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Geochemical and carbon isotopic characterization of particles collected in sediment traps from the East China Sea continental slope and the Okinawa Trough northeast of Taiwan

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Abstract

This paper reports results from various geochemical and carbon isotopic analyses of sediment particles collected at different water depths from an array of 5 sediment traps. The traps were deployed at places characteristic of distinct seafloor topography on the East China Sea continental slope and within the Okinawa Trough northeast of Taiwan during different durations from July 1993 to December 1995. Apparent sediment mass flux (ASMF) measurements show that particle fluxes are invariably high and fluctuate greatly within the canyons, as compared to those on the slope and in the Okinawa Trough, suggesting episodic sediment resuspension and a strong bottom transport from the East China Sea continental shelf to the Okinawa Trough within the canyons. The great terrigenous input thus overshadows any appreciable geochemical and isotopic changes in particles collected inside the canyons, which are otherwise seen in particles collected on the slope region where *in situ* biogenic input is enhanced by the intrusion of the nutrient-laden Kuroshio subsurface waters. In addition, the shipboard Acoustic Doppler Current Profiler (sb-ADCP) survey reveals that the persistent intrusion of the Kuroshio current then developed to a counter-clockwise circulation throughout all depths in the water column on the East China Sea continental slope. The countercurrent sweeps and redistributes the dispersed fine particles across the East China Sea continental slope, funnels massive sediments through the canyons, and deposits them on the northern slope of the Okinawa Trough. Our results are consistent with previous physical and hydrological observations. We thus conclude that all the spatial and temporal variability of geochemical and carbon isotopic characteristics of sediment particles collected in the region northeast of Taiwan can be attributed primarily to the nature of sediments sourced from the East China Sea continental margin, and the *in situ* biogenic modification in the water columns, as well

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as the dynamic transport of the dispersed fine particles by the counter flows developed in the region.

1. Introduction

The East China Sea continental margin northeast of Taiwan represents one of the most dynamic oceanic regimes in the world. Tectonically, it is the place where the oceanic Philippine plate collides and subducts underneath the Eurasian lithosphere (Chai, 1972; Uyeda, 1977; Wu, 1978; Tsai, 1986; Sibuet et al., 1987). The arc-continent collision tectonism is still active today and has resulted in the Okinawa Trough, a backarc basin, and the Ryukyu Arc (Fig. 1). The region is also known for the Kuroshio current to turn northwestwards and branch off from its mainstream before continuing to flow to the North Pacific (Nitani, 1972). The abrupt change in seafloor topography further causes the Kuroshio waters to intrude and upwell onto the East China Sea continental slope. The region therefore provides a rare opportunity for scientists to study the seawater exchange process and its associated nutrient transport mechanism between the East China Sea and Kuroshio waters (Fan, 1980; Liu, 1983;

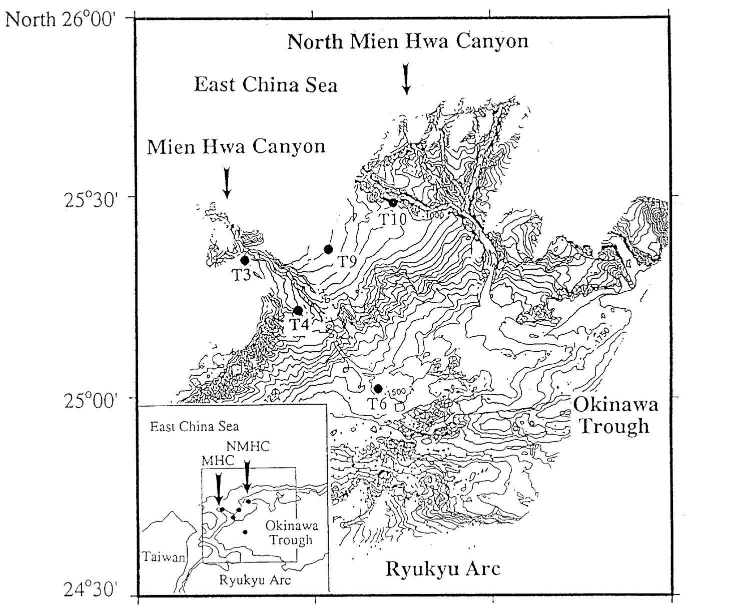

Fig. 1. Bathymetric map showing the locations of sediment traps deployed in this study. Note that the Mien Hwa canyon and the North Mien Hwa canyon are presently the two main conduits for transporting sediment particles from the East China Sea continental shelf to the Okinawa Trough northeast of Taiwan. (The map is modified from unpublished data of S. E. Lallemand and C. S. Liu (1996) with permission.)

Liu and Pai, 1987; Wong et al., 1991; Liu et al., 1992a, b; Wang and Wong, 1992; Li, 1994; Chen et al., 1995; Gong et al., 1995; 1996; 1997; Chen, 1996, references therein).

Nonetheless, studies conducted in the past have mainly emphasized the chemical hydrography of dissolved constituents and the dynamics of the upwelled flow, with scant attention to the geochemical characterization of settling particles. It is therefore the purpose of this study to perform various geochemical and isotopic measurements of particles collected from sediment traps. It is the hope that results from this study can help delineate the fate of particle transport in the region in general and the mechanisms responsible for its spatial and temporal variations in particular.

2. Experimental methods

Samples used in this study were split from sediments collected in each cup of the French-made time-series sediment traps (model PPS 3/3; Heussner, et al., 1990) deployed on the continental slope of the East China Sea and the Okinawa Trough northeast of Taiwan (Hung and Chung, 1997). An array of 5 sediment trap moorings were deployed and recovered aboard the *R/V Ocean Research I* during different durations from July 1993 to December 1995 (Fig. 1). Water depths and duration of trap deployment, sampling duration from each cup, and depths of sampling levels are summarized in Table 1. It should be noted that since these traps were deployed at different locations during different seasons over the years, a composite diagram (Fig. 2) of trap deployments was plotted on a monthly basis irrespective of the years of moorings in order to better furnish a temporal scale for later comparison of our results. As will be shown in the following discussion, the hydrographic conditions and transport processes (i.e. the counter-clockwise circulation and upwelling process) in the region are known to persist throughout the years with some seasonable

Table 1
Summary of the location, water depths and duration of sediment traps deployed in this study, and other pertinent information on the depths and intervals of collection

