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Middle to Late Pleistocene radiolarian biostratigraphy in the water-mixed region of the Kuroshio and Oyashio currents, northeastern margin of Japan (JAMSTEC Hole 902-C9001C)

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ABSTRACT – A **c**ontinuous Quaternary sediment sequence was recovered from Hole 902-C9001C during the D/V *Chikyu* 2006 mission along the northeastern margin of Japan. The age and rate of deposition of this core were estimated using calcareous nannofossil biostratigraphy and oxygen isotope curves measured from benthic foraminifera (*Uvigerina akitaensis*) and dated from 740 ka to the present, a period that spanned the Brunhes normal polarity epoch. Sediment consisted of diatomaceous siltstone and contained an abundance of radiolarians. A total of 91 radiolarian species was found in the core, of which 74 were analysed. Of these radiolarian species, 36 demonstrated continuous stratigraphical distribution over the past 740 ka and 38 had shorter ranges of biostratigraphical interest. Three of the 38 species were determined to be novel and are described in the present study (*Amphisphaera tanzhiyuani* sp. nov., *Schizodiscus japonicus* sp. nov. and *Siphonosphaera*? *paraphoros* sp. nov.). Based on 17 radiolarian bioevents, including four datums which have been commonly used across a wide area of the North Pacific, the radiolarian sequence of this core was divided into 8 zones: *Amphirhopalum virchowii* Zone (613–740 ka), *Spongaster tetras irregularis* Zone (516–613 ka), *Cyrtidosphaera reticulata* Zone (357–516 ka), *Spongurus cylindricus* Zone (238–357 ka), *Pterocanium depressum* Zone (209–238 ka), *Spongoliva ellipsoides* Zone (131–209 ka), *Ceratospyris problematica* Zone (33–131 ka), and the *Acanthodesmia vinculata* Zone (0–33 ka).

KEYWORDS: *Radiolaria, biostratigraphy, Pleistocene, offshore Japan*

INTRODUCTION

The region of the northwestern Pacific located along the northeastern margin of Japan is greatly affected by two warm currents (Kuroshio and Tsugaru currents), a cold current (Oyashio Current) and several deep-water masses. The mixture of nutrient-poor warm currents with nutrient-rich cold water has resulted in the presence of high-productivity water masses in the region, which are known to contain sediments rich in biosiliceous components. Sediments in the northwestern Pacific contain an abundance of well-preserved radiolarians, and radiolarian biostratigraphical schemes in the region have been proposed earlier by Sakai (1980), Kamikuri *et al.* (2004, 2007) and Motoyama *et al.* (2004). These studies focused primarily on the Lower to Middle Miocene, and the age resolution of Quaternary radiolarian biostratigraphy remains insufficient. Five Pleistocene radiolarian biozones in the Sea of Okhotsk were proposed by Matul *et al.* (2002, 2009); however, their studies examined only the past 500 ka and it was presumed that the radiolarian biozones established in the Sea of Okhotsk had been isolated from the rest of the northwestern Pacific by the Kamchatka Peninsula, the Kuril Islands and Hokkaido. In the present study, the drilled core Hole 902-C9001C (Fig. 1) was used to establish a new radiolarian biostratigraphical scheme in the northwestern Pacific for the Brunhes normal polarity epoch (the period spanning the last 740 ka). This core provided a continuous record of the past 740 ka and has been dated accurately using benthic foraminiferid oxygen isotope stratigraphy (*Uvigerina akitaensis*) and calcareous nannofossil datums (Domitsu *et al.* 2011) (Fig. 2). Siliceous microfossils (diatoms and radiolarians) are well preserved down-core. Examination of the stratigraphical distribution and species diversity of radiolarian assemblages within this core resulted in the identification of 91 species. Of the 74 species identified (Fig. 3), 36 occurred continuously through the core, and 38 species, including three novel species, were of biostratigraphical interest. Based on associated bioevents, eight radiolarian zones were established, and the novel biozones identified in the present study were correlated with those that had already been proposed in previous studies (Matul *et al.* 2002; Kamikuri *et al.* 2004; Motoyama *et al.* 2004).

MATERIALS AND METHODS

Core 902-C9001C was drilled at a water depth of 1180 m (41°10′38.28″N, 142°12′04.86″E) during the D/V *Chikyu* 2006 mission (Fig. 1). The core provided a continuous record from marine isotope stage (MIS) 18 (750 ka) to the present, a period that spanned the Brunhes normal polarity epoch (0–740 ka). The age model of this core was established through measurement of the stable oxygen isotopes of benthic foraminifera and calcareous nannofossil datums (Domitsu *et al.* 2011) (Fig. 2). In total, 163 samples were examined for radiolarians. Samples were initially freeze-dried with an Advantec VF-350 Vacuum Freezing Dryer. Dried samples were then disaggregated with hydrogen peroxide and diluted with hydrochloric acid. Undissolved residues within each sample were sieved using a 63 μm screen prior to being dried in an oven. Dried residues were subdivided evenly into several aliquots, and one aliquot was embedded with Canada Balsam and used to prepare microscopic slides. Observation of radiolarians was carried out at magnifications of 100–400× using optical microscopes. The studied material is deposited at the Tohoku University Graduate School of Science, Department of Geology and Paleontology.

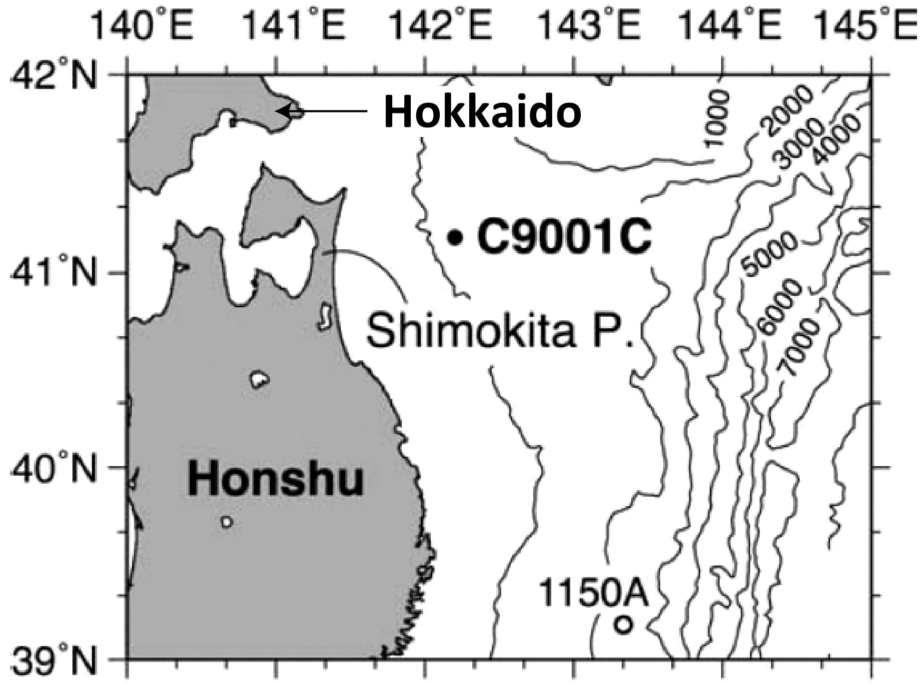


Fig. 1. Location of core 902-C9001C off the west coast of the Shimokita peninsula, NE Japan (41°10′38.28″N, 142°12′04.86″E).

SYSTEMATIC PALAEONTOLOGY

Thorough examination of species composition within the 163 samples revealed a total of 91 species (3 collodarians, 51 spumellarians, and 37 nassellarians). Among these species, the stratigraphical distributions of 74 are presented in Figure 3. Forty-eight important species are illustrated (Pls 1–3) and their taxonomic references are listed in Table 1. Of these 48 species, 38 demonstrated sufficiently discontinuous distributions to be biostratigraphically useful. Among these 38 species, three are newly described in detail below.

Class **Radiolaria** Müller, 1859
Order **Collodaria** Haeckel, 1882, *sensu* Petrushevskaya, 1984
Genus *Siphonosphaera* Müller, 1859

Type species. *Siphonosphaera tubulosa* Müller, 1859. [Subsequent designation by Campbell, 1954.]

Siphonosphaera? *paraphoros* Matsuzaki & Suzuki sp. nov.
(Pl. 1, figs 1–4)

Derivation of name. Greek female noun, παραφορος, meaning confusing.

Diagnosis. A single cortical shell relatively irregular in shape, platy surface with two types of pores.

Holotype. Plate 1, figure 1; sample 902-C9001C, 10H-1, 45.5–54.5 m (Middle Pleistocene). Catalogue number IGPS 111417.

Distribution in the NW Pacific. Extant off Shimokita.

Description. A single irregular and platy surface cortical shell bearing two types of pores, the first group comprises several rounded polygonal pores of relatively larger size with a short centrifugal tube, and the second group a small number of irregular pores throughout the platy cortical shell. A hook-like spine is present on some of the larger rounded polygonal pores. No spines or significant projections are present on the cortical shell.

Dimensions. Based on four illustrated specimens: average diameter 135 μm, maximum diameter 180 μm and minimum diameter 100 μm.

Occurrence. Continuous for the past 740 ka, living and fossil (this study).

Remarks. The main difference from *Acrosphaera spinosa* Haeckel, 1887 is the presence of a short centrifugal tube on each larger pore. This species is morphologically similar to members of the genus *Odontosphaera* Haeckel, 1887 in that a hook-like spine on some larger pores is present in this new species. However, the characteristic centrifugal tube is present on each larger pore, and thus we tentatively regard this new species as a member of *Siphonosphaera*.

