

## Organic carbon fluxes, degradation, and accumulation in an anoxic basin: Sediment trap results from the Cariaco Basin

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### *Abstract*

Organic carbon fluxes were measured in the anoxic water column of the Cariaco Basin under varying levels of primary productivity. Our results indicate that water column degradation of fresh organic matter in this anoxic setting is similar to what has been previously observed in the open ocean. Additionally, the rate at which carbon is consumed increases as primary productivity increases. These findings support the hypothesis that sulfate reduction is as efficient as aerobic respiration in degrading labile organic matter and that an anoxic water column does not necessarily result in an enhanced delivery of organic carbon to the sea floor. We estimate that 1–2% of the organic carbon produced at the surface reaches the seafloor and that approximately 50% of this is preserved in the sediments. This burial efficiency is comparable to that previously reported for both oxic and anoxic settings, and with sedimentation rates similar to that in Cariaco Basin.

Degradation and preservation rates of organic carbon in marine environments commonly are linked to oxygen availability, with decomposition under aerobic conditions often considered to be more efficient than under anaerobic conditions (Toth and Lerman 1977; Reimers and Suess 1983; Emerson 1985). Generally, anoxic basins are considered to be sites of enhanced carbon preservation and potential petroleum source beds (Thiede and Van Andel 1977; Demaison and Moore 1980). However, by as early as 1975, this concept of enhanced preservation under anoxic conditions was questioned (Deuser 1975; Richards 1975). A number of studies have concluded that sedimentation rate is the key parameter, with carbon preservation increasing as sedimentation rate increases (Henrichs and Reeburgh 1987; Canfield 1989; Calvert et al. 1991). More recently, there has been a growing body of evidence that suggests that surface productivity and carbon flux are the primary factors controlling the organic carbon richness of marine sediments rather than the degree of bottom water oxygenation (among others, Pedersen and

Calvert 1990; Calvert and Pedersen 1992; Bertrand and Lallier-Verges 1993; Arthur and Sageman 1994). Ingall and Jahnke (1997) have proposed a feedback system that links anoxic conditions, phosphorous regeneration, and surface productivity. According to this model, phosphorous is preferentially removed relative to carbon during anaerobic degradation of organic matter, and this phosphorous is then available to further stimulate surface productivity. In this scenario, both low oxygen conditions and high productivity work in concert to generate organic carbon-rich sediments in anoxic environments. Despite these studies, there is still considerable debate concerning the processes that control the preservation and accumulation of organic carbon in the oceans (Arthur and Sageman 1994; Hartnett et al. 1998).

In the open ocean, carbon fluxes through the water column decrease exponentially with depth due to aerobic decomposition (Suess 1980; Betzer et al. 1984; Pace et al. 1987), so that only a small fraction (~1%) of the carbon fixed in surface waters is delivered to the seafloor (Berger et al. 1988). Also, since metabolizable organic matter is more easily regenerated, the ratio of labile to refractory organic carbon flux decreases with increasing depth in the water column (Wakeham et al. 1984; Bertrand and Lallier-Verges 1993). Less is known about the fate of organic carbon settling through anoxic waters (Karl and Knauer 1991), although it has been suggested that sulfate reduction results in significant organic matter decomposition in such settings (Sorokin 1964; Jensen and Anderson 1987; Smith and Oremland 1987). Here we

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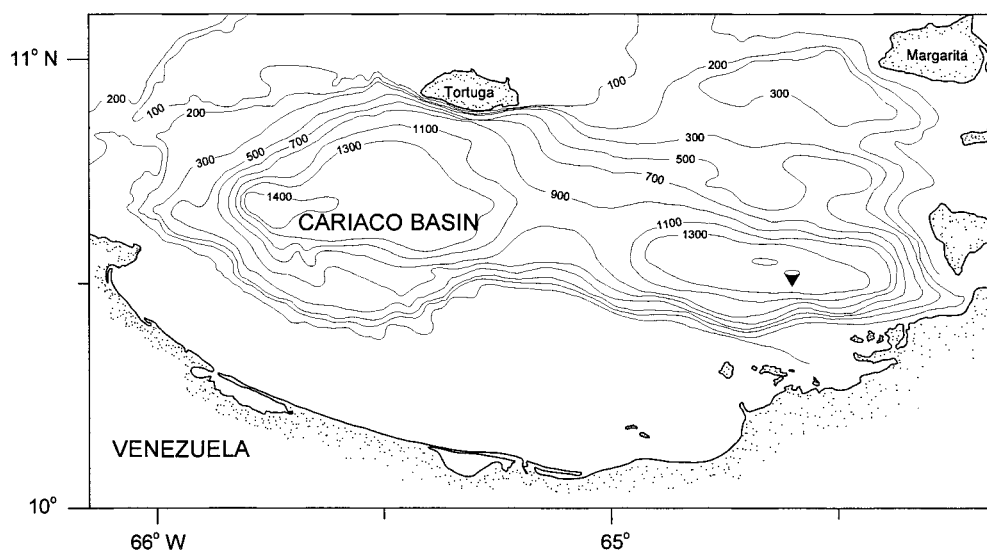


Fig. 1. Bathymetric map of the Cariaco Basin showing the location of the sediment trap mooring and time series station.

report results on depth-dependent changes in organic carbon fluxes in the Cariaco Basin, one of the world's largest marine anoxic basins (Richards 1975).

