Lateral transport of sediment particles in the Okinawa Trough determined by natural radionuclides

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Settling particles at 640 m, 1390 m, and 1920 m depths in the Okinawa Trough and bottom sediments at six sites in the East China Sea were analyzed for U and Th isotopes, ^{210}Pb , and ^{210}Po . Concentrations of ^{232}Th in the settling particles were higher than those observed in the open ocean and were relatively constant with depth compared with other radiogenic nuclides. Fluxes and concentrations of these radiogenic nuclides increased with depth and the measured fluxes were larger than those calculated from water column inventories. While sinking through the water column of 640–1390 m, the increases in ^{210}Pb and unsupported ^{228}Th fluxes originating intensively in the shelf region were much larger than the unsupported ^{230}Th fluxes produced evenly in sea water. The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in the settling particles was almost unity and the $^{228}\text{Th}/^{230}\text{Th}$ activity ratio of the radiogenic fraction was much smaller than the ratio of the production rates of these nuclides in the shelf water. These results suggest that a large fraction of the deeper settling particles, as well as the sediments in the trough zone originating in the continental shelf zone, are transported laterally and downward *via* the near bottom layer on a time scale of approximately 16 years on the average.

INTRODUCTION

Recently, much attention has been focused on the lateral transport of chemical species in the ocean. In the studies of the lateral transport of chemical elements taken up or released during their movement, the U/Th series of isotopes produced from their parents seems to be useful. The radioisotopes of elements, which are produced from their dissolved parents and have short residence times, show deficiencies in their radioactivities due to their removal by settling particles (Moore and Sackett, 1964; Nozaki *et al.*, 1981; Minagawa and Tsunogai, 1980; Matsumoto, 1975; Rama *et al.*, 1961; Tsunogai and Nozaki, 1971; Craig *et al.*, 1973; Li *et al.*, 1980; etc.). The examples are the pairs of $^{238}\text{U}-^{234}\text{Th}$, $^{234}\text{U}-^{230}\text{Th}$, $^{235}\text{U}-^{231}\text{Pa}$, $^{226}\text{Ra}-^{210}\text{Pb}$, $^{210}\text{Pb}-^{210}\text{Po}$, and $^{228}\text{Ra}-^{228}\text{Th}$, which provide time scales for the removal processes according to their half-lives.

Bacon *et al.* (1976) have found a pronounced

$^{210}\text{Pb}/^{226}\text{Ra}$ a disequilibrium in the Atlantic Ocean and concluded that the removal of ^{210}Pb is caused by scavenging at the sediment-water interface. Turekian (1977) and Nozaki *et al.* (1976) have claimed that particles have an important role in the removal of reactive elements. Anderson *et al.* (1983a, b) have suggested that ^{231}Pa relative to ^{230}Th is transported laterally from the open ocean to ocean margins and removed by settling particles. Taguchi *et al.* (1989) have also suggested that ^{231}Pa transported from oligotrophic regions is effectively removed in biologically productive seas, which is compatible to the distribution of the $^{230}\text{Th}/^{231}\text{Pa}$ ratio in the surface sediments in the Pacific Ocean mapped by Yang *et al.* (1986).

Brewer *et al.* (1980) and Tsunogai *et al.* (1982) have found from sediment-trap experiments that the vertical fluxes of Al increase with depth down to the bottom sediments. They have also reported that the Mn/Al ratio in the settling particles increases with depth. Since

manganese is known to be supplied from anoxic coastal and hemipelagic sediments (e.g., Tsunogai and Kusakabe, 1982), Tsunogai and Noriki (1987) have presumed that the manganese is incorporated into fine particles after it is oxidized and transported to the pelagic ocean by the lateral movement of sea water.

Since the coastal areas have high biological productivity, the transport process of biogenic and non-biogenic particles from the coastal zone to the pelagic zone is one of the major problems in oceanography. The Shelf Edge Exchange Processes (SEEP) program was organized by U.S. scientists to solve the problems (Walsh *et al.*, 1988). Biscaye *et al.* (1988) found that particles are transported from the continental shelf to the open ocean by observing the fluxes of ^{210}Pb , organic carbon, and calcium carbonate using sediment traps along the SEEP-I traverse.