Order **Spumellaria** Ehrenberg, 1876
Genus *Amphisphaera* Haeckel, 1882 emend. Suzuki *et al.*, 2009*b*

Type species. *Amphisphaera* (*Amphisphaerantha*) *neptunus* Haeckel, 1887.

Amphisphaera tanzhiyuani Matsuzaki & Suzuki sp. nov.
(Pl. 2, figs 21–24)

1974 *Stylatractus pyriformis* (Bailey); Kruglikova: 188, 190, figs 2.2, 2.3 [only].
1982 *Amphistylus* sp. Tan & Su: 141–142, pl. 3, fig. 10.
1984 ?*Stylatractus* sp. Nishimura & Yamauchi: 34, pl. 5, fig. 11.

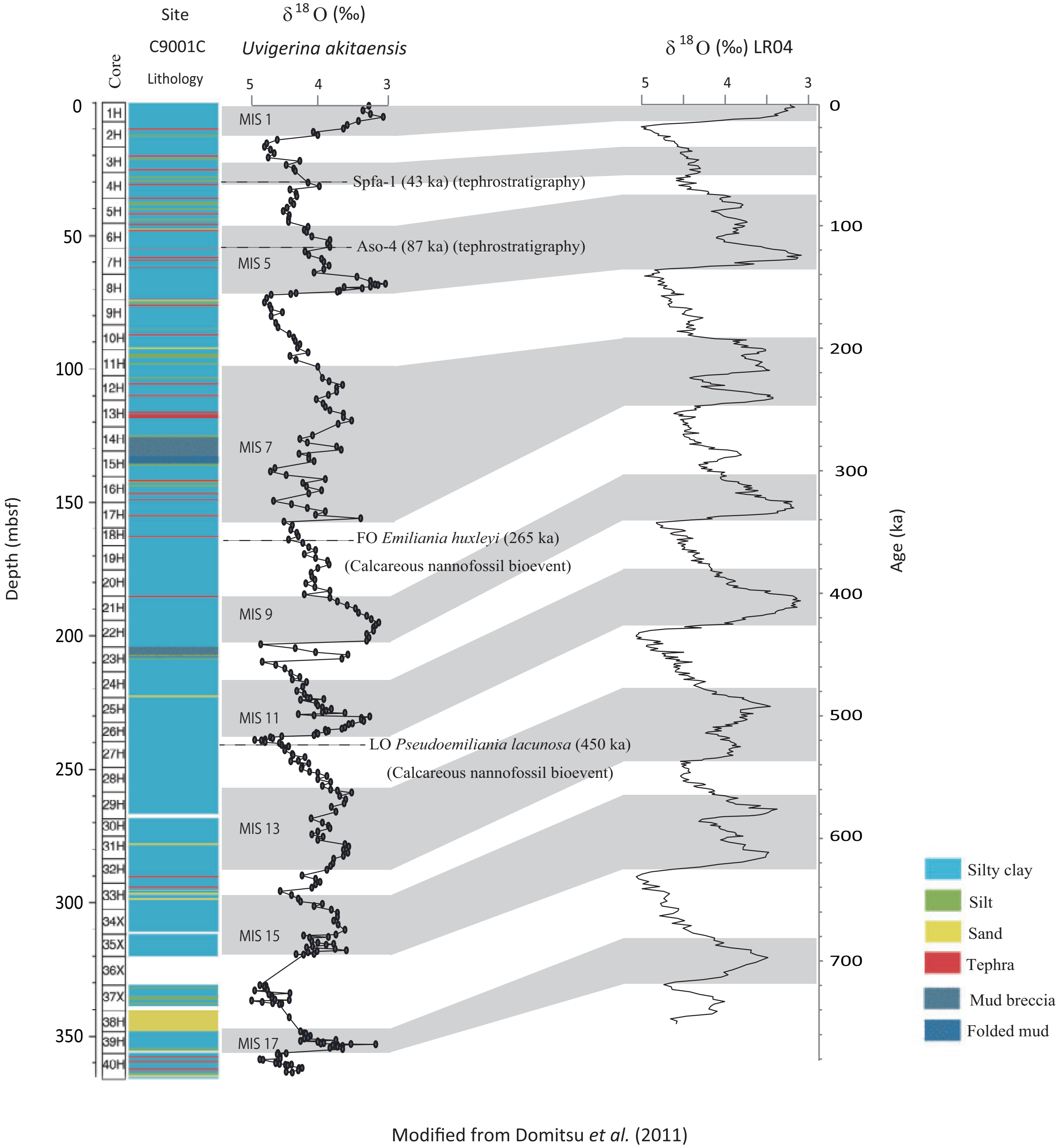


Fig. 2. Age model of core 902-9001C. The depositional age of core 902-9001C was established using oxygen isotope measured from benthic foraminifera (Domitsu *et al.* 2011), calcareous nannofossil datums (FO of *Emiliania huxleyi* (270 ka) and *Pseudoemiliania lacunosa* (450 ka)) and tephrostratigraphy datums (Spfa-1 (43 ka) and Aso-4 (87 ka)).

1992 *Lithatractus tochigiensis* Nakaseko [nomen nudum]; Alexandrovich: pl. 3, fig. 10.

1996 *Stylatractus disetanius* Haeckel; Chen & Tan: 177, pl. 11, figs 1–3; pl. 41, fig. 5.

2004 *Stylosphaera hispida* Ehrenberg; Okazaki *et al.*: pl. 2, figs 4, 5.

2005 ?*Stylatractus pyriformis* (Bailey); Abelmann & Nimmergut: pl. 7, fig. 19 [only].

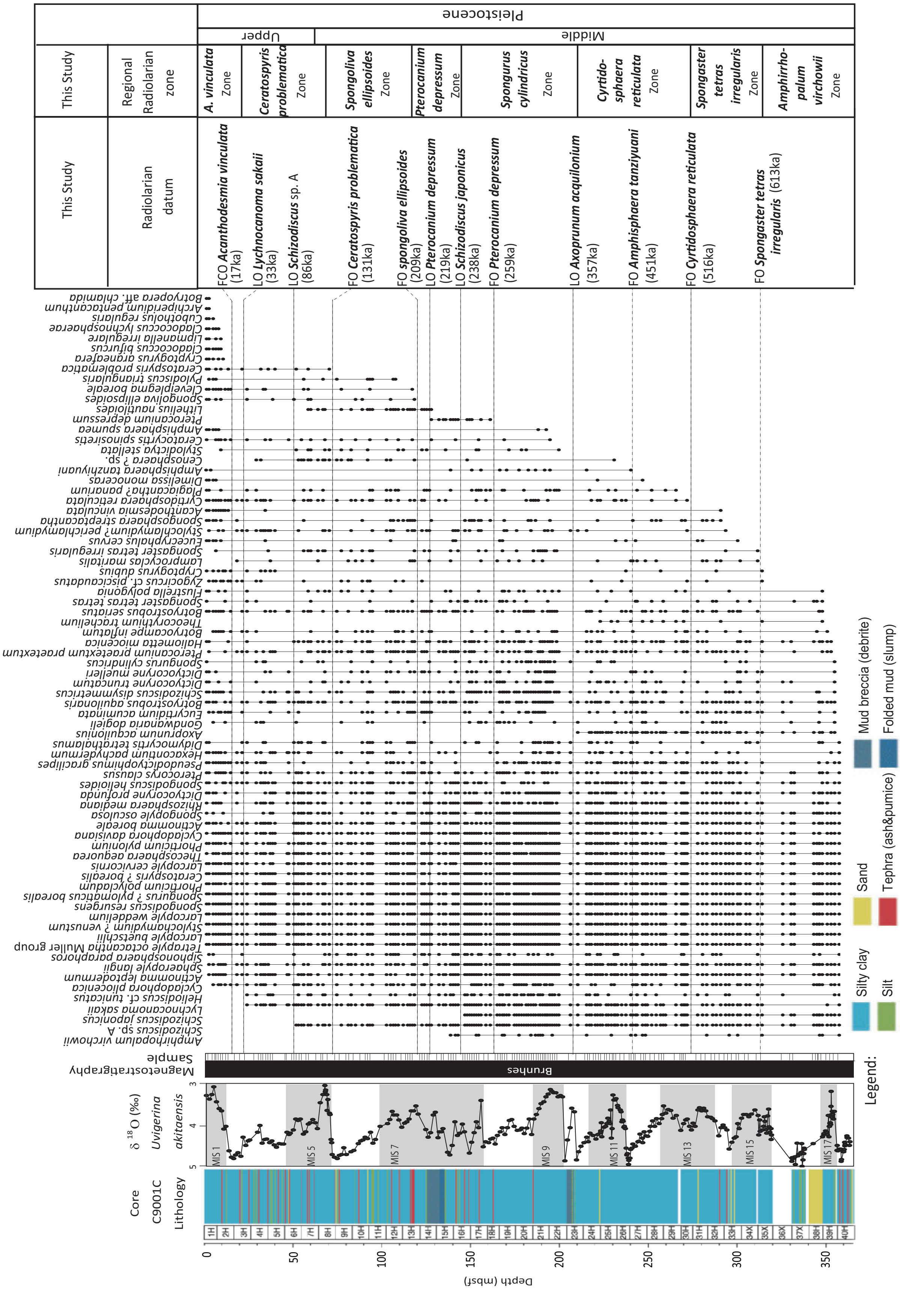


Fig. 3. Biostratigraphical distribution of the 74 selected radiolarian species over the past 740 ka in 902-9001C. Age assignments of the radiolarian zones based on the age model of core 902-9001C (Domitsu *et al.* 2011). FO, first occurrence; LO, last occurrence; FCO, first continuous occurrence.

