Abrupt ventilation changes in the Japan Sea over the last 30 ky: evidence from deep-dwelling radiolarians

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Abstract

The Japan Sea has its own deep-circulation system, with its deeper parts occupied by cold and highly oxygenated water formed by winter convection in its northwestern reaches. We elucidate the modern depth distribution of radiolarian species and their relation to water masses, from the study of plankton tows and surface sediments. *Cycladophora davisiana* occurs in a depth interval between 1000 m and 2000 m (deep layer of JSPW = Japan Sea Proper Water), and *Actinomma boreale/leptoderma* Group in depths below 2000 m (bottom layer of JSPW). The study of seven sediment cores located in water depths ranging from 807 to 3613 m show that the radiolarian assemblages have varied since 30 cal ka BP, indicating changes in water-ventilation strength in this marginal sea. During the interval from 30 to 17 cal ka BP, ventilation was restricted to an intermediate layer beneath the low-salinity surface water, while the deeper zone was filled with static, anoxic water. Deep ventilation began abruptly at 14 cal ka BP. Cold and oxygen-rich water began to sink into the bottom layer, as a result of cold oceanic inflow from the northwestern Pacific through the Tsugaru Strait in the north. Deep convection activity increased from 13 to 12 cal ka BP, which coincides with the Younger Dryas-like cooling event, and then stopped at 12–11.5 cal ka BP. Bottom-water ventilation during the Holocene has been dependent on high-salinity inflow through the Tsushima Strait in the south and winter cooling in the northwestern part of the Japan Sea. Deep water was being actively formed in the early Holocene, in contrast to the static bottom water. This bottom-water formation has resulted in relatively constant water composition since 9 cal ka BP, with the overall increase in high-salinity oceanic-water inflow, although the latter decreased transiently from 7 to 5 cal ka BP in concert with climatic warming.
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1. Introduction

The Japan Sea is a semi-enclosed marginal sea in the northwestern Pacific that has its own deep circulation system (like a thermohaline "conveyor belt"). A cold and highly oxygenated water mass occupies depths below 400 m and is supplemented by deep winter convection in the northern or northwestern parts of the Japan Sea (Gamo et al., 1986). The dissolved oxygen in Japan Sea bottom water, however, has decreased along with the stop in ventilation due to a global warming trend that began in the 20th century (Gamo, 1999). Anoxic bottom water in the Japan Sea

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developed significantly during the last glacial maximum (LGM), which coincided with the lowest stand in eustatic sea level (Oba et al., 1991, 1995). This was associated with a strong density stratification of the water column, along with the development of low-salinity surface water. Furthermore, during the last glacial period, sea-bottom conditions in the Japan Sea frequently became anoxic or suboxic as a result of Eastern China Sea Coastal Water input associated with the millennial-scale Dansgaad–Oescheger cycle (Tada et al., 1999). Such changes in the bottom-water oxygen level mean that the deep ventilation system of the Japan Sea is variable, compared to the global ocean.

Late Quaternary changes in the water circulation in the Japan Sea have been inferred mainly from reconstructions of sea-surface and sea-bottom conditions (Oba et al., 1991; Tada et al., 1999; Gorbarenko and Southon, 2000). Sea-surface conditions have been reconstructed using planktic microfossils, stable isotopes of planktic foraminifers (Oba et al., 1991) and organic geochemical analysis (Ishiwatari et al., 1999; 2001). In contrast, sea-bottom conditions (oxygen levels) have been inferred from the lithology of cores, benthic foraminifera (Ujiié et al., 1983; Oba et al., 1991) and geochemical analysis (Masuzawa and Kitano, 1984; Crusius et al., 1999; Tada et al., 1999). On the basis of these studies, the sea-surface and sea-bottom conditions are thought to be well understood. However, the vertical structure of the water column between the surface and bottom has remained poorly known.

Radiolaria are planktonic Protozoans widely distributed in the world ocean, and their skeletons composed of opal are preserved in marine sediments. Many radiolarian species are restricted to discrete depth intervals (e.g. Kling and Boltovskoy, 1995; Abelmann and Gowing, 1997) and the depths at which they dwell are closely related to the vertical water structure. As a result, radiolarians prove to be useful indicators not only in the reconstruction of the surface water conditions, but also for the conditions of the water masses at intermediate depths.

Recently, modern radiolarian depth distributions in the Japan Sea have been determined from both plankton tows and surface sediment samples, and were compared with the vertical distribution of water masses (Itaki, 2003). In the present study, we have established radiolarian-based proxies for paleoceano-graphic interpretation from the modern examination. In addition, deep circulation changes in the Japan Sea since 30 cal ka BP have been inferred from the past depth distribution of a particular radiolarian fauna, observed in seven sediment cores from a wide range of water depths.

2. Oceanographic setting

The Japan Sea connects with other marginal seas and the Pacific Ocean through four shallow straits (< 130 m in maximum sill depth; Fig. 1). The only oceanic water entering the Japan Sea is the Tsushima Warm Current (TWC), a branch of the Kuroshio Current, which enters through the Tsushima Strait (130 m in depth) in the south.

The Japan Sea Proper Water (JSPW) is relatively homogeneous deep water that occupies depths below 400 m and is characterized by low temperatures (0–0.6 °C) and high dissolved-oxygen content (220–280 µmol/kg) as well as a high salinity (34.05–34.08 psu). The JSPW is ventilated from surface waters in the northern and northwestern parts in the Japan Sea, and attains a density high enough to induce deep convection by salt advection from the TWC and by cooling during winter (Gamo et al., 1986; Martine et al., 1992). The JSPW is divided into three layers, an upper layer at 400–1000 m depth (UJSPW; upper portion of JSPW), a deep layer at 1000–2000 m depth (Deep Water) and a bottom layer at >2000 m depth (Bottom Water), owing to vertical gradient changes of oceanographic parameters such as temperature and oxygen content (Gamo and Horibe, 1983; Gamo et al., 1986; Senjyu and Sudo, 1994). Temperature ranges in the UJSPW, Deep Water and Bottom Water are 0.1–0.6, 0.04–0.1 and 0.04 °C, respectively. Oxygen minimum (220 µmol/kg) is observed between 900 and 1400 m (Gamo et al., 1986).