To confirm this evidence, we carried out a sediment-trap experiment in the Okinawa

Trough together with the sampling of bottom sediments from the continental-shelf zone to the trough. This paper will discuss the lateral transport of particles by using natural radionuclides.

SAMPLING AND METHODS

Settling particles and sediment samples were collected in the Okinawa Trough and the East China Sea during the 1987 Corona Borealis Expedition on the R/V *Hakuho-Maru* (Fig. 1).

Sediment traps were deployed at Station CB 7 in the Okinawa Trough on 14 May and retrieved on 26 May 1987. The settling particle samples were collected at three depths, 640 m, 1390 m, and 1920 m, with the D type traps (Tsunogai *et al.*, 1986) consisting of twin cylindrical cones each with four cups working in time series. Upon recovery, the settling particles were transferred onto a pre-weighed Nuclepore filter ($0.6\text{ }\mu\text{m}$).

Fig. 1. Location of sampling sites.

Their dry weights were measured by the method of Uemastu *et al.* (1978). In this study, preservatives were not used because the sampling period was short. The concentrations of phosphate in the supernatant solutions in the cups were not significantly different from the ambient sea water (Noriki, personal communication). The four time-series samples for one cylinder at each depth were put together and used to determine the radioactivities of U, Th, Pb, and Po. The other samples were used to determine the major elements and other trace elements.

The sediment samples were collected at Stations CB 13, CB 14, CB 15, and CB 17 in the continental shelf zone, Station CB 12 in the slope, and Station CB 7-2 in the Okinawa Trough with a box corer or a grab sampler. The core samples were cut into segments of one or two cm on ship-board. These core samples and the surface sediments were radiochemically analyzed for U, Th, and Pb.

Dried samples of 60–300 mg for the settling particles or 1–3 g for surface sediments were taken for the analysis. These samples were completely dissolved with a mixture of HNO₃, HF, and HClO₄ in a Teflon bomb for the settling particle samples and in a Teflon beaker for the sediment samples. To determine the accumulation rate of ²¹⁰Pb in the bottom sediment, dried samples of 5–10 g each were taken and leached with an almost boiling solution of 6 M HCl (Aller and Cochran, 1976) for 4 hours after heating at 450°C. Their natural radionuclides were analyzed by the methods of Harada and Tsunogai (1985) and Tsunogai and Yamada (1980). Their activities were measured by an α

spectrometer and a low-background 2 π gas-flow GM counter.

RESULTS AND DISCUSSION

The concentration of ²³²Th in the settling particles

The total mass flux (Table 1) increased with depth in the Okinawa Trough. The observed fluxes at 1390 m and 1920 m were 10 times or more larger than those observed in the central Pacific (Honjo *et al.*, 1982; Noriki and Tsunogai, 1986).

The concentrations of ²³²Th of land origin in the settling particles ranged from 1.8 to 2.1 dpm/g, which were a few to a few tens times greater than those reported in the usual open ocean (Anderson *et al.*, 1983a, Taguchi *et al.*, 1989). The vertical variation of its concentration was smaller than those of other radiogenic nuclides studied here. The concentrations of ²³²Th were approximately 60% of its concentration in the surface sediment at Station CB 7-2 (Table 3). Since about 90% of the sediment is lithogenic material (Saito, personal communication), about half of the settling particles consists of lithogenic material. The lithogenic fraction in the settling particles is relatively constant with depth.

The lateral transport of ²¹⁰Pb-bearing particles from the continental shelf

Both the observed concentrations (Table 1) and fluxes (Fig. 2) of ²¹⁰Pb increased during their settling through the water column. The flux of ²¹⁰Pb increased 10 times while sinking through the water column from 640 to 1390 m. This in-

Table 1. Concentrations of radionuclides in the settling particles, at CB 7 (25°47'N, 125°22'E, 1920 m)

Depth (m)	Total mass flux (mg/cm ² /yr)	Concentration (dpm/g)					
		²³⁸ U	²³² Th	²³⁰ Th	²²⁸ Th	²¹⁰ Pb	²¹⁰ Po
640	1.52	1.89±0.09	1.78±0.06	1.60±0.06	10.3±0.2	126±7	132±1
1390	5.83	1.59±0.06	2.06±0.04	1.99±0.04	18.9±0.2	325±7	314±2
1920	6.75	1.60±0.06	2.06±0.04	2.43±0.04	21.6±0.2	441±12	437±6

All errors are of 1 σ counting statistics.