2008 *Druppatractus ostracion* Haeckel; Tanaka & Takahashi: pl. 1, fig. 13.

Derivation of name. The name *tanzhiyuani* is in honour of Dr Tan Zhiyuan, one of the authors of the classic paper, Tan & Su (1982), which figured this species.

Diagnosis. Three concentric shells marked by numerous radial beams bearing two long cylindrical bipolar spines.

Holotype. Plate 2, figure 21; sample 902-C9001C, 29H-1, 47–53 (Middle Pleistocene). Catalogue number IGPS 111418.

Distribution in the NW Pacific. Bering Sea, East China Sea, Sea of Japan, Nankai Trough, Sea of Okhotsk, South China Sea, east off Shimokita; living and fossil.

Description. Three concentric shells with two long, cylindrical, bipolar spines. Innermost shell is a spherical microsphere with numerous radial beams. The second shell is a spherical macrosphere with numerous radial beams. The third shell is the first cortical shell with a spherical or rather oblong spherical shape. The surface of the third shell is neither rough nor smooth. The wall of the first cortical shell is thick in the mature form and the wall thickness is equal everywhere. Pores are hexagonal in shape and are arranged as six to seven pores in both the longitudinal and equatorial axes of the cortical shell. The pore frame tends to be robust, but pores always appear to be visible even in mature forms. Bipolar spines are thin, generally equal in length and are cylindrical or subcylindrical in cross-section. The ratio of the diameters of the microsphere, macrosphere and cortical shell is 1:2.8–2.2:3.8–4.2. Radial beams connecting between the cortical shell and macrosphere are visible as black, solid bars under transmitted light microscopy.

Dimensions. Based on 10 specimens, for axial diameter, diameter at the external cortical shell equator and the maximum and minimum diameters of the inner shell. Minimum axial diameter is 70 μm whilst maximum is 100 μm; average axial diameter is 86 μm. External cortical shell's equatorial diameter is between 70 and 90 μm and average is 78 μm. Inner shell maximum diameter fluctuates between 40 and 55 μm; average diameter is 51 μm. Minimum inner shell diameter ranges from 40 to 50 μm; average 42 μm.

Occurrence. From 451 to 0 ka at this site. Extant species.

Remarks. *Amphisphaera gracilis* Campbell & Clark, 1944 is similar to this morphotype, but the former differs from the latter by having significantly bladed bipolar spines. This morphotype has no similarity to *Stylosphaera hispida* Ehrenberg. *S. hispida* has only two shells, a pear-shaped macrosphere and an ellipsoid cortical shell. The pear-shaped macrosphere is connected to the cortical shell by six radial beams. This morphotype is occasionally misidentified as *Stylosphaera pyriformis* (Bailey), but is easily distinguished from the latter by having numerous thick radial beams between the cortical shell and the macrosphere and the presence of an ellipsoid macrosphere instead of a heteropolar macrosphere as in *S. pyriformis*.

Genus *Schizodiscus* Dogiel *in* Dogiel & Reshetnyak, 1952

Type species. *Schizodiscus disymmetricus* Dogiel *in* Dogiel & Reshetnyak, 1952. [Subsequent designation by Ling, 1972.]

Schizodiscus japonicus Matsuzaki & Suzuki sp. nov.
(Pl. 2, figs 27–30)

1973 *Spongodiscus* sp. Ling: 778, pl. 1, figs 9, 10.
1975 *Spongodiscus* sp. Ling: pl. 4, fig. 5; Ling, 1980: 368, pl. 1, fig. 7.
1980 *Spongodiscus* sp. Sakai: 709, pl. 6, fig. 5.
2002 *Spongodiscus* sp. Matul *et al.*: 30, figs 4.3, 4.4.

Diagnosis. The diagnosis of this new species is fully cited in Ling (1973, p. 778). The morphological characters of this morphotype are concordant with the description of *Spongodiscus* sp. in Ling (1973): discoidal biconvex shell whose surface consists of an irregular network with circular to subcircular pores approximately uniform in size and a darker central part.

Holotype. Plate 2, figure 30; sample 902-C9001C, 20H-3, 62–68 (Middle Pleistocene).

Catalogue number IGPS 111419.

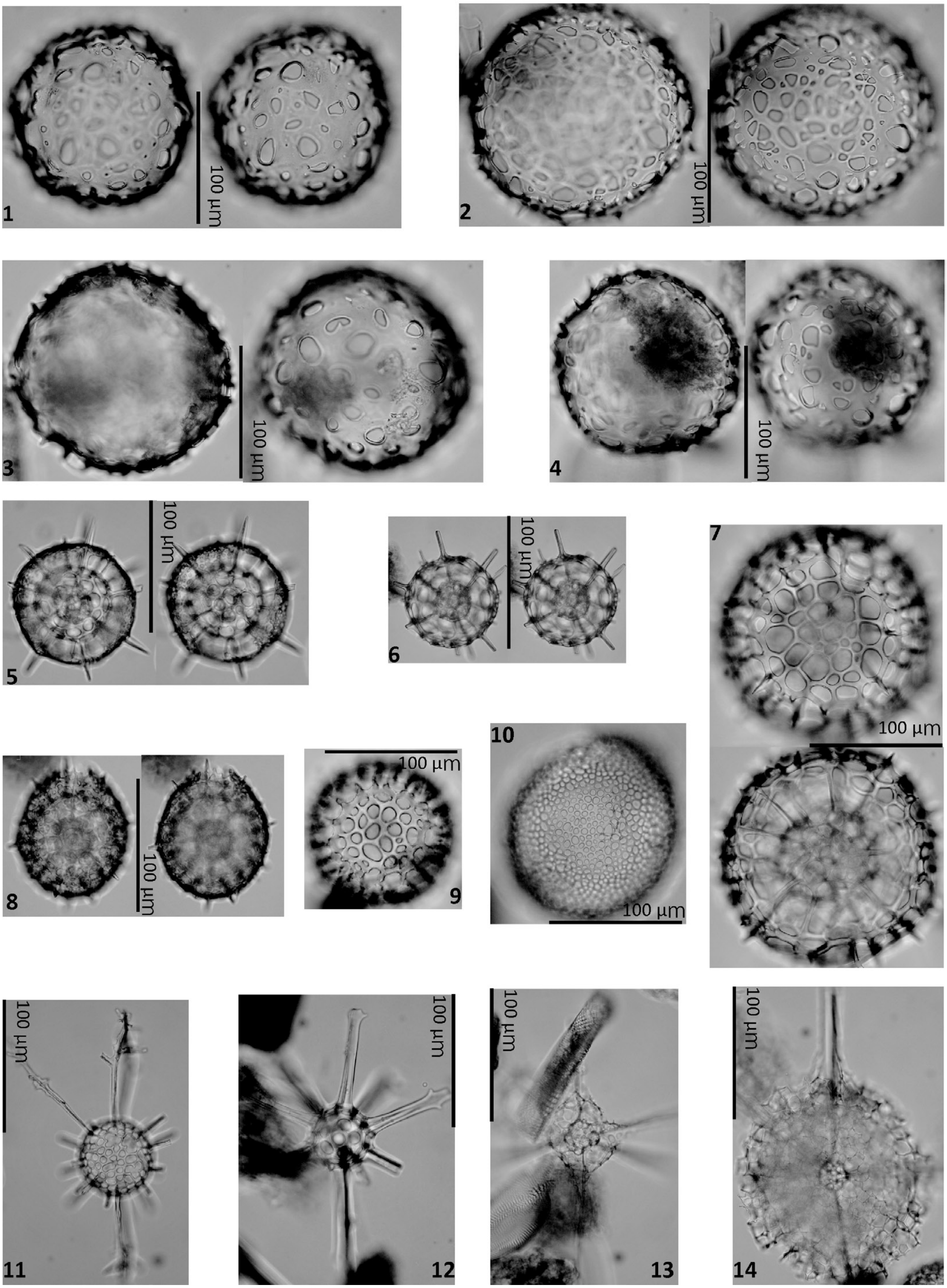
Distribution in the NW Pacific. Bering Sea, east off Sanriku, Sea of Okhotsk, east off Shimokita; fossil.

Description. Large inflated, opaque discoidal skeleton with flat sides presenting a porous structure. The pores are circular to subcircular and their sizes fluctuate between 8 and 11 μm. The central part of the disk is one-half to two-thirds of the diameter of the disc and appears darker than the rest of the shell, suggesting a thickening of the test. The diameter of this central part fluctuates from 70 to 100 μm and is also finely pored. The observed specimens were marked by an absence of spines while the siliceous microfossil preservation was good down-core. The absence of spines in the periphery of the skeleton is a strong taxonomic feature of *Schizodiscus japonicus*. The skeleton periphery is also marked by an absence of pylome for most of the encountered specimens; however, some specimens present a rounded tube-like aperture continuing inside the disk, close to a pylome, illustrated in Plate 2, figs 29–30.

Dimensions. Based on 20 specimens, average diameter is 237 μm; maximum size 260 μm and minimum 200 μm.

Occurrence. Middle Pleistocene only in this site.

