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PALEOENVIRONMENTAL CHANGES IN THE JAPAN SEA DURING THE LAST 85,000 YEARS

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Abstract. Five distinct changes in the paleoenvironment of the Japan Sea within the last 85,000 years are revealed from the sedimentary record of a piston core recovered from the Oki Ridge. Changes in both surface and deepwater conditions are registered by changes in lithology, calcium carbonate content, organic carbon content, oxygen and carbon isotope ratios, and microfossil assemblages including calcareous nannoplankton, diatoms, radiolaria, and foraminifera. Between 85 and 27 ka the warm Tsushima Current did not flow into the Japan Sea, and cold surface water conditions prevailed. Environments at the seafloor fluctuated between dysaerobic to weakly oxic conditions. Between 27 and 20 ka, freshwater input to the Japan Sea, probably from the Huang Ho River in China, stratified the water column, and the severe anoxic conditions eliminated most benthic fauna. Between 20 and 10 ka the cold Oyashio Current flowed into the Japan Sea through the Tsugaru Strait, reestablishing deepwater ventilation. Shallow water benthic assemblages of the North Pacific Ocean subsequently colonized the Japan Sea and occupied the vacant niches of the deep basins. Between 10 and 8 ka the foraminifer compensation level (FCL) gradually rose to a depth shallower than 1000 m, and bottom conditions changed from dysaerobic to oxic. At 10 ka the warm Tsushima Current started to flow into the Japan Sea through the Tsushima Strait to establish the modern oceanographic regime which has existed since 8 ka. The eustatic sea level during the last glacial maximum was above the sill depths (130 m) of the Tsushima and Tsugaru straits, assuming that tectonic movements at these straits were negligible for the last 20 ka.

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INTRODUCTION

The Japan Sea is a semi-isolated marginal sea with an average depth of 1350 m and a maximum water depth of approximately 3700 m in the northern basin. It is connected with the Sea of Okhotsk, the North Pacific, and the East China Sea through four shallow straits: Tatarskiy Strait (sill depth, 15 m), Soya Strait (55 m), Tsugaru Strait (130 m), and Tsushima Straits (130 m) (Figure 1). The only important current flowing into the Japan Sea today is the Tsushima Current, a branch of the warm Kuroshio Current, which enters through the Tsushima Strait between Kyushu and Korea and flows out to the

Pacific mainly through the Tsugaru Strait between Honshu and Hokkaido. Low temperature (0.1-0.3°C), low salinity (34.0-34.1‰), and high dissolved oxygen content (5-6 mL/L) characterize the Japan Sea Proper Water (JSPW) which occupies the deeper parts of the Japan Sea below water depths of 200-300 m. This water mass originates in the northwestern part of the Japan Sea by strong cooling of the surface water during the winter. Because of the high dissolved oxygen content and extremely low temperature of JSPW, surface sediments of the Japan Sea are oxidized uniformly, and the calcite compensation depth (CCD) stands at the relatively shallow depth of 2000 m [Ichikura and Ujiie, 1976].

Owing to the geography, particularly the very shallow sill depths, the paleoenvironment of the Japan Sea during the last glacial age must have been quite different from the present conditions. Study of the paleoenvironmental changes of the Japan Sea during the glacial-interglacial cycle is an interesting theme not only for regional paleoceanography but also because of the local effects of eustatic sea level fluctuations. During the last glacial age, eustatic sea level lowering would have severely restricted or completely blocked the inflow of the warm Tsushima Current into the Japan Sea and should have led to a considerable drop of sea surface temperatures. The purpose of this paper is to reconstruct the detailed paleoenvironmental history of the Japan Sea since the end of the last interglacial age.

The paleoenvironments of the Japan Sea during the last glacial and Holocene periods have been documented by various studies of the diatom floras and foraminiferal faunas recovered in piston cores [Koizumi, 1970, 1985, 1989; Tanimura, 1981; Ujiie, 1982; Ujiie and Ichikura, 1973; Ujiie et al., 1983; Ichikura and Ujiie, 1976; Maiya et al., 1976; Kato, 1978, 1979; Inoue, 1980; Oba et al., 1980; Kurihara, 1982]. For example, Ujiie and Ichikura [1973] identified the beginning of the present inflow of the Tsushima Current at 11 ka based on the replacement of sinistrally coiled *Neogloboquadrina pachyderma* by the dextral forms and the occurrence of a warm-water planktonic foraminiferal fauna. Because of the presence of authigenic framboidal pyrite in the glacial sequences, various authors have suggested an anoxic condition during the glacial interval [Miyake et al., 1968; Kobayashi and Nomura, 1972; Ujiie and Ichikura, 1973; Ichikura and Ujiie, 1976; Masuzawa and Kitano, 1977, 1983, 1984; Masuzawa et al., 1979]. These previous studies have all indicated that the Japan Sea was dominated by cold surface water and anoxic bottom conditions throughout the last glacial age and by warm surface waters coupled with oxidizing bottom conditions during the Holocene.

In this report we present new evidence and a more detailed paleoenvironmental history of the Japan Sea for the last 85 kyr obtained by a multidisciplinary analysis of a piston core. Detailed results of each microfossil and isotope study of this core have already been reported separately [Kato, 1984a, 1984b; Omura, 1984; Takayama and Kameo, 1984; Sakai, 1984; Koizumi, 1984; Mizota and Matsuhisa, 1984; Oba, 1984; Kitazato, 1984; Oba and Akasaka, 1991].

MATERIALS AND METHODS

One piston core, KH-79-3, C-3, was recovered from the top of the Oki Ridge in the southern part of the Japan Sea (37°03.5'N, 134°42.6'E, water depth 935 m). This 936-cm-long core is particularly well suited to monitor the paleoenvironmental history of the Japan Sea because it was collected from a location directly underlying the Tsushima Current (Figure 1), it contains fairly rich microfossil assemblages, as well as several well-known tephra layers (Figure 2), and it records a relatively high sedimentation rate (Figure 3). The core is divided lithologically into two units: a deeper main unit spanning from 936 cm to 75 cm and an upper unit representing the top 75 cm. The main unit consists of alternating intervals of a light olive gray burrowed clay containing few foraminifera (both benthic and planktonic) and a dark olive gray thinly laminated (thickness of 1-2 mm), clay yielding abundant planktonic foraminifera. Authigenic framboidal pyrite, an indicator of anoxic environments, is found sporadically in the main unit of the core (Figure 2). Two lower intervals of the main unit (936-900 cm and 800-770 cm) differ slightly from the major lithology, consisting of massive clays associated with framboidal pyrite but without burrows. Between 210 cm and 140 cm the thickest zone of thinly laminated clay is observed. Although planktonic foraminifera are abundant, benthic foraminifera and calcareous nannoplankton are extremely scarce in this interval. All three of these microfossil groups are almost absent at the transition (from 75 cm to 55 cm) between the main and upper units of the core. The top 75 cm of the core consists of a brownish (indicating oxidized, especially for the top 60 cm) olive gray massive clay with abundant siliceous microfossils and few calcareous microfossils.

The core contains five volcanic ash layers that have been petrographically identified by Arai et al. [1981]. These are the Akahoya (Ah), Ulreung-Oki (Oki), Aira-Tanzawa (AT), Yamato (Ym), and Aso-4 (Aso-4). The radiometric ages of these ash layers have been established by ^{14}C and uranium series dating of land samples (Table 1). For the AT ash an alternative date of 26 ka was measured by ^{14}C dating just below and above the ash in a piston core from the East China Sea [Kato, 1984a]. Because sedimentation is generally more stable in the marine realm than in terrestrial settings, the date of 26 ka is adopted for the AT ash in this report. Regarding the Aso-4 ash, the eruption age (80 ± 2 ka) which was determined by the uranium series dating [Omura et al., 1988] is consistent of the estimated age from the

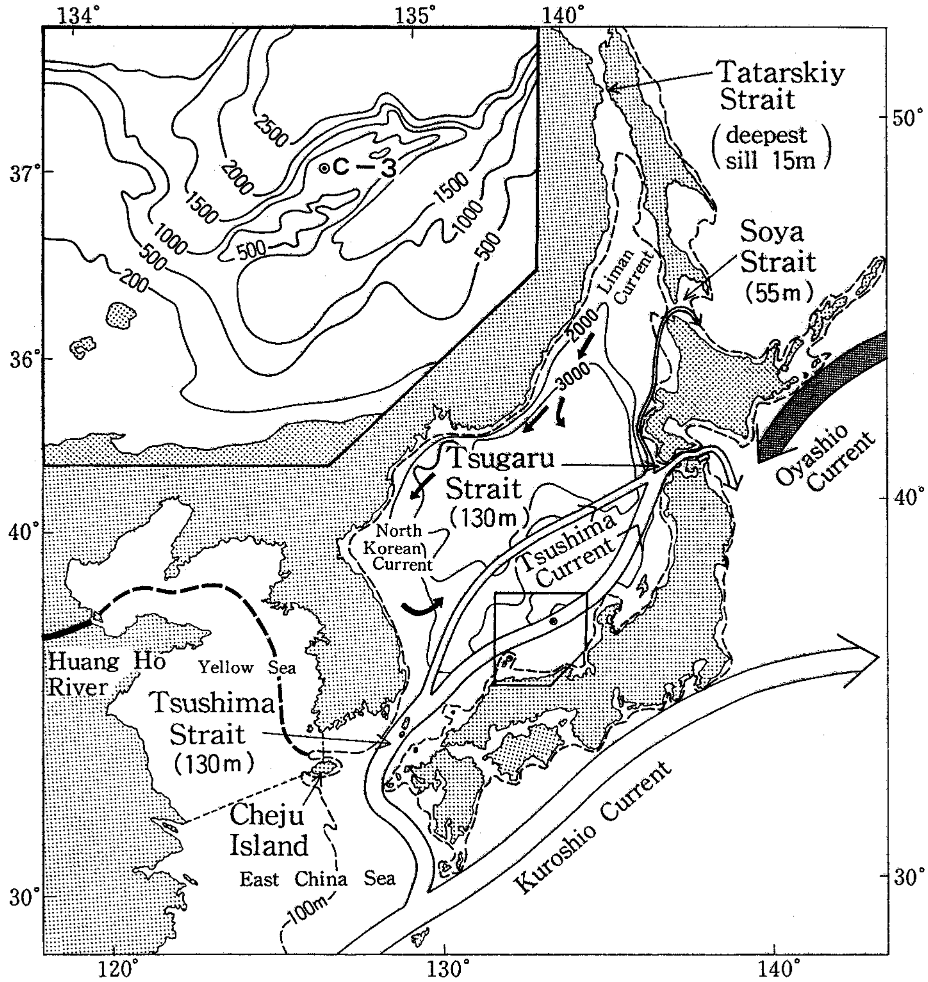

Fig. 1. Location of piston core KH-79-3, C-3 (37°04.3'N, 134°42.2'E, water depth 935 m) and the present current system around the Japanese islands. This figure also shows the present sill depths of four straits, contour lines of the 100-m, 2000-m, and 3000-m isobaths, and the submarine canyon of the paleo-Huang Ho River.