In November 1995, a time series experiment was initiated in the Cariaco Basin (Fig. 1) to study the relation between near surface biogeochemical processes and the downward flux of particulate material in an anoxic basin influenced by upwelling. This is a cooperative United States–Venezuelan research project and is referred to as CARIACO (for “carbon retention in a colored ocean”). Our sampling program has included routine hydrographic monitoring, water column chemistry measurements (including primary productivity), and sediment trapping. The Cariaco Basin is located along the northern coast of Venezuela and is effectively separated from the Caribbean Sea by a sill with a mean depth of approximately 100 m (maximum depth of 146 m). This shallow sill exerts a strong influence on the hydrographic and chemical properties of the Cariaco water column since only waters above the sill are freely exchanged with Caribbean surface waters. Because of this limited exchange and the high oxygen demand from organic matter decomposition, waters below the sill are poorly ventilated, and anoxic conditions exist at depth. For the period reported in this study (November 1995 through April 1996), the oxic–anoxic interface was positioned at a water depth of approximately 275 m, comparable to what has been previously reported for the depth of the chemocline (Richards and Vaccaro 1956; Scranton et al. 1987; Hastings and Emerson 1988; Holmen and Rooth 1990; Zhang and Millero 1993).

#### Sample collection and analysis

A single mooring containing four automated sediment traps (Honjo and Doherty 1988) was deployed on the eastern side of Cariaco Basin (10°30'N, 64°40'W) where the maximum water depth is approximately 1,400 m (Fig. 1). These cone-shaped traps have a 0.5-m<sup>2</sup> collection opening that is

covered with a baffle to reduce turbulence over the trap. The shallowest trap was positioned at the oxic–anoxic interface (~275 m), with the remaining traps at 455 m, 930 m, and 1,255 m. Samples were collected continuously for 2-week intervals, and data for the first 6-month deployment (November 1995 to April 1996) are presented here (Table 1). During this period, conductivity–temperature–depth (CTD) casts were made at the mooring location on a monthly basis. Primary production ( $\text{mgC m}^{-3} \text{h}^{-1}$ ) was measured on samples collected at eight depths (1, 7, 15, 25, 35, 55, 75, and 100 m) on four occasions during the 6-month sampling period using a modified Steeman Nielsen (1952)  $\text{NaH}^{14}\text{CO}_3$  uptake assay. Data were integrated for the upper 100 m to produce daily primary productivity estimates ( $\text{gC m}^{-2} \text{d}^{-1}$ ; Table 2).

A buffered formalin solution was placed in each trap cup prior to deployment and served as a preservative for the organic matter accumulating in the cups. Samples were stored in sealed containers and kept refrigerated after collection. Whole trap samples were split using a precision rotary splitter, and a quarter of each sample was used for bulk geochemical analyses. These subsamples were examined under a microscope, and all obvious swimming organisms not considered to be part of the particle flux, were removed before analysis. A Perkins-Elmer 2400 elemental analyzer was used to measure particulate organic carbon (POC) and particulate organic nitrogen (PON) contents following the procedures outlined in Froelich (1980). The carbon isotopic composition of the POC was measured by on-line combustion in a Carlo Erba elemental analyzer interfaced with a VG OPTIMA stable isotope ratio mass spectrometer. The lipid fraction of each sample was chromatographically separated from the total extracts and analyzed using a Hewlett-Packard 6890 gas chromatograph equipped with a flame ionization detector. Opaline silica analyses were carried out using the wet chemical leaching technique described by Mortloch and Froelich (1989).

Table 1. Flux data.