	Trap loations	Water depths (m)	Duration	Collection depths (m)	Interval of each cup (day)
T3	25°20.36′N; 122°17.90′E	578	7/21/1993–10/25/1993	378; 528	8
T4	25°12.64′N; 122°27.98′E	818	11/10/1993–3/9/1994	390; 490; 590	10
T6	24°59.63′N; 122°39.26′E	1440	11/14/1994–5/12/1995	740; 1340	15
T9	25°20.22′N; 122°32.91′E	607	7/13/1995–12/16/1995	407; 507	13
T10	25°30.03′N; 122°42.97′E	1006	7/13/1995–12/16/1995	606; 906	13

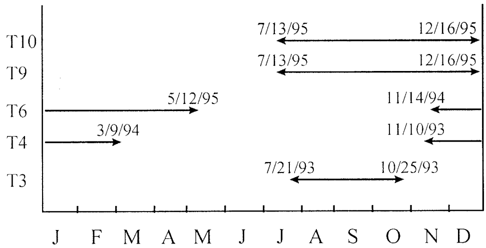

Fig. 2. A composite time series diagram showing various durations of sediment trap moorings conducted in this study during the years of 1993–1995.

variability. We feel that variations observed in this study are representative of the year-round phenomenon, and our interpretations are feasible in the overall aspects of particle transport in the region.

Current measurements were conducted by a 153 kHz sb-ADCP (Ship board-Acoustic Doppler Current Profiler) mounted on the hull of the R/V *Ocean Research I* during 10–17 August 1994 (Tang et al., 1997). The measurements were recorded per minute in depth bins of 8 m from a depth of 16 m to a depth of 304 m. The ship velocity was subtracted from the sb-ADCP measurements to obtain earth-referenced current velocities. Errors of measurements owing to the misalignment of the sb-ADCP and the GSP (Global Positioning System) fixes were eliminated and minimized by the methods of Joyce (1989) and Tang and Ma (1995). The resulting root mean square (rms) error in these measurements is $\pm$ 3.5 cm/s. Detailed sb-ADCP operation at sea and methods for removal of the tidal effect, a major current component in the study area, were described and discussed in Tang et al. (1997).

Sediment samples used for all analyses were removed from the cups, sieved (1.00 mm; 16 mesh), filtered through a pre-weighted 0.45 μm Millipore filter paper, dried in an oven at 40°C for 48 h, and then weighed to calculate the apparent sediment mass fluxes (ASMF; $g\,m^{-2}\,day^{-1}$). One aliquot of sediments was washed thoroughly with deionized water to remove salt and formalin solution (5 wt%), which was used as a preserver to prevent microbial degradation during collection and storage, and then dried in a freezer to constant weight. Approximately 20–30 mg of sediments were weighed and placed in a silver cup, digested with 2 N HCl to remove carbonates, dried in a vacuum oven, and then transferred to a Carlo Erba elemental analyzer (NA-1500) for total organic carbon (TOC) determinations. Another aliquot of sediments without the above acid treatment was used for total carbon (TC) and total nitrogen (TN) analyses. The weight percentage of carbonate concentration in sediment samples was then calculated from the difference between the measured TC and TOC. The TOC and TN thus obtained were used to calculate the C/N ratios.

Samples used for carbon isotopic analysis were first centrifuged, decanted to remove formalin, then removed from the centrifugal tubes and dried in an oven at 55°C. The dried sediment samples were ground to a powder and stored in a glass veil. An aliquot of these samples was then digested with 2.4N HCL at 55°C to eliminate the inorganic carbonates in an oven under vacuum. The interference of trace formalin that may have remained in sediment samples on carbon isotopic analysis was carefully examined and found to be negligible.

Preparation of CO_2 from carbonate-free sediments for isotopic analysis of organic carbon followed the conventional combustion method of Craig (1953). The evolved CO_2 was then purified and collected under vacuum. Approximately 50 mg of sediments were used and all samples were analyzed in duplicates. Isotopic measurement was performed with a VG Optima mass spectrometer. Results of the isotopic measurement were expressed with the conventional δ notation and reported as per mil (‰) difference relative to the PDB standard (Craig, 1957). Precision of full procedural analysis was better than $\pm 0.15\%$.

3. Results and discussion

Fig. 1 depicts the bathymetry of the study area and the sites of sediment traps deployed. As shown, the area is characteristic of abrupt changes in seafloor topography owing to the complex tectonism in the region. The Okinawa Trough, a curved backarc basin, had been formed by a multi-phase rifting, extension and subsidence since late Miocene (6 Ma) (Uyeda, 1977; Sibuet et al., 1987; Sibuet et al., 1995). Later tectonism, which began approximately during the early Pliocene (2 Ma), further resulted in the uplift of the Ryukyu arc and subsidence and block faulting in the central part of the Okinawa Trough (Ujiie, 1980; Kimura, 1985). Presently, the Trough is encompassed by the East China Sea continental slope to the north and the Ryukyu arc to the south, and has a maximum water depth of approximately 2300 m. Two distinct canyons, namely the Mien Hwa Canyon (MHC) and the North Mien Hwa Canyon (NMHC), incise across the East China Sea continental slope onto the Okinawa Trough. These canyons were formed by the slowly deepening of the northern flank of the Okinawa Trough, displacement of massive sediment block, and the downward-cutting of the bottom sediment transport. It is worthwhile to note, however, that although the NMHC is much larger in size than the MHC, the MHC is presently transporting more sediments from the East China Sea shelf into the Okinawa Trough (see below).

The abrupt change in seafloor bathymetry also caused the Kuroshio current, a strong western Pacific boundary current, to deflect and turn eastwards onto the East China Sea continental shelf (Nitani, 1972). As it flows over the northern flank of the Okinawa Trough and encounters the shelf, the Kuroshio water upwells and mixes with the East China Sea water. The upwelled Kuroshio water is readily identifiable in hydrographic profiles because of its characteristic temperature, salinity, dissolved oxygen and nutrient contents (Liu, 1983; Liu et al., 1988; Wong et al., 1991). The striking difference in these hydrographic properties had long been used to study the upwelling mechanism and its associated exchange process in the region northeast of Taiwan (Liu and Pai, 1987; Wong et al., 1991; Liu et al., 1992). The intrusion and accompanying upwelling processes have furnished the major mechanism for transporting nutrients to the East China Sea (Wong et al., 1991; Chen, 1995). Nonetheless, the deep water (approximately below 300 m isobath with temperatures below 15°C) in the Okinawa Trough did not participate in this cross-shelf mixing; that is, the intrusion of the Kuroshio water onto the East China Sea Shelf was confined mainly within the upper 300 m of the water column. The importance of this mechanism was further supported by the mass balance calculation reported by Li (1994) and Chen (1996). The water exchange rate between these two waters was estimated to be about 22,000 $\pm$ 9000 km^{-3} yr^{-1} or 0.7 $\pm$ 0.3 Sverdrups, which is about 25 times the amount of major river runoffs in the East China Sea (Li, 1994). Furthermore, Chen (1996) reported that the Kuroshio water is made up of 90% of the shelf water.

