Particulate Organic Carbon Fluxes Along Upwelling-Dominated Continental Margins: Rates and Mechanisms

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[1] Time series sediment trap samples were used to examine the rates and mechanisms of particulate organic carbon (POC) flux at three continental margin locations, Santa Barbara Basin, Cariaco Basin, and Guaymas Basin, marked by seasonal upwelling and high primary production. The mean POC flux in Santa Barbara Basin (0.096 g m\(^{-2}\) d\(^{-1}\)) is nearly twice that of Cariaco Basin and 4 times higher than that in Guaymas Basin, with all three sites having POC fluxes significantly higher than the open ocean average (0.007 g m\(^{-2}\) d\(^{-1}\)). In Cariaco Basin, the only site with available primary production numbers, there is no significant relationship between POC flux and monthly primary production. Rather, POC fluxes in all three areas strongly correlate with mineral (carbonate, opal, and lithogenic material) fluxes. This supports the “mineral ballast” hypothesis, where it has been suggested that higher-density minerals enhance the flux of organic matter to the deep ocean. On the basis of multiple regression analysis, the three mineral components explain 72% of the total variance in POC fluxes at the three study sites, with biogenic carbonate particles being the most effective transport mineral.


1. Introduction

[2] Particulate organic carbon (POC) fluxes serve as the primary vehicle by which carbon is exported to the deep ocean interior. Thus this process is a key component of the global carbon cycle. Oceanic uptake of CO\(_2\) from the atmosphere is controlled, in part, by the conversion of CO\(_2\) into biomass during photosynthesis. A fraction of this carbon containing biomass, for example, POC, subsequently sinks from the euphotic zone, sequestering CO\(_2\) on longer timescales. POC fluxes and the remineralization of sinking organic matter controls the depth profiles of both CO\(_2\) and nutrients in the ocean. During the last two decades there have been a large number of studies which have documented the spatial and temporal variability of POC fluxes, with the vast majority of this work being at open ocean locations (see Honjo [1996], Lampitt and Anitia [1997], Francois et al. [2002], and Lutz et al. [2002] for syntheses).

[3] Understanding the mechanisms that control the removal of POC from the surface ocean is critical to predicting how organic matter fluxes vary as a function of depth. Initial observations led to the development of a number of algorithms that related carbon fluxes at depth to primary production or export production [e.g., Suess, 1980; Betzer et al., 1984; Martin et al., 1987; Pace et al., 1987], with all showing exponential decreases in fluxes in the upper ocean and only about 1% of the primary production being transported to depths below 1500 m. Indeed, a majority of oceanic carbon cycle models utilize these algorithms [Schneider et al., 2004; Doney et al., 2003]. However, recent compilations of available data suggest that there is significant regional variability in the relationship between production and flux and that these parameterizations tend to over estimate POC fluxes [Francois et al., 2002; Lutz et al., 2002; Klaus and Archer, 2002]. It now appears that there are a number of variables other than primary production which exert a strong influence on POC fluxes.

[4] Despite the fact that particulate organic matter (POM) is almost neutrally buoyant in sea water (estimated density of 1.06 g cm\(^{-3}\) [Logan and Hunt, 1987]), it is well documented that there is rapid delivery of this material to the deep ocean [Honjo, 1980; Deuser et al., 1981]. To explain this observation, Ittekot and Haeke [1990] and Ittekot [1993] suggested that terrestrially derived detrital material may act as ballast and provide an “abiotic boost” to the settling rates of POM. Armstrong et al. [2002] subsequently proposed that there are two distinct categories of POM, one associated with ballast and one without. The organic matter lacking ballast is largely remineralized in the

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upper 1000 m of the water column and accounts for the exponential decrease in POC fluxes observed over this depth range. For the organic matter containing ballast; *Armstrong et al.* [2002] developed a model in which deep sea POC fluxes are proportional to the fluxes of total ballast minerals (opal, calcium carbonate and lithogenic material). *Klaas and Archer* [2002] and *François et al.* [2002] further refined this relationship and found calcium carbonate (calcite and aragonite) to be the most effective of these minerals in aiding the transport of organic carbon to depth in the open ocean because calcite and aragonite have the highest densities (2.71–2.94 g cm\(^{-3}\)) and in most regions are more common than lithogenic material. Furthermore, when all three minerals were considered, it was demonstrated that changes in ballast fluxes could explain greater than 85% of the variability in a global POC flux database [Klaas and Archer, 2002]. In addition to increasing the density and sinking velocity of POM, ballast minerals also are thought to physically protect organic matter from degradation in the water column, either through the adsorption of organic material onto mineral grains or by encapsulation [Hedges and Keil, 1995; Hedges et al., 2001; Lee et al., 2004].

