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**PARTICULATE BIOGEOCHEMICAL PROCESSES**

*Report of SCOR Working Group 71*

*September 1988*

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## **PARTICULATE BIOGEOCHEMICAL PROCESSES**

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## SUMMARY

This report summarizes the discussions and recommendations of the working group WG-71 on "Particulate Biogeochemical Processes." The working group held three meetings, one each during 1984, 1986 and 1988. The topics addressed by the working group included: (i) sources of particles and methods of their study, (ii) determination of particle fluxes, (iii) particle transport and transformation processes and (iv) relationship between particles and trace elements.

Most importantly, the working group agreed that the study of particles and particle-associated processes is central to our understanding of the production and fate of biogenic materials in the sea and the biogeochemical cycling of elements in the ocean. In this field of research there are some areas which require further attention. These include construction of improved global maps of primary production, standing crop, and new production; mechanisms and rates of particle transformation in the ocean; and refinements of the sediment trap technique. Specific recommendations on these topics are contained in the text.

The discussions of the working group were, by and large, restricted to the open ocean environment. However, the working group recognized that any program on biogenic fluxes in the ocean would be incomplete without the study of coastal oceans and marginal seas. The ocean margins are the pathway for river-borne material, which is to a large extent trapped in those areas or modified before being transferred to the open ocean. These areas also account for a significant fraction of the primary production.

Another important topic not covered in this report is the role played by boundaries (air-sea, ocean margins and sediment-water) as sources/sinks of dissolved and particulate materials to the oceans. There is increasing evidence that these boundaries are important.



It is recommended that a new working group be constituted to look into the above-mentioned aspects of biogeochemical cycling of carbon and trace elements in the ocean.

During its second meeting the working group was asked by SCOR to act as an international link for the U.S. Global Ocean Flux Study (GOFS). The working group recommended that "GOFS-related programs should be supported in all countries." The group is pleased to note that SCOR has initiated an international program in this direction, the Joint Global Ocean Flux Study (JGOFS).

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## 1- INTRODUCTION

A working group (SCOR WG-71) on "Particulate Biogeochemical Processes" was formed during early 1983. This working group had the following terms of reference:

- (i) To delineate the principal particulate transport processes which control trace element and nutrient element distribution in the open ocean.
- (ii) To clarify the definition of terms and processes used to describe particulate material in the ocean and to suggest the most appropriate methodology for the study of the material defined above.
- (iii) To ascertain the possibility of determining particulate fluxes of elements and organic matter to different depths in the sea.
- (iv) To prepare a state-of-the-art report on the particulate processes.

The members of the working group were :

S. Krishnaswami (India, Chairman), M.P. Bacon (USA), P. Buat-Ménard (France), S.W. Fowler (Monaco), D. Karl (USA), G.A. Knauer (USA), A. Lisitszyn (USSR), I. McCave (U.K.), Y. Nozaki (Japan), and R. Wollast (Belgium). The corresponding members are: T.C. Hung (Republic of China) and A. Trzonsinska (Poland).

The working group held the following meetings: University of Brussels, Belgium, 28-31 August 1984; Department of Earth Sciences, University of Cambridge, England, 14-18 April 1986; CNRS Castle, Gif-sur-Yvette, France, July 4-8 1988.

Prior to the second meeting SCOR had requested WG-71 to be an international link for the Global Ocean Flux Study (GOFS) a major oceanographic program of the USA, to assess the biogeochemical cycles of elements in the ocean and

their relation to climate and ocean circulation. Dr. K. W. Bruland, at the time a member of the executive committee of GOFS, was invited to address WG-71. A summary of these discussions and suggestions for the role WG-71 can play as the international link were included in the interim report of WG-71 submitted to SCOR in 1986. These are not included in the final report. Two other points need mentioning. Although we have drawn on many sources of information, we have cited only selected reviews and other key works. At the end of the report a glossary is given which provides an explanation of terms used in the report.



## 2 - PARTICLES IN THE OCEAN AND METHODS OF THEIR STUDY

The concentration of particulate matter in the open ocean averages about fifty parts per billion by weight. These particles, made of both biotic and abiotic materials, are the major sources of food for all marine organisms, and below the euphotic zone all communities depend on the downward flux of these particles. During their descent from surface waters to the sediments, these particles regulate the chemical composition of seawater. For example, the distribution of nutrients in sea water is primarily controlled by the settling and dissolution of biogenic particles. Similarly, the exchange of trace elements and radionuclides between seawater and particles is an important factor in determining their dissolved concentrations and vertical fluxes in the ocean (Figure 1). Likewise these exchange processes possibly dictate the fate of contaminants introduced into the ocean. Thus particulate matter, in spite of its very low abundance, significantly influences the chemical and biological make-up of seawater. These considerations make the study of marine particulate matter and its composition, fluxes and related processes important topics in the field of oceanography.

### 2.1 Sources of Particles to the Ocean

The major sources of particles to the ocean are continents and *in situ* production. There are also extra-terrestrial, anthropogenic, hydrothermal and other minor sources of production.

#### 2.1.1. *Continental materials*

Continental materials are transported to the oceans via rivers, the atmosphere and glaciers. The flux of materials introduced into the oceans presently by rivers is estimated to be in the range of  $(13-18) \times 10^{15} \text{ g yr}^{-1}$ . The riverine supply of particulates to the ocean is geographically variable. Table 1 gives two recent estimates of the fluxes of particulate materials transported by rivers into the major oceans. Only about 10% of these particles is delivered to the open ocean.

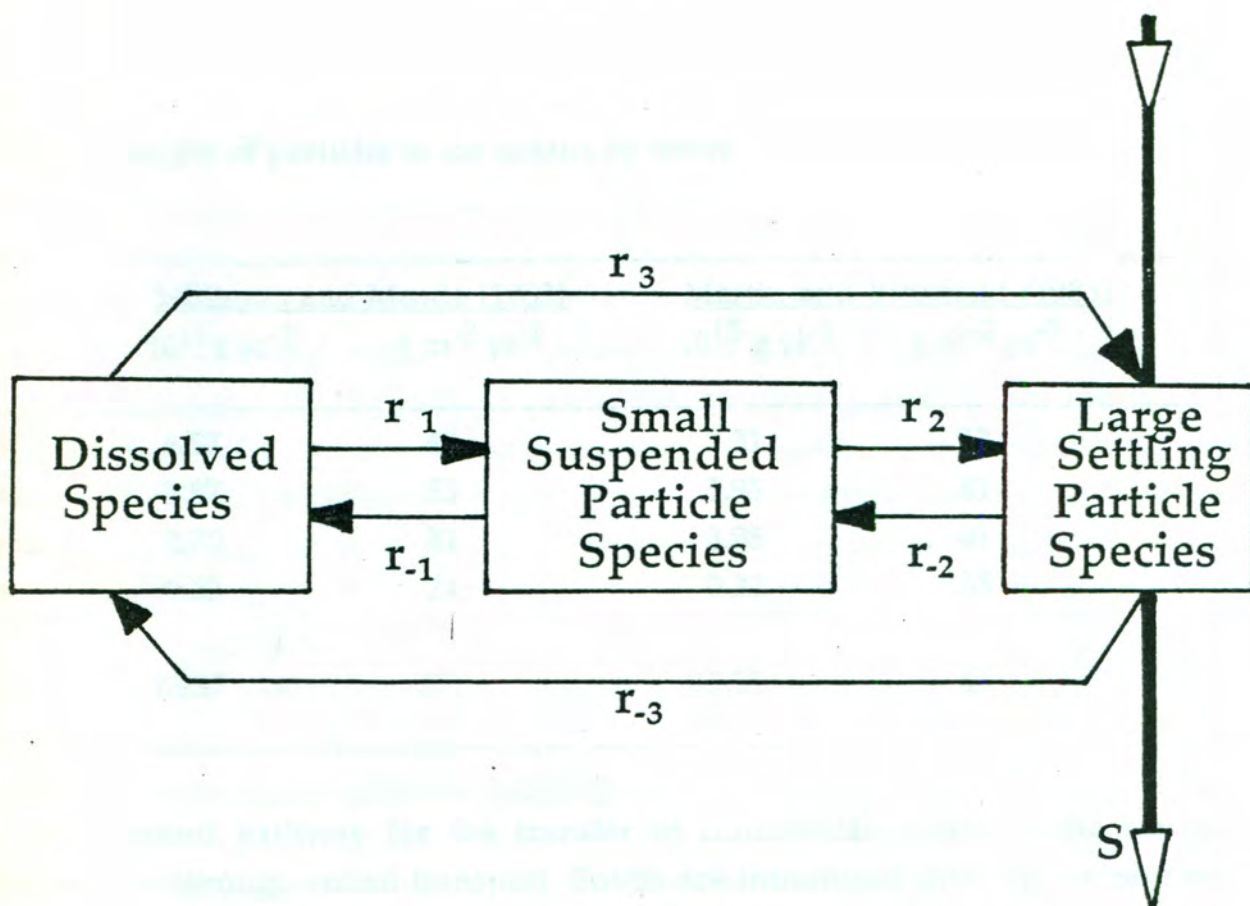


Figure 1. Diagram representing exchanges of dissolved chemical species and different size classes of particulate matter in the oceanic water column.  $S$  represents the sinking velocity of the particles. Transfer processes are represented by  $r$  values as explained in the text (see section 5).



