

# Efficient trapping of organic carbon in sediments on the continental margin with high fluvial sediment input off southwestern Taiwan

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## Abstract

Accumulation rates of marine and terrigenous organic carbon in the continental margin sediments off southwestern Taiwan were estimated from the measured concentrations and isotopic compositions of total organic carbon (TOC) and previously reported sedimentation rates. Surficial sediments were collected from the study area spanning from the narrow shelf near the Kaoping River mouth to the deep slope with depths reaching almost 3000 m. The average sediment loading of Kaoping River is 17 Mt/yr, which yields high sediment accumulation rates ranging from 0.08 to 1.44 g C m<sup>-2</sup> yr<sup>-1</sup> in the continental margin. About half of the discharged sediments were deposited on the margin within 120 km of the river mouth. Carbon isotopic compositions of terrestrial and marine end-members of organic matter were determined, respectively, based on suspended particulate matter (SPM) collected from three major rivers in the southwestern Taiwan and from an offshore station. All samples were analyzed for the TOC content and its isotopic composition ( $\delta^{13}\text{C}_{\text{org}}$ ). The SPM samples were also analyzed for the total nitrogen (TN) content. TOC content in marine sediments ranges from 0.45% to 1.35% with the highest values on the upper slope near the Kaoping River mouth. The TOC/TN ratio of the SPM samples from the offshore station is  $6.8 \pm 0.6$ , almost identical to the Redfield ratio, indicating their predominantly marine origin; their  $\delta^{13}\text{C}_{\text{org}}$  values are also typically marine with a mean of  $-21.5 \pm 0.3\%$ . The riverine SPM samples exhibit typical terrestrial  $\delta^{13}\text{C}_{\text{org}}$  values around  $-25\%$ . The  $\delta^{13}\text{C}_{\text{org}}$  values of surficial sediments range from  $-24.8\%$  to  $-21.2\%$ , showing a distribution pattern influenced by inputs from the Kaoping River. The relative contributions from marine and terrestrial sources to sedimentary organic carbon were determined by the isotope mixing model with end-member compositions derived from the riverine and marine SPM. High fluvial sediment inputs lead to efficient trapping of organic carbon over a wide range of water depth in this continental margin. The marine organic accumulation rate ranges from 1.6 to 70 g C m<sup>-2</sup> yr<sup>-1</sup> with an area weighted mean of 4.2 g C m<sup>-2</sup> yr<sup>-1</sup>, which is on a par with the mean terrestrial contribution and accounts for  $\sim 2.3\%$  of mean primary production. The depth-dependent accumulation rate of marine organic carbon can be simulated with a function involving primary productivity and mineral accumulation rate, which may be applicable

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to other continental margins with high sedimentation rates. Away from the nearshore area, the content of terrigenous organic carbon in surficial sediments decreases with distance from the river mouth, indicating its degradation in marine environments.

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## 1. Introduction

Continental margins play an important role in ocean biogeochemistry due to rich riverine inputs, strong physical forcing (such as upwelling), high biological productivity and active benthic processes (e.g., Walsh, 1991; Mantoura et al., 1991; Wollast, 1998; Liu et al., 2000c). Consequently, their collective contribution to the marine carbon cycle has drawn increasing attention (Liu et al., 2000b; Chen et al., 2003; Ducklow and McCallister, 2004). The well-known hotspots of fluvial sediment discharges are Oceania rivers, which contribute a disproportionately large amount (>40% collectively) to global riverine sediment export from less than 4% of Earth's land surface (Milliman, 1991; Milliman and Syvitski, 1992; Milliman et al., 1999). Along with the high fluvial sediment discharges, organic carbon can be efficiently trapped in these continental margins due to the rapid sedimentation, which helps to transport as well as to preserve organic carbon.

It has been well documented that extremely high production rates of sediment occur in Taiwan due to heavy rainfall, steep slopes, weak bedrocks and frequent earthquakes (Li, 1976; Milliman and Syvitski, 1992; Kao and Liu, 1996, 2002; Lyons et al., 2002; Dadson et al., 2003; Milliman and Kao, 2005). Kao and Liu (1996, 2000) have demonstrated that high denudation rate and fast sediment transportation help to preserve lithogenic organic carbon in sediments discharged from mountainous rivers. Recent estimates indicate that 17–35% of terrestrial particulate organic carbon flux entering the world oceans might come from Oceania islands, including Taiwan (Schlunz and Schneider, 2000; Lyons et al., 2002). However, it is little known what happens to the terrigenous organic carbon once it reaches the ocean.

There have been many studies on the relationship between sedimentation rate and preservation of total organic carbon (TOC) in marine sediments (Muller and Suess, 1979; Doyle and Garrels, 1985; Bralower and Thierstein, 1987; Henrichs

and Reeburgh, 1987; Canfield, 1989; Stein, 1990; Betts and Holland, 1991; Calvert et al., 1991; Reimers et al., 1992; Hedges and Keil, 1995). The carbon isotopic composition has been widely used to study the origin of organic matter in marine environments (e.g., Peters et al., 1978; Sackett, 1989; Kaldy et al., 2005). Generally, the terrigenous organic matter is more depleted in  $^{13}\text{C}$ , while the marine organic matter is usually more enriched in  $^{13}\text{C}$  (Peters et al., 1978; Wada et al., 1987; Sackett, 1989; Williams et al., 1992; Thornton and McManus, 1994; Middelburg and Nieuwenhuize, 1998). In the rather exhaustive review and synthesis on this subject by Tyson (2001), 75% of the referred study sites have sedimentation rates less than  $50\text{ cm kyr}^{-1}$  and 56% of their water depths are deeper than 1000 m, and scarcely any of the cited studies report organic carbon isotopic compositions nor differentiate terrigenous from marine organic carbon in sediments. As it stands now, few studies, if any, address the effect of rapid sedimentation of Oceania islands on organic carbon preservation in spite of their significant contribution to the global sediment fluxes.

Sedimentary environments surrounding Taiwan provide us opportunities to examine how efficient the sedimentation process may trap terrigenous as well as marine organic carbon. Especially suitable is the Kaoping River in the southwestern Taiwan, where a typical mountainous river discharges to a continental margin with narrow shelf and a well-developed submarine canyon on the continental slope (Liu et al., 2002). Concentrations of organic carbon and its isotopic composition were determined for marine sediments and marine and riverine suspended particulate matter (SPM) collected from the river-shelf-slope system. The carbon isotopic composition is used as a tracer to distinguish marine from terrigenous organics. Previously reported sedimentation rates and primary productivity in the study region are drawn for estimating the organic carbon accumulation rate and the trapping efficiency.

## 2. Background information

A narrow shelf, a long slope and complex submarine canyon systems characterize the continental margin off southwestern Taiwan (Fig. 1a). The narrow Kaoping Shelf, with a total length of 150 km, stretches from the southern tip of Taiwan to the Tsengwen (TW) River mouth, where the shelf broadens connecting to the shallow Taiwan Strait (Fig. 1a). Within our study area there are two major submarine canyons, namely, the Kaoping and Fangliao Canyons (KP and FL in Fig. 1a). The Kaoping Canyon begins at the Kaoping River mouth; the Fangliao Canyon extends seaward from

the Chaochou Fault (Chiang et al., 2004). To the west of our study area, there is the multi-head Penghu Submarine Canyon (PH in Fig. 1a), the lower part of which extends into our study area.

The Tsengwen, Erhjen and Kaoping Rivers are three major sources of sediments in southwestern Taiwan. In our study area, Kaoping is the main contributor delivering about 17 Mt sediments  $\text{yr}^{-1}$  on average (see discussion), whereas sediments from the other two rivers may be mostly carried northward by currents to be described later. The annual mean water runoff is  $7 \pm 3 \text{ km}^3$  during the past 30 yr. The estimated sediment accumulation rates (SARs) of modern sediments in the sea off southwestern Taiwan range from 0.08 to 1.44  $\text{g cm}^{-2} \text{ yr}^{-1}$  (stations marked in Fig. 1b). The SAR values are converted from sedimentation rates determined by methods using  $^{210}\text{Pb}$  (Tsai and Chung, 1989),  $^{10}\text{Be}$  (Lee et al., 1993) or magnetic inclination (Chen and Leu, 1984) for age dating. For the conversion, we assume 2.6  $\text{g cm}^{-3}$  for the sediment density and 60% for water contents in modern sediments off southwestern Taiwan (Chen, 1997). These SAR values are close to values reported off northeastern Taiwan (0.10–0.95  $\text{g cm}^{-2} \text{ yr}^{-1}$  (Chung and Chang, 1995; Lin et al., 2002)). They are similar to the range of SAR values reported for the shelf and canyon systems (0.02–0.92  $\text{g cm}^{-2} \text{ yr}^{-1}$  (Carpenter et al., 1982)) and are considerably higher than those for the non-canyon continental slopes ( $< 0.10 \text{ g cm}^{-2} \text{ yr}^{-1}$  (Carpenter et al., 1982)) and the open ocean ( $< 0.06 \text{ g cm}^{-2} \text{ yr}^{-1}$  (Berner and Raiswell, 1983)).