Fig. 2. Particulate fluxes of ^{210}Pb and activity ratios of $^{210}\text{Pb}/^{230}\text{Th}_{\text{EX}}$ observed with sediment traps in the Okinawa Trough.

crease was much larger than that in the $^{230}\text{Th}_{\text{EX}}$ flux, which is a fraction of the flux of ^{230}Th produced only from the radioactive decay of ^{234}U in sea water (Fig. 2). The ^{210}Pb fluxes observed at 1390 and 1920 m were 3–8 times larger than those observed at the same depths in the biologically productive northern North Pacific and Antarctic Oceans where ^{210}Pb and other metals are actively removed by settling particles (Tsunogai *et al.*, 1982, Harada and Tsunogai, 1986a).

The flux of ^{210}Pb at 640 m depth was only 10% of its deposition rate from the atmosphere observed at Naha City on Okinawa Island, 1.6 dpm/cm²/yr (Tsunogai *et al.*, 1985). Although we do not know the exact trapping efficiency, this small flux at 640 m depth can not be considered to be due to the low trapping efficiency for the following reasons. There was no significant difference between the two sets of total mass flux data obtained from our time-series type sediment trap consisting of twin collectors. We ob-

Fig. 3. Vertical profiles of excess ^{210}Pb in the sediments. (a) at Station CB 7-2 in the Okinawa Trough. (b) at Station CB 17 in the continental shelf zone in the East China Sea.

served the $^{230}\text{Th}_{\text{EX}}$ flux at 640 m to be 1.24 dpm/cm²/kyr, which is 75% of ^{230}Th produced in the overlying water column (Table 5). This percentage is typical of those observed in the oligotrophic open ocean. It seems likely that the removal of ^{210}Pb from the overlying water column is inefficient due to the smaller total mass flux in the trough region. Thus, a substantial

part of ^{210}Pb derived from the atmosphere is considered to be carried away with the Kuroshio current from the East China Sea, as found in the Japan Sea (Nozaki *et al.*, 1973).

The flux of ^{210}Pb during its sinking from 640 m to 1390 m increased by $1.7 \text{ dpm/cm}^2/\text{yr}$, which was 4 times the amount of ^{210}Pb produced from ^{226}Ra in the water column calculated from the data of Nozaki *et al.* (1990a). On the other hand, the accumulation rate of ^{210}Pb to the sediment of CB 7-2 is observed to be $2.4 \text{ dpm/cm}^2/\text{yr}$ (Fig. 3-a), being nearly equal to the flux observed at 1920 m. Although the duration of the sediment-trap deployment was only 2 weeks, the coincidence of these two values indicates that this observation may not be an extreme case. Thus, the addition of laterally transported ^{210}Pb -bearing particles is required to explain the large increase in the ^{210}Pb flux during 750 m of sinking.

Lead-210 is effectively scavenged from sea water at the margin of the ocean (Bacon *et al.*, 1976; Nozaki *et al.*, 1980; Spencer *et al.*, 1981; Cochran *et al.*, 1983; etc.). It has been also noted by Bacon *et al.* (1988) that a strong ^{210}Pb concentration gradient exists in the shelf-edge zone. In the East China Sea, the concentrations of ^{210}Pb in surface water decreased by a factor of 5–10 from the Kuroshio to the shelf (Nozaki *et al.*, 1990b), while the concentrations of ^{226}Ra increased by a factor of two (Nozaki *et al.*, 1989). This indicates that ^{210}Pb is actively removed by the settling particles in the shelf water relative to the Kuroshio water. Fig. 3-b shows that the "apparent" sedimentation rate at Station CB 17 is 0.18 cm/yr , which also indicates the accumulation rate of ^{210}Pb is $1.2 \text{ dpm/cm}^2/\text{yr}$. This value corresponds to 70% of the atmospheric influx of ^{210}Pb . As the shelf sediment was mostly compos-

ed of sandy deposits (Chin, 1979), ^{210}Pb removed by settling particles in the shelf water may not be incorporated into the shelf sediments. It is suggested that ^{210}Pb -bearing particles are laterally transported by the tidal current from the shelf region, via the near bottom layer, to the deep trough, and therefore, the Okinawa Trough acts as a large sink of particles containing ^{210}Pb and other reactive metals. Similar cases are found in the Santa Barbara Basin (Moore *et al.*, 1981) and in the Panama and Guatemala Basin (Anderson *et al.*, 1983b).