Despite the fact that previous current measurements and theoretical modeling have reported the existence of reversing flows in the area of this study (Chao, 1990; Chuang et al., 1993; Hsueh, et al., 1993; Tang and Yang, 1993; Chuang and Liang, 1994; Tang and Tang, 1994), an overall circulation pattern of this counter flow system on the East China Sea continental slope northeast of Taiwan has never been mapped until recently reported sb-ADCP measurements conducted by Tang et al. (1997). Chuang et al. (1993) first observed a subsurface current flowing southwestwards in a direction opposite the Kuroshio mainstream, which mainly flows northwards and then turns northeastwards off northeastern Taiwan after leaving its source area east of Luzon island for the North Pacific. By comparing the meteorological data, Chuang et al. (1993) and Chuang and Liang (1994) discounted wind forcing as the cause for the triggering of the observed reversing flow; instead, they suggested cooling in association with the Siberia highs in the region being the major cause for the changing flow directions. Within the MHC, this reversing current was found to flow mainly along the principal axis of the canyon in the southeastward direction. Moreover, the mean flow speeds at all stations measured decreased with increasing depth due to bottom friction.

Fig. 3 depicts the overall flow field measured at four different depths from 16 to 224 m using a sb-ADCP unit in this study. It shows that the Kuroshio intrudes northwards up onto the East China Sea slope through the NMHC, turns and whirls counter-clockwise accross the slope, changes to a southeastward direction through the MHC, and then rejoins its mainstream to continue flowing to the North Pacific. It further shows that although the flows become sluggish with increasing depths from more than 200 cm/s at 16 m to approximately 50 cm/s at 224 m (Fig. 3), the counter-current system thus developed is persistent throughout all depth and time (Tang and Yang, 1993; Tang et al., 1997). Thus, the intrusion and associated upwelling of the Kuroshio waters onto the East China Sea continental shelf not only facilitates a convey belt for transporting nutrients to the East China Sea, but also develops into a counter current system to help transport and redistribute the dispersed fine particles in the region as well.

Figs. 4–10 summarize results of the apparent sediment mass flux (ASMF; $g\,m^{-2}\,day^{-1}$), carbonate (wt%) and organic carbon (TOC; wt%) concentrations, C/N ratios, organic carbon flux (OCF; $mg\,m^{-2}\,day^{-1}$), and $\delta^{13}C$ of organic carbon analysed in this study. As can be seen, they all show strong temporal and spatial variations. Fig. 4 shows that the ASMF measured at all sites is invariably low at shallow depths and increases with increasing depths, regardless of duration of collection. However, the observed increase in particle loads with depths differs from

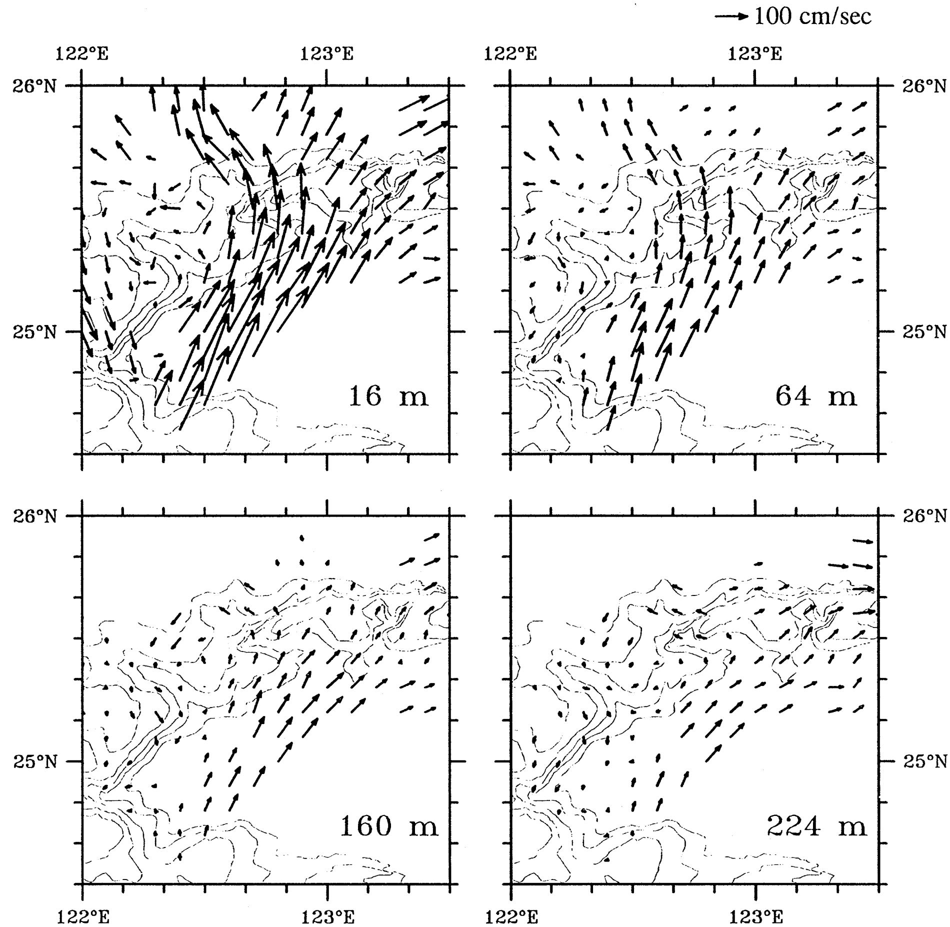

Fig. 3. Maps of the overall counter-current fields at different water depths in the study area using the shipboard Acoustic Doppler Current Profiler (sb-ADCP). Note that although the flows may vary temporarily and spatially in their speeds (scale was shown on the upper right corner), the counter-clockwise current field developed in the region is persistent throughout the years within the water columns.

different locations over different seasons, implying that processes and mechanisms controlling their variability cannot be attributed to a unique cause. For instance, the relatively small increase and variability of ASMF measured at T9 on the East China Sea slope and T6 in the Okinawa Trough suggest a downward particle settling and/or episodic sediment resuspension being the major controls. The marked increase in ASMF measured at T9 during December, but not seen at T6, may further be associated with the onset of the prevailed winter Monsoon in the region, which is known to intensify the countercurrent flow and therefore increases the bottom friction on the slope at shallow depths (i.e. T9), but does not affect bottom sediments at greater depths in the Okinawa Trough (i.e. T6).

