Radiolarian faunas and water properties in surface and subsurface waters of the Japan Sea in September 2005, off Tassha, Sado Island, central Japan

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Abstract

The vertical distribution of radiolarian faunas on September 28, 2005 and the temperature, salinity, density, and fluorescence intensity profiles are documented from surface and subsurface waters (> 100 m deep) in the Japan Sea, off Tassha, Sado City, Sado Island, Niigata Prefecture, central Japan. The features of the water mass structure shallower than 100 m deep are distinguished by gentle gradients of temperature and salinity in waters between 100 m and 20 m deep (the lower layer: LL) and a homogeneous temperature and salinity (24.0 ℃, 32.9 psu) in waters shallower than 20 m (the upper layer: UL). The species composition of the deeper fauna (ca. 77-54 m) is characterized by the abundant occurrence of *Acanthosphaera actinota*, *Pseudocubus* sp. A, *Lophospyris* sp., and *Acanthodesmia* sp. It is also noteworthy that each species in the deeper water fauna does not exceed 20 %. In the shallower fauna (ca. 35-0 m), *Spongosphaera streptacantha*, *Pseudocubus obeliscus*, and *Pseudocubus* sp. A comprise 87.5 % of the fauna. Considering the characteristics of vertical water properties, high standing stocks of these three species are likely caused by their temperature preferences and adaptive strategies for a summer environment in the Japan Sea. There is a slight difference in species composition between September faunas of 2000 and 2005 which is probably related to the Tsushima Warm Current (TWC). It is known that the flow force of the TWC varies in 2 to 3- and 10-year cycles, so the TWC fluctuation may influence the annual variation of the fauna around Sado Island.

Key words: Japan Sea, Radiolaria, Sado Island, Tsushima Warm Current, Water property.

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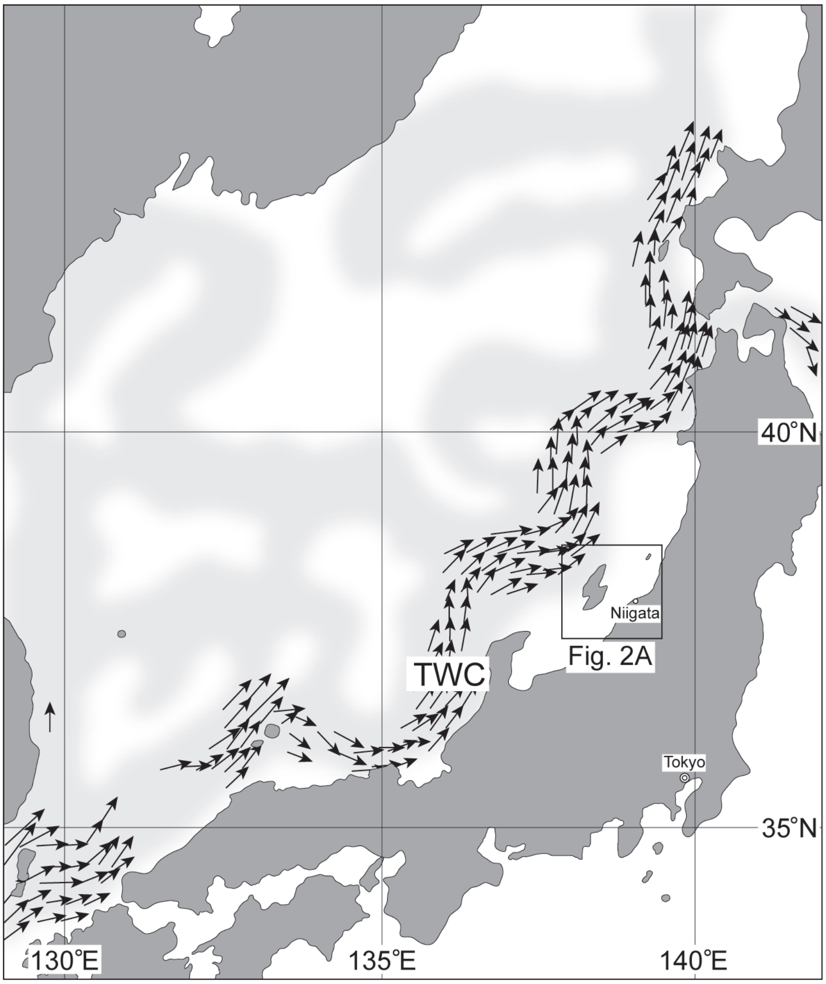

Fig. 1. The main surface current of the Japan Sea. Arrow indicates the current direction with ca. 0.2 to 0.3 m/sec. Gray areas without arrows indicate waters flowing below ca. 0.15 m/sec. Base map is after ten days mean sea surface current for September 21 to 30, 2005 (Japan Meteorological Agency, available online a). TWC: Tsushima Warm Current.

Introduction

The Japan Sea is a marginal sea surrounded by the Japanese Islands and the Eurasian Continent. There are four well-known main currents, namely the Tsushima Warm Current (TWC), the East Korean Warm Current, the Liman Current, and the North Korean Cold Current. Water exchange between the Japan Sea and adjacent seas occurs mainly through four shallow straits: the Tsushima, Tsugaru, Soya, and Mamiya straits. In the eastern and western channels of the Tsushima Strait, the TWC flows into the Japan Sea from the East China Sea and has a strong influence on the formation of warm water faunas and floras in the Japan Sea (Fig. 1). Many possible mean flow patterns of the TWC have been studied based on hydrographic information (e.g., Katoh, 1994; Hase et al., 1999; Morimoto and Yanagi, 2001).