Remarks. To establish the genus of this new species, comparisons were made with the type of the *Schizodiscus* genus which is *S. symmetricus* Dogiel & Reshetnyak (1952). This genus is characterized by a convex, dark and thick central part and slightly inflated disk margins. The skeletons comprise a porous structure defined by small, circular to subcircular, almost uniform pores. The pylome tube is present and extends to the central dark part of the disk. Based on this description, *Schizodiscus japonicus* seems to conform to the generic definition proposed by Dogiel & Reshetnyak (1952), except that the pylome is ambiguous in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this new species. Dogiel & Reshetnyak (1952) defined a clear tubiform pylome as a strong taxonomic feature that characterizes *Schizodiscus*. In our study (e.g. Pl. 2, figs 29–30), individuals were observed with a notch that can be associated with a pylome. However, this pylome feature is not observed in all the specimens (see Pl. 2, figs 27–28). Overall, the morphology of *Schizodiscus japonicus* seems to be close to *Schizodiscus* definitions and, based on present knowledge, thi\s genus is the most suitable.

Schizodiscus japonicus differs from *S. stylotrochoides* Dogiel by the absence of the short, main spine system and coronet, and differs from *S. spatangus* Dogiel by the absence of numerous short spines distributed in the disc periphery. *S. stylotrochoides* Dogiel is marked by a coronet, several relatively thick and short spines, while *S. spatangus* Dogiel possesses numerous fine, short spines and an absence of coronet. *Schizodiscus* sp. A (Pl. 2, fig. 26) is distinguishable from *S. japonicus* by the presence of many equatorial radial spines originating from the central part of the test, a finer test pore frame, and the presence of a thin cover over the central to medial regions of the disk. *S. japonicus* is completely different from *Spongodiscus biconcavus* Haeckel, 1887 in having very coarse pores.

CHARACTERISTICS OF RADIOLARIAN ASSEMBLAGES

Biostratigraphical interpretation was carried out using fractions greater than 63 μm. Figure 3 shows the 74 species included in subsequent examination. The present study revealed that 36 of the species examined occurred throughout the examined intervals (over the past 740 ka), while the remaining 38 species showed discontinuous occurrences throughout those same intervals. The assemblages were dominated by the continuous occurrences of pylonioid spumellarians (including *Larcopyle buetschlii* Dreyer, 1889, *Tetrapyle octacantha* group Müller, 1859, *Phorticium pylonium* Jørgensen, 1899, *Phorticium polycladum* Tan & Tchang, 1976 and *Tholospira cervicornis* Haeckel, 1887), flat-shaped spumellarians (*Stylochlamydium*? *venustum* (Bailey, 1856), *Spongodiscus resurgens* Ehrenberg, 1854, *Schizodiscus japonicus* sp. nov. and *Spongodiscus helioides* (Cleve, 1899)) and spherical spumellarians (including *Actinomma boreale* Cleve, 1899 and *A. leptodermum* (Jørgensen, 1899)). Episodic occurrences of three flat, triangular-shaped radiolarians, *Dictyocoryne profunda* Ehrenberg, 1873*a*, *D. truncatum* (Ehrenberg, 1862) and *D. muelleri* (Haeckel, 1862), and one spherical species, *Haliommetta miocenica* (Campbell & Clark, 1944), were also observed. In contrast to the high species diversity of Spumellaria, the diversity of Nassellaria appeared low. Both *Cycladophora davisiana* Ehrenberg, 1862 and *Ceratospyris*? *borealis* (Bailey, 1856) occurred throughout the intervals examined. Based on the distribution of the 74 species examined, 12 bioevents within core 902-C9001C were recognized as biostratigraphically useful (Fig. 3). First occurrence (FO) datums were detected at

- 613 ka (FO of *Spongaster tetras* Ehrenberg, 1862 *irregularis* Nigrini, 1967),
- 516 ka (FO of *Cyrtidosphaera reticulata* Haeckel, 1861*a*),
- 451 ka (FO of *Amphisphaera tanzhiyuani* sp. nov.),
- 259 ka (FO of *Pterocanium depressum* Ehrenberg, 1873*a*),
- 209 ka (FO of *Spongopila ellipsoides* Popofsky, 1912), and
- 131 ka (FO of *Ceratospyris problematica* (Dogiel in Petrushevskaya, 1969)).

A first continuous occurrence (FCO) datum was recorded at 17 ka (for *Acanthodesmia vinculata* (Müller, 1859)) and five last occurrence (LO) datums were identified at

- 357 ka (LO of *Axoprunum acquilonium* (Hays, 1970)),
- 238 ka (LO of *Schizodiscus japonicus* sp. nov.),
- 219 ka (LO of *Pterocanium depressum*),
- 86 ka (LO of *Schizodiscus* sp. A), and
- 33 ka (LO of *Lychnocanoma sakaii* Morley & Nigrini, 1995).

The relative abundance of *L. sakaii* changed significantly throughout this core and provided five additional datums: three abundance peaks at 229, 207 and 61ka, a rapid increase datum at 240 ka and a rapid decrease datum at 55 ka.

RADIOLARIAN BIOEVENTS

In the present study 12 bioevents were identified over the past 740 ka. Of these events, nine were identified for the first time in core 902-C9001C (Fig. 5), while the remaining three events had been identified previously as useful datums within the northwestern Pacific. Table 2 summarizes the stratigraphical horizons of the 12 bioevents and their correlative numerical ages with oxygen isotope stratigraphy. The correlation of datums with other regions is described in detail below.

Last occurrence datum of *Axoprunum acquilonium* (357 ka)

A. acquilonium has been recorded only in North Pacific sediment (e.g. Hays, 1970; Morley *et al.* 1995), including the Bering and Japan seas (Ling, 1973) and the Sea of Okhotsk (Matul *et al.* 2002). Hays (1970) and Ling (1973) noted that the relative abundance of this taxon never exceeded 5% in the Lower to Middle Pleistocene intervals. The LO datum of this taxon was identified at 310 ka in the North Pacific (Hays, 1970), at around 330 ka in the northwestern Pacific (Morley *et al.* 1995) and at 329 ka in the Sea of Okhotsk (Matul *et al.*, 2002). The LO of *A. acquilonium* in the present study was located between sample 23H-5, 54–60 cm (208.97 mbsf) and sample 24H1-1, 25–31 cm (213.16 mbsf) at 357 ka (Table 2). The LO of *A. acquilonium* identified in the present study appeared to be roughly synchronous with the LO previously identified in the northwestern Pacific, revealing a time gap of less than 27 ka.

Explanation of Plate 1. figs 1–4. Collodaria: **1–4**, *Siphonosphaera*? *paraphoros* sp. nov., holotype, fig. 1, IGPS 111417, sample 902-C9001C, 10H-1, 45.5–54.5 and 11H-3, 50.5–59.5. **figs 5–14.** Spumellaria: **5**, *Actinomma boreale* (Cleve), sample 902-C9001C, 21H-4, 47–53; **6**, *Actinomma leptodermum* (Jørgensen), sample 902-C9001C, 19H-6, 47–53; **7**, *Rhizosphaera mediana* (Nigrini), sample 902-C9001C, 1H-1, 24–30; **8**, *Sphaeropyle langii* Dreyer, 29H-4, 47–53; **9**, *Cenosphaera*? sp., sample 902-C9001C, 7H-5, 45.5–54.5; **10**, *Cyrtidosphaera reticulata* Haeckel, sample 902-C9001C, 7H-5, 45.5–54.5; **11**, *Cladococcus bifurcus* Haeckel, sample 902-C9001C, 1H-2, 50–56; **12**, *Cladococcus lychnosphaerae*, sample 902-C9001C, 1H-2, 50–56; **13**, *Cleveiplegma boreale* (Cleve), sample 902-C9001C, 1H-5, 30–36; **14**, *Spongosphaera streptacantha* Haeckel, sample 902-C9001C, 2H-2, 50–56.

Last occurrence datum of *Schizodiscus japonicus* (238 ka)

Schizodiscus japonicus sp. nov. has long been referred to as *Spongodiscus* sp. (e.g. Ling, 1973) and its LO has been recognized in the Middle Pleistocene at sites in the northwestern Pacific (Ling, 1973; Sakai, 1980; Matul *et al.* 2002). The numerical age of this datum was roughly estimated at 290 ka by Matul *et al.* (2002) in the Sea of Okhotsk. Based on benthic foraminiferal oxygen isotopic stratigraphy, the LO age at the site examined in the present study was estimated at 238 ka (Fig. 5), which revealed a time gap of 62 ka between this site and the site examined by Matul *et al.* (2002). These results left no doubt that the LO of *S. japonicus* was located in the upper Middle Pleistocene at sites in the North Pacific.

Stratigraphical events of *Lychnocanoma sakaii*

The LO of *L. sakaii* was the most recent of the radiolarian bioevents identified from larger radiolarian fractions (>63 μm) in the North Pacific (Sakai, 1980). According to Sachs (unpublished thesis, Brown University, 1973), this datum served as a useful bioevent in Pleistocene deep-sea sediments. In this section the *L. sakaii* curve will be presented as a stratigraphical proxy based on Figure 4.

1. Rapid decrease datum (50 ka) and last occurrence datum (33 ka) of L. sakaii.

The FO of *L. sakaii* was not detected in core 902-C9001C as the base of the core is only 740 ka, and the FO of *L. sakaii* is recognized at 1.6 Ma by both Morley & Nigrini (1995) and Kamikuri (2010). The LO of *L. sakaii* was detected here in the interval between sample 3H-4, 42–48 cm (20.91 mbsf) and sample 3H-6, 50–56 cm (23.74 mbsf), which corresponds to 33 ka (Table 1). According to several previous studies (Robertson, unpublished thesis, Columbia University, 1975; Morley & Nigrini, 1995; Kamikuri, 2010), the LO of this species was dated at 50 ka, while Matul *et al.* (2002) dated the LO of *L. sakaii* at 29 ka in the Sea of Okhotsk, and Morley *et al.* (1982) dated the LO between 16.7 and 34 ka. The LO of the species identified in the present study appeared to be similar to the LOs identified by Morley *et al.* (1982) and Matul *et al.* (2002). The long time gap between our *L. sakaii* LO datum of 33 ka and that identified in the records of Robertson (unpublished thesis, Columbia University, 1975), Morley & Nigrini (1995) and Kamikuri (2010) at around 50 ka requires examination. This date is almost the same as that at which the present study identified a rapid decrease datum (RD, Fig. 4). This phenomenon could have been plausibly interpreted as a LO in a low resolution study, while in a high resolution study – as the present study and that of Matul *et al.* (2002) – the RD datum and LO appear as two distinct events.

