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Polycystine radiolarians in the Tsushima Strait in autumn of 2006

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Abstract. A total of 92 species or taxa of polycystine radiolarians were identified in depth-stratified plankton samples collected from the Tsushima Strait between Japan and Korea in autumn 2006. This assemblage can be divided into three groups: shallow eastern channel, shallow western channel, and bottom western channel. The distribution patterns are most likely related to different water masses. The western channel is influenced mainly by the Taiwan Current and coastal waters, which are characterized by low salinity and high nutrients, whereas water in the eastern channel is mainly from the Kuroshio Current. *Cycladophora davisiana*, which lives deeper than 500 m in the Japan Sea, was abundant in the western channel at 100–140 m. This suggests that the deeper microzooplankton in the Tsushima Strait are associated with colder and less saline water originating from the greater depths of the Japan Sea.

Key words: Bottom cold water, coastal water, Kuroshio Current, plankton, Radiolaria, Taiwan Current

Introduction

The Tsushima Current (TC) originates from the Kuroshio Current in the northwestern Pacific Ocean and the Taiwan Current in the East China Sea and transports tropical biota together with warm seawater into the Japan Sea via the Tsushima Strait (130 m sill depth) between Japan and Korea (Figure 1). In one group of marine planktonic protozoa, polycystine radiolarians (hereafter, radiolarians), a total of 157 taxa have been identified in the Japan Sea (Itaki, 2009), and it is possible that most of these are warm-water species associated with the TC. Sediment core studies have shown that such warm-water radiolarians extended their distribution from the East China Sea through the Tsushima Strait during periods of higher sea level stand associated with each interglacial period (e.g., Sakai, 1984; Morley *et al.*, 1986; Itaki *et al.,* 2004, 2007).

The Tsushima Strait is divided by Tsushima Island into eastern and western channels. The TC passing through each of these channels is influenced by different water masses; there is a greater influence of Kuroshio water in the eastern channel and of the Taiwan Current and coastal waters in the western channel (e.g., Isobe, 1999; Senjyu *et al.*, 2008). In the deeper part of the western channel, a cold-water mass is being intruded from the intermediate or greater depths of the Japan Sea (e.g., Lim and Chang, 1969; Cho and Kim, 1998). However, little is known about the relationship between these different water masses and the distribution of marine plankton assemblages such as radiolarians. Understanding the local distribution of microorganisms in the Tsushima Strait is important for tracing their migration into the Japan Sea, and as fundamental information for reconstruction of past TC changes based on their fossil records.

We collected plankton samples from the western and eastern channels of the Tsushima Strait in autumn of 2006 and examined foraminifers (Kimoto *et al.*, 2009) and radiolarians (this study). We describe herein the radiolarian assemblages in these samples and discuss their relationship to hydrographic conditions.

Oceanographic setting

The volume transport of the TC flowing in the Tsushima Strait is high during August to October. Sea-surface temperature (SST) and salinity (SSS) vary seasonally between winter (average: 13°C, 34.5 psu) and summer (26°C, 32 psu) (e.g.,

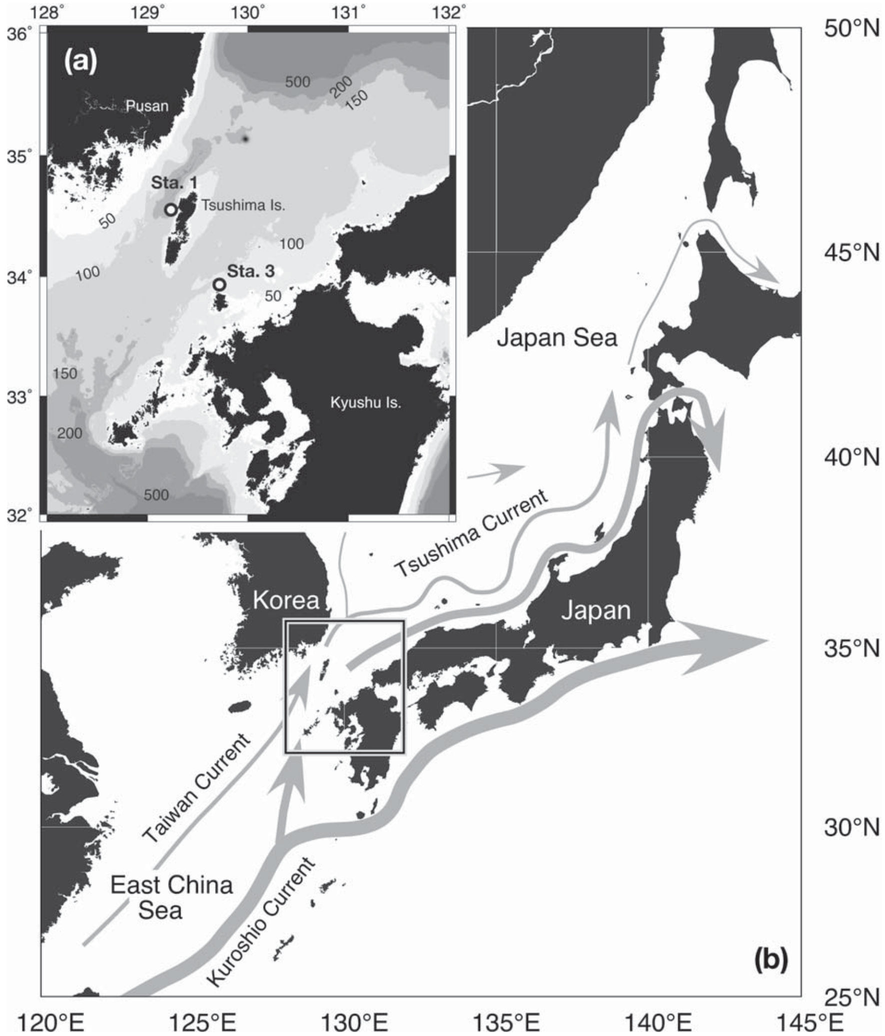

Figure 1. Maps of the study area showing **(a)** bathymetry and plankton sampling stations 1 and 3 and **(b)** the main surface currents.

Senjyu *et al.*, 2008). These surface water conditions reflect the mixing of the Kuroshio water with the Taiwan Current and coastal waters. According to Isobe (1999), the Taiwan–Tsushima Current system is the main component of the TC water from January to September, whereas the Kuroshio affects the TC from October to December.

The Tsushima Strait is divided into two channels by Tsushima Island. The sill depth is greater in the western channel between Pusan, Korea, and Tsushima Island (130 m) than in the eastern channel between Tsushima Island and Kyushu, Japan (80 m). Recently, Senjyu *et al.* (2008) reviewed hydrographic conditions in the Tsushima Strait. The TC in the western channel mainly originates from the Taiwan Current and coastal waters from the shelf area of the East China Sea, and separates into two flows—the second and third branches—in the southwestern Japan Sea. The water in the eastern channel, which is influenced more by the Kuroshio Current, becomes the main branch of the TC flowing northward along the Japanese coast. The bottom cold water (<10°C), recognized below approximately 100 m in the western channel, is probably an intrusion from intermediate or greater depths of the northern area of the Japan Sea, according to hydrographic and chemical data (Lim and Chang, 1969; Cho and Kim, 1998).