The Japan/East Sea Intermediate Water (JESIW) and the High Salinity Intermediate Water (HSIW) lie between the surface water and the JSPW, roughly corresponding to 200–400 m, at the northwestern and eastern parts of the Sea, respectively (Kim and Kim, 1999; Yoon and Kawamura, 2002). The JESIW is characterized by relatively low salinity (< 34.06 psu) and high oxygen (>250 µmol/kg) originated with fresh water from the Amur River. On the other hand,
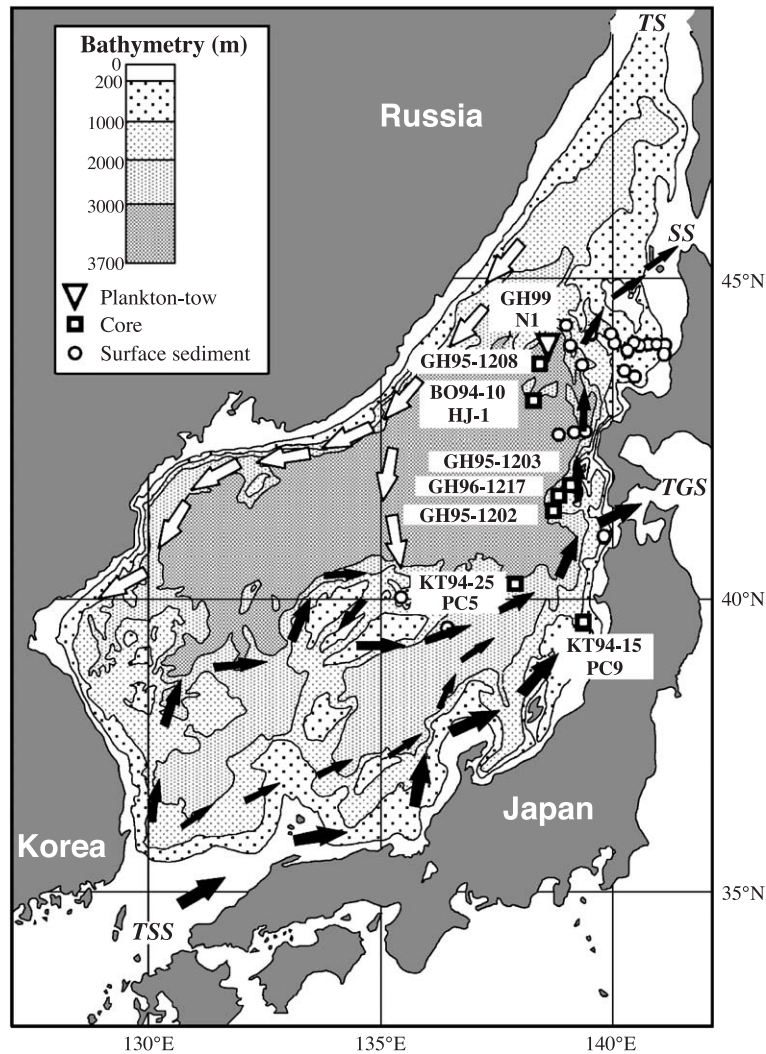
Fig. 1. Map of the Japan Sea showing location of plankton tows, surface-sediment samples and sediment cores. The black and white arrows indicate the Tsushima Warm and Liman Cold Currents, respectively. Four major straits are indicated as *TS* (Tatarskiy Strait, 12 m), *SS* (Soya Strait, 55 m), *TGS* (Tsugaru Strait, 130 m) and *TSS* (Tsushima Strait, 130 m).

the HSIW is characterized by high salinity (>34.07 psu) and high oxygen (>250 μmol/kg) from the TWC.

3. Sample sources and methods

3.1. Plankton samples

A closing plankton net with 63-μm mesh (frame diameter: 1 m) was towed vertically at Station GH99-N1 (Fig. 1; 42°52′N, 145°55′E) in July 1999, during

cruise GH99 of R/V Hakurei-maru of the Geological Survey of Japan (GSJ). Plankton samples from nine depth intervals, 0–40, 40–80, 80–120, 120–160, 160–200, 200–300, 300–500, 500–1000 and 1000–2000 m, were preserved in a solution of 4% formalin in seawater, and stained with Rose Bengal to distinguish living specimens from dead ones. Complete and lots of protoplasm in a radiolarian skeleton is well stained red, indicating a ''living specimen'', while a skeleton without protoplasm is not stained and indicates a ''dead specimen''. In case of incomplete or

Table 1
Locations of surface sediments, water depths and used sediment samplers

Cruise	Station	Latitude	Longitude	Water depth (m)	Sampler
GH92	703	39°30′N	136°30′E	2638	Gravity corer
GH96	1183	43°48′N	141°20′E	60	Grab sampler
	1189	43°56′N	141°20′E	93	Grab sampler
	336	43°60′N	141°15′E	165	Grab sampler
	1188	43°56′N	141°10′E	260	Grab sampler
	335	43°56′N	141°05′E	337	Grab sampler
	1162	43°28′N	140°45′E	509	Grab sampler
	334	43°60′N	140°55′E	460	Grab sampler
	327	43°52′N	140°40′E	672	Grab sampler
	260	43°44′N	140°30′E	802	Grab sampler
	279	43°56′N	140°15′E	683	Grab sampler
	286	44°00′N	140°10′E	781	Grab sampler
	270	43°52′N	139°51′E	1091	Grab sampler
	276	43°56′N	139°45′E	1264	Grab sampler
	261	43°48′N	139°35′E	1760	Grab sampler
	255	43°44′N	139°40′E	2282	Grab sampler
	145	42°36′N	139°15′E	2625	Grab sampler
	153	42°40′N	139°30′E	2994	Grab sampler
	143	42°36′N	138°55′E	3653	Grab sampler
KT94-15	PC3	40°00′N	135°36′E	983	Piston corer
	MC8	39°51′N	139°11′E	1473	Multiple corer
KT95-14	JSP1	41°04′N	139°58′E	502	Piston corer

little protoplasm on the outside or within a skeleton, it is classified as "dead specimen", because such small stained material might be bacterial organisms or only remnants dating from a long time after death.

Observation slides were prepared by the following method. (1) Larger zooplanktons were excluded from the original samples using a mesh with 1-mm openings. (2) Material smaller than 1 mm was split into aliquots ranging from 1/10 to 1/40 of the original quantity. (3) These were wet-sieved through two screens with 63- and 600-μm openings. (4) The residue on the 63-μm-mesh screen was filtered on membrane filters with 0.45-μm openings. (5) After drying, the filter was divided in half with a knife, cleared with xylene, and mounted on a slide with Canada Balsam. Material larger than 600 μm could not be observed for radiolarian counts due to large amount of other zooplanktons.

3.2. Surface sediments

Twenty-two samples of surface sediment (<2.5 cm below sea-floor) were collected from the Japan Sea during cruises GH92 and GH96 of R/V Hakurei-maru

by the GSJ and cruises KT94-15 and KT95-14 of R/V Tansei-maru by the University of Tokyo (Fig. 1; Table 1). Surface sediments were taken by using a grab sampler in depths of 60–3653 m. Six core-top samples of multiple, gravity or piston cores from the eastern and central parts of the Japan Sea were also used as surface sediments. Four samples from depths shallower than 260 m are composed of sandy silt, while the others are clay or silt. Wet sediment samples were sieved through 63-μm-mesh screens, and the residue in the sieves was mounted on a microscope slide with Entellan-new.

3.3. Sediment cores

Seven sediment cores were recovered from the northeastern and eastern parts of the Japan Sea at depths from 807 to 3613 m using gravity or piston corers, during cruises GH95 and GH96 of R/V Hakurei-maru of the GSJ, cruise KT94-15 of R/V Tansei-maru of the University of Tokyo, and cruise BO94-10 of research and training vessel Bosei-maru of Tokai University (Fig. 1; Table 2).

Only wet or freeze-dried samples were prepared for radiolarian analyses from these sediment cores, because a reduction in the radiolarian test count in sediment samples have been demonstrated by oven- and air-drying processes (Itaki and Hasegawa, 2000). The non-drying technique of Itaki and Hasegawa (2000) was used for cores GH95-1202, GH95-1203, GH95-1208, KT94-15-PC5 and KT94-15-PC9, while samples of cores BO94-10-HJ1 and GH96-1217 were freeze-dried. Weighted wet or freeze-dried samples were sieved through a mesh with 63-μm openings. For carbonate-rich samples, which were recognized in the washed residue, carbonate was removed with a HCl

Table 2
Locations of sediment cores, water depths and used samplers

Cruise	Station	Latitude	Longitude	Depth (m)	Sampler
BO94-10	HJ-1	43°02′N	138°28′E	3613	Piston corer
KT94-15	PC-5	40°01′N	138°12′E	2885	Piston corer
	PC-9	39°34′N	139°24′E	807	Piston corer
GH95	1202	41°22′N	138°55′E	1384	Gravity corer
	1203	41°50′N	139°10′E	2250	Gravity corer
	1208	43°46′N	138°50′E	3435	Gravity corer
GH96	1217	41°42′N	139°05′E	1785	Gravity corer

solution. The remaining coarse fraction was mounted on a microscope slide with Entellan-new.

