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Article

Summer surface water polycystine radiolarians in the eastern margin of the Japan Sea

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Abstract: In late August 2014, a living polycystine radiolarian assemblage was collected from the surface waters off the shore of Sakata, Yamagata Prefecture, in the eastern margin of the Japan Sea. The assemblage was dominated by the spumellarian *Spongosphaera streptacantha*, and included a few individuals of *Pseudocubus obeliscus* and *Tetrapyle octacantha*. The intraspecific variation in *S. streptacantha* observed in the main spine and spongiose layer was thought to reflect skeletal growth. Morphometric analysis of the main spine and spongiose layer indicated that most individuals of *S. streptacantha* were growing. On the sampling day, the surface water attained the annual maximum water temperature and was strongly influenced by the Tsushima Warm Current. *S. streptacantha* inhabited the summer surface water of this ocean area almost exclusively.

Keywords: living radiolarian assemblage, summer surface water, *Spongosphaera streptacantha* Haeckel, Tsushima Warm Current, Japan Sea

1. Introduction

The Japan Sea is a mid-latitude marginal sea enclosed by the Eurasian Continent, Japanese Islands, and Sakhalin (Fig. 1A). The surface water in the southeastern half of the Japan Sea is strongly influenced by the Tsushima Warm Current (TWC), which flows into the Japan Sea through the Tsushima Strait in the southwest and exits through the Tsugaru and Soya (La Perouse) straits in the northeast. Microplankton in the surface water of the TWC drift north and develop ontogenetically and heterogenetically under the influence of the warm water, salinity, and nutriments.

Polycystine radiolarians are useful paleoenvironmental indicators in the Japan Sea. Over the last 15 years, our knowledge of radiolarians in the Japan Sea has increased based on investigations using core sediments (e.g. Itaki, 2001; Itaki and Ikehara, 2003), surface sediments (e.g. Itaki, 2003; Motoyama *et al.*, 2016), and living material (e.g. Matsuoka *et al.*, 2001; Itaki *et al.*, 2003). This study reports a living polycystine radiolarian assemblage in the high summer surface waters of the eastern margin of the Japan Sea. The assemblage provides useful information on the skeletal growth of the radiolarian S*pongosphaera streptacantha* and is very suggestive of the seasonal change in surface-water radiolarians in the Japan Sea.

2. Oceanographic condition

Figure 1A shows the surface currents in the Japan Sea on the sampling day. After entering through the Tsushima Strait, the TWC branched, meandered, and eddied in the southeast Japan Sea and flowed toward the northeast at less than 1 knot (Japan Coast Guard, 2014a). On the sampling day, one of the main currents of the TWC passed through the Sado Strait and streamed along the west coast of Honshu, the main island of Japan. In 2014, the surface water temperature at the sampling site reached the annual maximum of 26–27 °C from August 25 to 27 (Japan Coast Guard, 2014b).

3. Sampling site and methods

The radiolarian assemblage investigated in this study was collected by the research vessel *Kaiyomaru No. 3* (Kaiyo Engineering) in the early morning of August 26, 2014. The sampling was conducted at a site located about 65 km off the shore of Sakata, Yamagata Prefecture (38° 59' 44" N, 139° 17' 46" E; Fig. 1B). A 200-mm-diameter, 450-mm-long plankton net with a 72-μm mesh, was used for the sampling. The net was towed by hand for 25 minutes at a depth of 10–15 m. The volume of water filtered while sampling was not estimated.