Living radiolarian study of the Japan Sea has been progressing off Tassha, Sado Island by the fourth author (A.M.) and his collaborators since introduction of the research boat IBIS2000 to the Sado Marine Biological Station of Niigata University (e.g., Matsuoka et al., 2001, 2002; Itaki et al., 2003; Kurihara et al., 2006). As Itaki et al. (2003) mentioned, sea water surrounding Sado Island is one of the best targets for studying the seasonal radiolarian faunal fluctuation influenced by the TWC, because the TWC flows into the vicinity of Sado Island along the eastern margin of the Japan Sea (Fig. 1). In 2005, we introduced a conductivity-temperature-depth (CTD) sensor and obtained water properties corresponding to the water mass targeted at our radiolarian sites (Kurihara et al., 2006). In order to know the relationship between the composition of the radiolarian fauna and the TWC system, it is essential to sample from different depth intervals together with utilizing hydrographic information. Kurihara et al. (2006) reported the radiolarian fauna and vertical profiles of water properties in early June 2005. This paper reports the radiolarian faunal characteristics of deeper and shallower parts in late September 2005, and their relationship to the vertical water properties. We discuss also the annual variation between September faunas of 2000 and 2005.

Materials and methods

Plankton sampling was conducted on September 28, 2005 using the research boat IBIS2000 of the Sado Marine Biological Station along with measurements of temperature, salinity, density, and fluorescence intensity by a CTD sensor (Alec Electronics Co., Ltd. COMPACT-CTD). Water temperature was recorded with a conventional digital thermometer. These operations were carried out at a location (38°05’N, 138°10’E) approximately 6 km west of Tassha, Sado City, Sado Island, Niigata Prefecture, central Japan (Fig. 2). We collected six plankton samples (928-6SD-1 to -6) using a 100 μm opening net of the Marukawa type with a 0.3 m diameter mouth. Considering the dip angle of the plankton net (ca. 45°to 60°), actual sampling depth (in parentheses) of each interval can be calculated as approximately 71 % to 87 % of the rope release length. Plankton samples 928-6SD-1 and -2 were obtained from a water depth between 100 (77) m and 70 (54) m and between 70 (54) m and 40 (31) m, respectively, by closing the net with a “messenger”. We collected sample 928-6SD-3 from a water depth between 40 (35) m and the surface without closing the net. Sample 928-6SD-4 was taken from 100 (71) m deep to the surface for the analysis of the total faunal composition. In samples 928-6SD-5 and -6 obtained from 100 (71) m deep to the surface, we collected plankton only from the bottle of the plankton net without rubbing the net for observation of healthy living radiolarians.

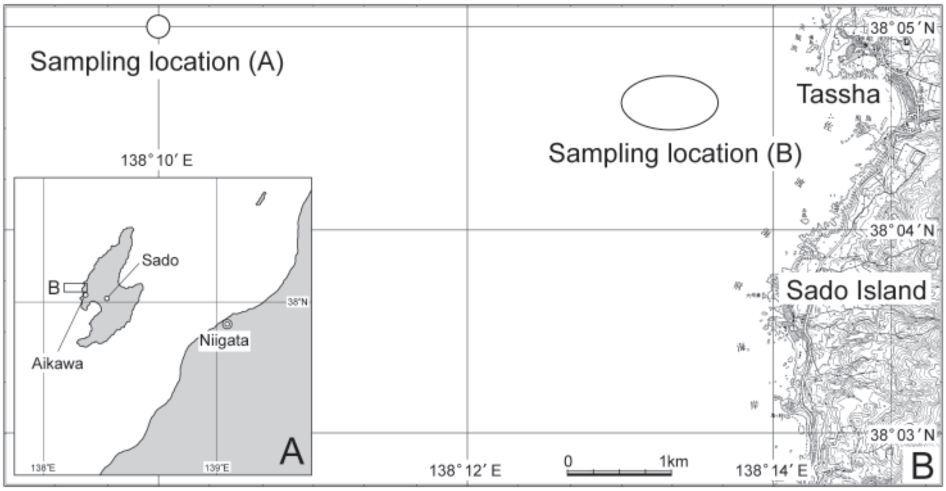

Fig. 2. Index map showing sampling locations. The topography is from the 1:25,000 scale "Aikawa" map sheet published by the Geographical Survey Institute of Japan. Sampling location (A) corresponds to the study area of Matsuoka et al. (2002), Itaki et al. (2003), Kurihara and Matsuoka (2004, 2005), Kurihara et al. (2006), and this study. Sampling location (B) corresponds to the study area of Matsuoka et al. (2001).

Plankton samples (928-6SD-1 to -4) for the analysis of faunal composition were placed in ca. 50 % sulfuric acid. The residues were collected on a 46 µm opening sieve and rinsed in water. Following this process, the residues were kept in an aqueous ethanol solution, and then mounted in Canada balsam. Microscopic images of radiolarian skeletons were taken with digital transmitted light microscopes (Keyence VH-7000 and Nikon Coolscope). The observation of living radiolarians has been explained in detail by Kurihara et al. (2006).

