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Particulate Organic Carbon Supply to the Sea Bottom: Stable Carbon Isotope Ratio Analysis of the Sediment Trap Samples at the Mouth of Otsuchi Bay, Northeastern Japan*

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Abstract: An array of sediment traps was deployed for the analysis of the pattern of particulate organic carbon (POC) supply to the sea bottom in April, May and July 1988 at the mouth of Otsuchi Bay (about 80 m depth), Northeastern Japan.

On the basis of a simple two-component mixing model using stable carbon isotope ratios, the POC flux was separated into marine planktonic and terrestrial components. Both the planktonic and terrestrial POC fluxes had maximum values at 30 m above the sea bottom throughout the three experiments. The planktonic POC flux showed a significant decrease with depth between 30 m and 10 m or 5 m above the bottom. Vertical supply of the planktonic POC and supply of the resuspended planktonic POC were estimated on the basis of regression lines between water depth and the planktonic POC flux in the depth range where the flux decreases with depth.

Vertical supply of the planktonic POC and supply of the resuspended planktonic POC to the sea bottom were largest in May (52.1 mgC m^{-2} d^{-1} and 19.5 mgC m^{-2} d^{-1} at 5 m above the sea bottom), and horizontal supplies of the terrestrial POC were almost constant (31.9 ± 3.5 mgC m^{-2} d^{-1} at 5 m above the bottom) throughout the three experiments.

1. Introduction

In the deep-sea where no *in situ* primary production exists, the mode of food supply is expected to be one of the most important factors determining abundance and structure of the benthic communities (Rowe, 1981, 1983; Smith and Baldwin, 1984). Recent studies using sediment traps and respirometers have shown that vertical transport of surface primary products does not suffice for the energy demand of the deep-sea benthic communities at least in some areas (Wiebe *et al.*, 1976; Hinga *et al.*, 1979; Smith, 1978, 1987), and the importance of horizontal transport of terrestrial and coastal materials to the deep-sea benthic communities has been pointed out (Wiebe *et al.*, 1976; Smith, 1978; Suchanek *et al.*, 1985; Kojima and Ohta, 1989).

To study an ecosystem in which organic materials are supplied from two or more sources, it is necessary to estimate the relative contribution of each source. Stable isotope ratios of bioelements have been deemed to be useful indicators to discriminate the sources (Fry and Sherr, 1984). Such investigations have been carried out in shallow waters including salt marsh (Haines and Montague, 1979; Hughes and Sherr, 1983), seagrass meadows (Dunton and Schell, 1987; Fry *et al.*, 1987) and estuary (Stephenson and Lyon, 1982). In the deep-sea little information is available (Suchanek *et al.*, 1985) with the exceptions of hydrothermal vent and seep fields (Rau, 1985; Saino and Ohta, 1989). The amount of organic materials supplied to the sea bottom from each source has been analyzed on the basis of stable isotope ratios of bottom sediments (Fry *et al.*, 1987; Wada *et al.*, 1987; Grebmeier *et al.*, 1988; Kojima and Ohta, 1989). Organic

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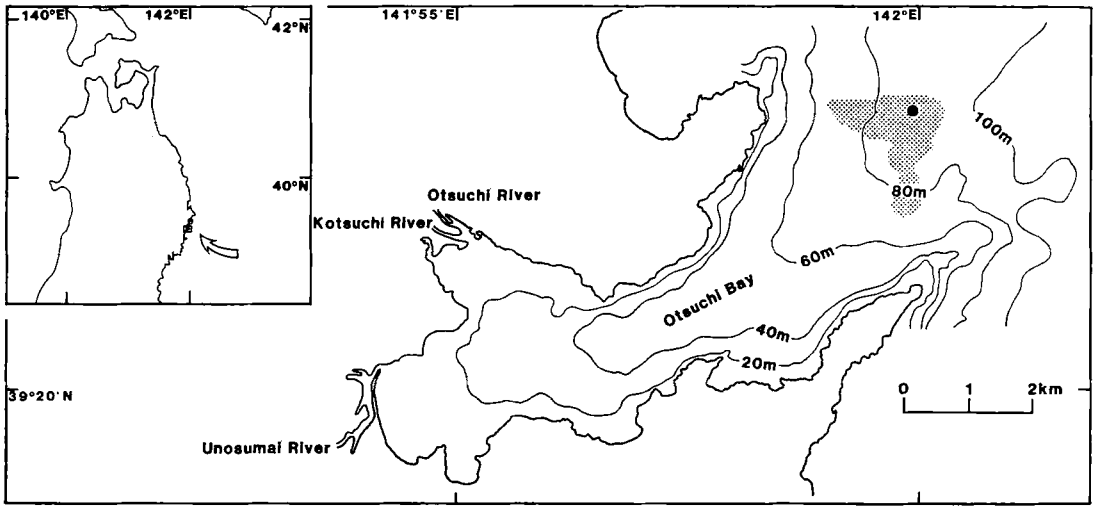