Radiolarians on each slide were counted until more than 300 individuals had been identified to show the faunal composition. When the radiolarian count was very low, all specimens on the slide were observed to count as much as possible. Absolute abundance of radiolarians (#/dry g) were calculated by following equations: (1) for freeze-dried samples, [total number of individuals on slide]/[dry sample weight (g)]; (2) for non-dried samples (Itaki and Hasegawa, 2000), [total number of individuals on slide]/[1 − water content of sediment (%)/100] × wet sample weight (g)].

4. Depth distribution of radiolarians based on plankton and surface sediment samples

Depth distributions of modern radiolarians in the Japan Sea have been documented from the plankton and surface-sediment samples (Itaki, 2003). Three major species, *Larcopyle buetschlii* Dreyer (Plate I, Figs. 1–5), *Cycladophora davisiana* Ehrenberg (Plate I, Figs. 18–20) and *Actinomma boreale* Cleve/*leptoderma* Jørgensen Group (Plate I, Figs. 6–15), account for 30–95% of the total assemblages from both the plankton and surface-sediment samples (Fig. 2). In particular, *L. buetschlii* was the most dominant species in the surface-sediment samples at all water depths. *C. davisiana* and *A. boreale*/*leptoderma* Group tend to increase with increasing water depth below 1000 m. These data strongly imply depth stratification for the radiolarians.

Radiolarian assemblages in the water column vary seasonally and interannually, while those in the surface sediment are mixed during the past tens or hundreds years according to Holocene sedimentation rate of the Japan Sea (>5 cm/ky; see Section 5.1) and often affected by opal dissolution effect. Nevertheless, the depth-distribution patterns of radiolarians from the plankton tows collected on July 1999 is similar to those from the surface sediments. This suggests that the depth-distribution patterns do not change seasonally and interannually. We can conclude that the living depths of radiolarians are also reflected in the surface-sediment assemblages.

The high relative abundance of *L. buetschlii* as much as in the Japan Sea has not been reported elsewhere (Lombari and Boden, 1985). Two different morphologies are recognized for this species, adults with a robust skeleton (Plate I, Figs. 3 and 5) and juveniles with an immature skeleton (Plate I, Figs. 1, 2 and 4). The adult form is dominant between 300 and 1000 m depth in the plankton samples, while the juvenile form has its main distribution in the shallower depths above 300 m. This result suggests that *L. buetschlii* lives mainly in shallower depths (warmer and less silicate) during its juvenile stage and in deeper depths (colder and higher silicate) during its adult stage.

The principal living depth of *Ceratospyris borealis* Bailey (Plate I, Figs. 21–23) in the Japan Sea is between 160 and 300 m (Itaki, 2003), which corresponds to the JEIW. *Ceratospyris borealis* has also been reported to live in intermediate depths of 200–500 m in the Okhotsk Sea (Nimmergut and Abelmann, 2002), similar to that in the Japan Sea. This is a minor species in the modern Japan Sea, but is a typical species in the subarctic Pacific, Bering Sea and Okhotsk Sea (Nigrini, 1970; Ling et al., 1971; Ling, 1974; Kruglikova, 1977; 1999 = *Tholospyris borealis* (Bailey)). Therefore, *C. borealis* might be indicative of the cold intermediate water.

Cycladophora davisiana occurs abundantly at depths below 1000 m in the zone corresponding to the deep layer of the JSPW. *Cycladophora davisiana* is known as a deep-dwelling species in the world's oceans, although its reported depth habitats (100–200 m in the NE Pacific, Kling and Boltovskoy, 1995; 300–1000 m in the Southern Ocean, Abelmann and Gowing, 1997; 200–1000 m in the Okhotsk Sea, Nimmergut and Abelmann, 2002) are distinctly shallower than in the Japan Sea.

Low relative abundances of *A. boreale*/*leptoderma* Group were found in both plankton and surface-sediment samples collected between 1000 and 2000 m. However, this species group becomes dominant in surface-sediment samples deeper than 2000 m, and its relative abundance increases with water depth. This suggests that *A. boreale*/*leptoderma* Group lives mainly in the bottom layer of the JSPW deeper than 2000 m. This species has been reported from shallower plankton tows (< 400 m) in the Greenland Sea (Swanberg and Eide, 1992), and
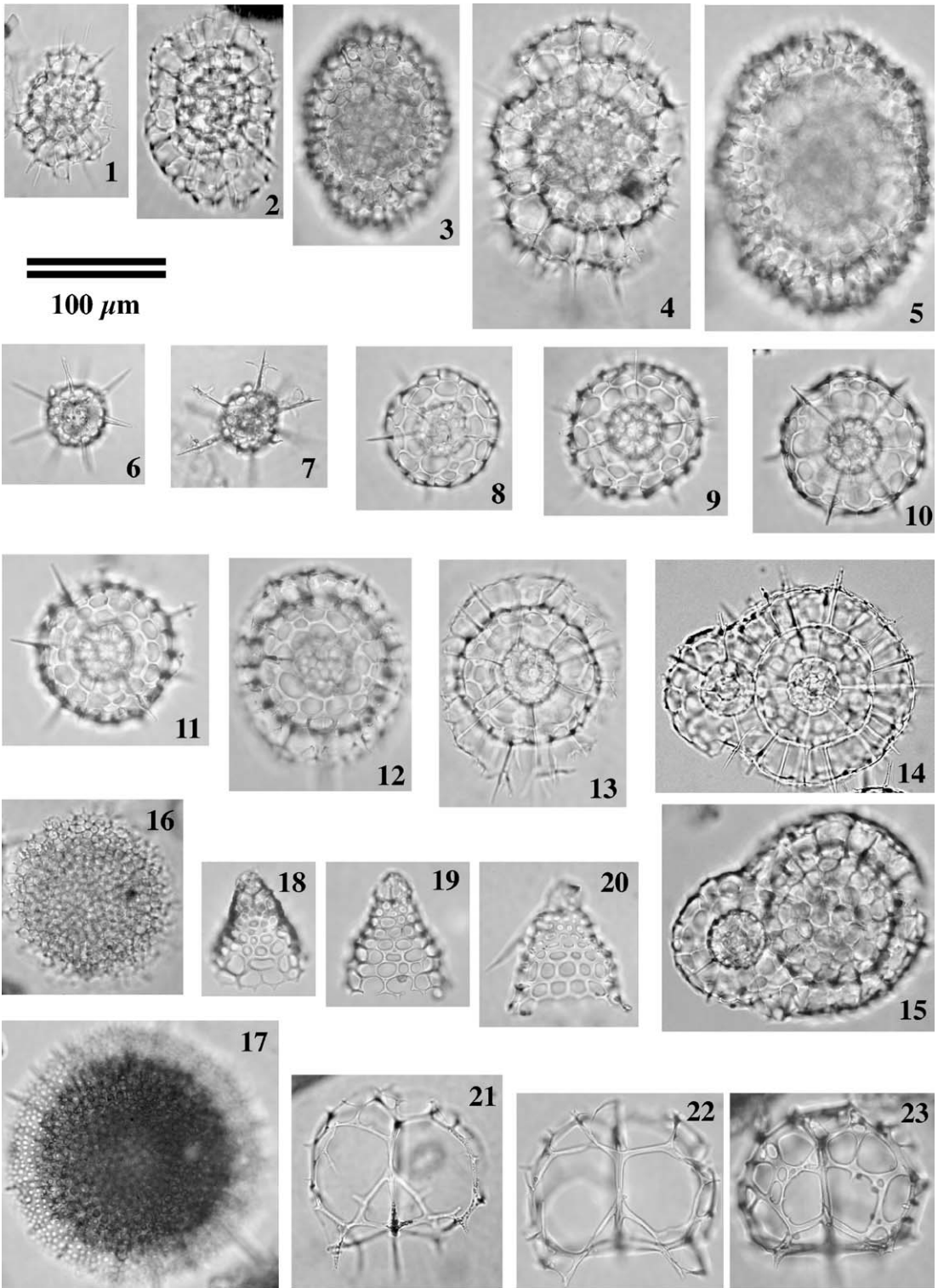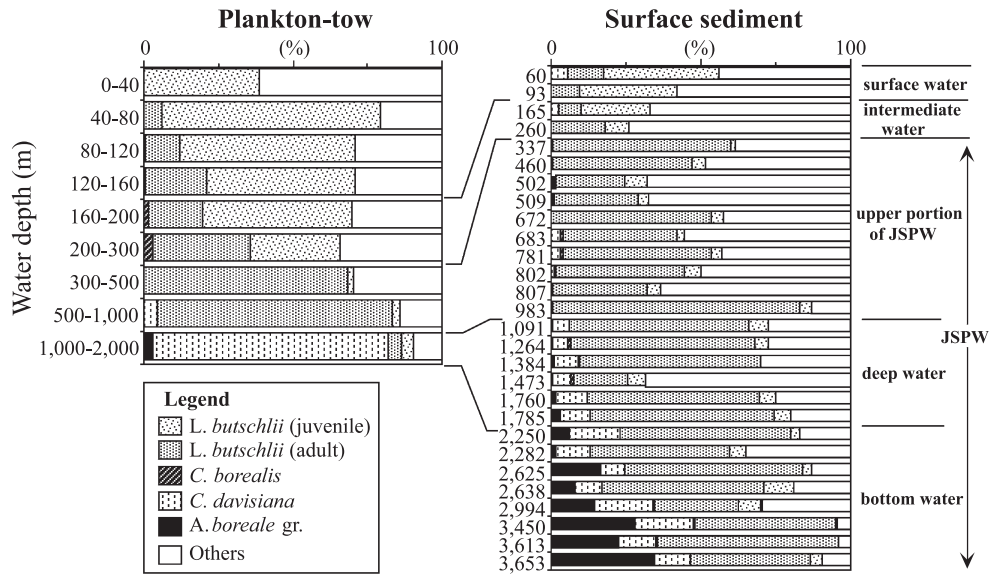
Fig. 2. Comparison of depth-related radiolarian assemblages between plankton tows (living populations) and surface sediments. Corresponding water masses are shown on the right (JSPW: Japan Sea Proper Water).