The $^{210}\text{Pb}/^{232}\text{Th}$ and $^{230}\text{Th}/^{232}\text{Th}$ activity ratios in the settling particles (Table 2) were significantly higher than those in the shelf and slope sediments (Table 4). This implies that the particles collected in the sediment trap did not come directly from the bottom sediments as resuspended particles, but that ^{210}Pb and ^{230}Th were incorporated into the particles during the lateral transport.

The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in the settling particles

The concentrations of ^{210}Po and the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in the settling particles are shown in Tables 2 and 3. Although the concentrations and fluxes of ^{210}Po increased with depth, the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio was constant and about unity. This is different from the results observed in the Sargasso Sea (Spencer *et al.*, 1978), the northern North Pacific (Tsunogai *et al.*, 1982), the East Pacific and the Antarctic Ocean (Harada and Tsunogai, 1986a) where the ratios were greater than unity, reflecting the greater reactivity or the shorter residence time of ^{210}Po in sea water. We have shown above that the ^{210}Pb flux increased 10 times while sinking from 640 to 1390 m. The flux of ^{210}Po also increased.

Table 2. Activity ratios of radionuclides in the settling particles

Depth (m)	$^{234}\text{U}/^{238}\text{U}$	$^{238}\text{U}/^{232}\text{Th}$	$^{230}\text{Th}/^{232}\text{Th}$	$^{228}\text{Th}/^{232}\text{Th}$	$^{210}\text{Pb}/^{232}\text{Th}$	$^{210}\text{Po}/^{210}\text{Pb}$
640	1.08 ± 0.08	1.06 ± 0.06	0.90 ± 0.05	5.77 ± 0.24	70.5 ± 4.5	1.05 ± 0.05
1390	0.90 ± 0.04	0.77 ± 0.03	0.97 ± 0.03	9.17 ± 0.20	158 ± 4	0.97 ± 0.02
1920	0.94 ± 0.05	0.78 ± 0.03	1.18 ± 0.03	10.5 ± 0.2	214 ± 7	0.99 ± 0.03

Table 3. Concentrations of radionuclides in the surface sediments

Code and location	Combustion loss (%)	Concentration (dpm/g)			
		²³⁸ U	²³² Th	²³⁰ Th	²¹⁰ Pb
CB 17	(28°30'N, 123°30'E, 65 m)				
	3.86	0.953 ± 0.035	2.44 ± 0.10	1.27 ± 0.05	4.67 ± 0.20
CB 15	(27°31'N, 123°51'E, 97 m)				
	0.73	0.859 ± 0.038	1.85 ± 0.07	1.06 ± 0.05	8.43 ± 0.22
CB 14	(27°13'N, 124°34'E, 110 m)				
	1.12	1.73 ± 0.07	2.14 ± 0.11	1.41 ± 0.06	9.64 ± 0.19
CB 13	(26°45'N, 124°32'E, 128 m)				
	1.22	1.08 ± 0.04	1.51 ± 0.07	0.978 ± 0.044	6.95 ± 0.15
CB 12	(25°47'N, 124°53'E, 1330 m)				
	1.40	1.13 ± 0.04	2.43 ± 0.07	1.41 ± 0.07	11.2 ± 0.3
CB 7-2	(25°47'N, 125°22'E, 2160 m)				
	4.16	1.44 ± 0.05	3.15 ± 0.13	3.41 ± 0.14	36.2 ± 0.8

All errors are of 1σ counting statistics.

The fact that the ²¹⁰Po/²¹⁰Pb activity ratio in the settling particles was unity means that the particles which were laterally transported from the shelf region should have the ratio of about unity. If the initial ²¹⁰Po/²¹⁰Pb ratio is significantly larger than unity, the particles must be transported from the shelf zone after spending more than one year there.