Fig. 1. Location of the sampling station. Shaded area denotes the muddy area around the station.

materials contained in the bottom sediments, however, did not necessarily agree with supplied materials (Williams and Gordon, 1970; Honjo *et al.*, 1982). Thus, it may be difficult to estimate macro-scale spatial difference and temporal change of the supply of organic materials based on the analysis of the bottom sediments.

The present authors adopted a methodology using a sediment trap system and stable carbon isotope analysis for a direct measurement of the organic supplies to the benthic ecosystem from two sources, namely sea-surface phytoplankton products and terrestrial materials at the mouth of Otsuchi Bay, Northeastern Japan. Otsuchi Bay including the Otsuchi River watershed offers an ideal field for a biogeochemical study, benefited by little human impact and compiled environmental information (see Wada *et al.*, 1983). Wada *et al.* (1987) demonstrated that the two source model of planktonic and terrestrial organic materials (Fry and Sherr, 1984) was applicable to the case of Otsuchi Bay, and relative contributions of the two sources of organic materials could be calculated from stable carbon isotope ratios of planktonic and terrestrial particulate organic carbon (POC).

2. Methods

Sinking particulate materials were collected directly using a sediment trap system at the mouth of Otsuchi Bay, Northeastern Japan (Fig. 1). The system was set for two days in April, May and July 1988 (Table 1). The sampling station was situated in a muddy area (Fig. 1) and the median diameter of the bottom sediment was reported to be 3.8 phi (Fujioka *et al.*, 1988). In this muddy area, terrestrial and resuspended materials transported horizontally are expected to be deposited to the sea bottom. Evidently, bottom sediment of this area contained terrestrial plant remains (unpublished data).

Table 1. Mooring data of the sediment traps.

Date	Position	Depth (m)
12–14 April 1988	39°21.82′N 141°59.52′E	80
30 May–1 June 1988	39°21.80′N 141°59.54′E	78
12–14 July 1988	39°22.39′N 142°00.05′E	83

The moored system consisted of five sediment traps set at 55, 30, 20, 10, and 5 m above the sea bottom in April and May 1988. An additional trap was set at 2 m above the sea bottom in July. The trap was a cylinder type (15 cm in mouth diameter and 50 cm in height) modified from that described by Sasaki and Nishizawa (1981). Six separated chambers (15 cm in height) were set at the bottom of each trap. No preservative was used.

Collected subsamples in the five chambers of each trap were filtered through Whatman GF/C glass fiber filters and living zooplankton were removed by hand as much as possible. These subsamples were freeze-dried after the treatment with 50 ml, 0.2 N hydrochloric acid to remove

inorganic carbon. Two of the five subsamples obtained from each trap were used for measurement of organic carbon and nitrogen contents using a CHN analyzer (Yanagimoto, CHN Corder Model MT-2) and two subsamples were used for measurement of the stable carbon isotope ratio. The water sample in the remaining chamber was preserved in 5% buffered seawater formalin for later microscopic study. Two hundred particles which were larger than 25 μm collected in each sediment trap were randomly selected and divided into four categories; amorphous aggregate, fecal material, biogenic remains and sand grains.

