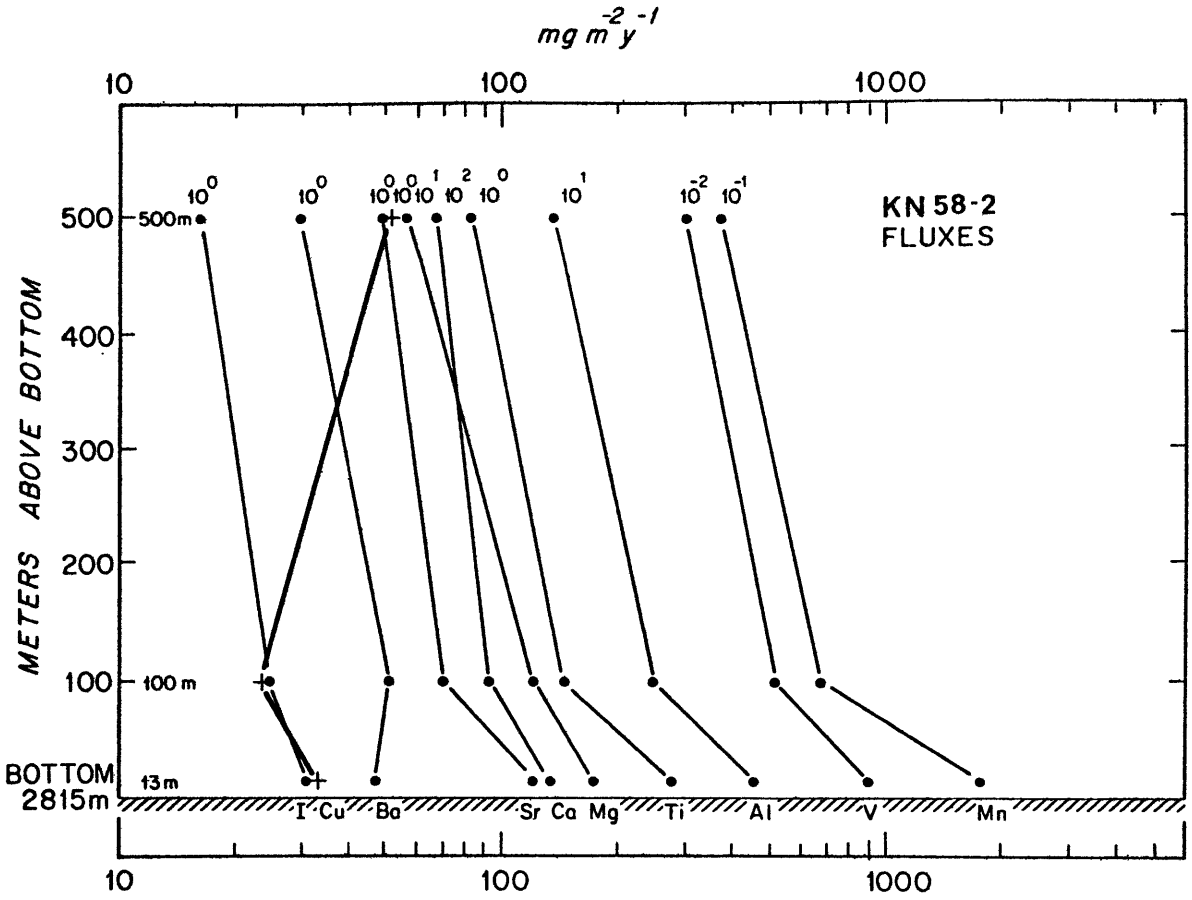
4% at 13 meters, and 13% in the surface sediment. Based on microscope examination (table 5.4) about 50% of the particles larger than 125 μm consisted of diatoms and radiolarians. Therefore, silica particles greater than 125 μm could account for the remaining material in the 13 meter and 100 meter traps, and leaves only 5-8% to be accounted for by the fraction <125 μm in the 500 meter trap and surface sediment. Given the imprecision of the extrapolations from C, Ca, and Al to organic matter, carbonate, and "clay", one could not expect better summations without further elemental analysis.

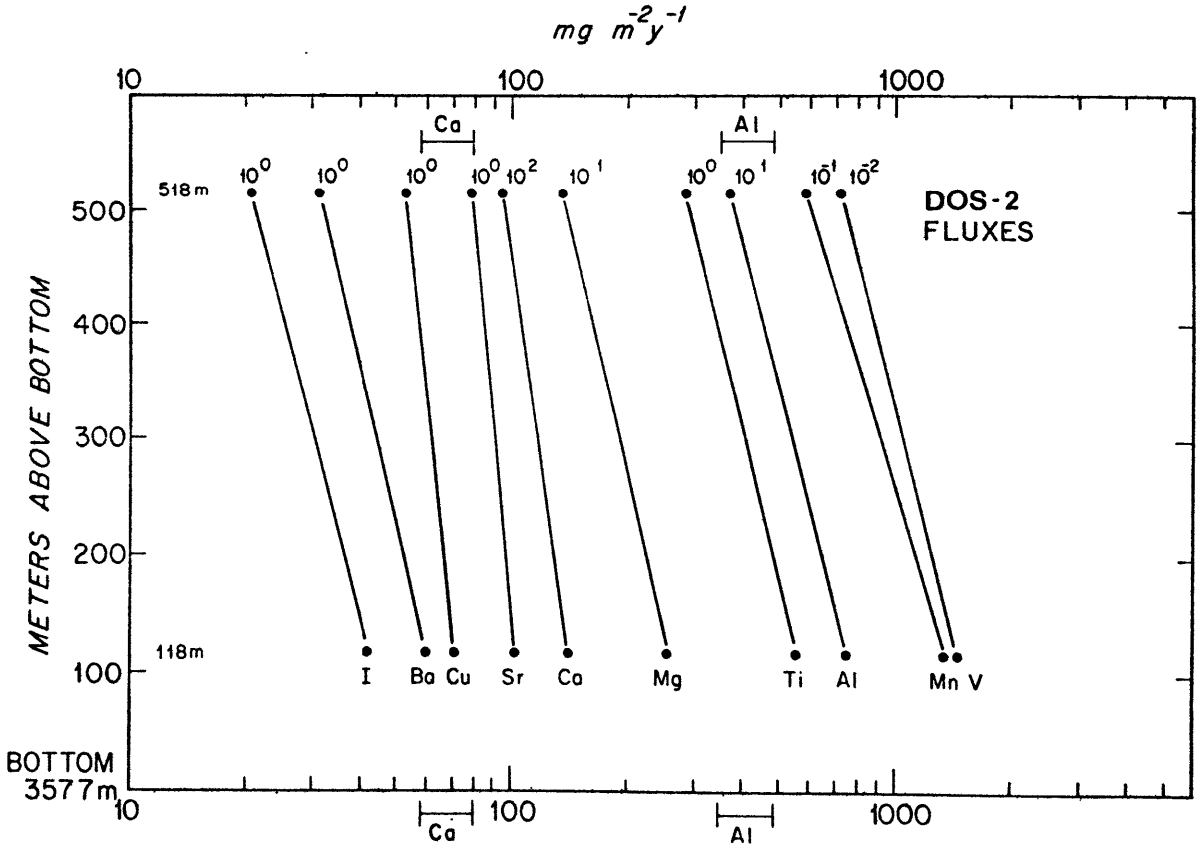
On the mid-Rise (DOS #2), summation of the organic, "clay", and carbonate fractions leaves 22%, 24%, and 7% to be accounted for in the 518 meter, 118 meter, and surface samples respectively.

4. Fluxes of Elements

As discussed in section 4-A, the flux calculated at the top trap was intended to represent the primary flux of material from the upper water column which is expected to reach the sea floor (fig. 5.21). The increase in flux calculated below this point is believed to be due to resuspension of sediment from the sea floor. The same elemental associations discussed in the last section about relative concentration are evident in the fluxes at each

Fig. 5.21 The flux for each element measured is shown for the Upper Rise (KN 58-2) and mid-Rise (DOS #2) as determined with sediment traps. The concentration of an element can be obtained by multiplying the number at the top of each profile times the scale at the top of the graph. The post-glacial Ca and Al flux measured in a core ten miles from DOS #2 are also shown (Turekian, 1965).


mg m-2 y-1
10
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
500m
100 m
13m
BOTTOM
2815m
KN 58-2
FLUXES
I Cu Ba Sr Ca Mg Ti Al V Mn


mg m-2 y-1
10
100
1000
Ca
Al
METERS ABOVE BOTTOM
500
400
300
200
100
518m
118m
BOTTOM
3577m
DOS-2
FLUXES
I Ba Cu Sr Ca Mg Ti Al Mn V

level. The flux of all elements increases in the bottom 500 meters at both sites with the exception of Ba and Cu on the Upper Rise (KN 58-2). These two elements are present in such small amounts that an anomalous particle on the filters analyzed could have caused the discrepancy.

One way of determining whether the traps 500 m above the bottom are really collecting only the primary flux would be to compare the atmospheric input of Al to the surface waters with the flux of Al where the primary flux is collected. This assumes that no glacial or river input is advected to the trap site without being deposited and resuspended. One problem with this approach is that no dust measurements were made during this study, and dust concentrations are highly dependent upon weather conditions. Nevertheless, Spencer et al. (1977) used the data of Chester (1972) for the Western North Atlantic to estimate an atmospheric flux of Al of 20-100 $mg/m^2/yr$. The primary fluxes of Al measured on the Upper Rise (KN 58-2) and mid-Rise (DOS #2) were 1400 $mg/m^2/yr$ and 3700 $mg/m^2/yr$. Even if the atmospheric flux estimates were an order of magnitude higher, they would not account for the flux of Al 500 m above the bottom. It should be noted, however, that the post glacial accumulation rate of Al measured in a core only 15 miles from DOS #2 on the mid-Rise was very close to the flux of Al calculated to be primary material.

Since the primary flux of Al appears too high, let us re-examine where the traps were located with respect to the nepheloid layer. The profile of total particulate matter at each site shows that the traps 500 m above bottom were at the clear-water particle minimum (fig. 5.13-5.14), but when the hydrocast samples at the trap levels were analyzed, they contained a much higher concentration of Al than midwater samples of the GEOSECS profiles (Spencer et al., 1977). However, the trap sites were much closer to the continental boundary of the ocean than GEOSECS stations, so higher concentrations of Al throughout the water column should not be surprising. It would have been helpful to analyze water samples higher off the bottom to see if an Al minimum existed and whether it corresponded with the total particulate minimum. In figure 4.2 showing the model used to pick trap levels it was acknowledged that resuspension may occur higher than the clear water minimum and that dissolution or consumption of particles may continue below that level. The high flux of Al at 500 m above the seafloor indicates that even at the clear-water particle minimum on the mid and Upper Rise, some of the material is resuspended. The concept of resuspension must include resuspension "upstream" and upslope of the traps and horizontal advection of the particles to

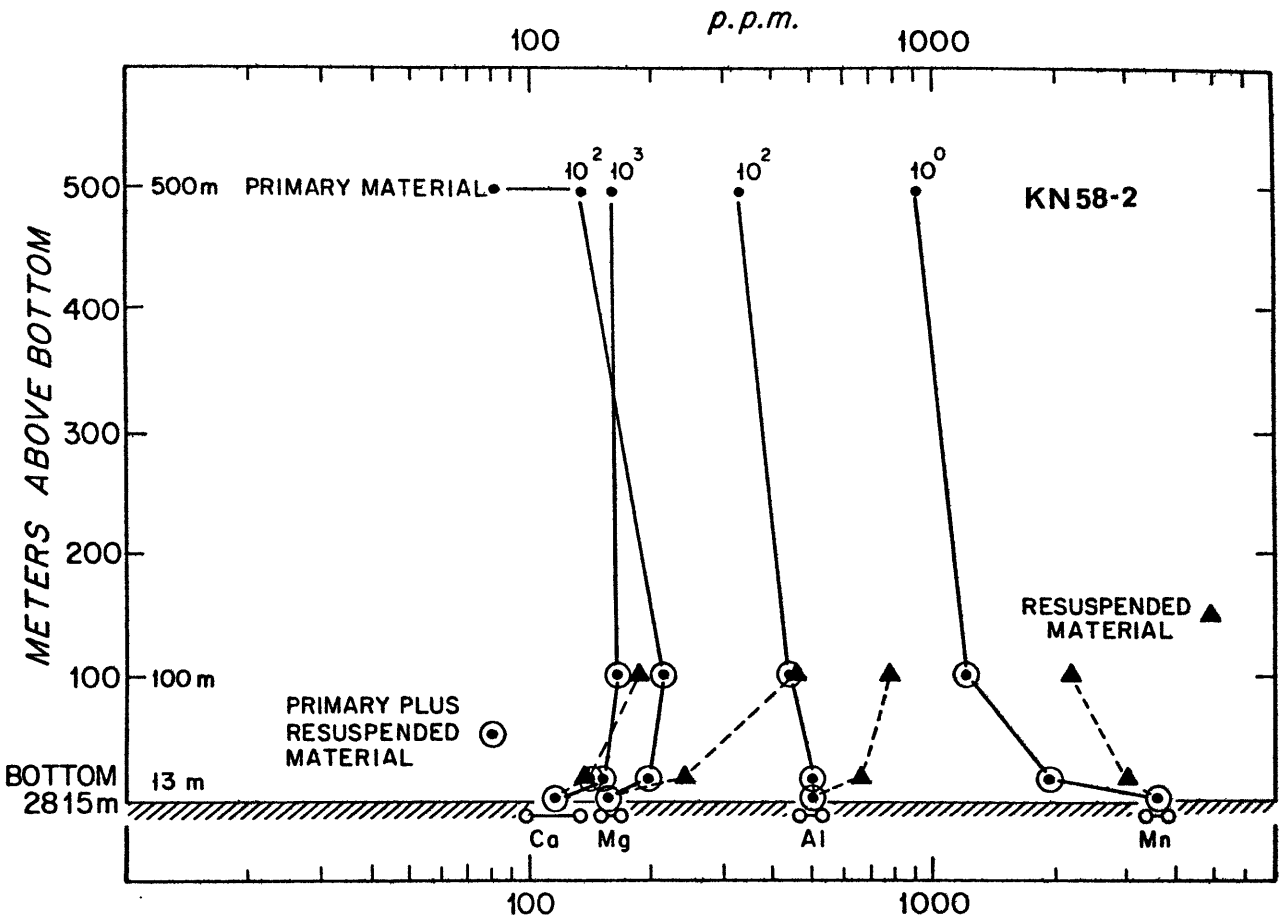
the trap site before they settle out. This interpretation was used in contouring the profiles of suspended particulate matter in figures 5.1 and 5.2.

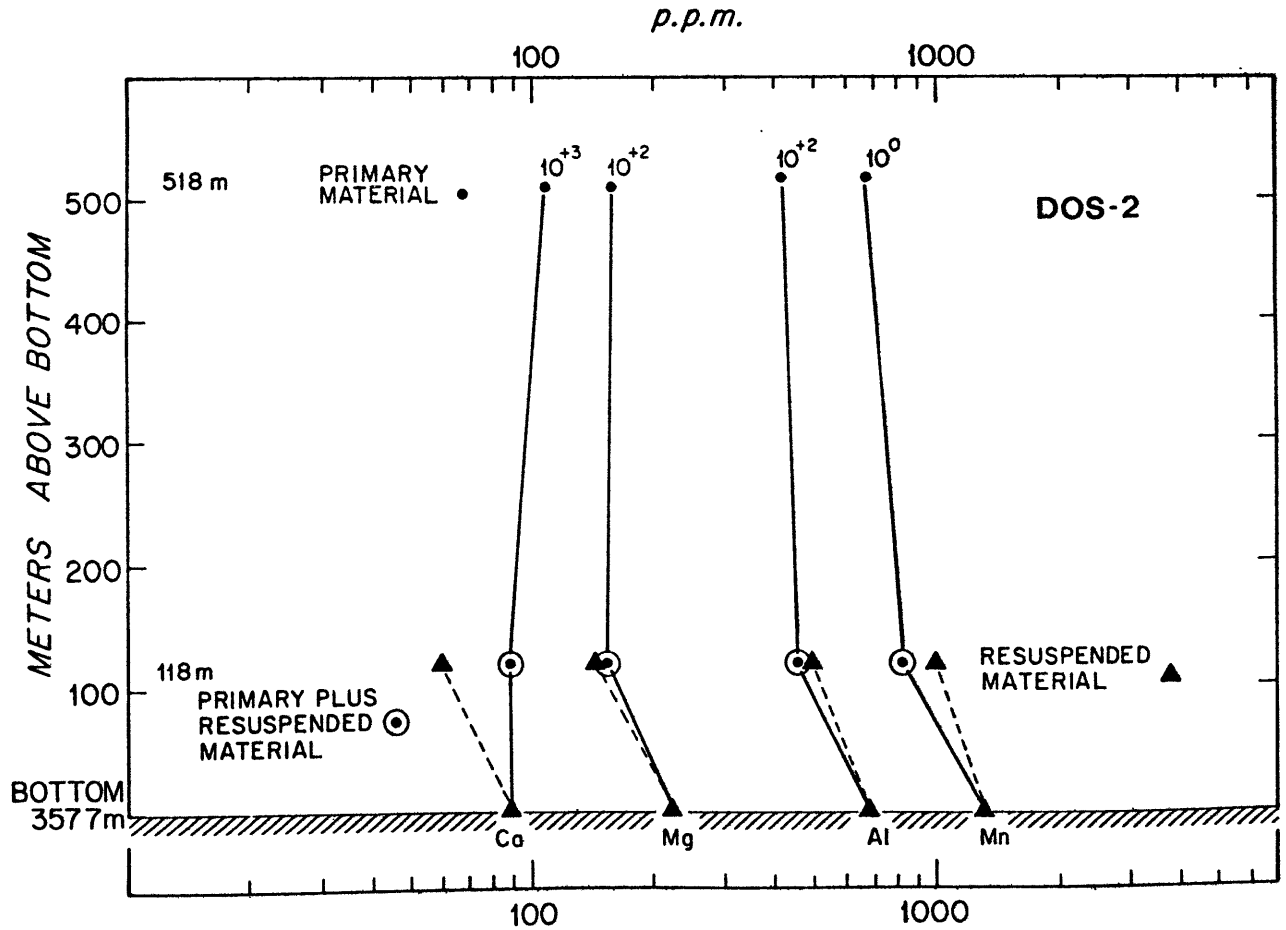
Although the flux measured at clear water appears to include more than just primary material, no attempt will be made here to correct for the amount of resuspended material because of insufficient information such as the real atmospheric flux during the deployment or the ratio of Al to resuspended material. The primary flux will be operationally defined as the flux measured 500 m above the bottom, and in the next section an attempt will be made to determine the composition of the resuspended material based on that definition.

5. Resuspension

Using the concepts of resuspension discussed before, we can look at figure 5.21 to see the resuspension flux of each element. The difference between the flux calculated with the top trap and lower traps is the flux of resuspended material. To calculate the percentage composition of the resuspended material in a trap, we can divide the resuspension flux of any element by the total resuspension flux for that trap. This has been done in figure 5.22 for four elements (Ca, Mg, Al, and Mn) which are present in sufficiently large quantities to reduce

Fig. 5.22 The composition of the resuspended material (▲) has been estimated by subtracting the primary material (●) measured 500 mab from the total material (⊙) collected near the bottom and determining the composition of the remaining material.


p.p.m.
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
2815m
500m
PRIMARY MATERIAL
100 m
13 m
PRIMARY PLUS RESUSPENDED MATERIAL
RESUSPENDED MATERIAL
KN58-2
Ca
Mg
Al
Mn


p.p.m.
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
BOTTOM
3577m
518 m
PRIMARY MATERIAL
118m
PRIMARY PLUS RESUSPENDED MATERIAL
RESUSPENDED MATERIAL
DOS-2
Ca
Mg
Al
Mn

the chances of a particle anomolously high in an element biasing the results. Differences in composition between the primary material and the resuspended particles would exist if primary particles differed from those already deposited. This could be caused by:

(1) temporal variations in the primary flux composition,

(2) diagenetic changes in the deposited sediment,

(3) differential resuspension of particles by type or size, or

(4) the original source of the resuspended material being different from the source of primary material.

Regarding these points:

(1) Seasonal variations in primary productivity will probably have an effect on the primary flux measured 500 m above the bottom, as will variations in the water mass characteristics such as the passage of a Gulf Stream ring (Wiebe, 1976);

(2) Chemical and electrochemical characteristics of transuranic elements cause some elements to be enriched in the deposited sediments relative to the concentrations associated with primary particles (Riley and Chester, 1971). This effectively tags particles and could be used to determine what proportion is resuspended (Tsunogai and Minikawa, 1974).

(3) A higher velocity is required to begin eroding clay than carbonate particles in flume experiments (Southard et al., 1971; Lonsdale and Southard, 1974) and presumably in the oceans. However, since clay particles are smaller than most carbonate particles they are likely to take longer to fall to the sea floor once they are resuspended, depending on their state of aggregation, so they should be higher in concentration in the nepheloid layer than carbonate particles;

(4) If the source of resuspended particles is both resuspended primary material and terrigenous material being advected laterally from submarine canyons, turbidity flows, or density flows, the composition of resuspended particles should be expected to differ from primary particles.