While a wealth of data on POC fluxes exists for the open ocean, there are comparatively few measurements of POC fluxes on continental margins. Recently, *Muller-Karger et al.* [2005] used satellite data to estimate global POC fluxes to the sea floor and concluded that >40% of the carbon sequestration in the oceans may occur along continental margins, despite the fact that less than 15% of marine primary production occurs in these areas. Clearly, continental margins play an important, but often ignored, role in the global carbon cycle. In this paper, we present POC flux data for three different continental margin locations, all of which are seasonally impacted by coastal upwelling. The study sites include the California Borderlands (Santa Barbara Basin), the Gulf of California (Guaymas Basin) and the northern continental margin of Venezuela (Cariaco Basin). All are typical of many coastal regions in the world’s oceans. At each location we have multiyear time series of sediment trap samples that allows us to quantify the magnitudes of POC fluxes, as well as the relationships between POC fluxes and the fluxes of other sedimentary components or ballast minerals. In addition, we have flux data from multiple depths in Cariaco Basin that allows us to evaluate how the relationship between POC fluxes and mineral fluxes changes in response to water column remineralization.

### 2. Sediment Trap Time Series: Sample Collection and Local Climatology

The data presented in this study were collected as part of an ongoing effort to document carbon fluxes along continental margins. The three study sites, Cariaco, Guaymas and Santa Barbara Basins share a number of common features. First, all three basins are marked by strong seasonal upwelling that influences the production and flux of organic carbon. Second, all three basins are anoxic at certain depths, which inhibits seafloor bioturbation and allows for the preservation of sediment laminae. The sample collection procedures and the prevailing climatological/hydrological conditions at each location are briefly described in the following three sections.

#### 2.1. Santa Barbara Basin, California Borderlands

*A time series sediment trapping study was initiated in the center of Santa Barbara Basin (34°14’N, 102°02’W; trap depth 500 m; Figure 1) in August 1993. Two-week-long samples have been collected continuously at this site since that time. For all three sediment trapping studies described in this paper, the samples were collected biweekly using automated Mark VI sediment traps [Honjo and Doherty, 1987].

Oceanographic conditions within the Southern California Borderlands are strongly influenced by the southward flowing California Current. Seasonal changes in the positions of the North Pacific High and the adjacent continental thermal low result in changes in wind speed and direction, which in turn control the strength of the California Current [Huyer, 1983]. The winds are strongest and from the north during spring and early summer, causing offshore Ekman transport, upwelling and high primary production along the margin. During fall and winter, the northerly wind component weakens, upwelling is diminished and productivity decreases. This coincides with highest rainfall and river runoff. The Santa Clara and Ventura are the two main rivers emptying into Santa Barbara Basin, and together account for 90% of the lithogenic material being delivered to the basin [Thornton, 1984]. A detailed description of the Santa Barbara time series project, along with some of the initial sediment trap data are given by Thunell [1998a].

#### 2.2. Guaymas Basin, Gulf of California

*Biweekly sediment trap collections began in Guaymas Basin (27°53’N, 111°40’W; trap depth 475 m; Figure 1) in August 1990 and continued until September 1997. Surface circulation and mixing in Guaymas Basin and throughout the Gulf of California are controlled by changes in the position of the North Pacific high-pressure center relative to the adjacent continental low that result in seasonally reversing winds [Bray and Robles, 1991]. From late fall through early spring, strong northwesterly winds induce net transport of surface waters out of the Gulf. Summer to early fall is the rainy period, with weak southern winds that allow equatorial Pacific surface waters to penetrate well into the Gulf. These seasonal climatological changes affect surface temperatures, upper ocean mixing, and primary production.*

In general, sea surface temperatures (SSTs) are lowest and primary production is highest during the period of strong, northwesterly winds. Strengthening of the northerly winds during the winter results in upwelling that starts along the eastern margin of the basin and expands across the Gulf [Badan-Dangon et al., 1985]. Conversely, primary production in Guaymas Basin is low when southern winds are weak. The heating of surface waters during the summer leads to a highly stratified water column, which results in nutrient depletion above the thermocline. As surface waters cool in the fall and the prevailing winds become northwesterly, the thermocline breaks down and upwelling is initiated. These observations indicate an inverse relationship between SST
and primary production in the Gulf of California, similar to the relationship that has been reported for the California Current region [Tont, 1981; Roemmich and McGowan, 1995].