The circulation in this region shows seasonality modulated dynamically by the relative strength of the southwest (summer) or the northeast (winter) monsoons (Liang et al., 2003). From May to August, the South China Sea Warm Current (SCSWC; Fig. 1b), driven by the southwest monsoon, flows northeastward along the shelf break in the northwestern South China Sea. This current splits into two branches when it approaches Taiwan due to the blockage of landmass (Wang and Chern, 1992). The southward branch takes 77% of the SCSWC inflow resulting in a southeastward current off the southwestern coast of Taiwan (Wang and Chern, 1992). During the wintertime, the Kuroshio (KC in Fig. 1b) intrudes from the Luzon Strait flowing northwestward. The intruding current bifurcates due to the shoaling bathymetry approaching the Taiwan Strait with the eastward branch forming an anti-cyclonic warm core eddy off southwest Taiwan (Wang and Chern, 1987).

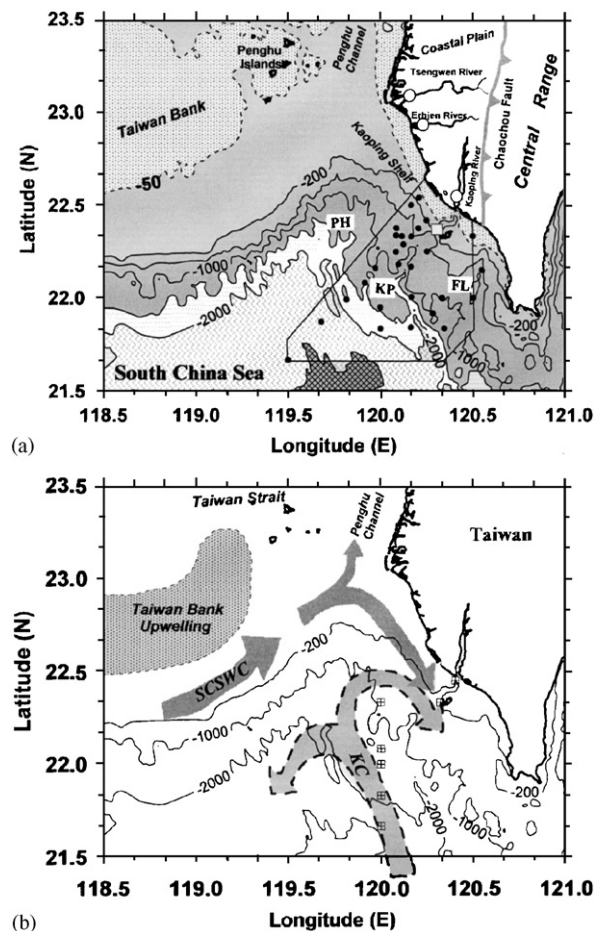


Fig. 1. (a) Map of the continental margin off southwestern Taiwan and bathymetry of the northeastern South China Sea off Taiwan. The sampling stations are marked as follows: (●) marine sediment stations, (○) riverine particle stations and (□) marine POM station and (b) Map showing circulation patterns in summer (dark gray arrow) and winter (dashed arrow). Also shown are stations of reported sedimentation rate (square with cross).

Consequently, the coastal current within our study area flows south and/or southeastward persistently and prevents northward dispersion of sediments discharged from the Kaoping River.

On the other hand, the current in the Penghu Channel, which is the narrow passage in the Taiwan Strait east of the Penghu Islands (Fig. 1a), flows consistently northward with only rare occasions of southward flow when the winter monsoon is in full blast for a prolonged period (Jan and Chao, 2003). The longshore current is also predominantly northward south of the Tsengwen River mouth (Liu et al., 2000a). It is conceivable that the persistent northward currents and wave dominated reworking

prevent southward transport of sediments discharged from the Tsengwen and the Erjeng Rivers (Fig. 1a) (Fang and Hong, 1999; Liu et al., 2000a).

### 3. Materials and methods

Sampling for surface sediments (Fig. 1a; Table 1) was conducted on R/V Ocean Researcher I (Cruises 346 and 405). A total of 30 stations were occupied at water depths ranging from 30 to 2809 m. Sub-cores from those box cores were obtained with plastic liners of 5.3 cm in inner diameter and 60 cm in length. All sediments were preserved in a freezer at about  $-20^{\circ}\text{C}$ . After returning to the laboratory,

Table 1

Total organic carbon contents and carbon isotopic compositions of surficial sediments collected from stations off southwestern Taiwan

Sta. no.	Long. ( $^{\circ}\text{E}$ )	Lat. ( $^{\circ}\text{N}$ )	Depth (m)	TOC (%)	$\delta^{13}\text{C}_{\text{org}}$ (‰)	TOC <sub>mar</sub> (%)	TOC <sub>terr</sub> (%)
1	120.210	22.541	133	0.48	-24.0	0.14	0.34
2	120.167	22.500	299	0.51	-23.0	0.29	0.22
3	120.087	22.376	690	0.72	-23.0	0.41	0.31
4	120.085	22.337	731	0.70	-23.0	0.39	0.31
4	120.283	21.917	731	0.78	-23.0	0.45	0.33
6	120.252	22.417	205	0.47	-23.3	0.23	0.24
7	120.207	22.374	370	0.49	-23.3	0.24	0.25
8	120.167	22.330	620	0.58	-23.1	0.31	0.27
9	120.124	22.289	750	0.59	-22.9	0.35	0.24
10	120.084	22.248	860	0.74	-22.5	0.52	0.22
10	120.084	22.248	860	0.64	-22.2	0.52	0.12
11	119.971	22.160	940	0.42	-22.8	0.26	0.16
12	119.916	22.082	1561	0.90	-21.5	0.90	0
13	119.817	21.991	1508	0.84	-21.8	0.77	0.07
14	119.678	21.872	2183	0.91	-21.3	0.91	0
15	119.499	21.667	2809	0.95	-21.5	0.95	0
16	120.333	22.332	244	1.28	-23.3	0.61	0.67
17	120.253	22.250	670	1.07	-23.2	0.54	0.53
18	120.099	22.180	1507	1.41	-23.3	0.68	0.73
19	120.167	22.167	734	0.87	-22.6	0.60	0.27
20	120.501	22.333	30	0.38	-23.7	0.14	0.24
21	120.335	22.167	587	0.64	-24.6	0.08	0.56
22	120.170	22.003	1234	1.09	-22.4	0.80	0.29
23	119.999	21.949	1207	0.43	-22.7	0.28	0.15
24	120.000	21.833	1570	0.50	-23.4	0.22	0.28
25	120.550	22.148	633	0.89	-23.4	0.41	0.48
26	120.334	22.000	812	1.33	-23.3	0.66	0.67
28	120.165	21.840	1713	1.16	-22.5	0.82	0.34
29	120.503	21.999	286	0.44	-24.4	0.08	0.36
30	120.345	21.836	1287	0.41	-23.6	0.16	0.25
31	120.117	22.333	56	0.69	-24.5	0.10	0.59
Max			2809	1.41	-21.3	0.95	0.73
Min			30	0.38	-24.6	0.08	0

Also shown are the percentages of marine and terrigenous organic carbon calculated from carbon isotopic compositions (see text in Section 4).

surface sediments (2 cm) were scraped from the core top with a stainless-steel spatula. Scraped sediments were washed by distilled water to remove pore water salt and then freeze-dried for 1 week. The dried sediments were later ground to powder by hand with pestle and mortar.

SPM samples were collected on board R/V Ocean Researcher I during Cruise 571 (21–24 December 1999) at a station located near the head of Kaoping Canyon with bottom depth of 250 m (square in Fig. 1a; Table 2). During the 2-d cruise, water samples were collected at six depths between 5 and 60 m with GoFlo bottles on five casts (one cast every 6 h). Temperature and salinity were recorded with a Seabird CTD. SPM samples were collected

by filtering 2-l water samples through glass fiber filters (Whatman, GF/F) under pressure of less than 200 mmHg. Filtered samples were covered with preheated (450 °C) aluminum foil and preserved in a freezer. After returning to the laboratory, filters were acidified with 1 N HCl and dried in oven (60 °C) for 48 h prior to analysis. Three samples of SPM were collected from the Tsengwen, Erhjen and Kaoping Rivers during the flooding brought by Typhoon Doug, which invaded Taiwan on 6–8 August 1994. (More info on Typhoon Doug is available at <http://www.cwb.gov.tw/V4/index.htm>.) The filtration and pre-treatment procedures were the same as the marine samples.