reaches a maximum abundance in depths of 100–200 and 400–500 m in fjords of western Norway (Bjørklund, 1974).

Thus, the living depths of *C. davisiana* and *A. boreale/leptoderma* Group in the Japan Sea are deeper than in other oceans, probably because both species are adapted to the cold and well-oxygenated deeper parts of the Japan Sea.

Consequently, we recognize the following radiolarians as characteristic of water masses in the modern Japan Sea: (1) *L. buetschlii* juvenile form, in the shallow-water masses above 300 m, (2) *C. borealis*, in the JEIW at 160–300 m, (3) *L. buetschlii* adult form, in the UJSPW at 300–1000 m, (4) *C. davisiana*, in the deep water at 1000–2000 m, and (5) *A. boreale/leptoderma* Group, in the bottom water at >2000 m.

5. Successional changes in the depth distribution of radiolarian assemblages

5.1. Sediment cores and age control

Sediment cores were mainly composed of clay or silty clay, intercalated with several volcanic ash layers (Fig. 3). The most characteristic feature of the sediment lithology was the presence of dark colored layers, most of which showed thin lamination, which are called thin lamination (TL) layers and are a well-known and ubiquitous feature of basins in the Japan Sea (Tada et al., 1999). The TL layers since 89 cal ka BP have been numbered from TL-1 to TL-21, and the depositional age of each TL layer has been estimated by Tada et al. (1999). As previously determined, the acceleration mass spectrometry (AMS) ^{14}C ages for

Plate I. Figs. 1–5, *Larcopyle buetchlii* Dreyer (1, juvenile form, GH95-1208, 1 cm; 2, juvenile form, GH95-1208, 1 cm; 3, adult form, GH95-1217, 106 cm; 4, juvenile form, GH95-1208, 1 cm; 5, adult form, GH95-1208, 1 cm). Figs. 6–15, *Actinomma boreale* Cleve/*leptoderma* Jørgensen Group (6, juvenile form, BO94-10, HJ-1, 40 cm; 7, juvenile form, BO94-10, HJ-1, 16 cm; 8, *Actinomma leptoderma leptoderma*, GH95-1208, 1 cm; 9, *A. l. leptoderma*, GH95-1208, 1 cm; 10, *A. l. leptoderma*, GH95-1208, 1 cm; 11, *A. boreale*, GH95-1208, 1 cm; 12, *A. boreale*, GH95-1208, 1 cm; 13, *A. boreale*, GH95-1208, 1 cm; 14, dimorphic form, GH95-1208, 67 cm; 15, dimorphic form, GH95-1208, 23 cm). Figs. 16–17, *Stylochlamydium venustum* (Bailey) (16, GH95-1217, 191 cm; 17, GH95-1217, 129 cm). Figs. 18–20, *Cycladophora davisiana* Ehrenberg (18, GH95-1208, 1 cm; 19, KT95-14, PC-5, 20 cm; 20, KT95-14, PC-5, 20 cm). Figs. 21–23, *Ceratospyris borealis* Bailey (21, GH95-1208, 93 cm; 22, GH95-1217, 191 cm; 23, GH95-1217, 191 cm).
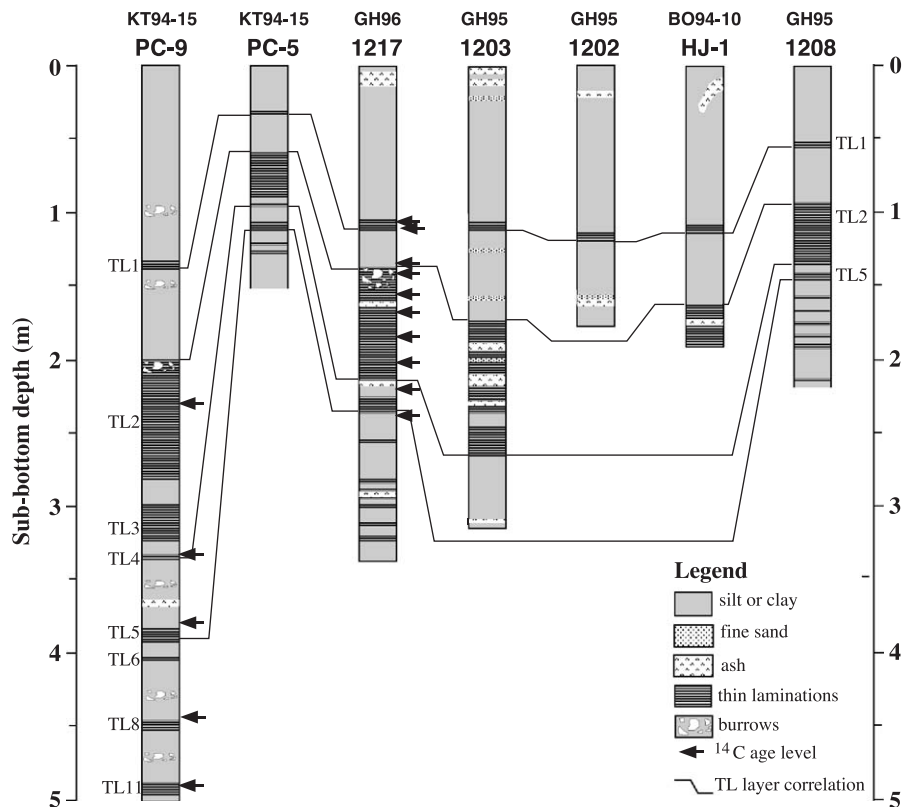
Fig. 3. Lithostratigraphic correlation among examined cores. The thin lamination (TL) layers are useful key beds in the Japan Sea. Small arrows on the right side of columns indicate ^{14}C age-control points.