The rivers in the vicinity of Guaymas basin have been dammed for a number of decades and as a result there is little riverine input of detrital material. Rather, most of the terrigenous input to the basin occurs during the summer and is via eolian transport associated with connective thunderstorms over the Sonoran desert region [Baumgartner et al., 1991]. A more in depth discussion of the Guaymas Basin sediment trapping program is given by Thunell [1998b].

2.3. Cariaco Basin, Southern Caribbean Sea

The Cariaco Basin time series study began in November 1995 and includes a sediment trap mooring in the deepest part (~1400 m) of the eastern subbasin (10°30'N, 64°40'W; Figure 1). The initial mooring contained four sediment traps positioned near 230 m, 410 m, 810 m, and 1200 m water depth. All of the sediment traps are programmed to collect biweekly samples. In addition, primary productivity using 14C throughout the upper 100 m of the water column is measured monthly at the mooring location [Muller-Karger et al., 2001, 2004].

The climatology of the southern Caribbean is largely driven by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) about the equator and associated variations in trade wind intensity and precipitation. During winter and spring, the ITCZ is in its most southerly position, rainfall is at a minimum and strong easterly winds cause intense upwelling and high primary production along the Venezuelan coast. As the ITCZ migrates to the north during the summer and fall, the trade winds diminish, upwelling ceases, and the rainy season begins. During this time of year, riverine discharge is highest, transporting weathered material from the Venezuelan coastal range into the Cariaco Basin. Additionally, a significant amount of Saharan dust is delivered to the Caribbean and this varies seasonally in response to ITCZ-induced changes in precipitation and wind direction over North Africa [Prospero and Lamb, 2003]. During the summer months, when the ITCZ is located near 10°N, the Sahel region is very arid, allowing the Saharan Air Layer (SAL) to transport large quantities of dust to the Caribbean.

3. Sample Processing and Analytical Techniques

Prior to sediment trap deployment, the sample collection bottles were filled with a solution containing either a poison or a preservative in order to minimize microbial degradation of particles after collection. A buffered sodium azide solution was used in the Gulf of California study, while a buffered formalin solution was used for Santa Barbara Basin and Guaymas Basin samples. After recovery, all sediment trap samples were split using a precision rotary splitter and refrigerated. A quarter split was used for bulk geochemical analyses and flux determinations. These splits were examined under a microscope and all obvious “swimmers” were removed from each sample before analysis. This group includes all organisms, primarily macrozooplankton, assumed to be alive at the time of trap entry and thus not part of the particle flux. The samples then underwent multiple rinses in deionized water coupled with brief centrifuging to remove salts. The samples were then dried, weighed for total mass flux, and ground. Particulate organic carbon, carbonate, and biogenic opal contents were determined for each sample using this ground material. A Perkin-Elmer 2400 Elemental Analyzer was used to measure organic carbon content following the procedures outlined by Froelich [1980]. Carbonate content was determined...
Table 1. Flux Values for the Three Study Sites