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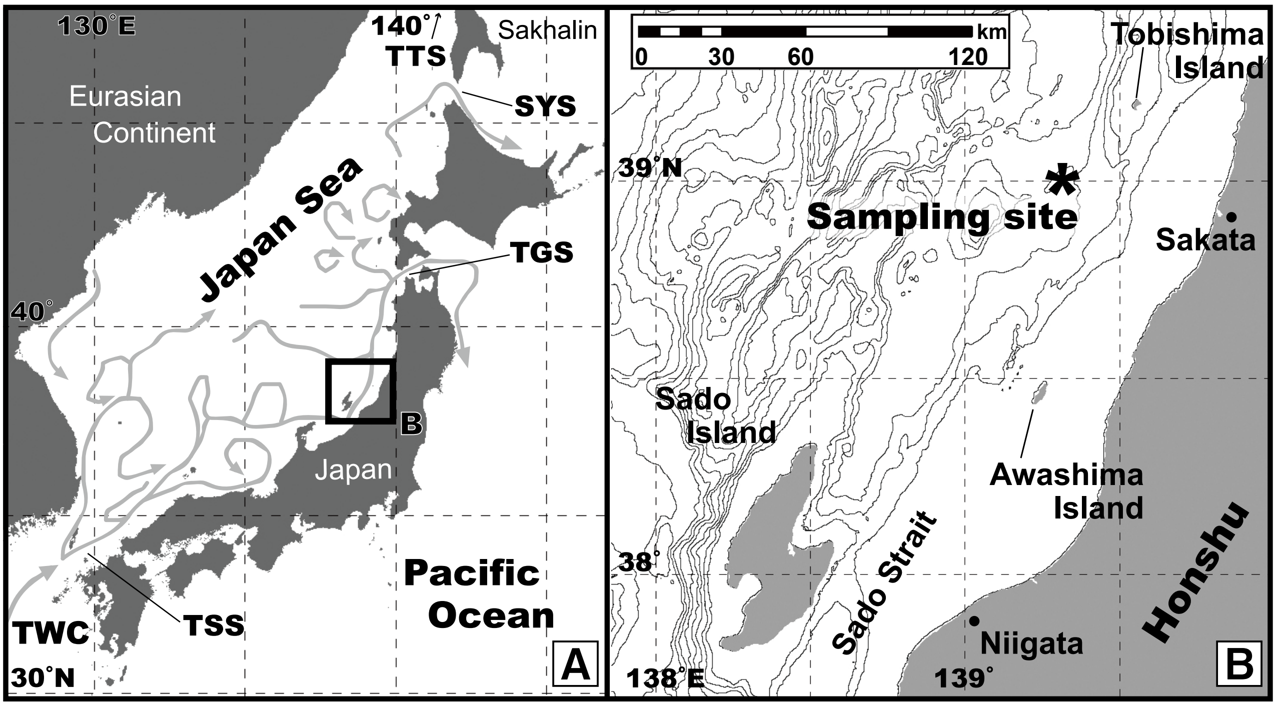


Fig. 1 A) Geographical setting of the Japan Sea and surface currents on the sampling day (from the Japan Meteorological Agency, 2014). Abbreviations are as follows: TWC, Tsushima Warm Current; TSS, Tsushima Strait; TGS, Tsugaru Strait; SYS, Soya (La Perouse) Strait; TTS, Tatar Strait. The black square indicates the area in B. B) Map showing the geography around the sampling site located off Sakata, Yamagata Prefecture. The sampling site is indicated by the asterisk.

The sample was placed in ca. 10 % hydrogen peroxide for several days to remove organic matter from the radiolarians. After rinsing with dilute hydrochloric acid to eliminate carbonates, the sample was sieved through a 41-µm mesh. The residue on the sieve was mounted on glass slides using "Entellan New" mounting medium. Radiolarians were observed and photographed by transmitted light using a biological microscope.

4. Radiolarians

4. 1 Faunal composition

The sample contained 48 polycystine radiolarians, of which 42 were *Spongosphaera streptacantha* Haeckel (87.5 %); a few *Pseudocubus obeliscus* Haeckel and *Tetrapyle octacantha* Müller were also found. Figure 2 shows photomicrographs of the radiolarian species and individuals from the sample.