Vertical profiles of temperature, salinity, density, and fluorescence intensity

Vertical profiles of temperature, salinity, density, and fluorescence intensity at every 1 m water depth from 100 m to the surface are presented in Fig. 3. These data were obtained by the CTD sensor with a 200 m long rope equipped with IBIS2000. Fluorescence intensity, which was prepared from output signal values of the CTD sensor, can be closely related to the relative abundance of algal chlorophyll.

Temperature: The temperature of the water mass from 100 m to the surface in the sampling site ranges from ca. 14.4 ℃ to 24.0 ℃. The water mass from 100 m to 51 m has a low temperature gradient of 0.9 ℃/10 m, although there are slight changes of the temperature gradient in water masses around 65 m and between 82 m and 78 m. The temperature gradient of the water mass between 51 m and 20 m is 1.6 ℃/10 m. The water about 46 m deep is slightly disturbed, and

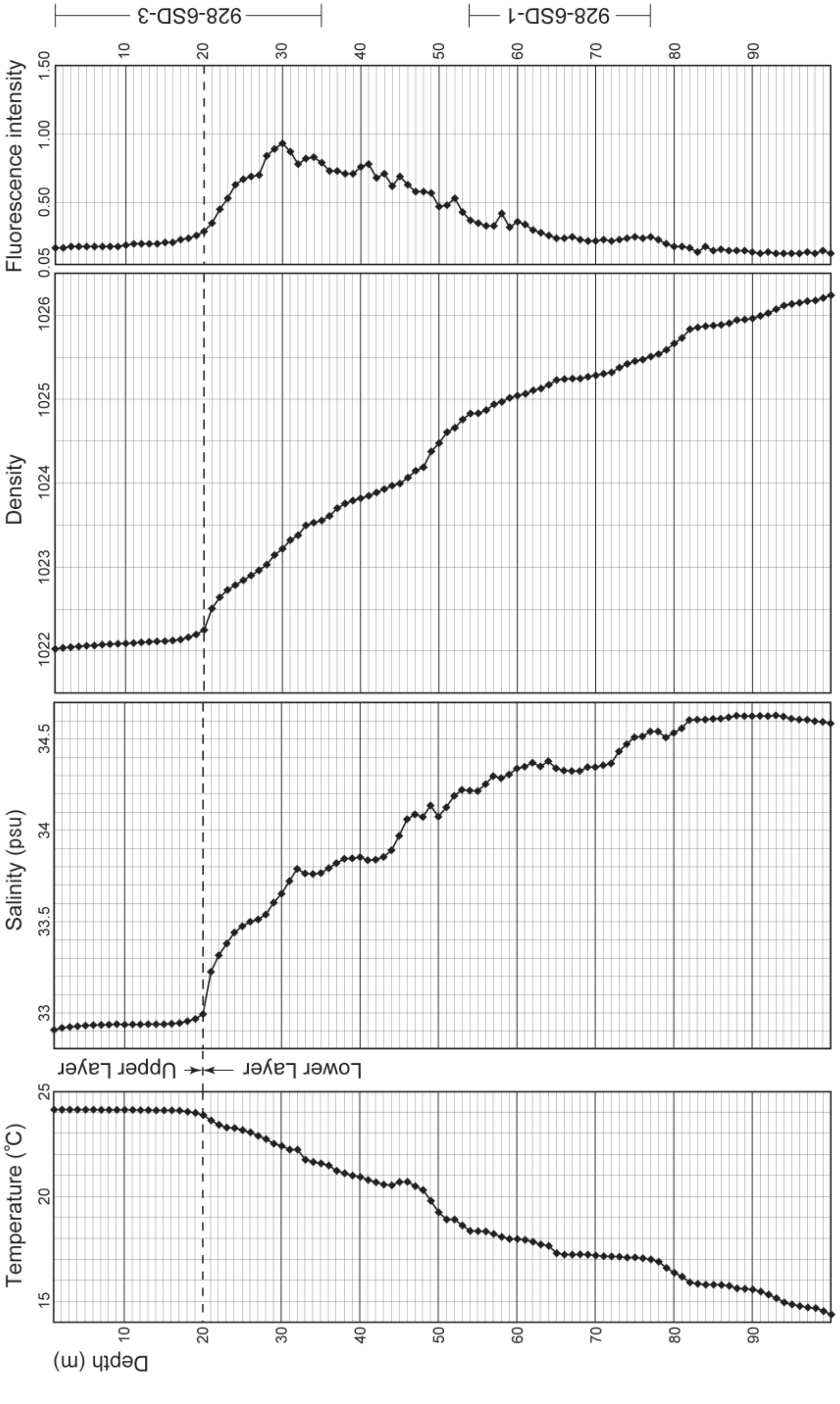

Fig. 3. Plankton sampling intervals of 928-6SD-1 and -3 and vertical profiles of temperature, salinity, density, and fluorescence intensity at sampling location (A) off Tassha, Sado Island.

Table 1. List of all solitary radiolarian species obtained from samples 928-6SD-1 and 928-6SD-3.