Materials and Methods

Plankton samples were obtained from the eastern channel (Station [Sta.] 3: 33°56.15′N, 129°43.34′E, 92 m water depth) on 31 October 2006, and from the western channel (Sta. 1: 32°72′N, 120°15.62′E, 148 m water depth) on 3 November 2006 (Figure 1a). Vertical tows were carried out with a closing net (63-μm mesh) with a 45-cm diameter mouth over three or four depth intervals: 0–30, 30–50, 50–

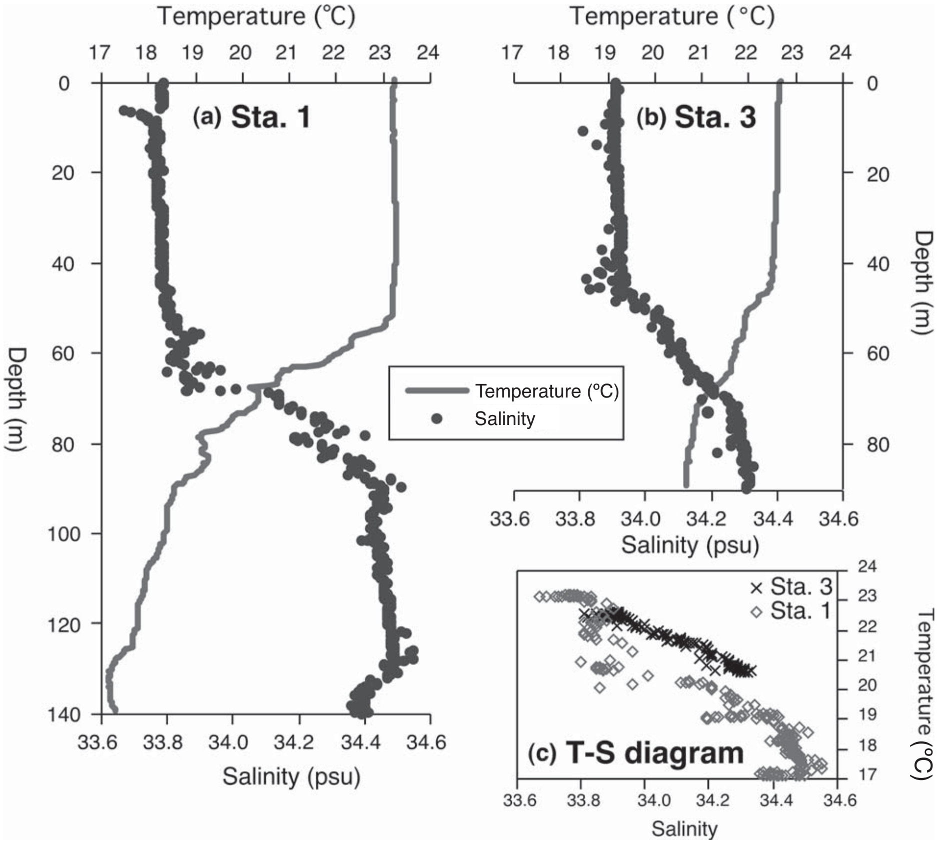

Figure 2. Depth profiles of temperature and salinity at stations 1 and 3 (**a** and **b**, respectively), and T–S diagram showing data from both stations (**c**).

80 m at Sta. 3; 0–30, 30–60, 60–100, 100–140 m at Sta. 1. A compact salinity–temperature profiler (Compact-CT, Alec Electronics Co. Ltd., Kobe, Japan) was attached to the net frame to collect in situ hydrographic data.

Material from plankton tows was preserved immediately after collection in >99.5% ethanol. Sample processing involved first picking out all foraminiferal tests; then the material was separated according to size by using a sieve with mesh-size 1 mm to exclude the large-sized zooplankton such as copepods, and the material left on the sieve with mesh size 45 μm was used for the present radiolarian studies. The residual material (45 μm–1 mm) was divided into two equal parts using a plankton splitter. One part was processed sequentially with 10% HCl and 10% hydrogen peroxide solutions to remove carbonates and organic material, respectively. The other half of the material was stained with Rose bengal solution for later identification of living specimens. To prepare slides for microscopic examination, both the chemically treated and stained subsamples were again passed through the 45-μm mesh sieve, and then split into aliquots of 1/4 to 1/8 of the original plankton volume of the plankton sample. These aliquots were transferred onto a glass slide and mounted in Canada balsam.

All polycystine radiolarians on the slides were identified and counted under an optical microscope at magnifications of 100X or 200X. Because the plankton nets were not equipped with flow meters, the exact volume of water sampled could not be calculated and data on the absolute radiolarian concentrations in the water column are unavailable. However, as an approximation, we used the net mouth diameter and the distance towed to estimate the volume of water passing through the net.

Results

Hydrographic observations

Vertical profiles of temperature and salinity at both Sta. 1 and Sta. 3 show a thermocline at 50–70 m (Figure 2). The thermocline was steeper, that is, stratification was stronger, in the western channel. In the layer above the thermocline, the water at Sta. 1 was very slightly warmer and less saline (23°C and 33.8 psu) than at Sta. 3 (22.5°C and 33.9 psu). In contrast, this trend was reversed below the thermocline (Sta. 1: <19°C, >34.4 psu; Sta. 3: ca. 20.5°C, ca. 34.3 psu). The cooler and more saline surface water at Sta. 3 may result from mixing with deeper water from below the thermocline,

