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^{10}Be profiles in the East China Sea and the Okinawa Trough

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Abstract

Dissolved beryllium-10 concentration profiles in sea water of the East China Sea and the Okinawa Trough in 1993 autumn and 1994 summer have been investigated. The results show that ^{10}Be concentrations in this area are mainly controlled by surface biological productivity, particle remineralization, and the degree of mixing with the Yangtze River and the Kuroshio waters. During the sampling periods (summer and autumn), the East China Sea was well stratified. Generally, the ^{10}Be water depth profiles can be divided into three layers: the surface mixed layer, the particulate ^{10}Be regeneration layer, and the bottom layer. Surface water ^{10}Be concentrations increase gradually towards the Kuroshio and increase sharply at the edge of the Kuroshio Current. Vertical distributions of ^{10}Be show that in the summer ^{10}Be is enriched in the bottom water near the Yangtze River estuary and the bottom water in the middle of the continental shelf. The two enriched areas are separated, probably by an intrusion of the Continental Coastal Water. In the autumn, ^{10}Be bottom enrichment only occurred in the western part of the East China Sea. This phenomenon is consistent with the seasonal circulation pattern change of currents induced by monsoon winds. The influence on ^{10}Be by the Kuroshio branch intrusion in the southern East China Sea northeast of Taiwan may be more significant than the Kuroshio main flow. Simple box model results indicate that ^{10}Be input from the Kuroshio Current is more important than Yangtze River input and atmospheric precipitation. About 81% of ^{10}Be input to the East China Sea is scavenged into the sediments and 19% of ^{10}Be flows out of the East China Sea by currents and water exchange. The ^{10}Be sedimentation flux in the East China Sea is nearly five times of the average global ^{10}Be production rate, suggesting that the East China Sea is an important sink for ^{10}Be.

1. Introduction

^{10}Be ($T_{1/2} = 1.5$ Ma) is a cosmogenic nuclide produced in the atmosphere by spallation of oxygen and nitrogen, and enters the oceans predominantly through rainfall. The atmospheric input of ^{10}Be to the oceans in both time and space is relatively constant on the several hundred thousand year time scale, which makes this isotope useful for dating of sediments (Ku et al., 1982; Southon et al., 1987) and as a tracer of change of particle flux (Anderson et al., 1990; Lao et al., 1993). It has been shown that ^{10}Be has the characteristics of a typical nutrient-type element that increases in concentration along the flow of

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the deep ocean water (Kusakabe et al., 1987, 1990; Ku et al., 1990). In previous work, much attention has been concentrated on the ^{10}Be distribution in the open ocean and deep-sea sediments. Although ^{10}Be scavenging at ocean margins recently has been investigated by using sediment traps (Lao et al., 1993), little work has been done on dissolved ^{10}Be distributions at ocean margins. Kusakabe et al. (1982) investigated ^{10}Be profiles in the San Nicolas Basin off the coast of southern California and found that ^{10}Be concentrations were influenced by the boundary current, the California Current, and freshwater input of ^{10}Be from the rivers on the California coast. In the present work, we have investigated ^{10}Be in a totally different type of ocean margin in the Pacific—the East China Sea and the Okinawa Trough.

The East China Sea is one of the largest marginal seas in the northwest Pacific with a broad continental shelf and high river runoff from the Yangtze River. In summer the river discharge reaches a maximum of $45,000\ m^3/s$, with a sediment load of 4.68×10^8 t/yr (Beardsley et al., 1985). Due to the rich supply of nutrients, the East China Sea is an area of high productivity and particle scavenging of trace elements. The Kuroshio Current water flowing over the continental slope mixes with the shelf water. Therefore, the East China Sea can be regarded as a mixing area for the ^{10}Be from the Yangtze River and the ^{10}Be