Sample number	928-6SD-1	928-6SD-3
Rope release length	100-70 m	40-0 m
Sampling depth	77-54 m	35-0 m
	Number of skeletons	
SPUMELLARIA		
Tetrapyle octacantha Müller	3	11
Larcospira quadrangula Haeckel	1	0
Didymocyrtis tetrathalamus tetrathalamus (Haeckel)	0	1
Spongoliva ellipsoides Popofsky	1	1
Spongosphaera streptacantha Haeckel	4	59
Styptosphaera spongiacea Haeckel	0	1
Acanthosphaera actinota (Haeckel)	14	2
Hexacontium hostile Cleve	2	0
Myelastrum trinibrachium Takahashi	1	6
Plegmosphaera pachypila Haeckel	6	0
NASSELLARIA		
Plectacantha trichoides Jørgensen	7	0
Plectacantha oikiskos (Jørgensen)	4	1
Pseudocubus obeliscus Haeckel	5	157
Pseudocubus sp. A	10	58
Pseudodictyophimus gracilipes (Bailey)	7	1
Neosemantis distephanus Popofsky	8	0
Phormacantha hystrix (Jørgensen)	5	2
Peridium spinipes Haeckel	1	0
Spirocyrtis scalaris Haeckel	2	2
Lophospyris sp.	11	4
Acanthodesmia sp.	19	1
others	3	6

varies from the temperature gradient of the water immediately above. Temperature stratification is strongly developed (24.0 ℃) in waters from 20 m deep to the surface.

Salinity: The salinity of the water mass from 100 m to the surface ranges from 34.629 psu to 32.907 psu. In the water mass between 100 m to 82 m, there is an almost constant salinity value (ca. 34.6 psu). The salinity of the water mass between 82 m to 20 m varies widely from 34.605 psu to 32.993 psu and expresses the basic trend that drops with shallowing depth. The water mass from 20 m to the surface is characterized by a low salinity of about 32.9 psu. This indicates that surface water shallower than 20 m deep is also stratified in terms of salinity as well as temperature.

Density: The density of the water mass between 100 m and 21 m gently drops from ca. 1026.24 to 1022.50 with shallowing depth in response to reduced salinity and rising water temperature. In contrast, the water mass shallower than 20 m is almost constant (1022.25 to 1022.02). This trend indicates that the density stratification of surface water shallower than 20

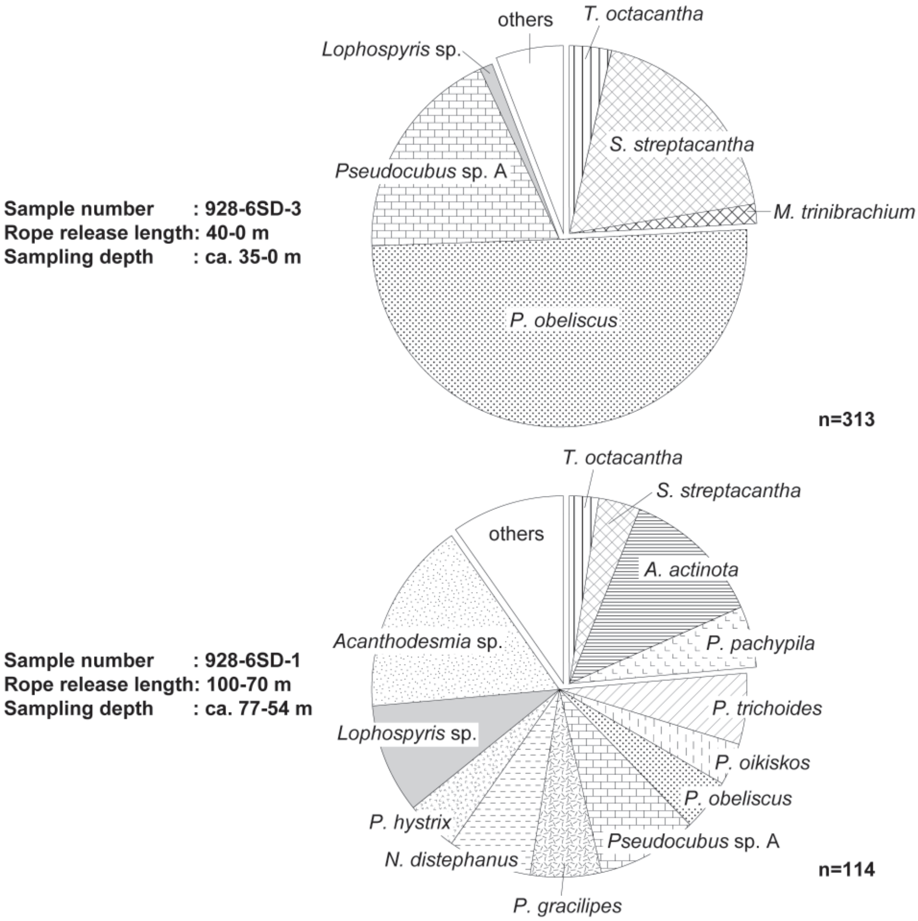

Fig. 4. Radiolarian faunal compositions at two different depth intervals.

m is obviously consistent with temperature and salinity.

Fluorescence intensity: The fluorescence intensity is generally low in the water mass between 100 m and 65 m. In the water mass from 65 m to 20 m, the fluorescence intensity fluctuates with every 1 m depth and reaches a peak at 30 m. The water mass shallower than 20 m shows a low and almost constant fluorescence intensity value as well as the water mass from 100 m to 65 m.