At the same station, contents of chlorophyll-*a* were determined by filtration of 600 ml of the water sample collected by a 8 l Van Dorn type water sampler through a Whatman GF/C, with extraction in dimethyl formamid and fluorometry using a Turner 111 fluorometer. Plankton samples were collected using a 95 μm mesh Norpac net which was towed vertically from 75 m depth and freeze-dried after the treatment with 0.2 N hydrochloric acid. Vertical profiles of water temperature were obtained using a memory thermometer (Rigosha, Model RMT).

Samples for stable carbon isotope analysis were burned to yield carbon dioxide in a stream of pure oxygen at a temperature of about 950°C. The stable carbon isotope ratio of the carbon dioxide was measured with a mass spectrometer (Finnigan, Model MAT250). The stable carbon isotope ratio was expressed in δ ^{13}C relative to PDB standard (Craig, 1957). Standard deviation of the analysis was 0.04‰ or less.

3. Results

Vertical profiles of the particulate organic carbon (POC) flux, the particulate organic nitrogen (PON) flux and stable carbon isotope ratio of POC are shown in Fig. 2. The profiles of the POC flux followed a similar pattern throughout the three moorings; increased with water depth between 55 m and 30 m above the sea bottom, decreased between 30 m and 10 m or 5 m above the sea bottom, and increased again toward the sea bottom. The PON flux showed an almost similar pattern as the POC flux.

Figure 3 shows microscopic composition of particles collected in sediment traps. Fecal material contained fecal pellets and fecal matter which is composed of degraded fecal pellets (Sasaki and Nishizawa, 1981). Biogenic remains contained diatoms, foraminifera and fragments of crustaceans.

Vertical profiles of the chlorophyll-*a* content in

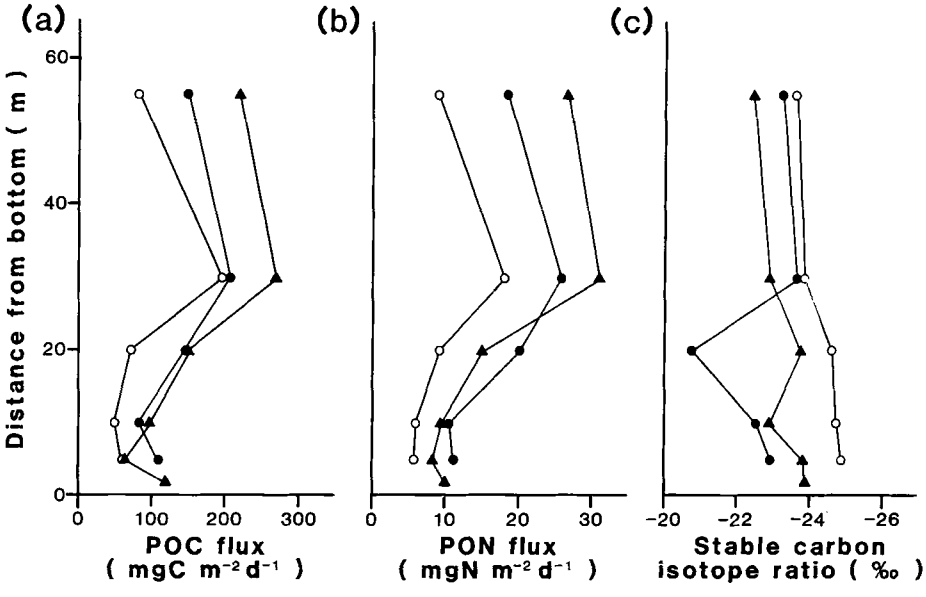

Fig. 2. Vertical profiles of the POC flux (a), the PON flux (b) and stable carbon isotope ratio of POC (c). Open circles, solid circles and solid triangles denote the data of April, May and July, respectively.