Table 2

Concentrations and isotopic compositions of particulate organic carbon and concentrations of particulate nitrogen collected from five hydrocasts at a station at the head of the Kaoping Submarine Canyon (Fig. 1a)

Cast	Depth (m)	Temp. (°C)	Sal. (‰)	PN (µg/l)	POC (µg/l)	C/N (wt./wt.)	$\delta^{13}\text{C}_{\text{org}}$
1	5	25.0	34.30	29	195	6.6	-22.0
	10	25.0	34.30	27	153	5.6	-21.8
	20	25.0	34.32	26	155	5.9	-21.9
	30	25.0	34.32	24	160	6.6	-21.6
	40	24.9	34.33	42	265	6.3	-21.4
	60	24.9	34.34	23	131	5.6	-21.3
2	5	24.6	34.18	30	176	5.8	-21.4
	10	24.7	34.21	29	175	6.0	-22.1
	20	24.6	34.18	27	159	5.8	-21.1
	30	24.5	34.17	23	142	6.1	-21.1
	50	24.7	34.22	30	169	5.6	-21.1
	70	24.7	34.34	31	212	6.9	-21.9
3	5	25.0	34.30	29	174	5.9	-21.5
	10	24.8	34.31	33	223	6.7	-21.7
	20	24.8	34.31	38	218	5.7	-21.2
	30	24.8	34.32	32	180	5.6	-21.5
	40	24.7	34.32	28	165	5.9	-21.5
	60	24.7	34.33	28	180	6.3	-22.0
4	5	25.0	34.29	24	155	6.6	-21.8
	10	24.8	34.28	41	231	5.7	-21.7
	20	24.6	34.24	35	221	6.3	-21.3
	30	24.5	34.28	32	205	6.4	-21.6
	40	24.3	34.31	40	225	5.7	-21.4
	60	23.3	34.38	34	184	5.4	-21.9
5	5	25.2	34.28	21	105	5.0	-21.4
	10	25.2	34.28	28	152	5.5	-21.0
	20	24.9	34.30	20	120	6.2	-21.0
	30	24.7	34.32	25	142	5.7	-21.3
	40	24.6	34.33	35	178	5.2	-21.4
	60	24.5	34.33	29	162	5.5	-21.1
	Average	24.7	34.29	30	177	5.9	-21.5
	St. dev.	±0.3	±0.05	±6	±36	±0.5	±0.3

Carbon isotope samples were prepared using sealed-tube combustion method (Wedeking et al., 1983). For decarbonation, about 0.2 g powdered sediment samples were acid-treated with 15 ml 1 N HCl for 2 d in precombusted (500 °C) glass test tubes and then centrifuged for removal of solution. The acid-treated sediments were further dried at 60 °C for analysis. Decarbonated filters and sediments were put into preheated copper capsules and then sealed in evacuated 9-mm quartz tubes amended with 1 g each of CuO and Cu pellets and a small portion of silver wool. Quartz tubes were then heated at 900 °C for 3 h, kept at 650 °C for over 12 h, and cooled to room temperature. CO<sub>2</sub> and N<sub>2</sub> gases were extracted and purified in a vacuum line and collected in sealed 6-mm glass tubes. The abundances of carbon and nitrogen were measured manometrically in the vacuum line. The recovery and accuracy had been verified by using pure organic compounds and the Certified Reference Material NIST 1547. The detection limits for carbon and nitrogen measurements were 5 µgC and 0.2 µgN, respectively, which result in relative precision better than 5% for all of our measurements. Carbon isotopic compositions were determined in a Finnigan Delta-Plus mass spectrometer. Results are presented in the standard  $\delta$  notation ( $\delta^{13}\text{C}_{\text{org}}$ ) with respect to standard of PDB carbon. The accuracy and precision of carbon isotopic determination are better than 0.1‰ for pure standard compounds and field samples.

We used chlorophyll-*a* (chl-*a*) data derived from ocean color images to calculate the monthly primary production in the sea off southwestern Taiwan with the Vertically Generalized Production Model (VGPM) of Behrenfeld and Falkowski (1997). The ocean color data are the SeaWiFS Level 3 Monthly Standard Mapped Image of chl-*a* concentration data from 1998 to 2002 ([http://daac.gsfc.nasa.gov/data/dataset/SEA-WIFS/01\\_Data\\_Products/index.html](http://daac.gsfc.nasa.gov/data/dataset/SEA-WIFS/01_Data_Products/index.html)). For the shelf area with water depth less than 100 m, the primary productivity is assumed to be the same as the mean value in the depth band between 100 and 200 m. This assumption is adopted to avoid using ocean color data near the coast, where the chlorophyll signal may be contaminated by suspended sediments and colored dissolved organic matter (Sathyendranath, 2000). More details of the calculation are described in Appendix A.

## 4. Results

### 4.1. Sedimentary organic carbon and its isotopic composition

The TOC content in surficial sediments ranges from 0.35% to 1.30% (Fig. 2; Table 1) with higher TOC values (>0.9%; Fig. 2a) in the area between the Kaoping and the Fangliao Canyons. This plume-like high TOC patch extends southward from the Kaoping River mouth, suggesting the riverine dominance in this high TOC patch. The distribution of TOC content is consistent with the circulation pattern such that the high TOC patch matches the center of the warm core eddy, which is an important feature off southwestern Taiwan (Wang and Chern, 1987). This indicates that the physical setting exerts a determinative effect on the particle transportation and deposition, thus the spatial distribution of sedimentary organic matter. High TOC contents (>0.7%) were also found outside this patch, further to the southwest in the lower reach of the Kaoping Canyon, where the water depth reaches 2000–3000 m (Fig. 2a).

The  $\delta^{13}\text{C}_{\text{org}}$  values in surficial sediments (Fig. 2b) range from –24.5‰ to –21.3‰ showing a pattern with relatively low  $\delta^{13}\text{C}_{\text{org}}$  (–23.5‰ or less) values that extend from the Kaoping River mouth along the coast and also seaward to the south. The highest value was found at water depths over 2000 m. The lower  $\delta^{13}\text{C}_{\text{org}}$  values (<–23.5‰) distribute along the coast to the southeast and south suggesting along-shore transport of terrigenous organics, which has typical  $\delta^{13}\text{C}$  values around –26~–25‰ (e.g., Smith and Epstein, 1971; Newman et al., 1973; Peters et al., 1978; Wada et al., 1987). Such a distribution pattern is consistent with the persistently southeastward coastal current (Wang and Chern, 1992), which tends to carry the terrigenous matter to the southeast and south. The heavier  $\delta^{13}\text{C}_{\text{org}}$  values in the offshore region to the southwest indicate higher contribution from marine sources of organic matter, which has typical  $\delta^{13}\text{C}$  values of –20 to –22‰ (e.g., Meyers, 1994, 1997).

### 4.2. Marine and riverine particulate organic carbon

The concentration of particulate organic carbon in seawater and its isotopic composition determined from samples collected at the head of the Kaoping Canyon are shown in Table 2. Also shown are concentrations of particulate nitrogen in the same

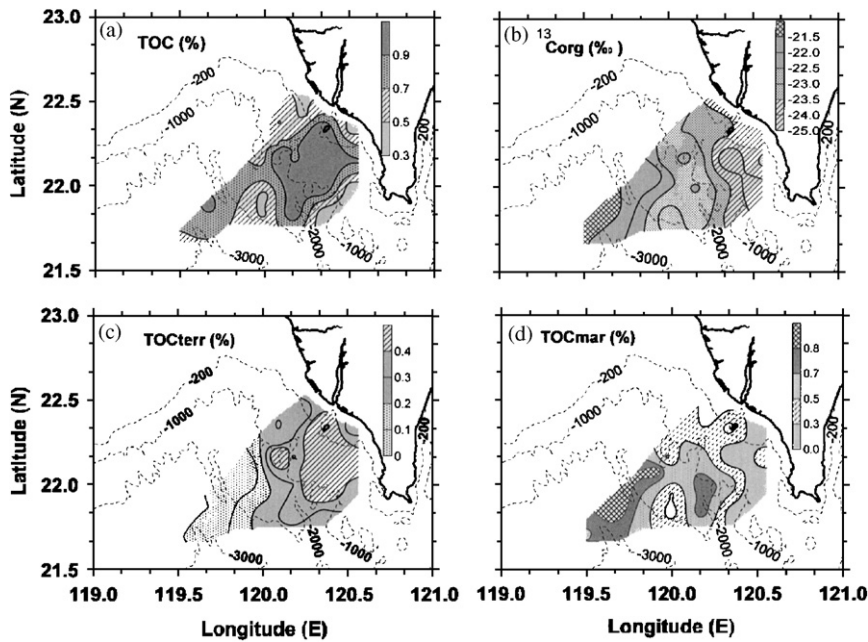


Fig. 2. Contour maps of organic carbon properties in surficial sediments off southwestern Taiwan: (a) content of total organic carbon as percentage of sediment weight, TOC; (b)  $\delta^{13}\text{C}_{\text{org}}$ ; (c) content of organic carbon from marine origin,  $\text{TOC}_{\text{mar}}$  and (d) content of organic carbon from terrestrial origin,  $\text{TOC}_{\text{terr}}$ .