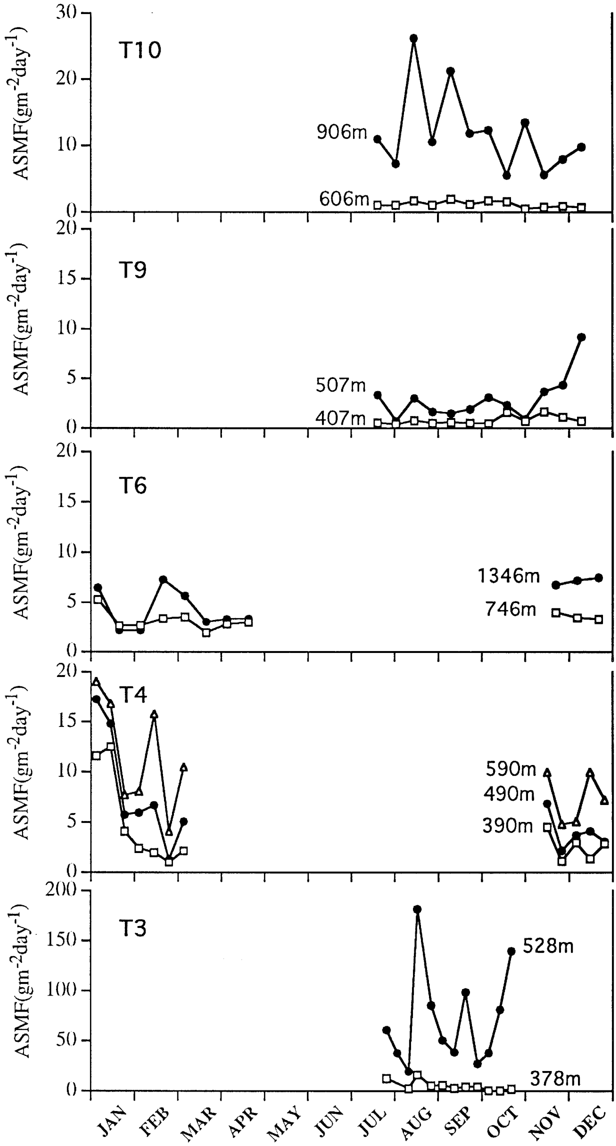

Fig. 4. Variations of the apparent sediment mass fluxes (ASMF; $g\,m^{-2}\,day^{-1}$) at various water depths through time from different sediment traps deployed in this study. Note that change on the ASMF scale of station T3.

In contrast, ASMF measured at T3 and T4 within the MHC shows a sharp increase with depth and a large variability of particle loads during trap collections, indicating that a strong bottom transport and/or resuspension of sediments dominates within the canyon. In particular, the highest ASMF measured at the lower traps of T3 within

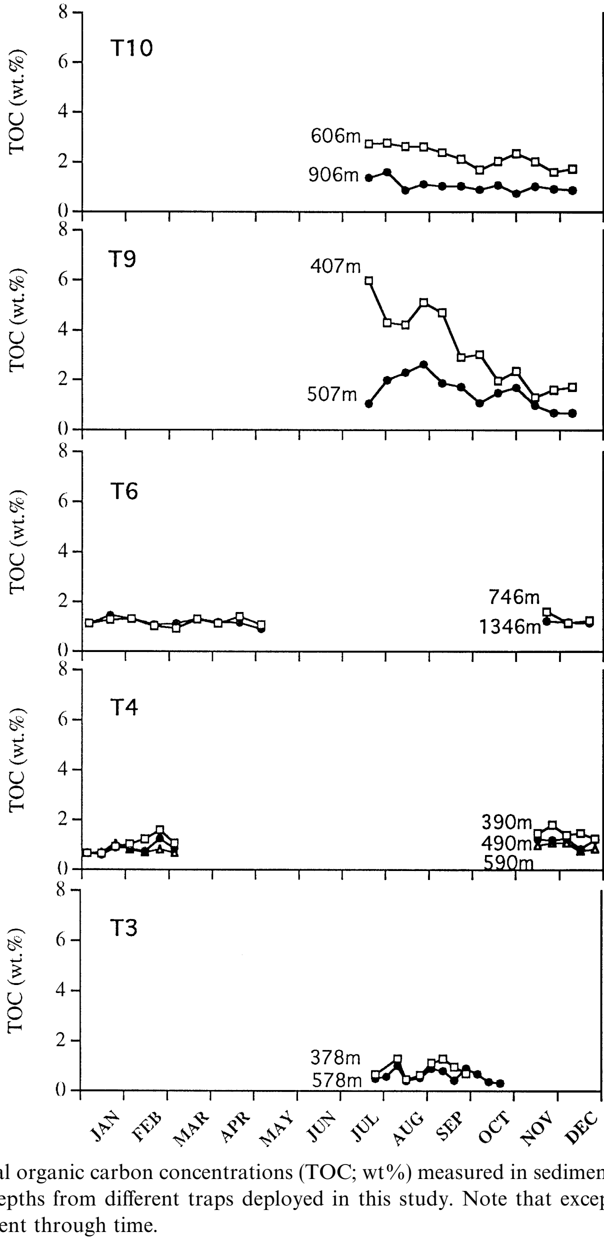

Fig. 5. Plots of total organic carbon concentrations (TOC; wt%) measured in sediment particles collected at various water depths from different traps deployed in this study. Note that except for T9, TOC are remarkably consistent through time.

the MHC further suggests that these particles originated from the East China Sea continental shelf and then funnel through the canyon downward onto the Okinawa Trough. Lin and Chen (1983) studied the mineralogical assemblage of muddy sediments in the Okinawa Trough and concluded that they were transported and