stratigraphic position, between oxygen isotope stage 5_1 and 5_2, in an oxygen isotopic curve of a piston core taken from the Shikoku Basin in the northwestern part of the Pacific Ocean [Oba, 1991]. Additional ^{14}C dates obtained from a piston core (KH-79-3, L-3), recovered as a duplicate of core C-3, also provide time controls for the C-3 core, based on the lithologic correlation between the two cores illustrated in Figure 2. Sedimentation rates for core C-3 were determined by plotting the ages and depths of the eight horizons, and ages of the examined samples were estimated from this plot (Figure 3). The bottom age of core C-3 is extrapolated to be 85 ka, approximately the end of the last interglacial age.

A set of samples was collected by cutting 2-cm-thick slices of core at 10-cm intervals. The sampling intervals span a time period of approximately 500 to 2000 years for the last 85 kyr (Figure 3). Each of the 92 samples, excluding those at the 225-cm and 235-cm levels which directly sampled the AT ash layer, were analyzed for lithology, calcium carbonate content, organic carbon content, oxygen and carbon isotopic compositions of foraminiferal tests, calcareous nannoplankton, diatoms, radiolaria, benthic, and planktonic foraminifera.

The calcium carbonate content was determined by measuring the CO_2 volume evolved from reaction with acid under vacuum. The carbonate-free organic carbon content was measured on the dried residue using a Yanagimoto CHN analyzer. Standard procedures were utilized for the analysis of the four microfossil groups. For example, washed

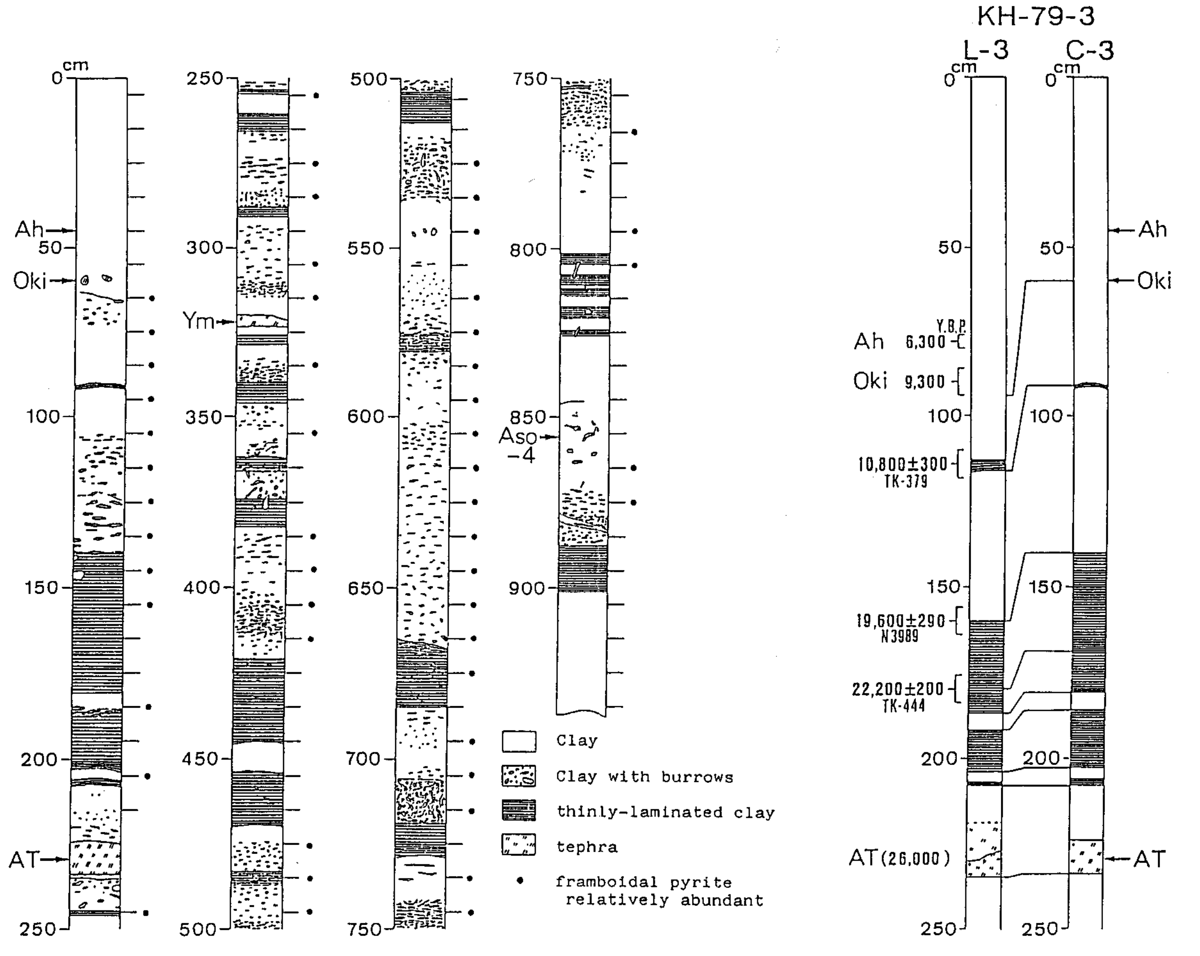

Fig. 2. Lithology of core KH-79-3, C-3 and lithologic correlation between cores C-3 and KH-79-3, L-3.

foraminiferal residues of each sample were split repeatedly with a microsplitter to obtain between 200 and 300 specimens, and all specimens were counted to get the foraminiferal abundance (foraminiferal number is specimens per 1 gram of dry sediment) and then identified. Members of the other three microfossil groups in each sample were also identified, counting at least 200 specimens of calcareous nannoplankton and diatom and 500 specimens of radiolaria. The oxygen and carbon isotope compositions of picked foraminiferal tests were analyzed in Hitachi RMU-6D (oxygen isotope only), Micromass 903, and Finnigan MAT 251 mass spectrometers by combining several or several tens of specimens larger than 177 μm or 250 μm for one analysis. Foraminiferal tests were reacted with 100% H_3PO_4 at 60.0°C without any pre-treatment. Isotope values are expressed in units of parts per thousand relative to the Pee Dee Belemnite (PDB) standard.

RESULTS

Microfossils

The C-3 core contains the four microfossil groups (calcareous nannoplankton, diatoms, radiolaria, and foraminifera) in relatively abundant numbers, except for the Carbonate-Barren-Zone (75-55 cm) and Benthic-Foraminifera-Barren-Zone (225-155 cm), where foraminifera and calcareous nannoplankton are very scarce and benthic foraminifera and calcareous nannoplankton are nearly absent, respectively. Calcareous microfossils are especially abundant in the thinly laminated layers of the main unit, and the intervals with high concentrations of $CaCO_3$ yield high planktonic foraminiferal abundances (Figure 4, columns 2-4). The benthic foraminiferal number is also high in the thinly laminated intervals (Figure 4, columns 2 and 4). In these intervals, three species (*Bolivina pacifica, Fursenskoina* sp., and *Nonionella*