The dissimilarity between primary and resuspended particles is greater on the Upper Rise (KN 58-2) than the mid Rise (DOS #2). Aside from the possible explanations given above, it may be that the "primary" flux measurement on the mid-Rise was more contaminated with resuspended material than on the UPper Rise, which would tend to mask any differences between the two sources. This is consistent with previous observations that currents were higher on the mid-Rise and that the "primary" flux of Al was twice as great on the mid-Rise. The increased concentration

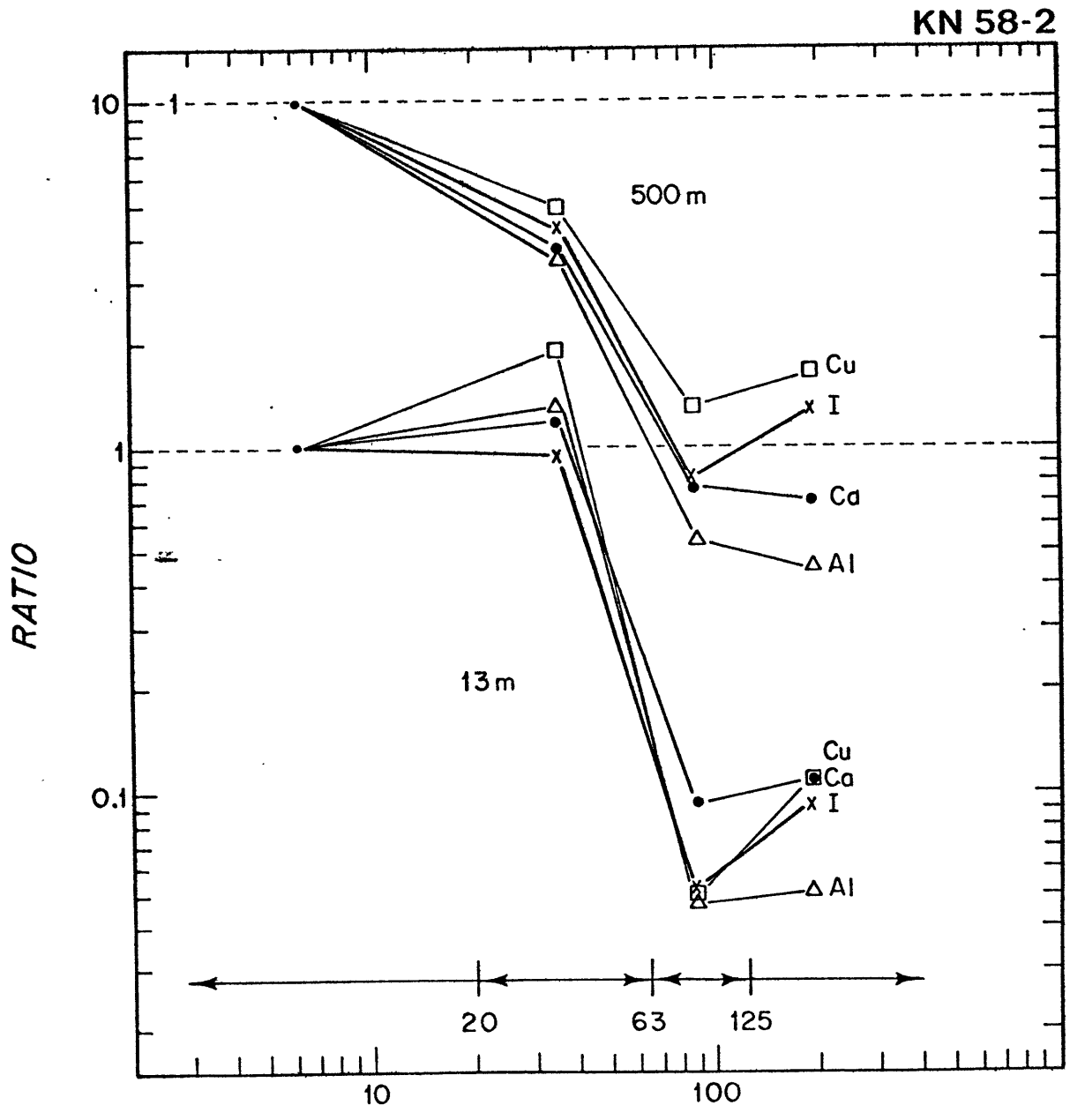
of Mn in the resuspended material on the Upper Rise (KN 58-2) is a result of Mn enrichment in the surface sediments due to remobilization of Mn from deeper sediments (Goldberg and Arrhenius, 1958). The reason for the high Mg concentration in the resuspended material cannot be easily explained and needs further examination.

6. Elemental Flux by Particle Size

The flux of any element carried by a particular size fraction will correspond closely with the total particulate flux of that size fraction unless the element is highly concentrated in that size and depleted in others. After comparing the data shown in figures 5.23 and 5.9, and applying that criterion it does not appear that any striking enrichment or depletion occurs. The particles from the sediment traps were wet sieved to separate them into the units in which they entered the trap rather than being broken down to individual particles before they were measured. Had they been broken down into individual particles, there may have been a stronger signal of element preference by size.

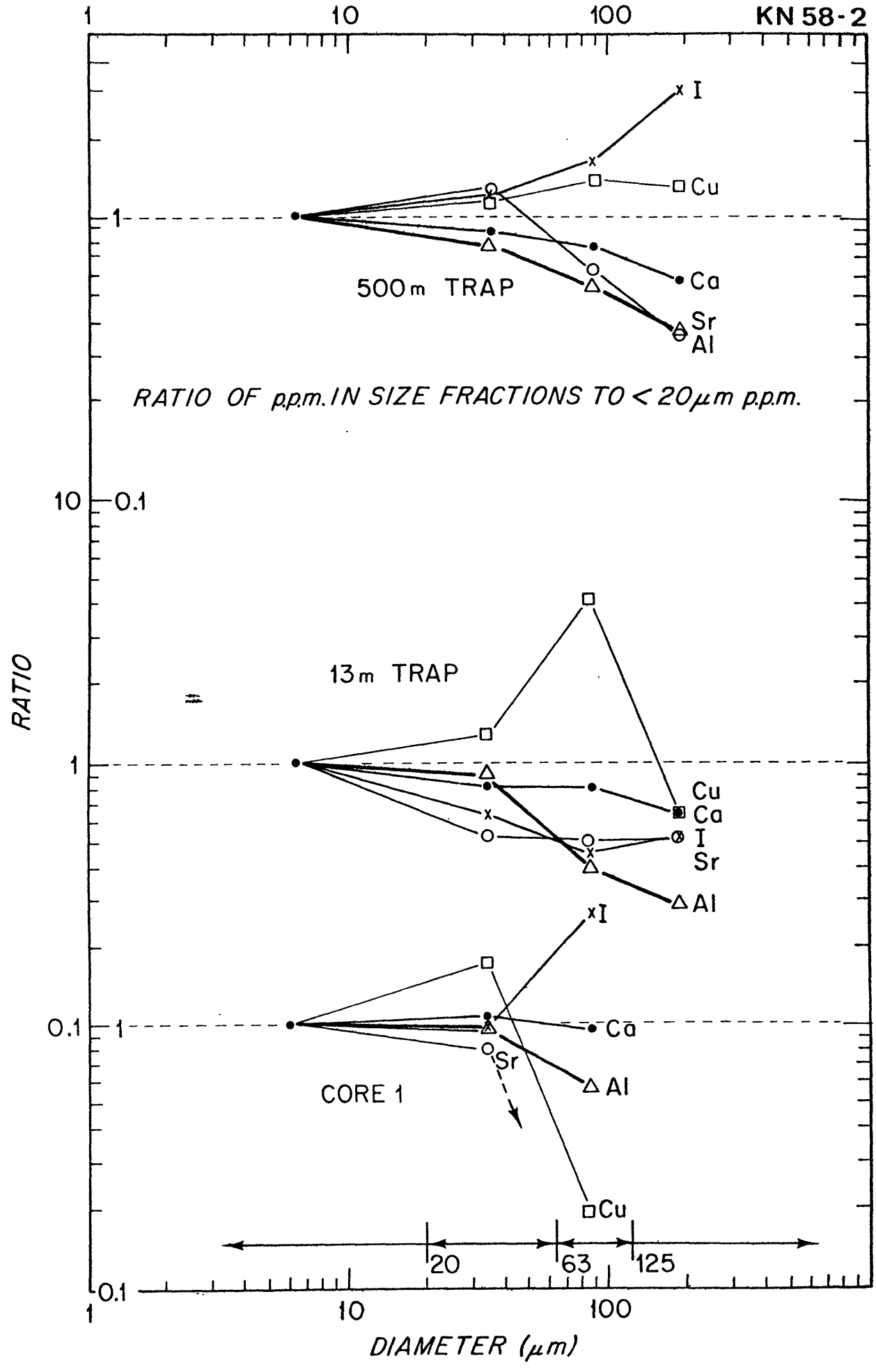
An examination of size preference of an element comes from plotting the concentration of the element in each size fraction relative to the concentration in the less than 20 μm fraction (fig. 5.24). The problem of

Fig. 5.23 The ratio of the flux in each size fraction to the flux in the <20 μm fraction is shown for four elements on the Upper Rise.



RATIO OF FLUX IN SIZE FRACTIONS TO < 20 μm FLUX

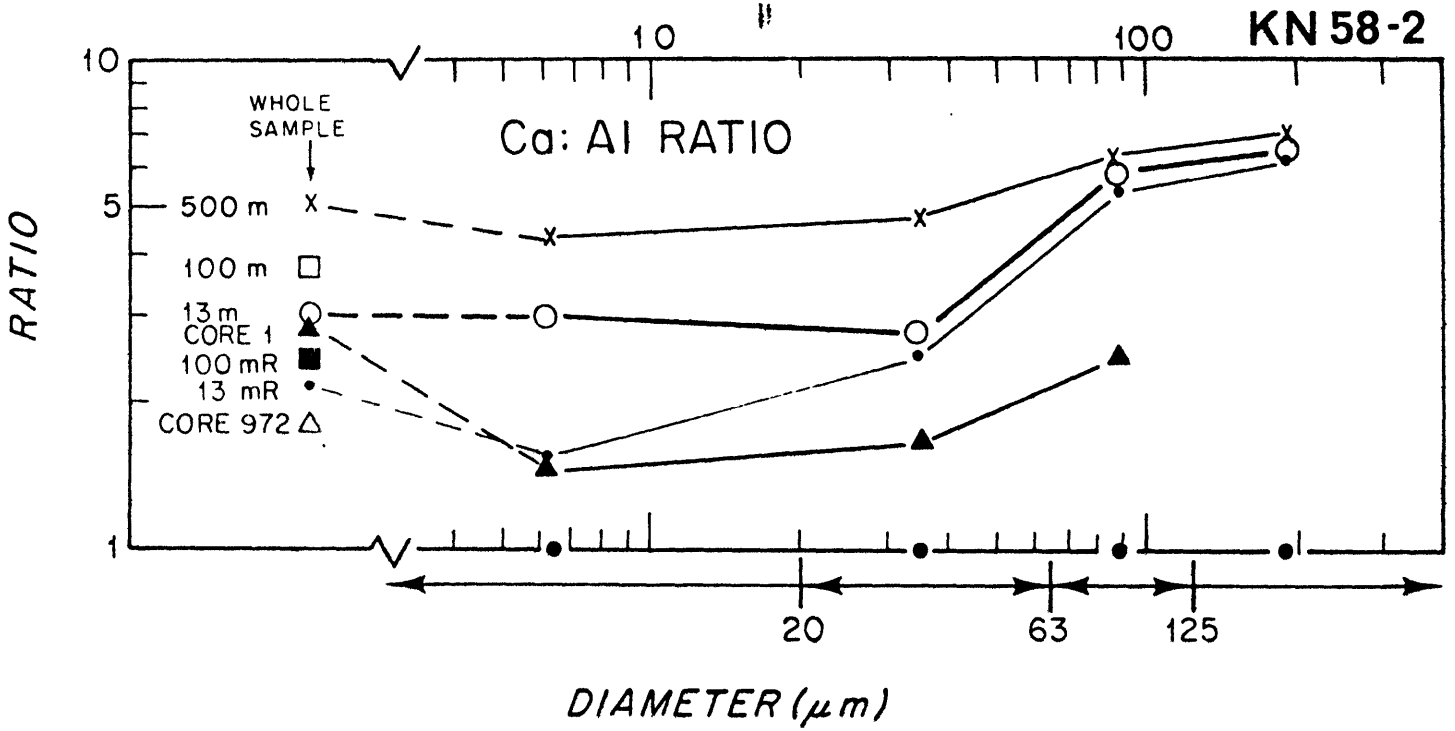
Fig. 5.24 The relationship between element concentration and particle size is shown by plotting the ratio of the concentration in each size fraction to the ratio in the <20 μm fraction.


KN 58-2
1
10
100
I
Cu
Ca
Sr
Al
500m TRAP
RATIO OF p.p.m. IN SIZE FRACTIONS TO < 20μm p.p.m.
10
0.1
RATIO
13m TRAP
Cu
Ca
I
Sr
Al
0.1
CORE 1
20
63
125
DIAMETER (μm)

individual particles versus agglomerations of particles also masks some of the effects of concentration versus size, but in general the Al content decreases more rapidly than Ca with increasing size. If the particles had been broken down to individual particles, the decrease in Al with increasing size would be much more pronounced because aluminosilicates tend to be small in size. In the core the concentration of Ca is nearly constant with size up to 125 μm, but the abundance of foraminifera >125 μm would have caused a high Ca value above that size. The elements Cu and I, which are predominantly associated with organic tissue, tend to be more concentrated in the larger particles than are Ca or Al suggesting that organic matter is more likely to be transported to the sea floor in the larger particles such as fecal pellets than in the smaller particles collected in the trap. This is especially true at the 500 m trap which is the closest measurement of material falling from the surface.

The Ca/Al ratio decreases with decreasing particle size and increases with distance from the bottom (fig. 5.25). The Ca/Al ratio of the calculated resuspended fraction of a trap is always closer to the Ca/Al ratio of the core than the primary flux material again indicating that the material in the lower traps has been mixed with sediment resuspended from the sea floor.

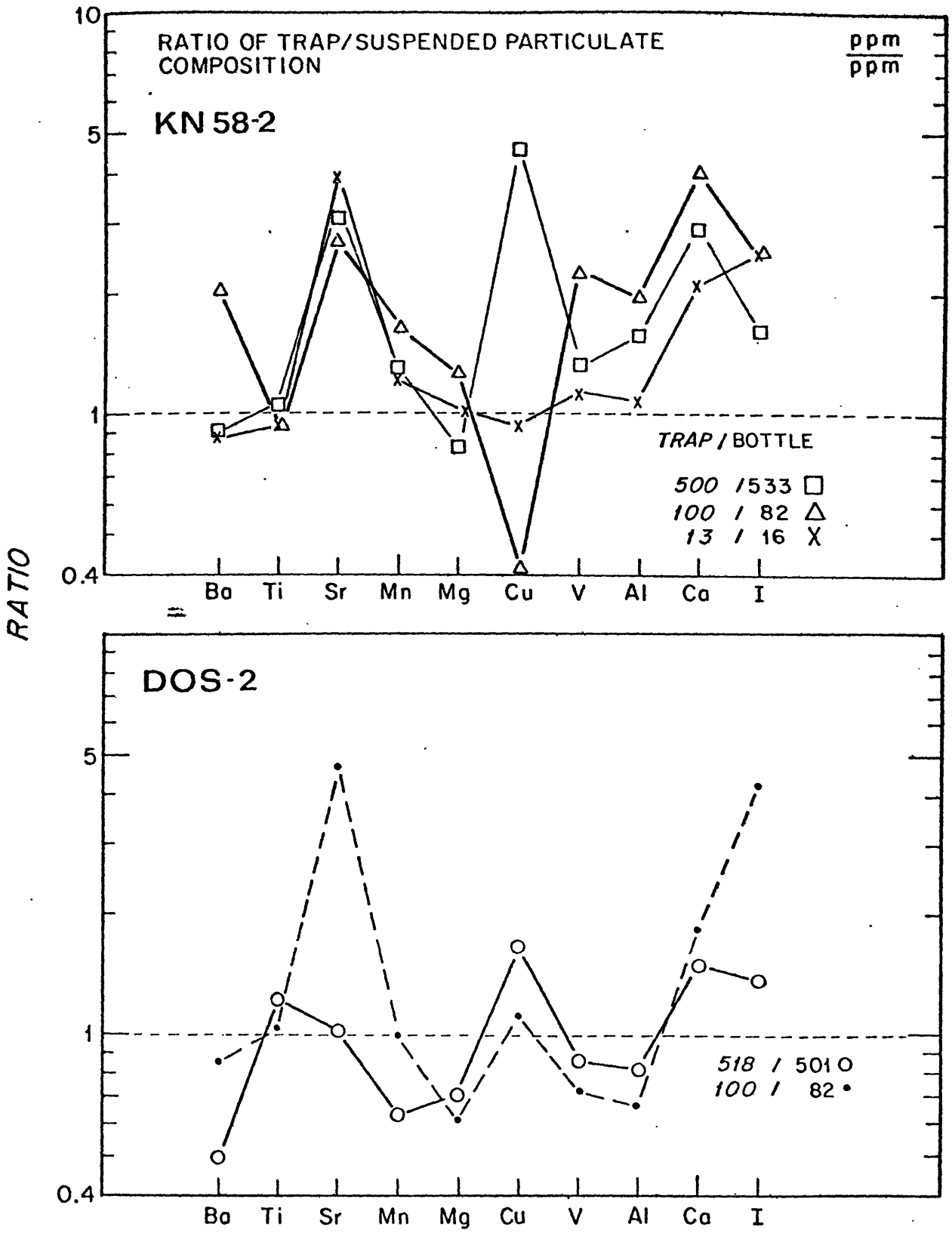
Fig. 5.25 The relative relationship between carbonate and clay in trap samples and surface sediments is shown by plotting the ratio of Ca to Al.


KN 58-2
Ca: Al RATIO
WHOLE SAMPLE
500 m
100 m
13 m
CORE 1
100 mR
13 mR
CORE 972
RATIO
10
5
1
10
100
20
63
125
DIAMETER (μm)

7. Composition of Particles in Flux Versus "in situ" Particles

One of the important questions to be answered by sediment traps is how closely the particles falling through the water column compare in composition with the "in situ" particles normally collected with water bottles. The ratios between the concentration of elements in the trap particles and filtered water samples show the same relative trend for most elements at the two sites, but the ratios tend to be higher at the Upper Rise site (KN 58-2) than at the mid-Rise site (DOS #2; fig. 5.26). For example, Al, V, and Mg at DOS #2 all comprise a greater abundance in the filtered water than the traps at both levels, whereas the opposite is true as KN 58-2. Calcium is more concentrated in the trap samples, which is consistent with the carbonate flux contributed by forams, pteropods, and fecal pellets rarely seen in water bottles. Cu and I are generally more concentrated in the traps indicating that the detritus falling through the water column is richer in organic matter than the "in situ" particles. Strontium is considerably more concentrated in the traps than in water bottles which is probably due to its association with the highly soluble but rapidly falling Acantharia. This data could be used to improve models of chemical cycles in the ocean.

Fig. 5.26 The ratio between the concentration of particles from traps and water bottles is shown for all elements measured.

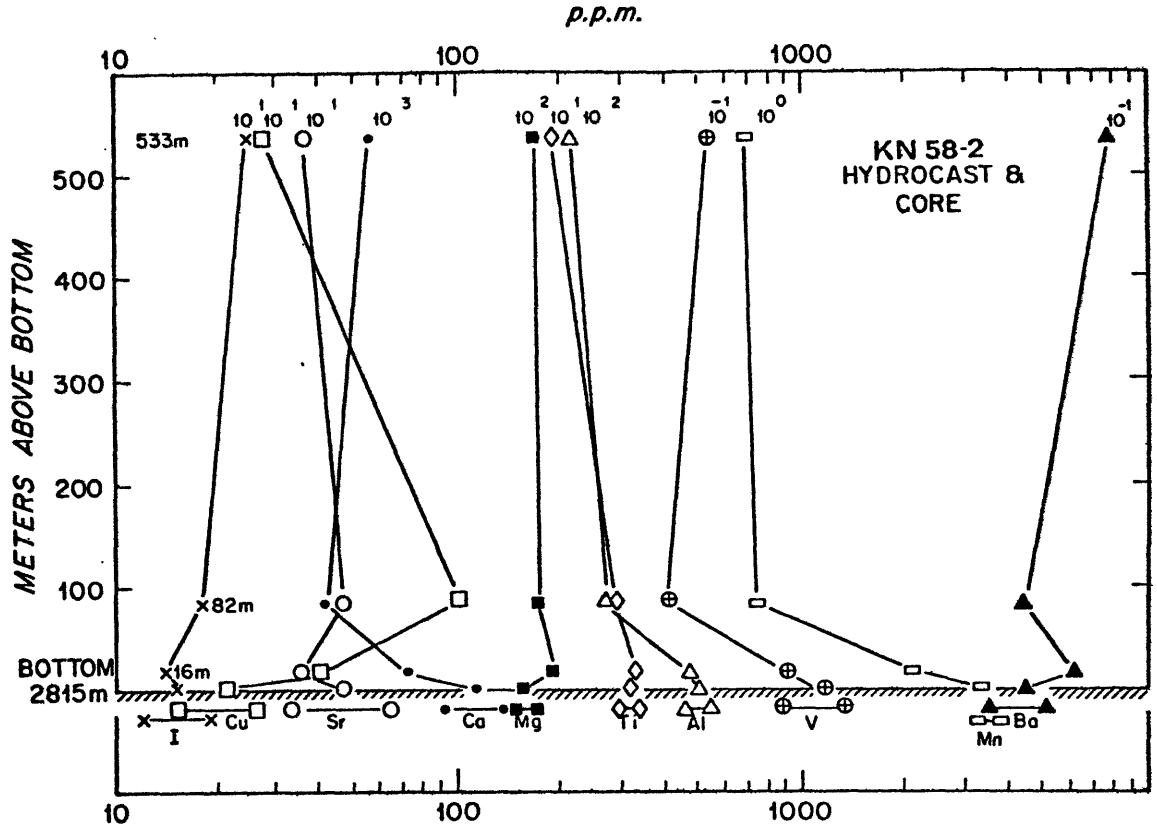

RATIO OF TRAP/SUSPENDED PARTICULATE COMPOSITION
ppm / ppm
KN 58-2
10
5
1
0.4
TRAP / BOTTLE
500 /533 □
100 / 82 △
13 / 16 X
Ba Ti Sr Mn Mg Cu V Al Ca I
RATIO
DOS-2
5
1
0.4
518 / 501 O
100 / 82 •
Ba Ti Sr Mn Mg Cu V Al Ca I