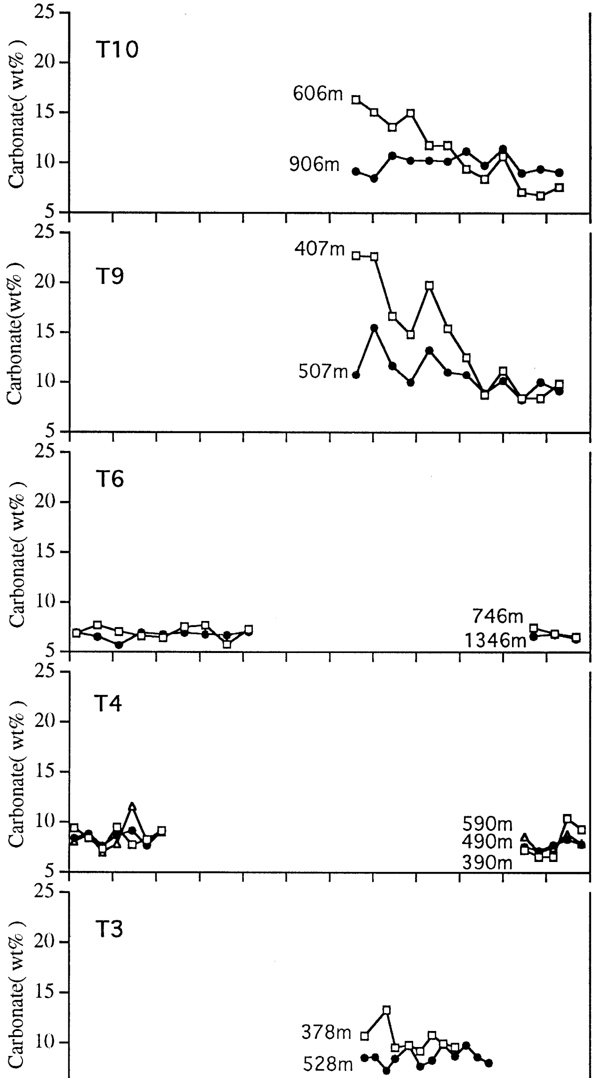

Fig. 6. Plots of carbonate concentrations (wt%) measured in sediment particles collected at various water depths from different traps deployed in this study.

dispersed from the East China Sea continental shelf by bottom currents. The source and transport of Okinawa Trough sediments from the East China Sea was further supported by Th-232 and Th-230 data of cored sediments recovered from the Okinawa Trough (Chung and Chang, 1996). It thus appears that unlike most slope regions in the world ocean that usually act as a major sink for sediment accumulation,

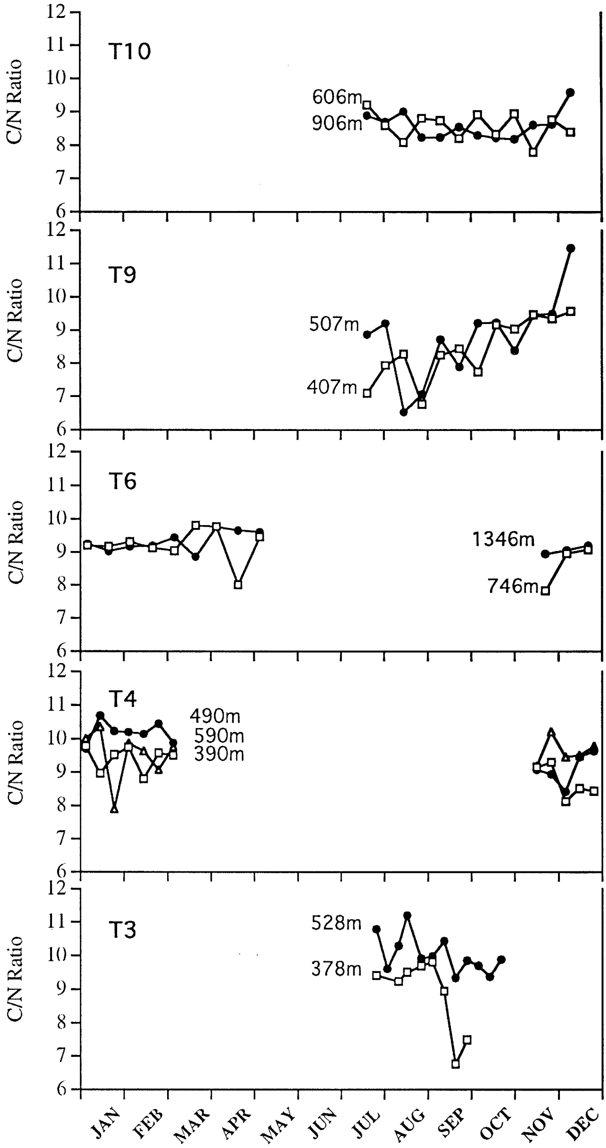

Fig. 7. Plots of the calculated C/N ratios of sediment particles collected at various water depths from different traps deployed in this study.

the East China Sea continental slope northeast of Taiwan served as a way station bypassing riverine detritus from the Yangtz and Yellow rivers to the Okinawa Trough (DeMaster et al., 1985; Milliman et al., 1985, Li, 1994). Our ASMF measurements at T3 and T4 therefore, are consistent with previous observations and support the