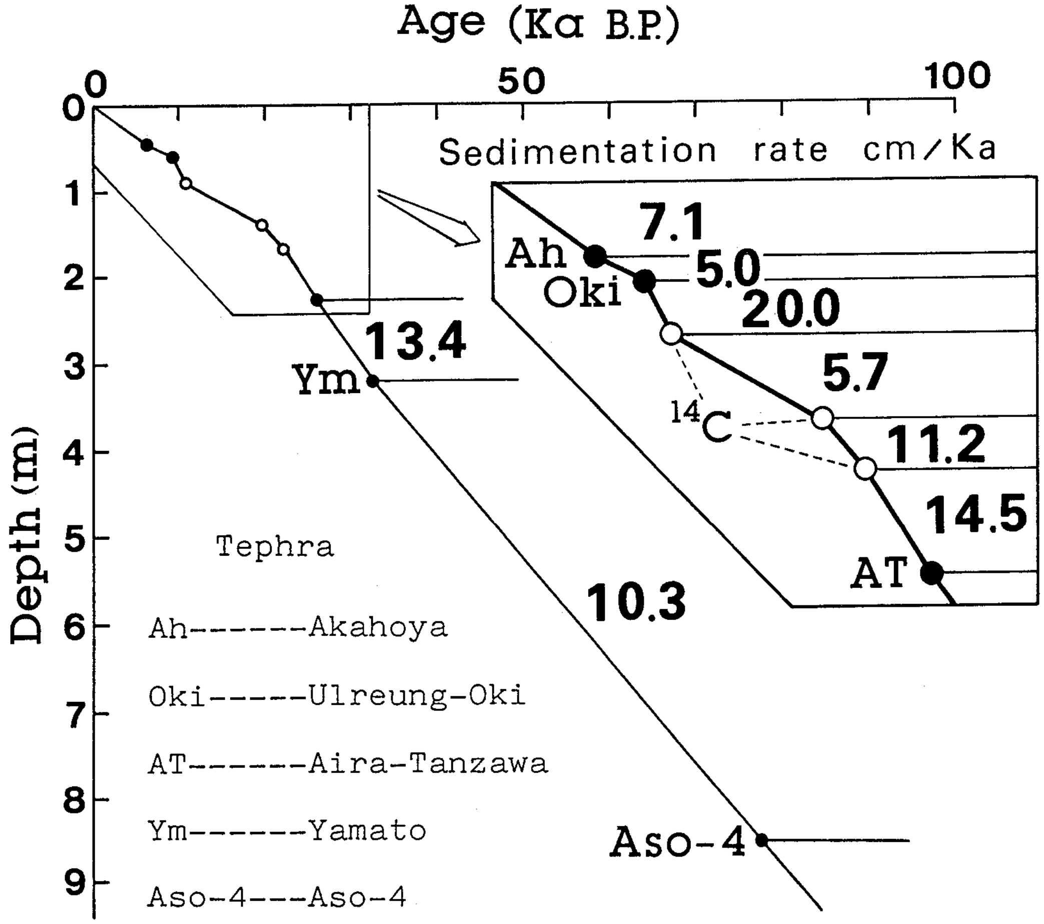

Fig. 3. Sedimentation rates for core KH-79-3, C-3. Ages for eight horizons are assigned on the basis of tephrochronology, ^{14}C, and uranium series radiochronology.

TABLE 1. Age Controls for Core KH-79-3, L-3 and C-3

Volcanic Ash ^{14}C Analysis No.	Depth, cm L-3	Depth, cm C-3	Age, years B.P.
Akahoya (Ah)	76-80	43-45	6,300[3]
Uleng-Oki (Oki)	86-94	52-60	9,300[3]
^{14}C TK-379[1]	110-118	87-93	10,800±300
^{14}C N 3989[2]	156-164	135-145	19,600±290
^{14}C TK-444[1]	176-184	165-173	22,000±200
Aira-Tanzawa (AT)	219-235	224-235	22,000[3]
Yamato (Ym)		321-323.5	circa 33,000[3]
Aso-4 (Aso-4)		855	80,000±2,000[4]

[1]Measured by H. Kobayashi, Faculity of Science, University of Tokyo.

[2]Measured by T. Hamada, The Institute of Physical and Chemical Research, Tokyo. These ^{14}C dates were obtained from core KH-79-3, L-3, and the correlative horizons of core C-3 are presented.

[3]Machida and Arai [1983] estimated these age from stratigraphic positions in land squences dated by ^{14}C method.

[4]Omura et al. [1988] determined the eruption age of Aso-4 ash by the uranium-thorium method.

globosa) dominate the assemblage at those times when the bottom waters presumably had low dissolved oxygen contents. Contrary to the specimen abundances, the number of benthic foraminifer species is smaller (average nine species) in the thinly laminated intervals than is found in the massive and burrowed intervals (average 17 species). This observation of diversity suggests a more aerobic bottom condition for the burrowed intervals than for the laminated intervals. Siliceous microfossils are far more abundant (from a few up to several hundred times) in the upper unit than in the main unit of the core (Figure 4, columns 6 and 7). Ichikura and Ujiie [1976] and Morley et al. [1986] observed similar increases in siliceous microfossil abundance within the Holocene sequences of the Japan Sea. The preservation of calcareous nannoplankton, diatoms, and foraminifers is better in the thinly laminated intervals than in the massive and burrowed intervals. Radiolaria are well preserved even in the massive and burrowed intervals and do not show any obvious signs of dissolution.

Globigerinoides sacculifer, Globigerinoides ruber, Globoquadrina dutertrei, and *Globorotalia menardii* are characteristic warm-water planktonic foraminiferal species [Bé, 1977] and are common inhabitants of today's Kuroshio and Tsushima currents. Occurrence of these species is restricted to the top 75 cm of C-3 core (Figure 4, column 8). Although sinistrally coiled *N. pachyderma* and *Globigerina umbilicata* occupy the greater part of the assemblage below 75 cm in the core, dextrally coiled *N. pachyderma* becomes predominant above 75 cm (Figure 4, column 8). Presently, the dextrally coiled form is abundant in the region of the Tsushima Current, whereas the sinistrally coiled form is common in cold areas of the Japan Sea [Kitazato, 1978].

Pseudoeunotia doliolus, which is a characteristic diatom species in the Kuroshio Current [Jouse et al., 1971], is also limited to the top 75 cm of the core (Figure 4, column 9). Warm-water diatoms and radiolarians, which can live over a much wider temperature range than the typical Kuroshio fauna of planktonic foraminifera or *Pseudoeunotia doliolus,* increase dramatically in the upper part of the core (Figure 4, columns 10 and 11). On the other hand, a cold-water species of calcareous nannoplankton, *Coccolithus pelagicus*, which is abundant in several horizons of the main unit, disappears above the 85-cm level (Figure 4, column 12). There is also a high-percentage occurrence of a cold-water diatom species, *Thalassiosira nordenskioldii*, between the 125-cm and 95-cm levels (Figure 4, column 13). This species is reported from surface sediments in the northernmost part of the present Japan Sea [Tanimura, 1981], and in the Oyashio Current [Kanaya and Koizumi, 1966; Sancetta, 1982]. In the main unit of the core, *Paralia sulcata* (diatom) is generally abundant (Figure 5, column 6), and *B. pacifica* (benthic foraminifer) dominates the fauna, particularly in the thinly laminated layers (Figure 5, column 7).

Oxygen and Carbon Isotopes

Oxygen and carbon isotope analyses were performed using mostly monospecific samples of benthic (*Cassidulina japonica, Casidulina norcrossi,* and *Uvigerina akitaensis*) and planktonic (*Neogloboquadrina pachyderma* and *Globigerina umbilicata*) foraminifera (Table 2). The $\delta^{18}O$ and $\delta^{13}C$ records of core C-3 show significantly different trends than the general pattern of deep-sea cores (Figure 5, columns 1 and 2). The benthic $\delta^{18}O$ values remain relatively constant throughout the core, except for the interval between 145 cm and 85 cm where the values fluctuate over a range of approximately 1.5‰. The planktonic $\delta^{18}O$ values are also uniform from the bottom of the core to just below the AT ash layer and then become successively lighter by about 2.6‰ until reaching a minimum at 165-cm subbottom. This depleted $\delta^{18}O$ excursion is the most pronounced feature of the planktonic isotope curve in core C-3 and is correlative with the horizons of increased relative abundances of the following three microfossils: (1) *Thalassiosira lacustris*, a diatom species which is common in the less saline waters of coastal regions [Sancetta, 1982] (Figure 5, column 3); (2) freshwater diatoms (Figure 5, column 4); and (3) reworked specimens of the Miocene to Oligocene calcareous nannofossil species, *Cyclicargolithus floridanus* (Figure 5, column 5).

The depleted $\delta^{18}O$ values recover abruptly between the 165-cm and 135-cm levels; the magnitude of the positive shift measures 2.2‰. At the base of this interval the benthic $\delta^{18}O$ values show an opposite trend. Above this both planktonic and benthic $\delta^{18}O$ values increase together up to 125 cm for planktonic foraminifera and to 105 cm for benthic foraminifera. At 125-cm subbottom, where the heaviest planktonic $\delta^{18}O$ value was measured, a cold-water diatom species, *T. nordenskioldii* [Kanaya and Koizumi, 1966; Sancetta, 1982], becomes abruptly abundant (Figure 4, column 13 and Figure 5, column 1). The planktonic and benthic $\delta^{18}O$ values become lighter above the 125-cm and 105-cm levels, respectively, and both values reach present $\delta^{18}O$ at the 75-cm level.