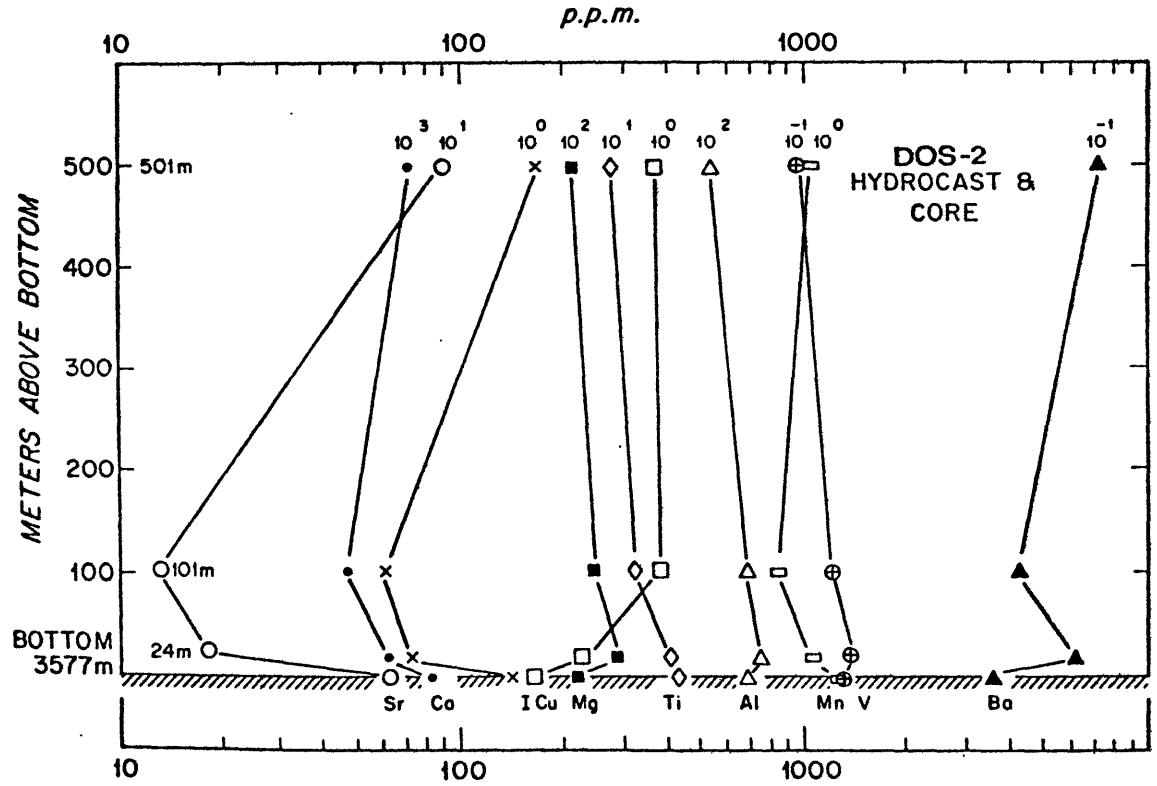
8. Composition of Suspended Particles Versus Surface Sediment

When the composition of particulates in water samples (as well as concentration) is plotted against depth, most elements exhibit near-bottom gradients (fig. 5.27). The reasons for these gradients were discussed in section 5-H.5 on resuspension. The sharpness of near-bottom gradients should be decreased by resuspension, but the total gradient between the surface sediment and particles above the level of resuspension should not be changed. Gradients on the Upper Rise (KN 58-2) appear to be stronger and more confined to the bottom 100 m than on the mid-Rise (DOS #2), which agrees with previous suggestions that more resuspension occurs at the latter site.

Gradients of concentration versus depth are much greater in the filtered suspended particles for most elements than in the trap samples, indicating that the surface sediments are closer in composition to the rapidly falling particles than the in situ particles. This may be because water bottles collect many small particles which, because of their small contribution to the total flux, have little impact on the composition of surface sediments. It has already been shown that the small particles differ in composition from the large particles (fig. 5.24).

Fig. 5.27 The composition of suspended particulate matter and surface sediments is shown at two trap sites. Compare profiles with profiles of trap sample composition in fig. 5.20.


p.p.m.
10
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
533m
82m
16m
BOTTOM
2815m
KN 58-2
HYDROCAST &
CORE
I
Cu
Sr
Ca
Mg
Ti
Al
V
Mn
Ba


p.p.m.
10
100
1000
METERS ABOVE BOTTOM
500
400
300
200
100
501m
101m
24m
BOTTOM
3577m
DOS-2
HYDROCAST &
CORE
Sr
Ca
I Cu
Mg
Ti
Al
Mn
V
Ba

9. Fecal Pellets

Fecal pellets have been suspected for many years to be responsible for transferring small particles from the surface waters to the sea floor (Marshall and Orr, 1955; Osterberg et al., 1963; Smayda, 1969, 1970, 1971; Schrader, 1971; Manheim et al., 1972; Fowler and Small, 1972; Honjo, 197 ; Cherry et al., 1975; Roth et al., 1975). Fecal pellets are generally greater than 63 μm yet, as was shown in figures 5.8 and 5.9, only 10-20% of the particle flux measured by these traps comes from particles that size or larger. It was also discussed in that section that the calculated resuspended material was predominantly in the 20-63 μm range and 40 to 80% of the larger than 63 μm particles in the lower traps were calculated to be resuspended based on flux differences. Most importantly, the number and size of fecal pellets collected increased in the lower traps. This gradient increasing toward the bottom indicated the sea floor as well as the sea surface was a source of fecal pellets. Thus, it was decided to determine the composition of fecal pellets from different traps.

Thirty-nine fecal pellets from the 13 m trap on the Upper Rise (KN 58-2) were placed on a Nuclepore filter and weighed a total of 104 μg or 2.67 μg per fecal pellet.

Eleven pellets from the 500 m trap weighed 17 μg or 1.55 μg per fecal pellet. The weighing accuracy of the 17 μg of material was only ±25%, but the weight per pellet agreed with the microscope observation of the difference in fecal pellet size in the two traps. No difference (e.g. color, morphology, etc.) between pellets within the trap or between traps was observed at low magnification other than size.

The fecal pellets from 13 and 500 m above the bottom contained 2.3% and 2.9% Al (table 5.6) compared with a mean Al content in Atlantic surface particles of 0.19% and a range of 0.03-0.9% including samples collected under the path of windblown Saharan dust. If these pellets came from surface feeding organisms, they must have selectively fed on clay particles rather than phytoplankton, which might seem a strange way to obtain nutrition. Another feeding area rich in clay is the bottom sediments, but if this is the source of Al-rich fecal pellets, they must then be carried upward into the traps where they were found 13 and 500 m above the bottom. Vertical diffusion is inadequate to resuspend 125 μm particles of density 1.2 $\mu g/cm^3$ tens to hundreds of meters without massive upwelling, because of high settling velocities. Horizontal advection may be able to bring in pellets from upslope to the 13 m trap, but

the fall velocity of fecal pellets--0.04-1.0 cm/sec--(Smayda, 1969; Harbison and Madin, personal communication), is too fast to allow fecal pellets to be carried horizontally from bottom feeders upslope to the 500 m trap. Organisms could feed on the bottom and then migrate upward and defecate. Ecologically there is no apparent reason for such migration. Benthic fish have been found hundreds of meters off the bottom (Haedrich, 1976), but this is principally near the continental slope and the fish may really be swimming horizontally away from the slope giving the appearance of vertical migration. Bentho-pelagic zooplankton are known to exist near the seafloor based on the results of net tows from Scripps Institution of Oceanography's deep tow package (Wishner, personal communication), from R/S ALVIN (Grice and Hulsemann, 1970), deep trawl nets (Vinogradov, 1970), and baited cameras moored on the bottom (Isaacs, 1969; Hessler et al., 1972) but no replicate information is available on the distribution as a function of distance from the bottom, and nothing quantitative is known about organisms migrating from the bottom to mid-water depths.

In searching for possible sources of food of the same composition as the fecal pellets, I considered the bottom sediments, the <u>in situ</u> particles, and the particles

falling downward. The fecal pellet Ca/Al ratio was much higher than the Ca/Al ratio of the sediment or the in situ particles but was very similar to the ratio in the traps, suggesting the organisms are feeding on rapidly settling material. Searching for food source by matching the Ca/Al ratio of the fecal pellets assumes in discriminate feeding, which in the deep sea is not unusual for copecods (Harding, 1974). The enrichment of elements related to organic matter such as I and Sr in the fecal pellets relative to bottom sediments or in situ particles further suggests that these two areas are not the source of food, or that organisms do feed selectively. If the organisms migrate or live off the bottom, there must be some advantage for them to do so.

The flux and relative abundance of organic matter at different heights above the bottom might shed light on where a filter feeder would have the highest food return for energy expended. It has been suggested that the "background" particulate organic matter collected in water bottles is largely refractory and not a good food source (Menzel and Ryther, 1970), whereas organic matter being carried rapidly from the surface provides organic carbon and other nutrients in a more useable form. The flux of organic carbon is not significantly different

between 13 m and 100 m above the bottom at KN 58-2, but the organic carbon content of the particles collected in the trap was 50% greater at 100 m than 13 m above bottom; thus more organic matter would be available when consuming the same mass of rapidly falling particles at 100 mab.

Riley (1970) showed that the distribution of non-living particulate organic carbon (POC) in the deep sea is nearly uniform. Even the existence of a nepheloid layer did not change the concentration of POC at one station in the western Atlantic (Gagosian, 1976). However, on a percentage basis, the POC in the nepheloid layer comprised only 10-15% of the total particulates, but it was up to 90% of the particulates above the nepheloid layer. Thus, it is ecologically advantageous from the standpoint of energy budgets for filter feeding organisms to position themselves above the nepheloid layer where the total amount of organic carbon, considering either the background particles or the rapidly settling particles, is not significantly diminished, but the percentage of organic carbon in the available particles is significantly increased. Fewer particles would have to be processed for the same amount of organic carbon to be consumed. Another small piece of evidence that filter feeding organisms are as much as 118 m off the bottom comes from having collected a 6 cm decapod in a trap at that level on the mid-Rise (DOS #2).

If the fecal pellets collected near the bottom are attributed to filter feeders near the bottom because of the high Al content, then where are the fecal pellets from zooplankton feeding near the surface? It is possible that the pellets analyzed were a mixture of pellets from surface and benthic filter feeders. However, as the pellets were selected and examined there were no differences in visual appearance.

A possible fate of fecal pellets produced at the surface is that they disintegrate in the upper few hundred meters of water column (Schrader, 1971) and never reach the bottom in tact. These particles remain in an aggregated state, have high settling velocities, and quickly carry their contents to the sea floor, but they are more accurately termed "fecal material" (Bishop et al., 1977), may be responsible for some of the "marine snow" observed throughout the ocean (Suzuki and Kato, 1953).

Fecal material could also be a food source for any organisms living in the water column, though animal abundance drops rapidly below 1500 m (Vinogradov, 1970). By recycling fecal material the organic content decreases and the percent of Al by weight increases. In this manner it would be possible to produce fecal pellets with an Al concentration much higher than is found in total surface water particles. For instance, the fraction

of particles >53 μm from the pump samples of Bishop et al. (1977) were analyzed for Al and it was found that while the amount of Al found per liter of seawater was uniform in the upper 400 m except for one or two samples, the concentration of Al in the particulate matter increased almost four fold from 0.04% to 0.15% (Mark Kurz, personal communication). For a fecal pellet to change its composition from 0.03-0.9% Al, as measured for the range of Al concentration in surface particulates (Krishnaswami and Sarin, 1976) to the 2.3% or 2.9% Al measured in fecal pellets in this study would require that 70-99% of the fecal pellet be decomposed. It is doubtful that a fecal pellet would be recognizable in that state, so reingestion must occur along the pathway from the surface to the bottom.

The interpretation of this data is not intended to dispute the evidence for rapid downward transport of small particles by incorporation into fecal pellets, but is presented to suggest that more recycling of fecal material occurs during the downward transit than has previously been implied. Downward transit of surface particles must be rapid to account for the close association between patterns of surface productivity and the underlying sediments (for example, see Murray and Renard, 1891; Bramlette, 1961; Smayda, 1970; Honjo, 1976).

10. Conclusions

From the data collected for this work it has been possible to confirm some of the findings of past workers and to make other findings less certain as well as make several new observations.

The principal conclusions are:

(1) Between 83% and 96% of the flux for all elements measured was in the portion less than 63 μm.

(2) The percentage of the elements measured in the surface sediments at the trap sites is within the range of previously measured values for deep-sea sediments.

(3) Calcium, strontium, and organic matter (as chemically traced by Cu and I) are more abundant in particles moving downward through the water column (and collected in sediment traps) than *in situ* particles (collected in water bottles).

(4) Using Cu and I as indicators of organic matter, we find that organic matter constitutes a larger percentage in the large particles than in the small particles. This organic matter is not necessarily associated predominantly with the well-formed fecal pellets since the fecal pellets measured had a lower percentage of Cu and I than the total fraction greater than 125 μm from which the fecal pellets came. A large percentage of the

organic matter must be associated with the individual tests of surface organisms or with agglomerated organic masses and fecal pellets which were sucked flat against the filter and couldn't be analyzed separately.

(5) The abundance of clay (based on content of Al, Ti, and V) is increased relative to organic matter (based on content of Cu and I) or carbonate (based on Ca) in the resuspended material indicating that even though carbonate ooze is more easily resuspended than red clay, the clay is retained in suspension longer. This is probably a function of particle size.

(6) The flux of Al from atmospheric dust estimated to fall on the surface waters is much less than the flux of Al calculated from the trap 500 mab. This suggests that either some resuspended material is being collected 500 mab or that we are overtrapping particles. The result in either case is that the primary flux is less than was calculated.

(7) The atmospheric flux of Al is also much lower than the post-glacial accumulation rate of Al on the mid-Rise. Most of the terrigenous material must therefore be advected in horizontally. Indications are that the transport to the mid-Rise occurs predominantly in the bottom 500 m because the flux of Al and Ca at that level are close to the post-glacial accumulation rates measured in a core.

(8) Based on a comparison of the Al content in particulates in surface waters, a fecal pellet produced at the surface would have to be 70-99% decomposed to match the Al content of fecal pellets collected in traps. This strongly suggests that fecal pellets are reingested several times during their transit to the bottom. Pelletization of fecal material and resuspended sediments by filter feeders in the nepheloid layer, where Al concentrations are higher, is a likely means of producing Al-rich fecal pellets. This would also help account for the increase in number and size of fecal pellets in the 13 m trap compared with the 500 m trap.

The strong gradients in the elemental composition of suspended and rapidly falling particles in the nepheloid layer indicate that reaction rates of physical and chemical processes are rapid in this region. Frequent resuspension can increase the exposure of particles to these processes. For instance the length of time carbonate and silicious particles spend in a resuspended state may be a major control of the degree of their dissolution. On a global scale the importance of the benthic boundary of the ocean in terms of chemical and physical processes is much greater than the percentage of the ocean included in that region.

CHAPTER VI

CONCLUSIONS AND SUMMARY

Sediment traps have been used for many years, but this is one of the first studies using them in the deep sea. The results of the experiments conducted support the following conclusions:

A. INSTRUMENTATION

1. Sediment traps can be designed to collect a mass of material equivalent to the downward flux of particles in advective flows of up to at least 15 cm/sec. Cylinders or square boxes with a height to width ratio between 2:1 and 3:1 or baffled funnels most consistently collect the correct mass necessary for this flux calculation. Containers with openings smaller than their bodies overtrap material.

2. Standard methods of filtering Niskin bottles allow many particles to accumulate below the spigot at the bottom of the bottle and escape sampling. The concentration of suspended particulates measured throughout the water column is increased by an average of 1.5 times when these lost particles--the dregs--are included. Sediment budgets and global residence times of elements are affected by this correction.

B. SIZE, COMPOSITION, AND MORPHOLOGY OF PARTICLES IN DOWNWARD FLUX

1. The mean diameter of particles collected in traps in the nepheloid layer was 20 μm and at the clear-water particle minimum the mean diameter was 11 μm. Between 80-90% by weight of the particles collected in all twelve traps were less than 63 μm in diameter. While these particles may have been disrupted somewhat during collection or analysis, the general indication is that large particles do not contribute as much to the total flux as has been presumed.

2. Recognizable fecal pellets were generally larger than 63 μm and constituted less than 10% of the total calculated flux. No well-formed pellets were found in any of the floating traps in the surface 100 m. Most of the detritus collected in traps was probably ingested at some time during its transit through the water column and therefore could be called fecal material, but discrete fecal pellets constitute a small portion of the total flux at the depths where collections were made.

3. A comparison of the Al content of surface particulate matter with the Al content of fecal pellets collected 13 m and 500 m above the bottom suggests that the fecal pellets could not have come from the surface water without so much decomposition of the pellets as

to make them unrecognizable. Zooplankton grazing and pelletization of small particles appear important in transporting detritus to the sea floor, but fecal pellets are probably reingested several times during their transit and the biogenic components are utilized and Al is concentrated.

4. Based on respiration rates measured on the lower slope and the primary fluxes of organic carbon on the mid and Upper Rise, between 97% and 177% of the organic carbon required for respiration by benthic organism is supplied by the particulate rain of detritus.

5. A large flux of carbonate and silica is carried to the deep sea by tests of radiolarians, diatoms, pteropods, and juvenile foraminifera. These forms were abundant in trap samples, but were rarely seen in surface sediments indicating dissolution during initial transit to the bottom, while resuspended, or while on the sediment-water interface.

6. Carbonate and organic matter are preferentially carried in the large particles which fall rapidly and are not collected in water bottles.

C. SEDIMENT DYNAMICS

1. The residence time of particles in the nepheloid layer--the time required to build up or deplete the stock

of resuspended particles--is on the order of days in the few meters above the bottom and is on the order of weeks to months for the entire nepheloid layer.

2. The nepheloid layer is maintained primarily by resuspension of sediment without which the nepheloid layer would last only a few months.

3. Because Al fluxes at the clear water particle minimum are much higher than expected from eolian input of dust at the sea surface, it appears that near continental margins terrigenous material is resuspended or advected in and contributes to the flux as high as 500 m above the bottom.

4. Horizontal transport of terrigenous material occurs predominantly within the nepheloid layer where frequent resuspension enables particles to be carried long distances.

The nepheloid layer is not a passive body of water containing an abundance of particles which remain in suspension indefinitely. It is a dynamic region where deposition and resuspension are occurring constantly; in fact, without resuspension the nepheloid layer would quickly lose its signature. Because of rapid recycling particles can be resuspended many times before they are finally buried and mixed below the level where bioturbation

could re-expose them. Resuspension allows particles to be transported much longer distances than would occur during a single transit through the water column. At the same time it exposes carbonate and silica particles to the corrosive action of sea water undersaturated in those ions, and could be a major control of their dissolution rates.

Although sediment traps have been used for over 80 years, their use has been limited to shallow waters. However, the sophistication of marine technology can now be combined with the important scientific questions being asked about chemical and physical cycles in the ocean to provide the impetus to launch large-scale GEOSECS-type experiments with sediment traps. Caution should be used in interpreting results until we more fully understand the hydrodynamics of sediment traps. Comparisons need to be made between collections made with moored traps and traps moving with the water mass on a neutrally buoyant float to check for differences in collection rates and the size of particles collected when a moored trap is exposed to a current.

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APPENDIX A

A LABORATORY EVALUATION OF SEDIMENT TRAP DYNAMICS

ABSTRACT

The geometric design of a sediment trap moored in flowing water determines its trapping efficiency since most particles are trapped during fluid exchange within the trap rather than falling through the water column into the trap. The use of dye as a flow tracer provides an effective view of the dynamics of fluid exchange. However, empirical sedimentation experiments must be combined with observations of flow characteristics to analyze the trapping efficiency of a specific container. Experiments in a recirculating sea-water flume using deep-sea lutite showed that at flow velocities up to 9 cm/sec, cylinders trap particles in the closest approximation to the actual rate of deposition in the flume. Funnels generally undertrap, but can be modified to nearly approximate the actual flux by constructing a baffle at the top of the funnel. Containers with narrow mouths and wide bodies consistently overtrap at an unpredictable rate of many times the actual flux of particulates.

INTRODUCTION

Determination of the composition and mass of particulate matter in the water column has become routine for

oceanographers and limnologists investigating a variety of processes. However, the solution to many questions is limited by our knowledge of the fluxes of particulate materials through the water column. The composition and distribution of sediments is dependent upon the particulate flux. The supply of food energy derived from the flux of organic matter is a primary control of the structure and diversity of benthonic communities. The chemistry of a body of water and the usefulness of any chemical species in tracing circulation is greatly affected by the formation, removal, and dissolution of particles.

One approach to determining the flux of particles is to measure the size (Bond and Meade, 1966; Sheldon, et al., 1967; Carder et al., 1971) and estimate the density of particulate material, calculate a Stokesian settling velocity, and use a diffusion-advection model to determine particulate fluxes (Feely, 1975; Ichiye, 1966; Tsunogai et al., 1974). The number of particles in sea water decreases exponentially with an increase in size (Bader, 1970). Particles larger than 20 μm are rare (Carder et al., 1971; Sheldon et al., 1967). Nevertheless, the exponential increase in mass and sinking velocity with size makes the larger particle sizes more important when considering mass fluxes (McCave, 1975). Because of their rarity, however,

larger particles have a statistically low probability of being caught in standard size water samplers. Even when large particles are caught they are seldom extracted due to the design of water samplers and methods of filtration (Gardner et al., 1977 (AGU); Gardner, 1977). The large volume *in situ* pump of Bishop and Edmond (1975) provides more complete sampling, but has been used to only 1500 m. Other methods of collection of large particles, such as net tows, have been used. However, none of these methods determine which particles are in actual flux. One *in situ* study on the settling velocity of particulate organic carbon found negative settling in surface waters of Lake Ontario (Burns and Pashley, 1974).