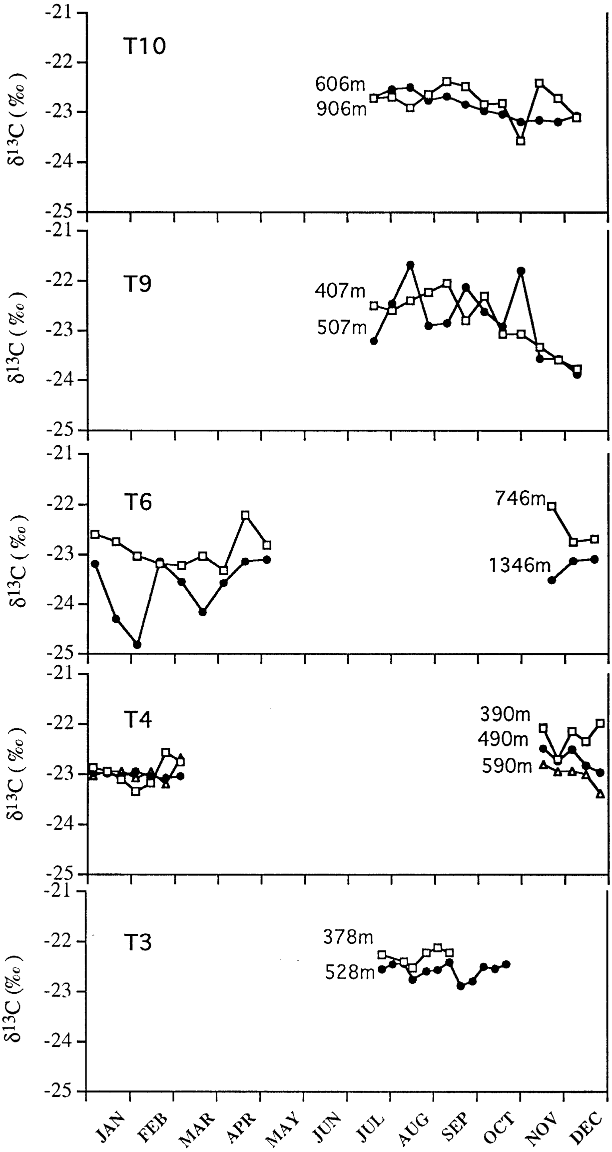

Fig. 8. Plots of C-13 compositions (TOC; wt%) of organic matter in sediment particles collected at various water depths from different traps deployed in this study.

contention that the MHC presently is the major conduit for transporting sediments into the Okinawa Trough.

As mentioned above, attempts to assess the fate of these particles between T3 and T4 within the MHC may be inconclusive because the traps were deployed over different seasons at different water depths. In effect, the ASMF measured at T3 and T4

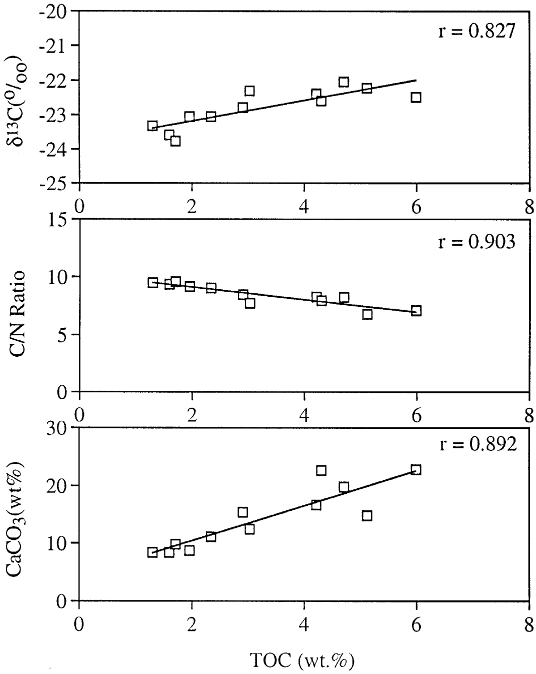

Fig. 9. Linear plots of total organic carbon (TOC) vs. $CaCO_3$, C/N ratios and organic carbon $\delta^{13}C$ in particles collected at the lower traps at station T9 on the East China Sea continental slope.

may have been underestimated and thus may not be representative of the highest particle loads that would be expected at the depths close to the bottom and during the winter when the flow within the canyon was intensified by the prevailed Monsoon. Nonetheless, a simple calculation, using the linear rate of the ASMF increase with depths at T3, can show that there is a large deficit of particle loads measured at T4 as compared to what would be expected at the same distance (50 m) above the floor, at which the lowest traps of T3 were deployed. Thus, it is conceivable that a great portion of these particles measured at T3 have settled and redeposited in the canyon before reaching station T4. The synchronous fluctuation of ASMF at various depths observed at T4 further suggests that the transport and resuspension processes have varied episodically through time, and that particles are being transported and/or resuspended actively throughout the water column at least 400 m above the floor within the canyon (the water depth at T4 is 818 m, while the shallowest traps of T4 were deployed at a water depth of 390 m).

Furthermore, T6 was deployed at a water depth of 1440 m in the Okinawa Trough and the lower traps were at 1346 m, yet the ASMF measured at 1340 m averaged only about 5 $g\,cm^{-2}\,yr^{-1}$. The relatively low ASMF measured at T6 thus suggests that particles being transported through the canyon could have never reached and been deposited beyond the point where T6 was located. Instead, they would have spread

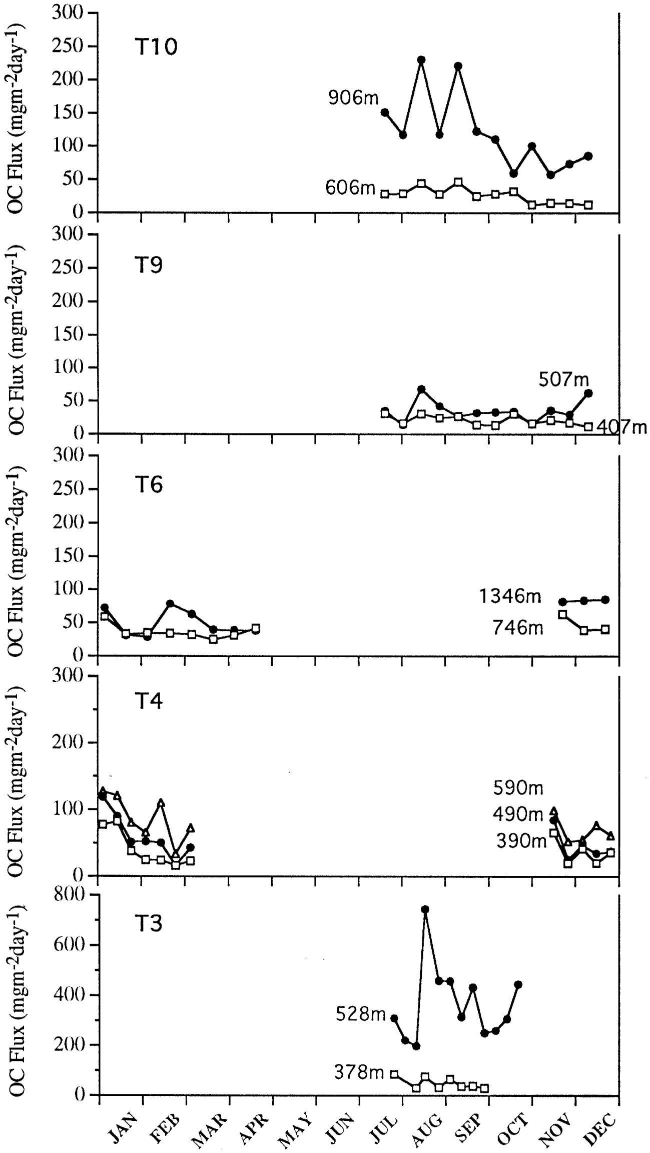

Fig. 10. Variations of the calculated organic carbon fluxes (OCF; mg m^{-2} day^{-1}) at various water depths through time from different sediment traps deployed in this study. Note that change on the OCF scale of statioin T3.