The $\delta^{13}C$ values of benthic and planktonic foraminifera fluctuate by approximately 1‰ between the bottom of core and the AT ash layer (Figure 5, column 2). In this interval the most negative values of $\delta^{13}C$ for benthic foraminifera tend to occur in the thinly laminated layers, corresponding to peaks in the relative abundance of *B. pacifica* (Figure 5, columns 2 and 7). The benthic and planktonic $\delta^{13}C$ values converge between the 145-cm and 85-cm levels, and

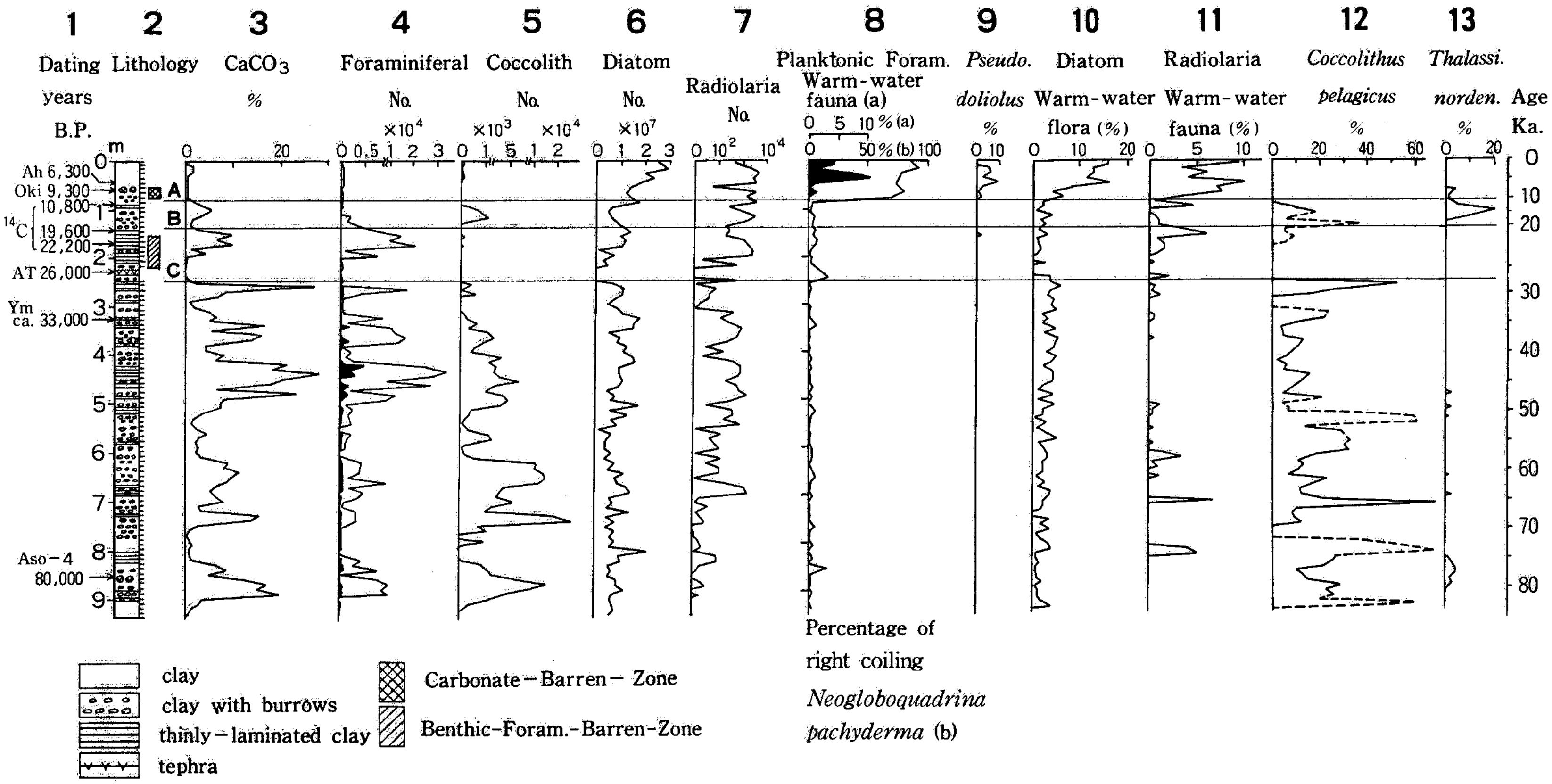

Fig. 4. Lithologic and micropaleontological characteristics of core KH-79-3, C-3. The boundaries of marked paleoenvironmental changes are shown as three lines labeled A, B, and C, which correspond to ages of 10, 20, and 27 ka, respectively. 1, Dating; 2, lithology and horizons of samples; 3, percent abundance of $CaCO_3$; 4, planktonic (open) and benthic (solid) foraminiferal numbers per gram of dry sediment; 5, coccolith number per 5 mg of dry sediment; 6, diatom number per gram of dry sediment; 7, radiolaria number per gram of dry sediment; 8, (a) relative abundance of warm-water planktonic foraminiferal fauna (solid). (b) percent of right-coiling *Neogloboquadrina pachyderma*; 9, relative abundance of *Pseudoeunotia doliolus* (open); 10, relative abundance of warm-water diatom flora; 11, relative abundance of warm-water radiolarian fauna; 12, relative abundance of *Coccolithus pelagicus* (dashed line indicates estimated percentages based on less than 200 specimens); 13, relative abundance of *Thalassiosira nordenskioldii*.

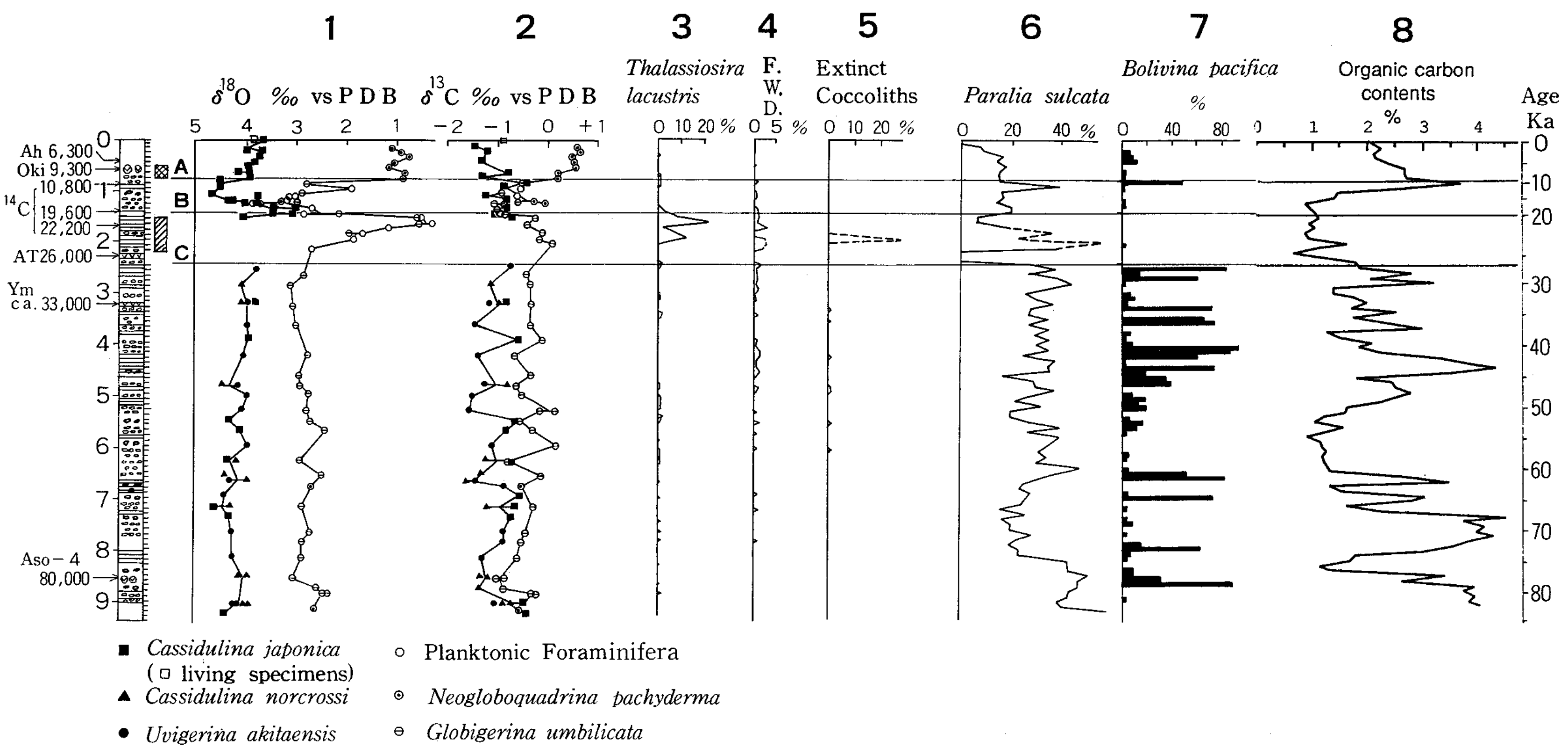

Fig. 5. Stratigraphic changes of oxygen and carbon isotopes, abundances of selected microfossil taxa, and of organic carbon content in core KH-79-3, C-3. Lines A, B, and C indicate the boundaries of marked paleoenvironmental changes (see Figure 4 caption for boundary ages). 1, Oxygen isotopes of both benthic and planktonic foraminifera; 2, carbon isotopes of both benthic and planktonic foraminifera; 3, relative abundance of *Thalassiosira lacustris*; 4, relative abundance of freshwater diatoms; 5, relative abundance of extinct calcareous nannoplankton (dashed line indicate data based on less than 200 specimens); 6, relative abundance of *Paralia sulcata* (dashed line based on less than 200 specimens); 7, relative abundance of *Bolivina pacifica*; 8, organic carbon contents [Oba and Akasaka, 1991]. See Figure 4 caption for explanation of lithology.