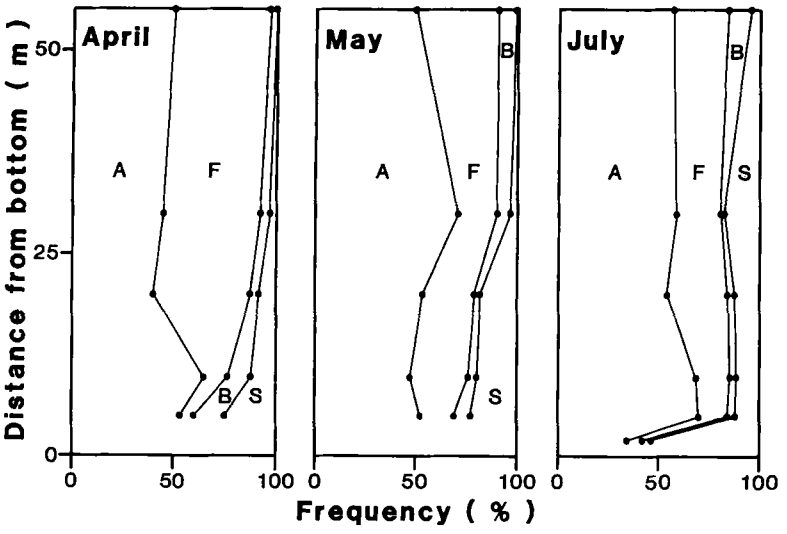

Fig. 3. Microscopic composition of particles collected in the sediment traps. A, F, B and S denote amorphous aggregate, fecal material, biogenic remains and sand grains, respectively.

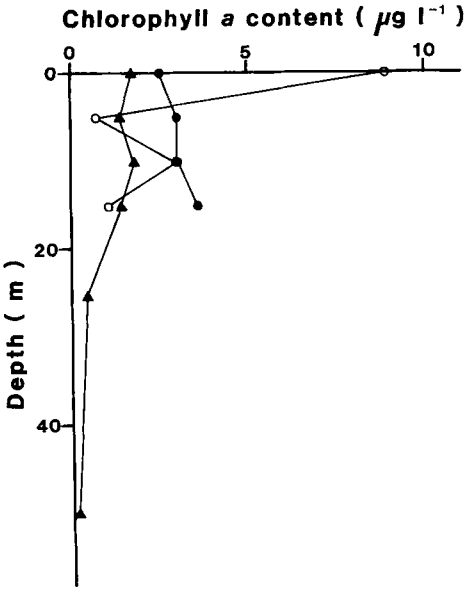

Fig. 4. Vertical profiles of chlorophyll-*a* contents in the seawater. Open circles, solid circles and solid triangles denote data of April, May and July, respectively.

seawater are shown in Fig. 4. Stable carbon isotope ratios of plankton samples collected in April, May and July were -23.1 ± 1.6‰ (mean $\pm$S.D.: $n=3$), -21.1 ± 1.1‰ ($n=3$) and -21.7 ± 1.1‰ ($n=3$), respectively. Water temperatures near the sea bottom in April, May and July were 6.65°C, 9.00°C and 10.78°C, respectively.

4. Discussion

Stable carbon isotope ratios of POC were utilized to discriminate between planktonic and terrestrial origins. The planktonic and terrestrial fluxes were calculated by the following equations (Wada *et al.*, 1983, 1987),

$$\text{Terrestrial POC flux} = (\text{POC flux}) \times \frac{(\delta\,^{13}C_{plankton} - \delta\,^{13}C_{sample})}{(\delta\,^{13}C_{plankton} - \delta\,^{13}C_{terrestrial})}, \quad (1)$$

$$\text{Planktonic POC flux} = (\text{POC flux}) \times \frac{(\delta\,^{13}C_{sample} - \delta\,^{13}C_{terrestrial})}{(\delta\,^{13}C_{plankton} - \delta\,^{13}C_{terrestrial})}, \quad (2)$$

where $\delta\,^{13}C_{plankton} = -23.1$‰ for the data of April, -21.1‰ for May or -21.7‰ for July (present data), and $\delta\,^{13}C_{terrestrial} = -26.5\pm0.6$ ‰ (measured by Wada *et al.* (1987) in June 1980 and July 1981), respectively. The result of the calculation was shown in Fig. 5. The stable carbon isotope ratios of plankton collected in April had low values compared with those of May and July. Low values (-24.0 ± 0.3‰) were obtained also in March 1989 (unpublished data). This is probably due to the inflow of plankton carried by the Oyashio Current into Otsuchi Bay in early spring (Terazaki, 1980). An index species of the cold Oyashio Current, *Themisto japonica* was collected at the present sampling station in April 1988 and March 1989.