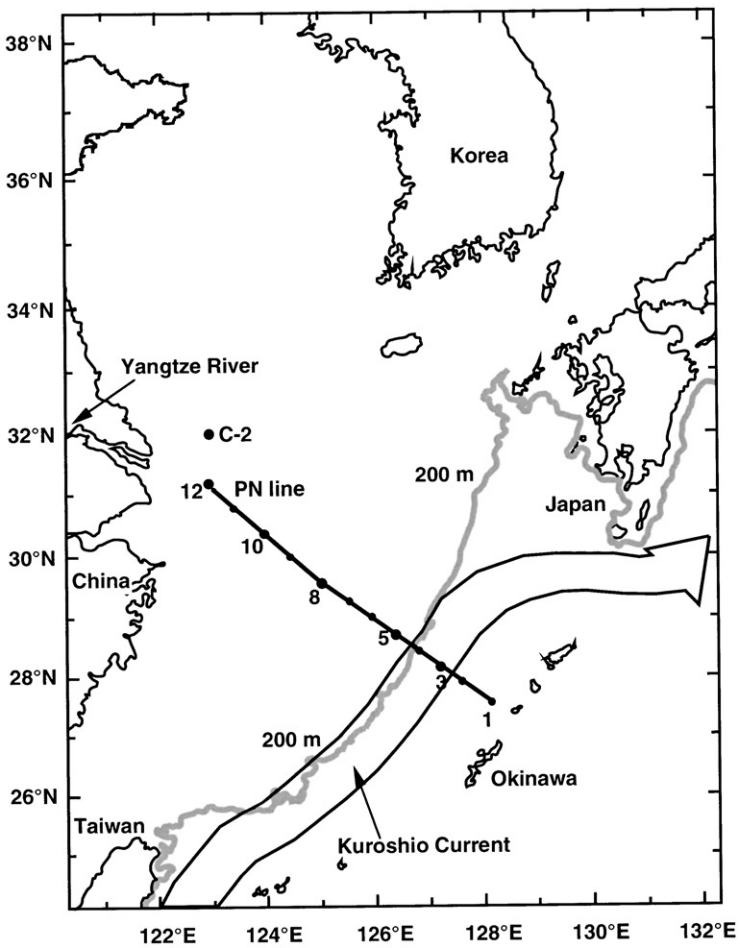

Fig. 1. Station locations occupied in this study. Two hundred meters isobath is also shown.

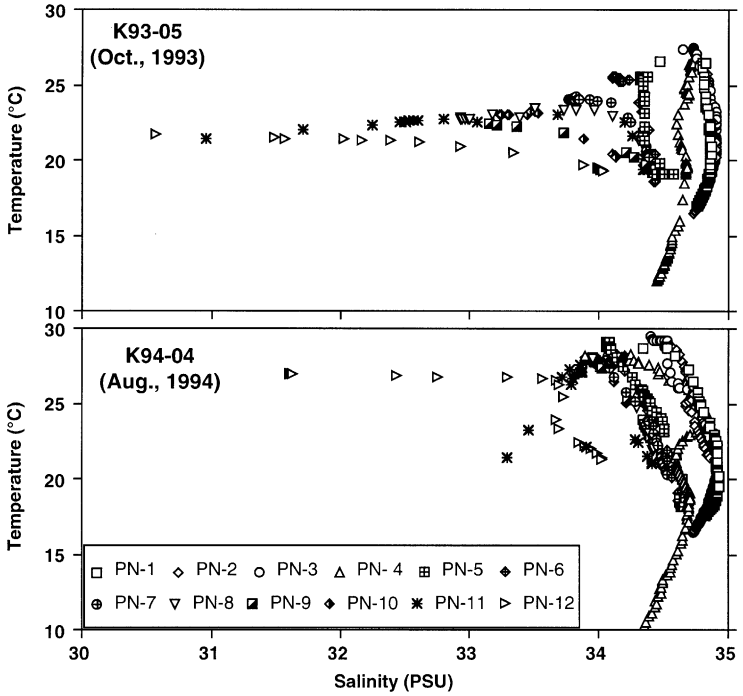

Fig. 2. *T–S* diagrams for stations on PN line in (a) 1993 autumn and (b) 1994 summer. Data are plotted from the surface to the 300 m depth.

from the open ocean carried in by the Kuroshio Current. The purpose of this work is (1) to investigate the influence of the water circulation on ^{10}Be distribution in the water column and (2) to gain an insight into the fate and budget of ^{10}Be in the East China Sea, and its role in the global cycle of ^{10}Be. In this work, we measured ^{10}Be vertical profiles in sea water along a transect (PN line, see Fig. 1) crossing the continental shelf of the East China Sea and the Okinawa Trough in summer and autumn. The results suggest that ^{10}Be distributions in the water column in the East China Sea are controlled mainly by surface biological productivity and water circulation. Understanding of these processes will shed light on the fate of particle reactive and trace elements in continental shelf areas.

2. Hydrological setting of the research area

The continental shelf of the East China Sea has a total area of about 7.5×10^5 km^2, one of the largest in the world. It is also one of the most productive areas of the world oceans. The major water masses in the East China Sea are Yangtze River Diluted Water, Continental Coastal Water, shelf water, and the Kuroshio branch (Miao et al., 1987). Due to the shallow water depth, seasonal variation of water circulation in the East China Sea is very large (Yanagi et al., 1996). In spring and summer surface water is transported seaward, and bottom water moves landward as compensation. In winter, northeasterly winds drive the surface water toward the land, while bottom water is transported seaward due to Ekman transport and compensation. A numerical model by Yanagi et al. (1996) shows that autumn water circulation is similar to winter rather than summer.

The Kuroshio Current flows northeastward along the eastern margin of the continental shelf. Sun (1987) demonstrated that the Kuroshio axis was close to the East China Sea continental shelf margin in fall and winter, and shifted offshore in spring and summer. Lin et al. (1992) analyzed

year-long satellite IR images and found that the Kuroshio front extended onto the shelf in winter and retreated to the shelf edge in summer and fall. Kuroshio water has been divided into the Kuroshio Surface Water (KSW), Kuroshio Subsurface Water (KSSW), and Kuroshio Intermediate Water (KIW) (Chen, 1996). Fig. 2 shows the T–S diagram along the transect of PN line. It can be seen that in summer the T–S values for the water at station PN-12 near the Yangtze River estuary are separated from those of the waters at other stations. In the southern East China Sea northeast of Taiwan, the impingement of the Kuroshio onto the continental shelf induces upwelling of the Kuroshio Subsurface Water (Gong et al., 1996) and the Kuroshio Intermediate Water (Chen, 1996). This upwelled Kuroshio branch flows northward and mixes with the shelf water.