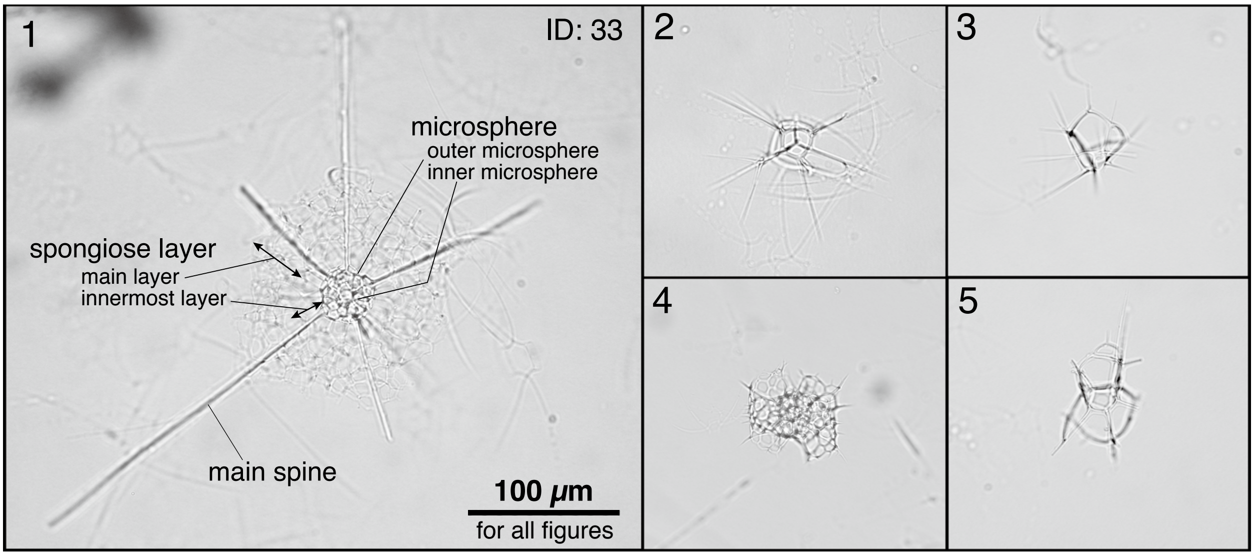
4. 2 Morphologic variation of *Spongosphaera streptacantha*

Haeckel (1860) originally described the spumellarian species *S. streptacantha*. According to Kurihara and Matsuoka (2004), a typical specimen of *S. streptacantha* is composed of three main elements: the microsphere, main spine, and spongiose layer (Fig. 2-1). The microsphere consists of two concentric microspheres, the inner and outer microspheres, which are situated in the center of the skeleton. Six to nine main spines arise from the surface of the outer microsphere. A main spine has three distinct ridges and grooves and is Y-shaped in cross-section. Teeth-like apophyses are arrayed along the ridges of the main spines.

Wide intraspecific variation was recognised in *S. streptacantha* in this assemblage. The microsphere and main spine were observed in all specimens, whereas the spongiose layer was sometimes absent. Figure 3 summarises the diameter of the outer microsphere, length of the main spine, and diameter of the spongiose layer of 37 specimens. The outer microsphere diameter ranged from 35.4 to 41.7 (mean $\pm 1\sigma$: 38.1 $\pm$ 1.6) µm and was fairly uniform, while the length of the main spine and diameter of the spongiose layer ranged widely (Fig. 3). This study subdivided *S. streptacantha* into three classes based on the developmental of the spongiose layer.

4. 2. 1 Morphotype-A

Nineteen specimens that lacked the spongiose layer were classified into Morphotype-A. Figure 4 shows three typical specimens of Morphotype-A. The main spines of this morphotype were shorter than those of Mophotypes-B and -C (Fig. 3). The specimen in Figure 4-1 had a 44-µm-long main spine, which was the shortest in the study assemblage. The main spines tapered toward the tips and were fairly slender compared with those of the specimens



Taxa (Photo No.)	Number of individuals	Taxa (Photo No.)	Number of individuals
SPUMELLARIA		**NASSELLARIA**	
Spongosphaera streptacantha Haeckel (1)	42	*Pseudocubus obeliscus* Haeckel (2, 3)	4
Tetrapyle octacantha Müller (4)	1	Nassellaria gen. et sp. indet. (5)	1
		Total number	48

Fig. 2 Transmitted light photomicrographs and list of polycystine radiolarians in the study assemblage. 1) *Spongosphaera streptacantha* Haeckel. The specimen ID and skeletal characters are indicated. 2, 3) *Pseudocubus obeliscus* Haeckel. 4) *Tetrapyle octacantha* Müller. 5) Nassellaria gen. et sp. indet.