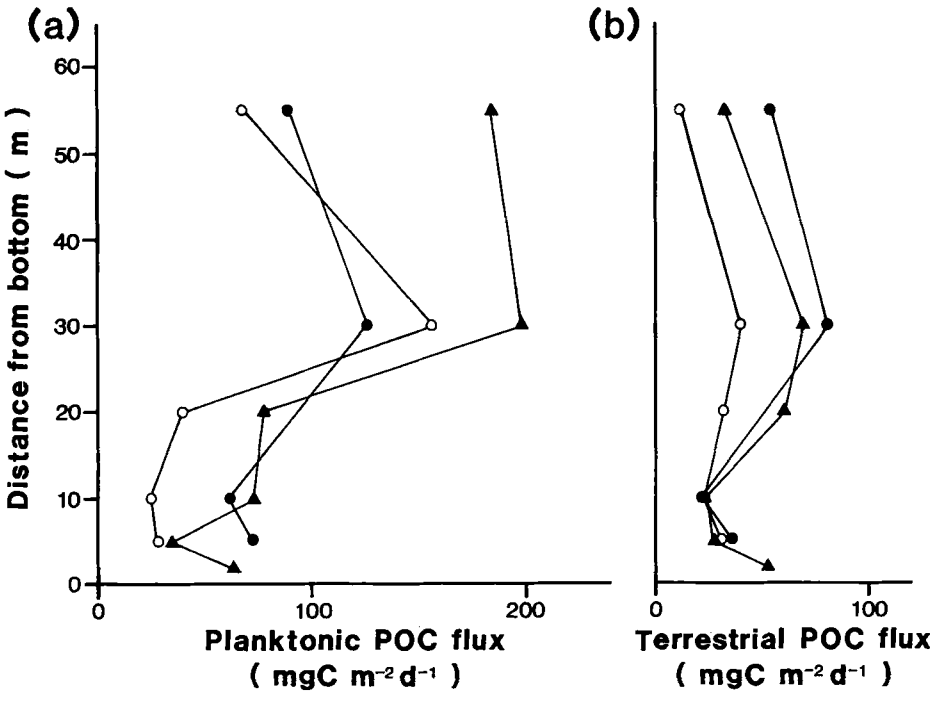

Fig. 5. Vertical profiles of the planktonic POC flux (a) and the terrestrial POC flux (b). Open circles, solid circles and solid triangles denote data of April, May and July, respectively.

The stable carbon isotope ratio of the POC collected in a sediment trap at 20 m above the sea bottom in May 1988 was so high (−20.7‰) that the planktonic and terrestrial fluxes could not be calculated. This is probably due to an accidental inflow of organic materials with high stable carbon isotope ratio.

The terrestrial POC flux was highest at 30 m above the sea bottom through three experiments. This suggests that a part of the terrestrial materials are transported through the midwater layer. On the other hand, the terrestrial POC flux increased toward the sea bottom suggesting the bed-load transport of terrestrial materials along the sea bottom from other areas. The vertical profile of the planktonic POC flux followed the same pattern as the whole POC (Fig. 2).