TABLE 1. Supply of particles to the oceans by rivers

	<u>Milliman and Meade (1983)</u>		<u>Martin and Whitfield (1983)</u>	
	$10^{15} \text{ g yr}^{-1}$	$\text{g m}^{-2} \text{ yr}^{-1}$	$10^{15} \text{ g yr}^{-1}$	$\text{g m}^{-2} \text{ yr}^{-1}$
Pacific	6.57	40	5.31	32
Indian	3.87	53	5.95	81
Atlantic	2.70	31	3.98	46
Arctic	0.23	24	0.32	35
Total	13.37	37	15.55	43

The second pathway for the transfer of continental debris to the marine environment is through eolian transport. Solids are introduced into the atmosphere either through wind erosion of land or through volcanic eruptions. Particles from the atmosphere are removed to the ocean surface by precipitation-scavenging and dry deposition. The total mass of continental solids mobilized annually through the atmosphere has been estimated to be in the range of  $(0.2 - 1.0) \times 10^{15} \text{ g yr}^{-1}$ . Analogous to that of rivers, the atmospheric supply also exhibits considerable spatial and short-term (weeks) temporal variations. Because most of the riverine supply of particles is deposited at the ocean margins, the contemporary fluxes of eolian and riverine particles to the open ocean are comparable in magnitude.

Glacial transport provides yet another pathway for the introduction of continental materials to the ocean. The quantity of materials transported by glaciers is uncertain. Amounts on the order of  $10^{15} \text{ g yr}^{-1}$  have been reported, but, little of this material reaches the open ocean.

Most of the materials transported by rivers, winds and glaciers are silicates. These systems also transport continental biogenic material to the ocean, but its flux is



not well known. It is estimated that the flux of continental biogenic materials is  $0.2 \times 10^{15} \text{ g C yr}^{-1}$ , only a minor fraction of the *in situ* biogenic production in the ocean (Meybeck, 1982).

### 2.1.2 . *In-situ production of particles:*

(a) Primary particle production (autotrophic production). Biological production in the upper layers of the ocean is the principle process which fixes dissolved inorganic carbon into particles in the water. These biogenic particles play a central role in global ocean fluxes. Since marine phytoplankton constitute the primary producers of biogenic particles in the water column, it is paramount that we obtain accurate measurements of the rate of formation of these primary particles. In this respect the upper 200 m of the oceans represent a particularly important area for study.

Primary productivity is the rate of formation of organic matter by photosynthesis. The most commonly used method to measure primary productivity is the  $^{14}\text{C}$  technique. With this method, seawater samples are spiked with  $^{14}\text{C}$  bicarbonate, incubated for definite periods of time after which the  $^{14}\text{C}$  activity in the filtered particles is measured. The principle of the  $^{14}\text{C}$  technique is straight-forward, but the field application of the approach can be compromised by several problems. Examples include bottle size effects, *in situ* vs. on-deck incubations, length of incubation, depth range studied and contamination from metals. In recent years, the  $^{14}\text{C}$  technique has been criticized as having grossly underestimated primary production. Although several independent investigators have indeed identified a potential for underestimating this parameter, the observed magnitude of the associated errors appears to be relatively small and often unpredictable. Some studies indicate that primary productivity measurements based on the  $^{14}\text{C}$  technique may underestimate by up to an order of magnitude. These studies involve dissolved oxygen budgets in the euphotic zone, estimate of oxygen consumption rates in mesopelagic waters, and the subsequent translation of these data into primary production. However, this conversion assumes values of time periods of accumulation and/or a constant ratio of new production to primary production. Calculations of primary production based on these assumptions have recently been challenged and indicate that carefully controlled  $^{14}\text{C}$ -based primary productivity



measurements are reliable. Some estimates of primary production are given in Table 2.

TABLE 2. Annual primary production in oceans

	<u>Total Area (a)</u>		<u>Offshore Areas (b)</u>		
	Area $10^6 \text{ km}^2$	Production $10^{15} \text{ g C}$	Area $10^6 \text{ km}^2$	Productivity $\text{gCm}^{-2}\text{yr}^{-1}$	Production $10^{15} \text{ g C}$
Indian	73.9	6.60	71.0	84	5.96
Atlantic	92.6	9.76	83.9	102	8.56
Pacific	177	11.40	16	55	9.14
Antarctic	11.8	3.30	11.8	325	3.30 *

\* Includes production within inshore areas.

(a) after Platt and Subba Rao (1975)

(b) after Eppley and Peterson (1979).

Due to the high degree of spatial and temporal variability in the distribution of phytoplankton in the sea, global-scale estimates of the magnitude and variability of annual primary production using the above mentioned methods are difficult to obtain. In recent years, however, satellite remote sensing of ocean color has been shown to be a promising tool to address this problem. In particular, data obtained with the NIMBUS-7 Coastal Zone Color Scanner (CZCS) have permitted identification of space and time variability scales for phytoplankton pigments (chlorophyll) and improved large scale description of pigment and primary productivity on regional to global scales. The use of this technique to obtain



quantitative information on plant biomass and primary productivity would require development of reliable algorithms to relate color imagery to chlorophyll and productivity. Further, the effects of interferences from atmospheric trace substances such as aerosols and ozone and incomplete sensing of the vertical distribution of pigment biomass need to be evaluated.

(b) Secondary production (heterotrophic production). This refers to the growth of heterotrophic organisms including: bacteria, micro- and macrozooplankton and nekton. These processes are important for the formation of a broad spectrum of organic particles with dimensions ranging from  $10^{-1}$  to  $10^6 \mu\text{m}$ . In addition, non-living particulate materials can also be produced (e.g., molts, carcasses, feces, skeletons) through normal metabolic processes and trophic interactions. The total rate of formation of organic carbon by the combined processes of secondary production is ultimately limited by the rate of primary production and generally does not exceed a value of 20-25% of the rate of photosynthesis in the open ocean. However, under certain conditions (e.g., immediately following a phytoplankton bloom) or in certain oceanic habitats (e.g., mesopelagic and bathypelagic zones) secondary production processes may be the most important for the formation of organic particles. Furthermore, secondary production by bacteria occurs at the expense of dissolved substrates and thus represents an important pathway for the introduction of soluble organic matter into particulate pools.

(c) Other biogenic particles:

#### *Fecal Material*

All consumer species produce fecal material of some sort. These are solid waste materials excreted from living organisms. Fecal material can occur as relatively loose, amorphous aggregates (fecal matter) which readily disintegrate, or as dense, tightly packed pellets (fecal pellets) encased in membranes which maintain their integrity. They are produced in a variety of shapes and their size range spans several orders of magnitude. The material is somewhat adhesive which increases its probability to agglutinate with smaller particles. Sinking rates of pellets vary according to shape, size and density but are normally in the range of a few tens to



several hundreds of meters per day. Sinking fecal pellets can be extremely important as transporters of energy (food) as well as numerous kinds of elements and compounds. The composition of fecal pellets is highly diverse and generally reflects the feeding habits of the producer organism. Fecal pellets contain a variety of materials including phytoplankton, protozoa, bacteria and inorganic substances.

#### *Marine snow/amorphous aggregates*

The amorphous, flocculent detrital material loosely termed "marine snow" is ubiquitous in the sea, and is most certainly derived from many sources (Alldredge and Silver, 1988). It probably represents the major component of material caught in sediment traps and may be an important site for production/decomposition processes in the water column. It is difficult to consider marine snow as a specific type of particle such as fecal pellets, molts, etc., because of the varied processes, both organic and inorganic, which produce this material. These aggregates are better thought of as both active and passive scavengers as well as sites for housing active communities of organisms. Marine snow has also been shown to represent a significant reservoir for numerous elements and compounds, such as trace elements, nutrients and organic compounds. It is also a site for active primary production in surface waters.