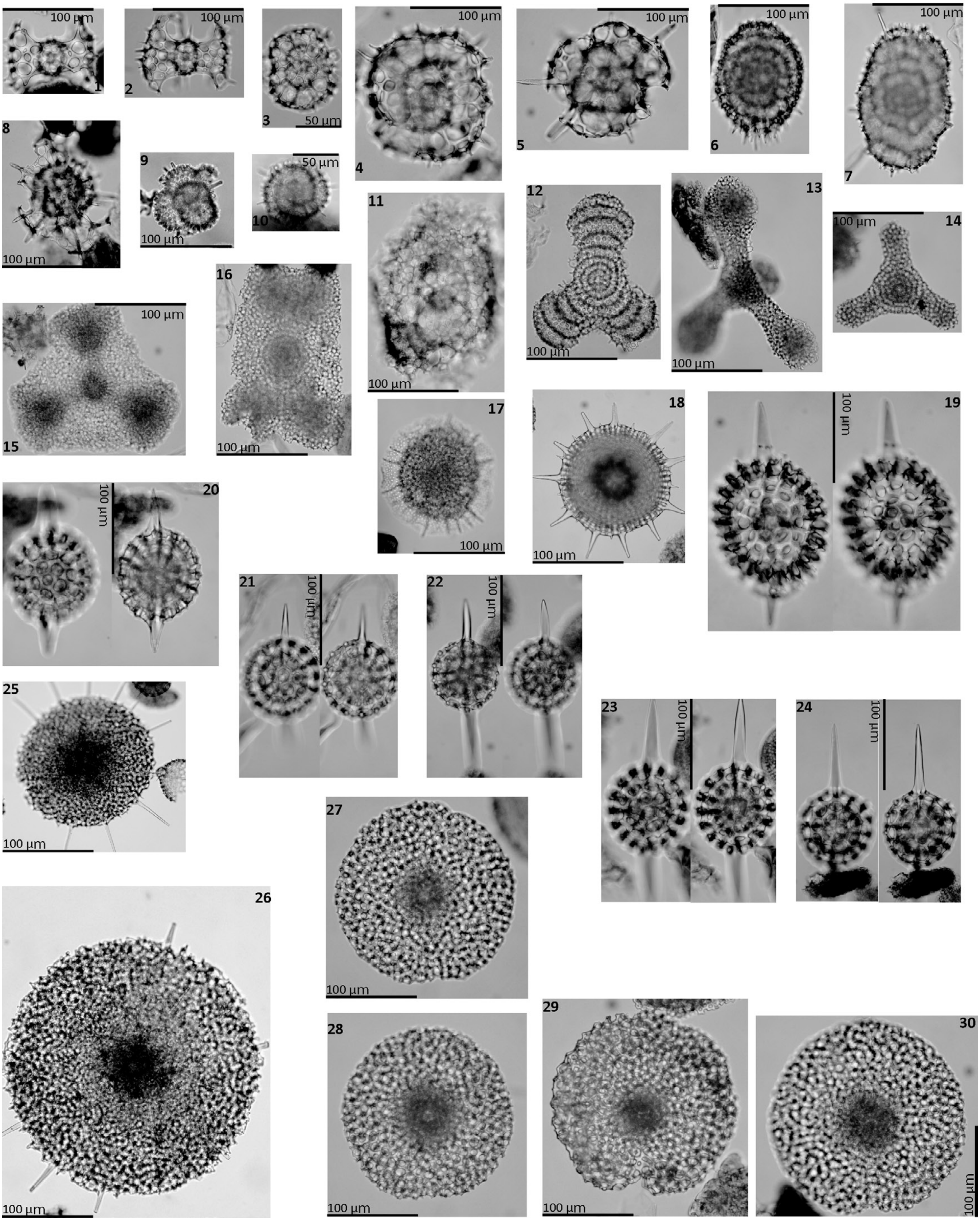
2. Rapid increase datum (240 ka) and abundance peaks (61, 207 and 229 ka) of Lychnocanoma sakaii.

As shown in Figure 4, the change in relative abundance of *L. sakaii* was so significant that the rapid increase (RI) datum and abundance peaks (AP) of this species were potentially applicable to biostratigraphical correlation with adjacent regions. This significance had already been noted for the North Pacific by Sachs (unpublished thesis, Brown University, 1973); however, in that study, *L. sakaii* was identified as *Lychnocanoma grande* Campbell & Clark, 1944. In the present study, one RID and three APs higher than 10% of the total assemblages were identified at 240, 229, 207 and 61 ka, respectively (Fig. 4, Table 3). The highest relative abundance peak of *L. sakaii* during the last 740 ka (AP3) was located at 61 ka during the early MIS 4. This event was detected at 60 ka in the northwestern Pacific by Robertson (unpublished thesis, Columbia University, 1975) and Sachs (unpublished thesis, Brown University, 1973), while Matul *et al.* (2002) recorded a high abundance peak for *L. sakaii* in the Sea of Okhotsk at 72 ka. *L. sakaii* AP3 appears to be a suitable age tie point in the northwestern Pacific.

RADIOLARIAN ZONATION

As documented in the previous sections, 12 bioevents were detected in 902-C9001C (Fig. 3). Among these bioevents, nine were recognized for the first time in core 902-C9001C (FOs of *Spongaster tetras irregularis*, *Cyrtidosphaera reticulata*, *Amphisphaera tanzhiyuani*, *Pterocanium depressum*, *Spongoliva ellipsoides* and *Ceratospyris problematica*; FCO of *Acanthodesmia vinculata*; LOs of *Axoprunum acquilonium* and *Schizodiscus* sp. A). Among these nine bioevents, seven define eight new radiolarian interval zones at the Shimokita site (Fig. 3). The LO of *Schizodiscus* sp. A was not selected as a zonal marker since identification proved difficult due to its strong morphological similarities with other species, although *Schizodiscus japonicus* is separated from other *Schizodiscus* species by the absence of radial spines around the disk and significant light contrast between the central part and its adjacent exterior thinner part of the disk (Dogiel & Reshetnyak, 1952; Petrushevskaya, 1968). The remaining bioevents could potentially be used subordinately for refinement and confirmation of age determinations using the zones proposed in the present study.

Explanation of Plate 2. figs 1–30. Spumellaria: **1–2**, *Tetrapyle octacantha* Müller group, sample 902-C9001C, 1H-2, 50–56 and 16H-8, 62–68; **3**, *Phorticium polycladum* Tan & Tchang, sample 902-C9001C, 16H-8, 62–68; **4**, *Phorticium pylonium* Haeckel, sample 902-C9001C, 20H-3, 62–68; **5**, *Pylodiscus triangularis* Haeckel, sample 902-C9001C, 1H-2, 50–56; **6–7**, *Larcopyle buetschlii* Dreyer, sample 902-C9001C, 1H-2, 50–56 and 16H-8, 62–68; **8**, *Larcopyle cervicornis* Haeckel, 11H-5, 45.5–54.5; **9**, *Tholomura plystyla* (Chen) comb. nov. sample 902-C9001C, 1H-2, 50–56; **10**, *Lithelius nautiloides* Popofsky, sample 902-C9001C, 10H-6, 45.5–54.5; **11**, *Spongoliva ellipsoides* Popofsky, sample 902-C9001C, 1H-1, 29–30; **12**, *Amphirhopalum virchowii* (Haeckel), sample 902-C9001C, 21H-4, 47–53; **13**, *Dictyocoryne profunda* Ehrenberg, sample 902-C9001C, 22H-4, 47–53; **14**, *Dictyocoryne muelleri* (Haeckel), sample 902-C9001C, 12H-4, 20.5–29.5; **15**, *Dictyocorine truncatum* (Ehrenberg), sample 902-C9001C, 27H-6, 69–75; **16**, *Spongaster tetras* Ehrenberg *irregularis* Nigrini, sample 902-C9001C, 1H-5, 30–36 ; **17**, *Stylochlamydium*? *venustum* (Bailey), sample 902-C9001C, 22H-4, 47–53; **18**, *Heliodiscus* cf. *tunicatus* O'Connor, sample 902-C9001C, 19H-6, 47–53; **19**, *Axoprunum aquilonium* (Hays), sample 902-C9001C, 39H-5, 57–63 ; **20**, *Amphisphaera spumea* (Dumitrica), sample 902-C9001C, 29H-4, 47–53; **21–24**, *Amphisphaera tanzhiyuani* sp. nov., holotype, fig. 21, IGPS 111418, sample 902-C9001C, 29H-1, 47–53 and 29H-3, 47–53; **25**, *Spongodiscus helioides* (Cleve), sample 902-C9001C, 1H-5, 30–36; **26**. *Schizodiscus* sp. A, sample 902-C9001C, 10H-6, 45.5–54.5; **27–30**, *Schizodiscus japonicus* sp. nov., holotype, fig. 30, IGPS 111419, sample 902-C9001C, 20H-3, 62–68.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Amphirhopalum virchowii Interval Zone (bottom of core–613 ka)
Definition. Base of zone is not defined. Top of zone defined by base of *Spongaster tetras irregularis* Interval Zone.