the younger TL layers, based on planktonic foraminifers, are: TL-1, 10–10.5 ^{14}C ka BP; and top of TL-2, 15 ^{14}C ka BP (Oba et al., 1995; Ikehara et al., 1996). Therefore, these two horizons, bottom of TL-1 and top of TL-2, are useful stratigraphic markers in the Japan Sea. Positions of bottom of TL-1 and top of TL-2 in each core are listed in Table 3. The upper part of TL-2 has been bioturbated in cores KT94-15-PC9 and GH96-1217 from sea bottoms shallower than 2000 m water depth, but has not been bioturbated in cores GH95-1203, GH95-1208 and BO9410-HJ1 from deeper sea bottoms.

A number of AMS ^{14}C ages based on planktonic foraminifers have previously been determined from core GH96-1217 (Ikehara, 2003) and core KT94-15-PC9 (Crusius et al., 1999) (Table 4). No ^{14}C dates have been obtained from other cores owing to poor carbonate preservation.

In the present study, age models for examined cores were constructed mainly by TL layers (bottom of TL-1 and top of TL-2) and ^{14}C dating. Radiocarbon ages were converted to calendar ages following Kitagawa and van der Plicht (1998). A reservoir-effect correlation of 400 years was made for each ^{14}C age. Constant linear sedimentation rates between the age control

Table 3
Datum (in cmbsf) of bottom of thin lamination (TL)-1 and top of TL-2 layers in seven examined cores

Core	Bottom of TL-1 (11.8 cal ka BP)	Top of TL-2 (17.7 cal ka BP)
BO94-10, HJ-1	112	164
KT94-15, PC-5	30	56
KT94-15, PC-9	139	215
GH95-1202	120	–
GH95-1203	119	167
GH95-1208	60	90
GH69-1217	110	135

Table 4

Accelerator Mass Spectrometry (AMS) ^{14}C ages determination of planktonic foraminifera in cores GH96-1217 (Ikehara, 2003) and KT94-15-PC9 (Crusius et al., 1999)

Depth (cm)	Conventional age (^{14}C yr BP)	Calibrated age (cal yr BP)
GH96-1217		
107–108	10,680	11,578
108–109	10,760	11,839
132–134	12,660	14,109
140.5–142.5	14,950	17,106
154–156	15,490	17,799
170–172	17,710	19,902
184–186	19,230	21,952
201–203	21,260	24,191
218–220	24,280	26,731
238–240	28,460	31,529
KT94-15-PC9		
231	16,200	18,444
337	23,980	26,379
383	23,870	26,343
447	30,340	32,266
489	30,570	32,610

points were assumed to calculate the ages of sample. Because of unrealistic low sedimentation rates, sample lost at core top (ca. 0–5 cal ka BP) in core KT94-15-PC5 and a hiatus (14–17 cal ka BP) in core GH96-1217 were inferred.

5.2. Radiolarian record

Radiolarian fauna in the Japan Sea have significantly changed during the late Pleistocene and Holocene (Morley et al., 1986; Itaki and Ikehara, 2003). Such changes occurred synchronously over the Sea (Itaki and Ikehara, 2003). The same pattern has been recognized for examined cores in this study. Furthermore, our results indicate the past depth distributions of radiolarian assemblages.

Radiolarian abundance varies remarkably since 30 cal ka BP (Fig. 4). It tends to high since 10 cal ka BP, and significantly decreases during 11.5–12 cal ka BP, 14 or 15–17 cal ka BP, and older than 21 or 25 cal ka BP. The first and second decreases correspond to TL-1 and just above TL-2, respectively. Last one observed in core GH95-1203 occurs older than that in cores KT94-15-PC5 and GH95-1208.

Fig. 5 shows radiolarian faunal changes since 30 cal ka BP in the examined cores, in correlation to the

δ^{18}O record of the GRIP ice core from Greenland (Dansgaard et al., 1993), eustatic sea-level changes (Shackleton, 1987; Fairbanks, 1989) and past surface and bottom-water conditions in the Japan Sea (Oba et al., 1991; Tada et al., 1999). In addition, the δ^{18}O record of planktonic foraminifer of core KT94-15-PC9 (Crusius et al., 1999) has been added to this correlation. The radiolarian record can be divided into three faunal stages consisting of the late glacial, transitional, and Holocene. Each assemblage of the faunal stages is dominated by one or two species.

The late glacial faunal stage (30–17 cal ka BP) is characterized by the dominance of *Ceratospyris borealis* (substages i–h, Fig. 5). *Stylochlamydium*
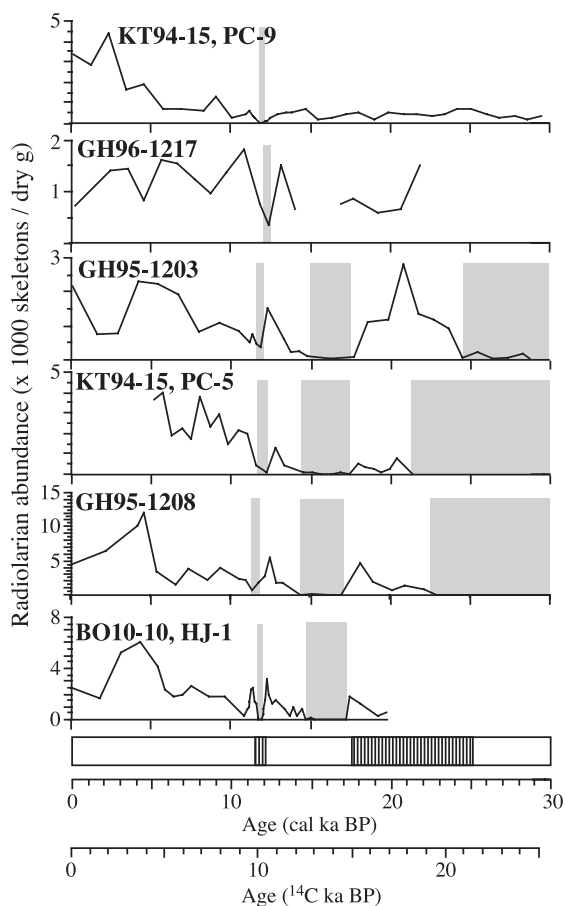

