

Reports

Sediment Trap Experiment on the Galápagos Spreading Center, Equatorial Pacific

Abstract. Two sediment traps were deployed for 234 days in 2670 meters of water at 0°36'N, 86°6'W. A comparison of the fluxes of ten elements into the traps and into the surface sediment indicates that the refractory elements iron, aluminum, and barium are accumulating in the sediments at rates very similar to those measured in the traps. In contrast, at least 80 percent of the opal, 50 percent of the carbonate, and 90 percent of the organic carbon is consumed at the sediment-water interface.

Variations in the flux and composition of particulate material raining on the ocean floor influence the sedimentary record and the chemical variations in the water column. Only recently, however, have direct measurements of the flux of particles to the sea floor become technically feasible, through the use of containers known as sediment traps, which are suspended in the water column (1).

We deployed two sediment traps on 4 July 1976, in 2670 m of water, 20 km south of the active hydrothermal vents located on the Galápagos Rift (2). The traps were located at 0°35.75'N, 86°05.66'W in a region that has "sediment mounds" encrusted with ferromanganese material, believed to have formed by the slow percolation of hydrothermal fluids through the 20 m of carbonate-siliceous ooze sediments of the area (3). The study area is characterized by a high primary productivity of approximately 150 g m⁻² year⁻¹ (4) and low near-bottom currents, averaging less than 5 cm sec⁻¹ (5). One trap was moored at 20 m above the bottom and the other at 100 m above the bottom. The traps, which were made entirely of fiberglass and plastic, had a collecting surface of 1 m². There were

baffles 20 cm high with openings 8 cm² in the tops of the traps to reduce internal turbulence and resuspension of the sample. The baffles were covered with nylon netting (1 cm) to keep large animals out of the traps. The traps were closed 234 days after deployment when a waterproof curtain was drawn over the lower half of each trap; they were released from the bottom by the research submersible *Alvin*.

Upon recovery, the samples were immediately poisoned with HgCl₂, concentrated by settling, and refrigerated to minimize bacterial degradation. Later the samples were washed with distilled water to remove salts and freeze-dried. The concentrations of Al, Si, Ca, Mn, Fe, Ni, Cu, Zn, and Ba in the trap material were determined by atomic absorption spectrophotometry (6). The organic carbon contents were measured by oxidation with dichromate (7). For comparison, the top 2 cm of 41 gravity cores recovered in the study area were analyzed in the same way. These data are reported in Table 1.

We used linear programming techniques to create a normative composition model (Table 2), based on phase

compositions taken from published data; this model converts the nine-element composition (excluding organic carbon) of the trap and sediment samples into fractions of aluminosilicate detritus, biogenic opal, biogenic calcite, Mn oxides, and nontronite (3). The normative model indicates that the trap samples have greater abundances of biogenic calcite and opal and lesser abundances of detritus, Mn oxides, and nontronite than the average surface sediment (Table 2). These differences reflect dissolution of CaCO₃ and SiO₂ at the sea floor and inputs of hydrothermal phases to the sediment from nearby bottom sources (2).

The flux of dry material into the upper trap was 4.51 mg cm⁻² year⁻¹; the flux into the lower trap was 4.02 mg cm⁻² year⁻¹. Although the 10 percent flux difference between the two traps may be real, we view the similarity of the two determinations as an indication of the precision of the experiment.

The Holocene sedimentation rate is difficult to estimate because of bioturbation and possible changes in the rate of sedimentation through time. Sedimentation rates determined in three different ways (8) range from 3.5 to 5.6 cm per 10³ years, and we have chosen a rate of 5 cm per 10³ years for purposes of discussion. The accumulation rate of dry material into the sediment based on this sedimentation rate and measured bulk density is 2.4 mg cm⁻² year⁻¹, approximately 50 percent lower than that measured in the sediment traps.

In Fig. 1 we compare the elemental fluxes into the traps with that accumulating in sediment. We recognize that errors in the sedimentation rate, the possibility of a nonrepresentative deployment period, and uncertainties in trap efficiency can cause problems in such a comparison. Nonetheless, this approach, when valid, is a powerful tool for understanding element partitioning reactions which take place at the sediment-water interface. With the collection of sufficient data of this type, we will have a basis for discerning failures in the approach.