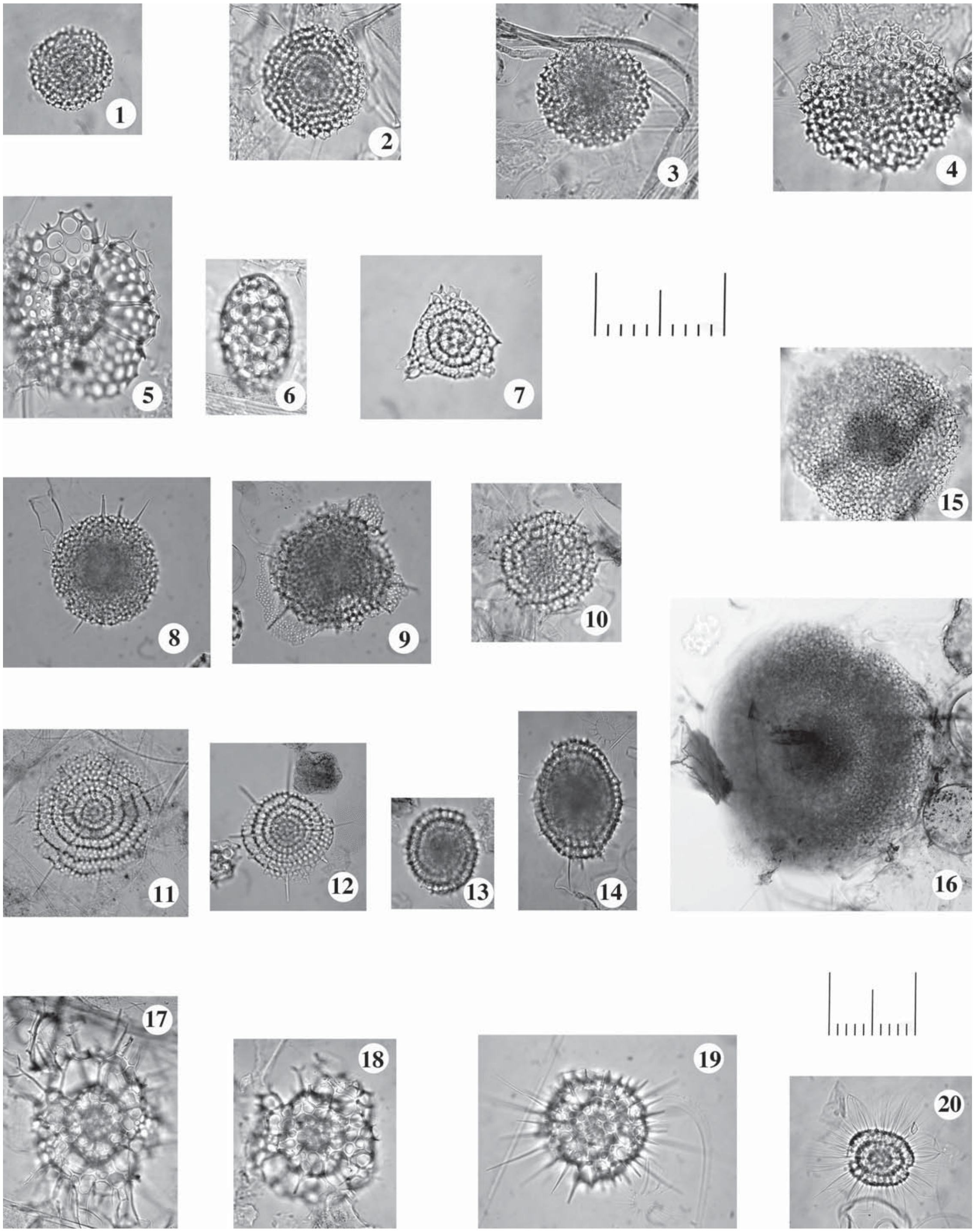

Figure 3. Spumellarians from the Tsushima Strait. Scale equals 100 μm: larger scale for 1 to 7 and smaller one for 8 to 20. **(1–2)** *Spongodiscus* sp. B (Sta. 1, 30–60 m), **(3)** *Spongodiscus resurgens* Ehrenberg (Sta. 1, 30–60 m), **(4)** *Spongodiscus* sp. C (Sta. 1, 30–60 m), **(5)** *Larcospira quadrangula* Haeckel (Sta. 3, 50–80 m), **(6)** *Larcopyle buetschlii* Dreyer (Sta. 3, 50–80 m), **(7)** *Triastrum aurivillii* Cleve (Sta. 1, 60–100 m), **(8)** *Spongotrochus glacialis* Popofsky (Sta. 1, 100–140 m), **(9)** *Perichlamydium praetextum* (Ehrenberg) (Sta. 3, 30–50 m), **(10)** *Perichlamydium* sp. cf. *P. praetextum* (Ehrenberg) (Sta. 1, 30–60 m), **(11)** *Stylodictya arachnia* Müller (Sta. 1, 30–60 m), **(12)** *Stylodictya arachnia* Müller (Sta. 1, 100–140 m), **(13)** *Larcospira minor* (Jørgensen) (Sta. 3, 50–80 m), **(14)** *Spongurus* sp. cf. *S. elliptica* (Ehrenberg) (Sta. 3, 0–30 m), **(15–16)** *Spongodiscus biconcavus* Haeckel (Sta. 3, 50–80 m), **(17–18)** *Phorticium polycladum* Tan and Tchang (Sta. 1, 30–60 m), **(19)** *Lithelius alveolina* Haeckel (Sta. 3, 0–30 m), **(20)** Lithelidae gen. et sp. indet. (Sta. 1, 60–100 m).

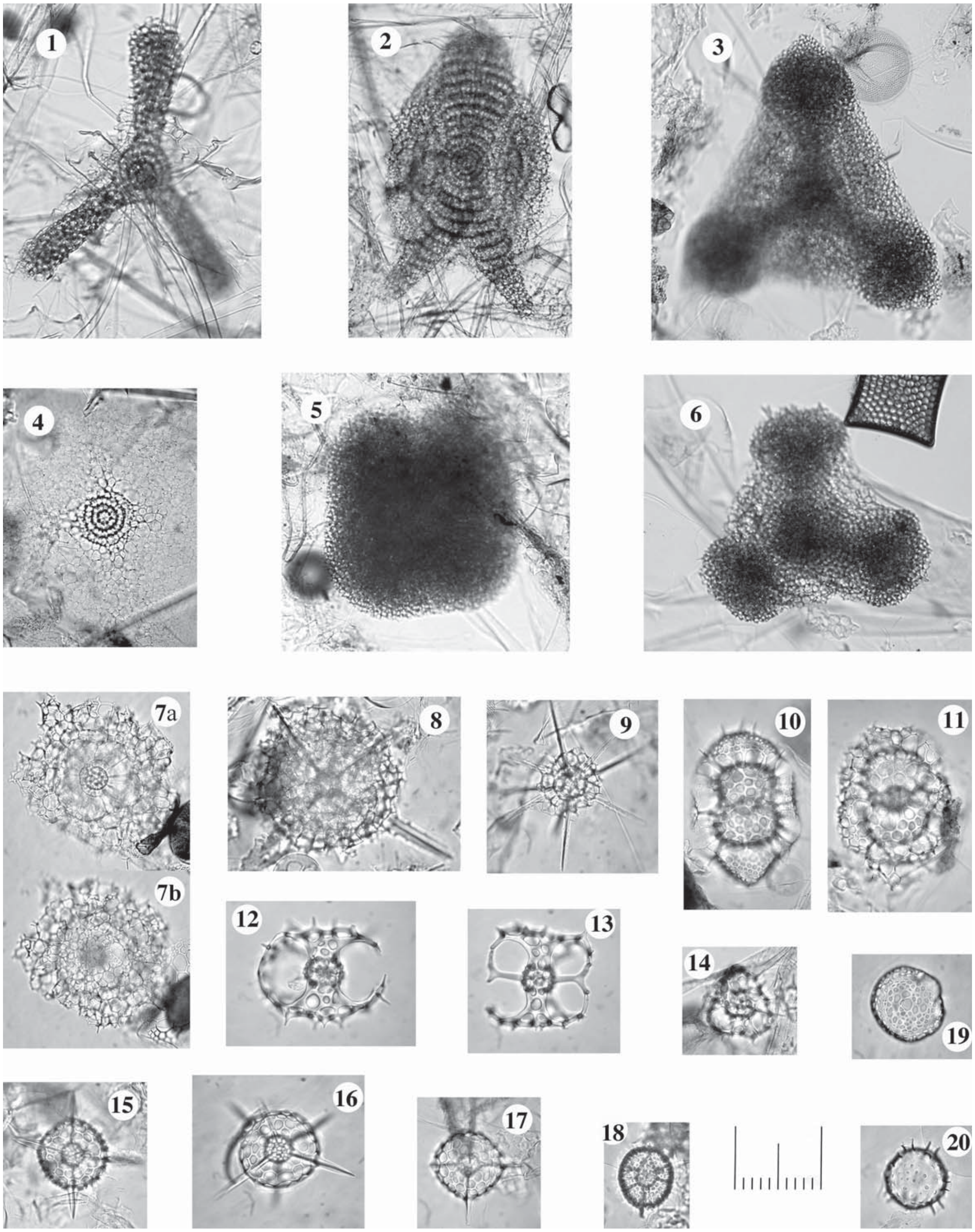

Figure 4. Spumellarians from the Tsushima Strait. Scale equals 100 μm. **(1)** *Euchitonia furcata* Ehrenberg (Sta. 1, 30–60 m), **(2)** *Amphirhopalum ypsilon* Haeckel (Sta. 1, 60–100 m), **(3)** *Dictyocoryne profunda* Ehrenberg (Sta. 3, 50–80 m), **(4)** *Myelastrum* sp. (Sta. 1, 30–60 m), **(5)** *Spongaster tetras tetras* Ehrenberg (Sta. 1, 30–60 m), **(6)** *Dictyocoryne truncatum* (Ehrenberg) (Sta. 3, 50–80 m), **(7)** *Tetrasphaera spongiosa* Popofsky (Sta. 1, 60–100 m), **(8)** *Spongosphaera streptacantha* Haeckel (Sta. 1, 30–60 m), **(9)** *Rhizoplegma boreale* (Bailey) (Sta. 3, 50–80 m), **(10)** *Didymocyrtis tetrathalamus* (Haeckel) (Sta. 3, 50–80 m), **(11)** *Spongoliva ellipsoides* Popofsky (Sta. 3, 50–80 m), **(12)** *Tetrapyle octacantha* Müller, group (Sta. 1, 60–100 m), **(13)** *Octopyle stenozona* Haeckel (Sta. 1, 60–100 m), **(14)** *Hexapyle* sp. (Sta. 1, 30–60 m), **(15)** *Hexacontium pachydermum* Jørgensen (Sta. 1, 30–60 m), **(16)** *Hexacontium enthacanthum* Jørgensen (Sta. 1, 60–100 m), **(17)** *Hexacontium hostile* Cleve (Sta. 3, 50–80 m), **(18)** *Druppatractus irregularis* Popofsky (Sta. 1, 30–60 m), **(19)** *Collosphaera invaginata* (Haeckel) (Sta. 1, 100–140 m), **(20)** *Siphonosphaera* sp. (Sta. 1, 100–140 m).

