

AN ABSTRACT OF THE THESIS OF

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ABSTRACT APPROVED:

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The rate of recycling of the major components of the biologically produced particulate flux (organic carbon, calcium carbonate, and opal) were measured at three sites in the North Equatorial Pacific. Reaction rate constants were derived assuming first order processes occurring during particle settling between adjacent pairs of sediment traps. Mid-water flux maximums were found at each site. Assuming a particle settling rate of 100 m/day, organic carbon, calcium carbonate and opal rate constants below the mid-water flux maximum were  $3.7\text{-}13\text{ yr}^{-1}$ ,  $2.3\text{-}4.5\text{ yr}^{-1}$ , and  $1.0\text{-}7.9\text{ yr}^{-1}$ , respectively. Ranges for rate constants above the mid-water flux maximum were  $15\text{-}32\text{ yr}^{-1}$  for organic carbon,  $11\text{-}20\text{ yr}^{-1}$  for calcium carbonate, and  $6.4\text{-}27\text{ yr}^{-1}$  for opal.

Near-bottom sediment trap moorings were recovered at three sites in the North Equatorial Pacific. Total particulate fluxes recorded in sediment traps moored within 50 m of the ocean floor were greater than those recorded in mid-water column traps. A simple model assuming all of the flux increase was due to

resuspended sediment does not account for increases in the major biogenic components of the particulate flux. The "rebound" of recently deposited biogenic detritus may account for these increases, however. Hydraulic fractionation probably enriches the "rebound" material in organic carbon with respect to calcium carbonate and opal.

To estimate the role of the rebound process (the resuspension of fresh biogenic detritus prior to incorporation into the sediment) in the recycling of biogenic material, a simple box model is used to balance the particulate flux to the sediment surface (primary flux) with accumulation rates in the sediments. The difference between the accumulation rate and the primary flux is divided between a diffusion flux out of the sediments and a "rebound process" flux. Using data from four sites in the Pacific, the modeling predicts that 30-60% of the primary flux of opal is recycled during the rebound process which occurs during 1 to 8 months. During this time, 50-99% of the primary flux of organic carbon and 22-89% of the primary flux of calcium carbonate is recycled.

RESUSPENSION AND THE REBOUND PROCESS:  
IMPLICATIONS OF SEDIMENT TRAP STUDIES IN THE NORTHERN PACIFIC

by

Ian David Walsh

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## CONTRIBUTIONS OF AUTHORS

The work in this thesis has been completed with the direction and support of Dr. Jack Dymond, and he is thus acknowledged as a co-author of each chapter. Dr. Robert Collier is a co-author of Chapter I in recognition of discussion and reviews which contributed significantly to the chapter. Dr. Kathy Fischer is a co-author of Chapter II in recognition of her work on MANOP sites M and H. H. David Murray supplied microfossil and size fraction chemistry data used in Chapter II and is acknowledged as a co-author.

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## RESUSPENSION AND THE REBOUND PROCESS:

### IMPLICATIONS OF SEDIMENT TRAP STUDIES IN THE NORTHERN PACIFIC

#### GENERAL INTRODUCTION

One of the goals of sediment trap research in the oceans is to be able to quantitatively relate the fluxes measured in the water column to the composition and accumulation rate of the underlying sediments. The transport of mass in the form of particles settling through the water column is dominated by relatively scarce fast settling particles (Fowler and Small, 1972; McCave, 1975; Komar, Morse, Small and Fowler, 1981) that are primarily of biogenic origin and composition (Schrader, 1971; Honjo, 1978; Spencer, Brewer, Fleer, Honjo, Krishnaswami and Nozaki, 1978; Honjo, 1980; Bishop, Collier, Kettens and Edmond, 1980; Brewer, Nozaki, Spencer and Fleer, 1980; Cobler and Dymond, 1980; Shanks and Trent, 1980; Urrere and Knauer, 1981; Honjo, Manganini and Cole, 1982).

The flux of biogenic particles is closely tied to the productivity of the euphotic zone (Deuser, Ross and Anderson, 1981), as is the transport of abiogenic particles (primarily aluminosilicates) to the sediment (Honjo, Spencer and Farrington, 1982; Fischer, 1984). The sediment surface thus receives periodic pulses of biogenic and abiogenic detritus, suggesting a dynamic seafloor far removed from early concepts of a slow, steady "rain" of particles to the bottom (Billett, Lampitt, Rice and Manoura, 1983).

Sediment traps, by sampling the flux at different depths in the water column, collect data that can yield estimates of the relationships between productivity, elemental recycling, and sediment accumulation rates (Suess, 1980; Lorenzen, Welschmeyer and Copping, 1983; Lee and Cronin, 1984; Betzer, Showers, Laws, Winn, DiTullio and Kroopnick, 1984). Sampling at a variety of depths can also yield data on the formation of particles by organisms (Urrere and Knauer, 1981; Karl and Knauer, 1984), and chemolithotrophic production (Karl, Knauer, Martin and Ward, 1984).

This thesis uses sediment trap data from the four MANOP sites in the Pacific. In the first chapter the flux profiles of the major biogenic components of the particle flux (organic carbon, calcium carbonate, and biogenic opal) are examined in relation to the recycling of the biogenic components. In the second chapter the processes that affect the fluxes measured in sediment traps moored near the seafloor are examined. The third chapter estimates the impact of "rebound" of biogenic detritus on the recycling of the major biogenic components at each of the MANOP sites.

## CHAPTER I

# RATES OF RECYCLING OF BIOGENIC COMPONENTS OF FAST SETTLING PARTICLES DERIVED FROM SEDIMENT TRAP EXPERIMENTS

## ABSTRACT

The rates of recycling of the major components of the biologically produced particulate flux (organic carbon, calcium carbonate, and opal) were measured at three sites in the North Equatorial Pacific. The biogenic fluxes measured in sediment traps were normalized to the particulate aluminum flux, and reaction rate constants were derived assuming first order processes occurring during particle settling between adjacent pairs of sediment traps. Mid-water flux maximums were found at each site. Assuming a particle settling rate of 100 m/day, organic carbon, calcium carbonate and opal rate constants below the midwater flux maximum were  $3.7\text{-}13\text{ yr}^{-1}$ ,  $2.3\text{-}4.5\text{ yr}^{-1}$ , and  $1.0\text{-}7.9\text{ yr}^{-1}$ , respectively. Ranges for rate constants above the mid-water flux maximum were of  $15\text{-}32\text{ yr}^{-1}$  for organic carbon,  $11\text{-}20\text{ yr}^{-1}$  for calcium carbonate, and  $6.4\text{-}27\text{ yr}^{-1}$  for opal.

## INTRODUCTION

The settling of biogenic detritus through the oceans and the concurrent recycling of this material is a major cause of observed chemical heterogeneities in seawater (Broecker and Peng, 1982). Biogenic detritus is transported through the water column by fecal pellets and "marine snow" settling at 100 to 180 m/day (Fowler and Small, 1972; Small, Fowler and Unlu, 1979; Shanks and Trent, 1980; Komar, Morse, Small and Fowler, 1981). At these settling rates, the particles may take one to two months to reach the sediment surface. Sediment traps sample settling particles, and by comparing the flux

recorded at different depths, or productivity in the euphotic zone, yield estimates of rates of recycling (Suess, 1980; Lee and Cronin, 1984; Betzer, Showers, Laws, Winn, DiTullio and Kroopnick, 1984; Betzer, Byrne, Acker, Lewis, Jolley and Feely, 1984; Byrne, Acker, Betzer, Feely and Cates, 1984).

Because of dissolution and degradation reactions the flux of biogenic material should decrease with depth. Empirical relationships for the decrease in the flux of organic carbon with depth have been derived from primary productivity and sediment trap data (Suess, 1980; Betzer, Showers, Laws, Winn, DiTullio and Kroopnick, 1984). The dissolution rate of aragonite has also been estimated from sediment trap data (Byrne et al., 1984). However, estimating dissolution and degradation rates from sediment trap data is complicated by the fact that biogenic fluxes measured in multi-trap experiments have commonly shown a mid-water maximum (Knauer and Martin, 1981; Fischer, 1984; Knauer, Martin and Karl, 1984). While we are primarily concerned with estimating the rates of recycling in the lower water column, a model of flux changes with depth should also account for the increase in flux in the upper water column.

In this paper we attempt to reconcile the observed mid-water maximum with dissolution and degradation reactions by estimating the rates in the water column below the maximum, and examining the processes in the upper water column that may contribute to the mid-water maximum. We make empirical estimates of the rates of decomposition of organic carbon and dissolution of calcium carbonate and biogenic

opal. Because we are interested in evaluating the steady-state rates, we use average fluxes from year long trap deployments to reduce effects of short term productivity changes (Deuser, Ross and Anderson, 1981). We derive reaction rate constants using fluxes normalized to aluminum in order to focus on the compositional changes in the settling particulate material. Normalization also allows calculation of rates in the upper water column where the raw data shows increases in biogenic fluxes with depth.

#### DATA

Data from long term deep ocean mooring arrays at three MANOP sites in the Pacific (Table I-1) are used. The moorings were equipped with single cone OSU sediment traps which collect sequential seasonal samples, and double cone Soutar traps which collect a single sample for the deployment period. The sample cups on the OSU traps were poisoned with sodium azide to prevent bacteriological decay. The Soutar traps were poisoned with buffered formalin. Recent comparisons between formalin and azide poisoned cups showed agreement within 5% for concentrations of the biogenic components (Moser, Fischer and Dymond, 1985). Trap samples were sieved through a 1 mm nylon mesh, freeze dried, ground, and split for analysis. Salt corrections were made by difference in weight after freeze drying. Aluminum and silicon concentrations were determined by Instrumental Neutron Activation Analysis (INAA). Organic carbon and calcium carbonate measurements were made with a LECO carbon analyzer using a phosphoric acid/wet

Table I-1. MANOP Site Locations

Site	Location	Bottom Depth	Deployment Period
H	6°30'N, 93°W	3575 m	9/80 - 10/81
S	11°2'N, 140°W	4260 m	12/82 - 2/83
C	1°3'N, 138°56'W	4470 m	12/82 - 2/83



oxidation procedure (Weliky, Suess, Ungerer, Muller and Fischer, 1983). Biogenic opal was calculated normatively by assuming all particulate Al is detrital aluminosilicate with a Si/Al value of 3.0, and all remaining Si is in opal (Fisher, 1984). Since non-biogenic Si in our samples never exceeds 3%, this normative determination of opal is insensitive to errors in the assumed Si/Al ratio of aluminosilicates. Site descriptions and details of the analytical techniques have been reported previously (Fischer, 1984; Emerson, Fischer, Reimers, and Heggie, 1985). The fluxes reported for site H differ slightly from those previously reported (Fischer, 1984) due to recalculation of the trap collection areas.

#### METHODOLOGY

Decreases in the flux of the biogenic components of the particle flux between two traps are attributed to loss due to dissolution or degradation occurring during the time the particles settled through the water column between the traps. We assume first order kinetics in our modeling of decomposition and dissolution. Reaction rates for first order processes can be derived from a pair of sediment traps using the equation:

$$1) k = (\ln F^i - \ln F_o^i)/z$$

where  $k$  is the reaction constant per meter,  $F^i$  and  $F_o^i$  are the measured fluxes of component  $i$  in units of  $\mu\text{g}/\text{cm}^2 \text{ yr}$  in the lower and upper traps, respectively, and  $z$  is the difference in depth between the traps, in meters. Reaction constants per meter can be converted

to rate constants by dividing by the mean particle settling rate. We have assumed a 100m/day settling rate in all our conversions (Fowler and Small, 1972; Small, Fowler and Unlu, 1979; Shanks and Trent, 1980; Komar et al., 1981).

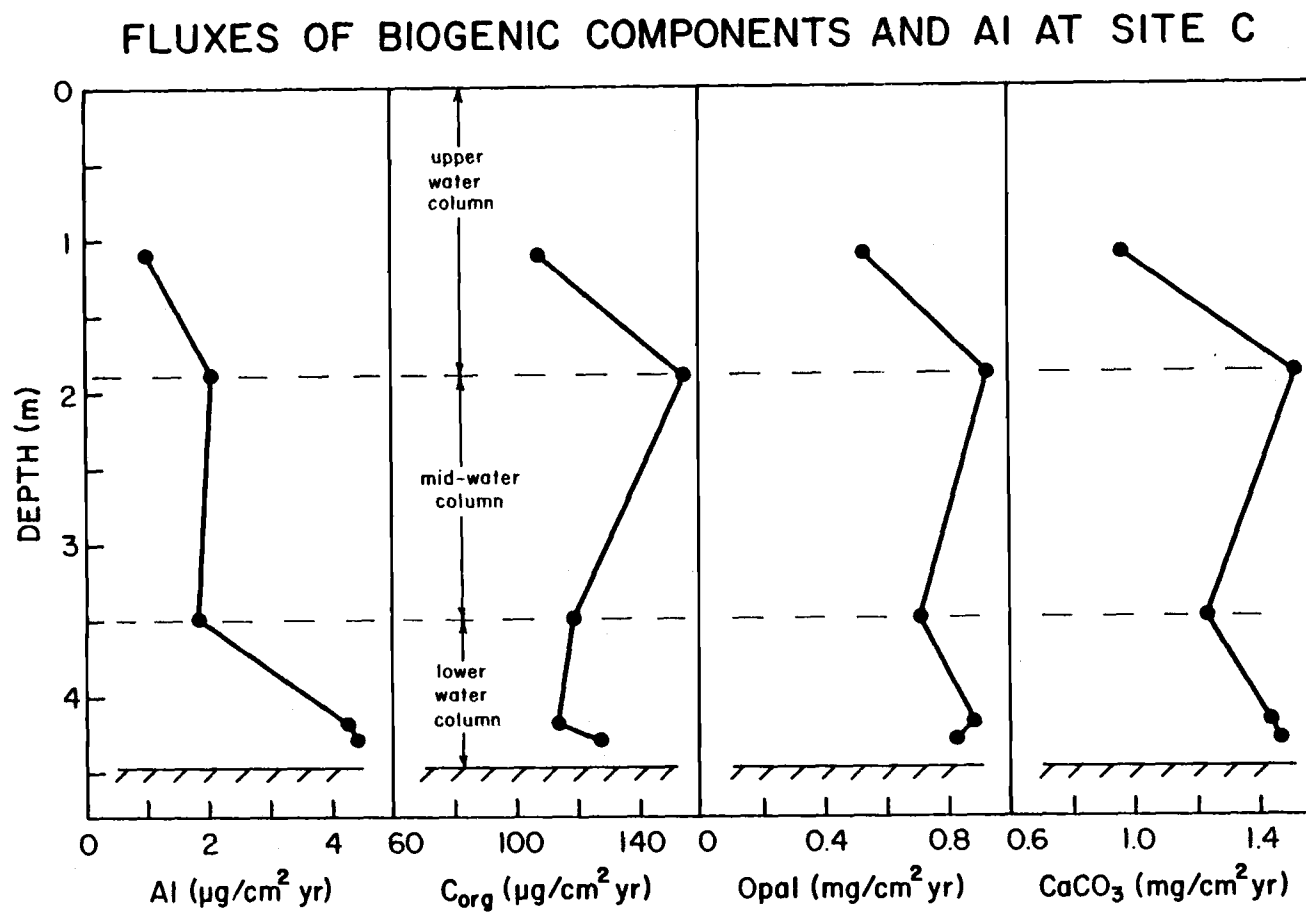
For this procedure to work, the traps must sample the same sources of population of particles. The observed difference in flux is then solely due to the reactions occurring during the time the particles take to traverse the water column between the two traps. Sampling artifacts and physical processes may change the measured flux in sediment traps beyond that caused by degradation and dissolution reactions. By minimizing the extraneous effects on our data through appropriate experimental design and data treatment, the calculated dissolution and degradation rate constants will best approximate in situ reaction constants.