3. Samples and methods

Seawater samples were collected from the R/V *Kaiyo* during two cruises in October 1993 (K93-05 Cruise) and in August 1994 (K94-04 Cruise) (Fig. 1). Water samples from 12 stations on the main observation line (PN line) from the north of Okinawa (27°30′N, 128°15′E) to the Yangtze River mouth (31°15′N, 123°00′E) and one station C-2 (K94-04 cruise only) were collected with the General Oceanic Rosette Multi-bottle Array System ($20\,l \times 24$ bottles). Immediately after sampling water samples ($110 \sim 300$ l) were filtered through a filter with a pore size of 0.4 μm and acidified with conc. HCl to pH 2–3. Then, Be and Fe carriers were added, and ^{10}Be was coprecipitated with ferric hydroxide by addition of ammonia.

Beryllium targets were prepared for the ^{10}Be AMS analyses from the hydroxide precipitation using the procedure of Kusakabe et al. (1987). Briefly, ^{10}Be was purified by using anion and cation exchange, DIBK solvent extraction, precipitation of $Be(OH)_2$, and conversion to BeO by heating to 1000°C in a Pt crucible. ^{10}Be was measured at the AMS facility of Lawrence Livermore National Laboratory, USA.

Table 1
^{10}Be concentrations in seawater in Autumn 1993 (K93-05)

Station	Depth (m)	^{10}Be (atoms/g)
PN-2	0	845±10
27°48.0′N		
127°48.0′E		
PN-3	0	829±10
28°06.4′N	25	770±19
127°21.3′E	50	772±10
	75	798±17
	100	754±14
	150	822±10
	200	804±10
PN-4	0	884±24
28°24.3′N		
126°54.0′E		
PN-5	0	320±8
28°42.3′N	10	301±5
126°25.9′E	25	326±5
	50	352±6
	75	404±7
	100	600±8
	125	568±10
PN-7	0	188±5
29°18.2′N		
125°34.4′E		
PN-8	0	153±4
29°34.9′N	30	179±5
125°05.5′E	50	435±6
	65	586±8
	70	703±9
	75	847±11
PN-10	0	126±3
30°22.5′N	10	138±5
123°59.5′E	20	127±4
	30	602±18
	50	631±2
PN-12	0	138±3
31°12.3′N	10	147±4
123°05.1′E	20	219±4
	30	747±13
	50	1092±15

4. Results

Concentrations of dissolved ^{10}Be in sea waters from the East China Sea and the Okinawa Trough

Table 2
^{10}Be concentrations in seawaters in Summer 1994 (K94-04)

Station	Depth (m)	^{10}Be (atoms/g)
PN-2	0	421±27
27°48.0′N		
127°48.0′E		
PN-3	0	675±12
28°06.4′N	25	793±15
127°21.3′E	50	782±15
	75	737±14
	150	835±12
	200	847±16
PN-4	0	620±8
28°24.3′N	25	540±22
126°54.0′E	50	651±18
	75	672±31
	100	585±51
	150	566±11
	200	767±16
	250	1105±26
PN-5	0	239±9
28°42.3′N	10	220±5
126°25.9′E	25	239±5
	50	231±7
	75	226±6
	100	562±10
	125	551±10
PN-6	0	206±6
28°59.9′N	20	209±7
126°00.2′E	60	359±7
	80	531±13
	100	212±7
PN-7	0	211±5
29°18.2′N		
125°34.4′E		
PN-8	0	201±5
29°34.9′N	10	240±9
125°05.5′E	30	215±8
	50	222±6
	65	841±23
	70	1288±18
	75	1393±68
PN-9	0	179±5
29°59.8′N		
124°30.0′E		
PN-10	10	155±6
30°22.5′N	20	186±9
123°59.5′E	30	178±9
	40	744±32
	50	277±8
PN-11	0	127±5
30°36.6′N		
123°39.6′E		
PN-12	0	62±4
31°12.3′N	5	84±6
123°05.1′E	20	95±11
	30	513±12
	40	500±12
	50	972±16
C-2	5	303±7
31°59.9′N	10	448±10
122°59.6′E	20	447±10
	30	766±16
	40	1700±32

are shown in Tables 1 and 2. The errors are based on 1σ uncertainties from the AMS measurements. Vertical profiles of ^{10}Be concentration are shown in Fig. 3, and surface ^{10}Be concentrations along the PN line are shown in Fig. 4. Several characteristics can be seen from these data. First, the surface ^{10}Be concentrations (60–320 atoms/g seawater) in the East China Sea are much lower than the average surface water ^{10}Be concentration (600–800 atoms/g seawater) in the Pacific Ocean (Kusakabe et al., 1987), suggesting intensive particle scavenging of Be at this ocean margin. The surface ^{10}Be concentration increases sharply at the Okinawa Trough stations PN-2, PN-3 and PN-4, reflecting that the ^{10}Be concentration in the Kuroshio Current originated from the tropical Pacific Ocean. Secondly, generally there are surface mixing layers in which ^{10}Be concentrations are homogeneous and the thickness of the mixing layers increases towards the Okinawa Trough. The ^{10}Be concentrations at station PN-3 in the Kuroshio Current are nearly homogeneous in the upper 200 m water because the thermocline in the Kuroshio Current may reach as deep as 200 m. Thirdly, below the mixing layer, the ^{10}Be