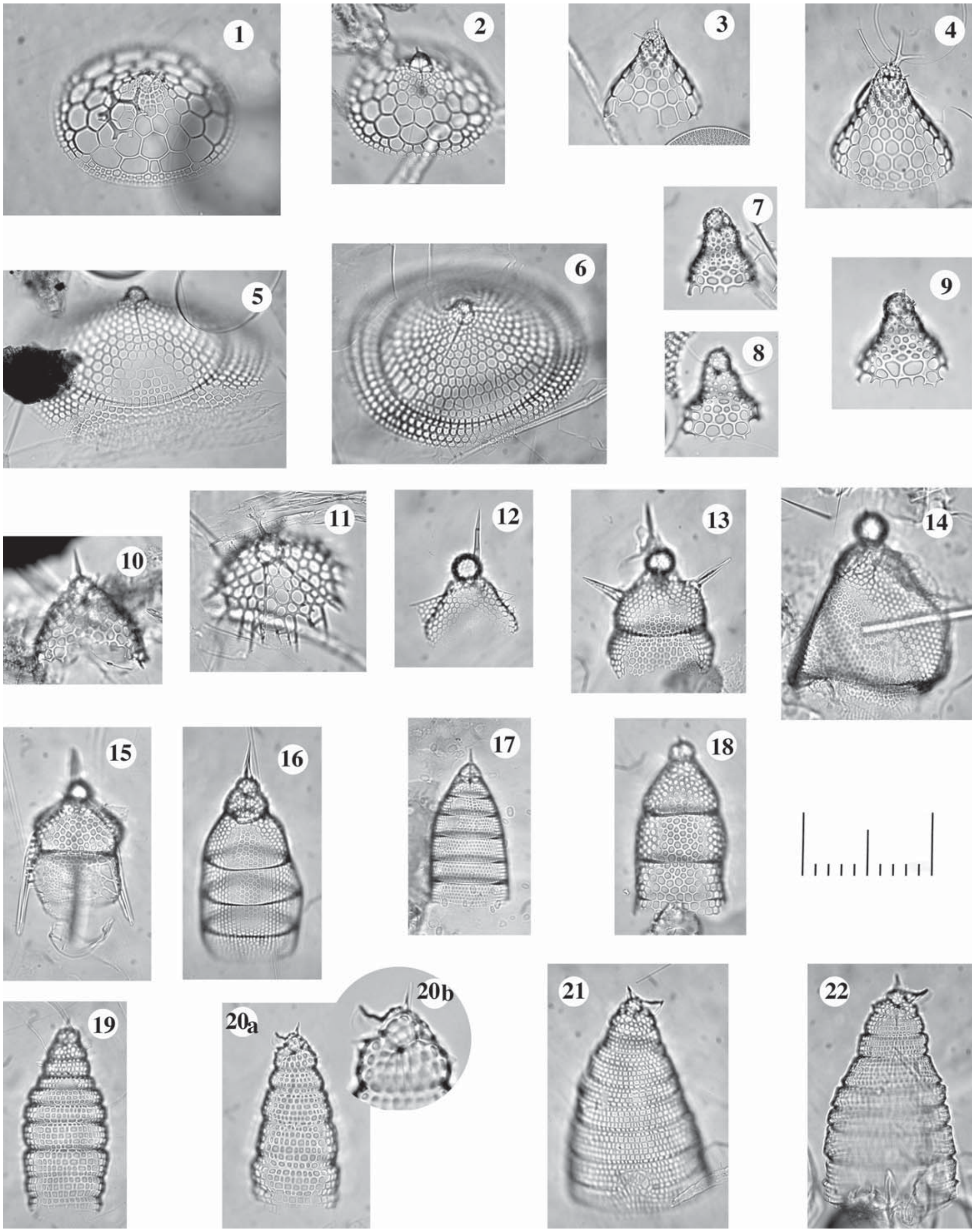

Figure 5. Nassellarians from the Tsushima Strait. Scale equals 100 µm. **(1)** *Eucecryphalus gegenbauri* Haeckel (Sta. 1, 60–100 m), **(2)** *Eucecryphalus gegenbauri* Haeckel (Sta. 1, 100–140 m), **(3)** *Eucecryphalus* sp. (Sta. 1, 100–140 m), **(4)** *Eucecryphalus cervus* (Ehrenberg) (Sta. 1, 60–100 m), **(5)** *Eucecryphalus elisabethae* (Haeckel) (Sta. 1, 60–100 m), **(6)** *Eucecryphalus elisabethae* (Haeckel) (Sta. 1, 30–60 m), **(7–9)** *Cycladophora davisiana* Ehrenberg (Sta. 1, 100–140 m), **(10)** *Ceratocyrtis* sp. B (Sta. 3, 50–80 m), **(11)** *Lampromitra erosa* Cleve (Sta. 3, 50–80 m), **(12)** *Lipmanella* sp. (Sta. 3, 0–30 m), **(13)** *Lipmanella dictyoceras* (Haeckel) (Sta. 1, 30–60 m), **(14)** *Lipmanella pyramidale* (Popofsky) (Sta. 1, 30–60 m), **(15)** *Pterocanium praetextum* (Ehrenberg) (Sta. 3, 0–30 m), **(16)** *Eucyrtidium hexagonatum* Haeckel (Sta. 1, 60–100 m), **(17)** *Eucyrtidium hexastichum* (Haeckel) (Sta. 1, 100–140 m), **(18)** *Eucyrtidium* sp. (Sta. 1, 100–140 m), **(19)** *Stichocorys seriata* Jørgensen (Sta. 1, 30–60 m), **(20)** *Stichocorys seriata* Jørgensen (Sta. 1, 60–100 m), **(21)** *Spirocyrtis scalaris* Haeckel (Sta. 1, 60–100 m), **(22)** *Spirocyrtis scalaris* Haeckel (Sta. 1, 30–60 m).