Fig. 4. Changes of radiolarian abundance for the last 30 ky in the Japan Sea. Gray bars indicate intervals that radiolarians reduced remarkably.
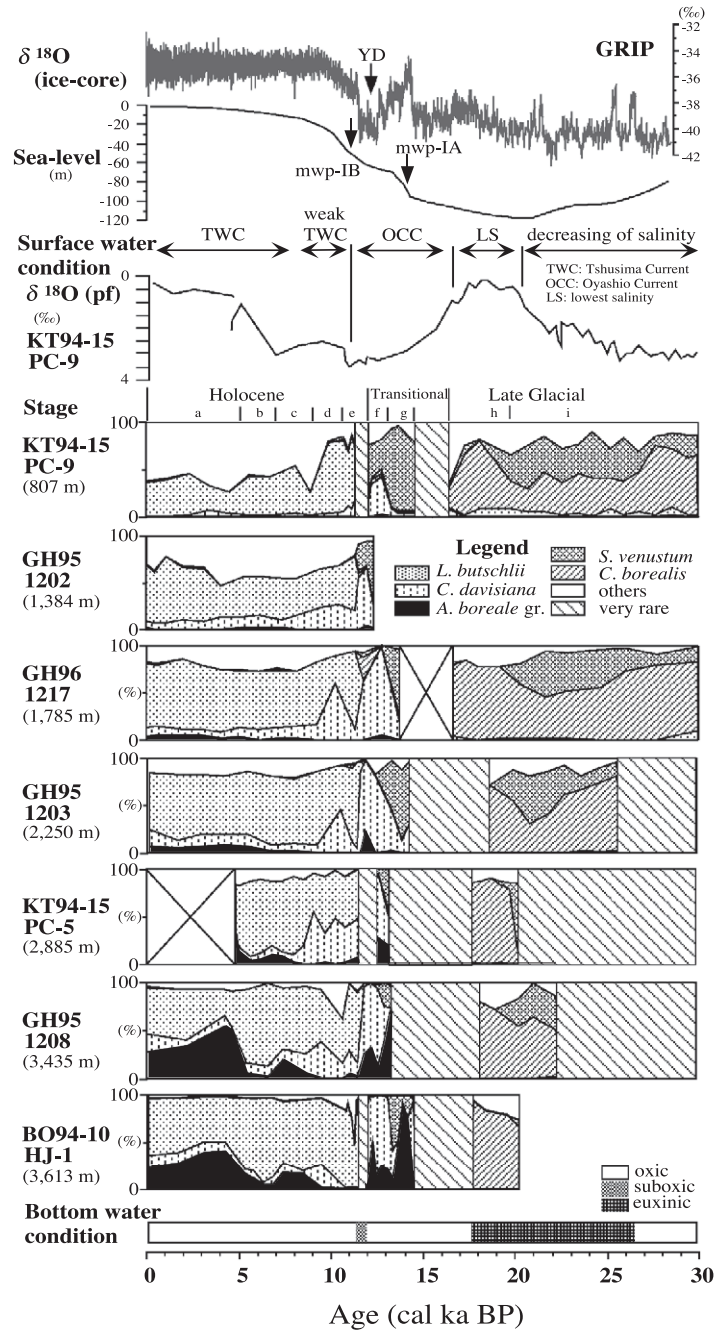
Fig. 5. Radiolarian faunal records in the Japan Sea over the past 30 ky. Cores are arranged in order of water depth, with correlations to the oxygen-isotope record of the GRIP ice-core from Greenland (Dansgaard et al., 1993), eustatic sea-level changes (Fairbanks, 1989; Shackleton, 1987), oxygen-isotope record based on planktonic foraminifera (pf) in core KT94-15-PC9 (Crusius et al., 1999), surface conditions (Oba et al., 1991, 1995), and bottom conditions (Tada et al., 1999). Small arrows on the sea-level curve and ice-core record indicate global/regional events: melt-water pulse (mwp) IB, Younger Dryas (YD) cold event, and mwp IA.

venustum (Bailey) (Plate I, Figs. 16 and 17) is abundant in the time period 30–20 cal ka BP (substage i), but very rare or absent in 20–17 cal ka BP (substage h) (Fig. 5). No apparent depth-related change in radiolarian assemblages was observed. Very low abundance of radiolarians was recognized in the early period of this stage in cores collected from deeper than 2000 m; older than 25 cal ka BP in core GH95-1203, older than 21 cal ka BP in cores GH95-1208 and KT94-15-PC5 (Fig. 4).

The transitional faunal stage (17–12 cal ka BP) is dominated by *S. venustum*, *C. davisiana* and/or *A. boreale/leptoderma* Group. This stage is subdivided into two periods, based on radiolarian faunal composition: approximately 14–13 and 13–12 cal ka BP. The 14–13 cal ka BP assemblage is dominated by *S. venustum* in cores obtained from depths shallower than 2500 m, and *A. boreale/leptoderma* Group in cores from water depths below 3000 m (substage g, Fig. 5). At ca. 13–12 cal ka BP, *C. davisiana* is dominant in all cores (substage f, Fig. 5). During the 17 to 15 or 14 cal ka BP period, the abundance of radiolarians declined remarkably.

The Holocene faunal stage (since 12 cal ka BP) is characterized by *L. buetschlii* (mostly the adult form); the bottom of this stage corresponds to the TL-1 layer. The radiolarian assemblage could not be determined in the TL-1 layer (12–11.5 cal ka BP) of cores KT94-15-PC5, -PC9 and BO94-10-HJ1, due to the scarcity of skeletons. The earliest period of this stage (11.5–11 cal ka BP) is dominated by *L. buetschlii* up to more than 70% of the assemblage (substage e), except in cores KT94-15-PC5 and GH95-1202 (Fig. 5). Depth-related changes in faunal population were restricted to smaller abundances of *C. davisiana* at the shallowest site (KT94-15-PC9), and more common to abundant occurrences of *A. boreale/leptoderma* Group at sites deeper than 2000 m. The maximum occurrence of *C. davisiana* was observed in the early period of this stage (substage d; 11–9 cal ka BP), except in core KT94-15-PC9 (Fig. 5). The relative abundance of *C. davisiana* during this period increased with water depth from 800 to 2000 m. *Actinomma boreale/leptoderma* Group has been constantly present since 9 cal ka BP at depths greater than 1500 m (substages c–a, Fig. 5), and its abundance increases with depth. A minimum occurrence of this species was recognized for 7–5 cal ka BP at depths greater than 2500 m

(substage b, Fig. 5). The modern depth distribution of radiolarians has continuously prevailed since 5 cal ka BP (substage a, Fig. 5).

6. Changes of ventilation pattern over the last 30 ky

The past depth-related radiolarian assemblage, as identified in seven sediment cores, is probably reflected in the different past vertical distribution of radiolarians in the water column. In consequence, the vertical distribution of water masses could be reconstructed on the basis of the past depth-related assemblages. Our data provide a further contribution to understand the ventilation system for the last 30 ky in the Japan Sea (Fig. 6).

6.1. Late glacial stages h–i

The very low to barren radiolarian abundance at deeper sites (>2000 m) prior to 21 or 25 cal ka BP might be the effect of opal dissolution or low radiolarian production.

The late glacial radiolarian assemblage is dominated by *C. borealis*, which is an intermediate-water species (see chapter 4). *Stylochlamydium venustum*, which is abundant at 30–20 cal ka BP, is a shallow-dwelling species (Kling and Boltovskoy, 1995; Nimmergut and Abelmann, 2002). Deep-dwelling species such as *C. davisiana* and *A. boreale/leptoderma* Group are absent or very rare during this period.

Such radiolarian assemblage showed no apparent depth-related changes, for two possible reasons: (1) only shallow assemblages have been recorded in sediments, due to the absence of deep-dwelling species, or (2) the same assemblage was present throughout the entire water column. However, reason (2) is excluded, because the fine laminations and high sulfur content in the late glacial (26–17 cal ka BP) sediments suggest anoxic bottom conditions (Oba et al., 1991; Tada et al., 1999) below 500 m in water depth (Ikehara et al., 1994). Low oxygen environments are not the ideal condition for radiolarian growth and reproduction, indicating that the radiolarians are absent in the deeper waters of the Japan Sea during this period.