#### *Plankton hard parts and carcasses*

Evidence from sediment trap studies indicates that a substantial portion of the large particle flux is composed of intact organisms and the hard parts of plankton, such as radiolarians, coccoliths, foraminifera, diatoms, crustacean molts, and pteropod shells. The skeletons of many of these marine organisms (primarily silica and calcium carbonate) can constitute a significant proportion by weight of the particles collected in the surface waters of the open ocean. Much of this biodebris will eventually undergo dissolution although at differing rates. For example, molts produced in the surface layers probably have little chance of reaching great depths despite rapid sinking speeds because of their high degradation rates. The rate of dissolution of calcium carbonate tests of foraminifera and coccoliths is a function of the degree of carbonate undersaturation in the surrounding waters. Similarly, sinking diatom frustules also undergo dissolution in the water column. Carcasses of



large organisms are another source of particles; however, most are probably eaten before reaching great depths.

(d) Production of non-biogenic particles:

The second category of particles produced within the oceans are the inorganic precipitates/colloids. Hydrogenous minerals such as Fe and Mn oxides and hydrous oxides on the deep ocean floor provide evidence for the formation of such inorganic precipitates. Black smokers associated with hydrothermal vent systems which eject dense particle plumes of Fe, Mn, Cu, Zn sulphide/hydrous oxides, provide another source of inorganic particles to the deep sea. Though these particles have been recognized as a potential source of metals to pelagic deposits, their quantitative significance and their spatial and temporal variations are yet to be understood. Other examples of inorganic particulate production are the formation of barite, celestites, pyrites, etc., in association with the remains of decaying plankton.

(e) Benthic fluffs or flocs

Unconsolidated marine fluff or floc layers have been observed at the sediment-water interface. The layer is very fluid, apparently structureless and reddish-brown in color. Comparisons of this material with sediment trap samples collected a few meters above the bottom indicates that the fluff material is of different composition. Little is known about the composition of the particles in this zone.

2.1.3. *Anthropogenic and Cosmogenic sources of particles:*

Anthropogenic particles are transported to the oceans both by rivers and through the atmosphere. River supply is relatively more important in the coastal zone whereas atmospheric input constitutes the major source to the open sea. Flux estimates of several anthropogenic components to some areas of the ocean are available (Buat-Ménard, 1986). Accretion of extraterrestrial material has long been recognized based on the presence of Fe-Ni spherules in deep-sea deposits. Recent estimates of the rate of accretion of extraterrestrial matter on the surface of earth is of



the order of  $10^{10}$ - $10^{11}$  g yr<sup>-1</sup>.

## 2.2 Methods of Collecting Particles in the Ocean:

Commonly used techniques to study particles and associated processes can be broadly classified into two categories: (i) measuring devices which do not involve the separation of particles from water (e.g. transmissometry, flow cell cytometry, fluorometry) and (ii) methods which are based on the separation of particles from water and their subsequent analysis.

Quantitative studies on the distribution of particles and their composition require their collection from sea water. Many of these collection techniques run the risk of altering the physical, chemical and biological characteristics of the particles. Methods for separating particles from seawater depend upon the classes of particle being studied. Two classes can be operationally defined, the suspended particles which account for most of the standing stock of particles in the water column and settling particles which account for most of the mass flux of the material (see Fig. 1).

### 2.2.1. Filtration

Filtration is the commonly used technique for the collection of suspended particles from seawater. The volume of water filtered and the pore size of the filter depend on the parameter being measured. For the measurement of particle concentrations and trace metals or organic compounds in particulate matter, generally water volumes in the range of 10-100 l are filtered through 0.4-1.0  $\mu$ m filters. These filtrations are usually done by collection of water in non-metallic or other appropriate samplers followed by pressure or vacuum filtration on board ship.

For certain determinations, such as radionuclides and trace organic compounds, water volumes in the range of thousands of liters are filtered. Such a large volume filtration is done using large diameter filters or cartridges. The filtrations can be done *in situ* using either mechanical or battery powered systems, or by using ship's power via cables. Some of these systems have been successfully used to filter water from depths of 5500 m.



It should be emphasized that filtration collects the standing stock of suspended particles and the water filtered may not contain the entire spectrum of particles, particularly the relatively rare, large particles. The abundance of the large particles in waters typically is very low and unless large volumes of water are carefully filtered, contributions from the large particles cannot be quantitatively assessed (McCave, 1975)

### 2.2.2. Centrifugation

Centrifugation, especially by continuous flow, offers the advantage that it can be used to extract suspended particles from large volumes of water. Quantitative separation of particles with density close to that of water requires very high forces which are difficult to attain on board ship.

### 2.2.3. Plankton nets

Plankton nets of various aperture sizes are commonly used to sample particles in the microplankton range (20-200  $\mu\text{m}$ ). Because of limitations in mesh size that can be used, nanoplankton (2-20  $\mu\text{m}$ ) and picoplankton (<2  $\mu\text{m}$ ) are not normally sampled in this way. While other biogenic particles like fecal pellets, marine snow and molts are routinely caught in towed plankton nets, this technique is rarely used for these collections. Nevertheless, plankton nets could be useful for discerning the spatial and temporal distribution of biogenic particles.

### 2.2.4. Hand collections

Several *in situ* studies have attempted to directly characterize large aggregates (i.e. 1 millimeter to meters) in the upper ~30 m of the water column. Such collections have typically involved SCUBA and have provided a considerable amount of data on marine snow and associated bacteria and protozoa. In addition to the use of SCUBA to collect particles in surface waters, one-person submersibles such as "Wasp" and "Deep Rover" and remotely operated vehicles are now available which allow manual collections of particles down to depths of about 1000 m.



#### 2.2.5. Particle interceptor traps (sediment traps)

Another method of particle collection is through the use of particle interceptor traps or sediment traps as they are commonly known. These traps predominantly collect settling particles from the water column, which are generally dominated by larger particle sizes. Traps are discussed in detail in Section 4.

### 2.3. RECOMMENDATIONS

It is recognized that the flux of materials through the water column is coupled to the production of biogenic particles in the upper layers of the ocean. Major global oceanographic programs such as JGOFS aim to study the cycles of carbon and other elements in the ocean, with a view to understand the relationship between them. Our recommendations given below on the topics discussed in earlier sections also focus on the carbon cycle in the ocean. A major step in this direction is to construct a global map of primary productivity and standing stock of phytoplankton biomass. Towards this end a multi-disciplinary approach is essential. We recommend the following studies:

- (1) Most of the available data on primary production is based on sparsely distributed samples. These data have to be augmented considerably by measuring geographical and temporal variations in the integrated production in the euphotic zone and the forcing factors ( biological, chemical and physical) which control this variability. In addition interannual variability in the production rates has to be determined at selected sites of different trophic status. Attempts should be made to develop small and large scale predictive models based on physical and biological processes and other environmental forcing factors to provide information on primary production.
- (2) Intercomparison experiments on primary production measurements should be conducted in various ocean areas of different trophic status and any discrepancies resolved. The rates determined by these methods should be compared with those using independent geochemical modelling approaches.



- (3) Satellite imagery can provide synoptic basin-wide estimates of standing crop (plant biomass) through measurement of chlorophyll. Reliable algorithms must be developed to relate satellite color imagery to chlorophyll, primary production and new production.
- (4) Large particles transfer organic matter from the surface to deeper layers. Studies on the mechanism and the rate of large particle production and their relation to primary productivity, and physical, chemical and biological forcing factors should be encouraged.
- (5) Direct observation of macroorganisms and particles (particularly larger ones) in the water column provides a better understanding of the link between the food web and vertical fluxes. This type of observation using submersibles and deep-sea cameras should be encouraged.

### 3- PARTICLE TRANSPORT AND TRANSFORMATION PROCESSES

A major goal in contemporary oceanographic research is to gain an understanding of those processes which control biogenic and abiogenic particle formation, dissolution, transport and diagenesis on basin-wide scales and time scales ranging from seasonal to decadal. In this respect, we know that both large and small (suspended) particles have far reaching effects on many ocean processes and play major roles in the cycling of numerous elements and compounds. Knowledge of the mechanisms and rates of the transformation of various particles from one size to another provide a better understanding of the factors affecting the vertical flux and element distribution.