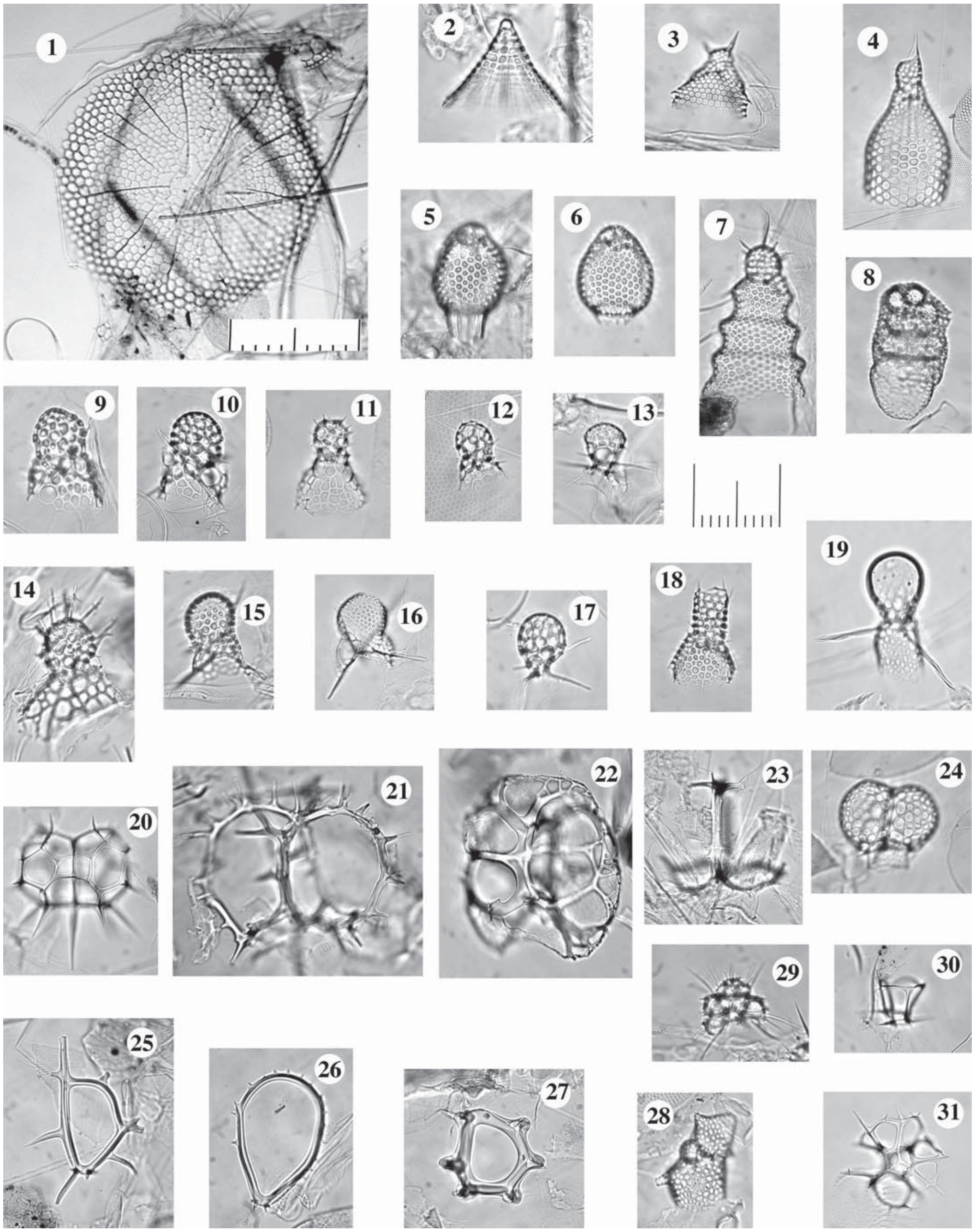

Figure 6. Nassellarians from the Tsushima Strait. Scale equals 100 μm: larger scale for 1 and smaller one for 2 to 31. **(1)** *Theophormis callipilium* Haeckel (Sta. 1, 60–100 m), **(2)** *Litharachnium tentorium* Haeckel (Sta. 1, 60–100 m), **(3)** *Stichopilium bicorne* Haeckel (Sta. 1, 60–100 m), **(4)** *Anthocyrtidium* sp. (Sta. 1, 100–140 m), **(5)** *Carpocanistrum* spp. (Sta. 1, 30–60 m), **(6)** *Carpocanistrum* spp. (Sta. 1, 100–140 m), **(7)** *Stichopilium anocor* Renz (Sta. 1, 60–100 m), **(8)** *Botryocyrtis scutum* (Harting) (Sta. 3, 0–30 m), **(9)** *Dimelissa thoracites* (Haeckel) (Sta. 3, 30–50 m), **(10)** *Dimelissa thoracites* (Haeckel) (Sta. 3, 0–30 m), **(11)** *Lophophaena hispida* (Ehrenberg) (Sta. 1, 60–100 m), **(12)** *Lophophaena hispida* (Ehrenberg) small form (Sta. 3, 0–30 m), **(13)** *Lophophaena* spp. (Sta. 3, 30–50 m), **(14)** *Lophophaena* sp. (Sta. 3, 50–80 m), **(15)** *Lophophaena* spp. (Sta. 3, 50–80 m), **(16)** *Lithomelissa laticeps* Jørgensen (Sta. 3, 50–80 m), **(17)** *Arachnocorallium calvata* (Haeckel) (Sta. 3, 0–30 m), **(18)** *Lophophaena variabilis* (Popofsky) (Sta. 3, 0–30 m), **(19)** *Peromelissa phalacra* Haeckel (Sta. 1, 60–100 m), **(20)** *Lophospyris pentagona* (Ehrenberg) (Sta. 3, 50–80 m), **(21)** *Acanthodesmia vinculata* Müller (Sta. 1, 30–60 m), **(22)** *Liriospyris reticulata* (Ehrenberg) (Sta. 1, 30–60 m), **(23)** *Acanthodesmia micropora* (Popofsky) (Sta. 1, 30–60 m), **(24)** *Phormospyris stabilis* (Goll) *scaphipes* (Haeckel) (Sta. 1, 60–100 m), **(25)** *Zygocircus productus* (Hartwig), group (Sta. 1, 100–140 m), **(26)** *Zygocircus productus* (Hartwig), group (Sta. 1, 30–60 m), **(27)** *Tholospyris* spp. (Sta. 1, 30–60 m), **(28)** *Acrobotrys teralans* Renz (Sta. 1, 30–60 m), **(29)** *Arachnocorys castanerides* Tan & Tchang (Sta. 3, 50–80 m), **(30–31)** *Pseudocubus obeliscus* Haeckel (Sta. 3, 0–30 m).

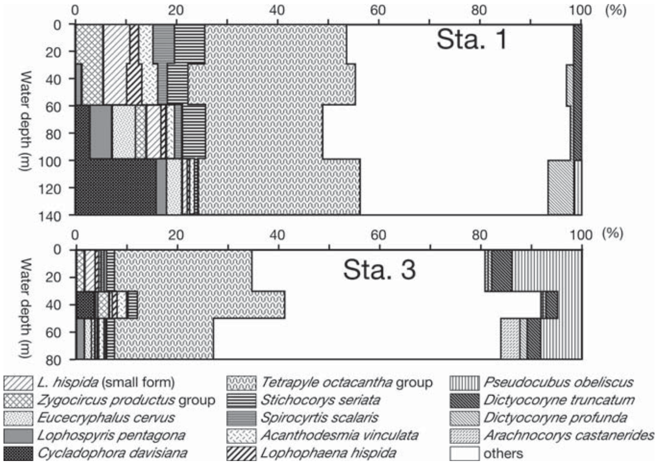

Figure 7. Radiolarian assemblages at stations 1 and 3.

made possible by the weaker stratification. At Sta. 1, the cooler (<17°C) and less saline (<34.4 psu) water at 130–140 m may be related to the bottom cold water.

Radiolaria

Radiolarians were found in all samples examined. The standing stock of total radiolarians ranged from 70 to 400 tests/m^3 (counts of stained and empty skeletons were combined); the maximum abundance was observed at 30–60 m at Sta. 1. A total of 92 taxa, including 42 spumellarians and 50 nassellarians, were identified in the samples (Table 1, Figures 3–6), with *Tetrapyle octacantha* as the most dominant species, accounting for 20–30% of the fauna in each sample (Figure 7). We performed Q-mode and R-mode cluster analyses based on the 32 most dominant taxa that occurred with an abundance of more than 3 tests/m^3 in any one sample, using a multivariate analysis program for the Macintosh Computer (Mac Multivariate Analysis Program ver. 1.0a; Esumi Co. Ltd., 2003) (Figure 8). Correlation coefficients were used as a measure of similarity between clusters.

Q-mode cluster analysis distinguished three assemblage groups (Figure 8a). Cluster Q-a was found from 0 to 80 m at Sta. 3 and is characterized by high abundance of *Pseudocubus obeliscus*. Cluster Q-b, corresponding to 0–100 m at Sta. 1, is characterized by *Stichocorys seriata*, *Spirocyrtis scalaris*, *Acanthodesmia vinculata* and *Lophophaena hispida*. The assemblage from 100 to 140 m at Sta. 1 was distinguished from other groups as cluster Q-c by the abundant occurrence of *Cycladophora davisiana*.

For R-mode cluster analysis, the standing stock of each species or species group in a sample (#/m^3) was normalized to the maximum standing stock for that species or group in all samples as follows (Itaki *et al.*, 2008):

Normalized standing stock = Sample standing stock/Maximum standing stock of all samples.

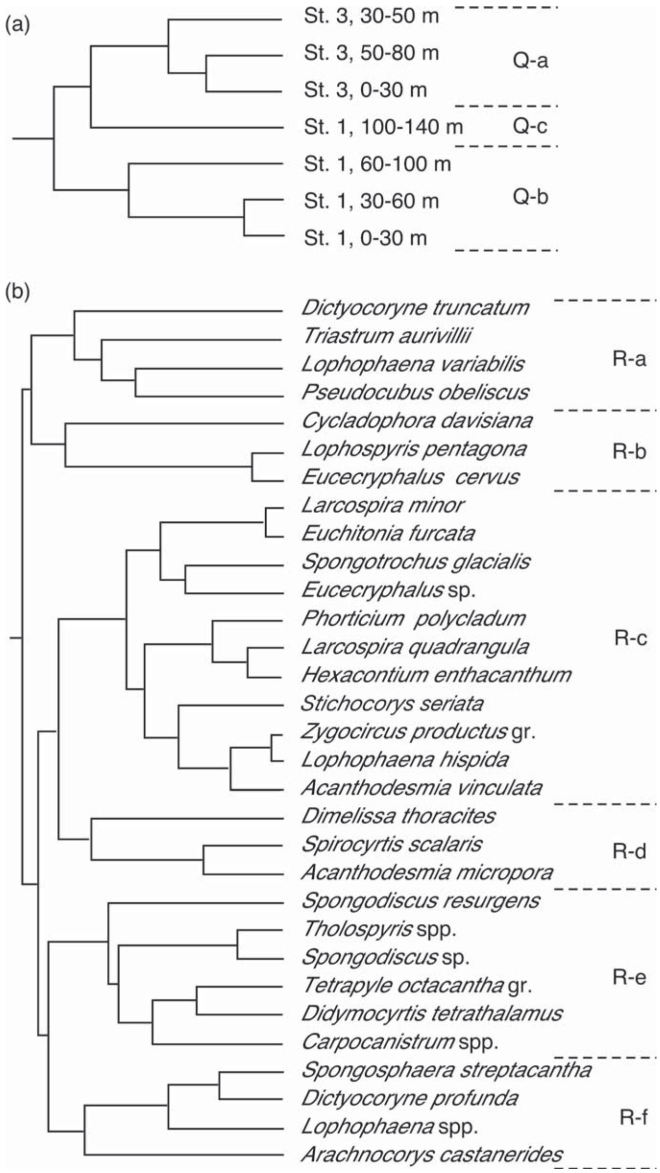

Figure 8. Dendrograms from Q-mode and R-mode cluster analysis (a and b, respectively).