General features of the water mass structure: Based on the vertical profiles of physical and chemical conditions (temperature, salinity), the water mass from 100 m to the surface can be subdivided into two prominent layers (Fig. 3). The lower layer (LL) is recognized in the water mass between 100 m and 20 m and is characterized by having temperature and salinity gradients ranging from ca. 14.4 ℃ to 23.9 ℃ and ca. 34.6 psu to 33.0 psu, respectively. There

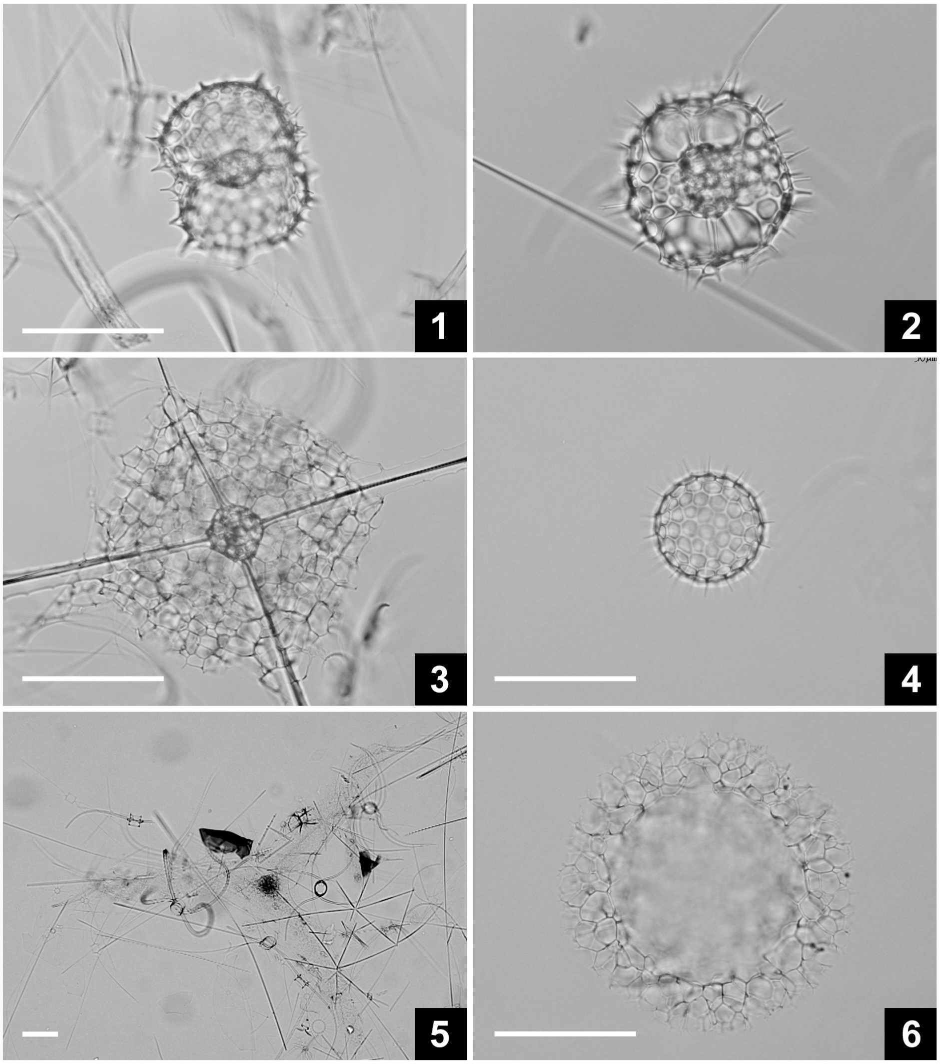

Fig. 5. Transmitted light microscopic images of radiolarian skeletons from sea water off Tassha, Sado Island. The scale bar for each figure equals 100 μm. 1. *Didymocyrtis tetrathalamus tetrathalamus* (Haeckel), 928-6SD-3, 2. *Tetrapyle octacantha* Müller, 928-6SD-3, 3. *Spongosphaera streptacantha* Haeckel, 928-6SD-3, 4. *Acanthosphaera actinota* (Haeckel), 928-6SD-1, 5. *Myelastrum trinibrachium* Takahashi, 928-6SD-3, 6. *Plegmosphaera pachypila* Haeckel, 928-6SD-1.

is a chlorophyll peak at 30 m deep which corresponds to the upper part of this layer. The upper layer (UL) recognized in the water mass from 20 m to the surface is distinguished from the LL by having almost constant values of temperature and salinity (ca. 24.0 ℃, 32.9 psu). This layer, characterized by a homogeneous temperature and salinity, is thought to be developed by solar insolation heating with wind disturbance.