A means of collecting the particles which gravitationally settle across a horizontal plane per unit of time is needed. Various sizes and shapes of containers have been deployed to act as collectors of particles in flux. Unfortunately, while some experiments have been conducted to independently corroborate the flux measurements of traps in relatively tranquil water (Davis, 1967; Pennington, 1974; Rigler et al., 1974; Kirchner, 1975; Moore, 1951; Deevey, 1964), no such experiments are known to the author where flux could be independently determined for traps moored in water known to be moving despite their frequent

use in moving water. However, some attempts have been made to evaluate the relative efficiency of different shapes of traps in moving water, though sometimes with conflicting results (Hoskin et al., 1975; Davis, personal communication; Johnson and Brinkhurst, 1971). Due to the lack of consistent experimentation in natural environments I decided to determine the nature of flow disturbance around sediment traps and their efficiency in catching particles under known conditions in low velocity flows (<10 cm/sec). The following pages include a brief review of trap calibrations in still water and intercomparisons of traps in moving water. Experiments using a recirculating flume will then be described. Dye was injected into the flow and observed and photographed as it moved around and in traps. The flume was then filled with salt water and deep-sea mud and collection rates of the traps were determined.

BACKGROUND

Sediment traps provide a unique method of collecting particulates in flux because trapping area and exposure time can be varied depending on the expected flux of material in a given area. Since the work of Heim (1900) there have been over one hundred reports in the literature of various sorts of sediment traps (see Appendix B).

These sediment traps can be divided into five categories: cylinders, funnels, wide-mouthed jars, containers with bodies much wider than the mouth, and basinlike containers with width much greater than height.

About half of the published studies were conducted in lakes, where turbulence and mixing are relatively slow, while the other half were in estuaries, bays, and coastal habitats where turbulence and advection are stronger. Attempts at using sediment traps beyond the continental shelf have been rare, but their potential is being recognized (Menzel, 1974; McCave, 1975) and technology now makes their use in the deep sea practical. The trap of Wiebe et al. (1976) can be used within the range of deep submersibles and has been deployed at 2150 m in the Bahamas. Mesecar and Carey (1975) described a trap designed to operate to a depth of 3000 m, but have reported no results. The present author has deployed and recovered four arrays of cylindrical sediment traps at depths up to 3600 m (Gardner et al., 1977). Izeki (1976) has deployed moored and floating traps in the North Pacific to 4000 m. Several investigators at the Woods Hole Oceanographic Institution, the University of Rhode Island, Oregon State University and the Scripps Institution of Oceanography have either deployed or are planning to deploy traps in the deep ocean for a variety of scientific purposes.

PREVIOUS WORK ON CALIBRATION OF TRAPPING EFFICIENCY

Still Water

For quantitative studies to be made with sediment traps it is necessary that the rate of deposition measured by a trap be equal to the vertical flux across the plane of the trap, or that the degree of over-accumulation or under-accumulation in the trap be known. It should also be determined whether particles are preferentially trapped according to size or density as a result of hydrodynamic differentiation. Attempts at absolute calibration of sediment traps by comparing fluxes with other methods of measuring sedimentation have been few, but significant.

Cylinders: Accumulation rates derived from cylindrical sediment traps in an oligotrophic lake (0.26 cm y^{-1}) compared favorably with rates derived from paleomagnetic evidence (0.20 cm y^{-1}), Pb-210 dating (0.27 cm y^{-1}), and with the thickness of sediment accumulated (0.23 cm y^{-1}) above a known horizon between 1940-1970 (Pennington, 1974). Rigler et al. (1974) found close agreement between the production and entrapment of zooplankton exuviae. One might expect that another test of whether a trap of given shape accurately measures the vertical flux of detritus would be to compare the flux measured by traps of differing

size but identical geometry. The amount of detritus collected should be proportional to the trap opening, and the extrapolation of data points must intersect the origin. Davis (1967) found this to be the case when using cylinders and wide-mouthed jars in the laboratory and in stratified lakes under tranquil conditions. A graph using Pennington's (1974) data with various cylinders yields the same result (see figure A-1). However, it was shown in chapter 2 of this thesis that traps with the same height to width ratio (hereafter referred to as H/W) will collect particles at the same rate, but traps with a different H/W will collect particles at a different rate in the same depositional regime (figure A-2). Therefore the comparison does not prove traps are accurately measuring the flux. When Pennington's data (1974) for sediment trapped per unit area in still water was plotted against H/W, no consistent trend was apparent (figure A-3). The effect of the H/W ratio is more important in moving water.

In an attempt to test for any possible interference of the sidewalls of the container in still water, Kirchner (1975) compared the trapping rate of 25 cm high Plexiglas cylinders with diameters of 3.2 cm to 43.2 cm in a lake. With the exception of two testing periods when fluxes

measured by different cylinders differed by as much as 5-6 times, the sedimentation rate derived from the different cylinders rarely varied by more than a factor of two and no dependency on H/W ratio was apparent.

A laboratory experiment in a still water tank indicated that a jar 1.8 cm wide overtrapped, but jars with openings 1.2 cm and 1.4 cm wide caught the same relative amount as jars 4-8.4 cm wide (Davis, 1967). The height of these jars was not reported.

Funnels: Watanabe and Hayashi (1971) used several funnels between 12 cm and 24 cm in diameter to collect particles in lakes. As with the cylinders, they caught particles in direct proportion to trap opening and in three of their four deployments the data could be extrapolated to the origin. However, since this comparison proved to be a function of geometry with cylinders, it is likely to be the same for funnels, i.e., steeper walls on the funnel may change the collection rate.

Cylinders vs. funnels: In comparing collection rates of cylinders and funnels, Pennington (1974) reported that the flux determined with cylinders (8 cm wide and 30 cm tall) was consistently two to three times the flux determined with a funnel 25 cm wide. Johnson and Brinkhurst (1971) compared collection rates of cylinders 5 cm and 17 cm

Figure A-1 Volume of sediment collected in cylinders of various diameters and heights during simultaneous deployment at two depths.

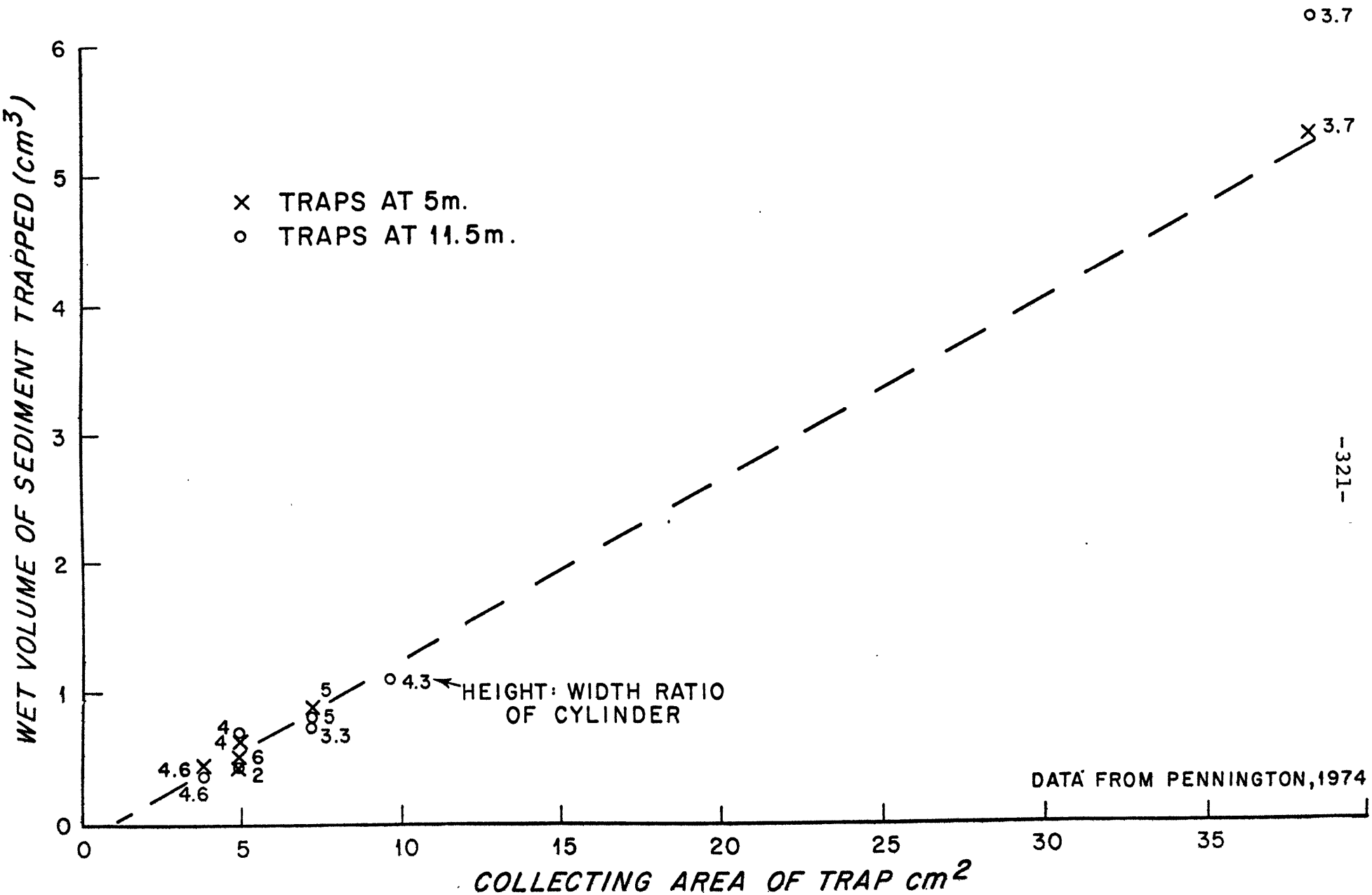
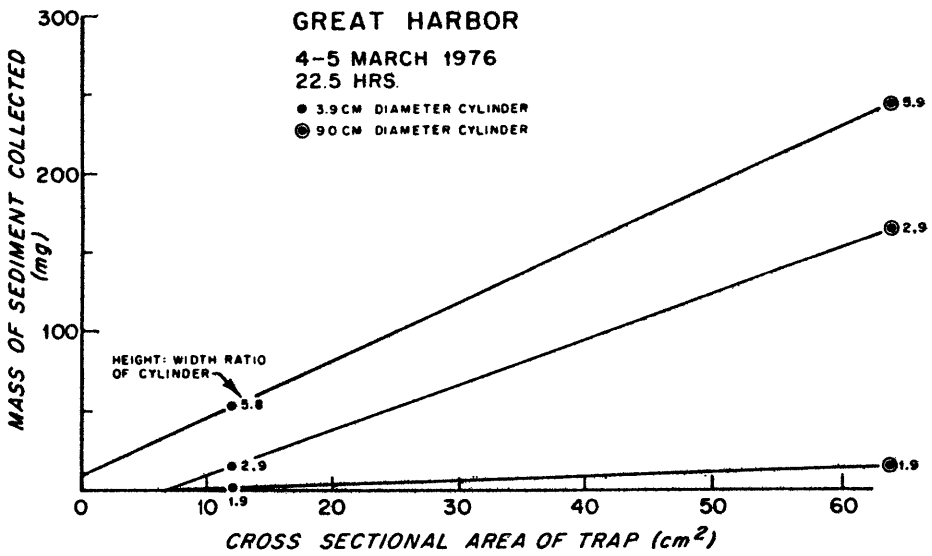
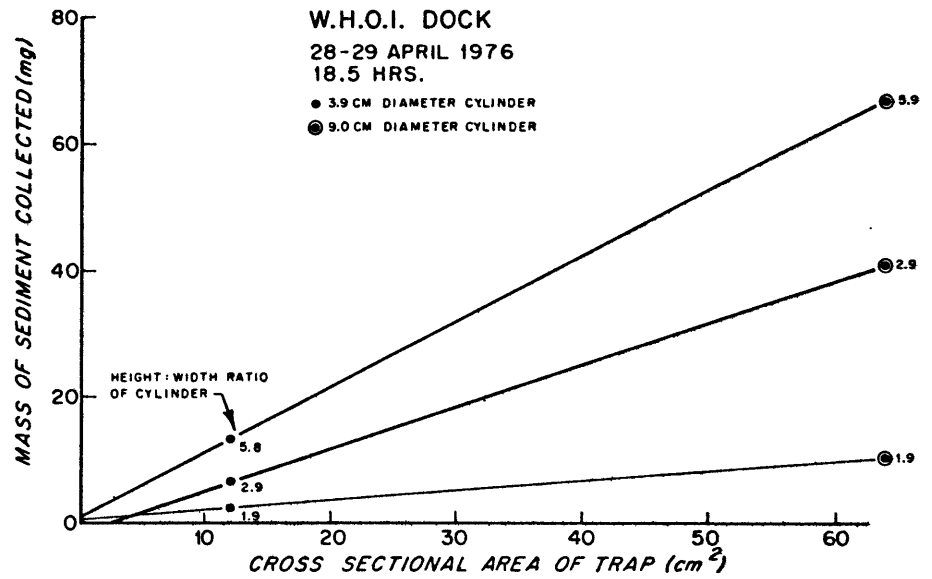

WET VOLUME OF SEDIMENT TRAPPED (cm^3)
COLLECTING AREA OF TRAP cm^2
× TRAPS AT 5m.
o TRAPS AT 11.5m.
HEIGHT: WIDTH RATIO OF CYLINDER
DATA FROM PENNINGTON, 1974
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
o3.7
×3.7
o4.3
5
5
3.3
4
4
6
2
4.6
4.6

Figure A-2 Mass of sediment collected in cylinders of different diameters and heights at three locations. The water in Oyster Pond was tranquil, while currents at the dock reached a maximum of 22 cm/sec and in Great Harbor currents may have been as high as 50 cm/sec.


GREAT HARBOR
4-5 MARCH 1976
22.5 HRS.
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
CROSS SECTIONAL AREA OF TRAP (cm²)
HEIGHT: WIDTH RATIO OF CYLINDER
5.9
2.9
1.9
300
200
100
0
10
20
30
40
50
60


W.H.O.I. DOCK
28-29 APRIL 1976
18.5 HRS.
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
CROSS SECTIONAL AREA OF TRAP (cm²)
HEIGHT: WIDTH RATIO OF CYLINDER
5.9
2.9
1.9
80
60
40
20
0
10
20
30
40
50
60

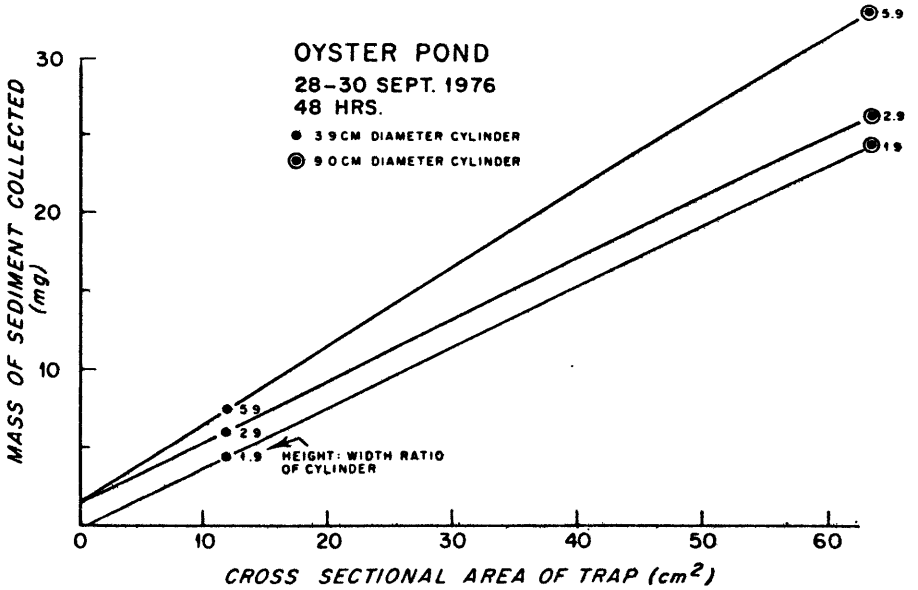
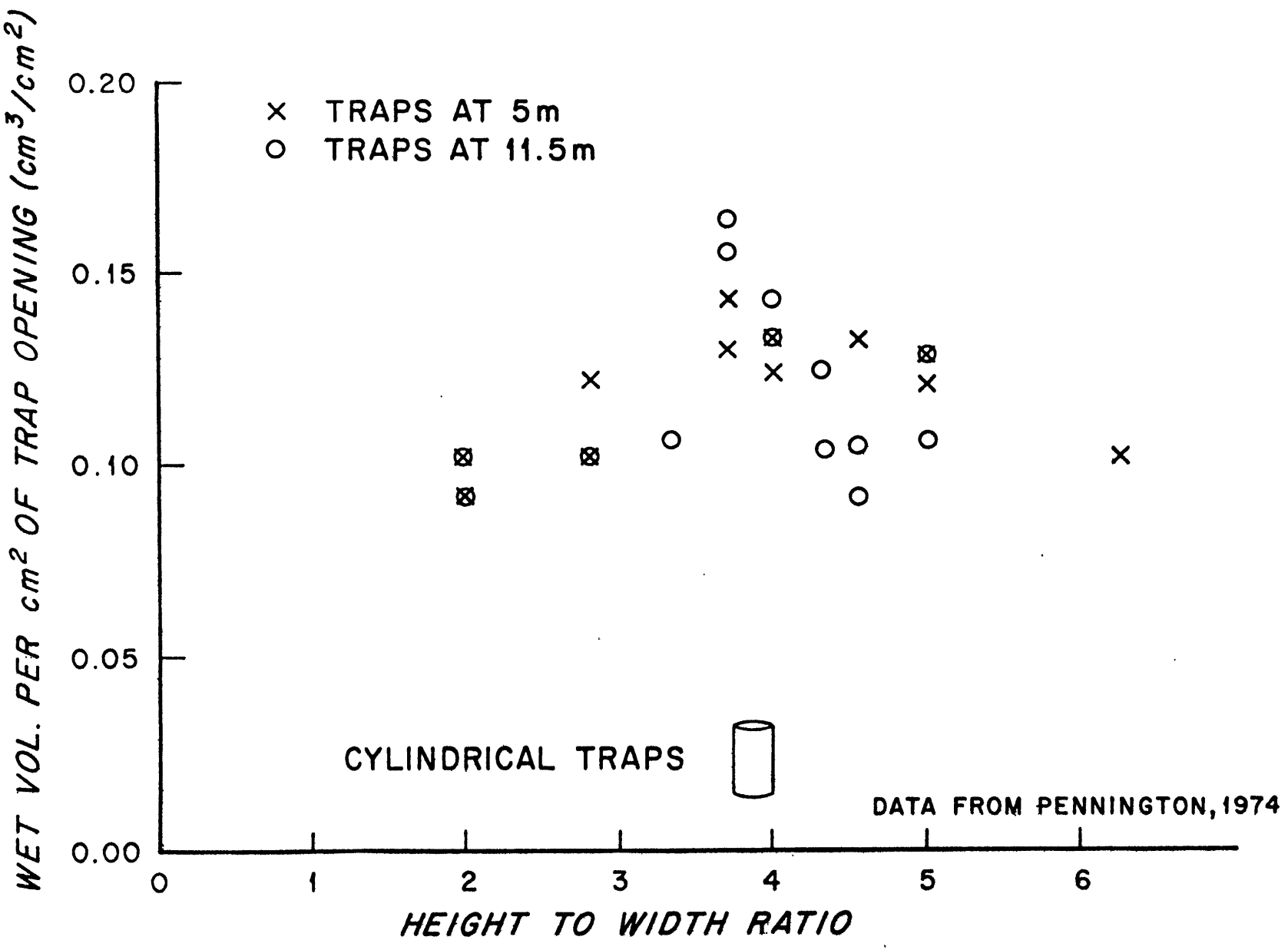

OYSTER POND
28-30 SEPT. 1976
48 HRS.
● 3.9 CM DIAMETER CYLINDER
◉ 9.0 CM DIAMETER CYLINDER
MASS OF SEDIMENT COLLECTED (mg)
CROSS SECTIONAL AREA OF TRAP (cm²)
HEIGHT: WIDTH RATIO OF CYLINDER
5.9
2.9
1.9
30
20
10
0
10
20
30
40
50
60

Figure A-3 Volume of sediment collected in cylinders with varying height to width ratios.


WET VOL. PER cm² OF TRAP OPENING (cm³/cm²)
0.20
0.15
0.10
0.05
0.00
× TRAPS AT 5m
○ TRAPS AT 11.5m
CYLINDRICAL TRAPS
DATA FROM PENNINGTON, 1974
0
1
2
3
4
5
6
HEIGHT TO WIDTH RATIO

wide with funnels 12 cm, 20 cm, and 41 cm wide. The small cylinder caught almost ten times as much as the other containers, which in turn varied by a factor of two to three. The variation was probably due to testing in turbulent waters. According to White and Wetzel (1973), variations in sedimentation rates in quiet lake waters among cylinders 4.8 cm, 10.3 cm, and 13.3 cm wide increased slightly with trap diameter.

Moving Water

To the author's knowledge, no sediment traps have been calibrated in water known to be moving where an independent determination of the sedimentation rate was obtained. Soutar et al. (1977) deployed traps off the California coast in the Santa Barbara Basin, where varved sediments allow the sedimentation rate to be resolved on nearly a one-year time scale, but current was not monitored. Their collection rate was 22%-88% of the long term bottom sedimentation rate with the trap 100-150 m below the surface, and 66-190% of the long term rate with the trap 10 meters above the bottom.

Some intercomparisons of trap sizes and shapes have been made, but generally only the trap widths are reported, making it impossible to test for a H/W effect on the collection rate. Patten et al. (1966) observed the

persistence of fluorescein dye in a BOD bottle (narrow-necked bottle) placed in a channel of flowing water, but they drew no conclusions about the trapping efficiency.