To this end we normalize the biogenic fluxes to the aluminum flux. The aluminum flux is an effective tracer of the refractory lithogenic flux and thus is not affected by dissolution or decomposition reactions (Spencer, Brewer, Fleer, Honjo, Krishnaswami, and Nozaki, 1978). Assuming that the aluminum content of the settling particles is fixed at the time of particle formation, normalization of the biogenic fluxes to aluminum avoids errors in the calculated reaction rates from disaggregation and/or horizontal fluxes.

We minimize the impact of boundary processes on the modeling by calculating rate constants from mid-water column trap data (Figure I-1). Observed increases in biogenic fluxes measured in sediment

Figure I-1. Particulate fluxes of the major biogenic components and aluminum at MANOP site C. Note the differences in scales and the mid-water column flux maximums. Similar flux profiles were observed at the other MANOP sites.

Figure I-1

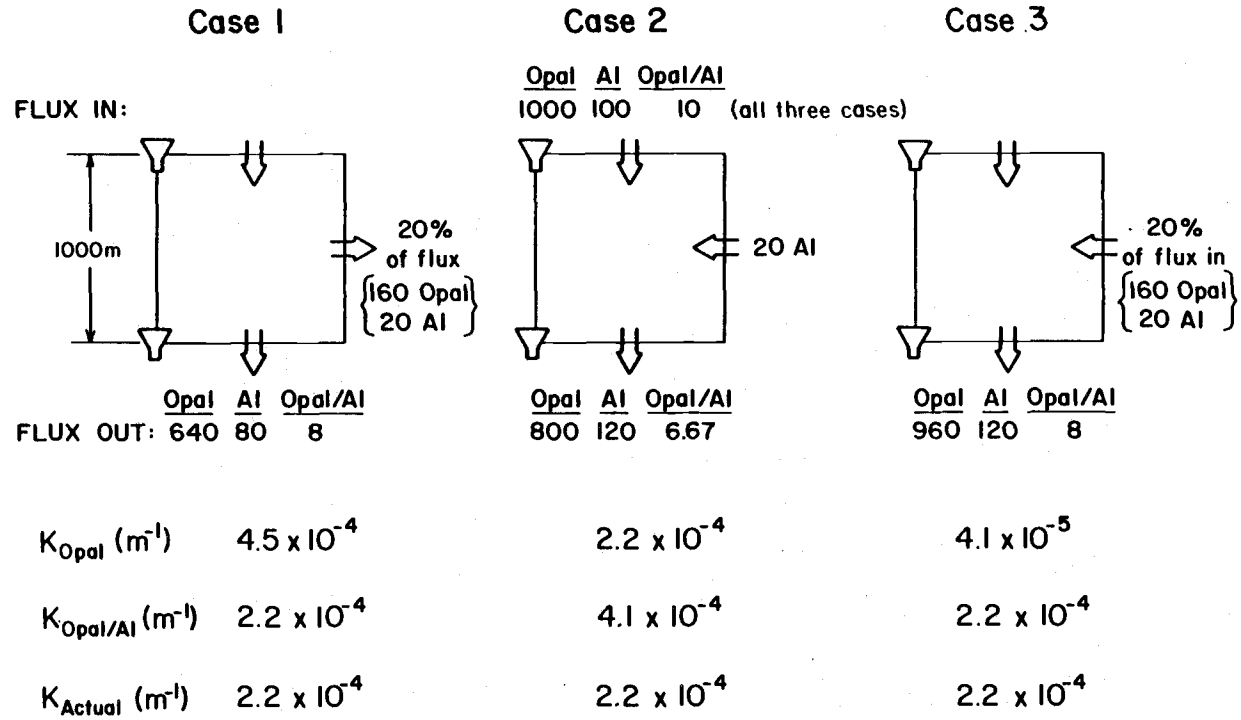


traps below the photic zone have been related to diel migration of zooplankton (Betzer, Byrne, Acker, Lewis, Jolley, and Feely, 1984), microbial production within and below the oxygen minimum zone (Karl and Knauer, 1984; Karl, Knauer, Martin and Ward, 1984) and the input of fecal material at depth by zooplankton (Urrere and Knauer, 1981). Resuspension of surface sediments (Rowe and Gardner, 1979) and fresh material (Billet, Lampitt, Rice and Mantoura, 1983; Walsh, Fischer, Murray and Dymond, 1985; Lampitt, 1985) results in near-bottom sediment traps recording higher fluxes than mid-water column traps. Additionally, benthopelagic plankton may play an important role in material transport in the water column near the sediment surface (Wishner, 1980a, 1980b). We compare the mid-water column results with the upper water column data to delineate the effects of the upper water column processes on the biogenic fluxes and reaction rates.

To demonstrate the value of normalized fluxes in aiding the interpretation of the data, three idealized examples of box models are shown in Figure I-2. Fluxes in and out of the boxes are the particulate fluxes of opal and aluminum, although any biogenic component (e.g., carbonate or organic carbon) could be used. The difference between the fluxes in and out are due to dissolution of opal and horizontal fluxes and/or disaggregation. All three cases assume 20% dissolution of the vertical opal flux, and the same flux at the level of the upper trap (into the box). From equation 1, the dissolution constant (k) corresponding to a 20% loss over 1000 m is  $2.2 \times 10^{-4} \text{ m}^{-1}$ .

Figure I-2. Theoretical effects of horizontal fluxes and/or disaggregation on the determination of first order dissolution rate constants for the opal particulate flux.

Figure I-2



In case 1 there is a horizontal flux out of the box of 20% of the settling particles. This model could represent a case in which a strong productivity gradient occurs in the surface water and currents disperse the settling particles. Alternatively, disaggregation could account for the decrease in flux. If the opal flux alone was used to calculate  $k$  it would be twice the actual  $k$ ; the  $k$  calculated from the normalized opal flux equals the actual value.

In case 2, there is a horizontal flux of particulate aluminum into the box. This case represents a situation such as observed in the Panama Basin (Honjo, Spencer and Farrington, 1982) where the lithogenic particle flux increased with depth due to resuspension from the continental margin. In this case, using the opal flux yields the actual  $k$  while using the normalized opal flux results in a calculated  $k$  almost a factor of 2 greater than the actual  $k$ .

In the third case, there is a flux into the box of particles compositionally similar to those entering the box from above. This case represents input of particles at depth such as observed off the California coast (Karl and Knauer, 1984). In this case the opal flux yields a  $k$  almost a factor of 6 less than the actual value, while the normalized data yields the actual  $k$ . These box models indicate that normalization to aluminum will lead to more accurate estimates of dissolution and decomposition rates as long as the particles gained or lost between traps have compositions similar to the bulk flux.

Essentially, this methodology selects a settling particle population measured in a sediment trap (assuming that particle composi-



tion is at steady state with respect to size frequency, density, and settling rate) and extrapolates the composition of that particle population through the water column under the assumption that only chemical and biologically mediated dissolution and decomposition act upon the particles.

## RESULTS

Rate constants for organic carbon were calculated for normalized fluxes using equation 1 (Table I-2). The normalized fluxes are displayed in Figure I-3. The mid-water column organic carbon rate constants ( $k_m$ ) vary by less than a factor of four between sites, and are within the range for oxic decomposition of organic matter suggested by other investigators (Lee and Cronin, 1984; Westrich and Berner, 1984, Emerson et al, 1985). Rate constants derived from the upper water column trap pairs ( $k_u$ ) are higher than those from the mid-water column at all three sites.

Similar calculations of the dissolution rates of calcium carbonate for the mid-water column ( $k_m$ ) suggests rates that vary by only a factor of two between the sites (Table I-3). Upper water column dissolution rates ( $k_u$ ) are higher than the mid-water column rates at all three sites.

Dissolution experiments conducted on a variety of calcitic materials have indicated order of magnitude differences in absolute dissolution rates (Honjo and Erez, 1978). Peterson (1966), in an in situ experiment with calcite spheres estimated a mid-water column

Table I-2. Organic Carbon Degradation Rate Constants in the Oceans

		$k \text{ (yr}^{-1}\text{)}$	$k \text{ (m}^{-1}\text{)}$
Particulate Organic Carbon§			
<u>Site</u> <u>Trap Depths (m)</u>			
H (ku)	505 - 1465	32	$8.8 \times 10^{-4}$
(km)	1465 - 3075	13	$3.5 \times 10^{-4}$
S (ku)	700 - 1600	24	$6.4 \times 10^{-4}$
(km)	1600 - 3400	7.5	$2.1 \times 10^{-4}$
C (ku)	1095 - 1895	15	$4.1 \times 10^{-4}$
(km)	1895 - 3495	3.7	$1.0 \times 10^{-4}$
Amino Acids*			
<u>Site</u>			
Vertex I		44	$1.2 \times 10^{-3}$
Vertex IIc		47	$1.3 \times 10^{-3}$
Peru		66	$1.8 \times 10^{-2}$
Parflux P		21	$5.8 \times 10^{-4}$
Surface Plankton^			
(assumes two reactive fractions, k1 and k2)			
k1		24	$6.6 \times 10^{-4}$
k2		1.4	$3.8 \times 10^{-5}$
Sediment Organic Carbon@			
<u>Site</u>			
H		$2-3 \times 10^{-2}$	$5-8 \times 10^{-7}$
C		$5-8 \times 10^{-2}$	$12-22 \times 10^{-7}$

§ this study

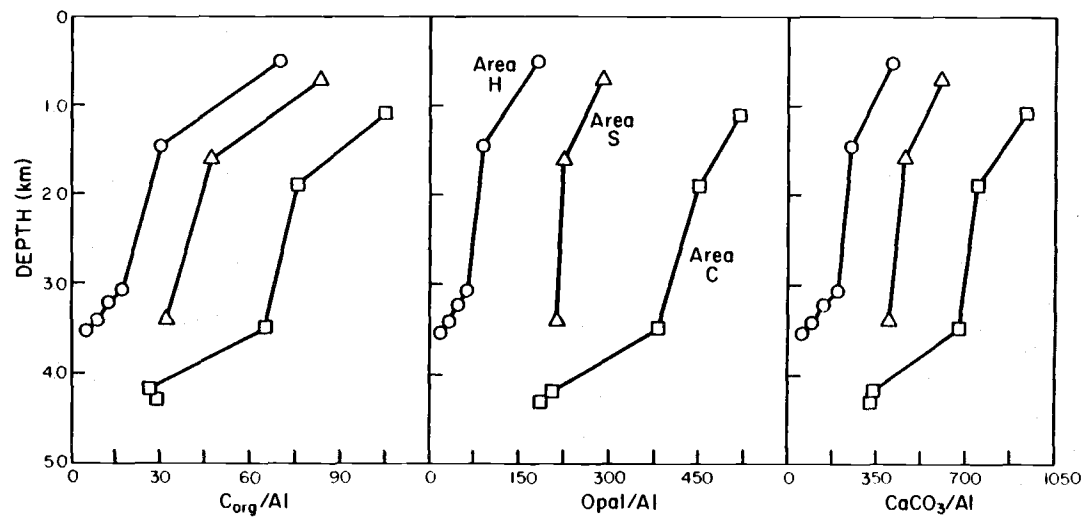
\* Lee and Cronin (1984)

^ Westrich and Berner (1984)

@ Emerson et al. (1985)

Figure I-3. Particulate fluxes of the major biogenic components normalized to the aluminum flux measured in sediment traps at MANOP sites H, S, and C.

Figure I-3



dissolution rate of 0.1 to 0.15 wt%/day, with a large increase in the rate below 3000 m. Berger and Piper (1972) using cleaned foraminifera tests in an in situ experiment estimated a dissolution rate of 0.02%/day.

Assuming a settling rate of 100 m/day, the Berger and Piper estimate is equivalent to a first order dissolution rate constant of  $2 \times 10^{-4} \text{ m}^{-1}$ . However, direct comparison of experimental rates with empirically derived rates not straightforward. The settling rate of the carbonate particles, their effective surface area, and the presence of dissolution inhibiting organic coatings will affect the in situ dissolution rate (Honjo, 1977). Additionally, microenvironments in fecal pellets may enhance dissolution due to the production of metabolic  $\text{CO}_2$  from the oxidation of organic matter, or inhibit dissolution due to an increase in the degree of saturation (Emerson and Bender, 1981; Honjo, 1977). While rates which are derived from settling material may be preferable to rates derived from calcite weight loss, the dissolution rate of calcium carbonate is strongly depth dependent below the lysocline (Honjo and Erez, 1978). Thus extrapolating the carbonate flux to the sediments using mid-water column dissolution rates results in maximum fluxes.

Dissolution rates for biogenic opal were computed from the fluxes measured by upper and mid-water column trap pairs (Table I-3). Again, dissolution rates in the upper water column are higher than those in the mid-water column at all three sites.

Table I-3. Dissolution Rate Constants for Calcium Carbonate and Opal

Site	Trap Depths	CaCO <sub>3</sub>	Opal	CaCO <sub>3</sub>	Opal
		$k \text{ (yr}^{-1}\text{)}$		$k \text{ (x } 10^{-4} \text{ m}^{-1}\text{)}$	
H (ku)	505-1465 m	20	27	5.4	7.3
	(km) 1465-3075 m	4.5	7.9	1.2	2.2
S (ku)	700-1600 m	11	10	3.1	2.8
	(km) 1600-3400 m	2.6	1.0	0.72	0.28
C (ku)	1095-1895 m	11	6.4	2.9	1.8
	(km) 1895-3495 m	2.3	3.7	0.63	1.0

Unlike calcium carbonate, the opal dissolution rate is not strongly depth dependent. Hurd (1972) estimates that the variation in dissolution rate for opal due to differences in temperature, pressure and degree of saturation in the oceans below 1000 m is only 10 to 12%. However, as with calcium carbonate, the available surface area, presence of organic coatings, and settling rates of opal particles may control the actual dissolution rate. Such considerations make it difficult to apply rates estimated from sediment and laboratory results to settling particles (Hurd, 1972; Schink and Guinasso, 1978).

Nelson and Gordon (1982) report net opal production and dissolution rates for the Southern Ocean. From their data, assuming an average transit distance of 4000 m and a particle settling rate of 100 m/day, the dissolution rate constant for the Southern Ocean ranges between  $0.5\text{--}1.2 \times 10^{-4} \text{ m}^{-1}$ . The average rate constant for the mid-water column at our three sites is  $1.2 \times 10^{-4} \text{ m}^{-1}$ , indicating substantial agreement between our methods.

## DISCUSSION

Understanding the decrease in reaction rates between the upper water column and mid-water column (Tables I-2 and I-3), and the mid-water flux maximum is crucial to estimating fluxes through the water column and approaching a balance between productivity and sediment trap fluxes. The processes that control the flux through the near-

bottom water column are explored in a subsequent paper (Walsh, Fischer, Murray and Dymond, 1985).