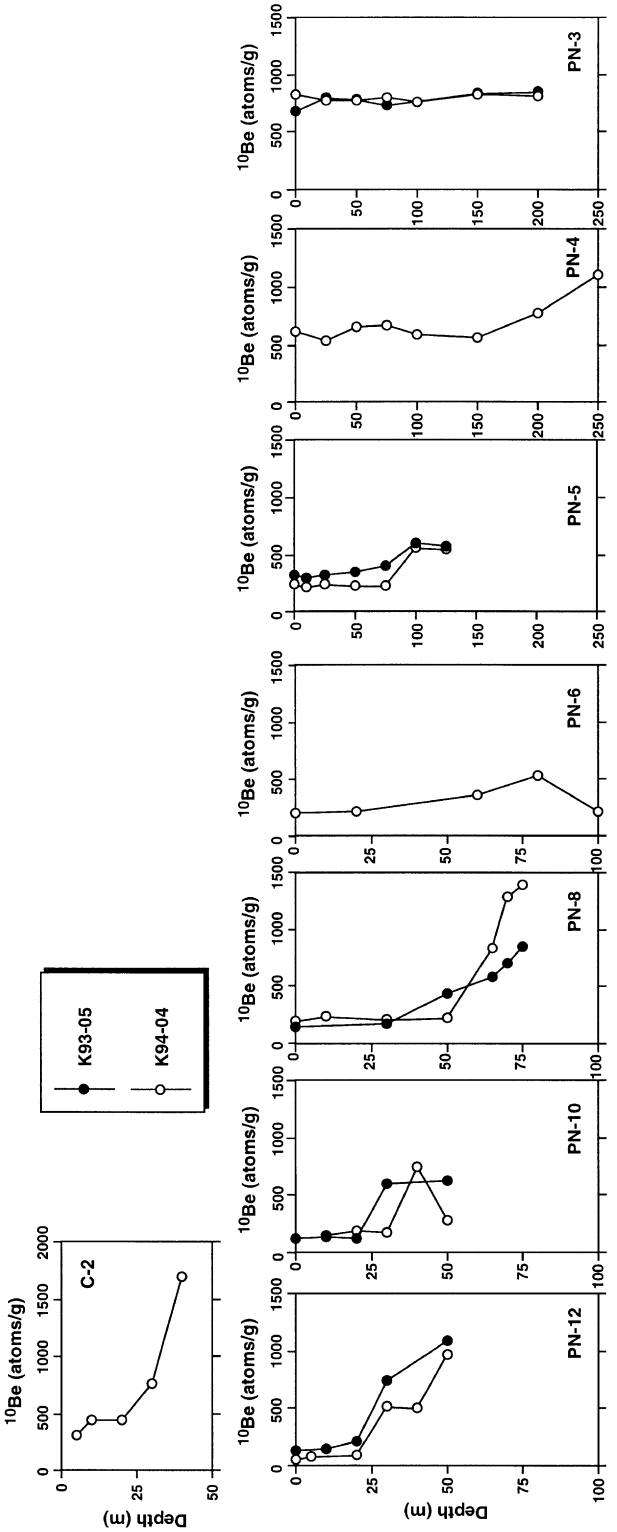

Fig. 3. Depth profiles of ^{10}Be concentration in sea waters from the East China Sea and the Okinawa Trough.

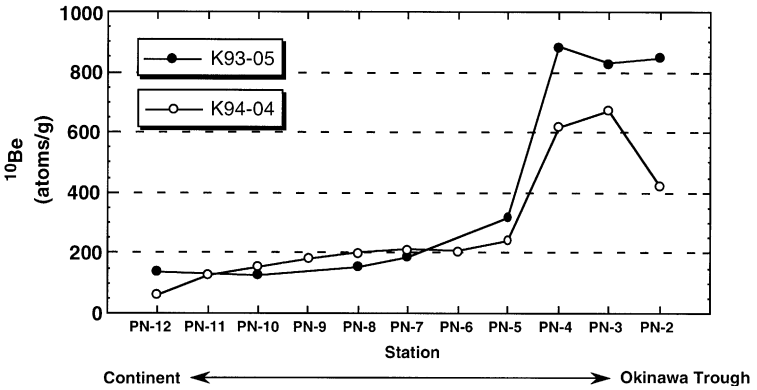

Fig. 4. Horizontal distribution of ^{10}Be concentration in surface waters along the PN line.

concentrations generally increase with water depth, reflecting the regeneration of particulate ^{10}Be scavenged from the overlying surface waters. Two areas of ^{10}Be enrichment occurred in the bottom water in summer (Fig. 5), one near the Yangtze River estuary and the other in the central continental shelf (PN-7 and PN-8). Finally, seasonal changes of ^{10}Be profiles have been observed at some stations with lower ^{10}Be concentrations in 1994 summer than in 1993 autumn. PN-10 in summer has lower ^{10}Be concentrations compared with surrounding stations. The reason is that the water-mass structure at PN-10 is different, as discussed below.