Flux measurements in Cape Cod Bay by Young & Rhoads (1971) with wide-mouthed bottles of 5.3 cm and 9 cm openings were reported as showing nonsignificant differences, but no mention was made of current velocity. Johnson and Brinkhurst (1971) reported that a cylinder 5 cm wide trapped four to eight times as much material per unit area as a cylinder 17 cm wide in a bay of Lake Ontario. Nothing was mentioned about possible currents, but some movement seems likely in such a large body of water. Most inconsistencies occur when using cylinders with diameters less than 2 cm: jars less than 2 cm across caught relatively more material than wider containers in a Scottish sea lock where tidal currents are less than 5-10 cm/sec (Davies, personal communication). Cylinders 30 cm tall with diameters of 0.25, 2.54, and 5.08 cm were tested by Hoskin et al. (1975) in Reid Inlet, Glacier Bay, where currents are 1-5 cm/sec. In this case the widest cylinder collected particles at the highest rate per unit area and had the least variation in consecutive measurements.

Comparison with Rain and Snow Gauges

An obvious corollary to the calibration of sediment traps is the calibration of rain and snow gauges. Precipitation collectors have been used for hundreds of years (Kurtyka, 1953), but only in the last hundred years has it been realized that the collecting efficiency of rain and snow gauges decreases with an increase in

wind speed (Wilson, 1954; see fig. A-4). The primary source of error with precipitation gauges is the wind effect. Any object placed in moving fluid (air or water) is an obstruction around which the fluid must flow. A straight-walled collector creates an updraft which carries rain and snow up and over the collector opening (fig. A-5). Encircling a collector with some version of a Nipher shield (an upward opening cone) reduces the updraft and improves the collection efficiency for rain and snow (Kurtyka, 1953).

Hydrodynamically the flow characteristics of air and water around a container are qualitatively very similar. However, due to differences in particle size and density and fluid velocity and viscosity, the path of rain drops or snow flakes around a container may be very different from the path of falling detritus in water. Raindrops of 0.5-5 mm diameters fall at 2.3-9.3 m/sec, and snow falls around 0.5 m/sec (Kurtyka, 1953). If most winds are less than 10 m/sec, then the fall velocity of rain and snow is seldom more than one order of magnitude less than the horizontal wind speed and may be one order of magnitude greater. Conversely, in the marine environment, a one-micron particle falls at about 10^{-4} cm/sec, a 40 μm particle falls at 10^{-1} cm/sec (Stokes' law for particles where (<2 g/cm^3) and fecal pellets fall at 0.04-1.0 cm/sec (Smayda, 1969; Fowler and Small, 1972), whereas current velocities are generally less than 200 cm/sec in estuarine and surface currents and less than 20 cm/sec in deep

Figure A-4. Collecting efficiency of rain (O) and snow (●) gauges as a function of wind speed.

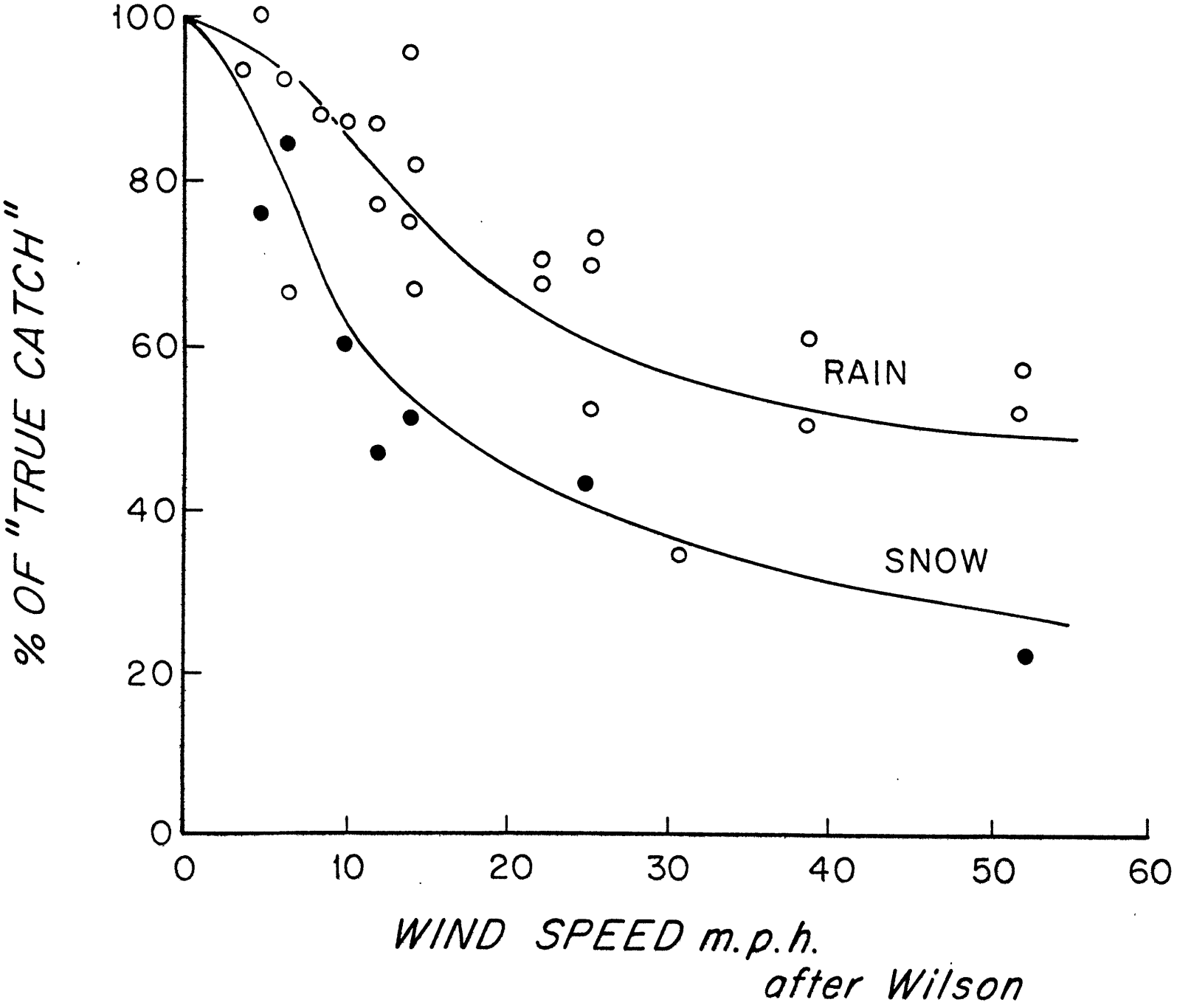
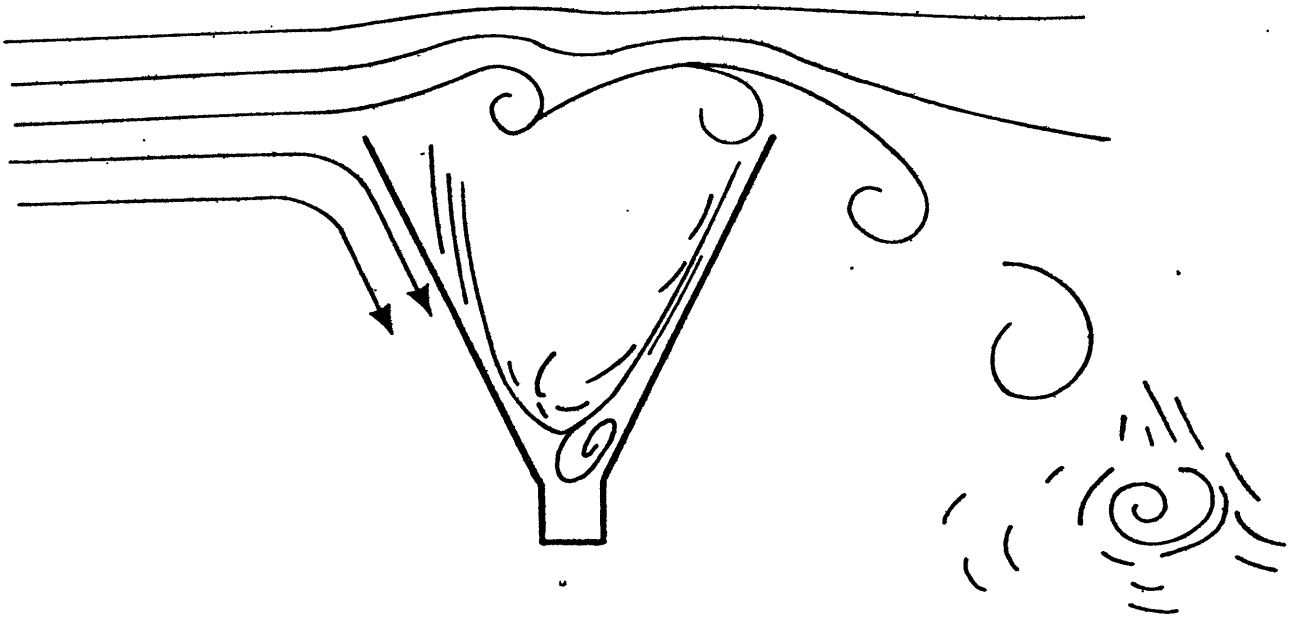
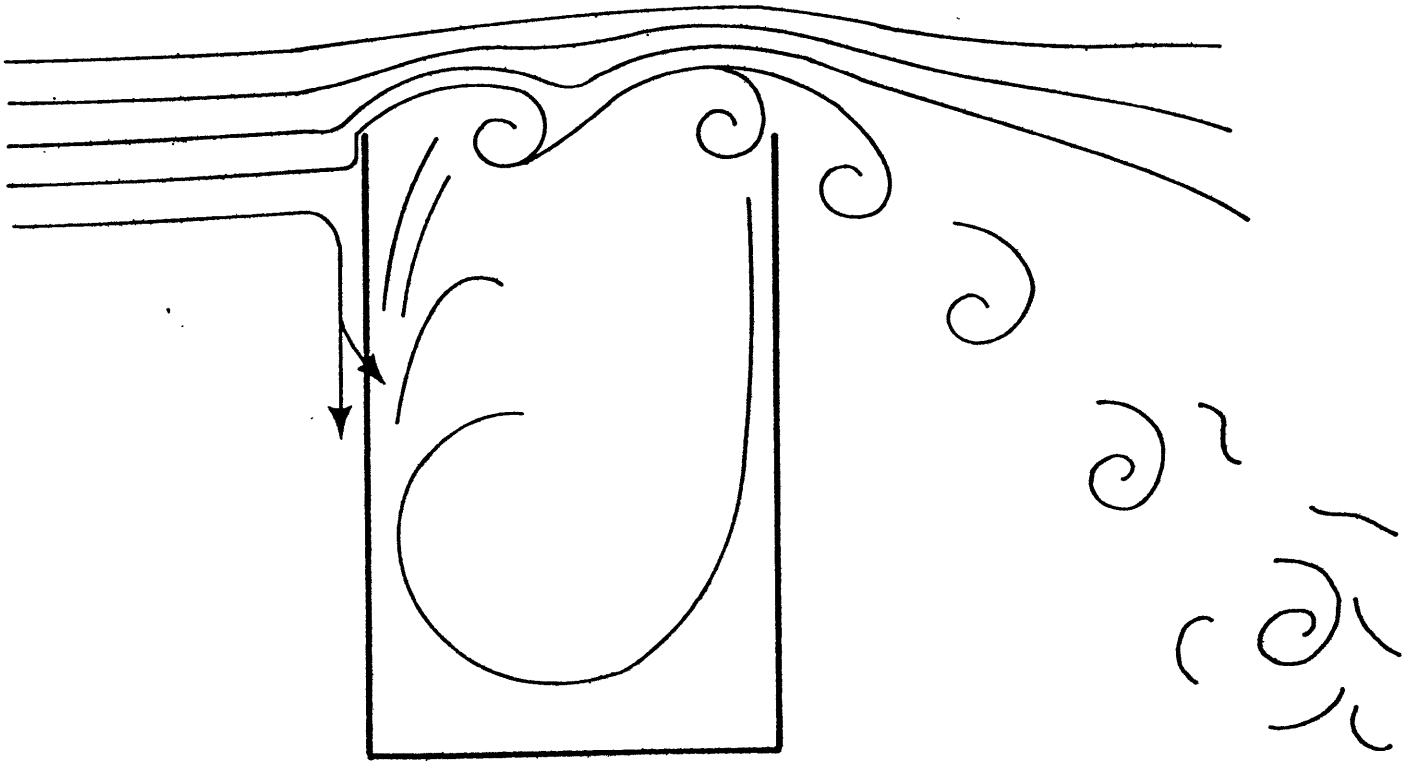

100
80
60
40
20
0
0
10
20
30
40
50
60
% OF "TRUE CATCH"
RAIN
SNOW
WIND SPEED m.p.h.
after Wilson

Figure A-5. Flow lines around and inside a funnel and cylinder in either air or water.





ocean water. Thus the fall velocity of most particles in water is between one and six orders of magnitude less than normal horizontal currents. Rather than descending vertically or at a slight angle, particles settling through water generally follow the fluid path lines and enter traps by being carried passively in turbulent eddies. Thus it is important to understand the flow patterns around and inside sediment traps. Some of the important variables affecting trapping efficiency are: current velocity and its variability; trap size and geometry; and size, concentration, and composition of settling particles.

METHODS AND INSTRUMENTATION

Traps with a variety of geometries were exposed to steady, uniform flow in a six meter recirculating flume. Flat plates, cylinders, wide-mouthed jars, funnels, narrow-necked wide-bodied bottles (Erlenmeyer flasks and salinity bottles), and segmented basins were among the forms tested (Table A-1). Patterns of fluid flow around and inside the different forms were observed by using fluorescein dye as a tracer in fresh water. Three series of experiments were then made with sea water and fine-grained sediments in the same flume to evaluate the effectiveness of these containers as sediment traps.

Dye Experiments

Each container was placed in a recirculating flume 17 cm wide with a flow depth of 15 cm. Limited observations were also made in a flume one meter wide. Steady, uniform flow conditions

were maintained over the range of 1-10 cm/sec. Fluorescein dye was released from a hypodermic needle at various heights and distances upstream of each form. Flow lines and zones of turbulence were observed, noted, and photographed. As a second means of observing the fluid exchange between the trap and the flowing water, the forms were filled with dilute fluorescein dye. The residence time--the time required for dye inside the container to be diluted to concentrations in the flume--was compared for several configurations (Table 1).

Sedimentation Experiments

Once the fluid motions around various geometric configurations were known, the next step was to measure the particle-collecting characteristics of the containers. Variables which needed to be tested were current velocity, fluctuations in the speed and direction of the current, size and density of particles trapped, concentration of suspended particles, duration of deployment, and construction material of the trap. It was also important to test for influences of the position of the trap in the flume.

Three series of experiments were made. The first experiment included a diversity of geometric forms and yielded a two-orders-of-magnitude range of trapping efficiencies between containers used. Based on the results of this experiment, a series of experiments was made using five different containers in which collection time and flow velocity were varied. The third series of experiments

primarily involved funnels under various flow conditions. Two experiments were made in a fish tank to test trapping efficiency in still water.

Trap Calibration

To test the trapping efficiency of different containers, the same six-meter recirculating flume used in the dye experiments was filled with water from the Sargasso Sea. Flow depth was 11 cm in the first experiment and 15 cm in all other experiments. Because of the author's interest in near-bottom sediment transport processes in the ocean, abyssal mud was used in all quantitative experiments. Disturbed flow-in was obtained from the 3065 cm level of Giant Piston Core 9 (Beverly, et al., 1976) taken on the Blake-Bahama Outer Ridge. The particles were all <63 μm with 95% less than 25 μm; the median grain size was 2.6 μm. Less than 10% was carbonate, and illite was the predominant clay mineral (60%). Sediment was prepared by wet sieving through a 63 μm mesh screen, disaggregated in 250 ml of distilled water in an ultrasonic bath for one hour,and added to the flume at the beginning of each series of experiments. The water and sediment were allowed to mix for 10-20 minutes before each experiment during which time the channel surfaces were wiped two or three times to resuspend all particles while the pump was at full discharge.

The return flow of the flume was through two-inch PVC pipe which resulted in return velocities much higher than the flume velocities, so sediment could not deposit in the return flow system.

There were no dead spaces in the system where sediment could accumulate, so all sediment was assumed to be deposited on the flume bed. The flume was tightly covered and no corrodible materials were exposed to the sea water, so no extraneous particles could be introduced into the system during an experiment. The flow velocity was lowered to the desired speed and the containers were spaced about 70 cm apart in the center of the flume. Most traps were placed on small pedestals to reduce the flow disturbance at the base of the containers. The height above the bottom of the container tops varied from 6 to 9 cm in Series I and II, but the tops of all containers in Series III were adjusted to 9 cm above the bottom. The variation in the early experiments was not considered serious because dye experiments showed that fluid 90 cm in front of a trap could still enter the trap when released 0.5 cm above the flume bed, so the fluid and sediment were well mixed.

Rate of Sediment Deposition

The initial concentration of suspended particles was determined from water samples taken by pipette, siphon, or by carefully dipping a beaker to the depth of the container tops. Inter-comparison showed that all methods produced the same results. Between 30 and 300 ml of water were filtered through a preweighed 0.6 μm Nuclepore filter and washed 10 times with distilled water to remove the salt. After oven drying at 60°C for six hours the filters were taken to a humidity-controlled room and after 24 hours

were weighed on a Perkin-Elmer electrobalance to the nearest microgram. Blank filters were used to check for weight changes during drying and weighing.

At the end of the experiment another water sample was taken to determine the final concentration of particles in suspension. Covers were placed on the containers and the containers were removed from the flume. The contents of each container were then removed with a clean hypodermic needle and filtered in the same manner as the water samples. The walls of all containers (especially funnels) were rinsed with distilled water to obtain sediment which had settled there. It was assumed that since the residence time of the fluid in most of the containers was on the order of minutes, the concentration of suspended particles in the fluid enclosed by the container was nearly the same as that in the main flow. Therefore the volume of each container was measured and the corresponding mass of particles still in suspension in that volume (as determined by the concentration at the end of each run) was subtracted from the total mass of sediment in each container. The mass of sediment collected per square centimeter of trap opening was calculated for each container.

Trap Efficiency

From the results of previous experiments on sediment deposition in the same flume (Gardner and Southard, 1975), it was assumed that deposition occurred over a 5.0 m length of the flume bottom. Observation showed that the distribution of sediment on the flume bottom was not uniform due to obstruction by the con-

tainers, but all deposition occurred on the flume bed.

The amount of sediment deposited is determined by multiplying the difference between the initial and final suspended particle concentration by the volume of water in the flume system. This is divided by the depositional area of the flume (8500 cm^2) to obtain the mass per unit area which should be trapped by the containers. The sedimentation rate was determined independently for each experiment. The still-water sedimentation rate was determined by multiplying the change in concentration between beginning and end of the experiment by the height above the trap.

The trapping ratio is determined by dividing the mass/cm^2 collected in a trap by the mass/cm^2 deposited on the flume bed. The ratio is multiplied by 100 and given as the trapping efficiency. The ideal trap has an efficiency of 100%: overtrapping (catching more sediment than the sedimentation rate) yields percentages greater than 100%, and undertrapping results in percentages less than 100%.

Velocities in the flume were measured in two ways. First, fluid velocity, as measured by the travel time of dye in fresh water over the working region of the flume, was calibrated against the rotation rate of the variable speed motor (as measured with a strobe light). Secondly, velocities were checked during the actual experiments by determining the travel time of a semi-submerged drogue over a fixed distance. There was close agreement between the two methods.

Traps and Conditions Tested

The Series I experiment (Table A-3) included five containers: 1) a 2 oz. wide-mouthed, screw-top, glass jar, 2) an identical jar with 1 mm mesh nylon screening slightly domed over the jar, 3) a domed polyethylene container, 4) a Plexiglas cylinder placed horizontally normal to the flow and containing a 0.11 cm slit parallel to the cylinder axis at the top of the cylinder, and 5) a flat Plexiglas plate.

Four experiments were conducted in Series II with five traps (Table A-4). Three of the containers were open Plexiglas cylinders placed vertically in the flow to test different H/W rations. Two of them has a 1:1 H/W ratio, but differed in their dimensions by approximately a factor of two. The third cylinder was the same width as the smaller cylinder, but had a 2:1 H/W ratio. The Plexiglas semi-model of the trap deployed by Wiebe et al. (1975) and described later in the dye experiments was the fourth configuration, and a dome-shaped container was the fifth trap. Flow depth, velocity, concentration of suspended sediment, and duration of each experiment in Series II are shown with the trapping efficiency in Table A-4.

Series III experiments were primarily for testing funnels. The traps used, flow conditions, and concentration of suspended sediment are listed in Table A-5. The effect of changing current direction was investigated in experiment No. 8 by rotating each container three times during the experiment. A clockwise rotation of 180°, 45°, and 135° was made on all traps at 3.0, 5.3

and 9.2 hours into the experiment. In experiment No.9 the initial concentration of suspended particles was increased to 82 mg/l by adding sediment which was mostly between 2-62 μm from the same GPC-9 core. Narrow-mouthed, wide-bodied containers were tested along with a baffled funnel and a cylinder in this experiment.

The fish-tank experiment also used sea water and the same sediment as the flume experiments. Traps tested included cylinders, a baffled funnel, a salinity bottle, and the domed trap (Table 5). The first experiment left the tank uncovered, which allowed air circulation in the room to create motion within the fish tank. The fish tank was covered during the second experiment to eliminate motion induced by air circulation, and allowed to equilibriate with room temperature for 24 hrs to reduce thermal convection, but no attempt was made to control room temperature.

RESULTS

Dye Experiments

Flat Plate: The simplest geometric form for a sediment trap is a flat plate--an unrealistic but first-order approximation of the ocean bottom. In still water a plate would collect the proper mass per unit area of material in a downward flux in the water column. However, in a current, a plate disturbs the flow and generates eddies from the upstream edge of the plate. If the plate is tilted down toward the oncoming flow, a positive pressure gradient develops along the plate and a critical angle is reached at which eddies are no longer shed along the plate.

The critical angle is a function of a Reynolds number VL/ν, where V is the fluid velocity, L the plate thickness and ν is the fluid viscosity. A 0.8 cm thick plate in 20°C fresh water (ν = 0.01 cm^2/sec) was observed to have a critical angle of 13° at a flow velocity of 5 cm/sec (R_e = 400). Flow over a circular disk was similar to flow around the rectangular plate.