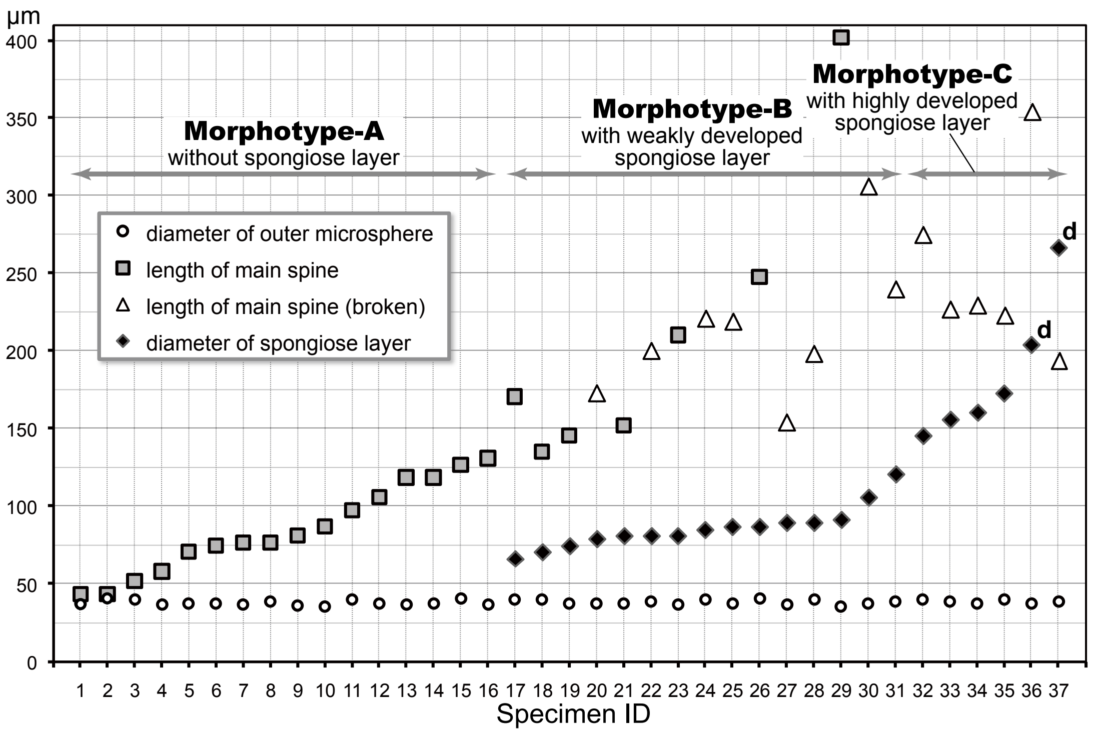


Fig. 3 The diameters of the outer microsphere, lengths of the main spine, and diameters of the spongiose layer of 37 specimens of *Spongosphaera streptacantha* in the study assemblage. *S. streptacantha* was subdivided into Morphotypes-A, -B, and -C based on the development of the spongiose layer. The black diamond with “d” indicates specimens with a delicate layer in the spongiose layer.