5. Discussion

Based on the above-mentioned features of ^{10}Be profiles in this area, three layers in the water column can be identified (Fig. 3). A surface layer represents the mixed layer in which productivity is high and ^{10}Be is depleted. The second layer is a depth interval in which ^{10}Be regeneration occurs due to the particulate matter degradation. The contour plots (Fig. 5) of the ^{10}Be distribution in the East China Sea and the Okinawa Trough further depicts that ^{10}Be was enriched (relative to the Kuroshio water) in the bottom waters near the Yangtze River estuary and in the central continental shelf.

5.1. ^{10}Be redissolution in subsurface water

Biogenic particles and terrestrial particles both influence the distribution of ^{10}Be in this area. However, along the PN line, sediments on the seabed are mainly coarse-sized silts (Saito and Yang, 1993). Olsen et al. (1986) investigated the distributions of ^{7}Be in the estuary and coastal areas in the eastern United States and found that the particulate ^{7}Be concentration is controlled by particle size, i.e. Be has stronger affinity to clay-sized particles than to silt-sized particles. Thus, the ^{10}Be sorption on the coarse terrestrial particles at the PN stations should be negligible. The high scavenging of ^{10}Be by particles in the surface water transports ^{10}Be into the subsurface water where ^{10}Be is subjected to regeneration with the remineralization of biogenic particles. Since the coarse terrestrial sediments cannot scavenge ^{10}Be effectively, the regenerated ^{10}Be either should be enriched in the bottom water or be carried elsewhere by water circulation. The contour plots (Fig. 5) shows that the ^{10}Be is enriched (relative to the Kuroshio water) in bottom waters near the Yangtze River estuary and in the central continental shelf. It should be noted that this enrichment of dissolved ^{10}Be in the bottom water may occur only in the stratified waters. We did not investigate the ^{10}Be distribution in winter season when the stratification disappears. From hydrographic data it can be expected that in winter some of the ^{10}Be will be transported to the open ocean

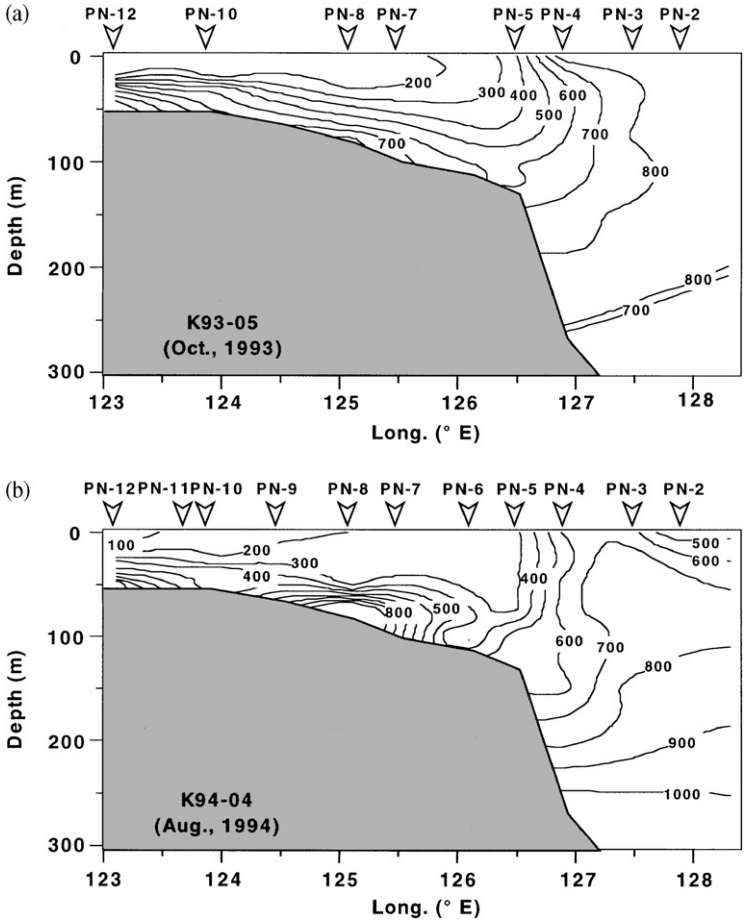

Fig. 5. ^{10}Be concentration (atoms/g) contour plots on PN line in (a) 1993 autumn and (b) 1994 summer. Arrows indicate sampling stations.

by bottom currents and the Kuroshio (Yanagi et al., 1996).