Cylinder: The next geometric form tested was a cylinder. Two cylinders whose H/W ratios were about one but whose dimensions differed by nearly a factor of two were placed in the flume. The dye makes a strong visual impact by distinctly tracing the turbulence and flow around the container and demonstrates how one must not think of a sediment collector as a "rain gauge" catching particles in a downward flux in the water column.

At velocities of 1-10 cm/sec it was observed that the only dyed water entering a cylinder approaches the container 1-4 cm below its top edge. The fluid enters the boundary layer of the outside cylinder wall and creeps up the side. The edge of the cylinder produces pressure instabilities which cause vortices to be shed and move downstream (Fig. A-5). Each vortex forms a spiral consisting of fluid leaving the cylinder from the upstream portion sandwiched by new fluid entrained from the outside boundary layer of the cylinder. This sandwiched vortex breaks on the downstream edge of the cylinder sending one part of the fluid beyond the container and the other portion is propelled down into the cylinder. The depth of penetration of the vortex is a function of a Reynolds number $Re = \frac{VL}{\nu}$ where V is the stream

velocity and L is the cylinder diameter. In a 9 cm/sec flow the downward-propelled fluid barely reached the bottom of a cylinder with depth twice the width. The fluid motions around the two cylinders were qualitatively similar in the velocity range of 1-10 cm/sec.

Domed Cylinder: In order to reduce the fluid exchange and vortex action of a sediment trap, the best solution seemed to be to introduce an inclined plane upstream of the opening of a container. This approach resulted in the dome-shaped container shown in Table 1, with a 1.8 cm opening at the top. Being axially symmetric, the design is also well suited to omnidirectional currents. The time required for a complete exchange of fluid in the dome-shaped container is more than an order of magnitude greater than for a straight cylinder at the velocities tested (Table 2). This is partly because the smaller dome opening resulted in smaller vortices, but more importantly, the shape of the dome prevented deep penetration of the vortex within the trap.

Narrow-Necked, Wide-Bodied Traps: A container with a narrow neck and a flared body, like an Erlenmeyer flask, restricts total fluid exchange even more than the dome container. A salinity bottle, whose body flares out at a much larger angle than an Erlenmeyer flask, was even more effective for preventing fluid exchange. Patten et al., (1966) reported that when a BOD bottle (similar in shape to a salinity bottle) was filled with

fluorescein dye and placed in a channel of flowing water, an equilibrium boundary layer was formed within the bottle which persisted for at least four hours. After twelve hours the dye had been removed by either diffusion or fluid exchange. Similar steady-state conditions were observed in the present study in the above containers whose bodies were wider than the mouths.

Horizontal Cylinder with Narrow Slit: Another configuration using an inclined plane upstream of the hole to reduce flow separation and vortex shedding is shown in Table 1. It consists of a closed cylinder 10.5 cm long and 4.8 cm in diameter with a 0.11 cm slit along the length of the cylinder. The cylinder is placed horizontally with the slit perpendicular to the direction of flow. If the cylinder is rotated so that the slit is in front of the point of flow separation, virtually no fluid exchange occurs. With the slit at the point of flow separation there is a pulsating exchange along the slit with fluid entering along one end of the slit and forcing fluid out the other end. When the slit is behind the point of flow separation, fluid exchange is erratic, and it is not clear whether the fluid exchange is greater or less than when the slit is at the point of flow separation.

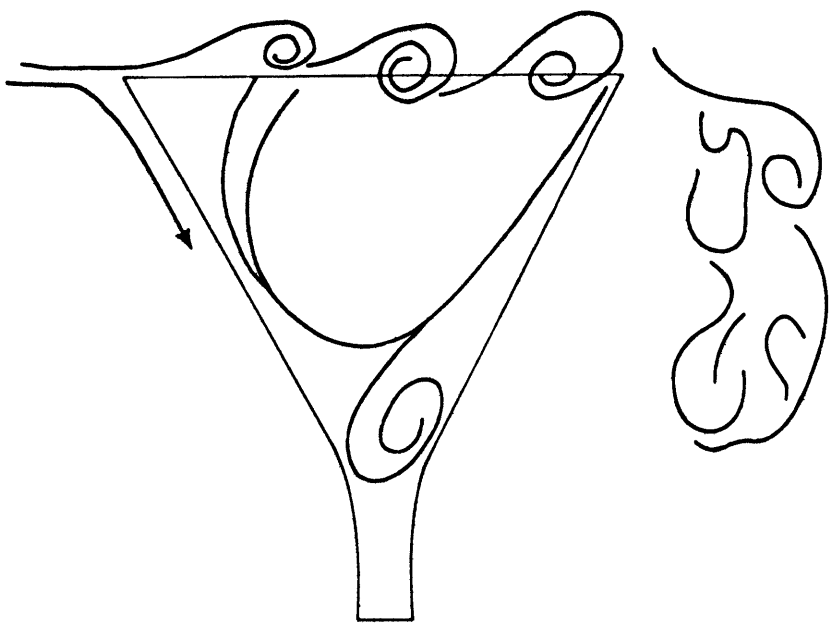
Funnel: Another axially symmetric configuration is a funnel. It has the apparent advantage that fluid encountering the funnel below the lip will be swept down and around the funnel, thus reducing updrafts which may carry large particles past the trap. Only fluid at the lip and slightly above (depending

upon the diameter of the funnel) enters the funnel. The funnels studied had a 60° sidewall slope. The diameter at the wide end ranged from 6 to 25 cm, while the narrow ends were 0.4 to 1.2 cm.

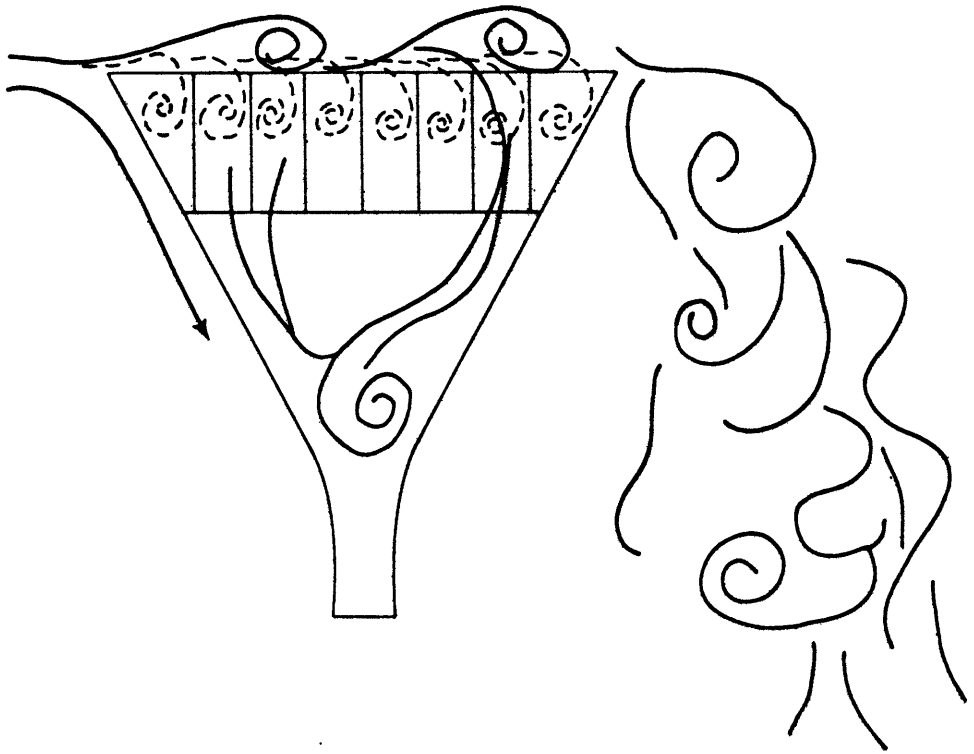
The fluid motion in funnels of different sizes was very similar. The leading edge of the funnel creates eddies which break on the trailing edge of the funnel. Part of the eddy spins downward behind the trap while the rest of it shoots towards the funnel neck along the downstream wall of the funnel and hits the upstream wall of the funnel slightly above the funnel neck (see Fig. A-6). Most of the incoming eddy moves along the upstream wall and mixes with the fluid in the funnel. The rest of the fluid produces a reversed-flow eddy at the bottom of the funnel. In an attempt to reduce the energetic mixing in the funnel, two baffles were made for use with two 6.3 cm funnels. One consisted of a grid with 1.5 cm cubes fitted inside the top of the funnel. The other was a grid of the same dimensions but enclosed by a ring and sealed on top of the funnel. The second configuration seemed to do very little to alter the flow pattern within the funnel or change the rate of fluid exchange. The vertical collar allowed fluid from below the cylindrical edge to enter the container. Table 2 shows the residence time to be about 2 minutes. The first configuration increased the residence time to 5-6 minutes and fluid velocities within the trap are noticeably decreased.

A large funnel 25 cm across was tested in a flume 1 m wide. It was topped with a baffle of squares with 2:1 H/W ratios. To

Figure A-6: Flow lines around and inside a funnel (1) without a baffle and (2) with a baffle at the top. It was hoped that the baffle would reduce the scale of turbulence and create the flow lines shown by the dotted lines, but even in laminar flow with velocities as low as 4 cm/sec. the general circulation within the funnel remains unchanged (solid lines in (2)).



1



2

a limited extent the baffle acted as a grid of square containers, each with its own circulation, but the predominant fluid motion still involved fluid descending in the downstream sections and rising in the upstream sections (Figure A-6). The motion would presumably have been more strongly damped had the baffle been recessed inside the funnel flush with the top of the sloping wall.

Segmented Basin: The sediment trap deployed by Wiebe et al. (1975) was the model for another configuration tested. The model had a 3:2:1 length:width:depth ratio and was divided into 4 cubes and one compartment twice as long as it was wide (Table A-1). Since fluid entering straight-edged containers encounters traps below the top of the trap, it was important to determine the effect of compartmentalization in a trap. The purpose of the divider in Wiebe's trap was for structural stability, multiple sampling, and turbulence reduction. Table A-2 shows that the residence time of the different compartments varied from two minutes to almost 30 minutes.

In summary, the rate of complete fluid exchange is controlled by container shape and current velocity, and can range from less than a minute to many hours when the stream velocity is less than 10 cm sec^{-1}. Other shapes were tested and some traps were tilted to observe the effects of oblique flow, but the basic patterns of fluid exchange were not altered.

Variables Affecting Trap Efficiency

The combination of variables which might affect the efficiency of a trap (current velocity, concentration of particles, size and density of particles, time length of experiment, construction material of trap) is far greater than the number of experiments made. However, some first-order observations can be made.

There was an obvious visual correlation between the dye experiments and the sedimentation experiments in that the sediment consistently accumulated in the regions of the trap where dye persisted for the longest time. On occasion the sediment accumulation and orientation outlined in a very detailed manner the steady-state flow lines both within and outside the trap, much as iron filings can outline the field lines of a magnet. For containers with a long residence time (greater than 30 min.), no preferential accumulations could be seen within the trap because the fluid never penetrated to the bottom. The trapping efficiency of a container was roughly proportional to the residence time of the dye.

Arrangement of Traps in the Flume: In testing the efficiency of cylinders or other containers in the flume, it was important to understand the effects of the flume on the results. Of particular concern was the way in which the turbulence of one container in the flume might influence deposition in the next container. Containers were generally 60-70 cm apart. This influence was tested by duplicating experiment II-2 (Series II,

experiments 2 and 4, Table 4) after rearranging the order of the traps in the flume. Rearrangement of the traps decreased the efficiency of the traps by 8% to 32%. Nevertheless, the relative ranking of efficiency among the traps remained the same.

The efficiency of traps used in Series II and III (Tables A-4 and A-5) is generally less in Series III under similar conditions. The main difference between the two series is that Series II primarily used cylindrical shapes, while most traps in Series III were funnels. The flow pattern in the flume was undoubtedly changed and resulted in changes in trapping efficiency of the same order as when the positions of traps were interchanged in Series II (Experiments II-2 and 4, Table A-4).

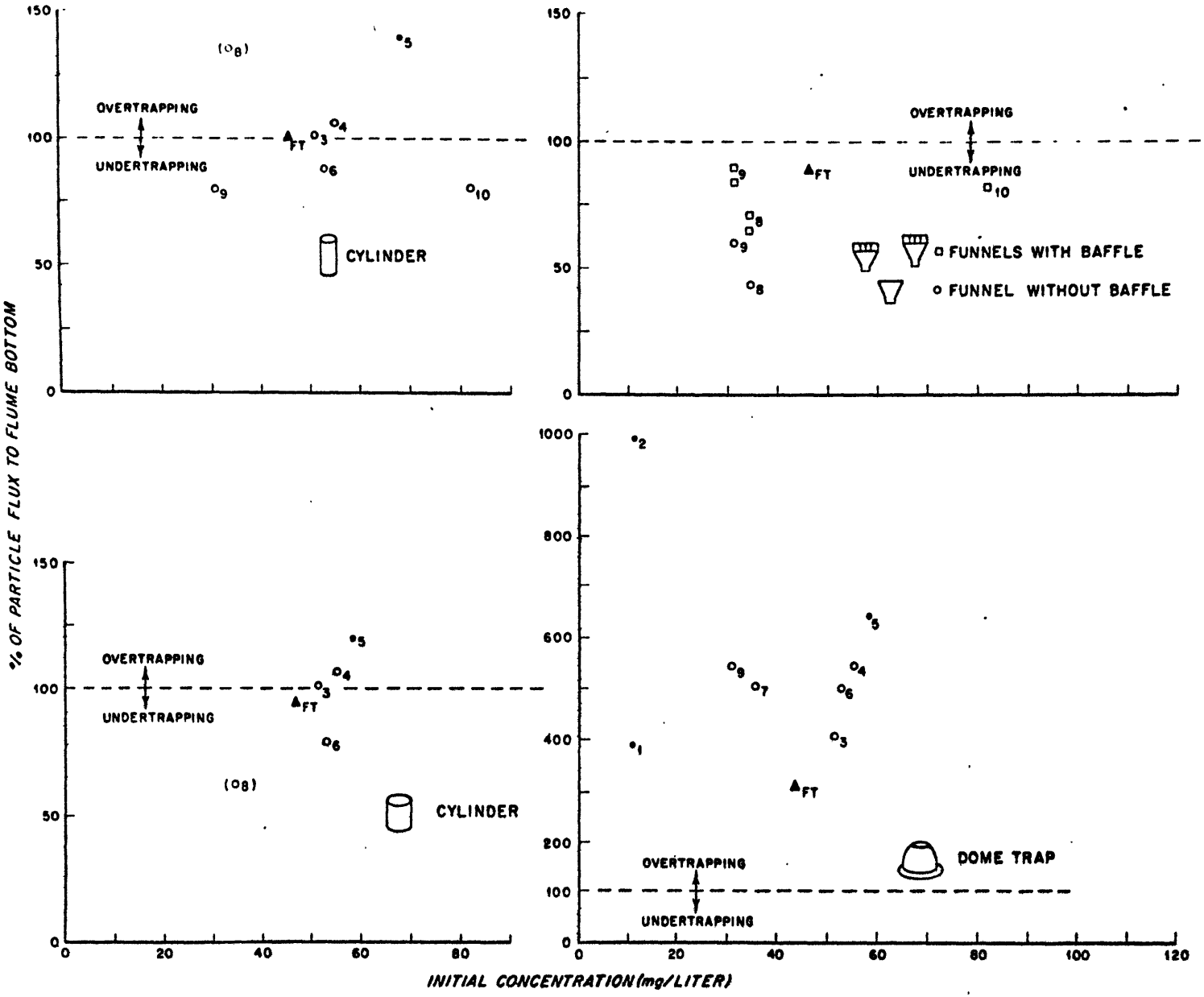
Concentration of Suspended Sediment

If the trapping efficiency of a container is plotted as a function of initial concentration of suspended sediment in the flume, no trend is obvious (Fig. A-7). It must be pointed out, however, that the duration of the experiment was not the same for all the points shown. Over the small range measured (12-82 mg/l), initial concentration does not appear to effect the trapping efficiency.

Collecting Time

In Series II, experiment 3 was run for 33 hours. Under identical conditions, experiment 4 was then run for 11 hours. The results (Table A-4) show that the trapping efficiencies are virtually the same for all containers except the dome, which is

Figure A-7. Trapping efficiency of containers at different initial concentrations of suspended particles in the flume.


% OF PARTICLE FLUX TO FLUME BOTTOM
INITIAL CONCENTRATION (mg/LITER)
OVERTRAPPING
UNDERTRAPPING
CYLINDER
FUNNELS WITH BAFFLE
FUNNEL WITHOUT BAFFLE
DOME TRAP
FT

usually more erratic than the other traps.

Collecting Time and Particle Size and Concentration

The size and concentration of particles in suspension in a flume experiment decrease with time (Gardner and Southard, 1975). The median grain size of the sediment used is 2.6 μm, and 95% is less than 25 μm. At the end of the experiment less than 1% of the volume of particles still in suspension are larger than 8 μm when the flow velocity is <10 cm/sec. The lack of significant change in the trapping efficiency of the same containers when exposed under the same flume condition for different lengths of time, as in Experiments II-1 and 2, is an indication that particle concentration and size do not affect trapping efficiency. If trapping efficiency were proportional to the concentration of available sediment, the eleven-hour run should have had a higher efficiency than the thirty-three hour run unless there were a compensating inverse relationship between particle size and trapping efficiency.

Size and Density of Particles Trapped

A further complication in the sediment trapping mechanism is a possible size/density differentiation of particles. As an eddy forms at the leading edge of a container and breaks at the downstream edge, centrifugation due to angular momentum of the vortex concentrates particles in the outer regions of the vortex (Jobson & Sayre, 1970). The larger and denser the particle, the more significant is the centrifugal force on the particle. It

was thus suspected that larger, denser particles might accumulate in traps at a rate different from their downward flux. Particles entrained in an eddy at the top of the trap could be catapulted beyond the trap, or they might be preferentially thrust into the trap. The larger particles are responsible for most of the mass flux of sediment through the water column (McCave, 1975), so one would expect an overwhelming predominance of large particles in sediment traps. but one must verify whether or not the trapping rate equals the downward flux.

In the flume experiments, the particles on the flume bottom should have the same size distribution as the particles in the traps. At the conclusion of the experiment in Series I, samples were taken from the sediment traps and from the flume bottom and tested for size distribution with a Coulter Counter. Particles deposited on the bed or in the traps are flocculated to a greater degree than when in suspension due to contact with other particles upon deposition. Therefore, the size distribution of the particles was compared in both their flocculated and unflocculated state. The volumetric distribution of particles between 0.8 μm and 25 μm was obtained. The beaker containing the sample was then put into an ultrasonic bath for two minutes and run immediately to obtain the size distribution of particles in an unflocculated state (Gardner and Southard, 1975). It is difficult to know the degree of flocculation of the particles at the time they entered the traps. However, the size distribution of particles trapped in the wide-mouthed glass jar and done trap was very similar to

the particles on the flume bed both before (median size = 6.9 μm) and after (median size = 3.2 μm) insonification. The cylinder with the slit trapped particles which were slightly larger than those on the flume bed (median size = 9.1 μm before insonification and 3.7 μm after). During the experiment large flocs were seen entering and piling up at one end of the horizontal cylinder.

Construction Material of the Trap

There was no obvious correlation between the material used to make the trap (glass, Plexiglas, and polyethylene) and the efficiency of the trap that could not be better accounted for by the geometric configuration of the trap. Sediment could be seen adhering to the walls of containers. More sediment was on the outside walls of cylinders than on the inside walls. There appeared to be much more sediment on the bottoms of cylinders than on the inside walls, though no tests were made for absolute comparison. There was more sediment on the inside walls of funnels than at the bottom. The translucent polyethylene did not allow examination of the inside walls of the domed trap. No test was made which could conclusively show that either the material used to make the trap or the interior surface area of the trap influenced its trapping efficiency.