### 3.1. New production and the flux of materials from the euphotic zone.

A fraction of the carbon fixed by photosynthesis in the surface layers is removed to deep waters, with the remainder being cycled in the euphotic zone. New production "as defined by Dugdale and Goering (1967)" is quantitatively equivalent to the organic matter that can be exported from the total production in the euphotic zone without the production system running down. However, field studies relating new production to primary production and downward particle flux in the open ocean are limited. The accurate estimation of new production is of considerable importance to budget calculations and to the understanding of many of the major ocean biogeochemical cycles (e.g. the  $\text{CO}_2$  cycle). The two principal methods used to estimate new production are:

- (1) *in situ* assimilation rates of oxidized (e.g.  $\text{NO}_3^-$ ) and reduced (e.g.  $\text{NH}_4^+$ ) nitrogen sources using  $^{15}\text{N}$  as a tracer and
- (2) the collection of particulate material exiting the euphotic zone using sediment traps.

There appear to be a number of unresolved problems associated with the first technique: (1) The method requires that large quantities of  $^{15}\text{N}$ -enriched nitrogen compounds be added; (2) such additions may alter the kinetics of nitrogen assimilation and therefore compromise the results; (3) non-autotrophic bacterial assimilation of the various species of added nitrogen may compromise new production estimates; (4) also atmospheric inputs of nitrogen, the assimilation of  $\text{N}_2$  have to be better evaluated; (5) finally bacterial nitrification may affect the cycling of dissolved nitrogen species independent of primary production processes.

The sediment trap method for estimating new production also has general limitations. First, this approach assumes that the export of nitrogen from the euphotic zone occurs exclusively in the form of passively sinking particulate matter. Second, the collection of particles immediately beneath the euphotic zone is influenced by the presence of swimmers which leads to an inaccurate estimate of particulate organic matter flux and hence, new production. Finally, selection of an acceptable reference depth is critical to the calculation of new production because there is a steep gradient in the downward flux of nitrogen in the upper 200 m. In this regard it is also not clear how deep a particle must sink before it can be considered



"exported" from the surface waters. Generally a depth varying from 100-200 m is selected as an appropriate reference level for new production calculations. These potential problems are in addition to the general limitations associated with the use of traps.

The ratio of new to total production ranges over an order of magnitude from 0.05 to 0.5 with the higher values found in coastal upwelling areas. Clearly, many more estimates will be necessary before we can fully understand the relation between these two important parameters. Some estimates of annual new production in individual oceans are given below in Table 3.

TABLE 3. Estimates of annual new production in the oceans (a)

	New production $10^{15} \text{ g C yr}^{-1}$	% total production
Indian	1.25	21
Atlantic	2.18	26
Pacific	1.26	14
Antarctic	1.49	45

(a) from Eppley and Peterson (1979).

### 3.2. Transformations of Particles Beneath the Euphotic Zone:

#### 3.2.1. Particle size, properties and behaviour

Large aggregates are responsible for the vertical flux in the oceans, but most of the standing stock of marine particles consists of fine suspended particulate material (McCave, 1975). Therefore it is important to know the shape of the particle size spectrum and the amounts of different materials in it. It is also important to understand the processes by which materials are moved from one part of the size spectrum to another. Areas which need attention are measurement of particle size spectra, determination of particle properties as a function of size, assessment of



settling velocities and aggregation mechanisms.

The size distribution of component parts of the particle spectrum greater than about 1  $\mu\text{m}$  is reasonably well-known. There is little prospect of a broad spectrum measurement from a single method in the near future. However, new measurements by image analysis of photographs are extending the upper end of the measured size range. Electronic and optical particle counters have been used for particles in the range from 1 to 500  $\mu\text{m}$  and electron beam instruments can extend the range down to the sub-micrometer size. If these sub-micrometer particles are primarily responsible for scavenging of trace elements from the water column, then knowledge of their size and properties is desirable.

Particle density distributions have been sought for calculation of settling velocity but they are poorly known for most types of particles. For fecal pellets the data are sufficient to permit satisfactory calculations. The settling velocity distribution is known for fecal pellets and some larger aggregates greater than 50  $\mu\text{m}$ . *In situ* experiments are now beginning to yield data on settling velocity of large aggregates.

Chemical properties of particles as a function of size can be obtained by SEM/EDAX methods. These methods are time-consuming, but advances in image analysis may yield more data more efficiently. Surface properties of particles are of primary importance since they may play an important role in the cohesive forces in aggregates and the processes of flocculation and deflocculation. Furthermore they control the exchange properties of the solid. Considerable effort is needed to develop appropriate methods to characterize physical and chemical surface properties of marine particles.

### 3.2.2. *Aggregation mechanisms*

Viewing the physical processes of aggregation as being the same as those affecting atmospheric aerosols allows estimation of coagulation rates. In the atmosphere there is a source of very fine particles from gas-to-particle conversion, but it is not clear whether there is an analogous source in the ocean. Perhaps flocculation of DOM provides a source of very small particles which would then be involved in aggregation via Brownian motion with coagulation times of a few days. However, larger particles that should be aggregated by shear are too few, and are in



an environment with such low shear (at mid-water depths) that the process of shear-controlled coagulation is too slow to effect significant change in the size/settling velocity distribution. Calculation of the collection efficiency of these Brownian aggregates by large sinking particles yields very low values. Natural series radionuclide data indicate that small particles must be removed from midwaters on time scales of a few years. If the particles do not aggregate progressively up the spectrum, they must be incorporated into larger particles directly. This is either by biological means (meso- and benthopelagic feeders whose activity may be stimulated by periodic rain of large particles) or by physical means directly onto large particles. In the latter case they must behave in ways that are not well understood.

The overall decrease in particulate organic matter flux which has been observed as a function of increasing water depth (Figure 2) implies that there is a net loss of mass as a result of the combined effects of fragmentation, solubilization, ingestion and remineralization as particles sink. Because all of these processes are potentially reversible (Table 4), it is important to emphasise that sediment trap collections can only monitor the net result of many complex and competing physical, chemical and biological processes. In order to understand the flux of materials through the ocean and to construct global predictive models, it is essential to identify the processes and mechanisms responsible for these depth-dependent changes in mass flux and to measure directly the various reaction rates.

This scenario suggests that the concept of phytoplankton ----> zooplankton/grazing ---> feces ---> trapped material is oversimplified. Several different interactions involving dissolved organic matter (DOM), suspended POM and sinking POM are continuously occurring in the water column, and all these reactions need to be fully understood to describe carbon fluxes.

The decrease in the flux of organic matter with depth has been assumed to represent active microbial decomposition of sinking particles. At the present time, we have few quantitative data on the *in situ* rates of decomposition and solubilization or the mechanisms involved. The production of CO<sub>2</sub> from sinking particulate organic matter (i.e. remineralization) can proceed by at least three independent pathways (Figure 3). Knowledge of both the site and mechanism of remineralization is required for a complete understanding of the oceanic carbon cycle.



TABLE 4. Processes affecting the downward mass flux of particulate organic matter (POM)

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REACTION 1:	Sinking POM	<----->	suspended POM
	----->		fragmentation
	<-----		aggregation
REACTION 2:	Sinking POM	<----->	DOM
	----->		solubilization/hydrolysis
	<-----		polymerization/flocculation
	<-----		chemoheterotrophic bacterial production
REACTION 3:	Sinking POM	<----->	metazoan biomass
	----->		ingestion/assimilation
	<-----		egestion/molting/death
REACTION 4:	Sinking POM	<----->	CO <sub>2</sub> + inorganic nutrients
	----->		microbial mineralization
	<-----		chemoautotrophic bacterial production