samples and the hydrographic parameters observed on the hydrocasts. During the sampling period, the temperature of the water column in upper 60 m showed a narrow range from 23.3 to 25.2 °C with a mean temperature of  $24.7 \pm 0.3$  °C. The salinity varied in a narrow range ( $34.29 \pm 0.05$  psi) as well. The temperature and salinity data agree with previously reported hydrographic data for surface water in this region (Fan, 1982). The salinity variation was small in the upper 60 m without significant freshening in the surface layer, suggesting that the water column during sampling period was little affected by the Kaoping River discharge. This is expected because the river plume may be limited in expansion during the low-flow condition, which occurs most of the time except shortly after torrential rains.

The concentrations of POC and PN in water column ranged from 105 to 265  $\mu\text{g C l}^{-1}$  and 20 to 41  $\mu\text{g N l}^{-1}$ , respectively (Fig. 3). Values of POC and PN are positively correlated showing a mean C/N ratio of  $5.8 \pm 0.5$  by weight or  $6.8 \pm 0.6$  by atom, which is essentially the same as the Redfield ratio (Redfield et al., 1963), indicating the collected particulate organic materials were predominantly of marine origin.

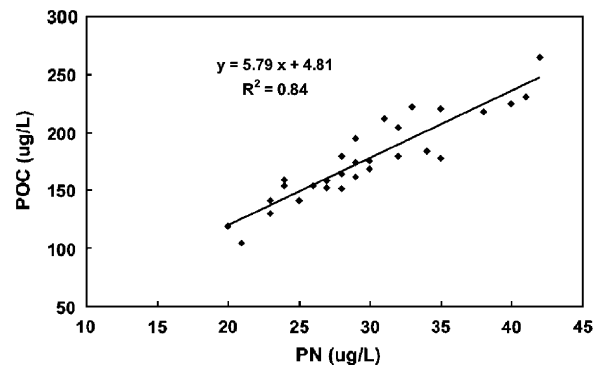


Fig. 3. C/N scatter plot for suspended particulate organic matter collected at the head of the Kaoping Canyon off southwestern Taiwan.

Compared to  $\delta^{13}\text{C}_{\text{org}}$  values of surface sediments, the variability of  $\delta^{13}\text{C}_{\text{org}}$  values in SPM showed a much narrower range varying from  $-22.4$  to  $-21.0$ ‰ with a mean of  $-21.5 \pm 0.3$ ‰. This mean value falls within the range of  $\delta^{13}\text{C}$  values of the aforementioned typical isotopic compositions of marine POC and also agrees with the mean  $\delta^{13}\text{C}_{\text{org}}$  value of SPM collected from surface waters in the southern East China Sea ( $-21.5 \pm 0.5$ ‰ (Chen, 2001)). Therefore,  $-21.5$ ‰ is assumed to be the

Table 3

Concentrations and isotopic compositions of organic carbon of suspended particulate matter collected from three riverine stations (Fig. 1a)

River	POC (%)	$\delta^{13}\text{C}_{\text{org}}$
TW	0.49	-25.2
ER	0.42	-24.9
KP	0.58	-24.8
Average	$0.50 \pm 0.08$	$-25.0 \pm 0.2$

$\delta^{13}\text{C}_{\text{org}}$  value of the marine end-member in our study area for the estimation of marine organic carbon in sediments.

For riverine suspended particles (Table 3), the mean  $\delta^{13}\text{C}_{\text{org}}$  value of SPM samples collected from the Tsengwen, Erhjen and Kaoping Rivers was  $-25.0 \pm 0.2\%$ . The mean value falls within the  $\delta^{13}\text{C}_{\text{org}}$  range of SPM samples collected from major western Taiwanese rivers during typhoon periods ( $-25 \pm 0.5\%$ ; (Kao, 1995)). It is also close to flux-weighted mean reported for POC collected during typhoon floods in the Lanyang-Hsi River ( $-24.8 \pm 1.1\%$  (Kao and Liu, 2002)). Our previous studies of Taiwanese watersheds demonstrated that most of the riverine particles were discharged during typhoon periods (Kao and Liu, 1996, 2002; Milliman and Kao, 2005). Therefore, these samples are representative of the terrigenous materials discharged to the continental margin off southwestern Taiwan and  $-25\%$  is assumed to be the  $\delta^{13}\text{C}_{\text{org}}$  value of the terrestrial end-member.

#### 4.3. Sediment accumulation

In order to calculate the organic carbon accumulation rate in surficial sediments, we compiled SAR data at stations within our study area (Fig. 1b) reported by Tsai and Chung (1989), Lee et al. (1993) and Chen and Leu (1984). The reported values of SAR show a coherent negative relationship with water depth (Fig. 4a) aside from the continental shelf, which is rather narrow, and the Kaoping Canyon, which has limited area. A similar trend of decreasing SAR with increasing distance offshore was also observed in the Taiwan Strait (Lee et al., 1993) and in the East China Sea shelf off the Changjiang River mouth to the Okinawa Trough (Oguri et al., 2003). The increasing distance away

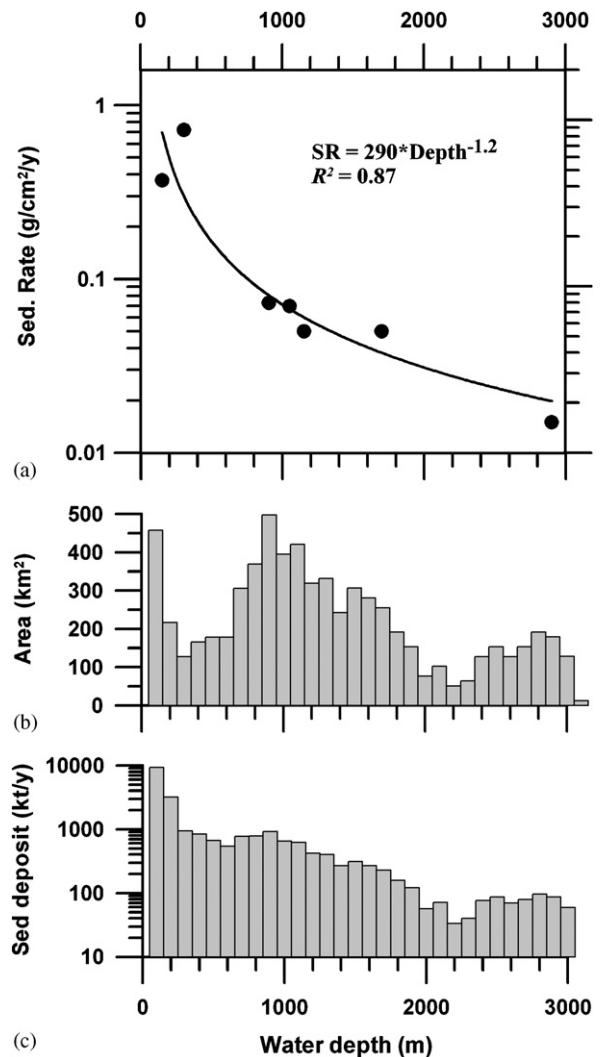


Fig. 4. (a) Relationship between sediment accumulation rate (SAR) derived from reported sedimentation rate and water depth. The empirical relationship may be used to calculate SAR in the study area. (b) Areas of depth bands in the study area off southwestern Taiwan. (c) Estimated sediment accumulation in the depth bands of every 100 m.

from the sediment sources explains the trend of decreasing SAR with increasing depth. The highest SAR occurs at the water depth around 200 m in the upper slope near the shelf break. By contrast, the station located near the Kaoping River mouth exhibits a slightly lower than the maximum, yet still fairly high, SAR. The higher tidal energy and other physical processes (such as waves) in the shallow environment that favor dispersion of fine-grained sediments may explain the slightly lower SAR found at this station.