Resuspension in the Flume

A factor which might increase the trapping efficiency of containers with time is resuspension of re-entrainment of sediment

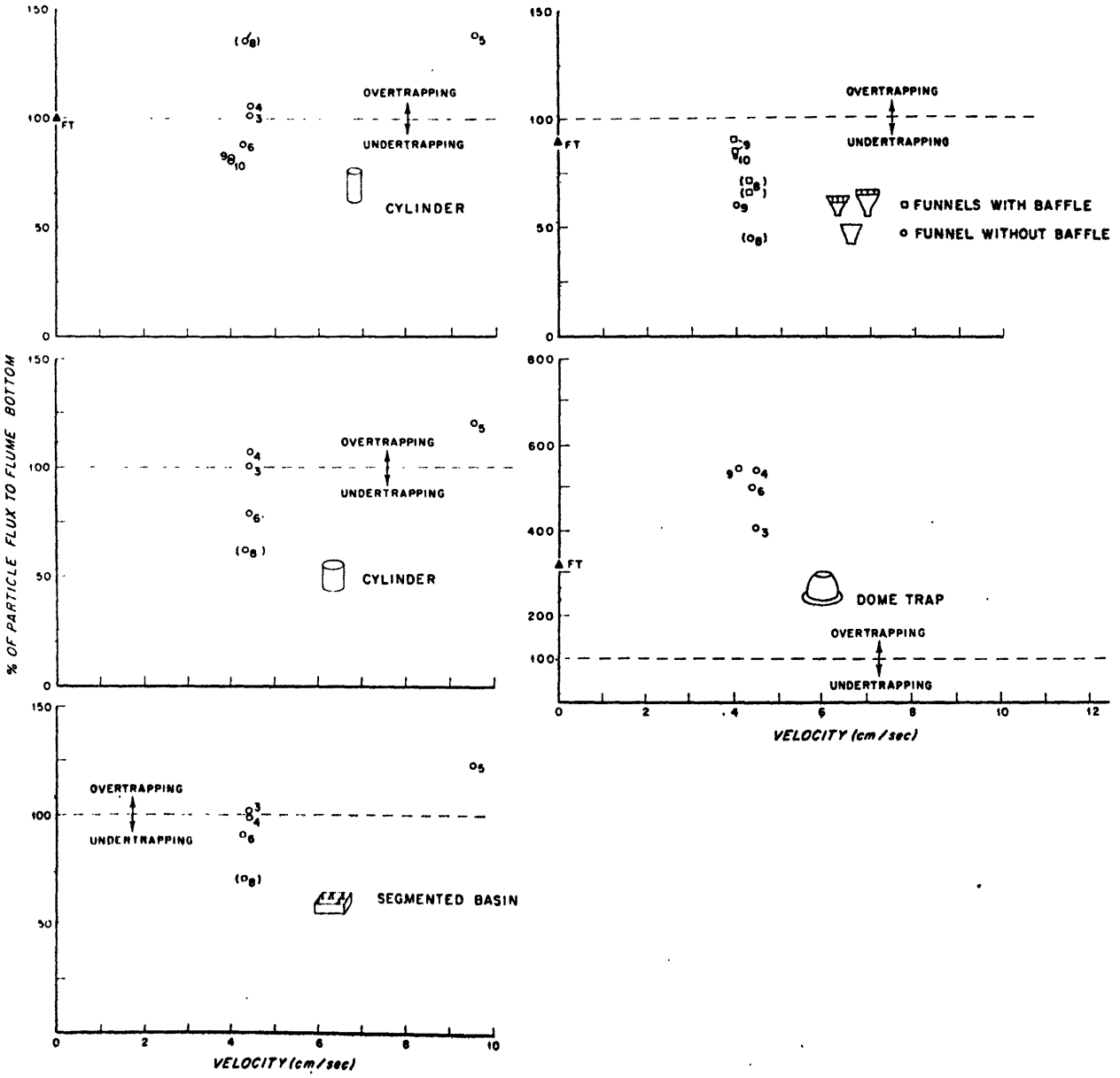
in the flume. If sediment deposited on the flume bed is returned to the flow either by resuspension or by moving along the flume bottom as bed load and being resuspended in the return flow, the sediment would have another chance to enter the traps. Assuming that sediment settled in the traps was not similarly resuspended, this would result in an increase in the amount of sediment trapped. Such re-entrainment does not seem to be a problem when the velocity is 5 cm/sec, since the trapping efficiency did not increase with time between experiments run for 11 hr and 33 hr (experiments II-3 and II-4, Table A-4).

When the velocity was increased to 9.5 cm/sec in experiment II-5, a device was placed at the end of the flume to prevent bed sediment from entering the return flow and thus being resuspended. The attempt appeared partially successful, but quantification of the resuspended sediment was not possible. Increasing the velocity from 4.4 cm/sec to 9.5 cm/sec increased the trapping efficiency of traps by 10-30% (compare II-4 and II-5). Some of this may be due to re-entrainment of sediment deposited on the flume bed, but the increase may also be due to a higher efficiency at higher velocities.

Effect of Current Velocity

In order to see if the trapping efficiency of a container was a function of velocity the trapping efficiency was plotted against velocity for the 2:1 cylinder, the large 1:1 cylinder, the dome trap, and the segmented trap (Fig. A-8). The maximum

Figure A-8. Trapping efficiency of containers versus current velocity.


% OF PARTICLE FLUX TO FLUME BOTTOM
VELOCITY (cm/sec)
OVERTRAPPING
UNDERTRAPPING
CYLINDER
FUNNELS WITH BAFFLE
FUNNEL WITHOUT BAFFLE
DOME TRAP
SEGMENTED BASIN
FT

velocity tested in the flume was only 9.5 cm/sec, because higher velocities caused re-entrainment of bed-load sediment into the system. The first experiments were run at 4-9.5 cm/sec and did not show substantial variability. Several of the traps were tested in still water in a covered fish tank using sea water and the same sediment as in the flume experiments (Table A-5). The fluxes measured by cylinders and the funnel were only slightly above the calculated flux. The dome and salinity bottle still caught substantially more than the calculated flux.

Later experiments with cylinders in natural waters where velocities exceeded 15 cm/sec showed a strong dependence on the H/W ratio in determining trapping efficiency (Chapter 2). The H/W ratio of traps used in this paper did not noticeably influence their trapping efficiency below 9.5 cm/sec.

Non-unidirectional Flow

All of the results discussed so far have been for steady, unidirectional flow. In coastal and deep ocean environments traps are more likely to encounter currents fluctuating in strength and direction. Therefore, in experiment 8 of series III (Table 5), the effect of changing current direction was simulated by rotating the traps clockwise by 180° after three hours, 45° after another two and one-half hours, and back to their original orientation three and one-half hours later.

When subjected to rotation, and a constant velocity of 4.3 cm/sec, the collection efficiency of the unbaffled funnel de-

creased from 60% to 44%. The efficiency of funnels with baffles decreased from 84-90% to 65-71%. Observations indicate the decrease is due to resuspension of material which has been preferentially deposited on the upstream wall of the funnel.

The trapping efficiency for shallow, straight-walled containers (cylinders and flat basins) is also decreased when exposed to changing current direction. In unidirectional flow the sediment is preferentially accumulated on the upstream end of the shallow containers. When the current shifts, the deposited sediment is exposed to incoming eddies and is resuspended. The cylinder with a 2:1 H/W ratio had an increased efficiency when rotated in the flume. Eddies did not reach to the bottom of this container, but the increase may have been caused by the currents pushing sediment accumulated on the lip of the trap wall into the trap.

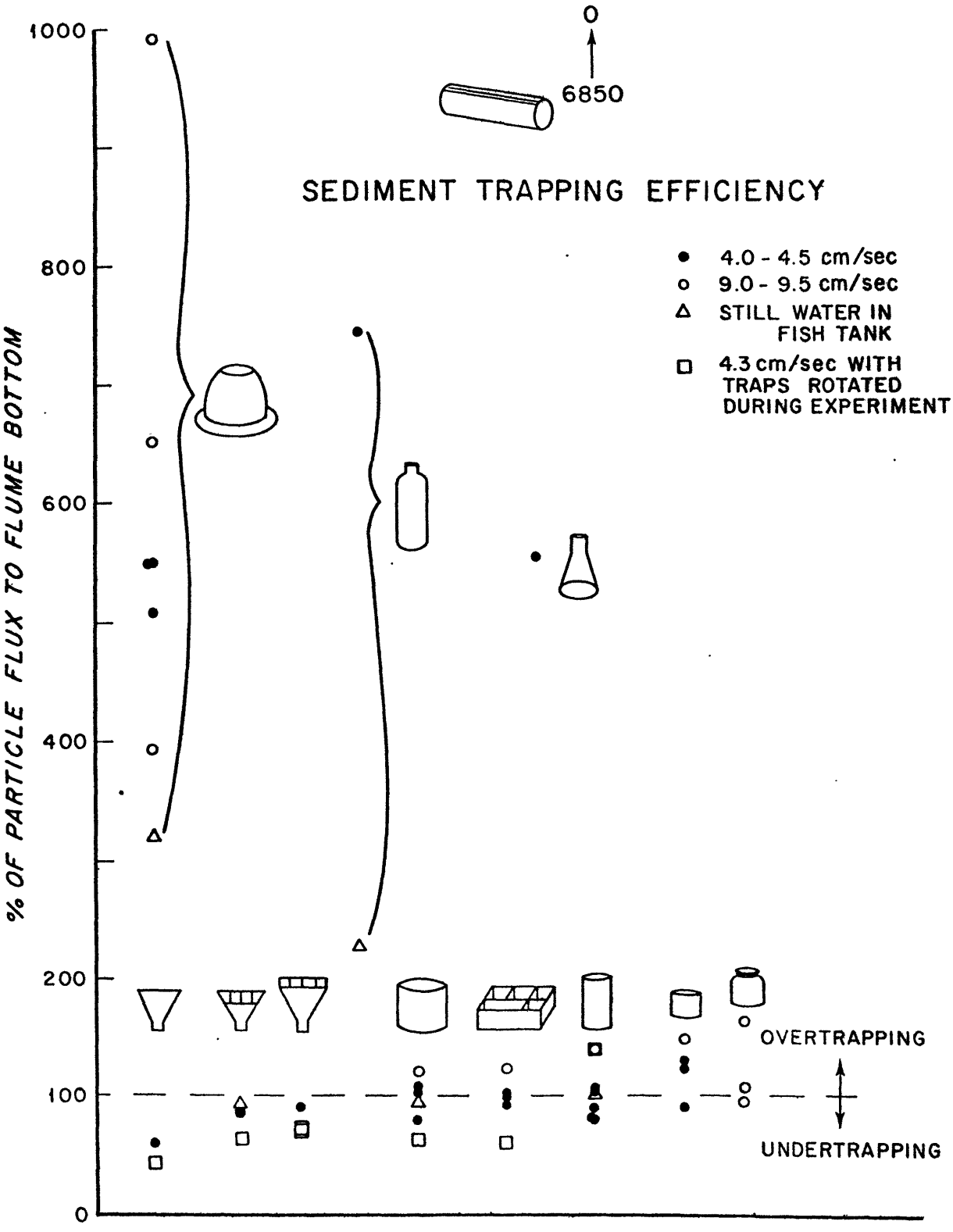
For field deployment an axially symmetric trap is preferable so that dynamically fluid exchange is the same for all flow directions.

DISCUSSION

The results of all the flume sedimentation experiments show that a two-order-of-magnitude range of sedimentation rates can be obtained from using different types of traps (Fig. A-9).

Cylinders: The average efficiency of cylinders was closer to 100% than other configurations tested at 4.0-9.5 cm/sec flow velocity. Still-water collection values in the fish tank were only slightly over the calculated flux. No strong trends in

Figure A-9. A compilation of the trapping efficiency of traps tested under a variety of conditions differing in flow velocity, length of experiment, initial concentration, and orientation of the container to the flow.


0
6850
SEDIMENT TRAPPING EFFICIENCY
4.0 - 4.5 cm/sec
9.0 - 9.5 cm/sec
STILL WATER IN FISH TANK
4.3 cm/sec WITH TRAPS ROTATED DURING EXPERIMENT
% OF PARTICLE FLUX TO FLUME BOTTOM
1000
800
600
400
200
100
0
OVERTRAPPING
UNDERTRAPPING

trapping efficiency were evident between different sizes of cylinders, but the ranges of dimensions and velocities were not very great.

Flat Plate: A flat plate is the closest approximation to the ocean bottom, but it is a highly inefficient collector when exposed to currents. Most of the particles landing there are moved along the plate without a chance to settle permanently and with no way to be trapped. Also, recovery of such a collector without losing sediment is difficult.

Funnels: In still water the trapping efficiency of funnels is not substantially different than for cylinders (Table 5). In a current of 4 cm/sec the unbaffled funnel was 25% less efficient than the cylinders, whereas the funnels with baffles caught sediment at about the same rate as the cylinder. However, in these experiments the accumulation of particles has been predominantly on the inside funnel walls. It is possible that on a mooring in open water particles aggregate with time and roll down the sides into the funnel neck and not be resuspended. Brunskill (1969) reported that a minor portion of the sediment stayed on the sides of his funnels.

There was insignificant difference between the efficiencies of the funnel with a baffle enclosed in a ring on top of the funnel versus a funnel with a baffle set inside the sloping funnel walls. Because the dye experiments showed the mixing to be more vigorous with the baffle on top of the funnel (dye residence time of 2 minutes versus 5-6 minutes for recessed baffle funnel and 2

minutes for unbaffled funnel), more of a difference had been expected for their collection efficiencies. This emphasizes the importance of combining sedimentation experiments with dye observations.

The purpose of the baffle was to reduce turbulence and mixing within the funnel. The size of eddies was reduced by the baffles, but the major circulation within the funnel was not affected (Fig. A-6). Most of the fluid still enters the downstream section of the funnel, descends to the bottom of the funnel, and rises out of the upstream end of the funnel. This has been observed in funnels as large as 140 cm in diameter. In a current of 7 cm/sec, plastic beads with a fall velocity of 0.8 cm sec^{-1} (690 m day^{-1}) were seen to enter the downstream end of the funnel and be carried out at the upstream end. The significance of this observation will be discussed at the end of this section.

Segmented Basin: Several traps have been constructed which approximate a flat basin with edges to prevent loss of collected material. One was designed for work in quiet lake waters (Kleerekoper, 1952, 1953) while others were built for deep ocean studies (Wiebe et al., 1975, Mesecar and Carey, 1975; Jack Dymond, personal communication). Because dye experiments with simple cylinders had shown that fluid entering a container rode up the outside of the container, it was important to determine the effect of segmenting a basin or clustering a group of cylinders. Field studies with grouped metal cylinders in a Massachusetts bay showed that when two or three cylinders were tied together and

deployed at the same level the amount caught varied greatly among the cylinders, but when four cylinders were tied in a tight cluster, the mass in each container was more uniform (Gilbert Rowe, personal communication). Hargrave et al. (1976) found that the detritus trapped in four cylinders attached at the ends of a square cross varied by 8-23%. The relative amounts collected in each compartment in Series II and III experiments was the same and the average for the trap was 100% at 4.4 cm/sec and 120% at 9.5 cm/sec. Under unidirectional flow the first cubicle compartment (Table A-4) under-collected particles, while there was a compensating collection in the second compartment. The two rear cubes (3 and 4) had an efficiency near the average of the entire trap, whereas the rectangular compartment (5) had a slightly lower efficiency than the trap average. When the trap was rotated during the experiment, there was little variation in the relative efficiency of the different compartments, but the overall efficiency was reduced to 60%.

Narrow-necked, wide-bodied traps: Containers with bodies larger than their openings had high trapping efficiencies, even in still water. Observations in the fish tank where suspended particle concentrations ranged from 1-40 mg/l showed why. Particle-laden water under an overhanging wall will soon lose particles due to gravitational settling. The overhanging wall prevents new particles from entering the particle-depleted water, and when sufficient particles have fallen out, the water becomes less dense than surrounding water and rises in a plume. These

plumes were identified by the lack of backscattering of particles in the plume and by dropping tiny dye particles into the traps and watching the dyed water rise (concentrated dye is slightly negatively buoyant). The light water is replaced by water outside the container which has more particles, and the cycle is repeated. Thus, particles are pumped into containers at a rate which depends on the particle characteristics (sinking rate, concentration) in the fluid and the proportion of overhanging wall area to trap-opening area. A plume also rose from a tall cylinder in still water (height:width = 3), but not from a short (height:width = 1) cylinder. This may be because horizontal diffusion and Brownian motion does not allow the fluid at the trap bottom to remain homogeneous, so as particles fall out at the trap bottom a less dense fluid is developed which rises.

The same basic mechanism applies to these traps in moving water because the fluid is in the container long enough for some of the particles to settle out. Enough particles fall out for the fluid either to become light and rise out of the container, or to lose much of its load before an eddy penetrates deeply enough to force old fluid out.

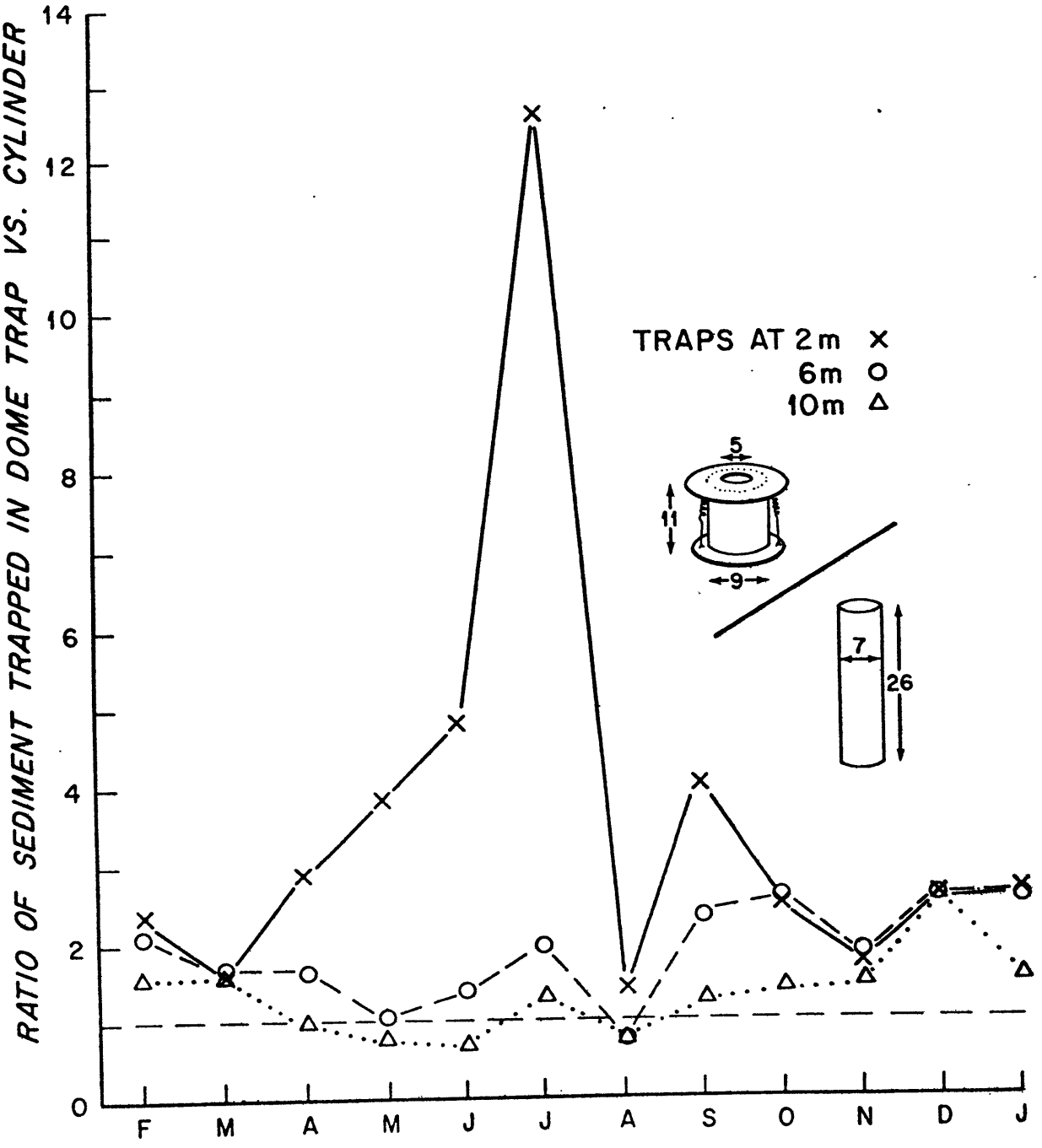
Suspended particle concentration in the fish tank was initially 46 mg/liter, so if 75% of the particles settled out of a parcel of water, the density difference would be 34.5 ppm; this corresponds to .035% change in salinity, which is both measurable and sufficient to cause a density instability. In the deep

ocean, where concentrations of particulate matter are seldom greater than 0.1 mg/liter, it is unlikely that any density instabilities would result if all particles settled out. The horizontal cylinder with a slit belongs in this class of traps with a narrow neck and wide body. Because this shape over collected particles so drastically it could prove useful in removing suspended particles for pollution control or industrial purposes.

One field study (Pennington, 1974) made a direct comparison of the trapping ability of cylinders as compared with an atmospheric pollen trap reported by Tauber (1965, 1967), which consisted of a cylinder capped by an inclined collar (similar to the dome trap) designed to reduce the turbulence generated at the trap opening. Her results showed that in still water the cylinder and Tauber trap caught material with nearly the same ratio of sediment per unit area of opening, whereas in circulating water the Tauber traps caught singificantly more material (Fig. A-10). Pennington attributed the difference to resuspension from the cylindrical traps; however, the above arguments indicate that the collar causes overconcentration of sediment in the trap, and the data from the cylinders should be considered more accurate.

General: After observing the turbulent eddies on top of sediment traps and observing that even large, fecal-pellet sized particles can be carried into and out of funnel-shaped traps when the current velocity is less than 10 cm/sec, one might

Figure A-10. Ratio of sediment collected with the shielded Tauber trap to a cylinder with a height to width ratio of 3.7. Data taken from Pennington (1974).


RATIO OF SEDIMENT TRAPPED IN DOME TRAP VS. CYLINDER
14
12
10
8
6
4
2
0
F
M
A
M
J
J
A
S
O
N
D
J
TRAPS AT 2m ×
6m O
10m Δ
5
11
9
7
26

wonder whether traps are effectively collecting falling particles. Although the horizontal current velocity is much greater than the fall velocity of most particles, a simple calculation will show that if all particles entering the trap stayed inside, the rate of collection would greatly exceed the accumulation rate on the flume bottom: the cylinder with H/W ratio of 2.3 has a trapping area of 11.3 cm^2. In one experiment the velocity was 4.0 cm/sec, the average concentration was 25 mg/l, and the experiment lasted 11.3 hr. If we assume fluid is entering one half of the cylinder and leaving from the other half, and only 1% of the particle mass remains inside, the mass in the trap at the end of the experiment would be 565 mg, whereas the mass actually collected was 2.6 mg; more than two orders of magnitude lower!

After making the above calculation, it is surprising that the collection of cylinders and funnels match the accumulation rate of particles on the flume bed and more importantly that the results are reproducible under a variety of conditions, because only a small percentage of the particles entering the trap remain there; taking a small fraction of a large number usually causes large errors. These experiments indicate that we can design traps which collect particles at the rate of the vertical flux despite the dominant horizontal advection of

particles. In reality, the traps only collect a mass of particles equivalent to the downward mass flux at that level; not all the particles contributing to the downward flux which entered the trap remained there, and it is possible that some particles which do not contribute significantly to the downward flux do remain inside the trap. This is an important point to realize when using sediment traps. More experimentation is needed to determine whether the particles are representative of the falling particles in terms of morphology and composition and not just equivalent in mass. If they are, then chemical and physical analyses of the collected particles will improve our understanding of many processes in aquatic systems.