The fluxes of ²²⁸Th_{EX} and ²³⁰Th_{EX}

Thorium-228 (half-life, 1.91 yr) and ²³⁰Th (half-life, 75200 yr) are produced from the radioactive decay of ²²⁸Ra and ²³⁴U of their direct parent nuclides, respectively. The sources of those nuclides are atmospheric and riverine lithogenic particles in a nearly equilibrium state with their parent nuclides and radiogenic particles from ²²⁸Ra and ²³⁴U dissolved in sea water. It is assumed that the ²³⁴U/²³⁰Th detrital ratio is equal to the ratio measured in the surface sediment. It is also assumed that ²²⁸Th and ²³⁰Th in lithogenic particles are in equilibrium with ²³²Th, which is a grandparent of ²²⁸Th, and ²³⁴U, respectively. We calculate the unsupported ²²⁸Th (designated ²²⁸Th_{EX}) and ²³⁰Th (designated ²³⁰Th_{EX}) as follows:

$$^{228}\text{Th}_{\text{EX}} = ^{228}\text{Th}_{\text{PR}} - ^{232}\text{Th}_{\text{PR}}, \quad (1)$$

$$^{230}\text{Th}_{\text{EX}} = ^{230}\text{Th}_{\text{PR}} - (^{234}\text{U}/^{232}\text{Th})_{\text{SED}} \times ^{232}\text{Th}_{\text{PR}}, \quad (2)$$

Table 4. Activity ratios of radionuclides in the surface sediments

Station code	²³⁴ U/ ²³⁸ U	²³⁸ U/ ²³² Th	²³⁰ Th/ ²³² Th	²¹⁰ Pb/ ²³² Th
CB 17	1.03 ± 0.02	0.39 ± 0.02	0.52 ± 0.02	1.91 ± 0.11
CB 15	1.05 ± 0.02	0.46 ± 0.03	0.57 ± 0.02	4.56 ± 0.21
CB 14	1.01 ± 0.02	0.81 ± 0.05	0.66 ± 0.04	4.50 ± 0.25
CB 13	1.01 ± 0.02	0.72 ± 0.04	0.65 ± 0.04	4.60 ± 0.23
CB 12	1.01 ± 0.02	0.47 ± 0.02	0.58 ± 0.03	4.61 ± 0.18
CB 7-2	0.95 ± 0.03	0.46 ± 0.02	1.08 ± 0.06	11.5 ± 0.5

where the subscripts PR and SED refer to settling particles and sediment, respectively, and the symbols of nuclides indicate their concentrations in radioactivity. The ²³⁴U/²³²Th activity ratio in the surface sediment used is 0.44 ± 0.02, which is observed at Station CB 7-2 (Table 4).

The calculated results (Table 5) show a steep increase in the fluxes of ²²⁸Th_{EX} and ²³⁰Th_{EX} with depth. The ²³⁰Th_{EX} fluxes at 1390 m and 1920 m depth are greater than the amounts produced in the overlying water. The increase in the ²³⁰Th_{EX} flux from 640 m to 1390 m is 5.1 dpm/cm²/kyr, which is almost 3 times greater than its production in the water column, 2.0 dpm/cm²/kyr. The (²²⁸Th/²³⁰Th)_{EX} ratio in the particles settling through this water column has increased from 10.4 to 15.6 (Table 5), although the ratio usually decreased with depth in the open ocean (Taguchi *et al.*, 1989; Tsunogai *et al.*, 1990). This trend is

Table 5. Concentrations and particulate fluxes of unsupported ^{230}Th and ^{228}Th

Depth (m)	$^{230}\text{Th ex}$			$^{228}\text{Th ex}$		$(^{228}\text{Th}/^{230}\text{Th})_{\text{ex}}$ Activity ratio
	Concentration (dpm/g)	Flux (dmp/cm ² /kyr)	Flux/Production*	Concentration (dmp/g)	Flux (dpm/cm ² /kyr)	
640	0.817 ± 0.082	1.24	0.75	8.52 ± 0.21	13.0	10.4
1390	1.08 ± 0.06	6.30	1.74	16.8 ± 0.2	97.9	15.6
1920	1.52 ± 0.06	10.3	2.06	19.5 ± 0.2	132	12.8

*Amount produced by the decay of uranium in the overlying water, $F_{\text{prod.}} = 2.6D$ (water column depth in km).