It is generally believed that Al, Fe, and Ba are refractory elements since they are

Table 1. The chemical composition of the trap samples and of 41 gravity core tops taken in the study area; ppm, parts per million. Organic carbon was not measured in all cores. The trap samples were washed with filtered, distilled water. The sediment sample analyses were corrected for salt content. The uncertainty in the sediment data is 1 standard deviation.

Sample	Organic C (%)	Al (%)	Si (%)	Ca (%)	Mn (%)	Fe (%)	Ni (ppm)	Cu (ppm)	Zn (ppm)	Ba (%)
Upper trap	4.51	0.592	11.4	23.9	0.521	0.472	54.1	72.5	109	0.154
Lower trap	4.12	0.757	11.2	23.8	0.955	0.560	74.0	74.2	132	0.177
Average surface sediment	1.02	1.47	8.21	23.1	3.23	1.26	257	121	202	0.347
		± 0.07	± 0.35	± 1.3	± 0.90	± 0.11	± 50	± 8	± 27	± 0.022

Table 2. The normative composition model, created from the Al, Si, Ca, Mn, Fe, Ni, Cu, Zn, and Ba contents of the samples, based on linear programming techniques and phase compositions taken from the literature (3).

Sample	Cal-cite (%)	Opal (%)	De-tritus (%)	Mn oxides (%)	Non-tronite (%)
Upper trap	64.5	27.1	7.18	1.22	
Lower trap	63.6	25.2	8.99	2.22	
Average surface sediment	62.5	11.0	18.5	7.57	0.52

associated predominantly with relatively stable phases, detrital aluminosilicates in the case of Al and Fe and barite in the case of Ba. The slightly greater fluxes of these three elements into the sediment may be due to any combination of the following: (i) the trapping efficiency of our traps is approximately 75 percent; (ii) the sedimentation rate is 3.8 cm per 10^3 years rather than 5 cm per 10^3 years; or (iii) the 234-day sampling period is not representative of the 400- to 2000-year integration represented by the core tops. The last explanation would be reasonable for biogenically associated elements since there are seasonal and annual changes in productivity in this region (4). However, productivity variations would not be expected to affect the flux of detrital elements such as Al and Fe.

The fluxes of Mn and Ni to the surface sediment are two to three times greater than the values measured in the traps (Fig. 1), an indication of the mobilization and concentration of these elements in surface sediments, which result from the reducing conditions that occur at depth in this area (9). In addition, there may be a bottom hydrothermal source of these elements, particularly Mn, which is not caught by our traps. The difference between the trap fluxes and sediment flux implies an additional flux of Mn into the upper 2 cm of approximately $0.05 \text{ mg cm}^{-2} \text{ year}^{-1}$. Earlier estimates of diffusional Mn flux in reducing sediments are two to four times lower than this measurement (10).

Organic C, Si, Ca, Cu, and Zn have larger fluxes into the trap than into the sediment (Fig. 1). This finding is consistent with a loss of these elements to the bottom water at the sediment-water interface. The rate of loss or flux from the sediment is the difference between the input flux estimated from the trap data and the accumulation into the sediment. These fluxes (in micromoles per square centimeter per year) are as follows: organic carbon, 13.4; SiO_2 , 14.2; CaCO_3 , 12.4; Cu, 4×10^{-4} ; and Zn, 5×10^{-4} (the fluxes of Si and Ca have been converted to SiO_2 and CaCO_3 , respectively). It might also be argued that these elements,

being introduced by way of biogenic particles, reflect changes in surface water productivity which may not have been representative during our experiment. Nonetheless, we believe that these five fluxes are minimum values for the following reasons: (i) the refractory elements exhibit either a 75 percent lower sedimentation rate or a trapping efficiency of 75 percent, either of which would indicate a higher flux back into the bottom water; (ii) some of the biogenic components trapped may have been dissolved during the deployment period; or (iii) hydrographic data indicates that 1976 may have been an El Niño year and productivity may have been lower as a result (11).