The following discussion will be developed on the basis of the data in July when the data at 2 m above the sea bottom was obtained. The increase of the planktonic POC flux between 55 m and 30 m above the sea bottom is explained by the addition of organic materials synthesized by phytoplankton in the depth range. The vertical profile of chlorophyll-*a* content in July 1988 (Fig. 4) shows the existence of phytoplankton within this depth range. The flux increased again between 5 m and 2 m above the sea bottom, probably due to deposition of resuspended organic materials. This is supported by the fact that the proportion of sand grains to particles collected in sediment traps increased between 5 m and 2 m in July 1988 (Fig. 3). Between 30 m and 5 m above the sea bottom, the planktonic POC flux decreased with water depth. This fact suggests that inputs of primary products and resuspended organic materials were almost negligible compared with the POC flux. Under such a situation, the planktonic POC flux is expected to decrease with depth as a result of microbial degradation and consumption by zooplankton.

The planktonic POC supplied to the deepest trap at 2 m above the sea bottom (81 m depth) contained both POC transported vertically from the sea surface and resuspended POC. Empirically it is well known that an inverse linear relationship can be observed between POC flux and water depth on a log scale, if particulate organic materials are transported vertically without an input of addition of particulate organic

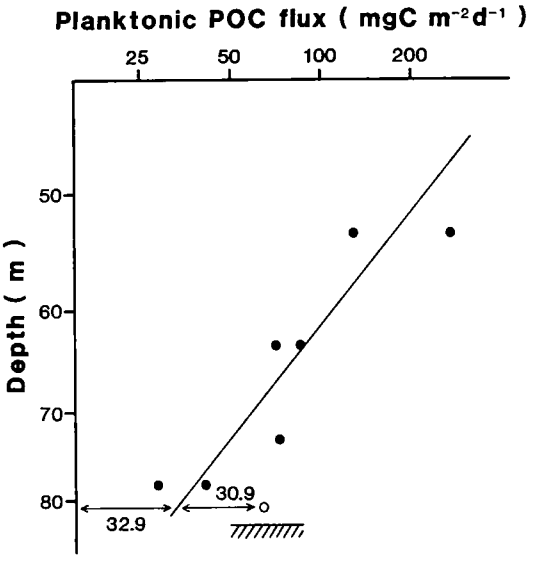

Fig. 6. Relationship between the logarithm of water depth and the logarithm of the planktonic POC flux in July 1988. Solid line represents the regression line on the basis of data between depths of 53 and 78 m. An open circle denotes a datum at 2 m above the sea bottom (81 m depth).

materials (Suess, 1980; Betzer *et al.*, 1984). The present data of the planktonic POC flux in July 1988 are shown in Fig. 6 on a log scale. The logarithm of the planktonic POC flux decreases linearly with that of water depth between the depths of 53 and 78 m and a significant regression line was obtained:

$$\log_{10} F = -3.97 \log_{10} D + 9.09, \quad (3)$$
$$(r = -0.906,\ n = 7,\ p < 0.05)$$

where F is the planktonic POC flux (mgC m^{-2} d^{-1}) and D is water depth (m). Assuming that all of the planktonic POC collected in the sediment traps between depths of 53 m and 78 m were transported vertically without an input of additional POC, the POC flux to the deepest trap by the vertical transport was estimated to be 32.9 mgC m^{-2} d^{-1} by substituting 81 for D in Eq. (3). As the total amount of the planktonic POC collected in the lowest-level trap was 63.8ngC m^{-2} d^{-1}, the planktonic POC flux to the deepest trap by the resuspension was estimated to be 30.9 mgC m^{-2} d^{-1} by subtracting the planktonic POC flux transported vertically from the total planktonic POC flux (see Fig. 6).

Table 2. POC supplies near the sea bottom.

Distance from the sea bottom (m)		Planktonic POC (mgC m^{-2} d^{-1})		Terrestrial POC (mgC m^{-2} d^{-1})
		vertical	resuspendedd	
April	5	15.2	13.0	31.2
	2	12.4	—	—
	0	10.9	—	—
May	5	52.1	19.5	36.6
	2	48.2	—	—
	0	45.9	—	—
July	5	35.1	0	28.0
	2	32.9	30.9	52.9
	0	29.8	—	—

On the basis of the planktonic POC flux between depths of 50 m and 70 m in April 1988, a significant regression line was obtained:

$$\log_{10} F = -5.23 \log_{10} D + 10.98, \quad (4)$$
$$(r = -0.934,\ n = 5,\ p < 0.05).$$