and accumulated on the lower northern slope of the Okinawa Trough between T4 and T6 (Fig. 1). Sediment accumulation rate estimates from Pb-210 flux by Chung and Chang (1995) revealed a locus of high rates of sediment accumulation (0.21–0.42 g cm^{-2} yr^{-1}) in the area south of T4 and that the rates decreased sharply with increasing water depths toward the east in the Okinawa Trough (averaged 0.08 g cm^{-2} yr^{-1}). The ASMF of T4 at the lowest traps measured in this study ranges from 4.06 to 19.02 g m^{-2} day^{-1} (equivalent to 0.15 to 0.69 g cm^{-2} yr^{-1}), thus in good agreement with the range of sedimentation rate estimates reported by Chung and Chang (1995). Chung and Chang (1995) reported no essential sediment accumulation occurring on the slope at the depth interval from 400 to 900 m. Our ASMF data from T3 and T4 further indicates that most of the sediment particles transported from the shelf are trapped and deposited within the canyons, and only a small fraction are transported onto the Okinawa Trough. That the canyon could serve as a reservoir for feeding particles to the lower portion of the slope of the southern Middle Atlantic Bight was reported by Biscaye and Anderson (1994) and confirms our contention.

Li (1994) estimated that there were about 300×10^6 tons of sediments deposited in the Okinawa Trough at depths greater than 900 m per year, and approximately half of the amount of this accumulation would account for about 10% of total suspended particle loading from the Yangtze River (490×10^6 t yr^{-1}) and the Yellow River (900×10^6 t yr^{-1}) (Milliman and Mead, 1983). The 10% given by Li (1994) is probably an overestimate because of a high rate of sediment accumulation of 0.3 g cm^{-2} yr^{-1} used in his calculation. According to Chung and Chang (1995), the average rate of sediment accumulation in the Okinawa Trough at depths greater than 900 m would not be greater than 0.15 g cm^{-2} yr^{-1}, thus the Okinawa Trough could only receive no greater than 5% of the dispersed fine particles from the East China Sea continental shelf, a half of Li's (1994) estimate.

A similar temporal variability of ASMF (Fig. 4) is also observed at T10 within the North Mien-Hwa Canyon (NMHC) and can be attributed generally to the same transport mechanism interpreted previously for T3 and T4 in the Mien-Hwa Canyon (MHC). However, as shown by ADCP measurements (Fig. 3), the countercurrent in this region is stronger at all depths than in the region where stations T3 and T4 located, and flows in an opposite direction. As a consequence, the particle transport from the East China Sea continental shelf through the NMHC would be less than that through the MHC, because the Kuroshio intrudes upward against the downward transporting of settling particles in the NMHC. The incompetence in transporting sediment particles through the NMHC further results in the low ASMF measured in the lower traps of T10. The overall sediment transport pattern and redistribution processes delineated from the ASMF data further constitute the sedimentary framework for later discussions of other geochemical and isotopic characteristics depicted in this study.

Contrary to the ASMF data, the total organic carbon (TOC) contents of settling particles collected at different depths in the traps are surprisingly uniform, with the exception of T9, which shows a progressive decrease at shallow depths throughout time (Fig. 5). In addition, all TOC measured in T3, T4, and T6 at all depths is nearly equal (averaging about 1.0 wt%) and remains almost constant over duration of collection, whereas TOC in T9 and T10 exhibits a downward decrease with depth. The consistency can be attributed to the great dilution of detrital particles, which have a characteristic TOC content of approximately 1 wt%, and a minimal *in situ* contribution from biological production in the overlying water column. The high TOC measured at T9 and T10 at shallow depths, however, could result from the high primary production in the area where the subsurface Kuroshio water upwelled (Liu, 1983; Liu, et al., 1988; Wong et al., 1991; Liu et al., 1995; Shiah et al., 1995). It is interesting to note that Liu et al., (1995) reported a mid-depth ($\sim$ 500 m) particulate organic carbon maximum (3.2–3.7 μM) at a station close to T9 in this study. Our TOC results at T9 thus are consistent with their observations. The decreasing TOC trend observed at T9 may further reflect a progressive decrease in the surface productivity from mid-July to mid-December on the slope region (Wong, et al., 1991; Liu, et al., 1992; Gong, et al., 1996, 1997). The very mechanism and process responsible for the above TOC variations can also explain the changes in carbonate concentrations (Fig. 6) because both TOC and carbonate trends are remarkably similar (cf. Figs 5 and 6). Thus, both the detrital dilution effect and changes in primary production can largely account for the observed spatial and temporal variations in TOC and carbonate concentrations of settling particles collected in the traps.

Fig. 7 shows the calculated C/N ratios of organic carbon in all sediment particles analyzed in this study. It can readily be seen that values of the C/N ratios at T6 and T10 are less variable (averaging about 9) through time than those of T3, T4 and T9 (ranging from 6–12). The former is also indistinguishable at different depths as compared to the latter. As mentioned previously, waters in areas where T6 and T10 are deployed, are predominant with the Kuroshio-type waters, whereas waters in T3, T4, and T9 are a mixture of the East China Sea shelf and Kuroshio waters. The constant C/N ratio of 9 given above thus can be representative of the settling particles laden in the Kroshio waters intruded onto the slope. Although they have not been extensively determined, particulate C/N ratios of 6-12 reported by Chen et al. (1996) and Liu et al. (1995) in the region are in good agreement with the C/N ratios measured in this study. The highly variable C/N ratios observed at T3 and T4, however, can be obtained by a combination of a new production from *in situ* biological activity and addition of detrital particle input from the shelf region. Plots of C vs. N (data not shown) further reveal that they covary very well (correlation coefficients $r = 0.910–0.998$) with positive intercepts on the C-axis for particles collected at each individual depth levels. The positive intercept could imply that a small fraction of biogenic material in all particles collected in the traps was derived from sources other than *in situ* primary production in the water column, thus pointing to a terrigenous organic input.