Sam- ple no.	Collection period	Trap depth (m)	Total flux (g m <sup>-2</sup> day)	Organic carbon flux (g m <sup>-2</sup> day)	$\delta^{13}\text{C}_{\text{org}}$	C/N
1	8 Nov 1995	250	0.478	0.040	-21.41	7.3
2	22 Nov 1995	250	0.318	0.038	-20.81	7.0
3	6 Dec 1995	250	0.316	0.037	-21.23	6.9
4	20 Dec 1995	250	0.078	0.012	-19.69	6.1
5	3 Jan 1996	250	0.124	0.024	-18.60	7.9
6	17 Jan 1996	250	0.303	0.031	-19.72	6.6
7	31 Jan 1996	250	1.645	0.114	-19.38	6.9
8	14 Feb 1996	250	0.599	0.059	-19.63	7.3
9	28 Feb 1996	250	1.122	0.113	-18.50	7.0
10	13 Mar 1996	250	1.749	0.168	-19.61	7.1
11	27 Mar 1996	250	0.435	0.062	-20.32	7.4
12	10 Apr 1996	250	0.387	0.045	-19.14	7.3
13	24 Apr 1996	250				
14	8 Nov 1995	475	0.475	0.039	-21.65	7.3
15	22 Nov 1995	475	0.344	0.037	-21.27	7.2
16	6 Dec 1995	475	0.266	0.029	-21.16	6.9
17	20 Dec 1995	475	0.097	0.012	-20.01	6.4
18	3 Jan 1996	475	0.121	0.014	-19.75	6.7
19	17 Jan 1996	475	0.387	0.037	-19.76	6.7
20	31 Jan 1996	475	1.543	0.104	-19.57	6.9
21	14 Feb 1996	475	0.693	0.074	-19.52	7.2
22	28 Feb 1996	475	1.309	0.149	-18.72	6.9
23	13 Mar 1996	475	1.166	0.138	-19.26	7.1
24	27 Mar 1996	475	0.550	0.075	-20.11	7.4
25	10 Apr 1996	475	0.447	0.077	-18.60	7.4
26	24 Apr 1996	475	0.157	0.032	-18.79	7.8
27	8 Nov 1995	950	0.422	0.035	-22.18	8.0
28	22 Nov 1995	950	0.283	0.030	-20.89	7.0
29	6 Dec 1995	950	0.133	0.017	-21.64	6.8
30	20 Dec 1995	950	0.040	0.008	-20.03	5.8
31	3 Jan 1996	950	0.042	0.009	-19.38	5.9
32	17 Jan 1996	950	0.097	0.015	-19.74	6.2
33	31 Jan 1996	950	0.664	0.053	-19.62	6.9
34	14 Feb 1996	950	0.196	0.026	-19.42	6.8
35	28 Feb 1996	950	0.455	0.063	-18.73	6.8
36	13 Mar 1996	950	0.302	0.044	-19.27	6.6
37	27 Mar 1996	950	0.172	0.027	-20.56	6.8
38	10 Apr 1996	950	0.169	0.032	-18.95	7.4
39	24 Apr 1996	950	0.191	0.026	-19.73	7.1
40	8 Nov 1995	1,255	0.390	0.032	-21.32	7.6
41	22 Nov 1995	1,255	0.238	0.028	-20.96	7.2
42	6 Dec 1995	1,255	0.117	0.014	-21.45	6.8
43	20 Dec 1995	1,255	0.029	0.006	-19.91	5.8
44	3 Jan 1996	1,255	0.019	0.004	-19.90	5.9
45	17 Jan 1996	1,255	0.040	0.008	-19.55	5.8
46	31 Jan 1996	1,255	0.354	0.029	-19.63	7.2
47	14 Feb 1996	1,255	0.114	0.015	-19.31	7.2
48	28 Feb 1996	1,255	0.262	0.034	-18.84	7.0
49	13 Mar 1996	1,255	0.165	0.023	-19.09	7.1
50	27 Mar 1996	1,255	0.096	0.017	-20.28	6.9
51	10 Apr 1996	1,255	0.110	0.020	-19.32	7.6
52	24 Apr 1996	1,255	0.097	0.014	-19.84	7.1

Table 2. Primary productivity, carbon fluxes, and *e*-ratios.

Date	Primary productivity (gC m <sup>-2</sup> d <sup>-1</sup> )	Carbon flux* (gC m <sup>-2</sup> d <sup>-1</sup> )	<i>e</i> -ratio
December 1995	0.582	0.029	0.05
February 1996	1.570	0.104	0.07
March 1996	2.103	0.138	0.06
April 1996	1.141	0.077	0.07

\* Carbon flux measured in the 455-m sediment trap.

First, we used the sample time series to illustrate temporal changes in organic carbon flux in response to changing hydrographic and climatic conditions. Second, we used the primary productivity measurements and depth-dependent changes in carbon flux to evaluate decomposition of organic matter in an anoxic water column. Finally, we compared water column fluxes and sediment accumulation rates to estimate the burial efficiency of organic carbon in Cariaco Basin.

#### Origin of organic matter in Cariaco Basin

Since Cariaco is a continental margin basin, there is potential for a significant influx of terrestrially derived organic carbon (Deuser 1973). Organic matter C:N ratios, carbon isotopic composition of bulk organic matter, and lipid distributions were used to identify the source or sources of organic carbon in our sediment trap samples. Marine organic matter typically has C:N ratios of 6–7, whereas organic matter from terrestrial sources typically has a C:N ratio greater than 20 (Hedges et al. 1986). Similarly, there is a distinguishable difference in the characteristic  $\delta^{13}\text{C}$  composition of marine phytoplankton (-18 to -22‰; Anderson and Arthur 1983) and terrestrial C<sub>3</sub> plants (-26 to -28‰; Collister et al. 1994a) or leaf lipids (-32 to -38‰; Collister et al. 1994b). The majority of the C:N and  $\delta^{13}\text{C}_{\text{org}}$  values for the sediment trap samples vary from 5.8 to 7.8 and -18.5‰ to -21.5‰, respectively, and thus are indicative of marine organic carbon (Table 1, Fig. 2).

The *n*-alkanes present in the samples are dominated by short chain homologues with a strong odd-carbon preference (*n*-C<sub>15</sub>, *n*-C<sub>17</sub>, and *n*-C<sub>19</sub>), which are characteristic of marine algae (Collister et al. 1994b). Similarly, the *n*-alcohols are dominated by the C<sub>18</sub> and C<sub>18</sub> homologues, which are also classic algal signatures. In contrast, long chain *n*-alkanes with a strong odd carbon preference were not observed in any of the sediment trap samples. The presence of these compounds is commonly used to infer input of organic matter from terrestrial epicuticular waxes (Eglinton and Hamilton 1963). Based on these molecular and isotopic signatures, we conclude that the organic carbon in our sediment trap samples is derived primarily from a marine source and that there is only a minor terrestrial component. A more in-depth presentation of the organic geochemistry results is in preparation (Collister and Thunell in prep.).