Dominances of two species, *C. borealis* and *S. venustum*, at 30–20 cal ka BP are related to surface
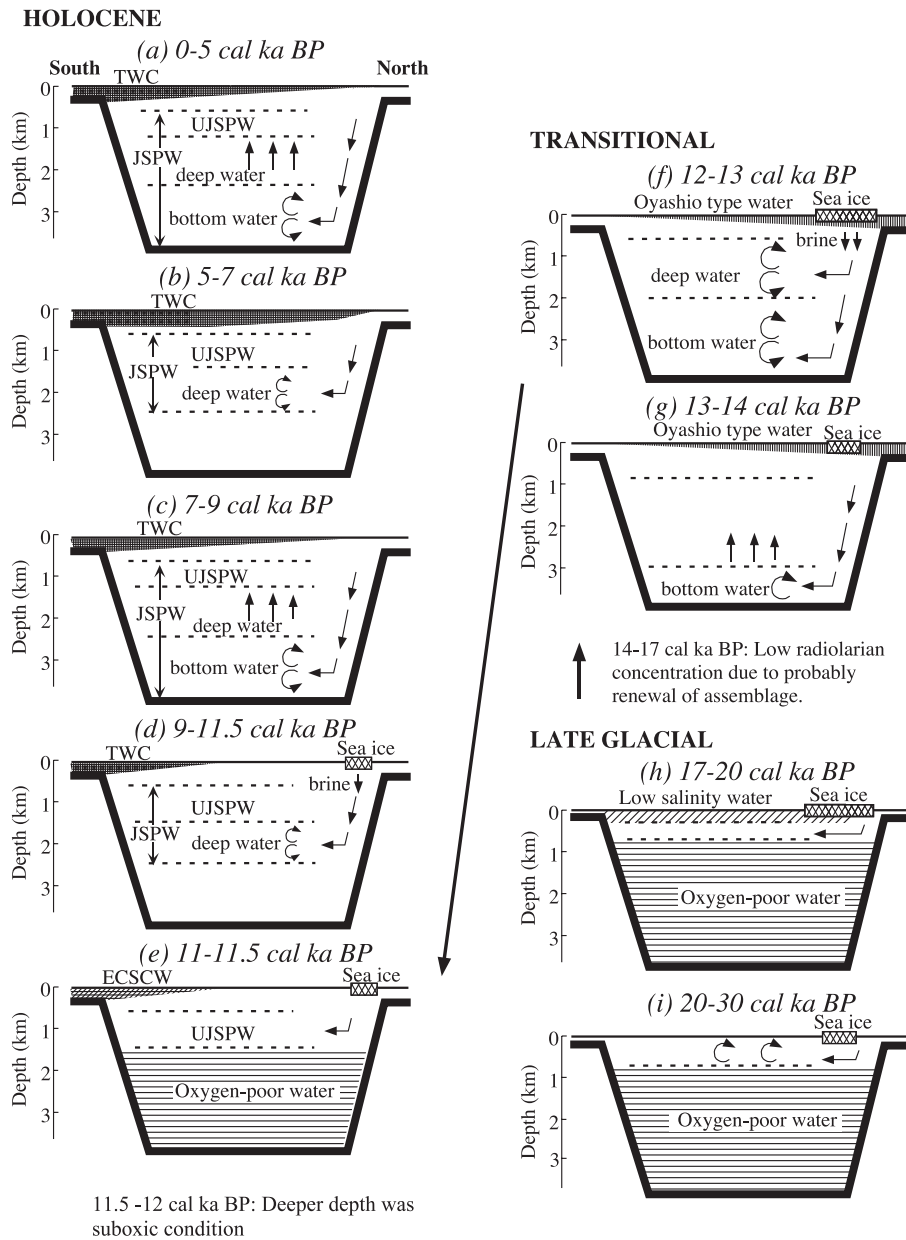
Fig. 6. Schematic models of past vertical water structure in the Japan Sea for nine periods during the past 30 ky. Abbreviations: TWC = the Tsushima Warm Current; ECSCW = the Eastern China Sea Coastal Water; UJSPW = the upper portion of Japan Sea Proper Water.

and intermediate water conditions of the Japan Sea. Both dominant species are minor in the modern Japan Sea (Fig. 2), but are abundant in the modern subarctic Pacific and Bering Sea (Kruglikova, 1969; Nigrini, 1970; Ling et al., 1971). The modern surface and intermediate conditions of the subarctic Pacific and

Bering Sea are characterized by low temperature: less than 15 °C in summer and less than 5 °C in winter. Therefore, surface and intermediate layers of the Japan Sea during 30–20 cal ka BP might have been characterized by cold oceanic water similar to that in the modern subarctic Pacific and Bering Sea (Fig. 6i).

Stylochlamydium venustum decreased between 20 and 17 cal ka BP as shown in Fig. 5, which suggests that surface conditions changed to become unsuitable for its survival. In this period, the Japan Sea was nearly isolated due to maximum sea level low stand (Fig. 5). Based on $\delta^{18}O$ values of planktonic foraminifers (Fig. 5), low-salinity water of 20–29.8 psu dominated at shallow depths during this period because of excess precipitation over the evaporation within the isolated environment (Oba et al., 1991, 1995; Keigwin and Gorbarenko, 1992; Matsui et al., 1998; Gorbarenko and Southon, 2000). This salinity might have been too low for *S. venustum* to survive. On the other hand, *C. borealis* was not affected by low-salinity surface water, because it was an intermediate dweller.

Deep-water convection declined with reduced sea-surface salinity during the late glacial (Oba et al., 1991). However, the dominance of *C. borealis*, the intermediate water indicator, implies the existence of cold intermediate water having normal salinity and a dissolved oxygen value intermediate between low-salinity surface water and oxygen-poor deep water (>500 m), which probably was a consequence of weak ventilation (Fig. 6h). Sea ice extension, which is indicated from the ice rafted debris (IRD), had reached around 40°N with cooling and decreased sea-surface salinity during the late glacial (Ikehara, 2003). The weak ventilation might have been related to brine rejection accompanying sea-ice development.

6.2. Transitional stages f–g

The decrease in radiolarian abundance at 17 to 15 or 14 cal ka BP might have resulted from renewal of the assemblage during the change from the late glacial to the transitional faunal stage.

The radiolarian assemblages during 14 to 13 cal ka BP are characterized by *A. boreale/leptoderma* Group at deeper sites and *S. venustum* at shallower sites (Fig. 5). The former species group lives in the cold and well-oxygenated bottom water in the modern Japan Sea (see Section 4). The latter species, as mentioned above, occurs abundantly in the subarctic Pacific (Kruglikova, 1969) and Bering Sea (Ling et al., 1971), and is a shallow-dwelling species in the north Pacific and the Okhotsk Sea (Kling and

Boltovskoy, 1995; Nimmergut and Abelmann, 2002).

The dominance of *A. boreale/leptoderma* Group at only deeper sites beginning at 14 cal ka BP is evidence for bottom-water convection supplying oxygen-rich water to the bottom layer. Deep convection reached as far as 3000 m. Tada et al. (1999) also pointed out the hyper-oxygenated bottom condition in this period, based on the S/C (sulfur/total organic carbon) ratio and lithology. The bottom condition changed during less than 3 ky from the anoxic condition of the late glacial to the hyper-oxygenated condition during the transitional stages.

Such a drastic ventilation change was closely related to the sea-surface condition. The maximum *S. venustum* abundance during this interval was almost coincident with a rapid eustatic sea-level rise (Fig. 5), known as melt-water pulse IA (mwp-IA; Fairbanks, 1989). The dominance of this species implies an inflow of subarctic oceanic surface water to the Japan Sea. Oba et al. (1991) pointed out that the Oyashio Cold Current (OCC) water of the northwestern Pacific flowed into the Japan Sea through the Tsugaru Strait. The bottom-water augmentation during this period might have been related to the cooling of dense OCC-type surface water (Fig. 6g).