R-mode cluster analysis distinguished six assemblage groups (Figure 8b). Species-specific standing stocks for the six groups are presented in Figure 9.

Cluster R-a is composed of 4 species: *Dictyocoryne truncatum*, *Triastrum aurivillii*, *Lophophaena variabilis*, and *P. obeliscus*. The highest standing stocks of these species were recognized in the surface sample (0–30 m) of Sta. 3.

Cluster R-b includes 3 species: *C. davisiana*, *Lophospyris pentagona,* and *Eucecryphalus cervus*. Standing stocks for all species in this cluster were higher below the thermocline. Abundances of *L. pentagona* and *E. cervus* reached maxima at 60–100 m at both stations; however, *C. davisiana* was rare

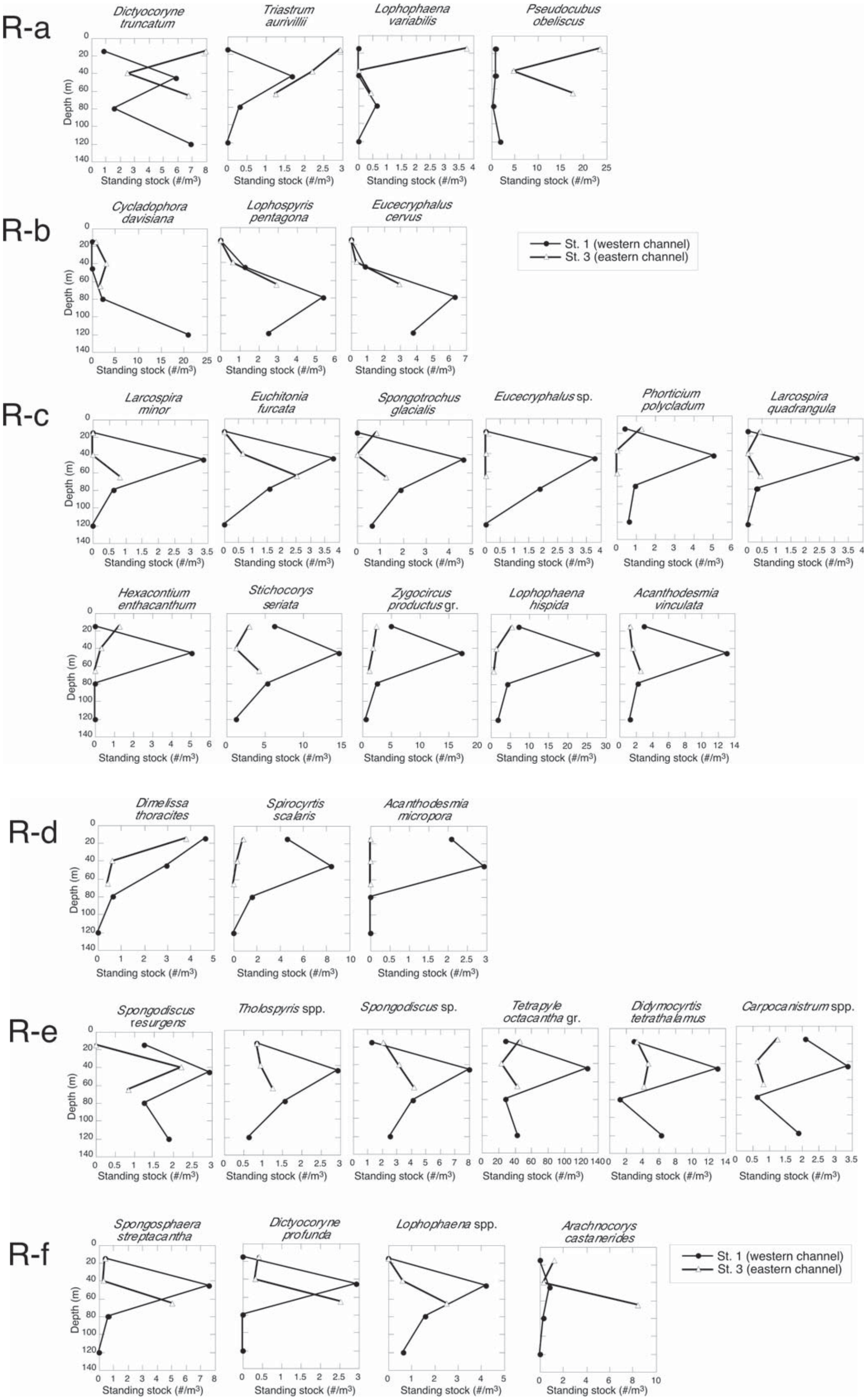

Figure 9. Standing stocks (#/m^3) at stations 1 and 3 of the 32 taxa used in cluster analysis.

Table 1. Polycystine radiolarians found in the Tsushima Strait in this study, references used for their taxonomic identification, and count data. Plus mark (+) indicates present in the sample. Asterisk (*) denotes species included in the R-mode factor analysis.