<table>
<thead>
<tr>
<th>Flux</th>
<th>Santa Barbara, 500 m</th>
<th>Guaymas, 475 m</th>
<th>Cariaco, 230 m</th>
<th>Cariaco, 410 m</th>
<th>Cariaco, 810 m</th>
<th>Cariaco, 1200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass, minimum</td>
<td>0.017</td>
<td>0.035</td>
<td>0.024</td>
<td>0.041</td>
<td>0.021</td>
<td>0.002</td>
</tr>
<tr>
<td>Total mass, maximum</td>
<td>9.089</td>
<td>1.394</td>
<td>5.584</td>
<td>3.765</td>
<td>4.106</td>
<td>4.536</td>
</tr>
<tr>
<td>Total mass, mean</td>
<td>2.241 ± 1.33</td>
<td>0.416 ± 0.23</td>
<td>0.897 ± 0.78</td>
<td>0.630 ± 0.57</td>
<td>0.451 ± 0.55</td>
<td>0.381 ± 0.56</td>
</tr>
<tr>
<td>POC, minimum</td>
<td>0.001</td>
<td>0.002</td>
<td>0.003</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>POC, maximum</td>
<td>0.369</td>
<td>0.058</td>
<td>0.242</td>
<td>0.249</td>
<td>0.205</td>
<td>0.186</td>
</tr>
<tr>
<td>POC, mean</td>
<td>0.096 ± 0.05</td>
<td>0.021 ± 0.01</td>
<td>0.074 ± 0.04</td>
<td>0.055 ± 0.04</td>
<td>0.039 ± 0.032</td>
<td>0.034 ± 0.02</td>
</tr>
<tr>
<td>Carbonate, minimum</td>
<td>0.001</td>
<td>0.003</td>
<td>0.004</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Carbonate, maximum</td>
<td>0.748</td>
<td>0.116</td>
<td>0.637</td>
<td>0.344</td>
<td>0.512</td>
<td>0.358</td>
</tr>
<tr>
<td>Carbonate, mean</td>
<td>0.181 ± 0.124</td>
<td>0.051 ± 0.02</td>
<td>0.114 ± 0.09</td>
<td>0.071 ± 0.06</td>
<td>0.048 ± 0.059</td>
<td>0.037 ± 0.04</td>
</tr>
<tr>
<td>Opal, minimum</td>
<td>0.001</td>
<td>0.014</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Opal, maximum</td>
<td>1.736</td>
<td>0.891</td>
<td>0.477</td>
<td>0.434</td>
<td>0.283</td>
<td>0.274</td>
</tr>
<tr>
<td>Opal, mean</td>
<td>0.371 ± 0.30</td>
<td>0.172 ± 0.13</td>
<td>0.088 ± 0.07</td>
<td>0.073 ± 0.06</td>
<td>0.050 ± 0.048</td>
<td>0.041 ± 0.04</td>
</tr>
<tr>
<td>Lithogenic, minimum</td>
<td>0.011</td>
<td>0.001</td>
<td>0.013</td>
<td>0.017</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Lithogenic, maximum</td>
<td>7.733</td>
<td>0.708</td>
<td>4.529</td>
<td>3.306</td>
<td>3.369</td>
<td>3.756</td>
</tr>
<tr>
<td>Lithogenic, mean</td>
<td>1.448 ± 0.94</td>
<td>0.142 ± 0.13</td>
<td>0.511 ± 0.56</td>
<td>0.35 ± 0.40</td>
<td>0.255 ± 0.40</td>
<td>0.217 ± 0.44</td>
</tr>
</tbody>
</table>

*Values are given in g m\(^{-2}\) d\(^{-1}\).*

4. Results and Discussion

4.1. Flux Rates

[15] The flux statistics for the various particulate components measured are given in Table 1. The range of fluxes, as well as the average flux rates, varies considerably amongst the different study sites. It is possible to compare the different sites by focusing on the traps positioned between 400 and 500 m. Overall, total fluxes are highest in Santa Barbara Basin and lowest in Guaymas Basin. With respect to carbon, Santa Barbara Basin has the highest average POC flux (0.096 g m\(^{-2}\) d\(^{-1}\)), as well as the highest maximum POC flux (0.369 g m\(^{-2}\) d\(^{-1}\)). In contrast, the average POC flux in Guaymas Basin is only 0.024 g m\(^{-2}\) d\(^{-1}\), 4 times lower than that in Santa Barbara Basin. POC fluxes for Cariaco Basin are 40% lower than those measured in Santa Barbara Basin but significantly higher than the Guaymas Basin POC fluxes (Table 1). In comparison, long-term mean POC fluxes at 150 m from the Hawaiian and Bermuda open ocean time series sites are 0.028 and 0.027 g m\(^{-2}\) d\(^{-1}\), respectively [Karl et al., 2001]. In addition, the average POC fluxes at all three continental margin locations (Table 1) are significantly higher (3–14 times greater) than the average global ocean POC flux of 0.007 g m\(^{-2}\) d\(^{-1}\) determined for the depth interval from 250 to 500 m [Lutz et al., 2002].

[16] Where we have multiple traps in Cariaco Basin, we can also examine depth-dependent changes in particle fluxes due to water column remineralization (Table 1). Total mass flux decreases by 63% between the shallowest trap (230 m) and the deepest trap (1200 m). Similarly, the mean POC flux decreases by ~60% from 0.073 g m\(^{-2}\) d\(^{-1}\) to 0.032 g m\(^{-2}\) d\(^{-1}\) over this 1000 m depth interval. We assume that most of the material lost is part of the POC pool lacking mineral ballast. This rate of loss is comparable to what has been observed in the open ocean [Martin et al., 1987; Pace et al., 1987] and clearly indicates that considerable degradation of organic matter is occurring in Cariaco Basin despite the fact that the water column is devoid of oxygen below 250 m [Thunell et al., 2000].