#### Possible Causes of Particle Flux Increases with Depth

Biogenic and aluminum fluxes at site C are presented in Figure I-1 as a typical example of mid-water flux increases. Horizontal transport from regions of higher primary productivity or from continental margins are a possible cause of increases in the fluxes of biogenic components below the euphotic zone. It is unlikely, however, that productivity patchiness would affect all the MANOP deployments in the same manner, and sites C and S are sufficiently far away from continental margins that input from that source must be minimal. Alternatively, an unknown sampling artifact might cause lower trapping efficiencies for the top traps. This also seems unlikely, as biogenic flux increases over similar depth ranges have been reported from other sediment trap deployments (Knauer and Martin, 1981; Karl and Knauer, 1984; Honjo, 1980).

Lower trapping efficiencies could be due to tilting of the top traps in a higher current (Gardner, 1985) but overall tilt for the moorings has been checked by current meters equipped with pressure sensors and is small for our deployments (Fischer, 1984). Zooplankton and small nekton could use the traps as food sources. However, the OSU traps collect samples in cups connected to the cone via a distributor valve. Most of the azide used to poison the sample is retained in a dense solution upon recovery, suggesting that there is little



circulation of fluid from the cups, and making it unlikely that an animal would swim in and out without being poisoned. The fact that mid-water biogenic flux increases have been observed at many sites, and by different sediment trapping techniques, argues that it is a general phenomena not related to sampling artifacts or horizontal transport.

Production of organic carbon by microbial chemolithotrophy has been related to increases in organic carbon fluxes with depth (Karl and Knauer, 1984; Karl et al., 1984), however, microbial production cannot explain increases in the fluxes of opal, carbonate, and aluminum. The increase in total particle flux and biogenic flux argues that there is a source of settling particles within the upper water column.

Increases in flux with depth may be related to the production of particles by zooplankton. Knauer, Martin and Karl, (1984) report that the depths where increases in the organic carbon flux occurred were also depths of increased fecal pellet fluxes and in situ microbial carbon production. Urrere and Knauer (1982) report increases in fecal pellet fluxes with depth, as well as a change in the dominant type of fecal pellet, indicating that changing zooplankton communities with depth may be linked to increases in the bulk flux.

Zooplankton activity has also been linked to changes in the composition of the particle flux. Wakeham, Lee, Farrington and Gagosian (1984) report an increase in the percentage of short chain fatty acids with respect to total fatty acids between the 988 and

2778 m traps at the PARFLUX P station, indicating that different communities of organisms were sources of fatty acids to the two traps. They also report a ten-fold increase in the flux of wax esters between the 988 and 2778 m traps, indicating input from zooplankton at depth.

Two possible processes, each involving zooplankton filtration, seem to provide possible explanations for the increase in particle fluxes. The first involves zooplankton ingestion of suspended particulates and subsequent packaging in fecal pellets. A second alternative is that zooplankton may be feeding above the level of our top traps and excreting fecal pellets below, a process we term "bioactive transport" to differentiate it from passive settling.

#### Possible Causes for Reaction Rate Constant Changes With Depth

Our modeling suggests that there is a decrease in the rate of reactions between the upper and mid-water column. In analyzing the change in the reaction rate constants we still assume first order kinetics, thus a change in the rate of reaction is reflected simply in the change in the reaction rate constant. An actual decrease in  $k$  with depth could be due to

- 1) a decrease in temperature,
- 2) an increase in the degree of saturation (dissolution),
- 3) a decrease in the oxygen concentration (carbon degradation),
- 4) a decrease in production of metabolic  $\text{CO}_2$  ( $\text{CaCO}_3$  dissolution)

- 5) a change in the composition of the reactants, i.e. loss of the most labile fractions, and
- 6) a decrease in the number of heterotrophic organisms which consume particles.

Or the decrease may be an artifact of the modelling as a result of:

- 1) an increase in the settling velocity with depth, and
- 2) an increase in the Al concentration in the settling particles with depth.

### Environmental Factors

As the traps were well below the thermocline, temperature differences are less than 5°C, and thus should not have a significant impact on the reaction rates. Hurd (1972), reported that the dissolution rate of opal decreased rapidly to 750 m and is stable through the rest of the water column, based on temperature, pressure and degree of saturation. Calcium carbonate is saturated through the upper water column and to depths greater than 3000 m in the Pacific, though dissolution in sediments above the lysocline does occur, probably through reactions with organic carbon (Emerson and Bender, 1981; Peterson and Prell, 1985). Since the degree of saturation of biogenic silica and  $\text{CaCO}_3$  does not change markedly between the upper and mid-water column, this cannot explain the decrease in dissolution rates with depth.

Oxygen concentrations are at a minimum from 300 to 500 m at H, 300 to 600 m at C and 250 to 650 m at S, and increase towards the

bottom at all three sites. Since  $O_2$  concentrations are highest where the carbon degradation rates are lowest,  $O_2$  variations cannot explain our data. Rather, the  $O_2$  profiles reflect the degradation rates. High rates of organic carbon degradation will result in high rates of oxygen consumption, and thus low oxygen concentrations.

A decrease in the rate of carbon degradation could decrease the rate of carbonate dissolution, since a mole of metabolic  $CO_2$  could dissolve a mole of  $CaCO_3$ . This reaction has been proposed to explain the dissolution of carbonate in sediments lying above the lysocline (Peterson and Prell, 1985). It is possible that the reaction is important in dissolution of carbonate particles settling above the lysocline, in which case the dissolution of carbonate during settling might be dependent on the rate of organic carbon degradation. However, on a molar basis the degradation of organic carbon is greater than the dissolution of carbonate in the upper and mid-water column at all three sites (Table I-4), indicating that carbonate dissolution is not limited by the availability of metabolic  $CO_2$ .

#### Decrease in the Flux of Labile Fractions

Westrich and Berner (1984) propose that oxic degradation of particulate organic carbon (POC) in seawater is a function of the first order decay of various groups of compounds that have different reactivities with regard to decomposition. Using their terminology:

$$2) \frac{dG_t}{dt} = \sum k_i G_i$$

Table I-4. Normalized Fluxes Converted to Moles. More moles of organic carbon are lost between traps than moles of  $\text{CaCO}_3$ .

Site	Trap Depth	Corg/Al (mol)	Net Loss	$\text{CaCO}_3$ /Al (mol)	Net Loss
H	505 m	5.8	-	4.2	-
	1465 m	2.5	3.3	2.5	1.7
	3075 m	1.4	1.1	2.0	0.5
S	700 m	7.0	-	6.1	-
	1600 m	3.9	3.1	4.6	1.5
	3400 m	2.7	1.2	4.0	0.6
C	1095 m	8.8	-	9.4	-
	1895 m	6.3	2.5	7.4	2.0
	3495 m	5.4	0.9	6.7	0.7

where  $G_t$  is the total POC, and  $k_i$  and  $G_i$  refer to individual fractions with different reactivity. They report that oxic decomposition of fresh plankton samples can be described by assuming that three types of organic matter are present: a highly reactive fraction ( $G_1$ ), a less reactive fraction ( $G_2$ ) and a non-reactive fraction ( $G_{nr}$ ). The change in the POC with time can be expressed as:

$$3) G_t(z) = G_1 e^{k_1 t} + G_2 e^{k_2 t} + G_{nr}$$

We have adapted this approach under the assumption that the mid-water column rates ( $k_m$ ) correspond to a less reactive fraction of each of the biogenic components ( $F_m$ ), and that the change in the normalized flux in the upper water column is a result of the degradation or dissolution of a more labile fraction ( $F_1$ ) with a reaction rate  $k_1$ . This can be expressed as:

$$4) F_t(z) = F_m e^{k_m z} + F_1 e^{k_1 z}$$

We can solve for  $F_1$  by assuming that all of the flux in the trap below the mid-water maximum trap is  $F_m$ , using the equation:

$$5) F_1(z) = F_u - F_m e^{k_m z}$$

where  $F_u$  is the normalized flux measured in the upper water column trap,  $F_m$  is the normalized flux measured in the trap below the mid-water maximum trap, and  $z$  is the difference in depth between the traps, in meters.

The labile component ( $F_1$ ) calculated from equation 5 ranges from 21 to 40% of the measured flux of organic carbon in the upper traps.

Similarly,  $F_1$  as a percentage of the measured flux ranges from 17 to 33% for  $\text{CaCO}_3$ , and 6 to 39% of the opal flux (Table I-5).

The small range in  $k_1$  ( $1.3\text{--}1.7 \times 10^{-3}$ ) from each of the sites and for each component (Table I-5) is a result of the assumption that the flux of the labile fraction in the trap below the mid-water maximum trap is 0. However, the resulting  $k_1$  for organic carbon is within the range reported by Lee and Cronin (1984) for the degradation rate of amino acids in the North East Pacific and Peru margin sediment traps (Table I-2). Additionally, the labile fraction of organic carbon is between 20-40% of the total organic carbon in the upper water column traps, which is similar to the range of amino acids expressed as a percentage of the total organic carbon flux reported by Ittekkot, Deuser and Degens (1984) (13 to 34%) and the maximum reported by Lee and Cronin (1984) (25-50%). The labile fraction in the upper water column traps may therefore represent the amino acid carbon flux, and the loss in the upper water column may reflect rapid decomposition of protein.

The form of the labile fractions of carbonate and opal are not known, but may correspond to the most fragile tests, small particles derived from broken large tests, or the aragonite flux. Betzer, Byrne, Acker, Lewis, Jolley and Feely (1984) report average aragonate fluxes at 100 and 2200 m on a transect of the northwest Pacific. Using equation 1, their data yields an aragonite first order dissolution rate of  $1.7 \times 10^{-3} \text{ m}^{-1}$ , close to the  $1.3\text{--}1.4 \times 10^{-3} \text{ m}^{-1}$  calculated as the rate constant ( $k_1$ ) for the labile carbonate fraction of

Table I-5. Labile Fractions of the Measured Biogenic Fluxes in the Upper Water Column Traps

	Site H 505 m	Site C 1095 m	Site S 700 m
Organic Carbon			
$F_1$ (%)	40	21	33
$k_1$ ( $m^{-1}$ )	$1.7 \times 10^{-3}$	$1.6 \times 10^{-3}$	$1.6 \times 10^{-3}$
CaCO <sub>3</sub>			
$F_1$ (%)	33	20	17
$k_1$ ( $m^{-1}$ )	$1.4 \times 10^{-3}$	$1.3 \times 10^{-3}$	$1.4 \times 10^{-3}$
Opal			
$F_1$ (%)	39	20	6
$k_1$ ( $m^{-1}$ )	$1.5 \times 10^{-3}$	$1.3 \times 10^{-3}$	$1.4 \times 10^{-3}$



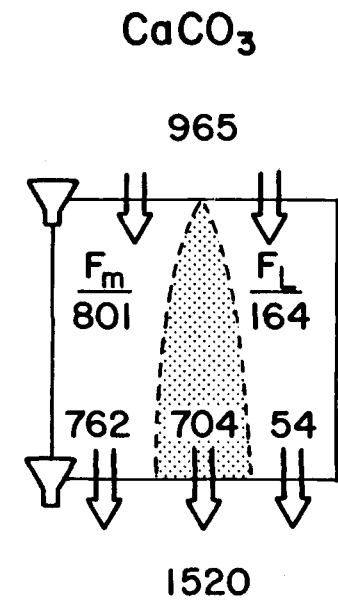
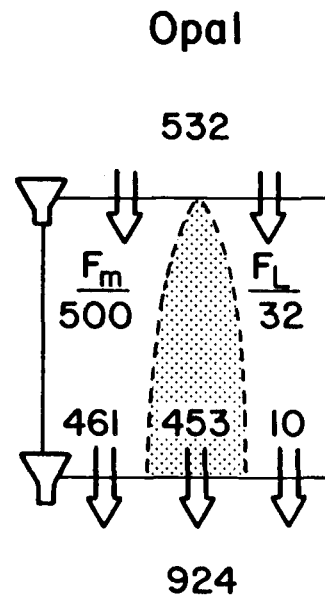
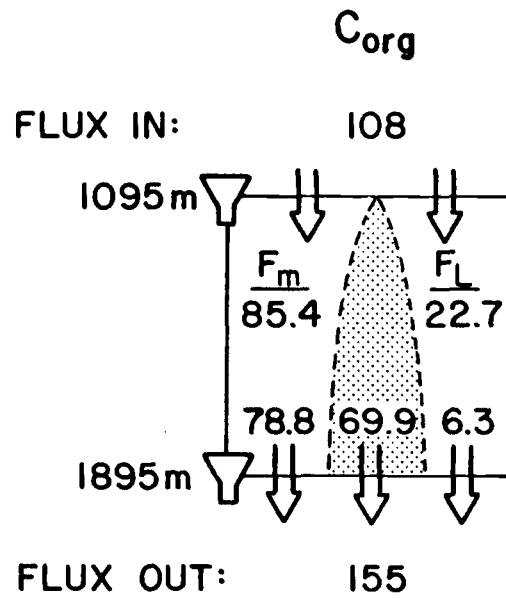
$\text{CaCO}_3$  at our sites. Thus, the decrease in reaction rates with depth could result from the dissolution and degradation of labile fractions within the upper water column. However, the loss of labile biogenic material in the upper water column must be balanced by an increase in the flux of other biogenic material in order to account for the observed mid-water flux maxima.

#### Site C Particle Mass Balance

In Figure I-4 we present particulate box models for the biogenic fluxes in the two shallow traps at site C and estimate the flux that must be generated within the upper water column to balance the input and output. The labile ( $F_l$ ) and less labile midwater ( $F_m$ ) fluxes for each component were calculated using equation 5. The particle flux generated within the upper water column was calculated as the difference between  $F_m$  and  $F_l$  out of the box, and the measured flux in the 1895 m trap. The box modeling shows that  $F_l$  contributes less than 4% of the measured biogenic fluxes in the 1895 m trap, and thus will have a minor effect on the determination of the rate constants in the mid-water column ( $k_m$ ). Additionally, the sum of  $F_m$  and  $F_l$  out of the box accounts for only 55% of the measured organic carbon flux, 51% of the opal flux, and 54% of the  $\text{CaCO}_3$  flux. Thus, almost half of the biogenic flux to the mid-water column is generated between the two traps rather than passively settling from above.

Figure I-4. Box models of the upper water column biogenic fluxes at MANOP site C. All fluxes are in units of  $\mu\text{g}/\text{cm}^2 \text{ yr}$ .  $F_l$  and  $F_m$  are the fluxes which degrade or dissolve at labile and mid-water column rates, respectively (see text). The flux in the stippled area is the flux that must be generated within the box to balance the flux in with the flux out.

Figure I-4



### Heterotrophic Activity

Organisms feeding on settling particles may affect changes in flux directly, such as by consumption of organic carbon, or indirectly, by reactions in the organisms' guts that may increase dissolution. A decrease in the rate of particle ingestion with depth would then lead to a decrease in the reaction rates. While this is a possible explanation for decreasing reaction rates with depth, we cannot distinguish this with our data.