A regression line on the basis of the planktonic POC flux between depths of 50 m and 70 m in May 1988 was obtained as follows, although the relationship was not significant due to the shortage of available data ($p > 0.05$):

$$\log_{10} F = -1.93 \log_{10} D + 5.32, \quad (5)$$
$$(r = -0.752,\ n = 4).$$

The POC flux near the sea bottom estimated from Eqs. (3), (4) and (5) is summarized in Table 2. Vertical supply of the planktonic POC and supply of the resuspended planktonic POC to the sea bottom were largest in May (52.1 mgC m^{-2} d^{-1} and 19.5 mgC m^{-2} d^{-1} at 5 m above the sea bottom), and horizontal supplies of the terrestrial POC were almost constant (31.9±3.5 mgC m^{-2} d^{-1} at 5 m above the sea bottom) through the three experiments.

Slopes of Eqs. (3), (4) and (5) were greater than those of empirical models derived from the data of the world oceans, especially in the deep-sea area (Suess, 1980; Betzer *et al.*, 1984). The slope calculated from Suess' model is 1.0 and that of Betzer's model is 0.628±0.121. Sasaki and Nishizawa (1981) reported a vertical distribution of POC flux in May 1977 in the pelagic area (deeper than 500m) off Sanriku near the present sampling station. Between depths of 100 m and 500 m, a significant regression line was obtained:

$$\log_{10} F = -1.56 \log_{10} D + 6.00 \quad (6)$$
$$(r = -0.850,\ n = 7,\ p < 0.05)$$

High water temperature probably contributed to the rapid decrease of POC flux with depth in Otsuchi Bay. Water temperature within the depth range where Eq. (3) was calculated (the mouth of Otsuchi Bay in July) was almost constant around 10°C, while the temperature deeper than 100 m in the coastal area off Sanriku in June was lower than 3°C (Sasaki and Nisnizawa, 1981). For the explanation of the relatively steeper slope in April in spite of low temperature, there is a possibility that heavy grazing by zooplankton contributed to the rapid decrease of POC flux in April. Terazaki (1980) reported that the settling volume of zooplankton in April was about six times as large as that in May at the mouth of Otsuchi Bay, and phytoplankton in Otsuchi Bay increased in May. In the present study a large dominant zooplankon *Themisto japonica* accounted for 37.3% in terms of dry weight of the plankton collected in April (unpublished data).

The present method enabled us to discriminate three modes of POC supply to the sea bottom. On the basis of the stable carbon isotope ratio of POC, the POC flux was separated into the planktonic and terrestrial POC fluxes. Further, the graphical analysis of the vertical profiles of the planktonic POC flux separated the planktonic POC flux into the vertically transported component, and resuspended component. We are convinced that the method will be effective for the analysis of food supply to the deep-sea benthic ecosystem.

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海底への粒状有機炭素供給
大槌湾湾口におけるセディメントトラップサンプルの安定炭素同位体分析

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要旨: 1988年4月，5月，7月，岩手県大槌湾湾口(水深約80m)において海底への粒状有機炭素（POC）の供給様式を解析するため，セディメントトラップ係留系を設置した．POCに占めるプランクトン起源有機物と陸上起源有機物の割合を，安定炭素同位体比に基づく二元モデルを用いて算出した．3回の調査を通じてプランクトン起源POC，陸起源POCともに海底上30mで最大値をとった．プランクトン起源POCは30mから10mまたは5mの間で水深とともに有意に減少した．この水深レンジにおける回帰直線から，プランクトン起源有機物の垂直輸送および再懸濁による海底への供給量をそれぞれ推定した．プランクトン起源の有機物は，垂直輸送，再懸濁ともに5月が多く（それぞれ海底上5mで52.1 mgC m^{-2} d^{-1}，19.5 mgC m^{-2} d^{-1}），陸起源有機物は3回の調査を通じてほぼ一定（海底上5mで31.9±3.5 mgC m^{-2} d^{-1}）であった．

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