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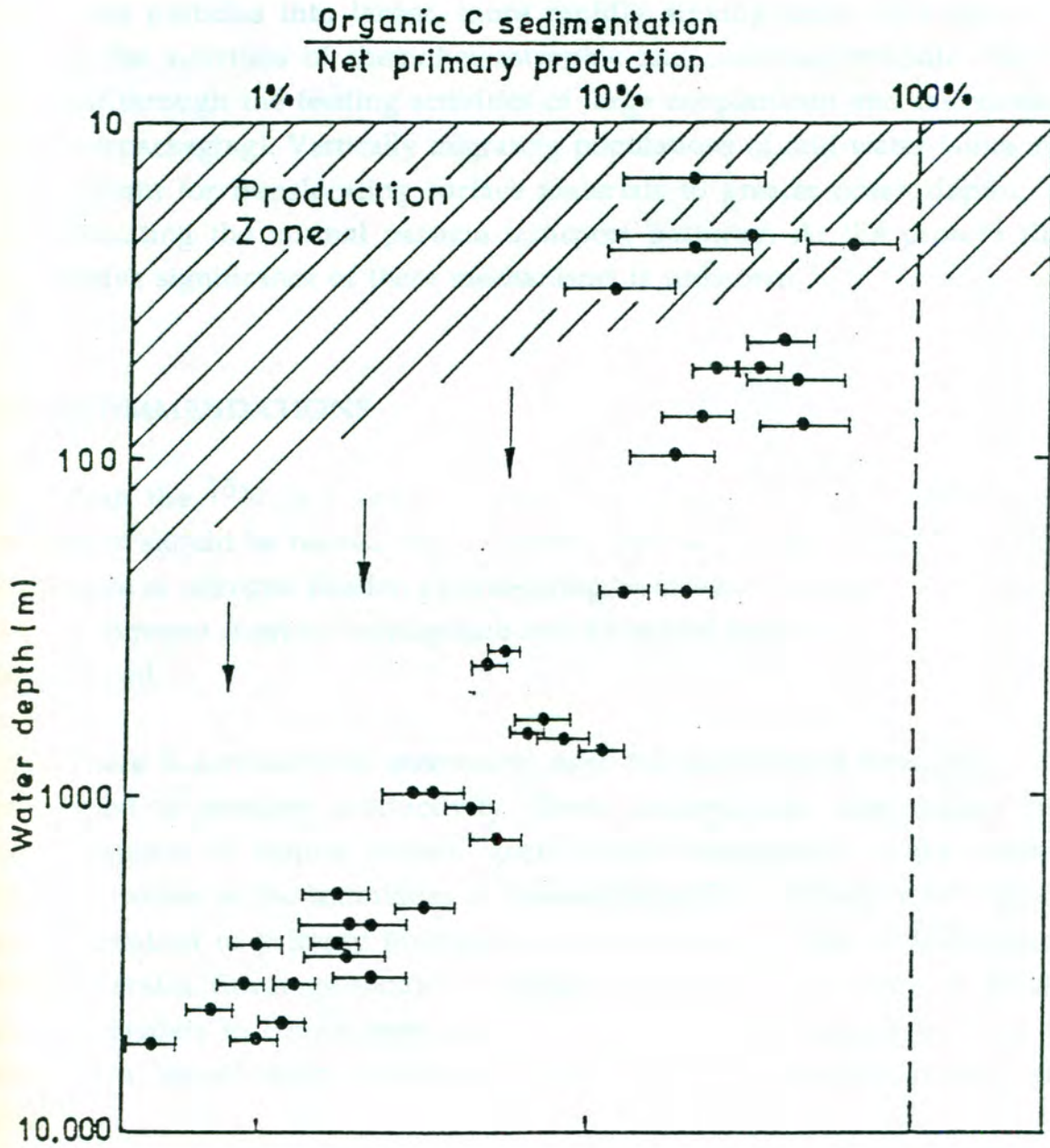


Figure 2. Percentage of the mean primary production at the ocean surface collected at different water depths (redrawn from Suess, 1980).



In addition to particle decomposition and consumption, biological processes beneath the euphotic zone may be responsible for the production of new particles from either dissolved organic and inorganic nutrient pools, or via the aggregation of suspended particles into larger, more rapidly sinking units. The former occurs through the activities of chemoheterotrophic and chemoautotrophic bacteria and the latter through the feeding activities of large zooplankton and micronekton (i.e. particle repackaging). Vertically migrating populations of mid-water fauna may also be important for translocating surface materials to greater ocean depths, thereby short-circuiting the normal particle transport pathway. At the present time, the quantitative significance of these mechanisms is unknown.

### 3.3. RECOMMENDATIONS

- (1) Both the  $^{15}\text{N}$  and sediment trap methods for the measurement of new production should be refined and alternative techniques developed. In addition, the importance of nitrogen fixation by free-living/symbiotic organisms as well as inputs of fixed nitrogen from the atmosphere and advective processes in the water should be evaluated.
- (2) There is considerable uncertainty over the estimates of new production and its relation to primary productivity. These uncertainties stem mainly from the undersampling of various oceanic areas, from inadequacies in the methods and from differences in the techniques of measurement. The controls of new production and its relation to primary production should be quantified on both spatial and temporal scales. Coverage should be expanded globally. One approach would be to develop models to couple new production to other parameters such as primary production, mixed layer dynamics, nutrient input and satellite sensing of ocean color.
- (3) Previous attempts to understand transformations of sinking particulate matter have frequently been limited by the fact that individual parts of the system (dissolved, fine-particle and large-particle pools) have been examined in isolation.

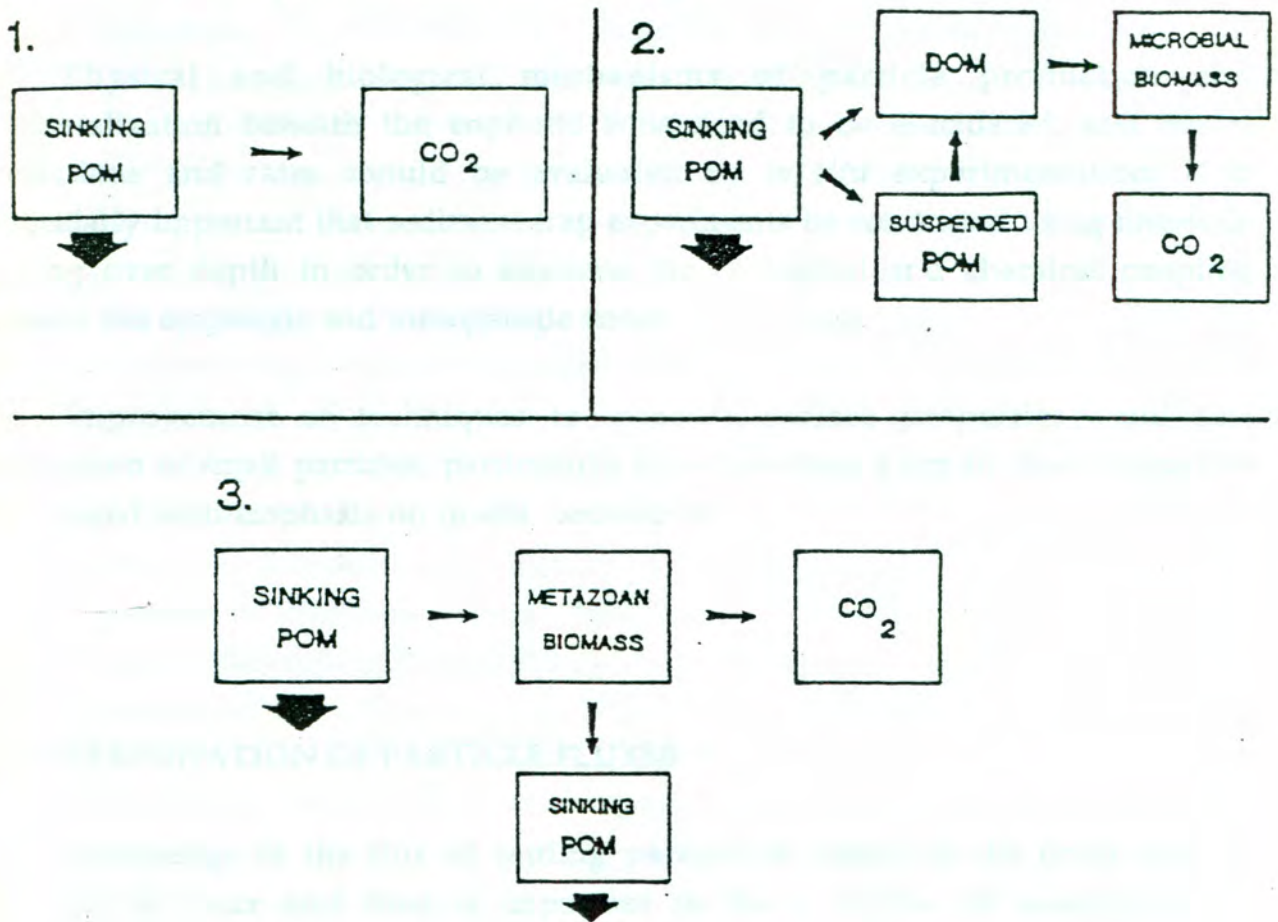


Figure 3 Decomposition models for sinking POM. Model 1 assumes that particle-associated microorganisms are responsible for the remineralization of sinking POM. Model 2 assumes that sinking POM fragments and solubilizes and is later remineralized by water column microorganisms. Model 3 assumes that metazoan feeding directly consumes and mineralizes sinking POM.



Studies that take a comprehensive approach by simultaneously examining all components of the systems should be encouraged.

(4) Physical and biological mechanisms of particle production and remineralization beneath the euphotic zone need to be elucidated, and model predictions and rates should be evaluated by *in situ* experimentation. It is particularly important that sediment trap experiments be conducted using fine-scale spacing over depth in order to evaluate the biological and chemical coupling between the epipelagic and mesopelagic zones of the ocean.