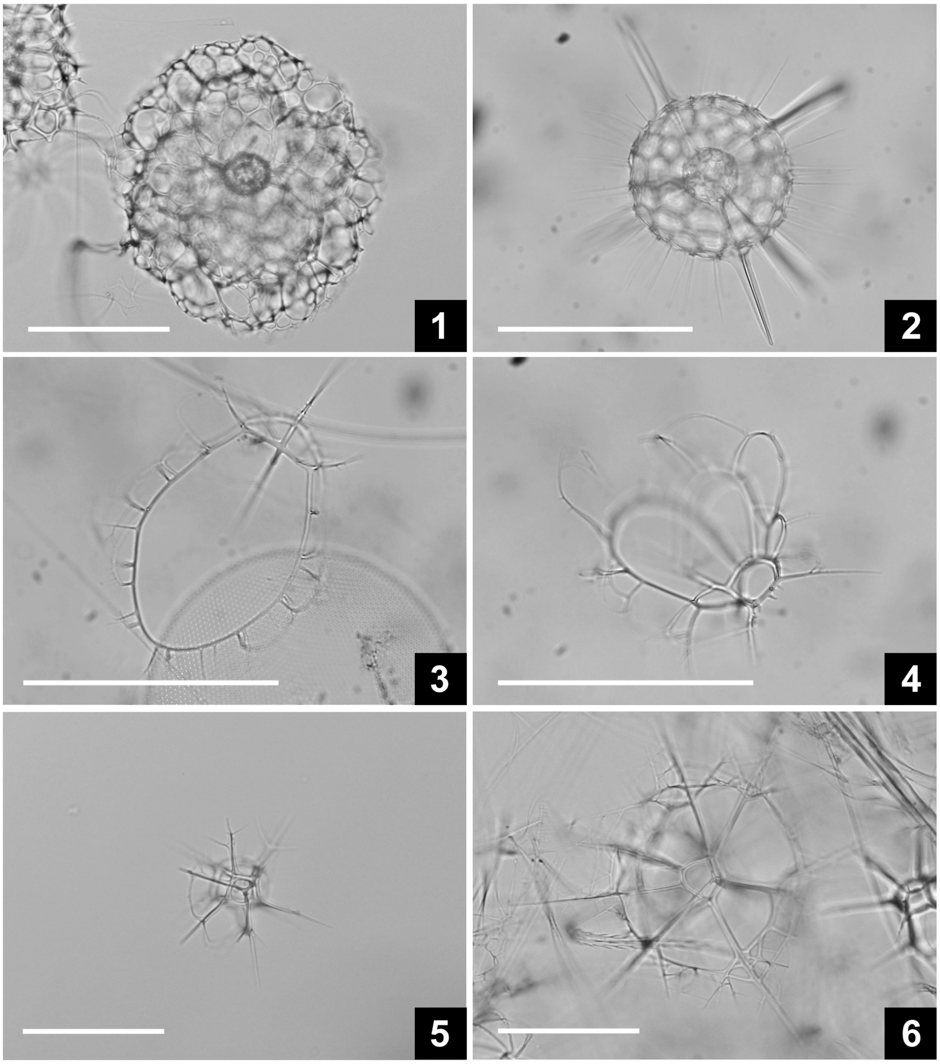

Fig. 6. Transmitted light microscopic images of radiolarian skeletons from sea water off Tassha, Sado Island. The scale bar for each figure equals 100 µm. 1. *Spongoliva ellipsoides* Popofsky, 928-6SD-3, 2. *Hexacontium hostile* Cleve, 928-6SD-1, 3. *Plectacantha trichoides* Jørgensen, 928-6SD-1, 4. *Plectacantha oikiskos* (Jørgensen), 928-6SD-1, 5. *Pseudocubus obeliscus* Haeckel, 928-6SD-3, 6. *Pseudocubus* sp. A, 928-6SD-3.

Vertical distribution of radiolarians

Plankton samples 928-6SD-1 (ca. 77-54 m) and -2 (ca. 54-31 m) were collected from the LL mentioned above, and sample 928-6SD-3 (ca. 35-0 m) from the upper part of the LL and