4.2. Primary Production and POC Fluxes

[17] As previously mentioned, the data from early sediment trap studies led to the hypothesis that POC fluxes at depth were proportional to either primary production or the export of organic carbon from the base of the photic zone [Suess, 1980; Martin et al., 1987; Pace et al., 1987]. The typical open ocean profile of POC flux is characterized by an exponential decrease in the upper 1000 m due to remineralization, with a small but generally linear decrease below this depth. On the basis of these observations, a number of algorithms were generated that relate POC flux to primary production (or export production) and used to predict carbon fluxes at depth [Suess, 1980; Martin et al., 1987; Pace et al., 1987].

[18] Of the three time series considered in this study, only the Cariaco Basin project includes routine measurements of primary production that can be used to directly evaluate the coupling between primary production and POC flux. Each month, depth-integrated (upper 100 m) primary production
measurements are made at the sediment trap mooring location (Figure 2; see Muller-Karger et al. [2001] for a description of the primary production measurements). These data indicate that there is a consistent or predictable annual cycle of primary production, although significant interannual variability exists in total production [Muller-Karger et al., 2001, 2004]. In particular, a strong inverse relationship exists between primary production and SST, reflecting the fact that productivity typically is higher during the first half of the year when upwelling is most intense [Muller-Karger et al., 2004].

Comparison of productivity measurements with time equivalent carbon fluxes indicates that no statistically significant relationship exists between these two parameters for any of the four sediment trap depths (Figure 3). Furthermore, introducing a time lag between production and flux does not improve the relationship. The apparent decoupling between the production and flux of POC in this continental margin setting is consistent with several recent open ocean observations. Specifically, multiyear comparisons of upper ocean carbon fluxes and primary production in the subtropical North Pacific [Karl et al., 1996], the equatorial Pacific [Armstrong et al., 2002] and the western Sargasso Sea [Conte et al., 2001; Lohrenz et al., 1992] reveal no direct correlation between the two processes. Similarly, in their synthesis of published sediment trap flux data, Lutz et al. [2002] found that while there was internal consistency in flux changes with depth, there was no correlation between either primary or export production and POC flux. Rather, these authors suggested that a variety of physical and biological interactions controlled POC fluxes and they concluded that production alone could not be used to accurately predict POC fluxes to depth. Both Lutz et al. [2002] and Francois et al. [2002] proposed that the composition of the organic matter may play a critical role in determining the depth-dependent changes in POC flux. In essence, in highly productive regions, the organic matter being exported is more labile and easily degraded, resulting in a lower transfer efficiency of organic carbon to depth [Francois et al., 2002].

Figure 2. Time series of upper ocean temperature (°C) and primary production (gC m⁻³ hr⁻¹) in Cariaco Basin for the period from 1996 through 2004.
4.3. Comparison of POC and Mineral Fluxes

Scatter plots of POC flux versus carbonate flux, opal flux, and lithogenic flux for each study area are presented in Figures 4–6. In all cases, simple linear regression analyses result in statistically significant ($P < 0.001$) correlations between POC flux and each of these mineral components, with Cariaco Basin consistently having the highest correlations (Table 2). However, for each of the three minerals (carbonate, opal, and lithogenic material), the rankings of the correlations vary slightly amongst the sites (Table 2). For example, in Cariaco Basin, the correlation between opal flux and POC flux ($r = 0.84$) is virtually identical to that between carbonate flux and POC flux ($r = 0.83$). For Santa Barbara Basin, these same correlation coefficients are also very similar ($r = 0.79$ for carbonate versus POC and $r = 0.77$ for opal vs. POC). At these two locations, the correlations are lowest between lithogenic and POC fluxes (e.g., 0.68 and 0.77). Conversely, for Guaymas Basin, the highest correlation exists between lithogenic and POC fluxes ($r = 0.75$). The lowest correlation ($r = 0.44$) for the entire data set is for POC flux versus opal flux in Guaymas Basin (Figure 6).