TABLE 2. Oxygen and Carbon Isotopic Data in Core C-3

Benthic Foraminifera				Planktonic Foraminifera			
Depth, cm	Species	^{18}O‰	^{13}C‰	Depth, cm	Species	^{18}O‰	^{13}C‰
0	C. jap.	3.87		15	N. pac.	1.11	0.56
2	C. jap.	3.74		25	N. pac.	0.78	0.46
25	C. jap.	3.74		45	N. pac.	1.06	0.48
25	C. jap.	3.71	-1.23	55	N. pac.	1.18	0.52
35	C. jap.	3.79		65	N. pac.	0.85	0.19
45	C. jap.	3.86		75	N. pac.	0.87	0.19
45	C. jap.	3.93	-1.33	85	G. um.	2.81	-0.54
55	C. jap.	3.97		95	um&pac	1.94	-0.56
61	C. jap.	3.95		105	G. um.	2.90	-0.94
65	C. jap.	4.19	-0.83	110	um&pac	3.04	-0.60
70	C. jap.	4.21		113	um&pac.	3.16	
70	C. jap.	4.22		117	um&pac.	3.19	
70	C. jap.	3.93		120	N. pac.	3.33	-0.30
75	C. jap.	3.95		120	G. um.	3.36	-0.61
75	C. jap.	3.98	-1.33	125	G. um.	2.97	-1.08
85	C. jap.	4.53	-0.46	125	G. um.	3.92	-0.87
95	C. jap.	4.53	-0.90	125	N. pac.	3.75	-0.07
105	C. jap.	4.70		135	G. um.	2.71	
110	C. jap.	3.84	-1.23	135	G. um.	2.74	-1.04
117	C. jap.	4.34		147	G. um.	2.16	
120	C. jap.	4.37	-0.85	147	G. um.	2.85	-0.87
125	C. jap.	3.84		153	G. um.	0.63	-0.27
125	C. jap.	4.03	-0.91	155	um&pac	0.51	
135	C. jap.	3.41	-0.82	165	G. um.	0.32	
135	C. jap.	3.05		165	G. um.	0.56	-0.42
147	C. jap.	3.10		175	um&pac	1.16	
147	C. jap.	3.49	-1.07	185	G. um.	1.68	
153	C. jap.	3.83	-0.74	195	G. um.	1.84	
285	C. nor.	4.12	-1.01	195	G. um.	1.97	-0.17
325	U. aki.	4.07	-1.06	195	G. um.	1.98	0.00
325	C. nor.	4.08	-0.81	215	um&pac	2.70	
325	C. jap.	3.85	-0.76	265	G. um.	2.89	-0.29
365	U. aki.	4.04	-1.35	285	G. um.	3.16	-0.19
395	C. jap.	4.03	-0.47	325	G. um.	3.04	-0.18
485	U. aki.	4.20	-1.14	395	G. um		0.03
485	C. nor.	4.50	-0.69	425	G. um.	2.80	-0.55
505	U. aki.	4.02	-1.42	465	G. um.	2.96	-0.51
555	C. jap.	4.15	-0.74	535	G. um.	2.82	0.31
605	aki&nor	4.01	-1.04	555	G. um.	2.75	-0.45
635	C. nor.	4.29	-1.16	575	G. um.	2.46	-0.18
635	C. jap.	4.32	-0.66	605	G. um.		0.34
665	C. nor.	4.46	-1.28	635	G. um.	2.96	-0.68
675	C. nor.	4.27	-1.52	665	G .um.	2.53	-0.39
685	U. aki.		-0.82	725	G. um.	2.89	-0.19
705	C. jap.	4.45	-0.43	775	G. um.	2.73	-0.35
725	nor&aki	4.36	-1.12	795	G. um.	2.93	-0.40
725	C. jap.	4.62	-0.59	825	G. um.	2.90	-0.52
745	jap&nor	4.38	-0.62	865	G. um.	3.05	-0.76
775	U. aki.	4.26	-0.80	865	G. um.	2.84	-0.93
795	U. aki.		-0.79	895	G. um.	2.41	-0.20
865	C. nor.	4.09	-1.09	895	G. um.	2.36	-0.14
865	C. nor.	3.94	-1.25	925	N. pac.	2.66	-0.43
885	nor&aki		-1.29				
915	C. jap.	4.14	-0.37				
915	U. aki.	4.13	-0.95				
915	C. nor.	3.98	-0.68				
915	C. nor.	3.98	-0.82				
935	C. jap.	4.38	-0.37				

Some measurements were made on only oxygen isotopes with a double collector mass spectrometer and during electronic trouble on oxygen isotopes. ^{18}O and ^{13}C are reported relative to the PDB standard. Addreviations are C. jap.(jap): *Cassidulina japanica*, C. nor.(nor): *Cassidulina norcrossi*, U. aki.(aki): *Uvigerina akitaensis*, N. pac. (pac): *Neogloboquadrina pachyderma*, and G. um.(um): *Globigerina umbilicata*.

their $\delta^{18}O$ values overlap within the lower part of this interval. Above the 75-cm level, the planktonic $\delta^{13}C$ values become significantly enriched, while the benthic $\delta^{13}C$ becomes somewhat more depleted.

Organic Carbon Content

Excluding some ash layers, the total organic carbon (TOC) content fluctuates between 0.9% and 4.6% (Figure 5, column 8). The C-3 core can be divided into six intervals based on the TOC content: (1) the deepest interval below 750 cm where TOC is high, except for the Aso-4 ash layer, which is dispersed between 860 cm and 835 cm; (2) a transitional section from high TOC values below 750 cm to low TOC values above 670 cm; (3) the section between 670 and 530 cm where TOC is low; (4) the 530-cm to 240-cm interval in which TOC values fluctuate greatly; (5) the low TOC interval between 240 and 100 cm; and (6) the top 100 cm that have intermediate TOC contents. The low TOC interval between 240 and 100 cm corresponds to the late last glacial (i.e., oxygen isotope stage 2) judging from age dates in this part of the core (Figure 4, column 1).

The TOC content in core C-3 has certain correlations with the lithology and distribution of benthic foraminiferal assemblages. The thinly laminated layers associated with abundant occurrence of *B. pacifica* occur at times of high TOC content (Figure 4, column 1; Figure 5, columns 7 and 8). In contrast, the thinly laminated layers without benthic foraminifera, observed between 210-cm and 140-cm levels, coincide with an interval of low TOC content. The massive layers, typical for the upper unit and for limited intervals within the basal part (936-900 cm and 800-770 cm) of the main unit, contain medium to high TOC contents. Such a drastic change in TOC content is clearly a reflection of paleoenvironmental changes, especially of changes in the oxidation and reduction states of the seafloor in the Japan Sea.

Foraminifera Compensation Level

The time-progressive changes in the depth of the FCL (foraminifer compensation level) in the Japan Sea was determined from the presence or absence of calcareous foraminiferal tests in six piston cores collected from water depths ranging from 935 m to 2455 m around the Oki Ridge. Figure 6 indicates the FCL change during the last 28 kyr. Data from the six cores (see Table 3) indicate that the FCL stood deeper than 2500 m between 28 ka and 18 ka and subsequently shoaled to the depth of 1500 m between 18 ka and 11 ka. A remarkable rise (shallower than 1000 m) in the FCL occurred between 10 ka and 6 ka. After 6 ka the FCL deepened to about 2000 m, which is nearly the same level as in the present Japan Sea.

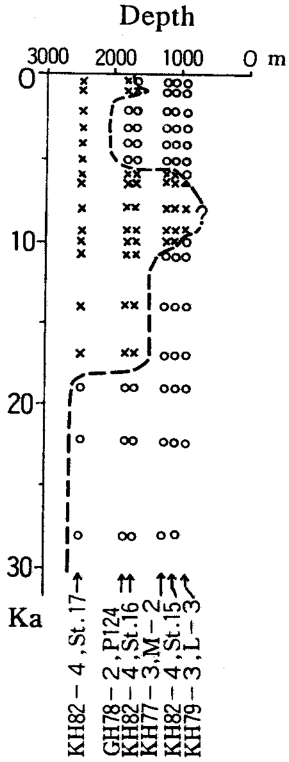

Fig. 6. History of the FCL (foraminifer compensation level) migration based on the preservation state of calcareous foraminifera in six cores (see Table 3) recovered around the Oki Ridge in the Japan Sea (foraminiferal tests are present (open circles) or absent (crosses)).

TABLE 3. Locations and Water Depths of Cores Used for the Investigation of the FCL Change in the Japan Sea

Piston Core	Latitude	Longitude	Depth, m
KH7903,L-3	37°04.0'N	134°42.2'E	935
KH82-4,St.15	36°44.3'N	133°33.6'E	1095
KH77-3,M-2	36°25.6'N	134°10.0'E	1115
KH82-4,St.16	37°47.3'N	133°54.2'E	1740
GH78-2,P124	36°47.3'N	134°57.5'E	1780
KH82-4,St.17	37°15.5'N	134°16.2'E	2455

PALEOENVIRONMENTAL CHANGES IN THE JAPAN SEA

The paleoenvironment of the Japan Sea underwent several marked changes during the last 85 kyr that can be used to divide this period into five stages. Four significant environmental changes are observed at 27 ka, 20 ka, 10 ka, and 8 ka (Figures 4 and 5).

The detailed environmental changes at these times are discussed in this section and are summarized in Figure 7.