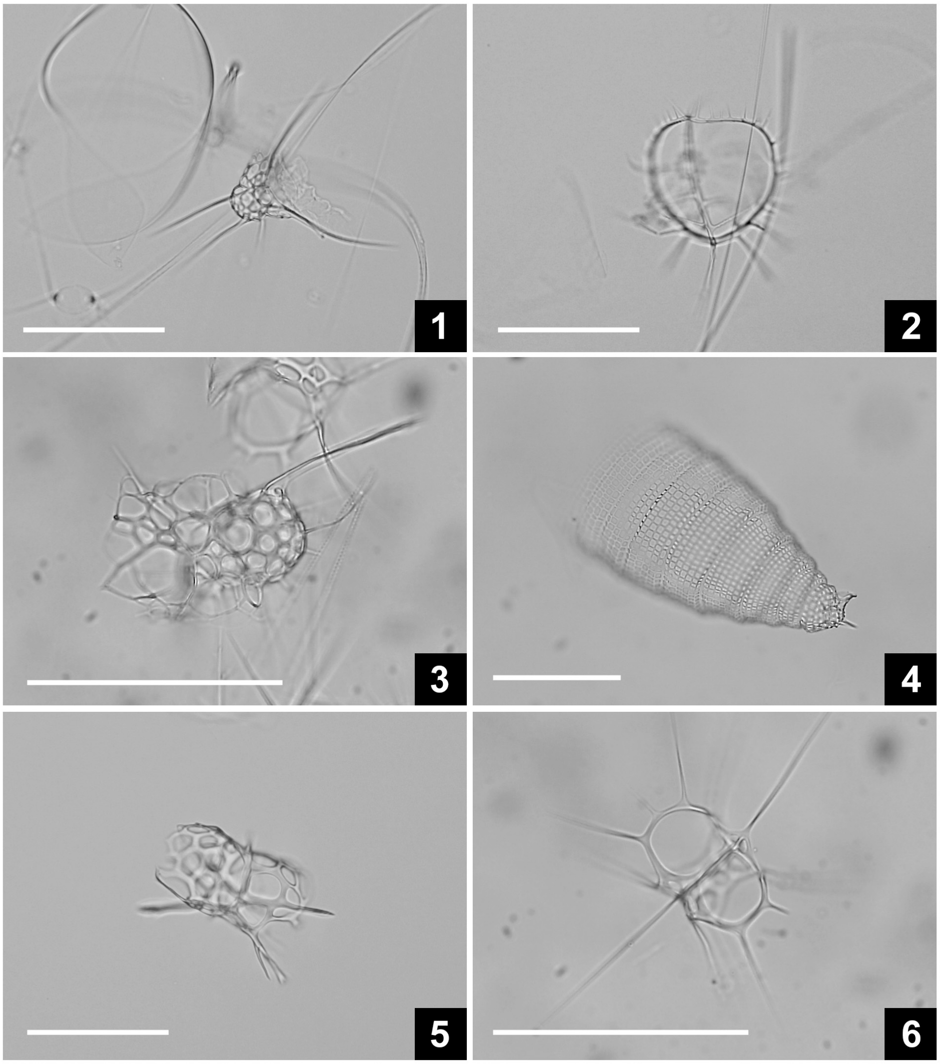

Fig. 7. Transmitted light microscopic images of radiolarian skeletons from sea water off Tassha, Sado Island. The scale bar for each figure equals 100 µm. All specimens were collected from sample 928-6SD-1. 1. *Pseudodictyophimus gracilipes* (Bailey), 2. *Neosemantis distephanus* Popofsky, 3. *Phormacantha hystrix* (Jørgensen), 4. *Spirocyrtis scalaris* Haeckel, 5. *Lophospyris* sp., 6. *Acanthodesmia* sp.

the UL. Radiolarian species in samples 928-6SD-1 and -3 are listed in Table 1; transmitted light microscopic images of representative faunal constituents are illustrated on Figs. 5 to 7. Data from samples 928-6SD-2 (ca. 54-31 m) are not available due to failed sample preparation. Pie charts of the faunal compositions of samples 928-6SD-1 and -3 are presented in Fig. 4. Twenty-one species of solitary radiolarians were obtained from 427 shells. Solitary radiolarian shells per 1 m^3 of sea water in samples 928-6SD-1 and -3 are 53.8 shells/m^3 and 110.8 shells/m^3, respectively.

Eight spumellarian and eight nassellarian species were identified from sample 928-6SD-1 collected from water of ca. 77-54 m deep as follows: *Tetrapyle octacantha* Müller, *Larcospira quadrangula* Haeckel, *Spongoliva ellipsoides* Popofsky, *Spongosphaera streptacantha* Haeckel, *Acanthosphaera actinota* (Haeckel), *Myelastrum trinibrachium* Takahashi, *Plegmosphaera pachypila* Haeckel, *Plectacantha trichoides* Jørgensen, *Plectacantha oikiskos* (Jørgensen), *Pseudocubus obeliscus* Haeckel, *Pseudodictyophimus gracilipes* (Bailey), *Neosemantis distephanus* Popofsky, *Phormacantha hystrix* (Jørgensen), *Peridium spinipes* Haeckel, and *Spirocyrtis scalaris* Haeckel. *Pseudocubus* sp. A, *Lophospyris* sp., and *Acanthodesmia* sp. were also obtained. Among these, *A. actinota*, *Pseudocubus* sp. A, *Lophospyris* sp., and *Acanthodesmia* sp. are relatively abundant, but the fauna is not monopolized by a few species as opposed to the surface water fauna (928-6SD-3) that is mentioned below.

Seven spumellarian and five nassellarian species were identified from the radiolarian fauna in sample 928-6SD-3 collected from waters ca. 35-0 m deep; these includes *Tetrapyle octacantha*, *Didymocyrtis tetrathalamus tetrathalamus* (Haeckel), *Spongoliva ellipsoids*, *Spongosphaera streptacantha*, *Styptosphaera spongiacea* Haeckel, *Acanthosphaera actinota*, *Myelastrum trinibrachium*, *Plectacantha oikiskos*, *Pseudocubus obeliscus*, *Neosemantis distephanus*, *Phormacantha hystrix*, and *Spirocyrtis scalaris*. *Pseudocubus* sp. A, *Lophospyris* sp., and *Acanthodesmia* sp. were also present. This fauna is characterized by the dominance of *S. streptacantha* and two species of the genus *Pseudocubus*: *P. obeliscus* and *Pseudocubus* sp. A. Other constituents include eleven specimens of *T. octacantha* but only 1-6 specimens each of the other species mentioned above.

Discussion

1. Relationship between the water mass structure and vertical faunal distribution

The radiolarian faunas in samples 928-6SD-1 and -3, collected from different depth intervals (ca. 77-54 m and 35-0 m), have a considerably different species composition suggesting that the vertical water mass structure may strongly influence every aspect of the depth-related faunal differences. As mentioned above, the sampling interval of 928-6SD-1 (ca. 77-54 m) corresponds to the LL which is characterized by a certain degree of temperature and salinity gradients; temperature of the sampling interval is ca. 17.0 to 18.4 ℃, and the salinity is ca. 34.5 to 34.2 psu. In sample 928-6SD-1, *Acanthosphaera actinota*, *Pseudocubus* sp. A, *Lophospyris* sp., and *Acanthodesmia* sp. are abundant compared to other species obtained i.e. less than ten specimens for each species (Table 1). The abundant occurrence of these species is the first detected characteristic of the deeper water mass in summer. In terms of comparison with the shallower fauna, it is also important to note that each constituent in the deeper fauna does not exceed 20 % of the fauna (Fig. 4). Regarding the relationship between the water mass structure and faunal composition, the sampling interval does not have distinct physical and chemical features, and the algal chlorophyll is low. The ecology of dominant species mentioned above is yet unknown, so the cause of their dominance and their relationship to the water mass structure remains to be solved.