### Possible Modelling Artifacts

Lastly, artifacts of the modeling could also account for a decrease in the calculated reaction rates with depth. A doubling of the mean particle settling velocity will decrease the calculated reaction rate constants by a factor of two. Assuming that  $k_m$  applies in the upper water column and that the differences between  $k_m$  and  $k_u$  are due only to lower particle settling velocities in the upper water column, the settling rates in the upper water column must be markedly lower than our assumed 100 m/day. Moreover, the settling rates derived from the organic carbon,  $\text{CaCO}_3$ , and opal data vary considerably at each site (23 to 41 m/day at H, 10 to 31 m/day at S, and 21 to 59 m/day at C). If a change in the settling velocity occurred uniformly over the particle population, the rates of each of the biogenic components should decrease proportionally. Additionally, a settling rate of 10-20 m/day is too low for the fecal pellets and

aggregates that dominate the particle flux (Fowler and Small, 1972; McCave, 1975; Silver et al. 1978; Small et al. 1979, Shanks and Trent, 1980; Komar et al., 1981). It thus seems unlikely that changes in the mean settling rate can account for all of the change in the rate constants.

In the previous calculations we have assumed that the change in the normalized fluxes was due to dissolution and degradation of the biogenic fluxes. However, as in case 2 of Figure I-2, when the aluminum flux increases relative to the biogenic fluxes the calculated rate constant will be greater than the actual rate constant. The decrease in rate constants may thus result from a decrease in the rate of aggregation of aluminosilicates with depth, and the apparent change in rates may be an artifact of our assumption that no aggregation occurs.

We can estimate the maximum aggregation rate of Al in the upper water column by assuming a first order aggregation process (Spencer, 1985) and assuming that  $k_m$  is valid for the upper water column.

Thus

$$6) \frac{dF_u^i}{dz} = k_u F_u^i = (k_m + k_a) F_u^i \text{ and}$$

$$7) k_a = k_u - k_m$$

where  $F_u^i$  is the normalized flux of biogenic component  $i$  measured in the upper water column trap,  $\frac{dF_u^i}{dz}$  is the change in the normalized flux of  $i$  with depth,  $k_u$  is the reaction rate constant for  $i$  in the upper water column calculated from the normalized fluxes in the upper

water column trap and the mid-water maximum trap using equation 1, and  $k_a$  is the aggregation rate constant for aluminum.

There is only a slight difference between the aggregation rate constant ( $k_a$ ) calculated from the biogenic flux data at H, but a factor of 2 to 3 difference at S and C (Table I-6). If aggregation of aluminum was the only process affecting the change in the observed rate constants, then the aggregation rate constant calculated from each of the biogenic fluxes should be equal. Since the aggregation rate constant varies depending on the biogenic flux data used in the calculation, it follows that a simple change in the aluminum flux cannot fully explain the change in reaction rate constants. Additionally, Spencer (1985) predicts that at sites far from the western boundary of an ocean basin (2400 km) the aluminum flux is essentially constant with depth. It is interesting to note however, that filtering and ingestion of particles by organisms may result in an increase in the aluminum flux (Spencer, 1985) and contribute to the loss of organic carbon (Lee and Cronin, 1984).

#### Sediment Implications

Our analysis which uses multiple rate constants for the decomposition of particulate carbon also has implications for the preservation of organic carbon in sediments. Emerson, Fischer, Reimers, and Heggie (1985) calculate first order degradation rate constants of organic carbon in the sediments at sites H and C about three orders of magnitude less than the mid-water organic carbon degradation rate

Table I-6. Aggregation Rate Constants for Aluminum in the Upper Water Column Necessary to Explain Change in Dissolution and Degradation Rates with Depth, Assuming No Aggregation in the Mid-Water Column (see text)

Site	Organic Carbon	Determined from	
		CaCO <sub>3</sub>	Opal
H	$5.2 \times 10^{-4} \text{ m}^{-1}$	$4.2 \times 10^{-4} \text{ m}^{-1}$	$5.1 \times 10^{-4} \text{ m}^{-1}$
S	$4.4 \times 10^{-4} \text{ m}^{-1}$	$2.4 \times 10^{-4} \text{ m}^{-1}$	$2.5 \times 10^{-4} \text{ m}^{-1}$
C	$3.1 \times 10^{-4} \text{ m}^{-1}$	$2.3 \times 10^{-4} \text{ m}^{-1}$	$8.0 \times 10^{-5} \text{ m}^{-1}$

we calculate. Moreover, benthic oxygen consumption experiments have shown a seasonal signal (Smith and Baldwin, 1984), whereas Emerson et al.'s (1985) data indicate that a seasonal input would result in a minor difference in benthic oxygen consumption due to the long residence time of organic carbon in the sediments. We suggest that our data reflects the reaction rate of the organic carbon flux which contributes to the seasonal oxygen consumption, while Emerson et al.'s (1985) data reflect the portion of the primary flux of organic carbon which is incorporated into the sediments.

The traps near the bottom at sites C and H show a rapid decrease in the normalized fluxes (Figure I-3), and a concurrent increase in biogenic fluxes (Figure I-4). Thus it appears that near-bottom processes contribute both biogenic and refractory components to the particle flux. Simple resuspension of surface sediments cannot be the sole cause of the flux increases since surface sediments have low biogenic component/Al ratios. This phenomena is explored more fully in a subsequent paper (Walsh et al., 1985). However, it is important to note here that near-bottom traps should not be directly compared to mid-water column traps due to the possibility of input of material through resuspension or bioactive transport by benthopelagic organisms (Fischer, 1984; Rowe and Gardner, 1979; Wishner, 1980).



## CONCLUSIONS

In contrast to previous reports of little or no loss of biogenic material by dissolution or degradation during settling (Ittekkot, Degens and Honjo, 1984; Wakeham et al., 1984) our results indicate that 23 to 53% of the organic carbon flux measured in the mid-water maximum trap is recycled during settling, along with 15 to 23% of the carbonate flux, and 8 to 37% of the opal flux.

Normalization of biogenic fluxes to aluminum, under the assumption that the aluminum content of the particles is fixed at the time of particle formation, allows for estimation of reaction rates and contributions to the particle flux from sources other than the vertical or primary flux. Thus, the methodology presented here allows for constrained analysis of sediment trap data and the processes involved in transport of material by fast settling particles.

The upper water column (above 1500 m) is a site of multiple particle input zones, and higher apparent reactivity. Packaging and transport of material by zooplankton and nekton is the most likely cause of the widely observed mid water column maximum of fluxes measured in sediment traps. The observed higher reaction rate constants for the normalized fluxes in the upper water column ( $k_u$  vs.  $k_m$ ) are probably a result of a combination of factors, including scavenging of alumino-silicates and the recycling of highly labile fractions of fluxes. From comparisons of our results with estimates of the dissolution rate of aragonite (Betzner et al., 1984) and the degradation rate of amino acids (Lee and Cronin, 1984) it appears that the recy-

ling of labile fractions of the biogenic components can account for the decrease in the reaction rates between the upper and mid water column. Consumption and repackaging of particles by organisms may mediate both the increase in aluminum flux and the loss of the labile fractions.

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## CHAPTER II

### EVIDENCE FOR RESUSPENSION OF BIOGENIC DETRITUS FROM NEAR BOTTOM SEDIMENT TRAPS.



## ABSTRACT

Near-bottom sediment trap moorings were recovered at three sites in the North Equatorial Pacific. Total particulate fluxes recorded in sediment traps moored within 500 m of the ocean floor were greater than those recorded in mid-water column traps. A simple model assuming all of the flux increase was due to resuspended sediment does not account for increases in the major biogenic components of the particulate flux (organic carbon, calcium carbonate and opal). The "rebound" of recently deposited biogenic detritus may account for these increases, however. Hydraulic fractionation probably enriches the "rebound" material in organic carbon with respect to calcium carbonate and opal.

## INTRODUCTION

Fecal pellets and "marine snow," composed of biogenic detritus derived from the euphotic zone form the primary flux of material to the sediment surface (Schrader, 1971; McCave, 1975; Honjo, 1978; Shanks and Trent, 1980; Dueser, Ross and Anderson, 1981; Urrere and Knauer, 1981). Settling at 100 150 m/day, these particles may take one to two months to reach the bottom of the deep ocean basins (Fowler and Small, 1972; Small, Fowler and Unlu, 1979; Shanks and Trent, 1980; Suess, 1980, Komar, Morse, Small and Fowler, 1981). The major components of this particle flux, organic carbon, calcium carbonate, and biogenic opal, are partially recycled during settling

(Walsh, Dymond and Collier, 1985). Consequently, without inputs from other sources, the flux of these biogenic components decreases with depth.

Sediment traps moored near the sediment surface collect both the particles settling from above and resuspended sediment (Spencer, Brewer, Fleer, Honjo, Krishnaswami and Nozaki, 1978; Rowe and Gardner, 1979; Fischer 1984, Gardner, Southard and Hollister, 1985). Since sediments are enriched in clay and strongly depleted in biogenic material relative to the primary flux (Fischer, 1984), near bottom sediment traps record strong increases in the flux of alumino-silicate bound elements such as Al, Fe, and Sc, as compared to sediment traps moored above the nepheloid layer.

Suspended particles in the nepheloid layer closely resemble the underlying sediment in composition, suggesting that resuspension of sediment is the source of these particles (Gardner, Southard and Hollister, 1985). Nepheloid layers can be hundreds of meters thick, as bottom mixed layers 30-200 m thick may separate from the bottom and disperse along isopycnal surfaces (Armi, 1978). Additionally, sediment resuspended from regional topographic features, such as mid-ocean ridges, continental slopes, and seamounts, may contribute to extending nepheloid layers 500 m or more above the local bottom.

Settling of individually suspended particles is too slow to contribute significantly to the downward flux of particles (McCave, 1975), and thus suspended nepheloid layer particles should not contribute significantly to the observed near bottom flux increases. However, Spencer et al. (1978) attribute the clay-rich fecal pellets

recovered from a sediment trap moored 214 m above the bottom (m.a.b.) in the Sargasso Sea to the filtering of nepheloid particles by benthopelagic zooplankton. Within the nepheloid layer production of fecal pellets probably increases towards the bottom as the biomass of benthopelagic zooplankton is greater 10 m.a.b. than 100 m.a.b. (Wishner, 1980a, b). Additionally, any large particles resuspended by transient currents probably settle rapidly back to the sediment surface and are not transported vertically to a great extent. It is thus likely that, through biologically mediated aggregation and hydraulic fractionation, the closer a trap is to the bottom, the higher the measured flux of resuspended sediments will be.

The composition of nepheloid layer particles, however, may reflect seasonal changes in surface water productivity. The flux of material through the water column has been shown to reflect seasonal productivity changes (Deuser et al, 1981; Billet, Lampitt, Rice, and Mantoura, 1983; Fischer, 1984), and interannual variations (Dymond and Collier, 1985). Lampitt (1985) reports that at a site 4000 m deep in the northeast Atlantic, the seafloor became covered with a carpet of biogenic detritus derived from the spring bloom during June, 1983. The material moved along the sediment surface and was resuspended when current measurements exceeded 7 cm/sec, at 1 m.a.b. Most of the biogenic detritus was no longer visible by mid-August of the same year, and previous photographic surveys indicate that the bottom in September resembled the pre-spring bloom conditions.

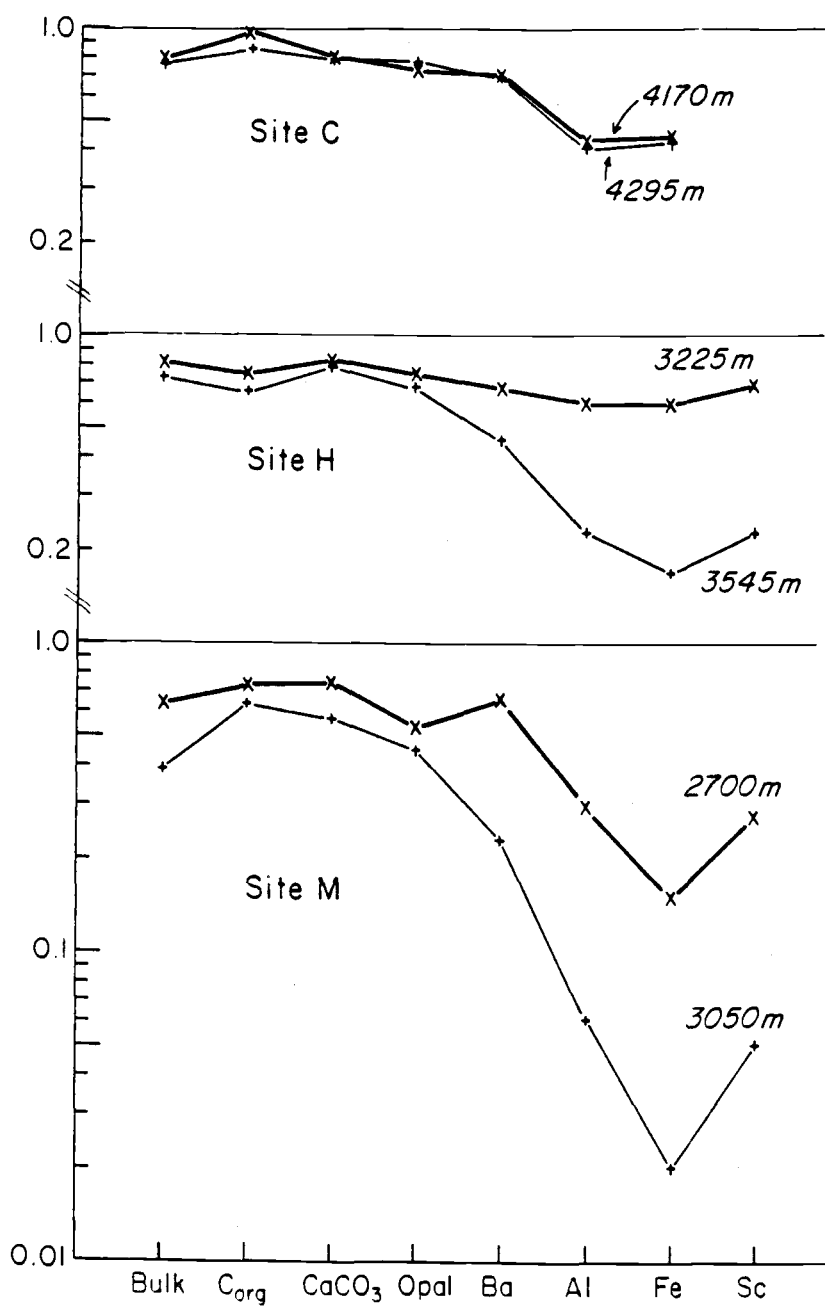
The resuspension of biogenic-rich material following high productivity periods in the surface water would result in a transient change in the particle composition in the nepheloid zone from a clay rich composition similar to the surface sediment composition to a biogenic rich composition reflecting the biogenic detritus composition. Sediment traps near the bottom may therefore collect biogenic detritus that has spent some period of time on the sediment surface prior to resuspension. Results of photographic surveys indicate that deposition and resuspension of biogenic detritus associated with high productivity events in the euphotic zone occurs over only a few months (Billet et al., 1983; Lampitt, 1985).

Processes occurring in the near-bottom layer of the water column are still poorly understood and have only recently begun to be explored on a year-long basis. We present here the results of three year-long deployments of sediment traps at MANOP sites C, H, and M in the north equatorial Pacific. We discuss the results of the near-bottom deployments, concentrating on the possible sources for the observed flux increases in the near bottom traps as compared to the mid-water column traps which define the primary flux (Figure II-1) (Walsh, Dymond and Collier, 1985). We address four possible mechanisms to account for flux increases and the composition of material in the near bottom traps:

- 1) resuspension of sediment,
- 2) fractionation of resuspended sediment,
- 3) benthic production, and
- 4) resuspension of biogenic detritus.