5.2. ^{10}*Be concentration in the Kuroshio water*

^{10}Be concentrations in the Kuroshio Current water (stations PN-2 and PN-3) are generally high (700–800 atoms/g seawater), comparable to the open-ocean surface water values (500–1000 atoms/g seawater, Raisbeck et al., 1979, 1980; Kusakabe et al., 1987) in the Pacific Ocean. Since the Kuroshio originates from subtropical and tropical regions with low nutrients and low productivity, it is expected that the scavenging of ^{10}Be in the Kuroshio surface water should be low. Another reason that the ^{10}Be concentration is high in the Kuroshio water may lie in the fact that it is formed in the tropical ocean (east of the Philippines) where precipitation, and hence ^{10}Be input, is high (Somayajulu et al., 1984). It has been suggested that the Kuroshio Intermediate Water, which is rich in nutrients compared to the surface water, is the major source of nutrients to the East China Sea (Chen et al., 1995; Chen, 1996). ^{10}Be has long residence time in the deep waters (600–1000 years, Raisbeck et al., 1980; Kusakabe et al., 1987) and behaves like a nutrient. The implication is that ^{10}Be also may be contributed from the Kuroshio significantly, and this will be discussed later.

5.3. Influence on PN-10 from the Continental Coastal Water

In contrast to the high primary productivity (> 1000 mg $C/m^2/d$) at stations PN-8 and PN-12, the primary productivity (300 mg $C/m^2/d$) at station PN-10 in 1993 autumn was so low as to be almost comparable to those at the Okinawa Trough (Hama, 1994). Other abnormal phenomena have been observed at this station such as low respiration gross production (Furuya et al., 1994), low nitrate uptake (Kanda and Watanabe, 1994), low turbid layer (Hoshika et al., 1994), and low nutrients (Watanabe et al., 1994). Hama (1994) postulated that the low productivity at PN-10 was partly affected by the Kuroshio branch. However, at this station, ^{10}Be concentrations in the bottom water were low (277 atoms/g seawater in summer and 630 atoms/g seawater in autumn) compared with the bottom water ^{10}Be concentrations in the neighboring stations PN-8 and PN-12 (850–1100 atoms/g seawater in summer and 940–1400 atoms/g seawater in autumn). One possibility is that since ^{10}Be behaves like nutrients such as phosphate (Kusakabe et al., 1982), ^{10}Be is being used up like nutrients on the course of the Kuroshio Current branch flowing to this station. However, from the above discussion it is clear that the Kuroshio water intrusion will cause a ^{10}Be enrichment in the bottom water. At station PN-10, the enrichment of ^{10}Be was not found in the bottom water and this station separates the two ^{10}Be-enrichment areas in the East China Sea. The possibility is that the Continental Coastal Water flows southward into this location as suggested by the temperature data from Watanabe et al. (1994). The upper 150 m water column temperature (26°C) at PN-10 in 1993 autumn was higher than the neighboring stations. Also, the salinity data (Watanabe et al., 1994) show that in the autumn of 1993 the water mass was different from those at stations PN-8 and PN-10. The Continent Coastal Water, regarded as a branch of the Tsushima Warm Current, flowing from the Yellow Sea in the north, contains low nutrients and therefore may cause the low productivity at the station PN-10.

5.4. Seasonal variation of the ^{10}Be profiles

For most stations, the ^{10}Be surface water concentrations show little difference between summer and autumn with slightly lower ^{10}Be in summer. For station PN-5, surface ^{10}Be concentrations were significantly lower in summer 1994. This decrease is mainly due to higher productivity in summer. Fei et al. (1987) obtained primary production rates in this area from 1500 to 2000 mg $C/m^2/d$ in summer, compared to those in autumn ($\sim$1000 mg $C/m^2/d$, Hama, 1994). The seasonal change of ^{10}Be concentrations in the Kuroshio Current with higher ^{10}Be concentration in autumn may be caused by seasonal changes in productivity and/or atmospheric precipitation in the tropical area where the Kuroshio Current originates. This needs to be proved by further work.

On the other hand, seasonal changes of ^{10}Be distribution in the bottom water are significant as can be seen from the contour plots of ^{10}Be. Generally, the bottom-water ^{10}Be concentration was higher in the autumn than in the summer. This can be explained by seasonal circulation in the East China Sea. In summer, the surface current along the PN line is seaward while the bottom current is landward (Yanagi et al., 1996). Thus, the accumulated ^{10}Be in the bottom water near the Yangtze River estuary is unlikely to be transported seaward. In autumn, the water circulation reverses and the accumulated ^{10}Be near the Yangtze River estuary can reach the central and eastern part of the continental shelf.