Faunal character. The assemblage is marked by continuous occurrences of *Tetrapyle octacantha*, *Larcopyle buetschlii*, *Stylochlamydium*? *venustum* and *Cycladophora davisiana*.

Interval and age. The stratigraphical interval between sample 40H-10 at 55–61 cm (362 mbsf) and 35X-5 at 47–53 cm (316 mbsf) in the 902-C9001C core. This zone covers the period from the core base to 613 ka.

Spongaster tetras irregularis Interval Zone (613–516 ka)
Definition. Base of zone defined by FO of *Spongaster tetras irregularis*. Top of zone defined by base of *Cyrtidosphaera reticulate* Interval Zone.

Faunal character. Assemblage is marked by the continuous occurrence of *Tetrapyle octacantha*, *Larcopyle buetschlii*, *Stylochlamydium*? *venustum* and *Cycladophora davisiana*, as in the previous zone. The FOs of *Spongosphaera streptacantha* and *Eucecryphalus cervus* are placed in this zone.

Interval and age. The stratigraphical interval between sample 35X-5, 47–53 cm (316 mbsf) and 31H-2, 25–31 cm (275 mbsf) in the 902-C9001C core. This zone covers the period from 613 to 516 ka.

Remarks. The FO of *Spongaster tetras irregularis* is recorded at the top of the *Stylatractus universus* Zone (Lower Pleistocene–Middle Pleistocene) in Morley (1985). In our site, this datum is found in MIS 15.

Cyrtidosphaera reticulata Interval Zone (516–357 ka)

Definition. Base of zone defined by the FO of *Cyrtidosphaera reticulata*. Top of zone defined by the base of the *Spongurus cylindricus* Interval Zone.

Faunal character. The assemblage is marked by the continuous occurrence of *Tetrapyle octacantha, Larcopyle buetschlii, Stylochlamydium*? *venustum* and *Cycladophora davisiana* from the *Amphirhopalum virchowii* Zone. The FO of *Amphisphaera tanzhiyuani* sp. nov (451 ka) is placed in this zone, but it cannot be used as a biostratigraphical marker because of limited geographical coverage.

Interval and age. The stratigraphical interval between sample 31H-2 at 25–31 cm (275 mbsf) and 23H-5 at 54–60 cm (208 mbsf) in the 902-C9001C core. This zone covers the period from 516 to 357 ka.

Spongurus cylindricus Interval Zone (357–238 ka)
Definition. Base of zone defined by the LO of *Axoprunum acquilonium*. Top of zone defined by the base of *Pterocanium depressum* Interval Zone.

Faunal character. The characteristic species in this zone are the same as in the *Spongaster tetras irregularis* Zone. In addition, the first occurrence (FO) of *Pterocanium depressum* (259 ka) is the key marker of this zone.

Interval and age. The stratigraphical interval between sample 23H-5 at 54–60 cm (208 mbsf) and 17H-2 at 24–30 cm (149.8 mbsf) in the 902-C9001C core. This zone covers the period from 357 to 238 ka.

Pterocanium depressum Interval Zone (238–209 ka)
Definition. Base of zone defined by the LO of *Schizodiscus japonicas* sp. nov.. Top of zone defined by the base of *Spongoliva ellipsoides* Interval Zone.

Faunal character. The important taxa are the same as in the previous zones, except for the disappearance of *Pterocanium depressum* (LO at 219 ka), *Schizodiscus japonicas* sp. nov. (LO at 238 ka), *Amphirhopalum virchowii* and *Amphisphaera tanzhiyuani* sp. nov. within this zone (Fig. 5).

Interval and age. The stratigraphical interval between sample 18H-4 at 42–48 cm (163.04 mbsf) and 13H-6 at 40.5–49.5 cm (118 mbsf) in the 902-C9001C core. This zone covers the period from 238 to 209 ka.

Remarks. The last occurrence of *Amphirhopalum virchowii* is not the true extinction event world-wide, because this species is extant based on the type locality of specimens collected from modern seawater (Sakai *et al.* 2009).

Spongoliva ellipsoides Interval Zone (209–131 ka)
Definition. Base of zone defined by the FO of *Spongoliva ellipsoides*. Top of zone defined by base of *Ceratospyris problematica* Interval Zone.

Faunal character. The assemblage is characterized by the same species as in the previous zones, except for the occurrence of *Cleveiplegma boreale*, *Spongoliva ellipsoides* and *Pylodiscus triangularis* (Fig. 3).

Interval and age. The stratigraphical interval between sample 13H-6 at 40.5–49.5 cm (118 mbsf) and 8H-6 at 42–48 cm (70.85 mbsf) in the 902-C9001C core. This zone covers the period from 209 to 131 ka.

Explanation of Plate 3. figs 1–19. Nassellaria: **1**, *Botryopera* aff. *chlamida* Petrushevskaya, sample 902-C9001C, 1H-2, 50–56; **2**, *Archiperidium pentacanthum* (Popofsky), sample 902-C9001C, 1H-2, 50–56; **3**, *Cryptogyrus araneafera* (Popofsky), sample 902-C9001C, 4H-6, 69–75; **4**, *Cryptogyrus dubius* (Dogiel in Dogiel & Reshetnyak), sample 902-C9001C, 4H-6, 69–75; **5**, *Dimelissa monoceras* (Popofsky), sample 902-C9001C, 1H-2, 50–56; **6**, *Zygocircus* cf. *piscicaudatus* Popofsky, sample 902-C9001C, 7H-5, 45.5–54.5; **7**, *Acanthodesmia vinculata* (Müller), sample 902-C9001C, 1H-1, 24–30; **8**, *Ceratospyris*? *borealis* Bailey, sample 902-C9001C, 2H-2, 50–56; **9**, *Ceratospyris problematica* (Dogiel in Petrushevskaya), sample 902-C9001C, 1H-5, 30–36; **10–12**, *Cycladophora davisiana* Ehrenberg, sample 902-C9001C, 2H-1, 55–61 and 7H-2, 53.5–62.5; **13**, *Lipmanella irregulare* (Cleve), sample 902-C9001C, 1H-5, 30–36; **14**, *Theocorythium trachelium* (Ehrenberg), sample 902-C9001C, 30H-2, 77–83; **15**, *Ceratocyrtis spinosiretis* (Takahashi), sample 902-C9001C, 2H-2, 50–56; **16**, *Lamprocyclas maritalis* Haeckel, sample 902-C9001C, 29H-1, 47–53; **17**, *Pterocanium depressum* (Ehrenberg), sample 902-C9001C, 13H-2, 45.5–54.5; **18–19**, *Lychnocanoma sakaii* Morley & Nigrini, sample 902-C9001C, 8H-4, 26–32 and 13H-2, 45.5–54.5.

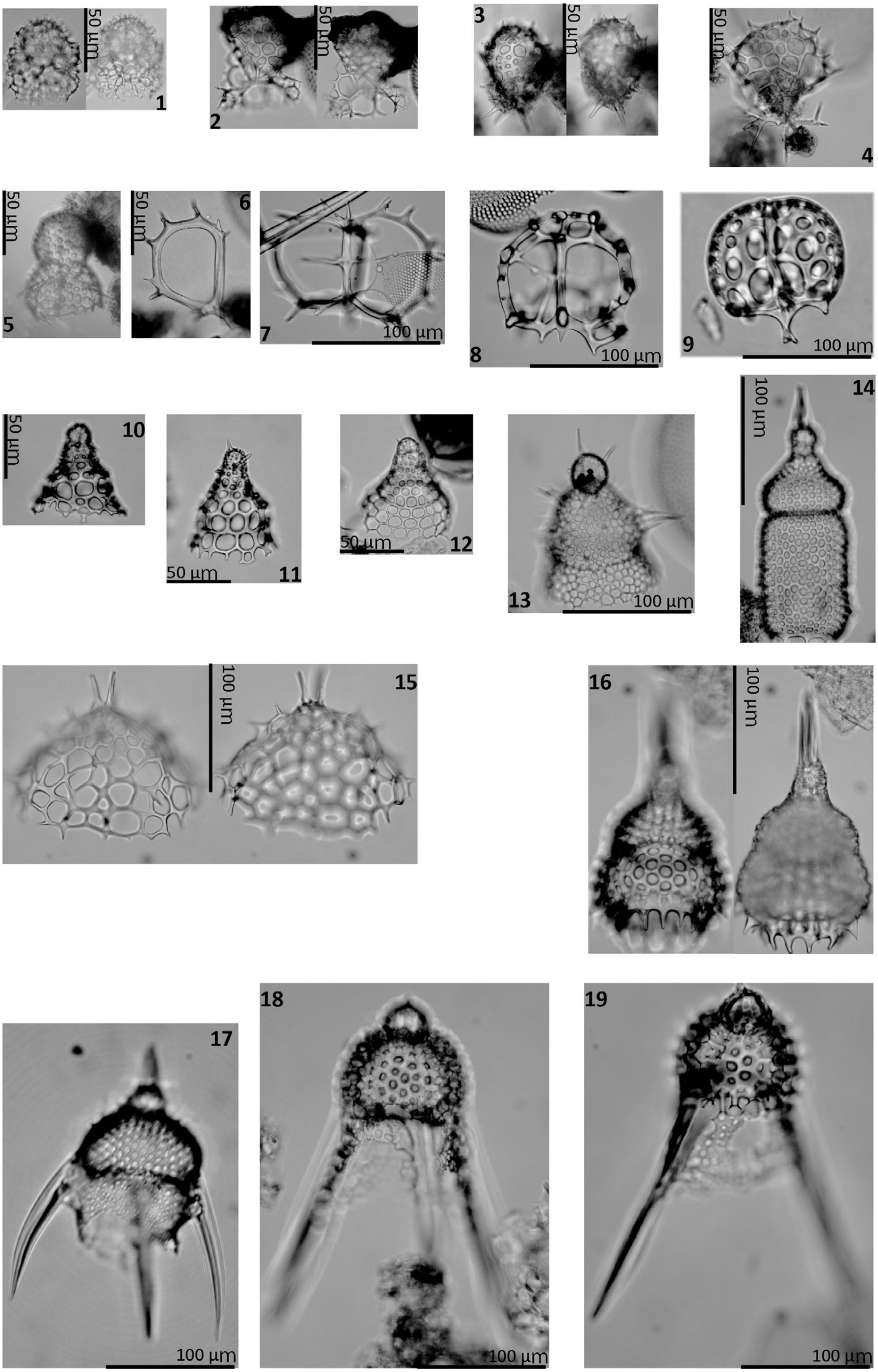
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Table 1. Species list and authors of the biostratigraphically important radiolarian species in core 902-9001C.