The SAR may be represented by a power law function of water depth as follows:

$$\text{SAR} = 290 \text{Depth}^{-1.2}, \quad R^2 = 0.87, \quad n = 7, \quad (1)$$

where SAR is in units of  $\text{g cm}^{-2} \text{yr}^{-1}$  and depth is in units of meters. It is noted that the calculated SAR values differ from the observed values with a mean relative deviation of  $\pm 44\%$ , which may be regarded as the uncertainty of the estimates.

To estimate the total sediment accumulation, we used the gridded topographic data (NGDC, 2001). For each grid point, the SAR is calculated according to Eq. (1), if the water depth is deeper than 150 m; for the coastal zone with water depths shallower than 150 m, the SAR is assumed to be the same as that for 150 m. The surface area and the SAR for each 100 m depth band are integrated in the study area and plotted in Figs. 4b and c. The annual sediment accumulation in the study area is found to be  $9298 \text{ kt yr}^{-1}$  by integrating SAR over the domain shown in the map (Fig. 1), which has a surface area of  $6763 \text{ km}^2$ . The integrated and the average SAR as well as the area of integration are listed in Table 4.

#### 4.4. Organic carbon accumulation

We calculated the TOC accumulation rate from the SAR and the TOC content in surficial sediments. The spatial distribution of TOC was interpolated from the observed values within the study area according to the grid of the topographic data. The organic carbon accumulation rate was calculated as follows:

$$R_{\text{TOC}} = \text{SAR} \times \text{TOC}, \quad (2)$$

where  $R_{\text{TOC}}$  is in units of  $\text{g C m}^{-2} \text{yr}^{-1}$ . The results are shown in Fig. 5a. The maximum TOC accumulation rate reaches  $52 \text{ g C m}^{-2} \text{yr}^{-1}$ , which occurs in the upper slope where both TOC and SAR are high.

It is desirable to quantify the accumulation rates of organic carbon from different origins, namely, the terrigenous vs. the marine origins. The  $\delta^{13}\text{C}_{\text{org}}$  value of the sediment sample allows us to separate the bulk sedimentary organic carbon into the marine organic carbon ( $\text{TOC}_{\text{mar}}$ ) and the terrigenous organic carbon ( $\text{TOC}_{\text{terr}}$ ) by using carbon isotope balance model (e.g., Sackett, 1989). The  $\delta^{13}\text{C}$  value of the sedimentary bulk organic carbon

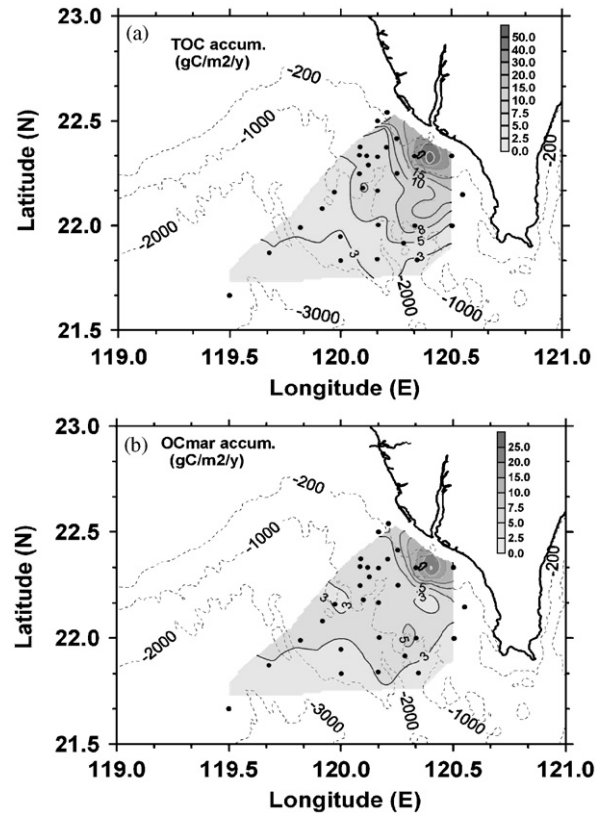


Fig. 5. (a) Distribution of total organic carbon accumulation rate calculated from the sediment accumulation rate and the total organic carbon content. (b) The same as (a) except for marine organic carbon.

Table 4

Integrated values of primary production, and accumulation of sediment, total organic carbon and marine organic carbon in the continental margin off southwestern Taiwan

	Area of integration ( $\text{km}^2$ )	Total integrated value ( $\text{kt yr}^{-1}$ )	Mean rate ( $\text{g m}^{-2} \text{yr}^{-1}$ )
Primary production	6763	1248	185
Estimated POC delivery flux to seafloor	6494	210	32
Sediments	6763	9298	1375
Total organic carbon accumulation	6660	56	8.5
Marine organic carbon accumulation	6494	27	4.2

( $\delta^{13}\text{C}_{\text{org}}$ ) is expressed as

$$\delta^{13}\text{C}_{\text{org}} = f_{\text{Mar}} \delta^{13}\text{C}_{\text{Mar}} + f_{\text{Terr}} \delta^{13}\text{C}_{\text{Terr}}, \quad (3)$$

$$f_{\text{mar}} + f_{\text{terr}} = 1, \quad (4)$$

where  $f_{\text{mar}}$  and  $f_{\text{terr}}$  are the proportions of marine and terrigenous organic carbon, respectively, and  $\delta^{13}\text{C}_{\text{Mar}}$  and  $\delta^{13}\text{C}_{\text{Terr}}$  represent the respective isotopic compositions of the two end-members, namely, the marine end-member ( $-21.5\text{‰}$ ) and the terrigenous end-member ( $-25.0\text{‰}$ ). In case the sedimentary  $\delta^{13}\text{C}_{\text{org}}$  value is lower (higher) than the terrigenous (marine) end-member, the  $f_{\text{terr}}$  ( $f_{\text{mar}}$ ) value is assumed to be 1. From the proportions of the two end-members, we may calculate the contents of organic carbon from the two sources:

$$\text{TOC}_{\text{mar}} = f_{\text{mar}} \text{TOC}, \quad (5)$$

$$\text{TOC}_{\text{terr}} = f_{\text{terr}} \text{TOC}. \quad (6)$$

Contour maps of estimated  $\text{TOC}_{\text{terr}}$  and  $\text{TOC}_{\text{mar}}$  in sediments are shown in Fig. 3c and d, respectively. The highest values of  $\text{TOC}_{\text{terr}}$  mostly occur on the upper slope between the Kaoping canyon and the Fangliao Canyon. This high  $\text{TOC}_{\text{terr}}$  area coincides with the reported anti-cyclonic warm eddy (Wang and Chern, 1992), illustrating that the deposition of terrigenous POM is strongly affected by the circulation pattern. By contrast, the highest  $\text{TOC}_{\text{mar}}$  values distribute on the lower slope, where the SAR is the lowest.

The choice of end-member compositions may change the results of the calculation, but the changes would be limited. An isotopically heavier value for the marine end-member by  $0.5\text{‰}$  may decrease the marine fraction by 12%, while a lighter value by  $0.5\text{‰}$  may increase the marine fraction by 17%. Changes in the terrigenous end-member of the same amount have the opposite effect with similar magnitudes. From the SAR and the  $\text{TOC}_{\text{mar}}$  values we are able to calculate the accumulation rate of marine organic carbon in the manner similar to the calculation of the TOC accumulation rate presented above. The results are shown in Fig. 5b. Although the highest  $\text{TOC}_{\text{mar}}$  values appear in the lower slope, the highest accumulation rate of marine organic carbon, which reaches  $26 \text{ g C m}^{-2} \text{ yr}^{-1}$ , is still on the upper slope, where the SAR is very high. The integrated and the average accumulation rates of TOC and marine organic carbon as well as the area of integration are listed in Table 4.

#### 4.5. Primary productivity

There has been one systematic study on the primary productivity in the sea off southwestern Taiwan by Hung et al. (1986), who conducted oceanographic survey at six stations in the area from  $119^{\circ} 30' \text{E}$  to  $120^{\circ} 30' \text{E}$  and from  $22^{\circ} \text{N}$  to  $22^{\circ} 40' \text{N}$  (Fig. 6). They reported primary production values for five different months of the year covering all seasons. The mean values and the standard deviation obtained in the five surveys are presented in Fig. 7a. The average of vertically integrated primary production is  $684 \pm 120 \text{ mg C m}^{-2} \text{ d}^{-1}$ .