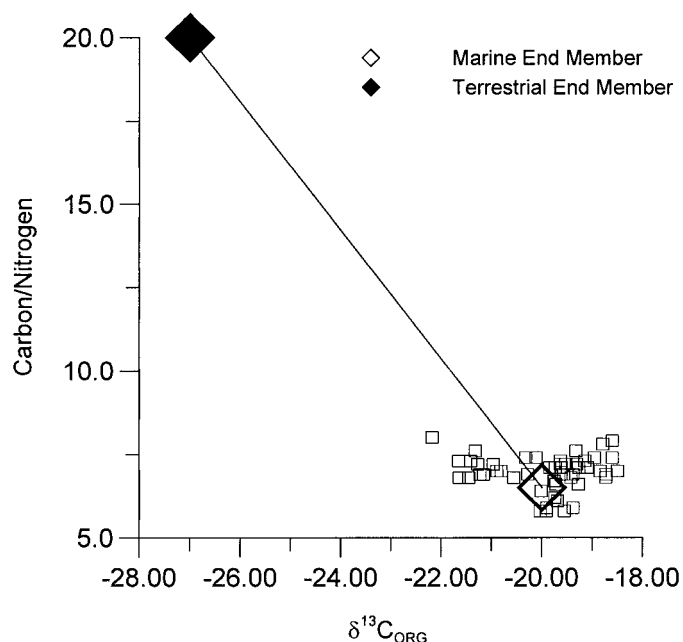


Fig. 2. Plot of carbon:nitrogen ratios and carbon isotopic compositions of organic matter collected in sediment traps in the Cariaco Basin.

#### Temporal variability in carbon fluxes

The temporal changes in carbon fluxes over the 6-month period from November 1995 to May 1996 are quite similar at all four trap depths, although there is a significant decrease in carbon flux with depth (Table 1, Fig. 3). Carbon fluxes increased in late January and remained relatively high through April in response to upwelling. The highest organic carbon flux measured during this period was  $0.17 \text{ gC m}^{-2} \text{ d}^{-1}$  in mid-March 1996. The magnitudes of the carbon fluxes measured for Cariaco are quite similar to those recently reported for coastal upwelling regions along the California margin (Pilska et al. 1996; Thunell 1998). Diatoms are the most significant contributors to the overall primary productivity in Cariaco Basin. This is reflected in the fact that the temporal trends in opal flux are quite similar to those for organic carbon (Fig. 3)—and indeed, the fluxes of these two components are highly correlated ( $r^2 = 0.94$ ; Fig. 4).

Changes in primary productivity and biogenic sediment fluxes in this region are a direct response to seasonal changes in the position of the intertropical convergence zone (ITCZ). From January to May, the ITCZ is in its most southerly position, resulting in strong easterly winds and intense upwelling along the Venezuelan coast (Muller-Karger and Aparicio 1994). Temperature measurements made during the study show a shoaling of isotherms and a decrease in surface temperatures marking the onset of upwelling in January (Fig. 5). Primary productivity nearly tripled with the initiation of upwelling, from  $582 \text{ mgC m}^{-2} \text{ d}^{-1}$  in December to  $1,570 \text{ mgC m}^{-2} \text{ d}^{-1}$  in February. Both organic carbon and opal fluxes increase significantly in early February in response to this increase in production (Fig. 3). The upwelling stimulated a phytoplankton bloom dominated by diatoms; opaline silica