(5) Improvement of techniques to measure surface properties and size distribution of small particles, particularly those less than 1  $\mu\text{m}$  in size should be encouraged with emphasis on *in situ* techniques.

#### 4 - DETERMINATION OF PARTICLE FLUXES

Knowledge of the flux of settling particulate matter in the ocean and its variation in space and time is important in many studies of biogeochemical processes. Particle fluxes can be determined in two ways: (i) by direct measurement, in which material settling through a given cross-sectional area over a definite period of time is collected in a sediment trap, and (ii) from a simultaneous measurement of the particle concentrations and settling velocities in the water column, the product of these two parameters yielding the settling flux. Most of the available data on fluxes rely on the first approach and are based on sediment traps. In the following we discuss these two different methodologies.



#### 4.1. Use of Sediment Traps

The principal tool that is used for flux measurements is the sediment trap. Several shapes and sizes of sediment traps have been employed in oceanographic research, but those most commonly used are the cylindrical and conical traps. The common modes of deployment are : (1) attachment to a taut-wire mooring that is anchored to the bottom and (2) suspension from a buoy that is free-floating at the surface. Moored traps provide flux for a given site, the free floating ones yield flux over their drifting paths. Traps are usually deployed for time intervals ranging from a few days to several months. The advent of time-series collectors has been an important development because it permits high resolution sequential sampling of fluxes (Honjo and Doherty, 1988).

The flux of materials at the trap depth is calculated from the mass of the material collected in the trap, the surface area of the trap and the period of deployment. The trapped material is analyzed for its various components, e.g. organic matter, calcium carbonate, opal, trace elements or clays, to obtain information on the settling fluxes of these components.

Though sediment traps are the best available tool today to determine settling fluxes, there are some lingering doubts about the collection efficiency of the traps. Collection bias can arise in a number of ways and can lead to errors not only in the quantitative determination of flux but also, because of possible fractionation, in the determination of the composition of the settling material. Proper use of sediment traps and correct interpretation of results require that potential collection biases be recognized and understood.

Collection bias can be discussed in terms of the trapping efficiency,  $E$ , which is given by

$$E = \text{Accumulation Rate in Trap} / \sum_i C_i W_i \quad (1)$$

where  $C_i$  is the concentration of particles in the  $i$ th size fraction and  $W_i$  is their mean fall velocity. In principle biased collection ( $E \neq 1$ ) can only occur when there is flow of the fluid relative to the trap. Thus, the efficiency of any collector approaches unity (or 100%) as flow approaches zero. In the ocean, flow never goes to zero, so the problem of assessing flux measurement error is one of determining how far



conditions can depart from the ideal before collection bias becomes significant.

Observations of flow through traps have been made with dyes in laboratory flume experiments (Butman, 1986). They show that, when traps are placed in a flow, a circulation system is set up that can carry particles into and out of the trap. A trap potentially receives particles by two different mechanisms: (1) particles fall directly into the trap mouth and (2) particles are carried into the trap by the circulation. Particles leave the trap only by being carried out in the circulation. A requirement for unbiased collection ( $E=1$ ) is that input of particles by circulation equals output, so that the accumulation of particles on the trap bottom would equal the flux falling into the trap mouth. Unless the flow is zero, this in turn requires that particle concentration inside the trap equals that outside, and, for unbiased collection without fractionation, this condition must hold over the entire particle size range. Resuspension from the trap bottom of previously deposited sediment can lead to an elevated concentration of particles inside the trap and cause undertrapping by losses in the circulation.

Laboratory flume studies (Butman, 1986) have indicated trends of decreasing trapping efficiency with increasing trap Reynolds number  $Re_t = U_f D / \nu$ , (where  $U_f$  is flow velocity,  $D$  is trap diameter and  $\nu$  is kinematic viscosity of fluid) and with decreasing trap aspect ratio  $H/D$  (ratio of trap height to diameter). Less controlled field observations have shown similar trends (Baker et al., 1985). These trends are in the direction expected for a mechanism of undertrapping due to resuspension. Optimal conditions for efficient trapping, therefore, are low current speed, small trap diameter and large aspect ratio. The guidelines cannot presently be quantified with confidence because appropriate experimental data are not available for the entire range of conditions applicable to trap deployments in the field. It should be noted that when traps are baffled, the aspect ratio of the baffle may also be an important factor. Because it is flow relative to the trap that is important in causing collection bias, traps are often deployed in the floating mode. This can help to minimize relative motion but does not, in general, eliminate it entirely. Mechanisms by which cylindrical or funnel-shaped traps might overcollect have not been carefully studied. It is not clear whether overcollection by such traps is likely to occur under conditions usually encountered in the field, though it has been shown that tilt can lead to overcollection and should thus be minimized. Small-mouthed, wide-bodied



traps have been shown to overcollect by large amounts; such traps are not recommended for flux studies.

Intercomparisons of moored sediment traps have been made in the field at quiescent sites ( $U_f < 10\text{cm/s}$ ). These studies (Spencer, 1981) have shown reasonable agreement among fluxes measured by cylindrical and funnel-shaped traps having a wide range of diameters ( $D=7\text{-}150\text{cm}$ ). However, some recent upper water column studies (Laws et al., in press) have shown definite inconsistencies between conical and cylindrical traps. Therefore, a series of well-designed intercalibration experiments at different depths are needed to help resolve these problems.

Several field assessments of sediment trap efficiency have been made by use of natural radionuclides (Knauer et al., 1979; Bacon et al., 1985). The radionuclides are potentially useful for this purpose because of the accurate geochemical budgets that can sometimes be constructed for them. Unfortunately the simple geochemical balance that this approach is based on cannot usually be assumed in areas of energetic flow, so it is not likely that the approach can be used to assess the extent of bias that might occur under these conditions. The most suitable radionuclides for measuring trapping efficiency are the thorium isotopes  $^{234}\text{Th}$ ,  $^{228}\text{Th}$  and  $^{230}\text{Th}$ . The only source of all these isotopes is production in the water column by radioactive decay of their parents. The trapping efficiency is calculated as :

$$E = \frac{\text{Measured flux of isotope to the trap}}{\text{Flux expected from deficiency in the overlying water column}} \quad (2)$$

$^{234}\text{Th}$  (half-life 24 d), and  $^{228}\text{Th}$  (half-life 1.9 y) are suitable for determining efficiencies of traps in the upper ocean, and  $^{230}\text{Th}$  (half-life 75,200 y) can be used to determine trapping efficiency in the deep ocean. The efficiency determined from Th isotopes can be subject to uncertainty due to lateral transport or sediment resuspension, but some constraints on the magnitude of contributions from lateral transport or resuspension can be obtained through the use of other radionuclides such as  $^{231}\text{Pa}$  and  $^{210}\text{Pb}$ .

The water column distribution of the Th isotopes, by and large, represents steady-state conditions attained over a period of the order of a month in the upper waters and over a period of tens of years in the ocean interior. Therefore the flux



estimated from the water column disequilibrium represents an average value over these time periods. To obtain meaningful estimates of trapping efficiency from Th isotopes, it is necessary to deploy traps in the upper waters for about a month or so and in the ocean interior at least for one year to average over seasonal productivity cycles. In addition to the Th isotopes, other radionuclides, such as  $^{210}\text{Pb}$ , have been used to estimate sediment trapping efficiency. These are generally less suitable because their supply rates are less certain or because their fluxes can be significantly influenced by lateral transport.

In addition to the physical factors that govern trapping efficiency are the equally important biological and chemical factors that control preservation of the sample within the trap during the period of deployment. It has been shown that the flux estimate and the measurement of the composition of the settling material can be altered significantly by various processes such as decomposition and dissolution occurring in the trap (Gardner et al., 1983; Knauer et al., 1984). The chemical and biological environment in the trap can bring about such transformations. Supernatant solutions can be analyzed to assess the extent of alteration. With some types of traps, solutes released from trapped particles are retained in a high-density salt solution. The effect of poisons and preservatives of various kinds in controlling decay of the organic matter and mobilization of other labile components in traps is not well understood. There is no general agreement as to which preservative is best or even whether any should be used.

An additional problem related to the reliability of sample collection is that of "swimmers," which almost inevitably are attracted to moored and free-floating sediment traps. This problem is usually most severe in the upper water column where standing stocks of metazoans are higher. Feeding and defecation by swimmers can lead to net transport of material either into or out of traps. The presence of swimmers in trapped particulates perturbs flux measurements. A great need exists for a practical solution to this problem. One approach is to use screens to exclude swimmers but this can also exclude large particles that are part of the sinking particulate pool.