The flux of organic carbon into the trap is approximately 1.5 percent of the primary productivity in the euphotic zone. Since only 0.15 percent of the primary productivity is preserved in the

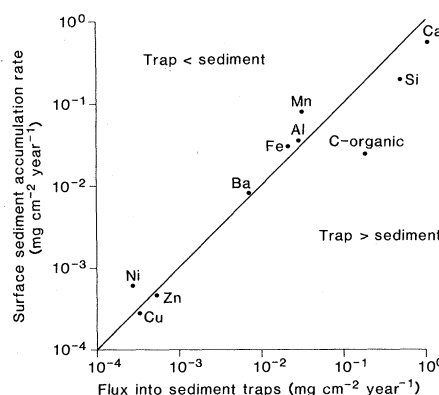


Fig. 1. Average elemental fluxes into the two traps plotted against the elemental accumulation rates of surface sediments. Fluxes are equal along the diagonal line. Points falling above the line indicate greater fluxes into the sediment than into the traps; points falling below the line indicate greater fluxes into the traps than into the sediment. The elemental flux into the traps is given by $A_E = C_E B$, where A_E is the accumulation rate of a given element, C_E is the weight fraction of that element in the dry sample, and B is the total flux of material into the traps. The elemental accumulation rate in the sediment is given by $A_E = C_E S \rho_T (1 - X_w)$, where S is the sedimentation rate, ρ_T is the wet bulk density of the sediment sample, and X_w is the weight fraction of water in sample.

sediment, at least 1.3 percent of the primary productivity is respired at the sea floor as CO_2 . The measured flux of organic carbon from the sediments ($13.4 \mu\text{mole cm}^{-2} \text{ year}^{-1}$) is in good agreement with the O_2 consumption predicted for the open ocean at this depth (12) ($18 \mu\text{mole cm}^{-2} \text{ year}^{-1}$ predicted, as compared to $17 \mu\text{mole cm}^{-2} \text{ year}^{-1}$ calculated from the carbon flux).

Trace element measurements of the water column suggest that Ni, Cu, and Zn have a bottom source (13). The measured fluxes from the sediments indicate a bottom flux of Cu and Zn; however, because of the Ni mobilization and concentration in surface sediments, any Ni fluxes out of the sediment are obscured. Because the differences between the trap fluxes and sediment accumulation fluxes are small for Cu and Zn, the computed fluxes of these elements to bottom water are relatively uncertain.

Our data indicate that approximately 80 percent of the opal and 50 percent of the carbonate reaching the bottom are dissolved at the sediment-water interface (14). It is difficult to compare the fluxes from the sediments to the bottom water with measured in situ dissolution rates (15). However, in situ studies show essentially no dissolution of calcite above the lysocline (approximately 3800 m). The carbonate losses reported here at a depth of 2570 m may suggest the importance of CO_2 production from the oxidation of organic carbon for the dissolution of carbonate in regions above the lysocline (16), and the similarity of the organic carbon and CaCO_3 fluxes from the bottom supports this hypothesis. Because of possible losses of organic carbon during deployment, however, this similarity may be fortuitous. Opal dissolution has been measured at all depths in in situ dissolution experiments (15), but the only reported in situ measurement of opal release from the sediments that we know of has been in the Atlantic (13). These values (2 to $14 \mu\text{mole cm}^{-2} \text{ year}^{-1}$) and the average estimates for the world's oceans (2 to $4 \mu\text{mole cm}^{-2} \text{ year}^{-1}$) (17) are lower than our SiO_2 estimate, reflecting the high biogenic flux of silica to the sea floor at our equatorial Pacific site.

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18. The deployment and recovery of traps was made possible by the captains, crews, and scientific parties of the R.V. *Melville* during Pleiades Leg II, and the R.V. *Knorr*, the R.V. *Lulu*, and the *Alvin* during Knorr 64. R. Stillinger and M. Clauson helped with the design and construction of traps. C. Chou carried out atomic absorption analyses on core samples. C. Meredith-Muratli aided in data processing. M. Stuiver measured the ^{14}C used in the sedimentation rates. We thank K. Fischer, R. Heath, and E. Suess for reviewing the manuscript. The experiment was funded by the Sea Bed Assessment Program, International Decade of Ocean Exploration Office, National Science Foundation (grant OCE 77-23978 to Oregon State University).

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Stable Isotopes in Benthic Foraminifera: Seasonal Variation in Large Tropical Species

Abstract. *The shells of large benthic foraminifera contain a record of seasonal temperature ranges and life history stages. Marginopora vertebralis and Cyclorbiculina compressa show distinct differences in life history, growth rate history, and life-span, as reflected in stable isotope patterns within their shells.*

Large, shallow-water, tropical foraminifera are an important component of modern and ancient carbonate reefs. These forams are usually associated with dinoflagellate or diatom symbionts ("zooxanthellae") (1, 2). This association gives rise to unusually high population densities in places and thus ultimately leads to a considerable contribution (10 to 15 percent) to carbonate deposition in shallow, warm-water areas (3). Rapid growth (50 to 100 times that of most temperate species) and a long life-span (one to several years) appear to be characteristic of most large to very large, tropical foraminifera (4). Their calcareous shells, therefore, should contain a record of seasonal variation at the time and place of growth. We report here evidence, based on the stable isotope composition of the shells, showing that this is so. Our findings imply that the growth rate and hence the carbonate production of large foraminifera can readily be determined, even in fossil specimens, if they are well preserved.