To improve spatial and temporal coverage, we used the SeaWiFS chl-*a* data to calculate the monthly primary production in the sea off southwestern Taiwan as described in 'Section 3' and the Appendix A. Fig. 6 shows the average of the vertically integrated primary productions calculated for the 60 months. The overall average of the mean primary production values for the pixels corresponding to the six stations of Hung et al. (1986) is calculated to be  $710 \text{ mg C m}^{-2} \text{ d}^{-1}$ , which is very close to the average of the observed values ( $684 \pm 120 \text{ mg C m}^{-2} \text{ d}^{-1}$ ). Therefore, we use the SeaWiFS data-derived primary production values shown in Fig. 6 to represent the production of marine organic carbon in the study area. The total and the mean annual primary production in the study area as well as the area of integration are listed in Table 4.

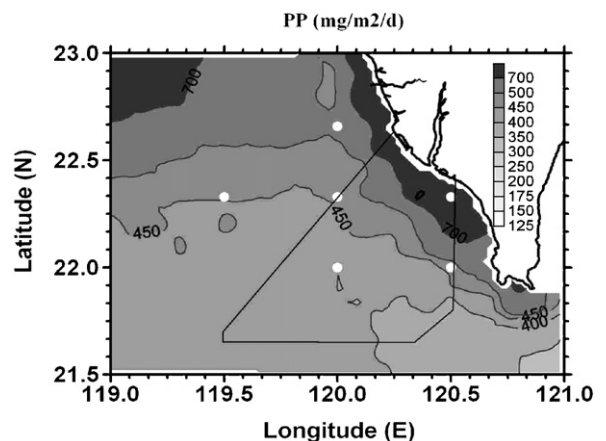


Fig. 6. The mean primary production ( $\text{mg C m}^{-2} \text{ d}^{-1}$ ) derived from the SeaWiFS chlorophyll data (see text). The location of the stations surveyed by Hung et al. (1986) is shown as the white dots in the plot.

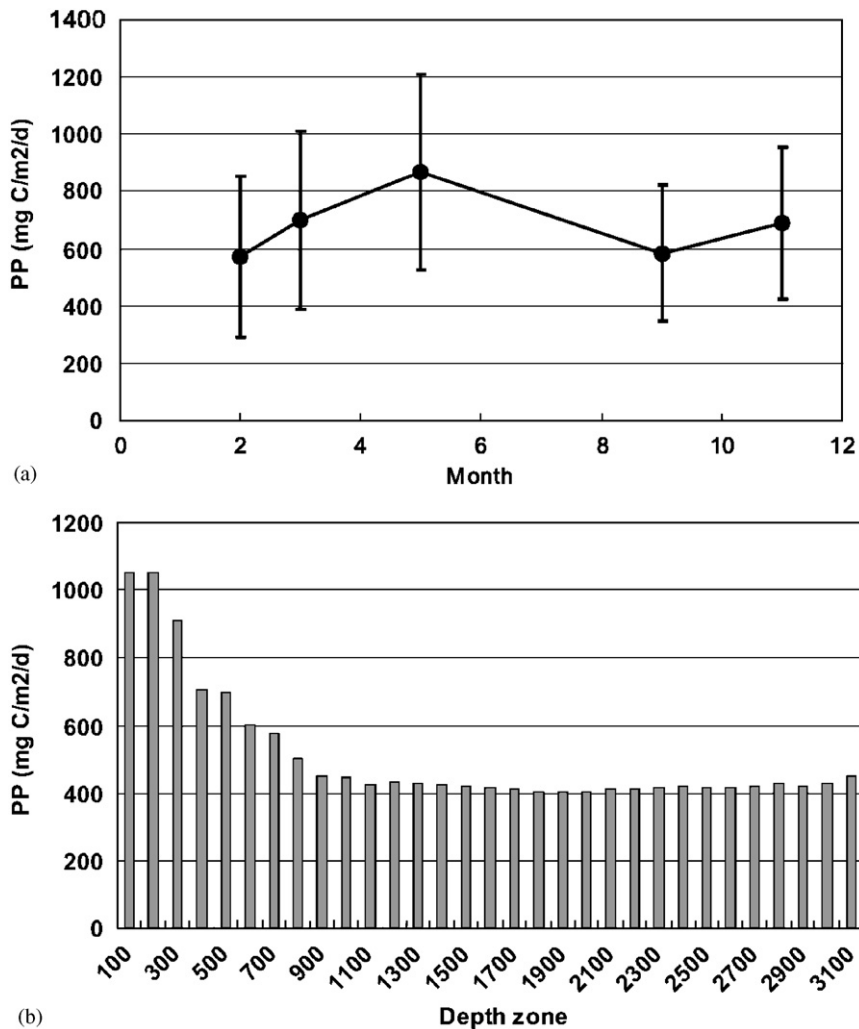


Fig. 7. (a) The mean values of measured primary production in different seasons at six stations (see Fig. 6) in the sea off southwestern Taiwan (Hung et al., 1986). (b) Average primary production ( $\text{mg C m}^{-2} \text{d}^{-1}$ ) calculated from the SeaWiFS data derived values (see Fig. 6) for zones of every 100 m in water depth (see text).

## 5. Discussion

We have calculated the organic carbon accumulation rates for the study area from observed SAR values and the TOC contents. In order to check the validity of our approaches we first compare the estimate of total sediment accumulation against the estimate of mean sediment discharge. Then we discuss how efficient the fast sedimentation preserves marine organic carbon in the continental margin off southwestern Taiwan by comparing organic carbon accumulation against primary production. Finally, we invoke a model to simulate the depositional flux of marine organic carbon to the seafloor with sediments as ballast for the transport.

### 5.1. Comparison between sediment discharge and deposition

The total annual sediment accumulation in the study area (Table 4) may be expressed as  $9.3 \pm 4.1 \text{ Mt yr}^{-1}$  by taking into consideration of the uncertainty associated with the SAR estimation using Eq. (1). To validate this estimate, we compare it with the long-term average of the sediment discharge rates from the Kaoping River, the major sediment source in this area. The annual suspended sediment discharge from the Kaoping River was derived from the hydrologic data reported by the Water Resources Agency (Hydrological Yearbooks, 1960–1994) by our previously published method

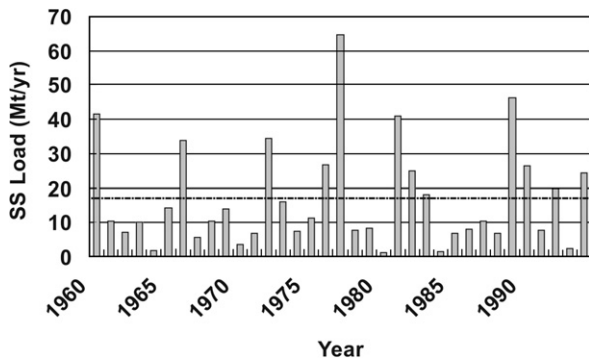


Fig. 8. Discharge rate of suspended sediments from the Kaoping River from 1960 to 1994. The dotted line indicates the mean value.

(Kao and Liu, 2001). The annual sediment discharges (Fig. 8) show large variability during the period from 1960 to 1994, ranging from 2 to 65  $\text{Mt yr}^{-1}$  with a mean of  $17 \pm 5 \text{ Mt yr}^{-1}$ , which is sufficient to sustain the estimated sediment accumulation.

It is noted that not all of the deposited sediments in the study area is derived from land. Instead, a finite fraction of the sediments originates from biogenic or authigenic sources in the ocean. The marine biogenic sediments consist mainly of marine POM, carbonate and opal. The deposition rate of marine POM was estimated by multiplying that of marine POC by 2 (Gordon, 1970; Monaco et al., 1990). This gave an annual marine POM accumulation of 56  $\text{kt/yr}$  corresponding to the area ( $6763 \text{ km}^2$ ) for the sediment integration. The deposition rate of biogenic carbonate was estimated from the mean carbonate content of 4.3% in the surficial sediments (Kao et al., 2004) and the mean SAR, which yielded a value of 400  $\text{kt/yr}$ . However, some of the deposited carbonate may be lithogenic rather than biogenic. Therefore, this value should be regarded as the upper bound of the biogenic input to the carbonate deposition. The opal deposition was estimated in the range from 17 to 34  $\text{kt/yr}$ , which was derived, respectively, from the opal accumulation rate of  $2.5 \text{ g m}^{-2} \text{ yr}^{-1}$  (Lin et al., 2002) and the observed opal to organic carbon ratio of 1.2 (Min-Te Chen, pers. comm.) in recent sediments in the northern SCS. Lastly, the authigenic sulfur was estimated from the total sulfur content of roughly 0.07% in surficial sediments (Kao et al., 2004), which yielded a deposition rate of 6.5  $\text{kt/yr}$ .