A similar linear regression analysis of the combined data for the three study sites indicates that POC flux is best correlated with carbonate flux ($r = 0.84$) (Table 3 and Figure 7), followed by its correlation with lithogenic flux ($r = 0.75$) and opal flux ($r = 0.65$). This ranking of correlation coefficients from highest to lowest of carbonate, lithogenic material, and opal reflects the densities of these minerals (carbonate = 2.71–2.94 $g \text{ cm}^{-3}$, quartz = 2.65 $g \text{ cm}^{-3}$, and opal = 1.73–2.16 $g \text{ cm}^{-3}$). Combining the three mineral components to create a total mineral flux yields a relationship ($r = 0.79$) that explains 63% of the variance ($r^2$) in POC flux for all three study areas (Figure 7), which is actually less than that explained by carbonate alone (71%).

In examining the pooled data sets, it is evident that distinct data clusters exist for each study area when comparing POC flux versus opal flux (Figure 7). For example, in Cariaco Basin, a unit of opal flux is associated with significantly more organic carbon than in Guaymas Basin. Such a distinction is not evident in the relationships between POC flux and either carbonate, lithogenic or total mineral flux (Figure 7). In all three areas, diatoms are the primary contributors to the opal flux. The size and cell volume of different diatom taxa can vary significantly and this in turn can impact sinking rates [Waite et al., 1997]. Thus the varying opal versus POC flux relationships observed in this study may signify fundamentally different diatom ecosystems in each location. Previous studies of the diatom floras in our Santa Barbara and Guaymas Basin sediment trap samples support this hypothesis. In Guaymas Basin, the late fall-early winter period of high opal fluxes is dominated by *Coscinodiscus* and *Rhizosolenia*, two genera with large cell volumes [Sancetta, 1995]. Conversely, the Santa Barbara
The diatom population is overwhelmingly composed of small Chaetoceros resting spores [Lange et al., 1997]. In Cariaco Basin, the upwelling period has a diatom assemblage that is dominated by small, fast growing taxa such as Leptocylindrus, Nitzchia, Asteriopnellopsis, Skeletonema and Dactyliosolen (Y. Astor, unpublished data, 2006). Thus the diatom populations in each location have significantly different species compositions and this may account for the varying POC to opal relationships we observe.

The lack of a significant relationship between POC flux and primary production in the Cariaco Basin combined with the high degree of covariance between POC flux and the fluxes of the various mineral constituents in all three study locations adds further support to the “ballast” model of Armstrong et al. [2002] developed for the open ocean. As discussed earlier, this model predicts that organic matter lacking ballast material (“excess” POC) is degraded and recycled in the upper part of the water column (<1000 m depth), while that containing ballast sinks to depth in the ocean. Thus the flux of POC to the deep ocean is proportional to the flux of ballast minerals. Specifically, these authors found that the ratio of POC flux to total mass flux \( F_{\text{OC}}/F_M \) becomes nearly constant or asymptotic at depth, with this ratio varying from \( \approx 0.05 \) in the equatorial Pacific to \( \approx 0.07 \) in the Arabian Sea. Klaas and Archer [2002] further developed this ballast concept by examining the relative importance of different ballast minerals (carbonate, opal and lithogenic material) in transporting organic carbon to the deep sea. Synthesizing available open ocean sediment trap data, these authors used multiple regression to calculate “carrying coefficients” (grams of organic carbon per gram of ballast) for each mineral and made two important

![Figure 4](image-url). POC flux versus total mineral, carbonate, opal and lithogenic fluxes for Cariaco Basin. All fluxes are in g m\(^{-2}\) d\(^{-1}\). Best fit linear regression lines and correlation coefficients (r) are shown.
observations. First, the magnitude of the carrying coefficients varies according to mineral density (carbonate has the highest density and the highest carrying coefficient, while opal has the lowest values for both of these parameters). Second, the carrying coefficient for carbonate is about 2 times higher than for lithogenic material and opal, signifying that most (~80%) of the organic carbon being delivered to the deep ocean is associated with carbonate. This latter finding is somewhat surprising since it has been previously suggested that high POC fluxes to depth occur in association with high diatom production and sedimentation rates [Michaels and Silver, 1988], while calcareous phytoplankton (cocolithophores) tend to be more abundant when diatom production is more limited owing to low-nutrient conditions [Brand, 1994].