Fig. 4. The budget of $^{230}\text{Th}_{\text{EX}}$ and $^{228}\text{Th}_{\text{EX}}$ in the water column between 640 m and 1390 m depth.

the same as that of ^{210}Pb which was shown above. This fact also means that the particles, which are removed in the continental shelf zone, are transported into the deep trough, because the concentration of ^{228}Ra in the shelf water is usually high due to its release from the sediments (Kaufman *et al.*, 1981; Nozaki *et al.*, 1989, 1990b).

Figure 4 shows the budget of $^{230}\text{Th}_{\text{EX}}$ and $^{228}\text{Th}_{\text{EX}}$ in the water column between 640 m and 1390 m depth. In the steady state, the balance of $^{230}\text{Th}_{\text{EX}}$ is expressed as follows:

$$V_{640} + P + H = V_{1390}, \quad (3)$$

where V_{640} and V_{1390} are the vertical fluxes of $^{230}\text{Th}_{\text{EX}}$ at 640 m and 1390 m depth, respectively, P is the production rate of ^{230}Th from ^{234}U in the water column of 750 m depth and H is the lateral flux of $^{230}\text{Th}_{\text{EX}}$. The units are dpm/cm²/kyr for all the terms. The lateral flux of $^{230}\text{Th}_{\text{EX}}$ into this water column is calculated to be 3.0 dpm/cm²/kyr as shown in Fig. 4.

For the concentration of ^{228}Ra in the Okinawa Trough deep water, we use values 2 dpm/10³l as a lower limit and 5 dpm/10³l as an upper limit, since we didn't measure it in the trough water. The lower limit is based on the assumption that the water of the Philippine Sea of 1000 m depth is the only source of the trough deep water, which contains 2 dpm/10³l of ^{228}Th (Taguchi, 1989). The upper limit is estimated from the assumption that all the ^{228}Ra from the trough bottom sediment of the Okinawa Trough, which is the same as that of the Japan Sea, decays in the trough deep water (below 500 m) after mixing thoroughly in the deep water. In the steady state, the diffusive flux of ^{228}Ra from the bottom sediment in the Japan Sea is given by:

$$F = \{ \lambda \times A_D + (A_D - A_S) / \tau \} \times L, \quad (4)$$

where F (dpm/cm²/yr) is the ^{228}Ra flux, λ (yr⁻¹) is the decay constant of ^{228}Ra , τ (yr) is the mean residence time of the Japan Sea deep water, and

L is the mean thickness of the deep reservoir. The ^{228}Ra flux from the bottom sediment of the Japan Sea turns out to be $0.078 \text{ dpm/cm}^2/\text{yr}$ by using the following values: $A_D = 7.7 \text{ dpm}/10^3\text{l}$, which is the mean concentration of ^{228}Ra in the deep reservoir below 500 m; $A_S = 50 \text{ dpm}/10^3\text{l}$, which is the mean concentration of ^{228}Ra in the surface reservoir above 500 m (Okubo, 1980); $L = 1000 \text{ m}$, which is based on the mean total depth of the Japan Sea (1500 m; Harada and Tsunogai, 1986a); and $\tau = 300 \text{ yr}$, which is estimated by Gamo and Horibe (1983) and Harada and Tsunogai (1986a). From this flux and the mean total depth of the trough area deeper than 1000 m (1600 m), the concentration of ^{228}Ra in the Okinawa Trough deep water is calculated to be $6 \text{ dpm}/10^3\text{l}$. Thus, if we can assume that the residence time of Th isotopes in the Okinawa Trough deep water is equal to that in the Japan Sea deep water (10 years; Nozaki and Yamada, 1987), the in situ production rate of ^{228}Th is $12 \sim 36 \text{ dpm/cm}^2/\text{kyr}$. Thus, the obtained lateral flux ranges $49 \sim 73 \text{ dpm/cm}^2/\text{kyr}$, indicating that the $(^{228}\text{Th}/^{230}\text{Th})_{\text{EX}}$ activity ratio is $16 \sim 24$ in the particles laterally transported from the shelf.