We chose two common representatives of large tropical forams for our seasonality test, *Marginopora vertebralis* and *Cyclorbiculina compressa*. The first grew in tropical waters with but little seasonal temperature variation. The second grew in warm-temperature waters

with a considerable temperature range.

Marginopora vertebralis was collected in January 1979 in shallow water (1 to 3 m) 50 m off Hadsan Beach Resort, Mac-tan, Cebu, Philippines (temperature range, 26° to 30°C; minimum in February and maximum in July) (Fig. 1a). Three stages of shell construction are known for *M. vertebralis*: embryonic, laminate, and reproduction chamber stages (5). The foraminifera is host to at least one species and perhaps several species of symbiotic dinoflagellates.

Cyclorbiculina compressa was collected in April 1978 in Harrington Sound, Bermuda, in 10-m water (temperature range, 16° to 29.5°C; maximum in August and minimum in February) (Fig. 1b). Three stages of shell construction are known for this foram, which partially depends on symbiotic algae for nutrition (6). Lee *et al.* (2) recently noted a new symbiont from *C. compressa*, the chlorophyte *Chlamydomonas provasolii*.

The specimens of *Marginopora* and *Cyclorbiculina* analyzed here had undergone asexual reproduction, and the adult tests contained little or no protoplasm. The protoplasm was concentrated in the two-chambered embryos present within the reproduction chambers. We subsampled the specimens, using a scalpel to separate individual chamber rings

from each test. Depending on their size, one to ten rings were used for each analysis. To remove the organic matter attached to the test, each subsample was soaked in a 10 percent aqueous solution of H_2O_2 for 1/2 hour. Then it was washed five times with deionized water, dried at 60°C, and heated for 30 minutes at 300°C under a vacuum. Analytical procedures were standard (7). The analytical precision was 0.1 per mil (one standard deviation).

Results show that the $\delta^{18}\text{O}$ variations follow closely those expected from ambient temperature variations, if the equation of Epstein *et al.* (8) is used (Fig. 1). The actual $\delta^{18}\text{O}$ values of *Marginopora* and *Cyclorbiculina* appear to be offset (by -0.5 and +0.75 per mil, respectively) from values expected for equilibrium precipitation at the two locations after corrections are made for water $\delta^{18}\text{O}$ compositions based on established relations between salinity and $\delta^{18}\text{O}$ (water) (9). Although depletion in ^{18}O is not unusual in benthic foraminifera (10, 11), an enrichment in ^{18}O is unexpected. The fact that the shell material consists of magnesium-rich calcite may be significant. For the Soritidae, of which *Marginopora* and *Cyclorbiculina* are members, values of 15 to 18 mole percent MgCO_3 have been reported (12). For an enrichment in ^{18}O by 0.06 per mil per mole percent MgCO_3 (13), an increase in $\delta^{18}\text{O}$ of about 1 per mil would be expected for each species. If this calculation is correct, both species are actually depleted in ^{18}O . Any variations in the $\delta^{18}\text{O}$ composition of the seawater apparently were negligible (14).

A linear growth scale is assumed for *Marginopora vertebralis* (Fig. 1a). It is broken at radius 1.2 mm (test diameter, 2.4 mm), because the high $\delta^{18}\text{O}$ value of the test center suggests initial growth in midwinter (January 1977). This inference is further supported by field observations of midwinter reproduction in January of 1979. The subsequent linear fit suggests that there was little change in growth rate during the transition from laminate to reproductive chambers (marked R in Fig. 1a). Growth apparently ceased in late summer (at a radius of 6.8 mm), and the foraminifera then waited until winter to produce offspring, which were found to occupy the test between 4.7 and 6.8 mm from the center. The tests of these embryos are distinctly enriched with $\delta^{18}\text{O}$ as compared with the last-formed chambers of the adult test. Our life-span estimate of 2 years for this species is in good agreement with direct observations by Ross (5, 15).