Taxa	Plates & figures	References
Collodaria		
Siphonosphaera? *paraphoros* sp. nov.	Plate 1, figs 1–4	This study
Spumellaria		
Actinomma boreale Cleve	Plate 1, fig. 5	Cleve (1899, p. 26, pl. 1, figs 5c, d)
Actinomma leptodermum (Jørgensen)	Plate 1, fig. 6	Jørgensen (1899, pp. 57–58); Nishimura & Yamauchi (1984, pp. 21–22, pl. 8, figs 7, 11); Itaki *et al.* (2012, pl. 3, fig. 3)
Rhizosphaera mediana (Nigrini)	Plate 1, fig. 7	Nigrini (1967, pp. 27–29, pl. 2, figs 2a, b); Levyikina (1986, p. 97, pl. 16, fig. 11)
Sphaeropyle langii Dreyer	Plate 1, fig. 8	Dreyer (1889, p. 89, fig. 54)
Cenosphaera? sp.	Plate 1, fig. 9	
Cyrtidosphaera reticulata Haeckel	Plate 1, fig. 10	Haeckel (1861*a*, p. 803)
Cladococcus bifurcus Haeckel	Plate 1, fig. 11	Haeckel (1862, pp. 368–369, pl. 13, figs 7, 8)
Cladococcus lychnosphaerae Hollande & Enjumet	Plate 1, fig. 12	Hollande & Enjumet (1960, p. 115, pl. 55, figs 1, 2)
Cleveiplegma boreale (Cleve)	Plate 1, fig. 13	Cleve (1899, p. 30, pl. 2, figs 4a, b, c); Dumitrica (2013, p. 25, pl. 1, figs 1–9)
Spongosphaera streptacantha Haeckel	Plate 1, fig. 14	Haeckel (1861*b*, pp. 840–841); Sakai *et al.* (2009, p. 52, pl. 1, fig. 8, pl. 3, fig. 10, pl. 7, fig. 1, pl. 8, fig. 8, pl. 11, fig. 4, pl. 13, fig. 5, pl. 22, fig. 1 [type specimens in Ernst-Haeckel-House collection])
Tetrapyle octacantha Müller group	Plate 2, figs 1–2	Müller (1859, pp. 33–35, pl. 2, figs 11–13, p1. 3, figs 1–6); Ling (1972, p. 168, pl. 2, fig. 3)
Phorticium polycladum Tan & Tchang	Plate 2, fig. 3	Tan & Tchang (1976, p. 267, text-figs 39a, b)
Phorticium pylonium Haeckel	Plate 2, fig. 4	Haeckel (1887, p. 709, pl. 49, fig. 10); Tan & Cheng (1990, pp. 121–122, text-fig. 16)
Pylodiscus triangularis Haeckel	Plate 2, fig. 5	Haeckel (1887, p. 570, pl. 48, fig. 17)
Larcopyle buetschlii Dreyer	Plate 2, figs 6–7	Dreyer (1889, pp. 124–125, pl. 10, fig. 70); Lazarus *et al.* (2005, pp. 106–108, pl. 1, figs 10–14)
Larcopyle cervicornis Haeckel	Plate 2, fig. 8	Haeckel (1887, p. 700, pl. 49, fig. 5); Itaki (2009, pl. 11, figs 14–17)
Tholomura polystyla (Chen) comb. nov.	Plate 2, fig. 9	Chen (1987, pp. 225–226, pl. 2, figs 8, 9)
Lithelius nautiloides Popofsky	Plate 2, fig. 10	Popofsky (1908, pp. 230–231, pl. 27, fig. 4)
Spongoliva ellipsoides Popofsky	Plate 2, fig. 11	Popofsky (1912, p. 117, text-fig. 28)
Amphirhopalum virchowii (Haeckel)	Plate 2, fig. 12	Haeckel (1862, pp. 503–505, pl. 30, figs 1–4); Sakai *et al.* (2009, p. 50, pl. 18, fig. 5 [Ernst-Haeckel Haus collection; lectotype])
Dictyocoryne profunda Ehrenberg	Plate 2, fig. 13	Ehrenberg (1873*a*, pp. 288–289, pl. 7, fig. 23); Suzuki *et al.* (2009*a*, pl. 49, fig. 1 [Type specimen, Ehrenberg Collection])
Dictyocoryne muelleri (Haeckel)	Plate 2, fig. 14	Haeckel (1862, p. 508, pl. 30, figs 5–10); Ogane *et al.* (2009, p. 91, figs 2C, D [Type specimen, Ehrenberg Collection: lectotype])
Spongaster tetras Ehrenberg *irregularis* Nigrini	Plate 2, fig. 16	Nigrini (1967, pp. 43–44, pl. 5, fig. 2)
Stylochamydium? *venustum* (Bailey)	Plate 2, fig. 17	Bailey (1856, p. 5, pl. 1, figs 16, 17); Kruglikova (1974, pp. 191–192, pl. 2, figs 7, 8)
Heliodiscus cf. *tunicatus* O'Connor	Plate 2, fig. 18	O'Connor (1997, pp. 67–68, pl. 1, figs 1–5, pl. 5, figs 1–5).
Axoprunum acquilonium (Hays)	Plate 2, fig. 19	Hays (1970, p. 214, pl. 1, figs 4, 5); Ling (1973, p. 777, pl. 1, figs 6, 7)
Amphisphaera spumea (Dumitrica)	Plate 2, fig. 20	Dumitrica (1973, p. 833, pl. 20, fig. 9)
Amphisphaera tanzhiyuani sp. nov.	Plate 2, figs 21–24	This study
Spongodiscus helioides (Cleve) comb. nov.	Plate 2, fig. 25	Cleve (1899, p. 34, pl. 4, fig. 5)
Schizodiscus sp. A	Plate 2, fig. 26	
Schizodiscus japonicus sp. nov.	Plate 2, figs 27–30	This study
Nassellaria		
Botryopera aff. *chlamida* Petrushevskaya	Plate 3, fig. 1	Petrushevskaya (1975, p. 592, pl. 20, figs 5, 6)
Archiperidium pentacanthum (Popofsky) comb. nov.	Plate 3, fig. 2	Popofsky (1913, pp. 366–368, pl. 32, figs 5, 6, text-figs 84–86)
Cryptogyrus araneafera (Popofsky)	Plate 3, fig. 3	Popofsky (1908, pp. 273–274, pl. 30, fig. 1)
Cryptogyrus dubius (Dogiel in Dogiel & Reshetnyak) comb. nov.	Plate 3, fig. 4	Dogiel in Dogiel & Reshetnyak (1952, pp. 19–20, text-fig. 12)
Dimelissa monoceras (Popofsky) comb. nov.	Plate 3, fig. 5	Popofsky (1913, p. 335, pl. 32, fig. 7, text-fig. 43)
Zygocircus cf. *piscicaudatus* Popofsky	Plate 3, fig. 6	Popofsky (1913, pp. 287–288, pl. 28, fig. 3)

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Table 1. (Continued)

Taxa	Plates & figures	References
Acanthodesmia vinculata (Müller)	Plate 3, fig. 7	Müller (1856, p. 484); Ling (1972, pl. 2, fig. 6)
Ceratospyris? *borealis* Bailey	Plate 3, fig. 8	Bailey (1856, p. 3, pl. 1, fig. 3); Itaki & Bjørklund (2007, pp. 450–451, pl. 1, figs 3–5, 6 [lectotype])
Ceratospyris problematica (Dogiel)	Plate 3, fig. 9	Dogiel in Petrushevskaya (1969, p. 134, pl. 1, fig. 6)
Cycladophora davisiana Ehrenberg	Plate 3, figs 10–12	Ehrenberg (1873*b*, pp. 288–289, pl. 2, fig. 11); Suzuki *et al.* (2009*a*, pl. 41, fig. 3, pl. 42, figs. 5, 9 [Type specimen, Ehrenberg Collection])
Lipmanella irregulare (Cleve)	Plate 3, fig. 13	Cleve (1899, pp. 32–33, pl. 4, fig. 1); Sugiyama *et al.* (1992, pl. 24, fig. 1)
Theocorythium trachelium (Ehrenberg)	Plate 3, fig. 14	Ehrenberg (1861, p. 768); Suzuki *et al.* (2009*a*, pl. 55, fig. 4 [Type specimen, Ehrenberg Collection])
Ceratocyrtis spinosiretis (Takahashi) comb. nov.	Plate 3, fig. 15	Takahashi (1991, p. 110, pl. 34, figs 1, 2, 7); Itaki (2009, p. 52, pl. 19, figs 3–10)
Lamprocyclas maritalis Haeckel	Plate 3, fig. 16	Haeckel (1887, p. 1390, pl. 74, figs 13, 14); Renz (1976, p. 145, pl. 6, fig. 26)
Pterocanium depressum (Ehrenberg)	Plate 3, fig. 17	Ehrenberg (1873*a*, p. 316); Ehrenberg (1873*b*, pp. 296–297, pl. 10, fig. 1); Suzuki *et al.* (2009*a*, pl. 72, fig. 3 [lectotype])
Lychnocanoma sakaii Morley & Nigrini	Plate 3, figs 18–19	Morley & Nigrini (1995, pp. 80–81, pl. 6, figs 1, 4)

Remarks. Spongoliva ellipsoides is commonly reported from various tropical to mid-latitudinal regions globally, but the range of this species is poorly documented except for our report.