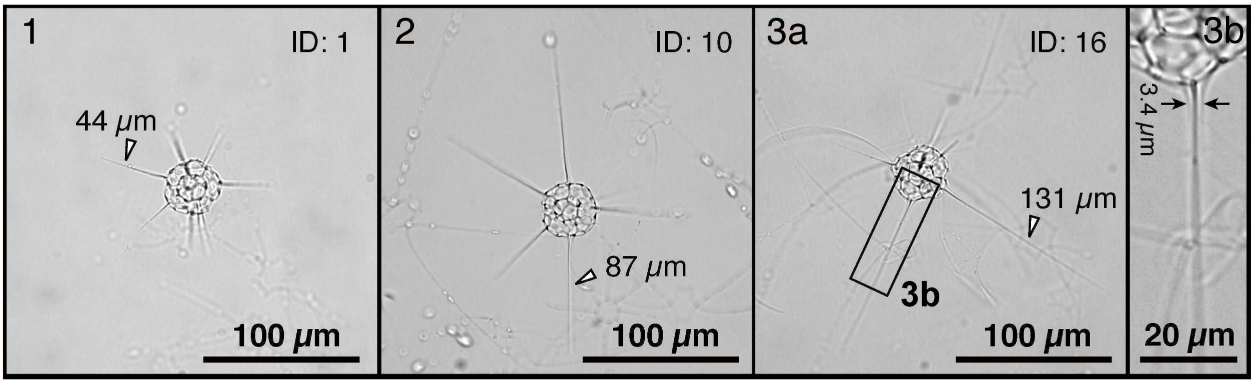


Fig. 4 Transmitted light photomicrographs of *Spongosphaera streptacantha* without a spongiose layer (Morphotype-A). The specimen ID is indicated in each photograph. 1) A specimen with short main spines. The left main spine is 44 μm long. 2, 3a) Specimens with longer main spines. 3b) Close-up view of the main spine of the specimen in 3a. Ridges and grooves are recognised only at the base and no serrated apophysis is seen. The base of the main spine is 3.4 μm wide.

in Figures 4-2 and 4-3.

The specimens shown in Figures 4-2 and 4-3 had main spines 87 and 131 μm in length, respectively. Distinct ridges and grooves were recognised only at the bases of these main spines (Fig. 4-3b). The main spine shown in Figure 4-3b was 3.4 μm wide at the base. Although teeth-like apophyses were visible along the edges of the main spines of Morphotypes-B and -C, as described below, none were observed in specimens of Morphotype-A (Fig. 4-3b).

4. 2. 2 Morphotype-B

Seventeen individuals were classified as Morphotype-B, which had a weakly developed spongiose layer (<120 μm in diameter). Figure 5 shows three specimens of Morphotype-B. The specimen shown in Figure 5-1 had a faint spongy network around the microsphere. The main spines, 248 μm in length, tapered distally, like those in Figure 4.

The specimens in Figures 5-2a and 5-3 had sparsely developed spongiose layers. The main spines of these specimens were over 300 μm in length; that of specimen in Figure 5-3 was 402 μm long and was the longest in the study assemblage. Distinct thin ridges and grooves were recognised proximally and distally on the main spine in Figure 5-2b. The maximum width of the main spine was 5.5 μm. Weakly developed teeth-like apophyses were visible at the edges of the ridges and were connected with the spongiose layer at the proximal part of the main spine.

4. 2. 3 Morphotype-C

Six individuals were classified into Morphotype-C, which had a large, dense developed spongiose layer (>120 μm in diameter). Three typical specimens of Morphotype-C are shown in Figures 2-1, 6-1, and Fig. 6-2. The total length of the main spines of Morphotype-C was unknown because most of the main spines longer than 150 μm were broken (Fig. 3). Figure 6-1b shows a close-up view of a main spine of Morphotype-C. The maximum width of the main spine was 10.3 μm. Teeth-like apophyses were visible at the edges of ridges. A delicate layer was recognised only in two specimens with larger (>200 μm in diameter) spongiose layers (Fig. 3). The specimen in Figure 6-2 possessed a delicate layer in part of the outer rim of the spongiose layer.

5. Discussion

5. 1 Intraspecific variation of *Spongosphaera streptacantha*

This study focused on the morphological variation of *S. streptacantha* in terms of the diameter of the outer microsphere, length of the main spine, and diameter of the spongiose layer. Previously, Kurihara and Matsuoka (2004) examined the skeletal development of *S. streptacantha* in 19 specimens that had spongiose layers ranging from 122.8 to 351.4 μm in diameter, which would be classified into Morphotype-C of this study. By contrast, as most specimens in the study assemblage were classified into Morphotype-A or -B, this study can examine the early stage of skeletal development of *S. streptacantha*.

All specimens had microspheres in the centers of the skeletons and the diameters were quite uniform (Fig. 3). The microsphere is evidently formed in the initial stage of morphogenesis before the formation of the main spine and spongiose layer. Matsuoka (2017) shows a specimen of *S. streptacantha* with extremely short main spines, ca. 10 μm in length.

The lengths of main spines were distributed continuously from 44 to 402 μm (Fig. 3). The width and structure of the main spine developed gradually in tandem with the length, as is shown in Figures 4-3b, 5-2b, and 6-1b. This character variation is considered to be a process of accretionary skeletal growth.