		Location	St. 1				St. 3		
		Water depth	0–30 m	30–60 m	60–100 m	100–140 m	0–30 m	30–50 m	50–80 m
		Assumed filtration	4.8 m^3	4.8 m^3	6.4 m^3	6.4 m^3	4.8 m^3	3.2 m^3	4.8 m^3
		Split	1/2	1/2	1/2	1/4	1/2	1/1	1/2
		Total counts	250	930	388	215	401	269	517
Taxa	Figure (s)	References	%	%	%	%	%	%	%
SPUMELLARIA									
Actinomma medianum Nigrini		Itaki, 2009			0.3				
Amphirhopalum ypsilon Haeckel	4-2	Itaki, 2009			0.3				
Collosphaera invaginata (Haeckel)	4-19	Bjørklund & Goll, 1979	0.8			0.5			
Dictyocoryne truncatum (Ehrenberg)*	4-6	Itaki, 2009	0.8	1.5	1.3	5.1	4.7	3.0	3.1
Dictyocoryne profunda Ehrenberg*	4-3	Itaki, 2009		0.8			0.2	0.4	1.2
Didymocyrtis tetrathalamus (Haeckel)*	4-10	Itaki, 2009	2.8	3.3	1.0	4.7	2.0	5.6	1.9
Druppatractus irregularis Popofsky	4-18	Tan & Chen, 1999		0.1					
Euchitonia furcata Ehrenberg*	4-1	Itaki, 2009	0.4	2.4	1.5			1.1	1.4
Heliodiscus asteriscus Haeckel		Itaki, 2009	0.4	0.1					
Heliodiscus echiniscus Haeckel		Itaki, 2009				0.5	0.5		
Hexacontium enthacanthum Jørgensen*	4-16	Nigrini & Moore, 1979		1.3			0.7	0.4	
Hexacontium hostile Cleve	4-17	Itaki *et al.*, 2008							0.2
Hexacontium laevigatum Haeckel		Itaki *et al.*, 2008				0.5			
Hexacontium pachydermum Jørgensen	4-15	Itaki *et al.*, 2008		0.4					0.2
Hexacontium sp.			0.4		0.3				
Hexapyle sp.	4-14		0.4	0.3	2.1	0.5	0.7	1.1	0.4
Larcopyle buetschlii Dreyer	3-6	Itaki, 2009		0.1	0.3				0.4
Larcospira minor (Jørgensen)*	3-13	Itaki, 2009		0.9	0.5				0.4
Larcospira quadrangula Haeckel*	3-5	Itaki, 2009		1.0	0.3		0.2		0.2
Lithelius alveolina Haeckel	3-19	Renz, 1976					0.2		
Lithelidae gen. et sp. indet.	3-20				+		0.0		
Myelastrum sp.	4-3								
Octopyle stenozona Haeckel	4-13	Itaki, 2009		0.3	0.3		1.0		0.8
Phorticium polycladum Tan & Tchang*	3-17, -18	Tan & Chen, 1999	0.4	1.3	0.8	0.5	0.7		
Perichlamydium praetextum (Ehrenberg)	3-9	Ogane *et al.*, 2009						0.4	0.4
Perichlamydium sp. cf. *P. praetextum* (Ehrenberg)	3-10			0.2				0.4	
Rhizoplegma boreale (Bailey)	4-9	Itaki, 2009				0.5			
Siphonosphaera socialis Haeckel	4-20	Tan & Chen, 1999				0.5			
Spongaster tetras tetras Ehrenberg	4-5	Itaki, 2009	0.4	0.1	0.3	0.5		0.4	0.4
Spongoliva ellipsoides Popofsky	4-11	Itaki, 2009		0.3	0.3			1.1	0.6
Spongodiscus biconcavus Haeckel	3-15, -16	Itaki, 2009		0.3	0.3				0.4
Spongodiscus resurgens Ehrenberg*	3-3	Itaki, 2009	1.2	0.8	1.0	1.4		2.6	0.4
Spongodiscus sp. B	3-1, -2	Itaki *et al.* 2003				1.4	0.5	1.9	0.8
Spongodiscus sp. C*	3-4		1.2	2.0	3.4	1.9	1.2	3.7	1.9
Spongosphera streptacantha Haeckel*	4-8	Itaki, 2009	0.4	1.9	0.5		0.2	0.4	2.3
Spongotrochus glacialis Popofsky*	3-8	Itaki, 2009		1.2	1.5	0.5	0.5		0.6
Spongurus sp. cf. *S. elliptica* (Ehrenberg)	3-14	Itaki, 2009					1.0	0.4	0.2
Stylodictya arachnia Müller	3-11, -12	Tan & Chen, 1999	1.2	0.6	1.8	1.9	0.5	1.1	0.2
Tetrapyle octacantha Müller, group*	4-12	Itaki, 2009	27.6	32.6	23.2	31.6	26.9	28.3	19.7
Tetrasphaera spongiosa Popofsky	4-7	Tan & Chen, 1999			0.3				
Tholospira sp.				0.3					
Triastrum aurivillii Cleve*	3-7	Tan & Chen, 1999		0.4	0.3		1.7	2.6	0.6
Other spumellarians			6.0	6.5	11.3	7.4	9.0	12.6	13.7

in samples from shallower than 100 m at both sites and drastically increased in abundance in the deepest sample (100–140 m) of Sta. 1.

Cluster R-c is composed of 11 species: *Larcospira minor*, *Euchitonia furcata*, *Spongotrochus glacialis*, *Eucecryphalus* sp., *Phorticium polycladum*, *Larcospira quadrangula*, *Hexacontium enthacanthum*, *S. seriata*, *Zygocircus productus* group, *L. hispida*, and *A. vinculata*, all of which had standing stocks notably higher in samples from 30–60 m at Sta. 1.

Cluster R-d consists of 3 species: *Dimelissa thoracites*, *S. scalaris*, and *Acanthodesmia micropora*. The pattern of abundance of these species was similar to that of those in cluster R-c, except that standing stocks in samples from 0–30 m exceeded 50% of the standing stocks at 30–60 m at Sta. 1.

Cluster R-e includes 6 species or species groups: *Spongodiscus* sp. cf. *S. resurgens*, *Tholospyris* spp., *Spongodiscus*

Table 1. (continued)

		Location	St. 1				St. 3		
		Water depth	0–30 m	30–60 m	60–100 m	100–140 m	0–30 m	30–50 m	50–80 m
		Assumed filtration	4.8 m^3	4.8 m^3	6.4 m^3	6.4 m^3	4.8 m^3	3.2 m^3	4.8 m^3
		Split	1/2	1/2	1/2	1/4	1/2	1/1	1/2
		Total counts	250	930	388	215	401	269	517
Taxa	Figure (s)	References	%	%	%	%	%	%	%
NASSELLARIA									
Acanthodesmia micropora (Popofsky)*	6-23	Itaki, 2009	2.0	0.8					
Acanthodesmia vinculata Müller*	6-21	Itaki, 2009	2.8	3.3	1.8	0.9	0.7	1.9	1.2
Acrobotrys teralans Renz	6-28	Renz, 1976	0.4	0.4		0.5			
Anthocyrtidium sp.	6-4					+			
Arachnocorallium calvata (Haeckel)	6-17	Itaki, 2009					0.7	0.4	0.2
Arachnocorys castanerides Tan & Tchang*	6-29	Itaki, 2009		0.2	0.3		0.7	0.4	3.9
Botryopyle scutum (Harting)	6-8	Itaki, 2009		0.2					
Carpocanistrum spp.*	6-5, -6		2.0	0.9	0.5	1.4	0.7	0.7	0.4
Ceratocyrtis sp. B	5-10	Itaki, 2009		0.1			0.2		0.4
Clathrocircus sp.					0.3			0.4	
Cycladophora davisiana Ehrenberg*	5-7, -8, -9	Itaki, 2009			1.8	15.3	0.5	3.7	0.8
Dimelissa thoracites (Haeckel)*	6-9, -10	Itaki, 2009	4.4	0.8	0.5		2.2	0.7	0.2
Eucecryphalus cervus (Ehrenberg)*	5-4	Itaki, 2009		0.2	5.2	2.8		0.4	1.4
Eucecryphalus elisabethae(Haeckel)*	5-5, -6	Itaki, 2009		1.0	1.5				
Eucecryphalus gegenbauri Haeckel	5-1, -2	Haeckel, 1862			1.5		0.2		1.2
Eucecryphalus sp.	5-3					+			
Eucyrtidium hexagonatum Haeckel	5-16	Nigrini & Moore, 1979		0.4	1.0		0.5	0.4	
Eucyrtidium hexastichum (Haeckel)	5-17	Itaki, 2009		0.1	0.5	0.5	0.5	0.4	0.6
Eucyrtidium sp.	5-18					0.5			
Lampromitra erosa Cleve	5-11	Itaki, 2009							0.6
Lipmanella dictyoceras (Haeckel)	5-13	Itaki, 2009	0.8	0.3			0.5		
Lipmanella pyramidale (Popofsky)	5-14	Itaki, 2009		0.2					
Lipmanella sp.	5-12			0.2					
Liriospyris reticulata (Ehrenberg)	6-22	Nigrini & Moore, 1979		0.1	0.3				
Litharachnium tentorium Haeckel	6-2	Itaki, 2009							+
Lithomelissa sp. cf. *L. laticeps* Jørgensen	6-16								+
Lithomelissa setosa Jørgensen		Itaki, 2009					0.5		
Lophophaena buetschlii (Haeckel)		Itaki, 2009	0.4						0.4
Lophophaena hispida (Ehrenberg)*	6-11	Itaki, 2009	5.2	4.5	3.1	0.9	2.0	1.1	0.2
L. hispida (small form)*	6-12		1.6	2.6	0.5	0.5	1.2	0.7	0.2
Lophophaena variabilis (Popofsky)*	6-18	Itaki, 2009			0.5		2.2		0.2
Lophophaena witjazii Petrushevskaya*		Itaki, 2009	0.4	0.1					0.2
Lophophaena spp. *	6-13, -14, -15			1.1	1.3	0.5		0.7	1.2
Lophospyris pentagona (Ehrenberg)*	6-20	Itaki, 2009		0.3	4.4	1.9		0.7	1.4
Peromelissa phalacra Haeckel	6-19	Petrushevskaya, 1971			0.3		0.2		
Phormospyris stabilis (Goll) *scaphipes* (Haeckel)	6-24	Itaki, 2009	0.4	0.5	0.8				
Plagiacanthidae gen. et spp. indet.			4.0	1.1		0.5	0.2	0.4	
Plectacantha cremastoplegma Nigrini		Itaki, 2009					0.2		
Pseudocubus obeliscus Haeckel*	6-30, -31	Itaki, 2009	0.8	0.2	0.3	1.4	14.0	5.6	8.1
Pseudodictyophimus gracilipes (Bailey)		Itaki, 2009				0.5			
Pterocanium praetextum (Ehrenberg)	5-15	Itaki, 2009				0.5	0.2		0.2
Pterocorys sp.						0.5			
Spirocyrtis scalaris Haeckel*	5-21, -22	Itaki, 2009	4.4	2.2	1.3		0.5	0.4	
Stichocorys seriata Jørgensen*	5-19, -20	Itaki, 2009	6.0	3.8	4.4	1.9	1.7	1.5	1.9
Stichopilium anocor Renz	6-7	Renz, 1976		0.3	0.5				
Stichopilium bicorne Haeckel	6-3	Nigrini & Moore, 1979		0.1	0.3				
Theophormis callipilium Haeckel	6-1	Itaki, 2009			0.5				
Tholospyris rhombus (Haeckel)		Itaki, 2009	0.4	0.2			0.2		0.4
Tholospyris spp.*	6-27		0.8	0.8	1.3	0.5	0.5	1.1	0.6
Zygocircus productus (Hartwig), group	6-25, -26	Itaki, 2009	4.8	4.4	2.1	0.5	1.5	2.2	0.6
Other nassellarians			14.0	7.5	10.6	8.8	14.0	8.9	21.7
			104	388	121	134	167	84	215