The sampling interval of 928-6SD-3 (ca. 35-0 m) corresponds to the upper part of the LL and the UL. The upper part of the LL has a gentle peak of fluorescence intensity, but this value is very low compared to that of August, 2006 (Matsuoka, unpublished data). The UL shows a homogeneous temperature and salinity of ca. 24.0 ℃ and 34.6 psu, respectively, and has a low fluorescence intensity value. The primary faunal characteristic of sample 928-6SD-3 is the dominance of *Pseudocubus obeliscus* and *Pseudocubus* sp. A which comprise about 68.7 % of the fauna (Fig. 4). In spumellarians, *Spongosphaera streptacantha* totals 18.8 % of the fauna. *Tetrapyle octacantha* is the next most abundant spumellarian species with 11 specimens obtained. The common to abundant occurrence of *P. obeliscus* and *S. streptacantha* in the August and September faunas off Sado Island has been reported by Matsuoka et al. (2001) and Kurihara and Matsuoka (2004, 2005). These species occurred in the deeper sample (928-6SD-1), but less than ten specimens were obtained which contrasts with their abundance in the shallower sample (928-6SD-3) (Table 1). Therefore, the abundant occurrence of *Pseudocubus* species and *S. streptacantha* are the general trend in the faunal composition of surface waters shallower than at least 40 m off Sado Island during the summer season. Concerning other faunal constituents in sample 928-6SD-3, the standing stock except for *Spongosphaera streptacantha*, *Pseudocubus obeliscus*, and *Pseudocubus* sp. A is very low (13.8 shells/m^3) and faunal diversity is low. Thus, it is reasonable to think that the high standing stock of these three dominant species is caused by their temperature preference and adaptive strategies for the summer environment of the Japan Sea. For example in waters off Tassha, *S. streptacantha* appears only from July to October and is absent from March to June (Matsuoka, unpublished data). Based on the surface water temperature measured in July, 2005, *S. streptacantha* prefers water over approximately 20 ℃. In addition, this species strengthens the symbiotic relationship with dinoflagellates in September more than in July and August (Kurihara and Matsuoka, 2006). It is a possibile that this symbiotic relationship is an adaptation for an oligotrophic environment in the UL. *Tetrapyle octacantha* has been reported from the warm surface waters (e.g., Kling, 1979; Kling and Boltovskoy, 1995; Yamashita et al., 2002), and its occurrence in the shallower sample is concordant with the temperature preference of this species. According to Matsuoka (2006, 2007 in press), the feeding behavior of *P. obeliscus* may be highly sophisticated for attracting small organisms such as bacteria. The peak fluorescence intensity is in the lower sampling interval, thus the abundant occurrence of *P. obeliscus* is likely to be related to bacterial decomposition of algal remains from the standpoint of the microbial loop. In future work, more sampling related to water mass structure and ecological study will be needed to understand the depth-related formation of the fauna.

2. Annual variation between September faunas of 2000 and 2005

Matsuoka et al. (2001) first reported a radiolarian fauna sampled in September, 2000 that was obtained at locations approximately 2-3 km west of Tassha (Fig. 2). The fauna collected from water shallower than 150 m contained the following species: *Dictyocoryne profunda* Ehrenberg, *Didymocyrtis tetrathalamus tetrathalamus*, *Hymeniastrum euclidis* Haeckel, *Spongaster tetras tetras* Ehrenberg, *Spongodiscus biconcavus* Haeckel, *Spongosphaera streptacantha*, *Tetrapyle octacantha*, *Acanthodesmia vinculata* Müller, *Lipmanella dictyoceras* (Haeckel), *Lophophaena hispida* (Ehrenberg), *Neosemantis distephanus*, *Pseudocubus obeliscus*, *Pseudodictyophimus gracilipes*, *Spirocyrtis scalaris*, and *Zigocircus productus* (Hertwig). These authors suggested that the radiolarian fauna off Tassha may have been derived from the Tsushima Warm Current (TWC), a branch of the Kuroshio Current. The fauna of the present study is basically similar to the fauna reported by Matsuoka et al. (2001), but differs mainly in spumellarian species composition; i.e. the present fauna lacks discoidal spumellarians such as *D. profunda*, *S. t. tetras*, and *S. biconcavus*. Nassellarian species diversity was also low in the 2005 fauna. It is known that the flow force of the TWC varies in 2 to 3- and 10-year cycles (Japan Meteorological Agency, available online b). Together with the sorting effect (Matsuoka et al., 2001), the TWC fluctuation is also likely to influence the annual variation of the TWC-derived fauna. Further, according to Isobe (1999), the TWC is a part of the Taiwan-Tsushima Warm Current System, and source waters of the TWC are derived from the Taiwan Strait and the Kuroshio surface layer associated with the Yellow Sea Cold Water and the fresh water from the mainland of China. Therefore, long-term plankton sampling monitoring ocean current fluctuations in the Japan Sea and East China Sea should be continued to understand the formation of the surface water radiolarian fauna.

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