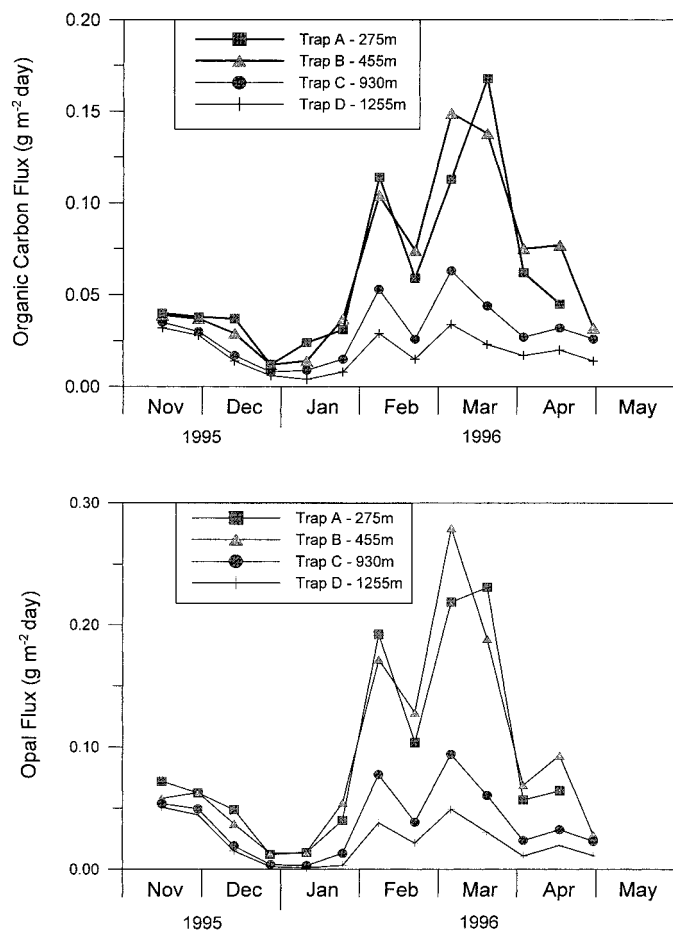


Fig. 3. Time series of carbon and opal flux measurements at four water depths in Cariaco Basin for the period November 1995 to April 1996.

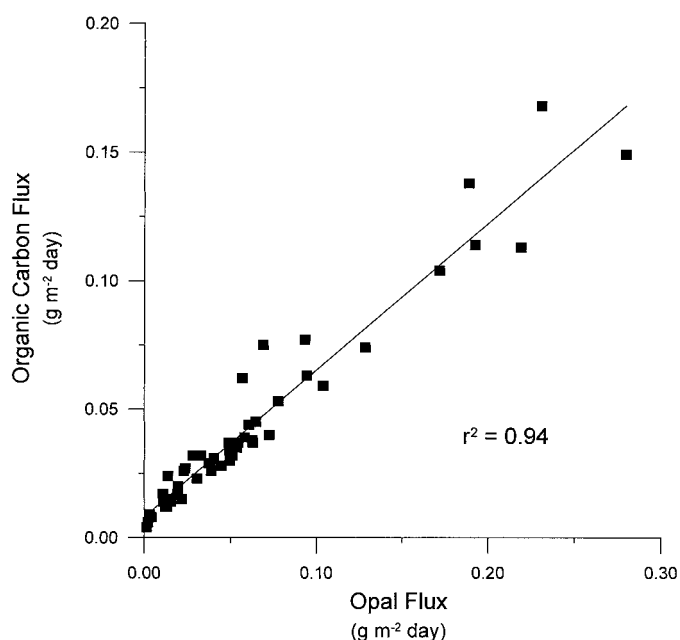


Fig. 4. Plot of opal fluxes versus organic carbon fluxes in the Cariaco Basin.

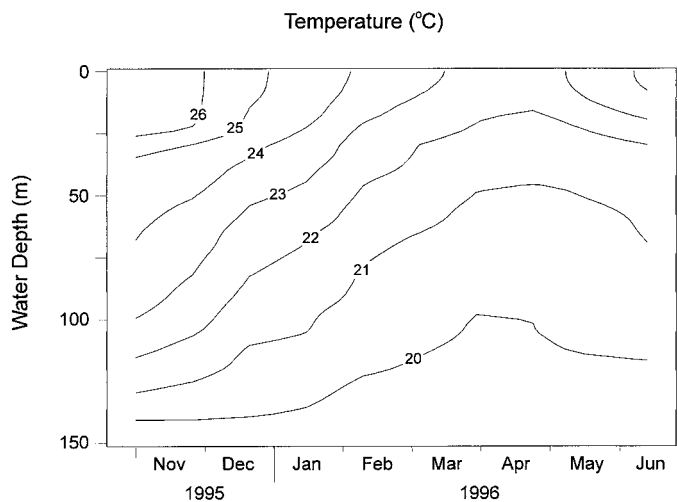


Fig. 5. Upper ocean temperature at the sediment trap mooring location for the period November 1995 to June 1996. Isotherms are in degrees centigrade.

accounts for over 50% of the total biogenic sediment fluxes during the upwelling period. High concentrations of the sterol brassicasterol, which is source specific for diatoms (Volkman 1986), indicate that most of the biogenic opal produced during upwelling is indeed derived from this phytoplankton group.

### Water column changes in organic carbon flux

Although there have been comparative studies of organic carbon preservation on the seafloor under oxic and anoxic conditions, we know little about how water column degradation of organic matter varies between these contrasting environments. Depth-dependent changes in carbon flux in the open ocean have been modeled as a function of primary productivity (among others, Suess 1980; Betzer et al. 1984; Pace et al. 1987). However, these studies are based only on carbon flux measurements from regions where aerobic regeneration is occurring in the water column. In the Cariaco Basin, there is a clear decrease in organic carbon flux with increasing water depth (Fig. 3). Carbon fluxes in our deepest trap (1,255 m) are, on average, 60% lower than those measured in the shallowest trap (275 m). This decrease in carbon flux with depth clearly indicates that significant degradation is occurring below the chemocline and is consistent with the observation that suspended particulate organic matter is diagenetically altered within the anoxic water column of Cariaco Basin (Karl et al. 1977; Wakeham and Ertel 1987).

The observed changes in carbon flux with depth in the anoxic Cariaco Basin are comparable to what has been reported for the open ocean. Using our primary productivity measurements, we estimate carbon fluxes through the water column using the following three empirical relationships developed for different ocean basins by Suess (1980), Betzer et al. (1984), and Pace et al. (1987), respectively (Fig. 6).