SUMMARY

Sufficient field and laboratory work has been done to instill confidence in the results of sediment traps deployed in tranquil waters (Davis, 1967; Pennington, 1974; Rigler et al., 1974; Kirchner, 1975; Moore, 1951; Deevey, 1964). When traps are exposed to advective currents, the velocity of flow and geometric design of the trap determine the amount of sediment trapped. Sediment traps in advective flows must not be thought of as "rain gauges" in low-velocity winds, which simply catch particles falling nearly vertically, because the fall

velocity of particulate matter in large bodies of water is so much lower than the horizontal flow velocities that most particles follow the hydrodynamic flow lines around and inside traps.

The sediment-trapping process is complex. It appears to be nearly coincidental rather than predictable that a container collects an amount of sediment equal to the actual flux. The particles are trapped during fluid exchange of particle-laden water. If the fall velocity of a particle in an incoming eddy is large compared to the residence time of the parcel of water carrying the particle, it will fall to the bottom of the container and be trapped, and a new parcel of water will replace the old parcel. Therefore, containers are appropriately called "sediment traps" rather than "sedimentation traps" which is a description of the desired result, but is grammatically and conceptually incorrect.

The overall performance of different shapes of sediment traps in flows up to 9 cm/sec and using sediment less than 25 μm indicated that:

1) cylindrical traps with a H/W ratio of 2 most accurately measured the real flux in the flume;
2) funnels underestimate the actual flux;
3) funnels with baffles on top of the funnel improve the trapping efficiency to 70-90%. (This

is a function of the baffle design);

4) containers with body diameters greater than the mouth openings overtrap sediment by a factor which depends on the mouth-to-body ratio, the concentration of particulate matter, and the geometry of the trap.

Variations in velocity, current direction, suspended sediment concentration, grain-size distribution and duration of deployment showed the following relationships:

1) The trapping efficiency of cylinders and the segmented basin trap increased only 20-35% between 4 and 9.5 cm/sec. Experiments in the fish tank showed that cylinders and funnels caught particles at the rate at which they were falling in still water.

2) Rotating the traps to simulate varying current direction reduced the trapping efficiency of a plain funnel to around 45% and the baffled funnels to around 70% (deeper baffles could improve this). Shallow containers were less efficient, and the tall cylinders were more efficient when they were rotated.

3) No variation was seen in the trapping efficiency when the initial concentration of suspended particles was varied between 12-82 mg/l.

4) There was no apparent preferential collection of large or small particles by cylinders or the dome trap using the fine-grained sediment of the experiment (95% < 25μ). The horizontal cylinder with a 1.1 mm slit trapped slightly larger flocs and particles than what was deposited on the flume bed.
5) In the time range of 11-39 hr, the duration of the experiment had no effect on the trapping efficiency.

The containers used in these experiments are smaller than most traps used in field experiments, and the flume is much smaller than the bodies of water in which sediment traps are used. While it is possible to scale the size of traps, it is not possible to model in the flume the scale of turbulence which exists in large bodies of moving water. However, the fluid motion around and within the traps and the dynamics of sediment trapping are similar in both situations.

Additional controlled experiments are needed to extend the scope of this study. Tests need to be made at velocities above 10 cm/sec and with particles larger than 25 μm. Absolute calibration of large traps in the field is difficult but can be done by comparing the field results with results from the smaller traps calibrated under controlled conditions in a flume.

Sediment traps have been used to study a variety of problems concerning the flux of particles in a wide range of characteristically different bodies of water. Acceptance of the reliability of trap results has been understandably slow since little effort has been put into determining the factors which control how much material a sediment trap collects. However, enough experience from experimentation has been gained to warrant increased effort in using these simple devices to answer questions about mass and elemental fluxes. Direct measurements of fluxes are particularly lacking in the deep ocean, where variables are less likely to skew trapping characteristics. Recent advances in deep-sea instrumentation and mooring technology make possible a new approach to problems of mass flux and sediment transport in abyssal waters.

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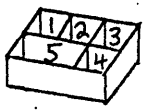
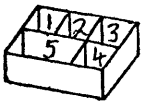
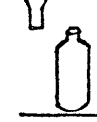
TABLE A.1

TRAP DESIGN							
Height (cm)	4.0	4.8	3.9	8.7	6.5	4.0	4.5
Diameter (Inside)							
Mouth (cm)	4.5	10.5 x 0.11	3.7	3.8	6.4	3.8	1.8
Body (cm)	5.0	10.5 x 4.8	3.7	3.8	6.4	3.8	4.5
Height/Width	0.8		1.0	2.3	1.0	1.1	
Area (Mouth) (cm^2)	15.9	1.2	13.7	11.3	32.2	11.3	
Volume (ml)	71	180	54	99	209	45	58

TRAP DESIGN								
Height (cm)	7.8	10.3	8.9	8.9	9.9	7.5	8.8	10.8
Diameter (Inside)								
Mouth (cm)	6.3	10.0	6.3	6.3	6.3	1.6	1.2	1.5
Body (cm) (at the neck)	0.5	0.5	1.2	1.2	1.2	4.6	3.5	4.5
Height/Width								
Area (Mouth) (cm^2)	31.2	78.5	31.2	31.2	31.2	2.0	1.13	1.77
Volume (ml)	61	230	57	55	102	60	64	1.29

Trap	Velocity (cm/sec)	Time for complete fluid exchange (min)	*Time for 100 vortices to be shed (sec)	Velocity (cm/sec)	Time for complete fluid exchange (min)	*Time for 100 vortices to be shed (sec)
	5.7	5	77	7.8	0.8-1.0	42
	5.7	10-15	66	7.8	1.7-2.0	41
	5.7	3-4	70	7.8	1.2-1.3	42
	5.7	>> 20 probably hours	72	7.8	several 10's of min.	55
	4.5					
1		20-30[1]				
2		3				
3		5-7[2]				
4		5-6[2]				
5 		2-3[3]				
	6	2				
	6	5-6				
	6	2				
	?[4]	< 12 hrs.				

*Average of 3-5 measurements
[1]Some dye still in corners after 70 minutes
[2]Some dye still in corners after 15 minutes
[3]Some dye still in corners after 30 minutes
[4]Patten et al., 1966.

TABLE A.2

SERIES I

Experiment No.		1	2
Time	(hr.)	39.3	42.7
Velocity	(cm/sec)	9.0	8.9
Flow Depth	(cm)	12	11.0
Initial Conc.	(mg/l)	11.8	11.5
Final Conc.	(mg/l)	2.8	2.3

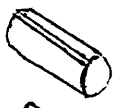
TRAP		
	106	163
	94	
		266
	391	994
		6850
		31

TABLE A.3

SERIES II

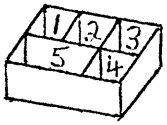
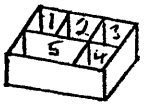
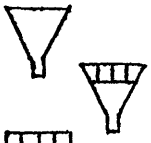
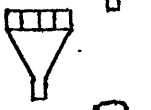
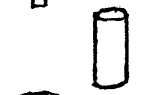
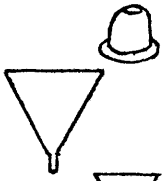
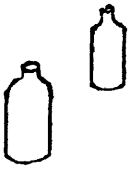
Experiment No.		3	4	5	6
Time (hrs.)		32.7	11.1	11.1	11.0
Velocity (cm/sec)		4.4	4.4	9.5	4.4
Flow Depth (cm)		15.0	15.0	15.0	15.0
Initial Conc. (mg/l)		51.0	55.0	58.2	53.0
Final Conc. (mg/l)		8.3	25.9	30.7	23.2
TRAP					
	1	78%	88%	105%	86%
	2	128%	114%	152%	105%
	3	106%	101%	130%	98%
	4	108%	110%	121%	89%
	5	97%	92%	115%	83%
	$\bar{\Sigma}$ 1-5	102%	99%	123%	91%
		101%	106%	139%	88%
		101%	107%	120%	79%
		123%	130%	148%	88%
		413%	550%	651%	508%

TABLE A.4

SERIES III

Experiment No.	8	9	10	Fish Tank
Time (hrs.)	10.8	11.3	17.3	17.3 hrs.
Velocity (cm/sec)	4.3	4.0	4.0	0
Flow Depth (cm)	14.3	14.8	14.8	24.2
Initial Conc. (mg/l)	34.4	31.2	82.4	46.1
Final Conc. (mg/l)	18.5	17.8	36.2	5.4
TRAP				
	1	64%		
	2	67%		
	3	59%		
	4	60%		
	5	56%		
	$\bar{\Sigma}$ 1-5	60%		
		44%	60%	
		65%	84%	82% 89%
		71%	90%	
		136%	80%	81% 98%
		62%		94%
		>264%*	550%	322%
			60%	
			65%	
				554%
				743% 231%
				896%

*Unknown amount lost during filtration

TABLE A.5

APPENDIX B

CLASSIFICATION OF SEDIMENT TRAPS ACCORDING TO GEOMETRY

CYLINDERS

lake	Bloesch	1967, 1977
lake	Burns & Pashley	1974
sea loch	Davies	1975
lake	Ferrante & Parker	1977
lake	Fuhs	1973
laboratory	Gardner	1977b
bay, lake	Gardner	1977a
ocean	Gardner et al.	1977
lake	Gasith	1975
bay	Hargrave	1976
estuary	Hoskin, et al.	1975
lake	Johnson & Brinkhurst	1971
lake	Kimmel, et al.	1977
lake	Kirchner	1975
lake	Mueller	1964
bay & continental shelf	Nichols & Rowe	1977
bay	Okuda	1960
lake	Pennington (Tutin)	1955, 1974
fjord	Petersen & Boysen Jensen	1911
estuary	Quasim & Sandaranarayanan	1972
lake	Rigler, et al.	1974
coastal basin	Soutar, et al.	1977
bay	Staresinic, et al.	1977
estuary	Trevallion	1967
bay	Webster, et al.	1975
lake	White & Wetzel	1973, 1975

WIDE-MOUTHED JARS

sea loch	Ansell	1974
	Bombawna	1962
lake	Davis	1967, 1968, 1973
lake	Davis & Brubaker	1973
lake	Deevey	1964
bay	Edwards	1973

WIDE-MOUTHED JARS

ocean shelf	Hartwig	1976
laboratory	Hopkins	1950
lake	Järnefelt	1955
lake	Lawacz	1969
lake	Mason, et al.	1977
sea loch	Moore	1931
lake	Mueller	1964
lake	Rossolimo	1937
lake	Scott & Miner	1936
sea loch	Steele & Baird	1972
bay	Stephens, et al.	1967
lake	Toyoda, Horie & Saijo	1968
lake	Wegelenska, et al.	1975
bay	Young	1971
bay	Young & Rhoads	1971

BASIN (width < height)

lake	Axelsson	1955
lake	Axelsson & Håkanson	1975
lagoon	Emery, et al.	1954
lake	Håkanson	1976, 1977
lake	Heim	1900
lake	Kleerekoper	1952, 1953
ocean	Mesecar	1975
ocean	Mesecar & Carey	1975
lake	Reissinger	1932
continental shelf	Revelle & Shepard	1939
continental shelf	Shepard	1948
lake	Thomas	1950, 1954a, 1954b, 1955, 1963
ocean	Wiebe, et al.	1976

CYLINDER WITH FUNNEL BOTTOM

lake	Anderson	1977
lake	Edmondson & Winberg	1971
ocean	Izeki	1976
lake	Lastein	1976
ocean	Nishizawa & Izeki	1975
lake	Ohle	1962, 1965
bay	Tsunogai & Minikawa	1974, 1976
continental shelf	Zeitschel	1965

FUNNELS

continental shelf	Bascom	1976
lake	Bachofen	1960
coastal basin	Berger & Soutar	1967
lake	Brunskill	1969
lake	Johnson & Brinkhurst	1971
lake	Matsuyama	1973
bay	Oviatt & Nixon	1975
lake	Pennington (Tutin)	1955, 1974
coastal basin	Schick, et al.	1968
lake	Stepanek	1963
lake	Watanabe & Hayashi	1971

BODY >> MOUTH

ocean reef	Glynn	1977
ocean reef	Glynn & Stewart	1973
lake	Grim	1950, 1952
bay	Hough	1939
river-estuary	Patten, et al.	1966
lake	Pennington (Tutin)	1975
bay	Raymond & Stetson	1931

UNKNOWN CONFIGURATION

bay	Erdtman	1950
lake	Hogetsu, et al.	1952
	Höhne	1966
	Niklaus	1967
lake	Saijo, et al.	1954
ocean reef	Ott	1975
ocean reef	Rubinoff	1974
	von Bröckel	1975

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APPENDIX C

ALTERATIONS ON PARTICLE COUNTERS FOR USE AT SEA

The ease and speed of measuring the size distribution and concentration of particles has increased with the introduction several years ago of electro-sensing particle counters such as the Coulter counter and the Electro Zone of Particle Data, Inc., although an understanding of the method of measurement is important when analyzing the results (Swift et al., 1972). It is becoming common for investigators to take their counting equipment to perform a variety of size analysis experiments, but a ship at sea provides problems of electronic noise, vibration, and continuous motion not always encountered in the laboratory.

The following solutions to these problems are based on experience with a Model TA II Coulter counter and discussions with Henri Bader, Ken Carder and Steve Eittreim who have taken similar equipment to sea.

Electronic noise, which is also a problem on land, can be reduced by

1. Building a wire or aluminum foil Faraday cage around the sensing stand;

2. Connecting the cage, stirring motor housing, sensing stand housing, and electronics housing to common ground;

3. Plugging the stirring motor into a separate socket and not into the electronics housing;

4. Use of a constant voltage supply and noise filter to compensate for voltage changes frequently experienced on ships, although the internal electronics of the Counter counter is usually sufficient to overcome the problem. Radio transmission can also interfere with counters and is most easily eliminated by using a separate power source, if available.

Vibration is reduced sufficiently by making a stack with 2-two inches of foam rubber, a half-inch steel plate, 3/4 inch plywood and 1/8 inch rubber onto which the instrument can be strapped. Flexible cord is used to lash the plywood to a table top. Four to six layers of 1/8 inch closed cell and open cell neoprene rubber under the front and back of the sensing stand further isolates the sensor from high and low frequency vibrations. A rubber strap across the bottom of the stand is used to make a flexible attachment to the plywood platform.

The biggest problem with particle counters at sea arises from the fluctuations in the manometer's mercury level caused by rolling and pitching of the ship. For two reasons it is erroneous to count for a known time with the mercury moving up and down and assume that the

average count is correct. First, in the TIME counting mode, there are large openings to the atmosphere on both ends of the manometer, thus allowing free and rapid flow of the mercury. These fluctuations cause changes in the flow rate through the sensing zone, thus changing the likelihood of particle coincidence in counting. More important is the possibility that while the mercury is falling, fluid from inside the aperature tube, which is a mixture of fluid and particles from the electrolyte reservoir and the sample already counted, may be flushed back through the sensing zone and recounted, thus counting particles in a different volume than intended.

In the MANOMETER mode the mercury is open to the atmosphere on one end and has access to the atmosphere through the aperature on the other end. The effect of the above problems are reduced, because the movement of mercury is restricted to the flow rate of a liquid through the aperature tube since liquids are essentially incompressible and only a liquid path exists between the mercury and the oriface. Still the problems exist. An elaborate method of circumventing the problem was suggested to me by Henri Bader (personal communication) which led me to a very simple method of eliminating the problem without necessitating the numerous calibrations of the original

method. Simply pinch the tubing connecting the aperature stopcock control and the manometer with an adjustable clamp so that the flow rate through the clamped tubing is less than through the aperature tube being used. This condition is met when very little movement (<1-2 mm) occurs at the mercury meniscus in the RESET mode. If the clamp eliminates all flow, the signal becomes noisy. An adjustable clamp allows the mercury to return to the pre-count level at a rapid rate rather than at the flow rate through the aperature. The flow restriction imposed by clamping this section of tube also reduces the chance of mercury rising up and into the aperature tube at sea. I found it necessary to make extension for the braces holding the manometer to make room for the clamp on the hose. An alternative would be to shorten the glass tubing on the stopcock control or above the mercury reservoir.

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APPENDIX D

SUSPENDED PARTICULATE CONCENTRATIONS

Sample depth (m)	Meters above bottom	Mass (µg)	Volume filtered (liters)	Uncorr. concn. (µg/liter)	Corr. concn. (µg/liter)
OC6, Sta. 710 38°33.8'N 72°12.0'W 5/12/76					
8	2708	160	0.9		178
1536	1180	99	5.2		19
2041	675	59	5.5		11
2344	372	52	4.0	13	65
OC6, Sta. 715 38°26.7'N 72°03.2'W 5/13/76					
5	2812	150	0.45		333
1528	1289	111	5.5		20
2023	794	26	5.1		5
2419	398	96	4.0	24	41
2717	100	119	5.4		22
2777	40	129	18.1	7	14
2787	30	196	17.5		17
OC6, Sta. 718 36°34.2'N 69°41.2'W 5/14/76					
28	4457	114	3.2		36
453	4032	203	5.0		41
1453	3032	128	5.0		26
2453	2032	164	5.3		31
3461	1024	104	5.7		18
4065	420				
4270	215	190	4.6		41
4373	112	438	5.2		84
4427	58	651	6.2	105	127
4457	28	542	5.5	99	107
4462	23	465	5.0	93	115
4467	18	470	4.5		104

Sample depth (m)	Meters above bottom	Mass (µg)	Volume filtered (liters)	Uncorr. concn. (µg/liter)	Corr. concn. (µg/liter)
OC6, Sta. 721 38°17.6'N 69°36.0'W 5/15/76					
5	3646	98	1.0		98
115	3536	373	5.2		72
315	3336	135	3.9		35
615	3036	822	5.1		161
1615	2036	143	5.1		28
2094	1557	140	4.9		29
2628	1023	132	4.9		27
2932	719	134	5.5		24
3150	501	226	13.1	17	23
3300	351	-	-		
3450	201	649	4.8		135
3550	101	370	6.8	54	67
3610	41	567	5.5		103
3625	24	566	8.8	64	81
3635	16	498	5.3		94
OC6, Sta. 727 36°39.3'N 68°28.9'W 5/16/76					
0	4840	738	2.0		369
1157	3683	151	4.7		38
2157	2683	256	5.0		51
3163	1677	117	5.2		23
3936	904	134	5.3		25
4339	491	282	15.1	19	22
4641	199	222	4.8		46
4741	99	929	13.0	72	86
4801	39	555	6.0		92
4816	24	1489	15.3	97	107
4826	14	465	5.1		91
OC6, Sta. 730 35°12.5'N 67°24.0'W 5/17/76					
0	5194	521	1.75		298
1204	3990	225	5.2		43
2204	2990	161	4.6		35
3204	1990	122	5.1		24
4204	990	195	5.5		36
4704	490	387	26.0	15	24
5004	190	506	5.3		96
5094	100	1463	22.1	66	90
5129	65	491	4.7		105
5154	40	651	6.0		109
5174	20	1899	21.3	89	102
5183	11	486	5.4		90

Sample depth (m)	Meters above bottom	Mass (µg)	Volume filtered (liters)	Uncorr. concn. (µg/liter)	Corr. concn. (µg/liter)
OC6, Sta. 734 34°36.8'N 68°08.3'W 5/17/76					
0	5247	240	1.5		160
1297	3950	141	5.1		28
2287	2960	115	4.8		24
3269	1978	147	5.2		28
4254	993	192	4.9		39
4747	500	250	21.8	12	19
5047	200	237	4.9		48
5147	100	1337	17.1	78	97
5182	65	524	4.6		114
5207	40	629	5.5		114
5227	20	1208	15.7	77	110
OC6, Sta. 738 33°30.8'N 70°29.1'W 5/18/76					
0	5378	105	1.5		70
437	4951	261	5.1		51
1437	3951	191	5.0		38
2400	2988	106	5.1		21
3397	1991	316	5.2		61
4386	1002	214	5.1		42
4888	500	248	27.1	9	17
4908	480	159	4.7		34
5188	200	302	5.2		58
5288	100	464	20.5	23	50
5333	55	341	4.2		81
5348	40	472	5.5		86
5368	20	737	19.7	37	48
5378	10	287	5.5		52
OC6, Sta. 743 37°41.)'N 70°01.0'W 5/20/76					
0	4100	1377	2.0		689
320	3780	260	4.7		55
1128	2972	137	5.0		27
2135	1965	120	5.0		24
3120	980	198	5.4		37
3600	500	369	17.5	21	34
3900	200	322	4.7		69
4000	100	624	5.7	110	159
4060	40	805	5.6		144
4080	20	2137	16.9	126	155
4090	10	635	5.5		116

Sample depth (m)	Meters above bottom	Mass (µg)	Volume filtered (liters)	Uncorr. concn. (µg/liter)	Corr. concn. (µg/liter)
OC6, Sta. 750 39°45.9'N 70°35.9'W 5/21/76					
0	1600	267	0.5		534
300	1300	456	5.0		91
600	1000	412	5.0		82
1100	500	423	26.6	15.9	27
1357	243	274	5.1		54
KN58-3 CTD#5 38°27.7'N 72°01.3'W 9/1/76					
300	2513	582	7.8		75
1000	1813	132	8.0		17
1750	1063	182	8.0		23
2080	733	129	7.5		17
2280	533	152	7.5		20
2430	383	118	7.3		16
2579	234	169	7.8		22
2679	134	325	7.55		43
2731	82	346	6.15		56
2749	64	263	7.75		34
2765	48	293	7.8		39
2797	16	562	7.6		74
Subsig-II, Sta. 1 39°49.1'N 70°39.9'W 6/8/76					
0	914	453	1.12		406
30	884	183	0.9		203
208	706	365	5.3		69
408	506	280	4.8		58
558	356	302	5.4		56
704	210	383	5.7		67
804	100	371	5.8		64
864	50	366	5.9		62
874	40	273	9.3	29.4	65
884	30	563	5.8		97
Dallas, Sta. 58 38°53'N 72°27'W 6/30/76					
18	2168	240	1.6	150	178
18	2168	300	2.0	150	166
108	2078	200	7.0		29
1174	1012	270	2.5	108	129
1974	212	180	8.0		23
2074	112	240	6.6		37
2104	82	300	8.0		38
2150	36	280	7.7		37
2156	30	310	7.9		39
2166	20	380	6.9		55