[24] How do our observations at the three continental margin sites compare with these findings regarding the relationship between POC fluxes and mineral fluxes in the open ocean? The ratios of organic carbon flux to total mineral flux (F_{OC}/F_M) at our sites range from 0.04 (Santa Barbara and Guaymas basins) to 0.08 (Cariaco Basin) and are very similar to the open ocean values of 0.05–0.07 [Armstrong et al., 2002]. Interestingly, for Cariaco Basin we observe no change in the F_{OC}/F_M ratio over the depth range of our sediment traps (230–1200 m water depth). This has two important implications. First, it indicates that ballast material is being remineralized at a rate that is proportional to the loss of POC. Second, these results suggest that there is no “excess POC” within this depth range in Cariaco Basin, as would be predicted by the Armstrong et al. [2002] model. Rather, the uniform F_{OC}/F_M ratio indicates that most of the POC in Cariaco Basin is associated with ballast material, even at depths as shallow as 230 m. Whether this relationship is peculiar to Cariaco Basin or typical of most continental margins remains to be seen.

[25] Using an approach similar to that of Klaas and Archer [2002], we can go beyond the single-ballast model of Armstrong et al. [2002] and quantify the individual contribution of each of the three mineral components to the overall ballast versus POC flux relationship. As such, we carried out a multiple regression analysis using all of the flux data for each individual study site, as well as on the

Figure 5. POC flux versus total mineral, carbonate, opal and lithogenic fluxes for Santa Barbara Basin. All fluxes are in g m^{-2} d^{-1}. Best fit linear regression lines and correlation coefficients (r) are shown.
combined data set for all three locations. This multiparameter approach explains more of the variance in the POC flux data, whether you consider each study site individually or pool all of the data (Table 3). For the Guaymas Basin and Santa Barbara Basin data sets, multiple regression yields very similar results (Table 3). For both regions, carbonate has the highest carrying coefficient and the cumulative variance in POC fluxes explained by the three minerals is 78% for Santa Barbara Basin and 73% for Guaymas Basin. In Cariaco Basin, 86% of the variance in POC fluxes at all four depths is explained by the three mineral components. Cariaco Basin differs from the other two sites in that opal has the highest carrying coefficient of the ballast minerals (Table 3). This is attributed to the fact that diatoms dominate the phytoplankton during the highly productive, winter-spring upwelling period in Cariaco Basin. Multiple regression analysis on the combined data set for all three sites yields an equation that explains 72% of the variance in POC fluxes, with carbonate having the highest carrying coefficient (Table 3). Thus carbonate appears to be the most effective mineral for transporting POC to depth both in the open ocean [Klaas and Archer, 2002] and along continental margins.

What effect does water column remineralization have on this relationship between mineral flux and POC flux? The Cariaco Basin flux data from multiple depths allows us

Figure 6. POC flux versus total mineral, carbonate, opal, and lithogenic fluxes for Guaymas Basin. All fluxes are in g m$^{-2}$ d$^{-1}$. Best fit linear regression lines and correlation coefficients ($r$) are shown.

Table 2. Linear Regression Correlation Coefficients for POC Flux Versus Mineral Fluxes$^a$

<table>
<thead>
<tr>
<th>Location</th>
<th>Total Mineral</th>
<th>CaCO$_3$</th>
<th>SiO$_2$</th>
<th>Lithogenic</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Barbara, 500 m</td>
<td>0.81</td>
<td>0.79</td>
<td>0.77</td>
<td>0.68</td>
<td>203</td>
</tr>
<tr>
<td>Guaymas, 475 m</td>
<td>0.81</td>
<td>0.69</td>
<td>0.44</td>
<td>0.75</td>
<td>171</td>
</tr>
<tr>
<td>Cariaco, 230 m</td>
<td>0.80</td>
<td>0.82</td>
<td>0.84</td>
<td>0.73</td>
<td>196</td>
</tr>
<tr>
<td>Cariaco, 410 m</td>
<td>0.81</td>
<td>0.86</td>
<td>0.87</td>
<td>0.73</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, 810 m</td>
<td>0.74</td>
<td>0.80</td>
<td>0.89</td>
<td>0.75</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, 1200 m</td>
<td>0.69</td>
<td>0.80</td>
<td>0.87</td>
<td>0.77</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, all depths</td>
<td>0.82</td>
<td>0.83</td>
<td>0.84</td>
<td>0.77</td>
<td>760</td>
</tr>
<tr>
<td>All sites</td>
<td>0.79</td>
<td>0.84</td>
<td>0.75</td>
<td>0.65</td>
<td>1134</td>
</tr>
</tbody>
</table>

$^a$All correlation coefficients are significant ($P < 0.001$); $r$ is the linear regression correlation coefficient; and $n$ is the number of samples used in the linear regression analysis.
to assess this question. For both POC and the three mineral components, the average fluxes in the 1200 m trap are consistently less than half of those measured in the 230 m trap (Table 1). Specifically, the mean fluxes of opal, POC, lithogenic and carbonate in the deepest trap are 47%, 44%, 40% and 30%, respectively, of the shallow trap values. Despite these depth-dependent changes in particulate fluxes, there is no significant difference in the multiple correlation coefficient (R) derived for each depth (Table 3). Thus the three mineral components jointly account for a similar percentage (80–86%) of the total variance (R²) in the POC fluxes measured at the four depths.