In the application of sediment traps to studies of biogeochemical processes, it is not just the ability to measure particle flux that is important. One also wants to measure change in flux down a water column by deploying a depth-series of traps



and, from the differences in flux between adjacent traps, to infer rates of chemical reactions and biological processes occurring in the intervening water masses. There is accumulating evidence that for some materials there exist sources or sinks at the ocean margins that are strong enough for their influence to be felt even at distant points in the ocean interior (U.S. GOFS, 1987). These effects must be considered in the interpretation of sediment trap data.

#### 4.2. Use of Filtration Techniques

There have been some attempts to determine fluxes of materials through the water column by filtration techniques (Bishop et al., 1977). Here flux is determined from the measured size distribution of the filtered particles and their settling velocities as calculated from Stokes' Law. The mass flux  $\Phi_i$  is:

$$\Phi_i = C_i W_i \quad (3)$$

where  $\Phi_i$  is the mass flux in the  $i$ th size fraction and the other terms are as defined in Eq.1. The inherent problems associated with this method are : (1) the size distribution of particles measured on the filter can be quite different from *in-situ* distributions because of fragmentation/agglomeration during filtration; (2) the validity of the application of Stokes' Law to obtain settling velocities is uncertain; (3) there is a lack of precise data for densities of natural particles, a parameter required for calculating velocities and (4) the sampling of rare, large particles by filtration techniques can be incomplete, resulting in underestimation of particle fluxes. Because of these problems, the flux estimates derived in this fashion should be approached with caution. Nevertheless, filtration techniques are extremely useful for the collection of fresh marine particulates, because the problems of sample preservation and interference by swimmers are largely avoided.



### 4.3. RECOMMENDATIONS

The sediment trap is the only tool that exists for the direct measurement of settling flux in the ocean. Its continued use is recommended. However, studies should be undertaken to refine its use. As with any measurement tool used in scientific research, there should be continuing assessment of the measurement errors associated with sediment traps and continuing efforts to minimize the errors.

(1) Past theoretical and experimental studies have shown that good accuracy in flux measurements can be achieved under favorable conditions but that large errors can occur under unfavorable conditions. It is not possible, given the present limitations in the understanding of the physics of particle trapping, to quantify the favorable range of conditions for accurate measurements of settling flux by traps. This should be a major aim of further research and both theoretical and experimental approaches should be continued.

(2) At present there is only a qualitative understanding of some of the important factors that control trapping efficiency. These parameters should be quantified. It is desirable to obtain simultaneous records from other instruments such as inclinometers, transmissometers and current meters during the period of trap deployment. Such records can be invaluable in the assessment of measurement error and in the interpretation of results.

(3) Well-controlled field intercalibration experiments should be encouraged to assess the intercomparability of flux measurements using different sediment trap configurations.

(4) The presence of swimmers in sediment trap samples can seriously bias results; it is essential that this problem be recognized and that studies be undertaken to resolve it.

(5) More study is needed to evaluate the use of preservatives that are compatible with the required analytical techniques for the samples.



(6) Methods to estimate vertical fluxes other than those based on traps should be encouraged. In this regard, direct observation (e.g. optical methods) of particles and the *in situ* measurements of settling velocities hold promise. *In situ* observations would also help to determine the extent to which swimmers are attracted to the trapping system. Other approaches should be to develop geochemical and biological models which can be used to provide constraints on the flux estimates.

## 5. PARTICLES AND TRACE ELEMENTS

Trace elements are introduced to the ocean from a variety of pathways such as eolian, fluvial, hydrothermal and groundwater. Their distributions in the water column are influenced by their interactions with particles. In general, marine particles contain high concentrations of many trace elements and radionuclides (Table 5). The production, sinking and decomposition of abiotic and biotic particles are now known to be important for controlling the distribution of trace elements within the ocean (Bruland, 1983; Buat-Ménard, 1986; Fowler and Knauer, 1986).

There are several ways to classify trace element distributions in the water column. One approach is to divide them into groups based upon residence time ( $\tau$ ) which is an index of reactivity of the element in ocean water (Whitfield and Turner, 1987). It is also a measure of their tendency to associate themselves with particulate matter in the water column. The first group includes elements which interact weakly with the particulate phase ( $\tau > 10^5$  yr) and are conservative in seawater. The second group of elements consists of those which tend to be incorporated into the biogenic particle cycle and display intermediate residence times ( $\tau \sim 10^3 - 10^5$  yr). Their concentration profiles exhibit surface depletions and deep enrichments. The third group of elements displays shorter residence times ( $\tau < 10^3$  yr) and have the strongest interactions with the particulate phase. These are the scavenged elements which usually show maximum concentrations close to their source (e.g. sea surface, sea floor, ocean margins).



The interaction between the dissolved and particulate phases is represented schematically in Figure 1. The transfer of dissolved trace elements to settling particles is considered to be a two-step process. Uptake ( $r_1$ ) occurs by active biological processes or passive adsorption, or both, and transfers elements to the fine suspended particle pool. Precipitation is another process by which material can be transferred from dissolved to particulate form. Aggregation ( $r_2$ ) then transfers the elements to the pool of large particles which sink rapidly. Both steps are considered to be reversible, and a continuous exchange of material can be envisioned. Release ( $r_{-1}$ ) of particle-borne elements can occur by desorption from the suspended particles or by remineralization of the suspended particles. Material can be returned from the large-to-small particle pool by disaggregation ( $r_{-2}$ ). Another interactive pathway is the direct uptake of dissolved elements on large particles ( $r_3$ ) and the release of elements from the large particles ( $r_{-3}$ ). The exact mechanism of removal of trace elements from the dissolved phase is not well understood, but in models it is usually represented as a first order adsorption process. Several properties of the particles such as size distribution, surface ligands and organic coatings may play an important role in the trace metal removal. In addition to adsorptive mechanisms, certain trace elements are removed from solution by active uptake into living organisms.

## 5.1 Upper Ocean

In surface waters biogenic particles which dominate the detrital particulate phases, can remove dissolved organic and inorganic species by both metabolic uptake and passive adsorption mechanisms. Depending on the relative amount of recycling within the upper ocean a variable fraction of the material removed will be carried to greater depths primarily associated with rapidly sinking particles (Fowler and Knauer, 1986). Scavenging rates of dissolved and particulate phases have been estimated primarily from experimental data on the distribution of natural radionuclides such as  $^{234}\text{Th}$ ,  $^{228}\text{Th}$ ,  $^{210}\text{Po}$ ,  $^{210}\text{Pb}$  (Cochran, 1982; Coale and Bruland, 1985). The estimated residence times are in the range of a few days to several months for particle reactive elements in surface waters. Larger residence times appear to be associated with regions of low particle flux. There is also evidence



Table 5. Concentrations\* of trace elements ( $\mu\text{g g}^{-1}$  dry weight) and radionuclides (pCi  $\text{kg}^{-1}$  dry weight) in suspended particles, zooplankton fecal pellets and molts, and marine snow.

Element or radionuclide	Surface suspended particles	Fecal pellets				Molts	Marine snow collected <i>in situ</i>
		fresh	Sediment Trap <sup>+</sup>	Sediment Trap <sup>"</sup>	Sediment Trap <sup>**</sup>	Fresh	
Al	3000	28,490	20,800	74,900	22,600	—	36,420
Sc	0.5	2.8	4	15	—	0.03	—
V	22	—	76	114	59	—	—
Cr	125	38	—	—	—	5.3	—
Mn	140	243	2110	768	790	12	148
Fe	8800	24,000	21,600	43,600	—	232	12,800
Co	5	3.5	15	10	—	0.8	—
Ni	70	20	—	—	—	6.7	25
Cu	145	226	650	308	310	35	10
Zn	640	950	<20	<20	—	146	40
Se	8	6.6	—	—	—	1.9	—
Ag	4	2.1	—	—	—	2.9	—
Sb	7	71	<5	<5	—	0.8	—
Au	0.4	—	<0.1	0.16	—	—	—
Hg	16	0.34	—	—	—	0.17	—
Pb	180	34	—	—	—	22	9
Th	0.4	4	—	—	—	—	—
La	—	—	24	49	—	—	—
I	—	—	496	83	260	—	—
Ba	—	—	192	526	—	—	—
Ti	—	—	0.13	0.31	910	—	—
Cd	—	9.6	—	—	—	2.1	3.4
Ce	—	200	—	—	—	1.2	—
Cs	—	6.0	—	—	—	0.02	—
Eu	—	0.66	—	—	—	0.0077	—
Sr	—	78	1430	50	1190	350	—
Pu-239,240	—	98	—	—	—	4.8	—
Am-241	—	72	—	—	—	—	—
Po-210	—	24,500	—	—	—	306	—
Pb-210	—	10,400	—	—	—	—	—
Th-228	—	973	—	—	—	—	—
Th-232	—	250	—	—	—	2.6	—
Th-234	—	338,000	—	—	—	—	—
U-238	—	520	—	—	—	245	—

\* Compiled by Fowler and Knauer (1986) and Fowler (1988). + "green" fecal pellets. " "red" fecal pellets

\*\* non-characterized fecal pellets from 500 m above bottom in water column of approx. 2800 m depth.