5.5. The mean residence times of ^{10}Be

The surface mixed layers in the East China Sea range from 20 to 80 m thick. The concentrations of ^{10}Be in the mixed layers and the whole water column range from 60 to 340 atoms/g. If we use the global mean ^{10}Be production rate of $(1.2 \pm 0.26) \times 10^6$ atoms/cm^2/yr (Monaghan et al., 1985), we can roughly estimate the ^{10}Be residence time in the surface layers and in the whole water column of the East China Sea. The estimated mean residence times in the surface waters range from 9 h near the Yangtze River estuary to

27 days near the Okinawa Trough. The mean residence times in the total water column range from 5 to 12 days. These estimations do not take into account of lateral advection and diffusion supply of ^{10}Be, and therefore should be viewed as an upper limit of the ^{10}Be residence times in the East China Sea and the Okinawa Trough. In addition, since the atmospheric flux to the area, which is controlled by annual rainfall and production rate in the atmospheric (Somayajulu et al., 1984), should not be the same as the global mean production rate, the residence time derived from the above calculation may include significant amount of error. Yet, compared with the ^{10}Be residence time (0.5 yr) in the surface mixed layer of the San Nicolas Basin in the eastern Pacific Ocean margin (Kusakabe et al., 1982), the scavenging residence time of ^{10}Be is much shorter in the East China Sea. The mean residence time for ^{10}Be in the surface Kuroshio was estimated to be 47 days.

5.6. *Influence from the Kuroshio branch water and the ^{10}Be budget*

One possibility for the enrichment of dissolved ^{10}Be in the bottom water is that the bottom water represents the remains of the vertically well mixed water formed in winter (Fukase, 1975), because the temperature and salinity of the bottom water in summer are almost the same as those of the vertically homogeneous water formed in winter. The winter biological productivity in the East China Sea is low (Hama, 1994), and thus the dissolved ^{10}Be concentration should be high. However, recent physical oceanographic research (Song, 1987) has shown that low-temperature feature of the bottom water in the East China Sea is caused by a cooling in spring, rather than a relic from winter. Also, by using T–S diagrams based on data over 18 yr, Maeda (1989) showed that the salinity of the bottom water in summer increases slightly in comparison with that in spring, which was interpreted as evidence of the supply of high salinity water from the Kuroshio. The Kuroshio water should play a significant role in the formation of the bottom water on the continental shelf.

The T–S diagrams (Fig. 2) show that the water masses at the two ^{10}Be bottom water enrichment areas (the area near the Yangtze River mouth represented by stations 11 and 12 and the central continental shelf area represented by stations 7 and 8) are completely different from each other. This suggests different sources of ^{10}Be for these two areas. There are two ^{10}Be sources in addition to the atmospheric input in the East China Sea: the Yangtze River and the Kuroshio. From the ^{10}Be contour plots, it can be seen that large-scale intrusion of surface Kuroshio water is unlikely. The alternative source of this Kuroshio intrusion is from the upwelling of Kuroshio Subsurface and Intermediate Waters northeast of Taiwan, as suggested by many workers (Maeda, 1989; Chuang and Liang, 1994; Chern and Wang, 1994; Gong et al., 1996). This Kuroshio branch intrusion flows northward and spreads in the central continental shelf area. It carries ^{10}Be, which, by scavenging in the surface and recycling in depth, is enriched in the bottom water.

In order to understand further the role of the Kuroshio intrusion, it is necessary to have a ^{10}Be budget in the East China Sea. To accomplish this, the following simple box model was employed. The balance of ^{10}Be in the East China Sea can be expressed by the equation

$$Q_R C_R + Q_K C_K + I_a A t = Q_S C_S + S, \quad (1)$$

where Q_R and Q_K are the water fluxes (km^3/6 months) of the Yangtze River, and the Kuroshio (for the 6 month wet season) into the East China Sea, respectively; Q_S is the water flux for the 6 month wet season flowing out of the East China Sea. The data of Q_R ($= 813$ km^3/6 months), Q_K ($= 27,360$ km^3/6 months), and Q_S ($= 28,593$ km^3/6 months) are adopted from Kim (1992), Yanagi (1994), and Chen (1996), and Q_K is the sum of the Kuroshio surface, subsurface and intermediate water fluxes (Chen, 1996). I_a is the atmospheric input of ^{10}Be, which is assumed to be equivalent to the average global ^{10}Be production rate ($(1.2 \pm 0.26) \times 10^6$ atoms/cm^2/yr; Monaghan et al., 1985), A is the area of the East China Sea (7.5×10^5 km^2); $t = 6$ months; C_R, C_K, and C_S are ^{10}Be concentrations in the Yangtze River water, Kuroshio water, and the shelf water,

respectively. S is the sedimentation flux of ^{10}Be buried in sediments. Here, we neglect the contribution from the waters coming through the Taiwan Straight and assume that ^{10}Be concentration in the Yangtze River water is the same as the average dissolved ^{10}Be concentrations in several North American rivers and the Pearl River, China (3220 ± 1960 atoms/g water, Kusakabe et al., 1991). The results show that the ^{10}Be flux into the East China Sea from the river, the Kuroshio, and the atmosphere are $(2.6 \pm 1.6) \times 10^{21}$, 1.9×10^{22} and $(4.5 \pm 1.0) \times 10^{21}$ atoms/6months, respectively. Therefore, the atmospheric contribution to the ^{10}Be concentration in the East China Sea is comparable to that from the Yangtze River but the Kuroshio ^{10}Be contribution is an order of magnitude higher.