85-27 ka

The lithology of this interval, which occurs between the base of the 936-cm-long core and the

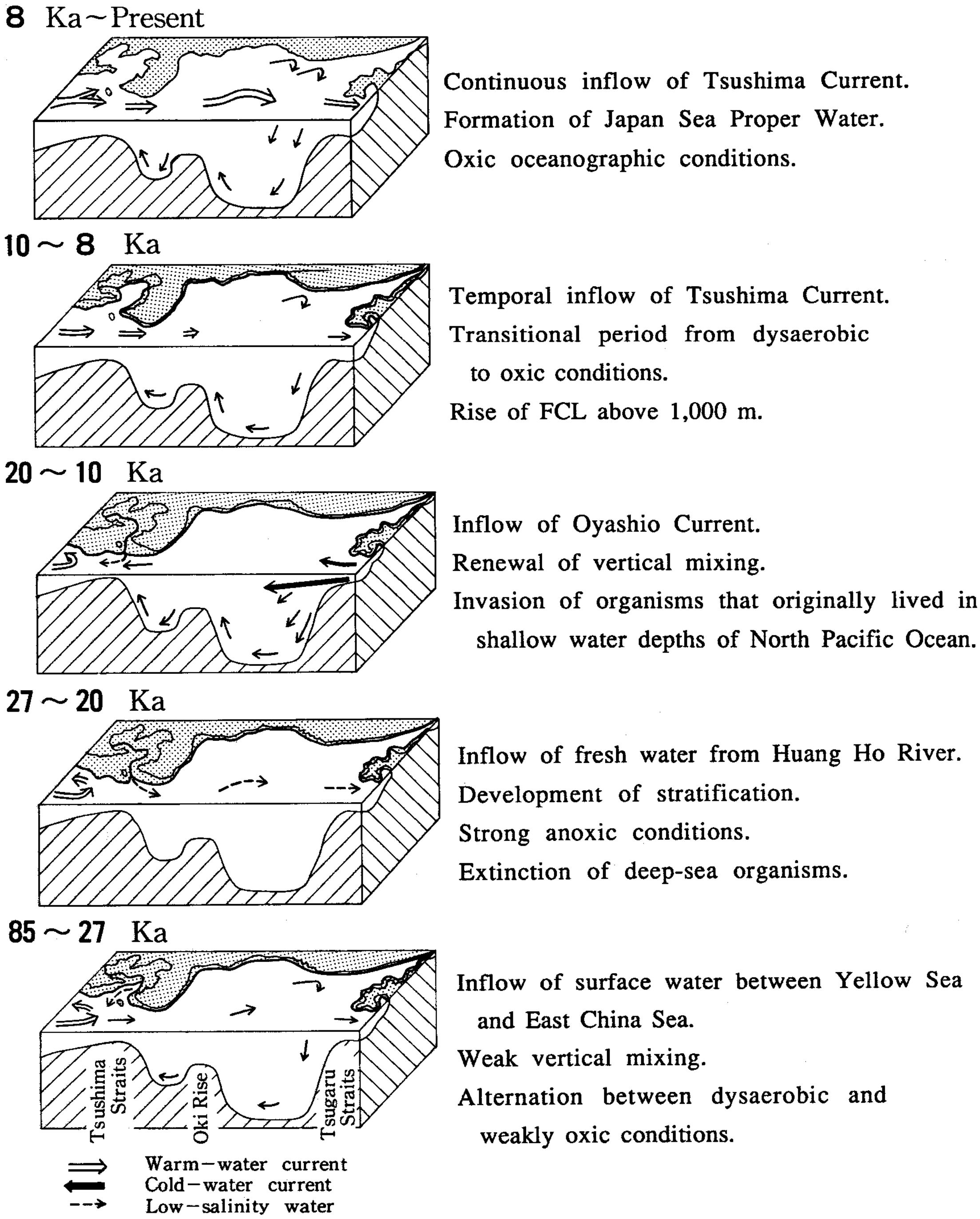

Fig. 7. Paleoenvironmental changes in the Japan Sea during the last 85 kyr and schematic profiles of the Japan Sea in a cross section cut through the Tsushima and Tsugaru straits.

240-cm level (below line C in Figures 4 and 5), is characterized by thinly laminated clays that alternate with burrowed clays. The extraporated age of the bottom of this core, 85 ka, corresponds in time to the late stage of the last interglacial period, namely oxygen isotope substage 5_1 [Martinson et al., 1987]. The bottom part of Core C-3, however, does not yield any warm-water planktonic foraminifera or *Pseudoeunotia doliolus;* this is a clear indication for the absence of the warm Tsushima Current that presently flows into the Japan Sea. Instead of these typical warm-water microfossils, this interval shows the following four characteristics: (1) the abundant occurrence of *P. sulcata,* which is a representative diatom species of the low-salinity water in the Yellow Sea and East China Sea [Asaoka, 1975]; (2) the continuous but low abundance occurrence of warm-water diatoms and sporadic occurrence of warm-water radiolarians; (3) the relatively abundant occurrence of the cold water nannoplankton *C. pelagicus*; and (4) the absence of benthic foraminiferal species living in the northwestern part of the Pacific Ocean. These observations suggest that the mixed surface water of the Yellow Sea and northern part of the East China Sea flowed into the Japan Sea during this period, which corresponds to the oxygen isotope stages 5_1 to 3. Morley et al. [1986] recognized a short warm period from 70 to 65 ka in a piston core taken from near the site of core C-3 based on analysis of radiolarian and pollen assemblages. In core C-3 there are also three horizons with slightly increased percentages of the warm-water radiolarian fauna in the lower part (Figure 4, column 11). This suggests an increased proportion of open ocean water mixing with Yellow and East China Water entering Japan Sea from the Tsushima Strait for very short time periods, although the mixed water had prevented the existence of warm-water planktonic foraminifera and *Pseudoeunotia doliolus*.

Because of the drop of surface water temperature, the $\delta^{18}O$ values of planktonic foraminiferal tests are expected to become heavier during the oxygen isotope stage 4 compared to those of relatively warm stages 5_1 or 3. The $\delta^{18}O$ value of planktonic foraminifera, however, remains constant throughout this period. The lack of significant $\delta^{18}O$ changes throughout these stages can be best explained by relatively large supply of the Yellow Sea water to the area south of the Tsushima Strait, as sea level dropped during the cold stage 4. The Yellow Sea water has a light $\delta^{18}O$ value due to the freshwater discharge of the Huang Ho River in China. For example, if the present surface water (temperature = 16°C, salinity = 34.0‰, $\delta^{18}O$ = 0‰; during winter season) in the area south of the Tsushima Strait is replaced by the cold and low-salinity surface water (T = 12°C, S = 30.5‰, $\delta^{18}O$ = -1.0‰) from the Yellow Sea, the $\delta^{18}O$ value of planktonic foraminifera does not change because of the effects between temperature drop and injection of the light $\delta^{18}O$ water are just offset. Similar offset effects must have occurred in surface water near the Tsushima Strait from stage 51 to stage 3 in connection with the eustatic sea level fluctuations, although cold surface water conditions in the Japan Sea had been maintained as a whole during this period for lack of the present-day warm Tsushima Current. The picture is more complicated for the $\delta^{13}C$ change of planktonic foraminiferal tests because the $\delta^{13}C$ values are affected also by the productivity of the surface water.

During this period the bottom conditions of the Japan Sea alternated frequently between dysaerobic and weakly oxic. The thinly laminated clay layers are deposits of the dysaerobic environment, as indicated by the lack of burrows, the abundant occurrence of *B. pacifica* which is capable of living in oxygen-depleted bottom waters [Phleger and Soutar, 1973], and by the decreased $\delta^{13}C$ values of benthic foraminifera. It is accepted that the $\delta^{13}C$ of benthic foraminiferal tests becomes lighter when organic matter decomposes in stagnant bottom water. On the other hand, weakly oxic conditions were maintained during the deposition of the burrowed clays as evidenced by the occurrence of a more diverse benthic foraminiferal assemblage and by their relatively heavy $\delta^{13}C$ values. The small amount of pyrite found in these layers, however, indicates a restricted oxic condition. Such paleoenvironmental changes in the bottom layer of the Japan Sea probably originated from periodic changes in the surface waters which were influenced by the mixing of water masses from the Yellow Sea and East China Sea as a result of eustatic sea level fluctuations.

Organic carbon content (TOC) during this period can be divided into three stages: the high TOC values in the early stage except for the Aso-4 ash layer which is dispersed between 860 cm and 835 cm, low TOC values with two fluctuated peaks in the middle stage, and the late stage when TOC values significantly fluctuated around an average medium-level. Such a change in the TOC content may be roughly correlated to the general pattern of the oxygen isotopic curve in the open ocean, i.e., high TOC content in the substage 5_1, low in the stage 4, and medium in the stage 3. If such a correlation is correct between the record of the TOC content and the general pattern of oxygen isotopes, the paleoenvironment of the Japan Sea was affected by the eustatic sea level fluctuations. The thinly laminated layers seem to have been deposited at the transitional periods of changes in water circulation in the Japan Sea during the sea level fluctuations in both transgression and regression phases, even in their minor phases. Many thinly laminated layers in the later stages of this period may be due to the minor sea level changes within stage 3. Chappell and

Shackleton [1986], for example, reported that sea level fluctuated at least 3 times during stage 3.

27-20 ka

This period corresponds to the regression phase which occurred between the inferred oxygen isotope stages 3 and 2 (between lines C and B in Figures 4 and 5). As already described in the previous section, the observed characteristics are: (1) the deposition of the thickest layer of thinly laminated clay without burrows; (2) the absence of benthic foraminifera; (3) the limited occurrence of calcareous nannoplankton; (4) an abrupt decrease by 2.6‰ in $\delta^{18}O$ values of planktonic foraminifera; (5) increased abundances of low-salinity and fresh water diatoms; (6) the occurrence of extinct calcareous nannofossils; and (7) low organic carbon content. The abrupt change in planktonic $\delta^{18}O$ was observed not only in core C-3 but also in five other cores recovered from the southern and eastern parts of the Japan Sea (Figure 8). Comparison of these records demonstrated a strikingly good correlation between these six cores. Gorbarenko [1983, 1987] also reported a marked decrease in planktonic $\delta^{18}O$ values at the last glacial age in several cores taken from the central and northwestern parts of the Japan Sea. Three other cores from the Japan Sea show increased occurrences of low-salinity and freshwater diatoms in an interval equivalent to this period (Figure 9). These facts indicate an injection of a significant amount of fresh water into the Japan Sea during this period.

Since the deep water in the present Japan Sea is formed by the surface cooling, the low-salinity surface water during this period stratified the water column and prevented vertical mixing of the deep water. Oxidation of organic matter in the water column and on the seafloor used up all of the dissolved oxygen in the bottom water, and the most anoxic conditions of the last 85 kyr developed. The resulting harsh environment eliminated many deep-sea organisms from the Japan Sea; even *B. pacifica* could not survive during this period. According to Nishimura [1977], marine organisms of the present Japan Sea were originally derived from the shallow water depths of North Pacific Ocean. The time of their invasion into the Japan Sea, probably through the bottom current at the Tsugaru Strait, must have occurred just after this period (19 ka). The measured low organic carbon content in this period is likely to be a result of low productivity in the surface water, because of the stratification which limits eddy diffusion of nutrients from below to the mixed layer. In general, anoxic bottom conditions provide a better situation for the preservation of calcium carbonate on the seafloor. Hence the FCL was deeper than 2500 m water depth during this period as illustrated in Figure 6.