Figure II-1. Normalization plots of the flux of primary material divided by the measured flux for near bottom traps at MANOP sites C, H and M. Included is the total particulate flux and major and minor components. Ratios of less than 1 indicate that the primary material flux is insufficient to account for the measured flux.

Figure II-1



## METHODOLOGY

Data was collected from long-term deep ocean mooring arrays at three MANOP sites in the Pacific (Figure II-2). Site H is located in the Guatemala basin about 900 km east of the East Pacific Rise, and 900 km west of the continental margin. Local relief is approximately 25 m. The sediments are hemipelagic and lie below the calcium compensation depth. Near-bottom current velocities during the deployment averaged 3 cm/sec with a maximum of 10 cm/sec.

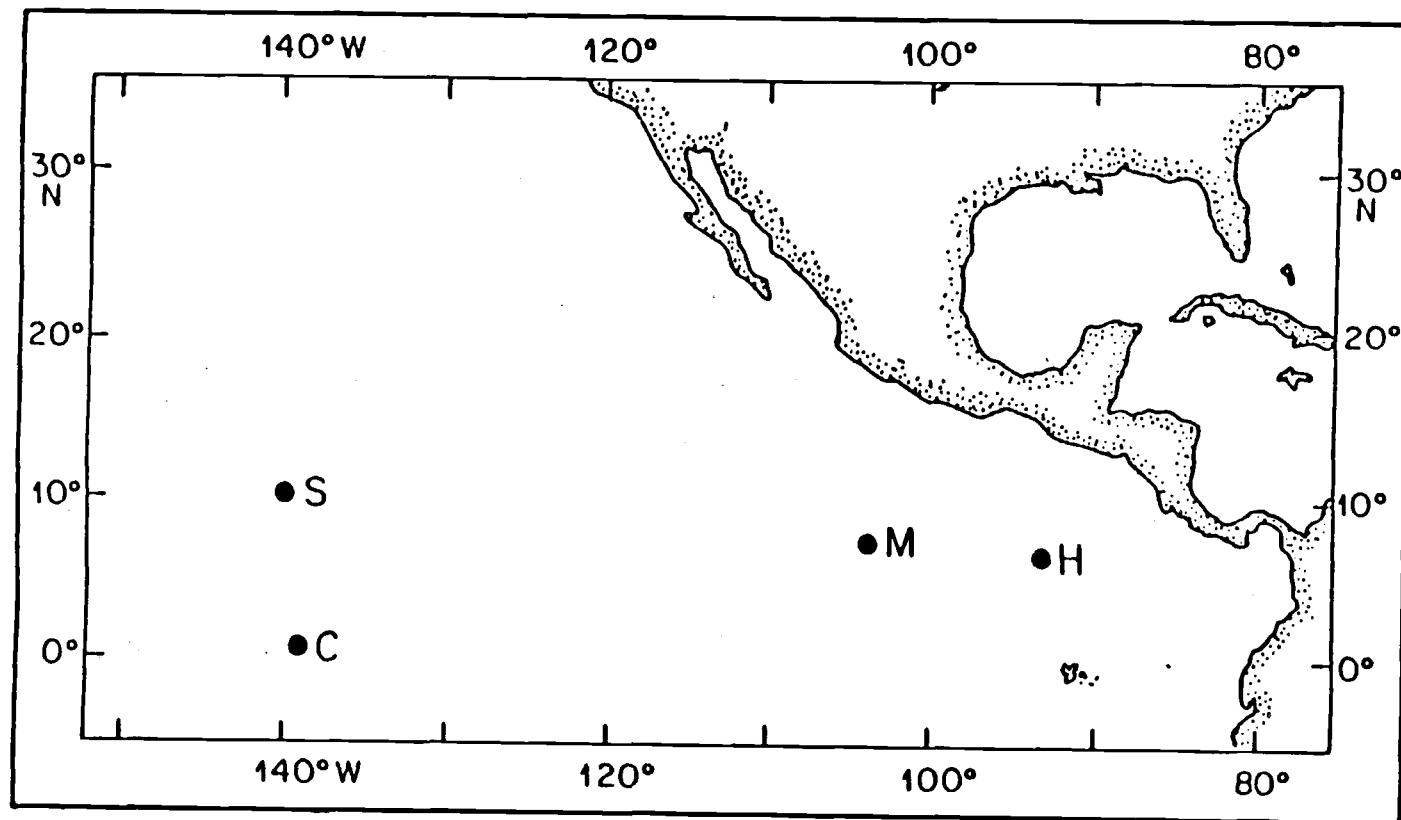
Site M is located in a sediment pond approximately 25 km east of the crest of the East Pacific Rise. Local relief is dominated by fault scarps and is on the order of 150 m. Carbonate is accumulating the metaliferous sediments of the site. Near bottom current velocities during the deployment averaged 4 cm/sec with a maximum of 13 cm/sec. Site C lies close to the equator under the high productivity region associated with the equatorial divergence. Local relief is slight, though the site lies in a basin between a number of seamounts.

The moorings were equipped with single cone OSU sediment traps which collect sequential seasonal samples, and double cone Soutar traps which collect a single sample for the deployment period. The sample cups on the OSU traps were poisoned with sodium azide to prevent bacterial decay. The Soutar traps were poisoned with buffered formalin. Recent comparisons between formalin and azide poi-

Figure II-2. Map of the North Pacific showing locations of MANOP sites C, H and M. The traps were deployed at site C from December 1982 to February 1983, and at sites H and M from September 1980 to October 1981.



Figure II-2



soned cups showed agreement within 5% for concentrations of the biogenic components (Moser, Fischer and Dymond, 1985).

Trap samples were sieved through a 1 mm nylon mesh, freeze dried, ground, and split for analysis. Salt corrections were made by difference in weight after freeze drying. Aluminum, barium, silicon, iron and scandium concentrations were determined by Instrumental Neutron Activation Analysis (INAA). Organic carbon and calcium carbonate measurements were made with a LECO carbon analyzer using a phosphoric acid/wet oxidation procedure (Weliky, Suess, Ungerer, Muller and Fischer, 1983). Biogenic opal was calculated normatively by assuming all particulate Al is detrital aluminosilicate with a Si/Al value of 3.0, and all remaining Si is in opal (Fischer, 1984). Since non-biogenic Si in our samples never exceeds 10% of the total Si, this normative determination of opal is insensitive to errors in the assumed Si/Al ratio of aluminosilicates. Details of the analytical techniques have been reported previously (Fischer, 1984).

Sediment concentrations were taken from the upper 5 mm of sediments recovered from Soutar box cores, which recover an undisturbed sediment surface (Soutar, Johnson, Fischer and Dymond, 1981). These samples contain the highest concentrations of the biogenic components of sediment samples at each site.

The primary flux is extrapolated from traps assumed free of resuspended material. The biogenic fluxes at depths below the primary flux traps are estimated using a first order decay model that assumes a particle settling rate of 100 m/day (Walsh, Dymond and Collier, 1985). Aggregation and disaggregation are not considered to

affect the primary flux below the depth of the primary flux trap. Primary fluxes of Al, Fe, Ba, and Sc are assumed to be in non-reactive phases through the near bottom zone and thus constant from the primary flux trap. The total particulate primary flux is corrected for the loss of opal,  $\text{CaCO}_3$  and organic carbon, assuming organic carbon is present as  $\text{CH}_2\text{O}$ .

## RESULTS

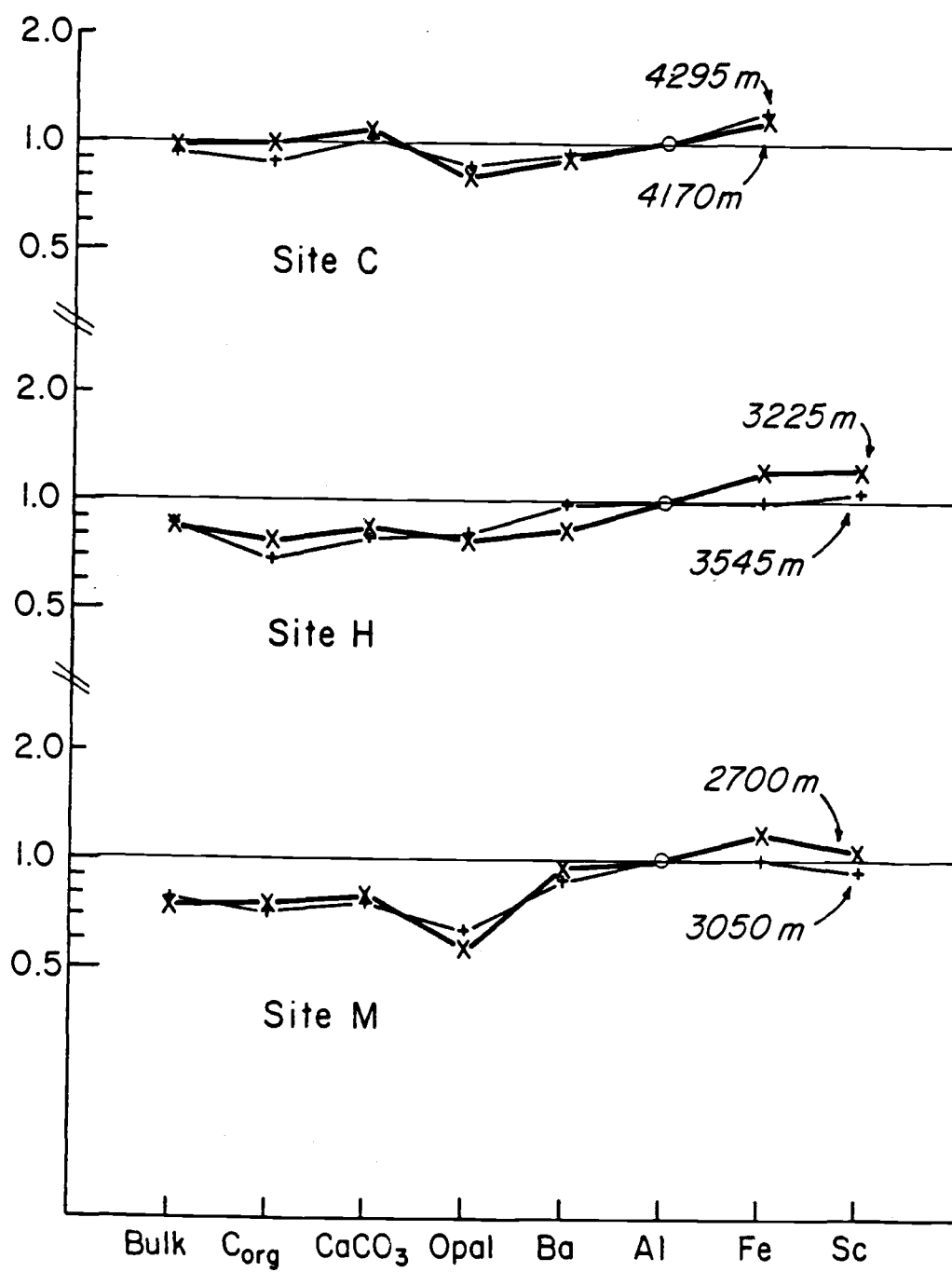
At all three sites the near-bottom traps recorded higher bulk fluxes than the extrapolated primary material flux (Figure II-1). Flux increases were observed in the biogenic components (organic carbon,  $\text{CaCO}_3$ , and opal) as well as the refractory elements: Ba, Al, Fe, and Sc.

The percentage of the total particulate flux contributed by primary material decreases towards the bottom at H and M. At site C the fraction of the total particulate flux contributed by the primary flux is similar in both traps. The difference between the sites in this respect may be because the lowermost traps at M and H were only 30 m.a.b. while the deepest trap at C was 175 m.a.b.

Generally, the primary material is insufficient to account for the measured fluxes in the near bottom sediment traps. Other sources of material must therefore be contributing to the measured fluxes.

Figure II-3. Normalization plot of the primary material and resuspended surface sediment fluxes divided by the measured flux for the near-bottom traps at MANOP sites C, H and M. Ratios less than 1 indicate that the primary material and the resuspended sediment are insufficient to account for the measured flux. Ratios greater than 1 result from an overestimation of the flux supplied by the resuspended sediment and primary material. Note that A1 is fixed at 1 by the model's assumptions.

Figure II-3



### Resuspension of Sediment

The most likely source of material is resuspended surface sediment, which has been observed to contribute to the measured flux in sediment traps in other locations (Rowe and Gardner, 1979; Gardner, Southard and Hollister, 1985). We therefore analyze the data under the assumption that the observed flux increases are the result of resuspension of surface sediments. We assume that all of the aluminum increase is due to resuspended sediment material. We use aluminum because it is highly enriched in the sediments relative to the primary flux and it is an effective tracer of refractory aluminosilicates (Spencer, et al., 1978; Dymond, 1981; Honjo, Spencer and Farrington, 1982). The measured flux of aluminum in the near bottom traps can be partitioned according to the relationship:

$$1) Al_m = Al_p + [Al]_s \times S.$$

where  $Al_m$  is the measured flux of aluminum in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ ,  $Al_p$  is the primary flux of aluminum in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ ,  $[Al]_s$  is the concentration of Al in the surface sediments in  $\mu\text{g}/\text{mg}$ , and  $S$  is the bulk flux of resuspended sediment in  $\text{mg}/\text{cm}^2 \text{ yr}$ . As all but  $S$  are known, this equation can be solved for  $S$  for any trap. The sediment flux of any other component ( $i$ ) is found by multiplying  $S$  by the concentration of that element in the sediment. Thus:

$$2) M^i = P^i + [i]_s \times S + R^i,$$

where  $M^i$  is the measured flux of component  $i$  in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ ,  $P^i$  is the primary flux of  $i$  in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ ,  $[i]_s$  is the concentration of  $i$  in the surface sediment in  $\mu\text{g}/\text{mg}$ ,  $S$  is the bulk sediment flux in

$\text{mg/cm}^2 \text{ yr}$  determined from equation (1), and  $R^i$  is the residual flux of  $i$  in  $\mu\text{g/cm}^2 \text{ yr}$ .

This approach shows that most of the refractory material could be supplied by resuspended sediments and the primary material (Figure II-3). However, substantial (>20%) portions of the measured biogenic component fluxes cannot be accounted for by sediment resuspension and the primary material. Additionally the Fe and Sc fluxes are overestimated ( $[P + S]/M > 1$ ) in the 3225 m trap at H, and the 2700 m trap at M, indicating that the amount of resuspended sediments is overestimated, most likely due to the assumption that all of the aluminum increase is due to resuspended surface sediment.

The model accounts for most of the measured fluxes at C to a greater extent than at M and H. However, less than 90% of the opal and organic carbon fluxes measured in the 4295 m trap can be supplied by the primary material and resuspended sediment, while iron and  $\text{CaCO}_3$  are supplied in excess of that measured in both traps, indicating that the resuspended sediment input to the traps is overestimated at site C also.