The major peak of the deep-water species *C. davisiana* is evident at 13–12 cal ka BP in all examined cores. This peak abundance at the shallowest site (core KT94-15-PC9; 807 m in water depth) indicates that the living depth of *C. davisiana* in the Japan Sea had transiently extended upwards into shallower depths during this interval. Such an assemblage dominated by *C. davisiana* is similar to that of surface sediments in the Okhotsk Sea (Morley and Hays, 1983). The living depth of *C. davisiana* in the Okhotsk Sea (200–1000 m; Nimmergut and Abelmann, 2002) corresponds to Okhotsk Sea intermediate water, which originates from dense water (brine) produced by sea-ice formation (Kitani, 1973). Thus, the dominance of *C. davisiana* and its extended depth distribution in the Japan Sea at 13–12 cal ka BP suggests an active augmentation of deep water with dense water, concurrent with sea-ice formation. Bottom-water convection was also active, as indicated by the abundance of *A. boreale/leptoderma* Group. This period coincided with the cooling event known as the Younger Dryas (YD) (Fig. 5). The cooling event of

sea-surface temperature during the YD period in the Japan Sea has been reported from alkenone analysis (Ishiwatari et al., 1999). The large degree of deep- and bottom-water production was probably caused by active convection during the YD-like cooling event (Fig. 6f). This active ventilation ceased abruptly at 12 cal ka BP.

6.3. Holocene stages a–e

Low radiolarian abundance at 12–11.5 cal ka BP might be related to poor oxygen conditions in the water column, as indicated by thinly laminated sediments (TL-1 layer, Oba et al., 1991; Tada et al., 1999).

The dominance of *L. buetschlii* over the past 11.5 cal ka BP suggests the existence of UJSPW. The beginning of UJSPW formation closely corresponds to the initial inflow of TWC (Oba et al., 1991; Ishiwatari et al., 1999). This coincides with an eustatic sea-level rise related to melt-water pulse IB (mwp-IB; Fairbanks, 1989) at 12 cal ka BP (Fig. 5), during the onset of the modern type circulation system, which might have been driven by an influx of high-salinity TWC water. Furthermore, the presence of the deep-water species *C. davisiana* and the bottom-water species *A. boreale/leptoderma* Group implies variations of ventilation activity during Holocene, as discussed below.

The absence or rare occurrences of *C. davisiana* and *A. boreale/leptoderma* Group during the earliest Holocene (11.5–11 cal ka BP) suggest the absence of deep- and bottom-water ventilation, while the dominance of *L. buetschlii* suggests the presence of the UJSPW. These occurrences imply that winter convection was limited to the depth of UJSPW in this interval (Fig. 6e).

It appears that deep-water formation in the early Holocene (11–9 cal ka BP) was more active than bottom-water formation, based on the predominance of *C. davisiana* and the absence of *A. boreale/leptoderma* Group. Sea ice persisted during this period in the northeastern part of the Japan Sea, based on the presence of IRD in hemipelagic mud (Ikehara, 2003). Active deep-water formation was probably related not only to the TWC inflow but also to brine ejection that accompanied sea-ice formation (Fig. 6d).

Bottom-water formation took place between 9 and 7 cal ka BP (Fig. 6c) and is closely related to the increase of TWC inflow supplying high-salinity water (Oba et al., 1991). Bottom-water formation decreased transiently at 7–5 cal ka BP (climatic optimum) (Fig. 6b), which was possibly related to the weakening of surface-water sinking with climatic warming (Sakaguchi, 1982; Koizumi, 1989). A cooling following the climatic optimum possibly caused a reactivation of bottom water production from 5 cal ka BP till present (Fig. 6a).

7. Conclusions

The modern depth distribution of radiolarian assemblages in both the water column and in surface sediments can be correlated to each other. The depth-related assemblages are influenced by the vertical water structure. Juvenile and adult forms of *Larcopyle buetschlii* dominated assemblages in depths shallower than 300 m and in UJSPW between 300 and 1000 m, respectively. *Ceratospyris borealis* lives in the JEIW between 160 and 300 m. *Cycladophora davisiana* occurs abundantly in deep water below 1000 m. *Actinomma boreale/leptoderma* Group occurs below 1000 m and increases in abundance with water depth, becoming a dominant species in bottom water deeper than 2000 m.

The past depth distribution of radiolarian assemblages during the last 30 ky was examined based on seven sediment cores in depths ranging from 807 to 3613 m in the Japan Sea. The radiolarian fauna varied abruptly and drastically during this period, and reflected an apparent depth distribution. Based on our results, we propose the following circulation changes for the Japan Sea.

Late glacial: The radiolarian assemblage is dominated by *Ceratospyris borealis*, an indicator of cold intermediate water. This implies that cold water ventilated to an intermediate depth that was situated between low-salinity surface water and oxygen-poor deep water.

Transitional: The bottom water species *Actinomma boreale/leptoderma* Group occurred abundantly at the deeper sites below 3000 m from 14 to 13 cal ka BP. In this interval, *Stylochlamydium venustum*, which is a cold, surface-water species, dominated the assemblage at the shallower sites. It is inferred that deep ventila-

tion, which reached 3000 m, started at 14 cal ka BP and was related to the OCC-type water inflow accompanying mwp-IA. The deep-water species *Cycladophora davisiana* increased in all examined cores and the bottom-water species *A. boreale/leptoderma* Group was abundant below 2000 m at 13–12 cal ka BP, which might have been related to increased convection strength along with the YD-like cooling.

Holocene: Over the past 11.5 ky, the radiolarian assemblage has been dominated by *Larcopyle buetschlii*, which is indicative of UJSPW formation. The bottom water has been formed since 9 cal ka BP, but with a lower intensity between 7 and 5 cal ka BP, according to the presence of abundant *Actinomma boreale/leptoderma* Group. This deep-oceanic circulation has been driven by TWC inflow and climatic change.

8. Taxonomic remarks

Actinomma boreale Cleve/*leptoderma* Jørgensen Group (Plate I, Figs. 6–15): According to Cortese and Bjørklund (1998), *Actinomma boreale* Cleve (Plate I, Figs. 11–13) and *Actinomma leptoderma leptoderma* (Jørgensen) (Plate I, Figs. 6–10) differ in the number of spines and the presence of the fourth cortical sphere. In the present study, *A. l. leptoderma* and *A. boreale* have been unified as *A. boreale/leptoderma* Group owing to similarities between *A. l. leptoderma* and *A. boreale* and the existence of dimorphic form of the two species (Plate I, Figs. 14 and 15).

Ceratospyris borealis Bailey (Plate I, Figs. 21–23): Most specimens of *C. borealis* in this study have a somewhat thinner trellis-type skeleton compared with forms found in the northern Pacific, Bering Sea and Okhotsk Sea (Nigrini, 1970; Ling et al., 1971; Ling, 1974; Kruglikova, 1977 = *Tholospyris borealis* (Bailey)).

Larcopyle buetschlii Dreyer (Plate I, Figs. 1–5): This species varies from 60 to 230 μm in length. There are two morphological types of *L. buetschlii*: with complete skeleton (adult form; Plate I, Figs. 3 and 5) and incomplete skeleton (juvenile form; Plate I, Figs. 1, 2 and 4). The juvenile form is similar to the inner structure of the adult form. In general, the radial spines of the adult form are fewer than those of the juvenile form.

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