5. Conclusions

[27] Multiyear measurements of sediment fluxes have been made at three continental margin locations, Cariaco Basin, Guaymas Basin and Santa Barbara Basin, all of which are marked by seasonal upwelling and high primary production. On the basis of these data, we make the following conclusions regarding rates and mechanisms of POC fluxes.

[28] 1. Mean organic carbon fluxes measured between 400 and 500 m depth at the three continental margin study sites range from 0.024 to 0.096 g m⁻² d⁻¹ and are significantly higher than the open ocean average of 0.007 g m⁻² d⁻¹ at this depth. Clearly, continental margins must be incorporated

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**Figure 7.** POC flux versus total mineral, carbonate, opal, and lithogenic fluxes for the combined Cariaco, Santa Barbara, and Guaymas data sets. All fluxes are in g m⁻² d⁻¹. Best fit linear regression lines and correlation coefficients (r) are shown.

**Table 3.** Mineral Carrying Coefficients and Multiple Correlation Coefficients for Multiple Regression Analysis of POC Fluxes Versus Mineral Fluxes*

<table>
<thead>
<tr>
<th></th>
<th>CaCO₃</th>
<th>Opal</th>
<th>Lithogenic</th>
<th>R</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Barbara</td>
<td>0.143</td>
<td>0.094</td>
<td>0.015</td>
<td>0.89</td>
<td>203</td>
</tr>
<tr>
<td>Guaymas</td>
<td>0.140</td>
<td>0.019</td>
<td>0.042</td>
<td>0.86</td>
<td>171</td>
</tr>
<tr>
<td>Cariaco, 230 m</td>
<td>0.237</td>
<td>0.345</td>
<td>0.004</td>
<td>0.91</td>
<td>196</td>
</tr>
<tr>
<td>Cariaco, 410 m</td>
<td>0.329</td>
<td>0.327</td>
<td>0.002</td>
<td>0.93</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, 810 m</td>
<td>0.233</td>
<td>0.439</td>
<td>0.006</td>
<td>0.93</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, 1200 m</td>
<td>0.175</td>
<td>0.391</td>
<td>0.007</td>
<td>0.89</td>
<td>188</td>
</tr>
<tr>
<td>Cariaco, all depths</td>
<td>0.252</td>
<td>0.367</td>
<td>0.002</td>
<td>0.93</td>
<td>760</td>
</tr>
<tr>
<td>All sites</td>
<td>0.313</td>
<td>0.049</td>
<td>0.009</td>
<td>0.85</td>
<td>1134</td>
</tr>
</tbody>
</table>

*All correlation coefficients are significant (P < 0.001); R is the multiple correlation coefficient; and n is the number of samples used is the multiple regression analysis.
into any realistic and comprehensive model of the ocean carbon cycle.

[30] In Cariaco Basin, where we have data for multiple depths, the rate at which POC flux decreases with depth owing to remineralization is similar to that previously reported for the open ocean. This occurs despite the fact that Cariaco Basin is anoxic below 250 m depth. Also, the relationship between POC flux and mineral flux is not significantly altered by water column remineralization.

[31] No significant relationship exists between POC flux and primary production in Cariaco Basin, the only one of our study sites where we have paired carbon production and flux data. This observation of a decoupling between primary production and carbon flux in this continental margin setting is consistent with other long-term observations in open ocean regions such as the subtropical North Pacific [Karl et al., 1996], the equatorial Pacific [Armstrong et al., 2002] and the western Sargasso Sea [Conte et al., 2001; Lohrenz et al., 1992].

[32] The availability of mineral ballast appears to be the most important factor controlling the flux of POC from the surface waters at the three study sites. Mineral fluxes explain most of the variability in POC fluxes; overall, biogenic carbonate is the most effective ballast mineral. The nature of the relationship between opal flux and POC flux is significantly different at the three study sites and may reflect different diatom ecosystems at each location.

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References


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