Since ^{228}Th in the shelf zone in the New York Bight is quickly removed after a residence time of less than 10 days (Kaufman *et al.*, 1981), we assume that all ^{228}Th produced in the East China Sea is at once removed to sediments. The concentration of ^{228}Ra is reported to be $470 \text{ dpm}/10^3\text{l}$ (Nozaki *et al.*, 1989). The flux of ^{228}Th (F_{228} , $\text{dpm/cm}^2/\text{kyr}$) at $Z \text{ m}$ depth is given by:

$$F_{228} = 470 \times 10^{-4} \times Z \times \lambda_{228}, \quad (5)$$

where λ_{228} is the decay constant of ^{228}Th ($3.63 \times 10^2 \text{ kyr}^{-1}$).

From the average salinity of the shelf water of 31‰, the ^{234}U concentration of the shelf water is calculated to be 2.5 dpm/l ($0.0708 \times S_{\text{‰}} \times 1.14$; Ku *et al.*, 1975). Similarly with ^{228}Th , the flux of ^{230}Th (F_{230} , $\text{dpm/cm}^2/\text{kyr}$) at $Z \text{ m}$ depth can be assumed to be:

$$F_{230} = 2.5 \times 10^{-1} \times Z \times \lambda_{230}, \quad (6)$$

where λ_{230} is the decay constant of ^{230}Th

($9.22 \times 10^{-3} \text{ kyr}^{-1}$).

Therefore, the $^{228}\text{Th}/^{230}\text{Th}$ activity ratio in the settling particles formed in the shelf zone at any given depth turns out to be:

$$\begin{aligned} (^{228}\text{Th}/^{230}\text{Th})_{\text{PR}} &= F_{228}/F_{230} \\ &= 7400, \end{aligned} \quad (7)$$

This initial ratio is much larger than the activity ratio of $16 \sim 23$ obtained above. Since both ^{230}Th and ^{228}Th transported laterally in the deep trough are mainly produced in the shelf zone, the difference in the activity ratio should be due to the radioactive decay during the lateral transport. Thus, the necessary time for the decrease in the ratio from 7400 to $16 \sim 24$ turns out to be nearly 16 years, because it is 9 times the half-life of ^{228}Th of 1.91 years. It is suggested that the particles laterally transported from the shelf zone were neither virgin particles nor older particles, with an average age of 16 years.

SUMMARY AND CONCLUSIONS

(1) About half of the settling particles in the deep Okinawa Trough consists of lithogenic particles. This is based on the concentration of ^{232}Th in the settling particles, which is relatively constant with depth.

(2) The increments of ^{210}Pb , $^{228}\text{Th}_{\text{EX}}$ and $^{230}\text{Th}_{\text{EX}}$ fluxes while they are sinking through the water column of 640–1390 m, were much higher than those expected from the vertical profiles of these nuclides and their parents in sea water. Particularly, the increases in the fluxes of ^{210}Pb and $^{228}\text{Th}_{\text{EX}}$ originating intensively in the shelf region were larger than $^{230}\text{Th}_{\text{EX}}$ produced evenly in sea water.

(3) The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in the settling particles was about unity. The $(^{228}\text{Th}/^{230}\text{Th})_{\text{EX}}$ activity ratio caused by particles transported from the continental shelf was $16 \sim 24$. This value is about 350 times smaller than the activity ratio calculated from the production rate of these nuclides in the shelf water.

These results indicate that the particles are laterally transported from the continental shelf in the East China Sea to the Okinawa Trough.

The concentrations and fluxes of radiogenic nuclides such as ^{210}Pb , $^{228}\text{Th}_{\text{EX}}$, and $^{230}\text{Th}_{\text{EX}}$ increased with depth and their fluxes were larger than those calculated from the inventories of the nuclides and their respective parents in the water column above the sampling depth. About 70% of ^{210}Pb , 60% of $^{228}\text{Th}_{\text{EX}}$, and 50% of $^{230}\text{Th}_{\text{EX}}$ fluxes observed at 1390 m depth in the Okinawa Trough originated in the continental shelf zone. These particles were neither fresh particles nor older particles such as resuspended particles, and the particles removed first from the shelf region may be transported laterally on the time scale of about 16 years.

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