1 pCi = 2.22 dpm



that the residence time is coupled to new production and grazing. Similar mechanisms may also be involved in the transport of some of the anthropogenic substances through the water column. Thus there are strong biological controls on the distribution of trace elements in surface waters. The extension of the conclusions reached from radionuclides to other elements requires thermodynamic and kinetic studies, as well as knowledge of the role of active-passive biological uptake.

## 5.2. Deep Ocean

Data on the dissolved profiles of several trace elements show evidence for the central role played by particle-associated processes in controlling their distribution. Many of these dissolved profiles (e.g. Cu, Ni, Cd) have been interpreted in terms of diffusion, advection, and scavenging models to obtain elemental residence times in the deep sea. The dissolved and particulate thorium isotope profiles in the water column have provided better insight into particle transformation/exchange processes. These profiles require a continuous exchange of particles from one size to another, with residence times of the order of a few years for the suspended particles. The relatively long residence time of particulate matter may allow the establishment of equilibrium between dissolved and particulate phases. Several equilibrium chemical models have been described based on metal ion complexation by suspended particles to estimate residence times of trace elements.

The distributions and fluxes of trace elements in the ocean interiors are determined not only by the particulate transport processes discussed above but also by ocean circulation and mixing. It is especially important to recognize that the ocean margins can act as sources (e.g. Mn) or sinks (e.g.  $^{210}\text{Pb}$ ) for trace elements and that their effects are felt in the ocean interior because of lateral transport (U.S. GOFS, 1987). For reactive elements it can be shown that large-scale chemical fractionation may come about because of differential partitioning of the elements between vertical and horizontal transport pathways (Bacon, 1988). The influence of the benthos on trace element distribution can also be mediated by particulate phases. For example, sediment trap studies in near-bottom waters have demonstrated that certain



elements such as Ca, Cu, Si and Zn have larger fluxes into traps than into the sediments implying release of these elements from particulate phases to bottom waters.

### 5.3. RECOMMENDATIONS

- (1) Laboratory and field tracer studies using living and detrital particles should be encouraged in that they show promise in furnishing rate information on element transfer between the soluble and particulate pools and information on their distributions in the sea.
- (2) Measurements of trace elements and radionuclides should be made on particles caught in sediment traps, suspended particulate matter and dissolved pools at the same site in order to examine the linkage between these different pools. Particular emphasis should be placed on the suspended pool because it is often overlooked in flux studies. Radionuclides, and other tracers should be used to elucidate the rates of important particle-associated processes.
- (3) Sampling devices should always be constructed with materials that will not pose contamination problems for the elements (i.e. trace metals) or compounds (i.e. trace organics) being examined.
- (4) More detailed examination of element/radionuclide-particle interactions in the mesopelagic zone should be made since information in this key region of the water column is sparse.



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surfaces.

**Aggregation:** Process by which smaller particles are transformed into larger ones. Aggregation can occur as a result of both physical and biological processes.

**Aspect ratio:** Length of a sediment trap divided by its diameter. For satisfactory performance of traps a minimum aspect ratio of 3 is recommended.

**CCCC:** Joint SCOR/IOC Committee on Tropical Oceans and Coasts

**Decomposition:** Conversion of organic matter and the release of inorganic substances (e.g.,  $\text{CO}_2$ ,  $\text{H}_4$ ,  $\text{PO}_4$ ) through metabolic activities of micro-organisms.  
mineralization

**Detritus:** Non-living particulate material

**Disaggregation:** Process by which larger particles are broken apart. This term is often used interchangeably with fragility.

**Fecal material (or pellets):** Solid waste materials excreted by organisms.

**GOPS (Global Ocean Flux Study):** A U.S. supported international research program designed to gain an understanding of the controlling marine biogeochemical cycling on both regional and global spatial scales and at time scales from days to years. The program is the component of a larger effort.



## GLOSSARY

**Adsorption:** Process of adherence of ions and molecules from solution to particle surfaces.

**Aggregation:** Process by which smaller particles are transformed into larger ones. Aggregation can occur as a result of both physical and biological processes.

**Aspect ratio:** Length of a sediment trap divided by its diameter. For optimum performance of traps a minimum aspect ratio of 3 is usually recommended.

**CCCO :** Joint SCOR/IOC Committee on Climatic Changes and the Ocean.

**Decomposition:** Conversion of particulate and dissolved organic matter to inorganic substances (e.g.,  $\text{CO}_2$ ,  $\text{NH}_4$ ,  $\text{PO}_4$ ) usually as a result of the metabolic activities of micro-organisms; also referred to as remineralization.

**Detritus:** Non-living particulate material.

**Disaggregation:** Process by which larger particles are broken up into smaller ones. This term is often used interchangeably with fragmentation.

**Fecal material (or pellets):** Solid waste materials excreted by heterotrophic organisms.

**GOFS (Global Ocean Flux Study):** A U.S. supported interdisciplinary oceanographic research program designed to gain an understanding of the processes controlling marine biogeochemical cycling at regional, basin-wide and global spatial scales and at time scales from annual to decadal. This program is one component of a larger global geosciences research initiative



currently sponsored by the U.S. National Science Foundation.

**Grazing:** Term used to describe the feeding activities of organisms which involve the direct ingestion of living and non-living particulate materials.

**JGOFS (Joint Global Ocean Flux Study):** An internationally co-ordinated research program whose main goal is to determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean.

**Marine snow:** Amorphous, flocculent detrital material.

**New production:** The rate of primary production, generally defined in terms of the element nitrogen, resulting from the flux of available nitrogen into the surface waters from outside the euphotic zone. Under steady-state conditions, new production is available for export out of the euphotic zone without affecting the total rate of primary production.

**Nitrogen fixation:** A metabolic process which involves the reduction of dinitrogen ( $N_2$ ) to  $NH_4^+$ . The ability to fix  $N_2$  is restricted to a relatively few species of free-living and symbiotic bacteria.

**Nutrient:** Elements that are required by all living organisms for viability and growth such as N, P and Co.

**Particulate Material:** Solid material that can be collected from seawater by a number of methods. The exact definition is operational and depends on the method employed. That collected by filters is usually called suspended particulate matter, and that intercepted by sediment traps is considered to be settling particulate matter. The quantity of suspended particulate material in seawater is often reported as the amount that is collected on a filter of approximately  $0.5 \mu m$ .



**Preservative:** A chemical that can be added to samples of organic matter to retard the degradation and microbial decomposition and to maintain the structural integrity. Examples include true preservatives such as glutaraldehyde and formalin, poisons such as mercuric chloride and copper sulfate and metabolic inhibitors such as sodium azide and antibiotics.

**Primary production:** Rate of fixation of dissolved inorganic carbon into particulate organic matter; also referred to as photosynthesis and autotrophic production.

**Radioactive Equilibrium/Disequilibrium:** A special case of steady state applied to radionuclides in which the supply of a radioactive nuclide is balanced by its removal by radioactive decay. Within a radioactive decay series, at radioactive equilibrium, the activities of all members of the series are equal. When such a condition does not hold, it is referred to as radioactive disequilibrium.

**Residence Time:** The average lifetime of a species in a particular phase or particular state.

**Scavenging:** Process by which dissolved constituents of seawater are transferred to particulate phases and removed from the water column. This term is occasionally used to describe the removal of small particles by accretion to larger, sinking particles.

**Settling velocity:** Rate at which particles settle through the water column, usually expressed in units of  $\text{cm. s}^{-1}$  or  $\text{m. d}^{-1}$ .

**Steady-State:** A time-independent state the system may attain when constant conditions are imposed upon it. At steady state the input flux of a property



to the system is balanced by its output, and the concentration of the property in the system remains constant with time.

*Swimmers:* Varieties of living zooplankton and fish which are frequently collected in sediment traps primarily in the upper 1 km of the ocean. Swimmers are not part of the passive flux of particulate matter.