The spongiose layer forms in the latter stage of skeletal

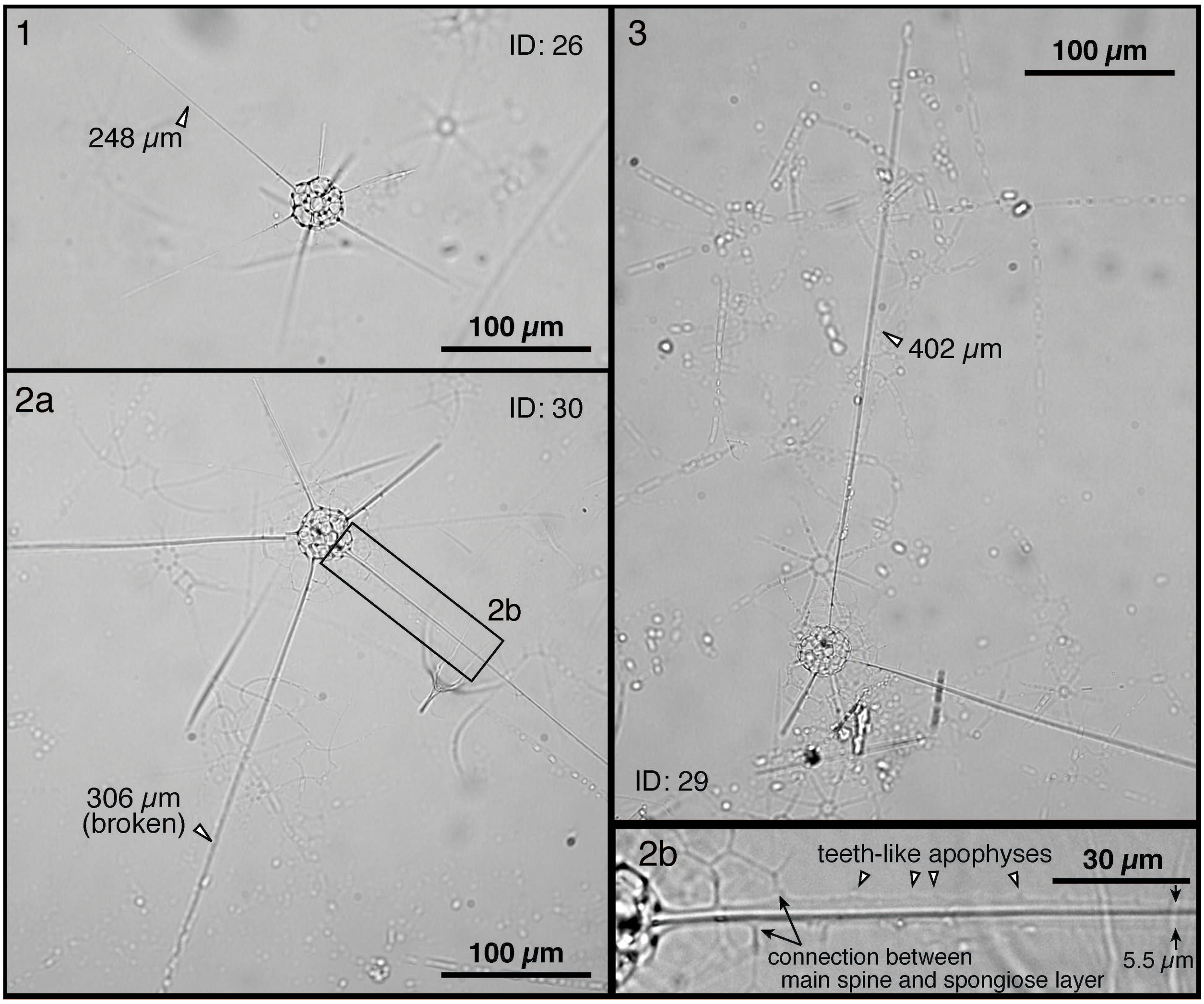


Fig. 5 Transmitted light photomicrographs of *Spongosphaera streptacantha* with a weakly developed spongiose layer (Morphotype-B). The specimen ID is indicated in each photograph. 1) A specimen with slightly developed spongiose layer. The main spines of this specimen are thread-like and taper at the top. The main spine is 248 µm long. 2a) A specimen with main spines with distinct ridges and grooves. The spongiose layer is clearly observed. 2b) Close-up view of the main spine of the specimen shown in 2a. Weakly developed serrated edges are seen. The maximum breadth was 5.5 µm. 3) A specimen with a 402-µm-long main spine.

growth (Fig. 3). The delicate layer, which is in the peripheral part of the spongiose layer, forms in the final phase of ontogenesis. Morphometric analyses of this study and those of Kurihara and Matsuoka (2004) found that the delicate layer develops in larger spongiose layers, over 200 µm in diameter.