Furthermore, it is interesting to note that the progressive increase in C/N ratios through time at T9 coincides with the gradual decreases in TOC and carbonate concentrations. ASMF measurements show that T9 is located in the area least affected by the bottom sediment transport. The area around T9 has been shown to be the upwelling center of the Kuroshio subsurface waters (Wong et al., 1991; Liu et al., 1992; Wong and Wang, 1992; references therein). It is also the region characteristic of high phytoplankton biomass with concentrations of chlorophyll *a* and nitrate as high as up to 60 mg m^{-2} and 6 μM, respectively (Gong et al., 1995; Gong et al., 1996). A high-primary production would give rise to high TOC and carbonates of settling particles, which in turn would lead to a low C/N ratio because marine organisms are shown to enrich in N, as compared to the terrestrial plants. The increasing C/N ratios accompanied by decreasing TOC and carbonates through time at station T9 thus can be attributed to a decrease in surface primary production. Such a progressive decrease in planktonic productivity would imply an increasing dilution effect, and thus results in a decrease (i.e. more negative) in the $\delta^{13}C$ compositions of organic carbon (Fig. 8) as organic matter of terrestrial origin is usually characteristic of a lighter $\delta^{13}C$. In a study of POC collected in sediment traps from the south Chukchi sea, Naidu et al. (1993) observed a general seaward increasing trend of $\delta^{13}C$ as opposed to the decreasing C/N trend, and attributed it to the mixing of the two end members of POC of terrigenous and marine origins. Here, for the first time, we showed the evidence of the vertical sinking of freshly biogenic particles mixed with lateral transport of particles of terrigenous origins. The corresponding changes in TOC, $CaCO_3$, C/N ratios and organic carbon $\delta^{13}C$ of particles collected at T9 are shown in Fig. 9.

$\delta^{13}C$ of organic carbon in all particles collected varies between -21 to $-25‰$, yet falls well within the known range of $\delta^{13}C$ values in continental margin sediments of which a mixture of organic matter of terrestrial and marine origin are present (Fig. 8). The remarkably constant $\delta^{13}C$ (averaged $-22.48‰$) observed at T3 can be attributed to the large terrestrial input from the East China Sea continental shelf, which has a characteristic $\delta^{13}C$ composition and superimposes any changes that may be caused by the addition of biogenic matter from *in situ* biological production. In a study of organic carbon $\delta^{13}C$ of surface sediments in the East Sea shelf, Sheu et al., (1995) reported a narrow range of -20.1 to $-22.9‰$ with an averaged value of $-21.24‰$ (48 samples). Their results thus support our contention that the sediment particles transporting through the MHC have a uniform $\delta^{13}C$ composition. Furthermore, according to Sheu et al., (1996). $\delta^{13}C$ of dissolved CO_2 in the surface waters off eastern Taiwan is invariably depleted by approximately 1‰ owing to the addition of ^{13}C-depleted CO_2 from *in situ* decomposition of organic matter. Thus, the approximate 1‰ lighter of $\delta^{13}C$ measured in the sediment particles collected at T3 with respective to the shelf surface sediments (i.e. -22.48 vs. $-21.24‰$) can be obtained by the addition of organic matter from the freshly-killed microorganisms which utilize the ^{13}C-depleted CO_2 source. Accordingly, all other variations of $\delta^{13}C$ measured in the sediment particles can be attributed to the addition of organic matter of varying $\delta^{13}C$ compositions from *in situ* biological production in the water column.

As would be expected, variations in the calculated organic carbon fluxes (OCF) through time (Fig. 10) are parallel to the ASMF trend because of the large quantity of the ASMF. OCF in the Okinawa Trough (T6) and in the slope region between two canyons (T9) are seen to be relatively constant over the seasons when traps were deployed, as compared to those in the canyons (T3 and T10) where the sharp increase in OCF with increasing water depths mainly reflects the large increase in ASMF. A simple calculation further shows that within the MHC, the averaged OCF in the lower trap at T3 is about 4.6 times that at T4 (368 vs. 80 mg m^{-2} day^{-1}), while the averaged ASMF of the former is about 7.2 times that of the latter (71.5 vs. 9.9 g m^{-2} day^{-1}). In other words, while about 14% of sediment particles is survived without being trapped in the MHC, about 22% of organic carbon is removed from stations T3 to T4 in the process. In a study of sediment organic carbon distribution in the continental margin northeast of Taiwan, Lin et al. (1992) observed a zone of high organic carbon concentrations in the upper continental slope and suggested a strong lateral particle transport being the major controlling mechanism for the enrichment. The expert of organic matter from the shelf region to the continental slope was also reported by Walsh et al. (1988) and Biscaye et al. (1988). The above 8% excess OCF found at T4 within the MHC therefore supports the importance of the role of canyons on transporting terrigenous organic carbons to the open ocean.

4. Conclusions

In this study, we performed systematic measurements of the current field and various geochemical analyses of particles collected from sediment traps in the region northeast of Taiwan. Current measurements confirm the presence of a persistent counter-clockwise circulation previously reported in the region (Tang and Tang, 1994; Tang et al., 1997). More specifically, as the Kuroshio current flow over the Okinawa Trough and turns eastwards to continue its journey to the North Pacific, the shelf-side of the Kuroshio water branches off from its mainstream and intrudes northwestwards through the NMHC onto the East China Sea continental slope. It then turns counter-clockwise and reverses its direction, flowing southeastwards through the MHC, then regions its mainstream and continues to the North Pacific. The circulation pattern, however, may vary seasonally and spatially because of the variability of the winter Monsoon and botton topography, and provides the driving force for transporting sediment particles in the region as seen in our ASMF measurements from the traps. In addition, the central region of this counter flow system is located at the exact place where persistent upwelling of the cold and nutrient-rich subsurface waters is found, yet varies throughout the years. The increased supply of nutrients by these upwelled waters would therefore support a high biological activity in place. After death, remains of the organisms would be incorporated into the particles that fall through the water column. Changing this biogenic input would change the TOC and $CaCO_3$ contents, C/N ratios, and $\delta^{13}C$ of organic carbon of the particles. As a consequence, results from this study unequivocally demonstrate the importance of flow circulation and associated biological processes in controlling the transport and geochemical variability of particles in a very unique hydrographic regime where the upwelling and its associated transport and flux are constantly operating throughout the water column, and organic matter could have been recycled many times before accumulation in sediments.

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