## DISCUSSION

The results demonstrate that a process of simple resuspension of sediments in addition to the settling of the primary material is inadequate to explain the near bottom fluxes. Since we assume that all of the difference between the measured and primary fluxes of aluminum are the result of the input of resuspended sediments, and since we used the compositional data from surficial sediments which

have the highest ratios of biogenic components to Al in the sediments, this model results in a maximum estimate for resuspended fluxes of the biogenic compounds, provided that only sediments are resuspended. Since the sum of the primary and resuspended sediment fluxes of biogenic components are exceeded by the measured fluxes there must be an additional source of these components.

Hydraulic fractionation of resuspended sediment, however, could complicate this simple model. We have examined the effects of hydraulic fractionation by measuring the concentration of carbonate and opal in different size fractions of the surface sediments at sites C and H. Generally, the weight percentages of opal and carbonate within a size fraction increase with increasing size. Tests of foraminifera and radiolarians were found to make up almost all of the  $>150\text{ }\mu\text{m}$  fraction in the sediments. Since hydraulic fractionation results in preferential resuspension of small particles, this process would be expected to result in a resuspended sediment depleted in opal and carbonate relative to the clay fraction. Thus, hydraulic fractionation of resuspended particles cannot explain an underestimated flux of  $\text{CaCO}_3$  or opal.

Hydraulic fractionation may explain why the model overestimates the near bottom  $\text{CaCO}_3$  flux at site C. The  $>150\text{ }\mu\text{m}$  fraction at site C comprises 16.6% by weight of the surface sediment and is 94%  $\text{CaCO}_3$ . It is likely that the  $>150\text{ }\mu\text{m}$  fraction of the sediment is resuspended to a lesser degree than the clay fraction. The  $\text{CaCO}_3$  to aluminum ratio in the resuspended material may therefore be less than that of the sediment composition, as was used in the model, which



would result in the model overestimating the sediment flux of  $\text{CaCO}_3$ .

Dissolution and oxidation reactions during resuspension may also occur, but again, these processes cannot explain an underestimated biogenic flux. These reactions would enrich the clay fraction over the biogenic components of the resuspended material. Benthic production of calcium carbonate is not sufficient to explain the difference between the fluxes estimated by the model and those measured, as benthic foraminifera comprise less than 5% of the species assemblages found in the near bottom traps. In addition, those found in the sediment are included in the surface sediment analysis, and thus are already included in the sediment resuspension model.

Chemolithotrophy by bacteria may be a source of organic carbon in the near bottom (Karl, Knauer, Martin and Ward, 1984). This process, however, has not been investigated in the lower water column. In any case, chemolithotrophy can not explain enhanced opal or  $\text{CaCO}_3$  fluxes in the near bottom zone.

To summarize, the biogenic components: organic carbon,  $\text{CaCO}_3$ , and opal, are not supplied in sufficient magnitude by sediment resuspension to account for the increase of their fluxes in the near bottom. This suggests that a component enriched in biogenic material relative to aluminum is required to balance the fluxes. The refractory elements: Fe, and Sc, which are relatively enriched in the sediment compared to primary material, are overestimated by the maximum sediment flux, suggesting that a source depleted in Fe and Sc relative to Al contributes to the flux captured in near bottom

traps. In addition, shell counts of microfossils that are not found in the sediment have been found to increase in the near bottom traps at site H (Murray, unpublished data). Therefore, sources of material other than the underlying sediments must be present in the near bottom zone to explain the measured flux increases (Figures II-1 and II-3).

#### Resuspension of Sediment and Phytodetritus: the "Rebound" Model

To account for the flux components not well explained by the simple sediment resuspension model, we consider resuspension of biogenic detritus (BD). This component represents freshly deposited primary material (such as observed by Billet et al., 1983; and Lampitt, 1985). Because the primary material spends at most a few months on the bottom prior to resuspension (Billet et al., 1983; Lampitt, 1985), we have termed this process the "rebound" of the primary material.

To quantify the sediment and biogenic detritus contributions to the measured flux we assume that all the Al and organic carbon can be accounted for by the primary material, and resuspended sediment and biogenic detritus. Organic carbon was chosen because of its low concentration in the surface sediments at all three sites. For Al:

$$3) Al_m = Al_p + [Al]_s \times S + Al_{bd}$$

where  $Al_m$  is the measured flux of Al in  $\mu g/cm^2$  yr,  $Al_p$  is the primary flux of Al in  $\mu g/cm^2$ ,  $[Al]_s$  is the concentration of Al in the surface sediments in  $\mu g/mg$ , S is the bulk flux of the sediment com-

ponent in  $\mu\text{g}/\text{cm}^2$ , and  $\text{Al}_{\text{bd}}$  is the flux of Al contributed by the resuspended biogenic detritus in  $\mu\text{g}/\text{cm}^2\text{yr}$ . For organic carbon:

$$4) C_m = C_p + [C]_s \times S + (C/Al)_{\text{bd}} \times \text{Al}_{\text{bd}}$$

where  $C_m$  is the measured flux of organic carbon in  $\mu\text{g}/\text{cm}^2\text{ yr}$ ,  $C_p$  is the primary flux of organic carbon in  $\mu\text{g}/\text{cm}^2\text{ yr}$ ,  $[C]_s$  is the concentration of organic carbon in the surface sediments,  $S$  is the bulk flux of the sediment component in  $\text{mg}/\text{cm}^2\text{ yr}$ ,  $(C/Al)_{\text{bd}}$  is the flux ratio of organic carbon to Al in the biogenic detritus, and  $\text{Al}_{\text{bd}}$  is the flux of Al contributed by the resuspended biogenic detritus in  $\mu\text{g}/\text{cm}^2\text{ yr}$ . We assume that  $(C/Al)_{\text{bd}}$  is the same as that of the primary material extrapolated to the sediment surface. As only  $S$  and  $\text{Al}_{\text{bd}}$  are unknown in equations (3) and (4), we can solve these equations simultaneously.

For all other flux components (i), the partitioning equation is:

$$5) M^i = P^i + [i]_s \times S + (i/Al)_{\text{bd}} \times \text{Al}_{\text{bd}} + R^i,$$

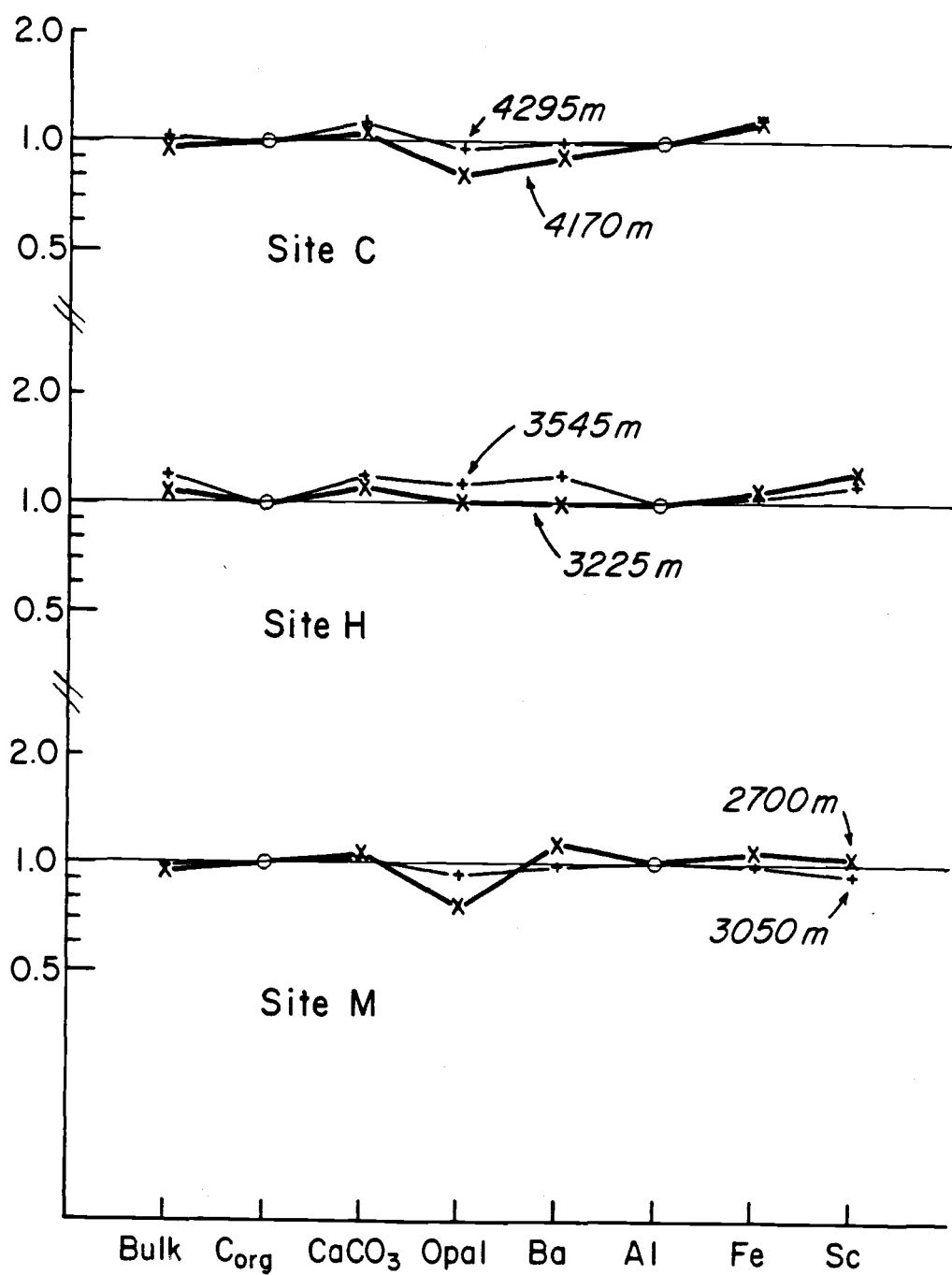
where  $M^i$  is the measured flux of component i in  $\mu\text{g}/\text{cm}^2\text{ yr}$ ,  $P^i$  is the primary flux of i in  $\mu\text{g}/\text{cm}^2\text{ yr}$ ,  $[i]_s$  is the concentration of i in the surface sediments in  $\mu\text{g}/\text{mg}$ ,  $S$  is the bulk sediment flux in  $\text{mg}/\text{cm}^2\text{ yr}$  from equations (3) and (4),  $(i/Al)_{\text{bd}}$  is the ratio of i to Al in the biogenic detritus (i.e., the primary material extrapolated to the bottom),  $\text{Al}_{\text{bd}}$  is the flux of Al in  $\mu\text{g}/\text{cm}^2\text{ yr}$  contributed by the resuspended biogenic detritus determined using equations (3) and (4), and  $R^i$  is the residual flux of i in  $\mu\text{g}/\text{cm}^2\text{ yr}$  needed to balance the equation.

The rebound model rather closely matches the observed fluxes of most components (Figure II-4). However, this model generally overestimates the bulk and biogenic fluxes in the near bottom traps. These subtle discrepancies could be the result of the probability that resuspension of biogenic detritus is a seasonal phenomena (Billett et al., 1983; Lampitt, 1985), and our use of a yearly average flux may be a source of discrepancy between the modeling and the measured fluxes. This may be particularly important for  $\text{CaCO}_3$  and opal since the proportion of primary production contributed by opaline vs.  $\text{CaCO}_3$ -bearing organisms changes through the year (Murray, Pisias and Dymond, 1985). Additionally, our model assumes that the composition of the biogenic detritus does not change from the time it first reaches the sediment to the time it is collected in the sediment trap. The validity of this assumption depends on the length of time between initial deposition and a rebound event and the distance between the area of resuspension and the traps. While this assumption may be adequate for the traps 30 m.a.b., there may be compositional differences between the resuspended biogenic detritus reaching the traps further above the bottom and the estimated composition. This is because it is unlikely that the biogenic detritus from the site itself was mixed directly upwards for 300 m. Rather, it is more likely that this material comes from some distance away, resuspended from topographic highs or dispersed along pycnoclinal surfaces via detached bottom mixed layers (Armi, 1978).

Hydraulic fractionation may also affect the composition of resuspended biogenic detritus. The bulk fluxes of the three seasonal

Figure II-4. Normalization plot of the results of the rebound model. The rebound model flux is the sum of the primary material, resuspended surface sediments, and resuspended biogenic detritus. Note that both organic carbon (Corg) and Al are fixed at 1 by the model's assumptions.

Figure II-4



samples from a trap assumed free of resuspension influence (3075 m) and the trap closest to the bottom (3545 m) at site H were partitioned into four size fractions (Figure II-5). Since dissolution and breakdown of particles is expected to result in decreases of the flux of large particles with depth, we assume that the increases in the fluxes between the two traps are due to resuspension and rebound.

The periods of highest total flux (cup 1), and highest velocity bottom currents (cup 3, Fischer, 1984) recorded flux increases in the three smallest size fractions between the traps, and the same (cup 3) or larger (cup 1) fluxes in the  $>150$   $\mu\text{m}$  fraction. It therefore appears that the degree of hydraulic fractionation is inversely related to both high flux and high bottom current velocities. As noted previously, the larger size fractions are mostly carbonate and opal tests. Hydraulic fractionation may therefore explain the overestimated fluxes of  $\text{CaCO}_3$  and opal in the rebound model, and the relative enrichment of organic carbon in the near bottom trap material.

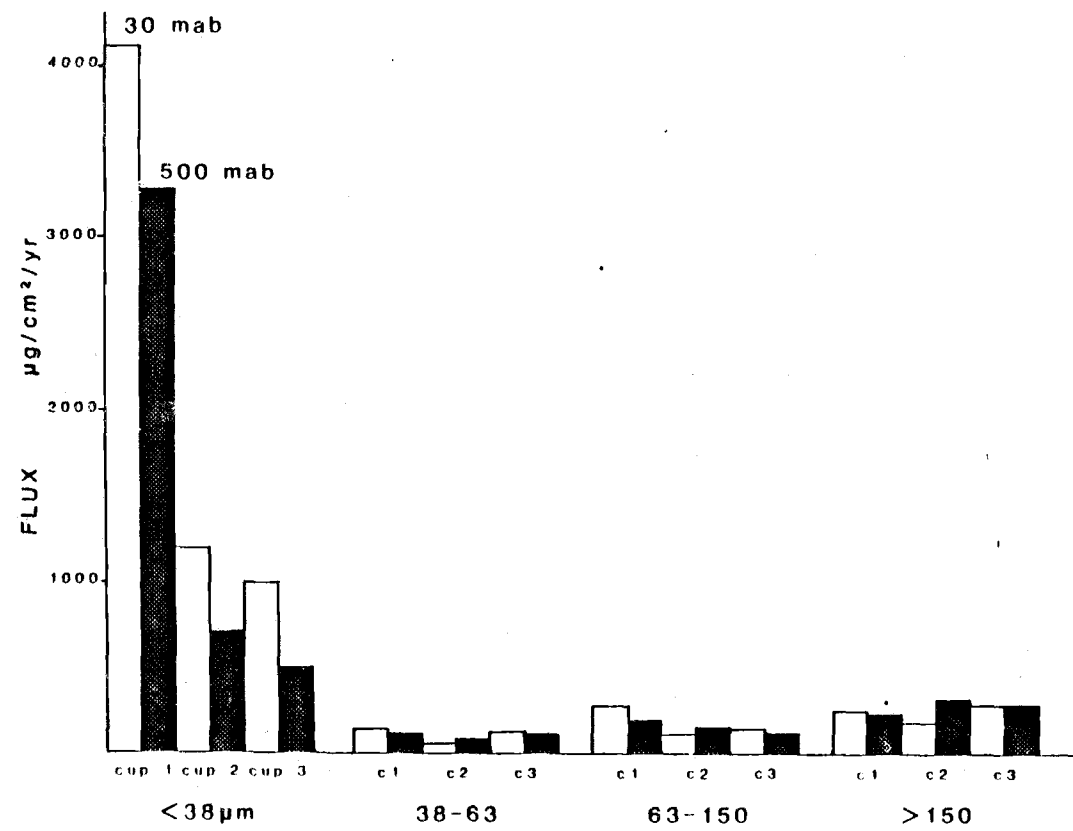
## CONCLUSIONS

Our modeling indicates that the fluxes measured in near bottom sediment traps cannot be explained by simple resuspension of surface sediments. Nor can the fluxes be explained by a combination of hydraulic fractionation and resuspension. Microbial chemolithotrophy could increase the near bottom organic carbon fluxes, but it cannot account for similar increases in near bottom  $\text{CaCO}_3$  and opal.