The total ^{10}Be flux into the East China Sea is $(2.6 \pm 0.2) \times 10^{22}$ atoms/6 months, which should balance the ^{10}Be fluxes flowing out of the East China Sea and buried in sediments. Next, we can calculate the flowing flux of ^{10}Be out of the East China Sea. We use the surface ^{10}Be concentrations (average 172 ± 1.5 atoms/g seawater for the stations on PN line except the two stations PN-3 and PN-4 located in the Kuroshio Current) as the ^{10}Be concentration in the shelf water that flows out of the East China Sea. The reason for the choice of surface ^{10}Be as C_S is that in summer only the surface water in the East China Sea can flow out due to the water circulation pattern, i.e. the surface water flows seaward and the bottom water flows landward. The estimated outflow flux is $(4.9 \pm 0.04) \times 10^{21}$ atoms/6 months, and the sedimentation flux is $(2.1 \pm 0.2) \times 10^{22}$ atoms/6 *months*, which is 81% of the total ^{10}Be input and equivalent to $(5.6 \pm 0.5) \times 10^6$ atoms/cm^2/yr, almost five times of the average global ^{10}Be production rate (1.2×10^6 atoms/cm^2/yr). Taking into account of the possible contribution by the water from the Taiwan Strait that we neglected in our model, the ^{10}Be sedimentation flux should be even higher, so the value of 5.6×10^6 atoms/cm^2/yr is only a lower limit. Taking into account of the errors in the above calculations, the ^{10}Be sedimentation fluxes in the East China Sea are 3–6 times of the average global ^{10}Be production rate. Therefore, the East China Sea is an important ^{10}Be sink. Since the sand and silt sized sediments are not expected to scavenge ^{10}Be efficiently, most of the ^{10}Be sedimentation may be focused in the clay-sized sediment areas north of the PN line and in the near-shore areas. This needs to be proved by further work. It should be noted that the above conclusion is only valid for the spring and summer seasons. In the autumn and winter, the water circulation pattern (also the surface biogenic productivity) will change, and therefore the proportion of the ^{10}Be sedimentation flux in the total ^{10}Be input also should be changed.

About 19% of the ^{10}Be input to the East China Sea will eventually flow out of the East China Sea. The outlets for the East China Sea and the Yellow Sea waters are limited in summer season, as the Kuroshio Current effectively blocks the shelf water flowing to the open Pacific Ocean due to the density difference. The only available outlets are the Taiwan Straits (to the South China Sea) and mixing with the Tsushima Current (to the Japan Sea) (Nozaki et al., 1989), and both are very shallow. From the above calculation, it is clear that ^{10}Be in the East China Sea is effectively trapped in summer by the continental shelf.

6. Conclusions

The seawater profiles of ^{10}Be presented here have given us a first look at the ^{10}Be distribution in a continental shelf influenced by one of the world largest rivers and the Kuroshio Current. The results show that the ^{10}Be distribution in the water column is controlled by the river input, the primary productivity in surface, particle remineralization, and mixing with Kuroshio water. ^{10}Be is introduced to the East China Sea through atmospheric precipitation, river discharge, and the Kuroshio Current, and the input flux of ^{10}Be is much higher than in the open ocean. Although the scavenging of ^{10}Be in the surface water is high due to the high productivity in this area, the recycling of ^{10}Be in the bottom water is also effective along the PN line as the coarse terrestrial particles cannot further scavenge ^{10}Be. ^{10}Be is expected to be laterally transported by bottom currents either

northward on the continental shelf or to the coastal areas where sediment focusing occurs.

Three water masses in the East China Sea can be identified in the T–S diagram: the Yangtze River Diluted Water, the Shelf Water, and the Kuroshio water. The ^{10}Be concentrations in the Diluted Water are extremely low (30–60 atoms/g seawater) in the surface water and high in bottom waters (970–1700 atoms/g seawater), suggesting high river input of ^{10}Be and efficient scavenging and recycling of ^{10}Be in this water. The Shelf Water occupies the central and the eastern parts of the continental shelf with ^{10}Be concentration of $\sim$200 atoms/g seawater in the surface water and as high as 1400 atoms/g seawater in the bottom waters. Abnormally, low ^{10}Be concentrations observed at station PN-10 confirm that this station has low primary productivity, supporting the postulate that this location may be affected by the Continental Coastal Water. Seasonal variations of ^{10}Be profiles are consistent with seasonal water circulation pattern found both by observation and models.

^{10}Be input from the Kuroshio Current is more important than the Yangtze River input and the atmospheric precipitation in the East China Sea. Kuroshio Current serves as a conveyor belt that transports ^{10}Be from the open ocean and mixes it with ^{10}Be in the shelf water. ^{10}Be is trapped in the East China Sea in summer and enriched in the bottom water. Due to its particle reactive nature, most of this trapped ^{10}Be should find its way to the sediments. Simple box model results indicate that about 81% of the ^{10}Be input in the East China Sea may be scavenged into the sediments and 19% of ^{10}Be may flow out of the East China Sea by currents and water exchange. The ^{10}Be sedimentation flux in the East China Sea is nearly five times of the average global production rate, suggesting that the East China Sea is an important sink for ^{10}Be.

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