Based on these estimates, the total marine input of sediments amounts to 479–496  $\text{kt/yr}$  or about

0.5  $\text{Mt/yr}$ , which comprises only 5% of the total SAR. As a result, the estimated total accumulation rate of terrigenous sediments in the study area is  $8.8 \pm 3.9 \text{ Mt/yr}$ . This estimate suggests that about half of the discharged sediments are deposited within 120 km of the river mouth. It also implies that the study area is a major depositional site of the Kaoping River system. Moreover, the compatibility of the two estimates, which are based on independent methods, lends strong support to the approach that we adopt for the scaling of the SAR.

### 5.2. Comparison between primary production and organic carbon accumulation

In order to scale the trapping efficiency of marine organic carbon in this depositional system, we compare primary production with the estimated marine organic carbon accumulation rate. The integrated primary production in the study area is  $1248 \text{ kt yr}^{-1}$  and the integrated accumulation rate of marine organic carbon is  $27 \text{ kt yr}^{-1}$  (Table 4), which represents roughly 2% of the total primary production. Because of the slight differences in data coverage areas for different integrations we compare the area-specific rates.

The average accumulation rate of TOC is  $8.5 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Table 4), which is about equally attributed to marine and terrigenous organic carbon. The mean marine organic carbon accumulation rate is calculated to be  $4.2 \text{ g C m}^{-2} \text{ yr}^{-1}$ , which represents 2.3% of the average primary production of  $185 \text{ g C m}^{-2} \text{ yr}^{-1}$  in the study area. The mean terrigenous organic carbon accumulation rate is calculated to be  $4.3 \text{ g C m}^{-2} \text{ yr}^{-1}$ , which gives a mean terrigenous organic carbon content of 0.31% in the deposited sediments. This value is lower than the mean value (0.5%) observed in the riverine suspended particles (Table 3) and deserves further discussion.

### 5.3. Fate of terrigenous organic carbon

The change in terrigenous organic carbon content in sediments may be attributed to three processes, dilution by extra input of sediments from marine sources, sorting of sediment grains and/or degradation of sedimentary organic carbon. As discussed earlier, the marine sources, which provide mainly carbonate, organic matter and opal, contribute only about 5% of extra sediment load to the seafloor. Sorting of sediment grains of different sizes and

densities, which usually have different organic carbon contents, during the transport process may result in change of organic carbon content. Sediments with finer grain sizes or lower density are usually more enriched in organic carbon (Hedges and Keil, 1995), while the coarse grains are usually more depleted in organic carbon. Because the latter tend to deposit closer to the river mouth, the nearshore sediments often contain less organic carbon. A closer examination of the distribution of terrigenous organic carbon (Fig. 2c) reveals that about half of the shelf region (within 200 m isobath) in the study area has terrigenous organic carbon content less than 0.4%, indicating the sorting effect. On the other hand, whether the sorting effect causes the decrease of the average terrigenous organic carbon content of the surficial sediments due to loss of organic rich fine particles by dispersion out of the study area is not clear. However, the most distant sites from the river mouth have the lowest terrigenous organic carbon contents (Fig. 2c). This is contrary to the expected distribution resulting from sorting effect, which favors dispersion of organic rich finer particles to more distant sites. Although this does not rule out sorting as one of the possible mechanisms for lowering the terrigenous organic carbon content in the study area, it certainly cannot explain the aforementioned distribution.

As it stands, the last possibility, namely, degradation of terrigenous organic matter must be a very important process responsible for the lower average terrigenous organic carbon content as well as the decreasing trend of terrigenous organic carbon with depth and distance. This implication is consistent with the notion that the terrigenous organic carbon experiences continuous degradation during its transport in the ocean (Keil et al., 2004). In addition, the rapid decrease of terrigenous organic carbon concentration in the surficial sediments on the lower slope (Fig. 2c) suggests that the presumably finer grain size in the more distant sites enhances organic degradation. This agrees with previous findings that fine-grained marine sediments on the Washington slope are associated with the most degraded organic matter (Keil et al., 1998).

#### 5.4. Comparison with other continental margins

The average SAR in the study area is  $1375 \text{ g m}^{-2} \text{ yr}^{-1}$ , which is comparable to the sediment fluxes ( $500\text{--}1400 \text{ g m}^{-2} \text{ yr}^{-1}$ ) on the slope of the western flank of the Okinawa Trough to the east

of the Changjiang River mouth observed during the MASFLEX project (Oguri et al., 2003). It is noted that these MASFLEX stations were about 500 km from the Changjiang River mouth; this explains why the observed SAR in the Okinawa Trough are not much greater than those determined for our study area, though the Changjiang discharges much more sediments than the Kaoping River. The TOC accumulation rate ( $8.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) obtained for our study area is comparable to those ( $4.2\text{--}12 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) reported for the MASFLEX sites. It is noted that the organic carbon burial rate is usually calculated from the SAR and the TOC content in the sediment column below the bioturbation zone (Reimers et al., 1992). Kao et al. (2004) show that there is no significant decreasing trend of TOC content in the top 100 cm of sediment on the seafloor off southwestern Taiwan. Therefore, the organic carbon accumulation rate calculated above may be considered essentially the organic carbon burial rate.

In contrast to the fast depositional environment, continental margins with lower SAR, such as the northwestern European continental margin in the northern Bay of Biscay (OMEX Sta. 2 and 3), where the SAR value range between 16.5 and  $29.7 \text{ g m}^{-2} \text{ yr}^{-1}$ , the TOC burial rates are only  $0.05\text{--}0.08 \text{ g C m}^{-2} \text{ yr}^{-1}$  (van Weering et al., 2001). Compared to the primary production, the organic carbon burial rate represent less than 0.1% (Wollast and Chou, 2001), which is much lower than the percentage (2.3%) observed in our study area.

#### 5.5. Trapping of organic carbon in fast accumulating sediments

Sequestration of organic carbon in marine sediments is achieved by a series of biogeochemical processes, including primary production, delivery to the deep sea, deposition on the seafloor, diagenetic alteration and burial in the sediment column (Henrichs and Reeburgh, 1987; Hedges and Keil, 1995). In rapidly accumulating sediments, sequestration is essentially done, once the organic carbon is buried in the surficial sediments, because the dissolved products from diagenesis, namely dissolved organic carbon (Burdige et al., 1999) as well as dissolved inorganic carbon, would not diffuse out of the sediment column in significant amount. In other words, most of the carbon found in the surficial sediments in environments of rapid sedimentation would be buried eventually.

It has been proposed that the delivery of marine organic carbon from the surface ocean to the lower water column is enhanced by ballast minerals during vertical transport (Armstrong et al., 2002). It is conceivable that the ballast effect should also work in lateral transport on continental margins. The only difference is that the ballast minerals do not descend vertically from the sea surface to the seafloor. Instead a major fraction of the ballast minerals may be transported obliquely through lateral transport (e.g., Heussner et al., 1999; McCave et al., 2001) or winnowing along the continental slope in a hop-scotch fashion (Keil et al., 2004). As proposed originally in the ballast hypothesis (Armstrong et al., 2002), the mineral ballasts protect organic matter associated with them and accelerate its transport down the water column. In the lateral transport of POM addressed in this study, the protecting and carrying ability of the mineral grains should still function.