The maximum size of the spongiose layer examined by Kurihara and Matsuoka (2004) was 351 µm in diameter, while the largest one in this study was 267 µm. In addition, no specimen in this study assemblage had a fully developed delicate layer, as shown in Figure 9 of Kurihara and Matsuoka (2004). Therefore, all the *S. streptacantha* found in the study assemblage were immature individuals.

5. 2 Implication for radiolarian seasonal change in the Japan Sea

Kurihara *et al.* (2007) noted that *S. streptacantha* is present in surface waters from late summer to early autumn and prefers warmer water (>ca. 20 °C) based on observations southwest of Sado Island, which is located ca. 140 km southwest of the sampling site of this study. For example, Matsuoka *et al.* (2001) and Kurihara and Matsuoka (2004, 2005) reported that *P. obeliscus* and *S. streptacantha* were abundant in August and September. In addition, Kurihara and Matsuoka (2007) collected an assemblage dominated by three species, *S. streptacantha*, *P. obeliscus*, and *Pseudocubus* sp. A, at 0–35 m depths on September 28, 2005.

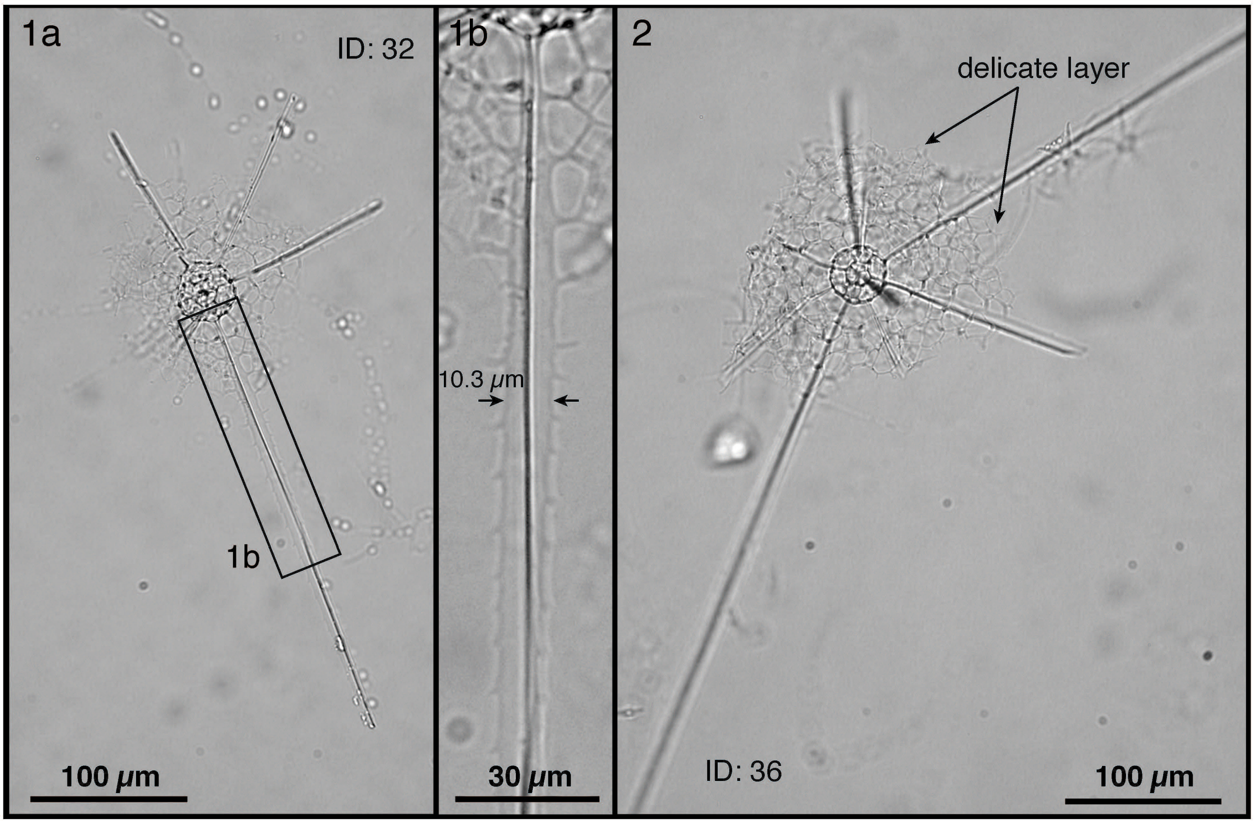


Fig. 6 Transmitted light photomicrographs of *Spongosphaera streptacantha* with highly developed spongiose layers (Morphotype-C). The specimen ID is indicated in each photograph. 1a) A typical specimen of Morphotype-C. The total length of main spine of this specimen is not known because it was broken. 1b) Close-up view of the main spine of specimen of 1a. Distinct ridges and groove are developed. Serrated apophyses align along the ridge lines. The maximum breadth was 10.3 μm. 2) A specimen with a weakly developed delicate layer in the outer periphery of the spongiose layer.

In comparison, *S. streptacantha* was absent from the assemblage collected from surface waters on May 20, 2002 off Sado Island (Itaki *et al.*, 2003). A sample obtained at 63–90 m depths on June 6, 2005, contained one possible *S. streptacantha* (Kurihara *et al.*, 2006). Each sample at 0–40 and 40–70 m depths on June 4, 2007 yielded one individual (Kurihara *et al.*, 2008). On June 7, 2010, only one dead *S. streptacantha* was recovered at 100–200 m depths (Kurihara and Matsuoka, 2011).