The negative $\delta^{18}O$ excursion of planktonic foraminifera is 2.6‰ lighter than values that characterize the prior and subsequent periods. If the $\delta^{18}O$ values and the salinity of the surface waters were maintained at the same levels as present (0‰ and 34.0‰), and if the $\delta^{18}O$ value of the injected fresh water was -15‰, which is slightly smaller than the present values of meteoric water around the Japanese islands [Matsubaya et al., 1973] and Huang Ho River (-10‰ near Hsi-an city in China; T. Oba, 1988), then the salinity of the surface water in the Japan Sea could have decreased to approximately 28‰ during this period. The scarcity of calcareous nannoplankton within this period is probably due to the decreased salinity of the surface water.

The most probable source of fresh water is the Huang Ho River in China [Oba, 1983]. The mouth of the Huang Ho River advanced with the glacial lowering of sea level and shifted from the west side of the Cheju Island (Figure 1) to the east side of the island at 27 ka when sea level dropped by 100 m from the present sea level [Chang and Cheong, 1987, Figure 31]. During this period the fresh water that had drained to the area south of the Tsushima Strait must have flowed into the Japan Sea. The sudden shift of the river mouth from the west side to the east side of the Cheju Island provides a possible explanation for the abrupt decrease in planktonic $\delta^{18}O$ values at 27 ka in the Japan Sea (Figure 8). The occurrences of warm-water diatoms, warm-water radiolarians, and small amounts of right-coiling *N. pachyderma* in this period indicate the supply of fresh water from south, i.e., through the Tsushima Strait. Furthermore, the concurrent occurrences of extinct calcareous nannofossils and both low-salinity and freshwater diatom species in this interval can also be explained by the erosion of Tertiary sediments from the flat bottom at 100 m to 110 m water depths of the Tsushima Strait [Honza et al., 1979].

20-10 ka

Two characteristic features are noticed during this period: the abrupt increase in planktonic $\delta^{18}O$ values from 20 ka to 16 ka and the reappearance of benthic foraminifera at 19 ka. The benthic foraminiferal fauna includes for the first time in core C-3 *Adercotryma glomeratum, Trochammina* spp., *Reophax* sp., *Buccella* sp., and *Elphidium clavatum*. This fauna is characteristic to the shallow water depths less than 200 m of the northwestern Pacific Ocean [Saidova, 1961]. Appearance of these new taxa suggests the beginning of an Oyashio Current inflow into the Japan Sea at 19 ka through the Tsugaru Strait. Morley et al. [1986] also suggested some degree of exchange between the Japan Sea and the Northwest Pacific during the last glacial maximum period. Because the ice stored in continental glaciers during the glacial age is isotopically light, the Oyashio Current as well as the

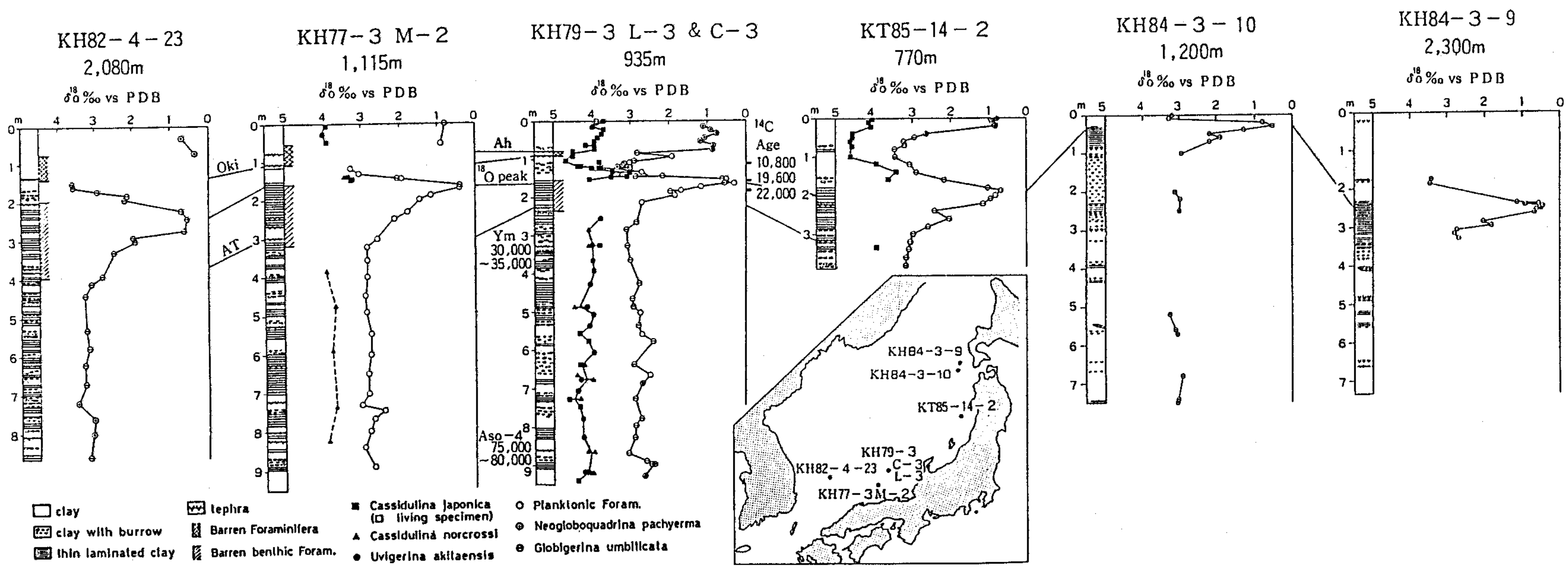

Fig. 8. Oxygen isotopes of planktonic and benthic foraminiferal tests in six piston cores recovered from the Japan Sea [Oba, 1988].

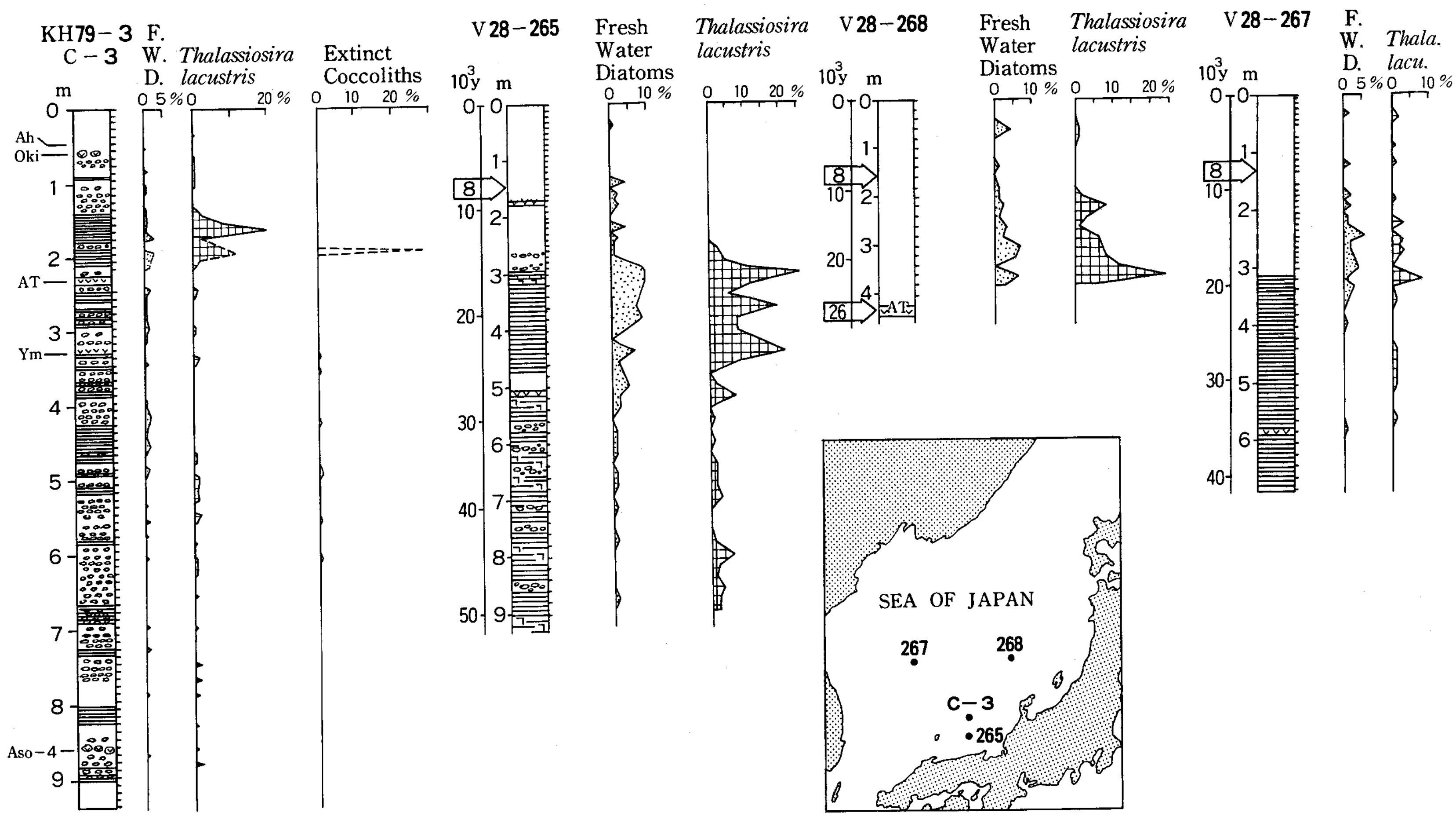

Fig. 9. Stratigraphic changes in the relative abundance of low-salinity diatoms, freshwater diatoms, and extinct coccoliths in four piston cores collected from the Japan Sea [Koizumi, 1985].