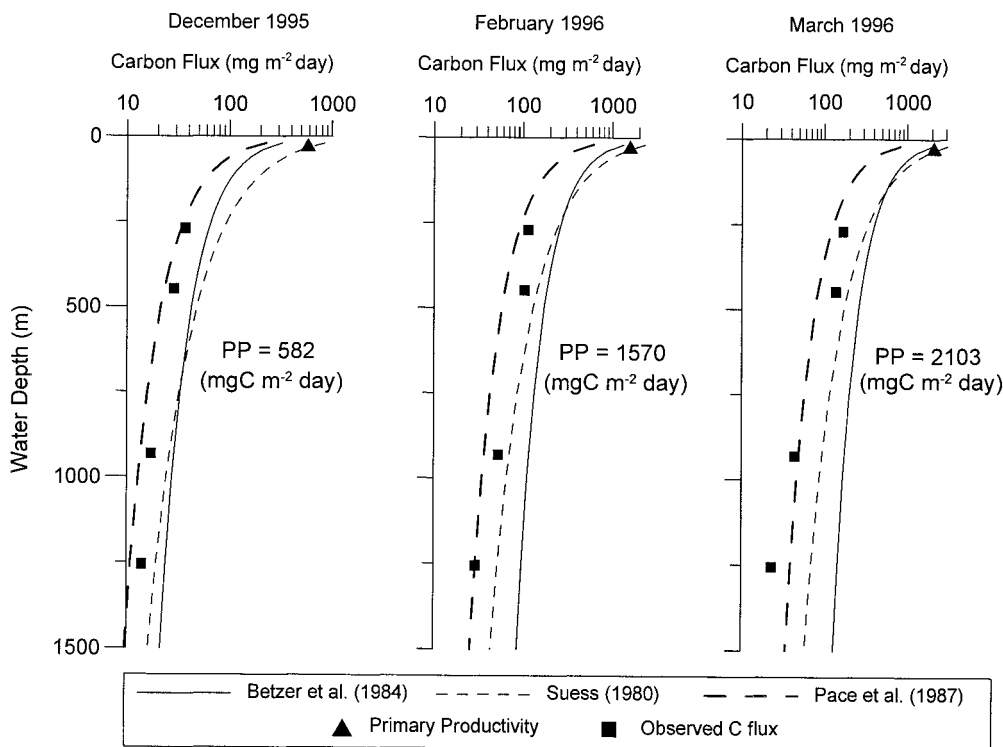


Fig. 6. Comparison of predicted changes in carbon flux with depth for three different time periods calculated using measured productivity (solid triangles) and empirical models presented in Suess (1980), Betzer et al. (1984), and Pace et al. (1987). The actual measured carbon fluxes (solid squares) are most similar to those predicted using the Pace et al. (1987) equation.

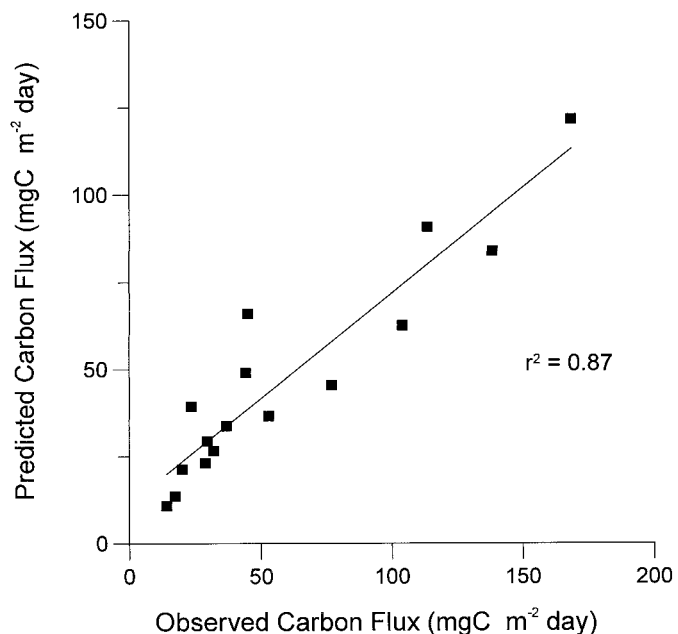


Fig. 7. Comparison of carbon fluxes measured in Cariaco Basin sediment trap samples with those predicted using the Pace et al. (1987) model.

$$C_{\text{flux}(Z)} = PP \div (0.0238Z + 0.212) \quad (1)$$

$$C_{\text{flux}(Z)} = 0.409PP^{1.41}Z^{-0.63} \quad (2)$$

$$C_{\text{flux}(Z)} = 3.523Z^{-0.734}PP^{1.000} \quad (3)$$

where  $C_{\text{flux}}$  is the estimated particulate organic carbon flux ( $\text{mgC m}^{-2} \text{d}^{-1}$ ), PP is the measured primary productivity ( $\text{mgC m}^{-2} \text{d}^{-1}$ ), and Z is water depth (m). All these models predict a decrease in carbon flux with depth, with the upper several hundred meters of the water column being the zone of most intense regeneration. Our observed carbon fluxes are in excellent agreement ( $r^2 = 0.87$ ) with predicted fluxes determined using the Pace et al. (1987) model developed for the eastern Pacific ocean (Fig. 7) and suggest that organic matter degradation occurring in an anoxic water column is as efficient as that occurring in well-oxygenated waters. The other two models (Suess 1980; Betzer et al. 1984) predict higher fluxes than we observe, and this also argues against reduced degradation of organic carbon in the anoxic water column of Cariaco Basin.