Figure II-5. Measured fluxes of four size fractions of the bulk flux from three seasonal samples of two sediment traps at site H. The 3075 m samples are assumed to reflect the size composition of primary material. Increases in fluxes in the 3545 m samples compared to the 3075 m samples are assumed to reflect input of resuspended material.



Figure II-5



The inadequacy of the simple sediment resuspension modeling, and the fact that shell counts of microfossils not found in the sediments increase in the near bottom, lead us to conclude that biogenic detritus, composed of slightly altered primary flux material, is resuspended before incorporation into the sediments, a process we term the "rebound" of primary material. Hydraulic fractionation of this material may account for the relative enrichment of organic carbon vs. opal and  $\text{CaCO}_3$  in the excess near bottom fluxes, as large ( $>150 \text{ } \mu\text{m}$ ) foraminifera and radiolarian tests may not be resuspended except during very high velocity currents.

The rebound material may be similar to the "fluff" layer reported by observers in deep sea submersibles. As the flux of biogenic components in the water column is seasonal the rebound process is also likely to be seasonal. Benthic organisms may respond to the rebound process, as holothurians which normally feed on the surface sediments have been observed to consume large nepheloid particles in the water column (R. Carney, personal communication).

Since we have recorded increases in biogenic fluxes in near bottom traps from three sites with different productivity, topographic, and sediment characteristics, and resuspension of biogenic detritus has been observed in the northeast Atlantic (Billet et al. 1983; Lampitt, 1985) it appears likely that this is a common phenomena in ocean basins.

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### CHAPTER III

#### BIOGENIC RECYCLING DURING THE REBOUND PROCESS

## ABSTRACT

A simple box model is used to balance the particulate flux to the sediment surface (primary flux) and accumulation rates in the sediments for the major biogenic components of the particulate flux (organic carbon, calcium carbonate and opal). The difference between the accumulation rate and the primary flux is divided between a diffusion flux out of the sediments, and a "rebound process" flux resulting from recycling of the biogenic detritus prior to incorporation into the sediments. Using data from four sites in the Pacific, the modeling predicts that 30-60% of the primary flux of opal is recycled during the rebound process which occurs during 1 to 8 months. During this time, 50-99% of the primary flux of organic carbon and 22-89% of the primary flux of calcium carbonate is recycled.

## INTRODUCTION

Despite the effects of degradation and dissolution during settling (Suess, 1980; Walsh, Dymond and Collier, 1985), the flux to the sediment surface of biogenic detritus components (calcium carbonate, biogenic opal, organic carbon) is often two to three orders of magnitude larger than their accumulation rates in the sediment (Fischer 1984, 1985; Emerson and Dymond, 1985). The difference between the flux to the bottom and accumulation rate for organic carbon has been ascribed to diagenetic processes that occur within the sediment (Emerson, Fischer, Reimers and Heggie 1985). However,

dissolution susceptible microfossils found in sediment traps 50 m above bottom (D. Murray, unpublished data) and in the guts of bathypelagic organisms (Berger, 1976, and references therein) are not found in the sediments, suggesting that a fraction of the flux to the sediments is recycled before burial.

Sediment trap deployments (Walsh, Fischer, Murray and Dymond, 1985) and photographic surveys of the ocean bottom (Billett, Lampitt, Rice and Mantoura, 1983; Lampitt, 1985) have shown that resuspension of fresh biogenic detritus occurs prior to its incorporation into the sediment column. Fresh biogenic detritus is enriched in the biogenic components relative to the sediments and may form an easily disturbed carpet for a few months following high productivity events in the euphotic zone (Billett et al., 1983; Lampitt, 1985).

The residence time of biogenic detritus prior to incorporation into the sediment is an important factor in the relationship between the flux to the sediment surface and the accumulation rate. For instance, the degree of saturation of biogenic opal is lower in the bottom water than in the pore waters of the sediment (Hurd, 1973; Shinck, Guinasso and Fanning, 1975; Schink and Guinasso, 1978). Since the rate of dissolution is dependent on the degree of saturation (Hurd, 1972), the time that opal tests spend in contact with bottom waters will result in a larger dissolution loss than during a similar period of time after burial.

Resuspension of biogenic detritus before burial will result in dissolution and degradation occurring under bottom water conditions. The resuspension of fresh biogenic detritus has been termed the



"rebound process" (Walsh, Fischer, Murray and Dymond, 1985) Here we extend this term to include the time the plankton detritus spends at the sediment-water interface prior to incorporation.

A simple box model is used to estimate the fraction of the opal flux which dissolves during the rebound process. This analysis is extended to calcium carbonate and organic carbon by estimating the time required to dissolve the fraction of the opal flux recycled during the rebound process, and using this reaction time to estimate the dissolution of calcium carbonate and degradation of organic carbon occurring during the rebound process.

#### METHODS

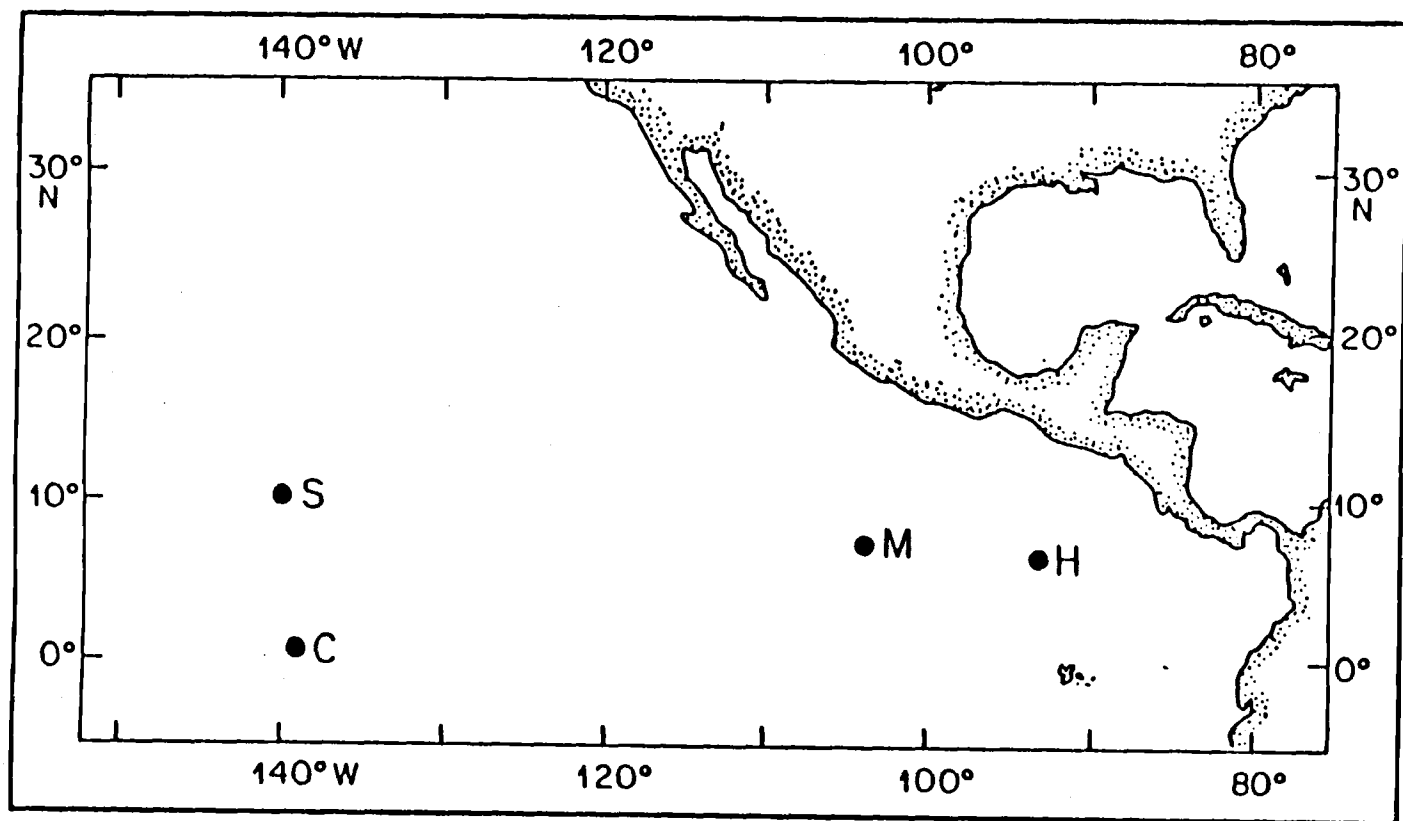
The primary flux to the sediment surface was extrapolated from data gathered by long-term deep ocean sediment trap arrays deployed at four MANOP sites in the Pacific (Figure III-1). Extrapolations were made assuming a settling rate of the plankton detritus of 100 m/day, first order reactions, and rate constants derived from mid-water column sediment traps (Walsh, Dymond and Collier, 1985).

Sediment accumulation rates are derived from the concentrations of the biogenic components in the upper 2.0 cm of sediments recovered from Soutar box cores, which recover an undisturbed sediment surface (Soutar, Johnson, Fischer and Dymond, 1981). These samples contain the highest concentrations of the biogenic components of sediment samples at each site within the top 10 cm.

Site H is located at a depth of 3575 m in the Guatemala basin. The sediments are hemipelagic, and lie below the carbonate compensa-

Figure III-1. Map of the North Pacific showing location of MANOP sites where sediment trap deployments were made.

Figure III-1



tion depth. The bulk accumulation rate is estimated to be  $105 \mu\text{g}/\text{cm}^2$  yr. Site M is located in a pond of metaliferous sediments lying approximately 25 km to the east of the East Pacific Rise at a depth of 3080 m. The bulk accumulation rate is estimated to be  $203 \mu\text{g}/\text{cm}^2$  yr.

Site C lies 4470 m below the high productivity region associated with the equatorial divergence. The accumulation rate of the carbonate rich sediments is estimated as  $540 \mu\text{g}/\text{cm}^2$  yr. Site S is located in an area of slowly accumulating siliceous clay sediments. There is evidence of sediment erosion within the site. The opal rich sediments are accumulating within a range of 0 to  $40 \mu\text{g}/\text{cm}^2$  yr. We have used the highest accumulation rate in our calculations.

#### OPAL DISSOLUTION

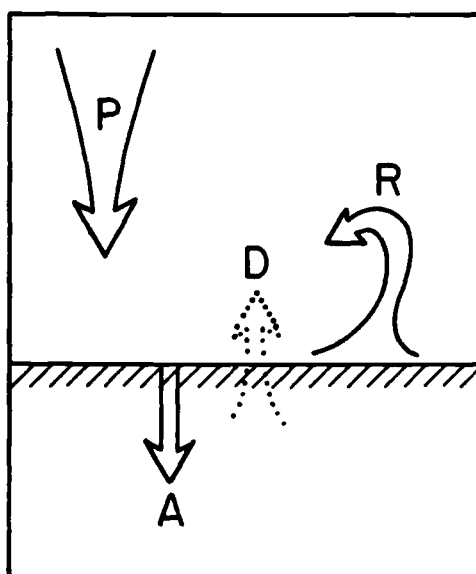
The opal flux ( $\mu\text{g}/\text{cm}^2$  yr) recycled during the rebound process was estimated using a box model which balances the primary flux of opal (P) with the accumulation rate (A), an estimated dissolution flux out of the sediment (D), and the rebound process flux (R) (Figure III-2). Hence:

$$1) R = P - (A + D)$$

Estimates of the flux of opal from average deep sea sediments range from  $150 \mu\text{g}/\text{cm}^2$  yr to  $180 \mu\text{g}/\text{cm}^2$  yr (Heath, 1974; Fanning and Pilson, 1974). The higher estimate was used in the model to estimate the rebound fluxes. Similarly, the accumulation rates used were the highest found in the upper 2 cm of the sediments.

Figure III-2. Generalized box model of the bottom water-sediment flux system.  $P$  is the primary flux to the sediment surface,  $A$  is the accumulation rate in the sediments,  $D$  is the diffusion flux out of the sediments, and  $r$  is the rebound process flux. The rebound process flux includes the dissolution and degradation which occur after initial deposition of the primary biogenic detritus, prior to incorporation into the sediments.

Figure III-2



$$P = A + D + R$$

Assuming first order kinetics, the residence time for the opal particles in the rebound process is:

$$2) t_r = (\ln (A+D) - \ln P)/k$$

where  $k$  is the dissolution rate constant ( $\text{yr}^{-1}$ ), and  $t_r$  is in years.

Opal was used to estimate the residence time of the biogenic detritus because the absolute dissolution rate for opal in deep ocean waters varies by less than 10-12% (Hurd, 1972). The average  $k$  from the three other sites was used for site M (Table III-1).

## RESULTS AND DISCUSSION

The model predicts that a substantial portion (30 to 60%) of the primary flux of opal is recycled within a matter of months at the sediment-water interface at all four sites (Figure III-3). The rebound process residence times for all but site S are similar to Lampitt's (1985) observation that a carpet of detritus arrived at the sediment-water interface and was removed, without major disturbance of the sediment surface, within three months. The diffusion flux at site S is probably underestimated, given the silicious nature of the sediments and low accumulation rate. Hence the rebound flux of opal and the rebound process residence time are probably overestimated.

The analysis, however, relies upon the assumption that dissolution occurs at a similar rate as during the settling of the primary material. Disaggregation of the primary flux material may affect this assumption.