In order to explore the possible relationship between organic carbon deposition and the flux of ballast materials, we tried to simulate the deposition flux of particulate organic carbon on the seafloor using a mathematical expression similar to that of Armstrong et al. (2002). Instead of examining organic fluxes received by man-made sediment traps, we treated the seafloor as the ultimate sediment traps, which receive organic fluxes as a function of depth as well as the ballast flux. The equation format remains the same:

$$F(Z) = F_{\text{inf}} + (F_S - F_{\text{inf}}) \exp(-(Z - Z_0)/\delta_S), \quad (7)$$

where  $F(Z)$  is the flux at depth ( $Z$ ),  $Z_0$  the thickness of the surface layer, which is excluded from the calculation,  $F_{\text{inf}}$  the flux of organic carbon protected by the ballast minerals that may accumulate on the seafloor, and  $\delta_S$  the scaling depth of organic carbon decomposition.  $F_{\text{inf}}$  may be estimated as a fixed fraction of the ballast flux ( $F_B$ ), but it cannot exceed the available flux of particulate organic carbon ( $F_S$ ) sinking through the water column. Therefore, the following form is adopted for the evaluation of  $F_{\text{inf}}$ :

$$F_{\text{inf}} = \text{Min}(\rho F_B, F_S), \quad (8)$$

where  $F_B$  is assumed to be the same as the SAR on the seafloor, and  $\rho$  the maximum of the protected organic carbon fraction in the sediment deposited on the seafloor, and  $F_S$  is calculated as follows:

$$F_S = f_S \text{PP}, \quad (9)$$

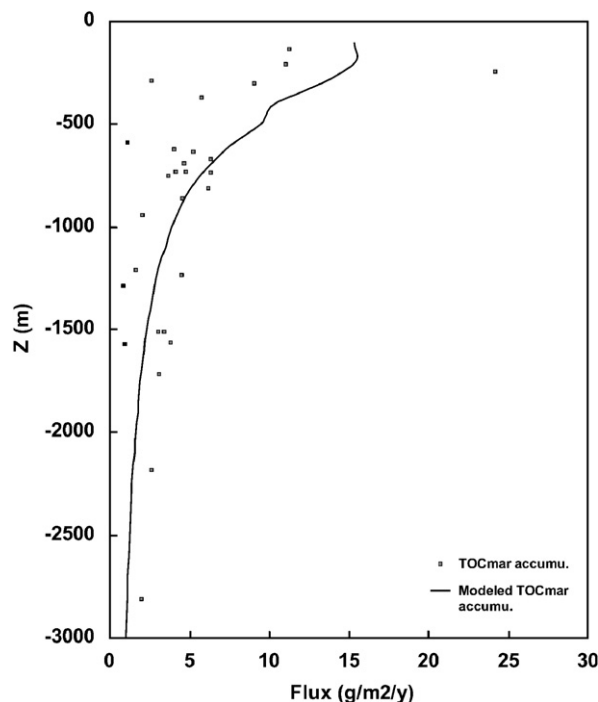


Fig. 9. The observed accumulation rate of marine organic carbon (dots) vs. depth in the continental margin off southwestern Taiwan. The solid curve is the modeled accumulation rate of marine organic carbon (see text).

where  $f_S$  is the average fraction of primary production that may survive biological attack in the water column and form organic–mineral aggregates (Keil et al., 1998) during descent to the seafloor.

Despite the rather crude approach, we have obtained parameters that make the function fit the observed marine organic carbon accumulation rates reasonably well (Fig. 9). The empirical parameters are as follows:  $\rho_S = 0.005$ ,  $f_S = 0.04$  and  $\delta_S = 200$  m. The fraction ( $\rho_S$ ) of ballast protected marine organic carbon is about 1/10 of the optimal value (0.052) used for the water column process. This fraction ( $\frac{1}{10}$ ) is similar to the burial efficiency observed in areas of high sedimentation rate, such as the depositional center off the eastern coastal of the US, where the burial efficiency is around 12% (Anderson et al., 1994).

The fraction ( $f_S$ ) of primary production, which may survive biological attack to form organic–mineral aggregates, is about  $\frac{1}{8}$  of the observed mean  $f$ -ratio of 0.33 (Chen, 2005), which represents the fraction of primary production descending from the euphotic zone. This lower fraction indicates that the POM has undergone considerable degradation

before establishing close association with the mineral ballasts, which presumably protect the organics. In the continental margin setting, the organic degradation may occur both in the water column and at the water-sediment interface. If the degradation occurs mainly in the water column and if the decreasing POC flux follows the power law of  $(z/100)^{-0.858}$  (Martin et al., 1987), then the average depth of the formation of organic-mineral aggregates is about 1130 m below the bottom of the euphotic zone. This is quite reasonable in view of the depth range (30–2809 m) of the study area. The scaling depth ( $\delta_S$ ) of the degradation of unprotected organic carbon is less than half of that (480 m) found for the water column process (Armstrong et al., 2002), indicating that the degradation at the water–sediment interface is more enhanced than in the water column.

## 6. Summary and conclusions

Surficial sediments from the continental margin sediments off southwestern Taiwan contain TOC between 0.35% and 1.30% with  $\delta^{13}C_{org}$  values ranging from  $-24.5\text{‰}$  to  $-21.3\text{‰}$ . The marine and terrigenous fractions of the sedimentary organic carbon are determined by a simple isotope mixing model with the marine and terrestrial end-members assumed to be  $-21.5$  and  $-25.0\text{‰}$ , respectively. The calculated terrigenous and marine organic carbon contents reach maxima of 0.5% and 0.8%, respectively.

Using previously reported sedimentation rate, we have derived an empirical relationship between the SAR and the water depth as follows:

$$SAR = 290 \text{Depth}^{-1.2},$$

where SAR is in units of  $\text{g m}^{-2} \text{yr}^{-1}$  and depth is in units of meter. This relationship allows us to calculate the accumulation rates of TOC as well as those for the marine and terrigenous organic carbon in sediments in the study area. The mean organic carbon accumulation rate in the study area is  $8.5 \text{ g C m}^{-2} \text{yr}^{-1}$ , which is attributed about equally to the terrestrial and marine sources. The mean annual accumulation rate of marine organic carbon represents 2.3% of the annual primary production, which is much higher than that (less than 0.1%) observed in the northern Bay of Biscay, where the topography is similar but the SAR is much lower.

The much enhanced trapping efficiency of organic carbon is attributed to the high input of fluvial

sediments, which serve as mineral ballasts that in turn assert a protective effect on the organic matter (Armstrong et al., 2002). Using a function, involving primary productivity and mineral accumulation rate, which is similar to the formulation proposed by Armstrong et al. (2002), we are able to simulate the marine organic carbon accumulation rate on the seafloor off southwestern Taiwan. Further study is warranted to investigate whether this empirical relationship is applicable to other continental margins with various level of sediment supply. If so, this type of relationship may be further refined to assess the accumulation rate of marine particulate organic carbon on the continental slope based on sediment transport.

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## Appendix A

In order to estimate the mean primary production in the study area, we used a 5 yr chl-*a* data derived from ocean color images to calculate the monthly primary production in the sea off southwestern Taiwan. The calculation is based on the VGPM of Behrenfeld and Falkowski (1997). The ocean color data are the SeaWiFS Level 3 Monthly Standard Mapped Image of Chl-*a* concentration data with a  $9 \times 9 \text{ km}^2$  resolution from 1998 to 2002 ([http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01\\_Data\\_Products/index.html](http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01_Data_Products/index.html)).

The VGPM for estimation of the vertically integrated primary productivity (IPP) is expressed below:

$$IPP_{eu} = 0.66125 P_{opt}^B [E_0 / (E_0 + 4.1)] C_{sat} Z_{eu} D_{IRR}, \quad (\text{A.1})$$

where  $IPP_{eu}$  is the daily euphotic zone-integrated primary production ( $\text{mg C m}^{-2} \text{d}^{-1}$ ),  $C_{sat}$  the surface chlorophyll concentration ( $\text{mg Chl m}^{-3}$ ),  $D_{IRR}$  the daily photoperiod (h),  $E_0$  the sea surface daily photosynthetically active radiation ( $\text{Einstein m}^{-2} \text{d}^{-1}$ ),  $Z_{eu}$  the thickness of the euphotic

zone (m) which is related to the vertically integrated Chl-*a* stock in the euphotic zone, and  $P_{\text{opt}}^{\text{B}}$  the optimal specific primary productivity.

The vertically integrated Chl-*a* stock in the euphotic zone is derived from the SeaWiFS surface Chl-*a* concentration following the algorithm of Behrenfeld and Falkowski (1997). The depth of the euphotic zone is calculated from the relationships given by (Morel and Berthon, 1989). The optimal specific primary productivity ( $\text{mg C mg Chl}^{-1} \text{h}^{-1}$ ) is calculated from the empirical equation provided by Behrenfeld and Falkowski (1997), which is dependent on the sea surface temperature.

The photosynthetically active radiation data are the SeaWiFS Level 3 Monthly standard mapped image of PAR, taken from the GES Distributed Active Archive Center of the SeaWiFS Project of NASA ([http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01\\_Data\\_Products/index.html](http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01_Data_Products/index.html)). The sea surface temperature data are AVHRR Oceans Pathfinder global equal-angle best SST with  $9 \times 9 \text{ km}^2$  resolution taken from the Physical Oceanography Distributed Active Archive Center (<http://podaac.jpl.nasa.gov/products/product102.html>). The lengths of solar radiation are taken from the data bank of IMCS Ocean Primary Productivity Team (<http://marine.rutgers.edu/opp/>).

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