What is controlling the observed water column degradation of organic carbon in the Cariaco Basin? Karl and others (1977) found high concentrations of anaerobic bacteria within the uppermost part of the anoxic zone, with a significant microbial population also existing below this depth. These anaerobes would actively degrade organic matter throughout the anoxic portion of the water column. This is supported by a study of lipids collected from the water column in Cariaco Basin (Wakeham and Ertel 1987). These authors found that alteration of organic matter usually assumed to occur on the seafloor was actually occurring in the anoxic portion of the water column. The presence of hydrogen sulfide below the chemocline (Richards and Vaccaro 1956) indicates that

sulfate reduction by obligate anaerobes is the primary pathway for this organic matter degradation within the anoxic zone. In fact, Hastings and Emerson (1988) have shown that sulfate-reducing bacteria also are present in the suboxic region of Cariaco Basin and may outcompete aerobic bacteria under low levels of oxygen. These water column results are supported by laboratory experiments that have demonstrated that sulfate reduction and oxic respiration are equally efficient in degrading fresh organic matter (Westrich and Berner 1984; Kristensen and Blackburn 1987).

Several studies in the Black Sea provide the only other available data on carbon fluxes from multiple depths in an anoxic water column (Honjo et al. 1987; Hay et al. 1990; Karl and Knauer 1991). Both Honjo and others (1987) and Hay and others (1990) reported on carbon fluxes at 250 and 1,200 m water depth from two locations fairly close to the southern margin of the Black Sea. In these studies, total sediment fluxes, as well as organic carbon fluxes, commonly were higher in the 1,200-m sediment trap. This suggests significant downslope transport of material to the deeper traps and thus precludes us from using this data for evaluating depth-dependent changes in carbon fluxes in the Black Sea. In contrast, the Karl and Knauer (1991) study was at a station in the central part of the Black Sea where advection of material from the margin should be reduced substantially. At this location, organic carbon fluxes decreased by a factor of 2–3 within the suboxic region of the water column (60–80 m), leading Karl and Knauer (1991) to conclude that the oxic–anoxic transition was a zone of intense decomposition of particulate material. The observed change in carbon flux across the oxic–anoxic interface is consistent with results from other studies which have shown the Black Sea chemocline to be a zone where organic matter is intensely altered by anaerobic microbial processes (Wakeham 1989; Wakeham and Beier 1991). Within the anoxic portion of the Black Sea water column, organic carbon fluxes decreased from  $39.3 \text{ mgC m}^{-2} \text{d}^{-1}$  at 80 m to  $23.6 \text{ mgC m}^{-2} \text{d}^{-1}$  at 350 m (Karl and Knauer 1991). This represents a loss of ~40% and indicates that carbon degradation continues below the chemocline in the Black Sea. Thus, for both the Cariaco Basin and the Black Sea, there is evidence for significant loss of particulate organic carbon within the anoxic regions of the water column. Our water column results are consistent with the seafloor observation that organic matter degradation via sulfate reduction under anaerobic conditions occurs at a rate comparable to that of aerobic respiration in normal marine sediments (Henrichs and Reeburgh 1987; Canfield 1989; Cowie and Hedges 1992).

Export production is the carbon flux measured at depth, and when expressed as a proportion of the original primary production, it is referred to as the export ratio, or  $e$ -ratio (Murray et al. 1989). Thus,  $e$ -ratios are controlled, to a large extent, by the rate at which carbon is regenerated in the water column. We calculated  $e$ -ratios for Cariaco Basin using the carbon flux data at 455 m that coincides with our primary production measurements (Table 2). Carbon fluxes from 455 m were used so that we could compare our results with  $e$ -ratios recently reported for two California margin regions where carbon fluxes were measured at comparable depths (450 m for Monterey Bay, Pilskalns et al. 1996; 500 m for

Santa Barbara Basin, Thunell 1998). All three areas are regions marked by seasonal upwelling and high productivity.

The Cariaco Basin  $e$ -ratios are relatively low, ranging from 0.05 to 0.07 (Table 2). These values are at the low end of the range of  $e$ -ratios reported for both Monterey Bay (0.02 to 0.14) and Santa Barbara Basin (0.07 to 0.16). This suggests that the rate at which carbon is being consumed in the Cariaco Basin is equivalent to the highest rates of carbon regeneration at these other two locations. In addition, we calculate an  $e$ -ratio of 0.04 for the Black Sea based on a primary productivity of  $575 \text{ mgC m}^{-2} \text{ d}^{-1}$  and an associated carbon flux estimate of  $23.6 \text{ mgC m}^{-2} \text{ d}^{-1}$  at 350 m water depth (Karl and Knauer 1991). Thus, both Cariaco Basin and the Black Sea have similar  $e$ -ratios for comparable levels of primary production.