sp., *T. octacantha* group, *Didymocyrtis tetrathalamus*, and *Carpocanistrum* spp., all of which have similar abundance patterns to species in cluster R-c. However, members of this cluster had higher standing stocks at Sta. 3 than did members of cluster R-c.

Cluster R-f consists of 4 species or species groups: *Spongosphaera streptacantha*, *Dictyocoryne profunda*, *Lophophaena* spp., and *Arachnocorys castanerides*. Members of this cluster were characterized by a pattern of standing stock maxima at 30–60 m at Sta. 1 and in the bottom layer (50–80 m) at Sta. 3.

Discussion

Faunal characteristics of the Tsushima Current

Most radiolarian species found in the Tsushima Strait, except for *C. davisiana*, have been reported from the East China Sea (Tan and Chen, 1999; Chang *et al.*, 2003), whereas they are very rare or not found in the northern Japan Sea (Itaki, 2003). Surface sediment studies in the Pacific Ocean also show that these species are widely distributed in low latitude areas (e.g., Lombardi and Boden, 1985; Pisias *et al.*, 1997; Motoyama and Nishimura, 2005; Kamikuri *et al.*, 2008). Therefore, it is likely that radiolarian assemblages in the Tsushima Strait are closely associated with the warm TC water originating from the East China Sea and the Kuroshio Current, which reaches a maximum during the sampling interval, i.e., end October/beginning November. Similarly, the faunal components of planktonic foraminifera in the same samples used in this study are related with the East China Sea water (Kimoto *et al.*, 2009).

The faunal differences between the western and eastern channels of the strait, evident in clusters Q-a and Q-b, probably reflect surface water of different origins and hydrographic conditions. A comparison of the characteristics of water above the thermocline (Figure 2) shows a generally lower salinity and higher temperature at Sta. 1 compared with Sta. 3, suggesting the greater influence of coastal water in the western channel, as pointed out by Senjyu *et al.* (2008). During autumn, when we obtained samples, the volume transport in the eastern channel increases because of the enhanced intensity of the Kuroshio Current at this time (Isobe, 1999; Takikawa *et al.*, 2005). Furthermore, radiolarian production in the shelf area of the East China Sea peaks during this season as a result of increases in the Taiwan Current or decreases in the coastal water influence related to Yangtze River discharge (Tan and Chen, 1999). Consequently, radiolarian assemblages in the Tsushima Strait should be largely under the influence of the Kuroshio water in the eastern channel and the Taiwan Current and coastal waters in the western channel. Yamada (1933) reported a similar scenario for the plankton assemblages in this region.

Chang *et al.* (2003) described radiolarian assemblages in 72 surface-sediment samples from the northern East China Sea, and distinguished 3 groups associated with “Kuroshio Water,” “Tsushima Warm Current Water,” and “Mixed Water.” They included *Tetrapyle circularis* and *Tetrapyle quadriloba* (the *T. octacantha* group that was more abundant in the western channel in this study) in the Mixed Water group influenced by shelf water, and *D. truncatum* and *D. profunda* (more common in the eastern channel in this study) in the Kuroshio Water group. This is consistent with our results showing that the *T. octacantha* group was associated with water from the East China Sea shelf area, whereas *D. truncatum* and *D. profunda* were associated with water originating from the Kuroshio Current.

Relationships with bottom cold water

Cycladophora davisiana, a dominant species accounting for 20% of the assemblage at 100–140 m at Sta. 1 ($\sim$20 tests/m^3), is known as a deep dweller distributed throughout the world oceans (e.g., Bjørklund and Ciesielski, 1994). In the Sea of Okhotsk, this species is abundant. It accounts for up to 40% of the radiolarian fauna in surface sediments (Morley and Hays, 1983) and its primary habitat is at depths of 200–500 m in a water mass characterized by cold temperatures, high oxygen content, and with a high supply of organic matter (Nimmergut and Abelmann, 2002; Okazaki *et al.*, 2004; Abelmann and Nimmergut, 2005).

Although *C. davisiana* lives in the Tsushima Strait, it has not been reported in studies from the East China Sea (e.g., Tan and Chen, 1999; Chang *et al.*, 2003). In the Japan Sea, this species is absent in the upper 200 m throughout the southern and eastern areas (Ishitani and Takahashi, 2007), whereas it occurs below 500 m and dominates the fauna (20% of total radiolarians; $\sim$1 test/m^3) at 1000–2000 m in the northern part of the sea (Itaki, 2003). *Cycladophora davisiana* appears to be adapted to the cold, well oxygenated deep water in the Japan Sea (Itaki, 2003).

Cold water originating from the intermediate or deep layers of the Japan Sea is present in the bottom layer of the western channel of the Tsushima Strait (e.g., Lim and Chang, 1969; Cho and Kim, 1998). The cold, less saline water found at 130–140 m at Sta. 1 (Figure 2) most likely corresponds to the upper part of this cold water mass. The shallower habitat depth of *C. davisiana* in the Tsushima Strait might be related to such cold-water intrusion from greater depths.

A similar unusually shallow habitat for *C. davisiana* (100–200 m) as that in the Tsushima Strait has been observed in the northeastern Pacific Ocean off the coast of California, possibly related to upwelling of cold water there (Kling and Boltovskoy, 1995). The Tsushima Strait and off the coast of California exhibit similar intrusion of deep, cold water to shallower depths, which might explain the upward shift in habitat depth of *C. davisiana* in these areas.

Summary

A total of 92 polycystine radiolarian taxa were found in the Tsushima Strait in autumn of 2006. Most of the taxa are known as warm-water species, except for *Cycladophora davisiana*. Three Q-mode cluster groups were distinguished: 1) surface waters of the eastern channel, 2) surface waters of the western channel, and 3) bottom waters of the western channel. Radiolarians that were found preferentially in the surface waters of the eastern or western channels were associated with the Kuroshio water or the Taiwan Current and coastal waters, respectively. In contrast, the abundant presence of *C. davisiana* in the bottom layer of the western channel may be related to cold-water intrusion from the deeper layers of the Japan Sea.

Our results provide a better understanding of the distribution of radiolarians in the Tsushima Strait. This insight is important for understanding the composition of the biological communities in the Japan Sea, and is also important for paleoceanographic studies applied to the microfossil record. However, further investigation of the plankton assemblages in the East China Sea and southern Japan Sea is required before a more detailed conclusion about the source areas of the Tsushima Strait assemblages can be made.

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