Except off Sado Island, only a few living *S. streptacantha* in the Japan Sea have been studies. *S. streptacantha* was not collected at a site northwest of Hokkaido in July 1999 (Itaki, 2003). Samples from depths shallower than 100 m in the Tsushima Strait on October 31, 2006 rarely contained *S. streptacantha* (Itaki *et al.*, 2010). Matsuzaki *et al.* (2016) investigated the vertical distribution of polycystine radiolarians in the East China Sea southwest of the Tsushima Strait in late May 2008 and noted that *S. streptacantha* was dominant at 20–50 m depths characterised by high temperatures (>20 °C) and high chlorophyll *α* levels.

This study obtained a polycystine radiolarian assemblage composed mainly of *S. streptacantha* with a few *P. obeliscus*. The faunal composition of the study assemblage matches the assemblage reported in surface waters around Sado Island in August and September. Although *S. streptacantha* dominated the study assemblage, all the individuals were immature and in the process of growing. Therefore, *S. streptacantha* likely started proliferating just before the sampling and grows predominantly in the warm summer surface waters under the strong influence of the TWC.

6. Summary

Living polycystine radiolarians were collected in late August, 2014 from surface water at the eastern margin of the Japan Sea. This assemblage was dominated by *Spongosphaera streptacantha*, with small numbers of *Pseudocubus obeliscus* and *Tetrapyle octacantha*. Many of the *S. streptacantha* specimens were immature forms in various stages of growth. *S. streptacantha* matured almost exclusively in the warm summer surface water in this ocean area, which is strongly influenced by the Tsushima Warm Current.

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日本海東縁における夏季表層水の放散虫（ポリキスティナ）群集

石田直人

要　旨

2014年８月の後半, 日本海東縁に位置する山形県酒田市沖の表層水から放散虫（ポリキスティナ）群集を採取した. この群集は*Spongosphaera streptacantha*が大多数を占め, 少数の*Pseudocubus obeliscus* と*Tetrapyle octacantha*を伴う. *S. streptacantha*にはmain spine やspongiose layerに種内変異が認められ, これは殻成長の過程を反映したものと考えられる. main spine とspongiose layerの形態計測の結果は, この群集の*S. streptacantha*の全てが成長途中の未成熟個体であることを示している. 対馬暖流の強い影響下にあり, 年最高水温に達していた採取地点の表層水では, *S. streptacantha*が優占的に生育していたことが明らかとなった.