Besides being low, the Cariaco Basin  $e$ -ratios do not vary as a function of primary production, as has been reported in other regions. For example, Pilskaln and others (1996) and Thunell (1998) found that export ratios decreased as productivity increased, meaning that proportionately less carbon makes it to depth when productivity is high at these two California margin locations. However, in both of these studies the lower  $e$ -ratios during times of high production were attributed to increased offshore transport of particles associated with stronger upwelling and enhanced Ekman flow. The uniformity of  $e$ -ratios in Cariaco Basin suggests that this mechanism is not at work along the northern Venezuelan coast. Although the uniform export ratios indicate that a similar proportion of the original production survives to a given depth, they do not imply that the rate of carbon degradation in the water column is uniform for different levels of productivity. Rather, as production increases, the absolute rate of carbon regeneration also must increase in order for the higher carbon fluxes to be consumed.

### Seafloor preservation of organic carbon

As we have already discussed, there has been considerable debate in recent years concerning the importance of various factors in controlling the preservation and accumulation of organic carbon on the seafloor. Organic carbon burial rates have been related to primary productivity and organic carbon fluxes (Pedersen and Calvert 1990; Calvert and Pedersen 1992), bulk sediment accumulation rates (Henrichs and Reeburgh 1987; Canfield 1989), bottom water oxygen concentration (Emerson 1985), and oxygen exposure time (Hartnett et al. 1998). These factors interact to control the burial efficiency of organic carbon, where burial efficiency is the proportion of the carbon flux to the seafloor that is buried in sediments (Henrichs and Reeburgh 1987). For marine sediments accumulating in oxic environments, Henrichs and Reeburgh (1987) found that burial efficiency increased as sedimentation rate increased. According to Hartnett et al. (1998), this relationship between burial efficiency and sedimentation rate may be secondary, and it is the length of time that organic matter is exposed to dissolved oxygen in pore waters that is critical to carbon preservation. However, Canfield (1989) examined burial efficiencies in a number of anoxic environments and found that burial efficiencies were

similar for oxic and anoxic conditions when sedimentation rates were high ( $>0.1 \text{ cm yr}^{-1}$ ). Moreover, several laboratory experiments have found that fresh organic matter decomposes at similar rates under oxic and anoxic conditions (Westrich and Berner 1984; Kristensen and Blackburn 1987).

We use our sediment trap data and published data on sediment organic carbon accumulation to estimate burial efficiency in the deep Cariaco Basin. The deepest sediment trap ( $\sim 1,255 \text{ m}$ ) is fairly close to the seafloor ( $\sim 1,400 \text{ m}$ ), and we use the measured carbon fluxes in this trap as an estimate of the amount of organic carbon reaching the seafloor. For the 6-month study period from November 1995 to May 1996, the average carbon flux to the 1,255-m trap was  $\sim 20 \text{ mgC m}^{-2} \text{ d}^{-1}$ . The average primary productivity for this same 6-month period was  $\sim 1500 \text{ mgC m}^{-2} \text{ day}$ , which means that only 1–2% of the organic carbon fixed in the surface layer reached the deepest trap. Studies of box cores from the central portion of the eastern Cariaco Basin indicate that recent sedimentation rates are approximately  $0.1 \text{ cm yr}^{-1}$  (Hughen et al. 1996; Black 1998). The upper 10 cm of sediment have an average dry bulk density of  $\sim 0.14 \text{ g cm}^{-3}$  and an organic carbon content of 2–3% (Black 1998; Black pers. comm.). These parameters yield an organic carbon accumulation rate of  $8\text{--}12 \text{ mgC m}^{-2} \text{ d}^{-1}$ . This represents a burial efficiency of 40–60% based on our sediment trap estimate of the amount of organic carbon reaching the seafloor. Although this preservation rate is high, it is comparable to that reported both for other anoxic (i.e., Black Sea and Baltic Sea; Canfield 1989) and oxic settings (Henrichs and Reeburgh 1987) with similar sedimentation rates. Collectively, our water column results and studies of seafloor preservation of organic matter argue against the concept that anoxia is the primary mechanism responsible for the accumulation of organic carbon-rich sediments in the oceans.

### Conclusions

Results from a time series study of sediment fluxes at multiple depths in the Cariaco Basin allow us to draw the following conclusions regarding the nature and preservation of organic carbon settling through this anoxic water column.

Molecular biomarker and stable isotope data indicate that the organic carbon in the sediment trap samples is primarily derived from surface productivity with only a minor contribution of terrestrial organic carbon. Diatoms are the primary contributor to the total organic carbon flux.

Carbon fluxes at depth in the basin vary seasonally and are proportional to surface productivity. In addition, export ratios are uniform and do not vary as a function of primary production.

The observed decrease in carbon flux with depth in the water column is similar to that previously reported for the open ocean. This indicates that anaerobic degradation of organic carbon in the anoxic Cariaco Basin water column is as efficient as aerobic respiration.

Approximately 50% of the organic carbon reaching the seafloor in the Cariaco Basin is preserved in the sediments. This burial efficiency is comparable to that estimated for both oxic and anoxic depositional environments with sedi-

mentation rates similar to that of Cariaco Basin. This suggests that anoxia is not the primary mechanism responsible for the accumulation of organic carbon-rich sediments in the ocean.

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