whole ocean had a greater salinity and heavier $\delta^{18}O$ values than the present levels, in contrast to the low-salinity and light $\delta^{18}O$ surface water of the Japan Sea and southwestern region of the Tsushima Strait at that time. The more saline Oyashio water inflowed through the Tsugaru Strait, mixed with the surface water of the Japan Sea, and sank to the deeper parts of the basin, thus regenerating vertical circulation as well as aiding the recolonization of benthic organisms. Such an inflow of the Oyashio Current in the Japan Sea is reflected in the benthic $\delta^{18}O$ values which first became lighter and then turned heavier. The close agreement in $\delta^{13}C$ values, as well as a part of the $\delta^{18}O$ values, between benthic and planktonic foraminiferal tests is also concordant with this explanation. Planktonic $\delta^{13}C$ values in the open ocean record the most prominent negative peak at the transition from stage 2 to stage 1 [Williams, 1985]. This may produce the different trends between $\delta^{18}O$ and $\delta^{13}C$ values of both benthic and planktonic foraminiferal tests during the later half of this period. If this interpretation (inflow of the Oyashio Current) is correct and the tectonic movement at the Tsugaru Strait is negligible for the last 20 ka, the eustatic sea level had to be above the sill depth (130 m) of the Tsugaru Strait even at the last glacial maximum period.

Habe and Kosuge [1970] reported the occurrence of fossil molluscs (^{14}C ages of 16-14 ka), which presently live in shallow water off southern Hokkaido, from a water depth of 140 m at the Tsushima Strait. During this period the surface waters of the Japan Sea were kept cold and probably were the coldest at about 15 ka as indicated by the abundant occurrence of the cold-water diatom, *T. nordenskioldii*. The seafloor conditions were dysaerobic similar to the early part of the last glacial age, i.e., oxygen isotope stage 4.

As the global climate changed at the terminal stage of the last glacial age, the $\delta^{18}O$ value of the open oceans became lighter due to the melting of continental glaciers. In the Japan Sea, warming of the surface water started at 15 ka as suggested by the decrease in abundance of cold-water species *C. pelagicus* and *T. nordenskildii* and by the decrease of planktonic $\delta^{18}O$ value. Subsequently, the benthic $\delta^{18}O$ values also became lighter by the continuous inflow of the Oyashio Current whose $\delta^{18}O$ value was lighter than during the glacial period. During the deglacial warming period the current system in the northwestern Pacific Ocean was changed by the northward advancement of the Kuroshio Current [Chinzei et al., 1987]. Such a strengthening of the Kuroshio Current could have affected the Oyashio Current, shifting the polar front northward, and perhaps causing the change of current system in the Japan Sea. Water circulation in the Japan Sea became stagnant for a short period at the transitional phase between the cessation of inflow of the Oyashio Current and the beginning of the inflow of the Tsushima Current. This stagnation, dated at 10,800 years B.P. by ^{14}C dating, caused the last episode of deposition of thinly laminated layers and the significantly high abundances of *B. pacifica*, as well as enhanced TOC percentages (Figure 5).

10-8 ka

This period corresponds to the Carbonate-Barren-Zone at the transition between the main and upper units (Figure 4). At 10 ka, *P. doliolus* appeared in the core, the coiling direction of *N. pachyderma* changed from sinistral to dextral, and warm-water species of diatom and radiolaria became more prevalent. These facts record the initiation of an open ocean current flowing into the Japan Sea through the Tsushima Strait with physical properties identical to that of today's Tsushima Current. The absence of pyrite above the 8-ka core level suggests that the present oxidized bottom conditions of the Japan Sea began at 8 ka. This interval between 10 and 8 ka therefore records a transitional phase from dysaerobic to the completely oxic modern conditions of the Japan Sea. The almost complete absence of calcareous nannoplankton and calcareous foraminifera indicates a rise of the FCL during this period. The newly developed oxic conditions decomposed organic matter that had accumulated on the seafloor during the previous dysaerobic conditions. As a result, the partial pressure of carbon dioxide in the bottom water increased, and consequently the FCL moved upwards to depths shallower than 1000 m during this period (Figure 6).

8 ka-Present

Since 8 ka the planktonic foraminiferal fauna have been similar to that found in the present Tsushima Current. The microfossil assemblages of the other three taxonomic groups, including benthic foraminifera, are also similar to those of present surface sediments of the Japan Sea. Both $\delta^{18}O$ and $\delta^{13}C$ values of planktonic and benthic foraminifera achieved their present levels at 8 ka, or at the latest by 6.5 ka. These observations indicate that modern oceanographic conditions have been established in the Japan Sea since 8 ka. The abundance of diatoms and radiolaria, as well as their numbers of species, increase markedly after 8 ka. This change records the beginning of high surface productivity at 8 ka that is caused by the strong vertical circulation which occurs presently in the Japan Sea. Changes in the $\delta^{13}C$ values of both planktonic and benthic foraminifera are consistent with the productivity increase. As organic matter generated by plankton removes ^{12}C selectively from the surface water, the $\delta^{13}C$ of planktonic foraminiferal tests becomes heavier (Figure 5, column 2). At the same time, the $\delta^{13}C$ value of benthic foraminifera becomes lighter because of the recycling of isotopically light organic matter on the seafloor. Despite the increased productivity in the surface water, the organic carbon content in the sediment remains at an intermediate level (2-3%) because of the increased oxidation of organic matter that is still continuing in the present Japan Sea.

CONCLUSIONS

A comprehensive study was performed on a 936 cm piston core from the southern part of the Japan Sea to detail the paleoenvironmental history. The results reveal that the Japan Sea has experienced five periods of significantly different paleoenvironmental conditions during the last 85 kyr.

1. Between 85 and 27 ka the lithology consisted of alternating dark olive gray thinly laminated clays and light olive gray burrowed clays. The laminated clays yield a high concentration of $CaCO_3$ as well as high abundances of planktonic foraminifera, benthic foraminifera, and calcareous nannoplankton. The relative abundances of *Bolivina pacifica* and organic carbon content are also high, whereas the $\delta^{13}C$ value of the benthic foraminifera is depleted. The dark thinly laminated layers were deposited under dysaerobic to anoxic bottom water conditions. On the other hand, the burrowed clays are characterized by a more diverse benthic foraminifera assemblage associated with heavy $\delta^{13}C$ values and low organic carbon content and by the sporadic occurrences of pyrite. These lighter colored, burrowed clays were deposited under weakly oxic to oxic conditions. The absence of warm-water species of planktonic foraminifera and *Pseudoeunotia doliolus* indicates that the present-day Tsushima Current did not flow into the Japan Sea between 85 and 11 ka. Instead of the Tsushima Current, cold and low-salinity surface water mixed with the Yellow Sea and East China Sea was supplied to the Japan Sea from 85 to 27 ka.

2. Between 27 and 20 ka the thickest layer of dark olive gray, thinly laminated clay was deposited. This bed is characterized by the absence of burrowed structures and benthic foraminifera, the scarcity of nannoplankton, very light $\delta^{18}O$ values of planktonic foraminifera, the increased presence of low-salinity and freshwater diatom species, the occurrence of extinct calcareous nannofossil species, and low organic carbon content. During this period a significant amount of fresh water was injected into the Japan Sea, probably from the Huang Ho River in China. Strongly anoxic conditions had developed in the bottom water during this period due to a well-stratified surface layer, and many benthic and deep-sea organisms were eliminated from the Japan Sea.

3. Between 20 and 10 ka, a benthic foraminiferal fauna that presently exists in the northwestern Pacific Ocean appeared for the first time in the Japan Sea, and the planktonic $\delta^{18}O$ values became heavier. The $\delta^{13}C$ values of benthic and planktonic foraminifera became similar to each other, and a cold-water diatom species (*T. nordenskioldii*) increased its abundance. All these phenomena suggest that the cold-water Oyashio Current flowed into the Japan Sea and that the coldest surface water paleoconditions prevailed during this period.

4. The absence of calcareous microfossils between 10 and 8 ka indicates a shoaling of the FCL during this transitional period in which the bottom conditions changed from dysaerobic to oxic.

5. For the last 8 ka, a brownish massive clay layer has been deposited. It contains abundant diatoms and radiolaria, typical warm-water species of planktonic foraminifera and a diatom species, and dextrally coiled *N. pachyderma*. The disappearance of cold-water calcareous nannoplankton and diatoms that were dominant elements of the flora during the preceding intervals is also a significant new characteristic of this interval. These faunal-floral characters coupled with the consistent levels of both $\delta^{18}O$ and $\delta^{13}C$ in benthic and planktonic foraminifera throughout this period indicate that the Japan Sea has maintained the same conditions as the present over the last 8 kyr.

6. The pattern of time-progressive change in organic carbon content observed in core C-3 is similar to the general trend of the oxygen isotope observed in the open ocean, except for the Holocene when very oxic bottom conditions have prevailed. This suggests that the paleoenvironmental changes in the Japan Sea have been affected by eustatic sea level fluctuations.

7. The inflow of the Oyashio Current into the Japan Sea during the last glacial maximum suggests that the drop of sea level was less than 130 m, assuming that the tectonic movement at the Tsugaru Strait is negligible for the last 20 kyr.

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