Table III-1. Dissolution and Degradation Rate  
Constants in the Water Column

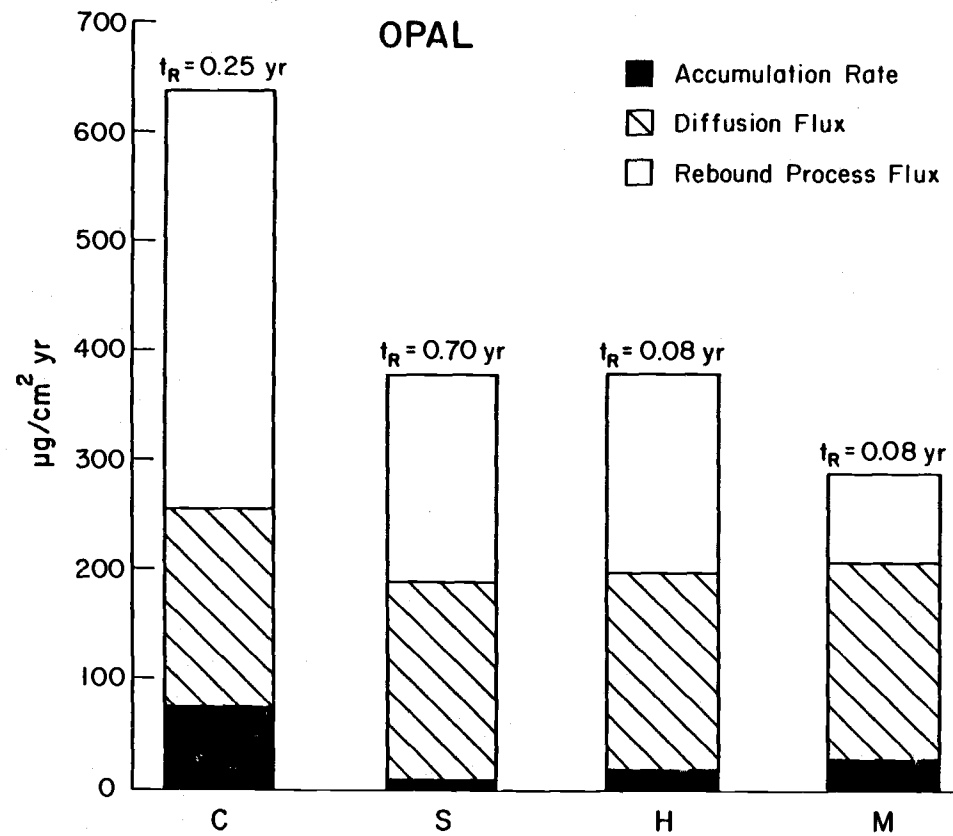
Site	Corg	CaCO <sub>3</sub> k(yr <sup>-1</sup> )	Opal
C	3.7	2.3	3.7
S	7.5	2.6	1.0
H	13	4.5	7.9
M*	8.0	3.1	4.2

\* average of sites C, S, and H.



Figure III-3. Partitioning of the primary flux of opal at the MANOP sites between accumulation in the sediments, dissolution in the sediments and dissolution during the rebound process.  $T_r$  is the residence time for the biogenic detritus in the rebound process.

Figure III-3



Disaggregation of primary flux particles would expose more opal surfaces directly to the bottom water, and may therefore result in higher dissolution rates than those found in the mid-water column where the opal particles are transported within large organic aggregates and fecal pellets.

There is evidence, however, that the primary flux particles survive for a time in the near-bottom region. Observations through the water column indicate that there is an increase in the abundance of large amorphous aggregates near the bottom in the Northern Pacific, possibly due to resuspension (Honjo, Doherty, Agrawal, and Asper, 1984). In the northeast Atlantic, aggregates of organic rich material have been observed moving off the sea floor within hours of deposition (Billett et al., 1983). Similarly, large amorphous aggregates were observed in pictures of the sea floor taken during the sediment trap deployment at the site H (Gardner, Sullivan and Thorndike, 1984). It is unlikely that such large particles could disaggregate and reaggregate without the opal particles associated with them, though it may be possible that some of the opal tests are shed from the aggregates during the rebound process.

#### CARBONATE DISSOLUTION AND ORGANIC CARBON OXIDATION

Box modelling is not sufficient to estimate the rebound process flux (R) for the other two major biogenic components as the diffusion fluxes are not well known. Instead, we have estimated the rebound flux by using the residence time calculated for opal, and

assuming first order reactions (Walsh, Dymond and Collier, 1985).

Thus:

$$3) R = P(1 - e^{-kt_r}),$$

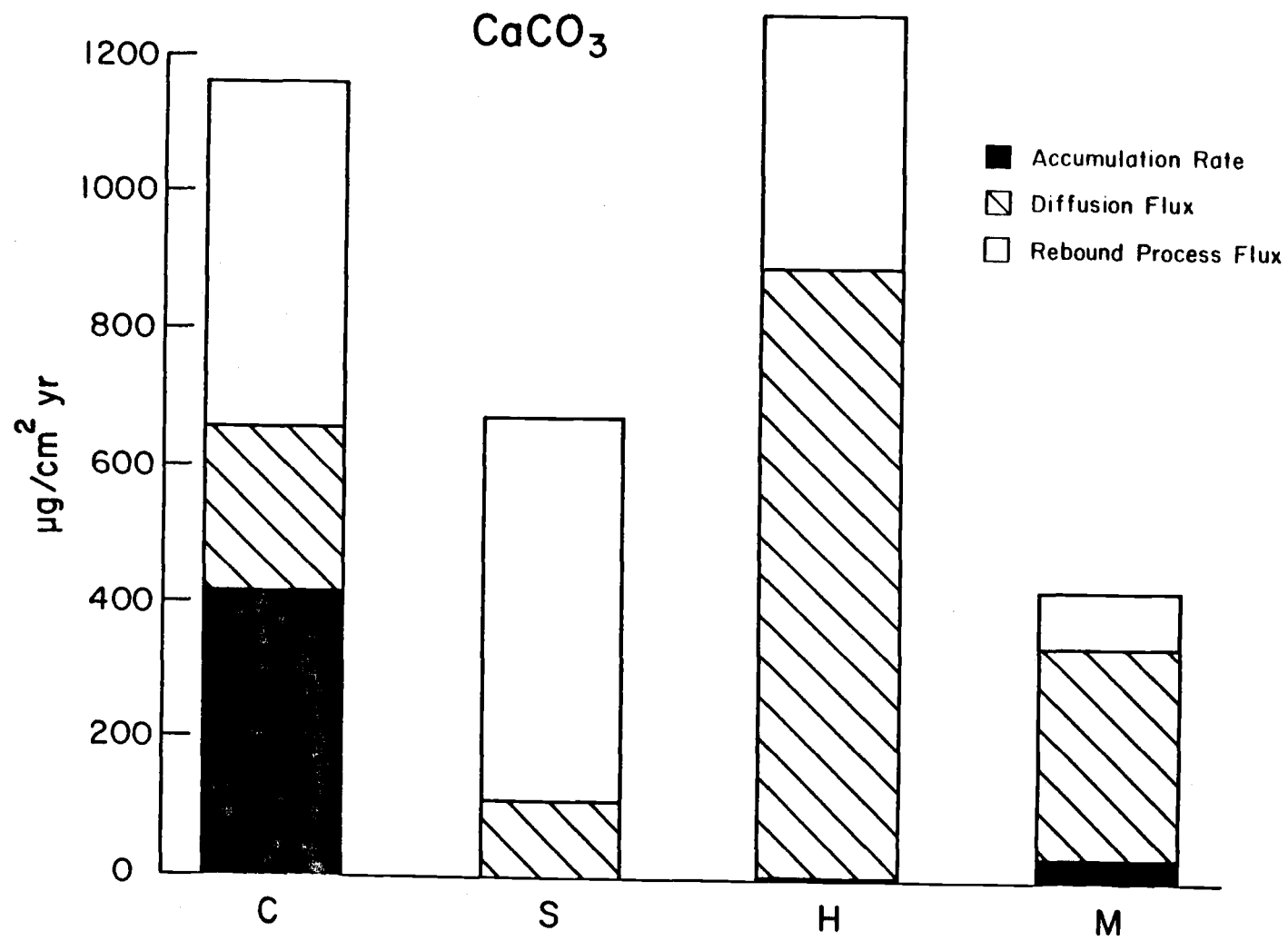
where R is the rebound flux in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ , P is the primary flux in  $\mu\text{g}/\text{cm}^2 \text{ yr}$ , k is the reaction constant ( $\text{yr}^{-1}$ ), and  $t_r$  is the residence time of the primary flux particles in the rebound process determined from the opal box model.

For calcium carbonate, the model predicts that 22 to 89% of the primary flux is recycled during the rebound process (Figure III-4). However, the dissolution constants used in the model (Table III-1) were derived from mid-water column sediment traps, and carbonate dissolution rates may increase rapidly in the bottom water column (Peterson, 1966; Honjo and Erez, 1978). The rebound process fluxes of carbonate are thus likely to be minimums, except at site S where the rebound process residence time is probably overestimated.

The results indicate that the rebound process can be very important in calcium carbonate diagenesis. Schink and Guinasso (1977) concluded that bottom currents or turbulence can have a significant influence on calcium carbonate accumulation. Their conclusion is supported by Honjo's (1977) analysis of the parameters governing the dissolution of carbonate particles in the water column. Dissolution is thus dependent on the dissolution rate, the surface area of the particles in contact with seawater, and the residence time of the particles in undersaturated water. The rebound process can therefore be seen as enhancing the dissolution of carbonate by increasing the residence time of the carbonate material in

Figure III-4. Partitioning of the primary flux of  $\text{CaCO}_3$  at the MANOP sites between accumulation and dissolution in the sediments and dissolution during the rebound process. The rebound process flux was calculated using the rebound process residence times determined from the opal box models.

Figure III-4



the undersaturated bottom waters, and may also enhance the available surface area through disaggregation.

The results of the rebound process modelling for the particulate organic carbon flux at the MANOP sites (Figure III-5) indicates that a substantial portion (50-99%) may be consumed prior to incorporation in the sediment column. Again, the site S rebound flux is probably overestimated.

Other investigators have reported similar results. Analysis of pore water and sediment sampling at five sites near the Pacific-Antarctic Ridge and the Peru continental margin indicated that 35-85% of the primary flux of organic carbon to the sediment surface was consumed prior to incorporation in the sediment column, with the higher values occurring at sites where resuspension events occur (Reimers and Suess, 1983). Pore water data from the four MANOP sites indicates that 50% or greater of the particulate organic carbon flux to the sediment degrades within the sediment (Emerson and Dymond, 1985), which complements our results, though with some overlap. However, given the uncertainties in the pore water and sediment trap data, and the somewhat overlapping models (i.e. how does a transient carpet of biogenic detritus affect pore water profiles?), both methods may be consistent with each other.

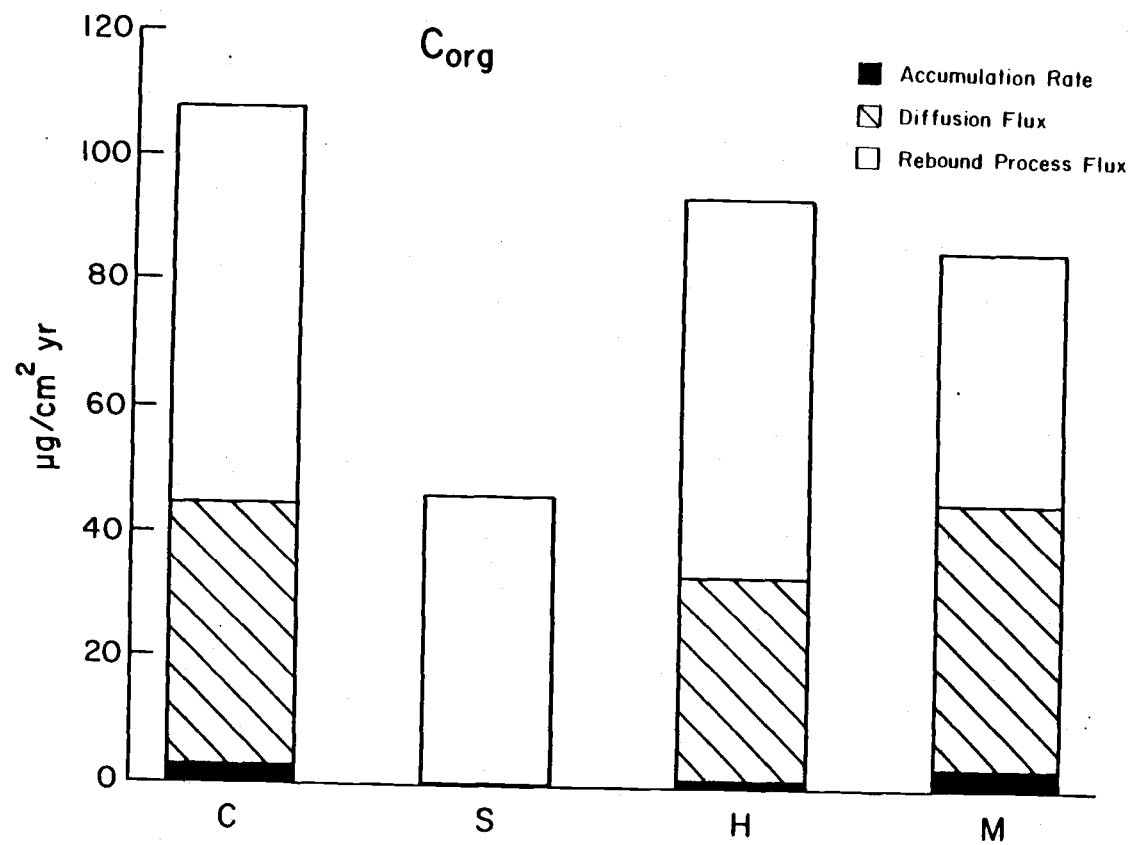
## CONCLUSIONS

The rebound process may be as important to the recycling of the flux of biogenic material to the sediment-seawater interface as that which occurs within the sediments. Thus, periods during which bottom

Figure III-5. Partitioning of the primary flux of organic carbon at the MANOP sites between accumulation and degradation in the sediments and degradation during the rebound process. The rebound process flux was calculated using the rebound process residence times determined from the opal box models.



Figure III-5



current velocities do not exceed the threshold velocity for the resuspension of fresh biogenic detritus (approximately 7 cm/sec (Lampitt, submitted)) may result in an increase in the accumulation rates of the biogenic components.

The rebound process may also explain local patchiness on the sea floor, such as observed at site H where nodule free patches occupy slight depressions (Walsh, Lyle, Finney and Heath, 1981, reports of Alvin dives, 1981). Pore water profiles from the bare patches indicate more reducing conditions than the nodulated areas of the site (M. Lyle, unpublished data). The rebound process may result in the slight depressions that the bare patches occupy receiving a larger flux of organic carbon due to preferential settling within the depressions. The higher organic flux may thus account for the more reducing conditions in the pore waters.

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## GENERAL CONCLUSIONS

1. Injection of particles, probably through the action of zooplankton, increases the settling particle flux through the upper thousand meters at the MANOP sites and results in a mid-water column flux maximum.

2. The dissolution rates of opal and calcium carbonate are lower below the mid-water column flux maximum than above. Dissolution between the mid-water maximum and the sediment surface results in the recycling of from 8 to 37% of the opal and 15 to 23% of the calcium carbonate flux at MANOP sites C, S, and H. The degradation rate of organic carbon also decreases below the mid-water flux maximum. Degradation between the mid-water maximum and the bottom accounts for the recycling of 23 to 53% of the maximum organic carbon flux.

3. After initially settling to the bottom, the biogenic detritus is resuspended, in some cases over 300 m above the general bottom depth, in those cases the material was probably resuspended by topographic highs. We have termed the resuspension of biogenic detritus the "rebound process" to differentiate it from the resuspension of sediments.

4. The degradation and dissolution of the biogenic components of the biogenic detritus which occur during the rebound process may account for the recycling of 50 to 99% of the organic carbon, 22 to 89% of the calcium carbonate, and 30 to 60% of the opal that initially settles to the seafloor.

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