Ceratospyris problematica Interval Zone (131–33 ka)

Definition. Base of zone is defined by the FO of *Ceratospyris problematica*. Top of zone defined by the base of the *Acanthodesmia vinculata* Interval Zone.

Faunal character. This zone is characterized by several bioevents, such as the LO of *Schizodiscus* sp. A. (86 ka), AP3 of *Lychnocanoma sakaii* (61 ka), RD of *L. sakaii* (55 ka) and LO of *L. sakaii* (33 ka).

Interval and age. The stratigraphical interval between sample 8H-6 at 42–48 cm (70.85 mbsf) and 3H-4 at 42–48 cm (20.91 mbsf) of the 902-C9001C core. This zone covers the period from 131 to 33 ka.

Remarks. Ceratospyris problematica has not been identified from other regions previously, except for the original description by Petrushevskaya (1969). We confirm this species here and its stratigraphical range (Fig. 5).

Acanthodesmia vinculata Interval Zone (33–0 ka)

Definition. Base of zone defined by the LO of *Lychnocanoma sakaii.* Top of zone not defined – top of the core (0 mbsf).

Faunal character. All the species that occur in the previous zone are found in this zone. The FCO of *Acanthodesmia vinculata* (17 ka) and the reappearance of *Amphisphaera tanzhiyuani* sp. nov. occur in this interval zone.

Interval and age. The stratigraphical interval between sample 3H-4 at 42–48 cm (20.91 mbsf) and the top of core 902-C9001C (0 mbsf). This zone covers the period from 33 to 0 ka.

Remarks. Acanthodesmoidea vinculata is well recorded in the Upper Pleistocene sediments (Nishimura & Yamauchi, 1984; Bjørklund & de Ruiter, 1987).

CORRELATION OF RADIOLARIAN BIOEVENTS IN THE NORTHWESTERN PACIFIC SINCE THE MIDDLE PLEISTOCENE

Based on thorough examination of the distribution of radiolarian species within the 902-C9001C core, eight radiolarian regional zones are proposed for the past 740 ka within the Shimokita region (northwestern Pacific off the east coast of northern Japan). As seven bioevents in this region were first recognized in the present study, direct comparison with previously established zones in the North Pacific was necessary to locate these new radiolarian zones against the North Pacific standard radiolarian zonation for the Quaternary period established by Kamikuri *et al.* (2004, 2007) and Motoyama *et al.* (2004). These studies proposed a Neogene radiolarian biostratigraphy for the North Pacific in which the Middle to Upper Pleistocene comprised only two radiolarian zones: the *Stylatractus universus* Zone and the *Botryostrobus aquilonaris* Zone, which were defined by the LO of *Eucyrtidium matuyamai* at 1050 ka and by the LO of *S. universus* at 430 ka, respectively (e.g. Motoyama *et al.* 2004; Fig. 5). In the present study, a major problem regarding these last datums was identified, as *S. universus* was not recorded at the study site, despite the fact that the LO of *S. universus* has been established as the tie point in the Middle Pleistocene within the North Pacific. This absence indicates that this datum is not always applicable in regions within the North Pacific, and that updates to the North Pacific radiolarian zonation are necessary in order to determine the regional suitability of each datum. Figure 5 shows the updates in which the radiolarian zones identified in the present study have been compared to the East Japan radiolarian zonations (after Motoyama *et al.* 2004; Kamikuri *et al.* 2007) and the Sea of Okhotsk radiolarian zonation (after Matul *et al.* 2002).

The *S. universus* Zone established by Motoyama *et al.* (2004), which was defined by the LO of *E. matuyamai* at 1050 ka (Base) and by the LO of *S. universus* at 430 ka (Top), was correlated with the *A. acquilonium* Zone established by Matul *et al.* (2002). The LO of *A. acquilonium* defined the top of this zone at 330 ka. Matul *et al.* (2002) determined that *S. universus* was not present in the

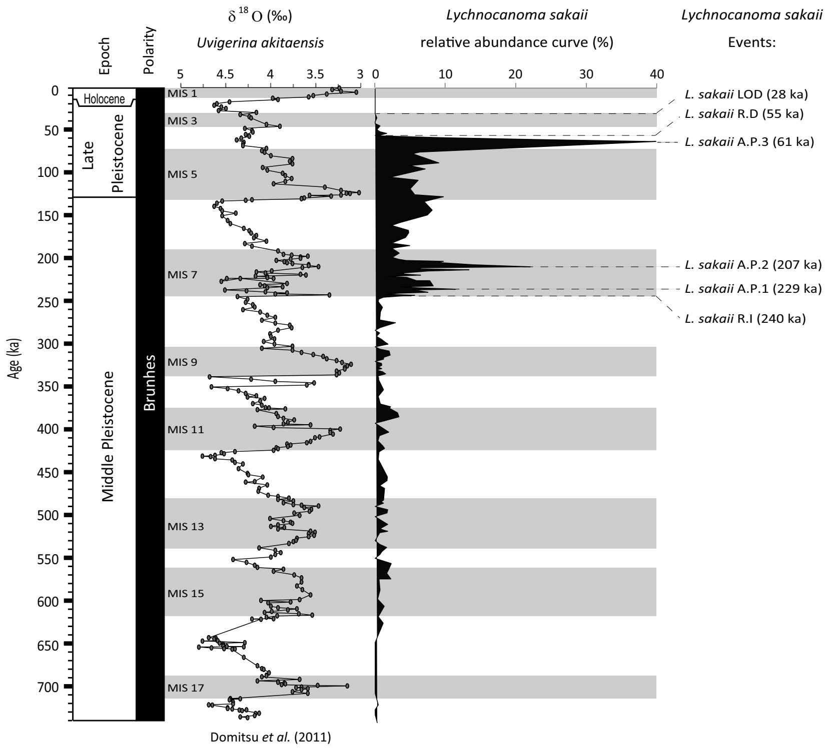

Fig. 4. *Lychnocanoma sakaii* abundance curve serving as a possible stratigraphical tool in the northwestern Pacific. Rapid increase (RI) at 240 ka, rapid decrease (RD) at 55 ka, and the three highest abundances peaks at 229 ka (AP1), 207 ka (AP2) and 61 ka (AP3) serving as alternative stratigraphical proxies in the northwestern Pacific. LOD, last occurrence datum.

Table 2. Radiolarian events in the northwestern Pacific (core 902-9001C).

Radiolarian event	Core section, interval (cm)	Depth (mbsf)	Age (ka)	Position in the chemostratigraphy (MIS)
FCO *Acanthodesmia vinculata*	2H-5, 71–77	12.96	17	Late MIS 2/MIS 1 boundary
	2H-6, 65–71	14.36	18	
LO *Lychocanoma sakaii*	3H-4, 42–48	20.91	29	late MIS 3
	3H-6, 50–56	23.74	33	
LO *Schizodiscus* sp. A	6H-5, 45.5–54.5	50.6	83	late MIS 5
	6H-6, 45.5–54.5	51.93	86	
FO *Ceratospyris problematica*	8H-6, 42–48	70.85	131	MIS 5/MIS 6 boundary
	9H-2, 45.5–54.5	75.16	141	
FO *Spongoliva ellipsoides*	13H-6, 40.5–49.5	118.37	209	middle MIS 7
	13H-7, 35.5–44.5	119.62	210	
LO *Pterocanium depressum*	14H-6, 67–73	128.18	218	middle MIS 7
	14H-7, 47–53	129.27	219	
LO *Schizodiscus japonicus*	17H-2, 24–30	149.8	237	MIS 7/MIS 8 boundary
	17H-3, 37–43	151.2	238	
FO *Pterocanium depressum*	18H-4, 42–48	163.04	259	MIS 8
	19H-2, 35–41	167.07	268	
LO *Axoprunum acquilonium*	23H-5, 54–60	208.97	350	Late MIS 10
	24H-1, 25–31	213.16	357	
FO *Amphisphaera tanzhiyuani*	27H-4, 107–113	243.62	451.13	MIS 12
	27H-5, 47–53	244.72	455.36	
FO *Cyrtidosphaera reticulata*	31H-2, 25–31	275.79	516	middle MIS 13
	31H-7, 47–53	281.82	525	
FO *Spongaster tetras irregularis*	35X-5, 47–53	316.21	613	early MIS 15
	35X-7, 47–53	318.74	621	

FOD, first occurrence datum; LO, last occurrence datum; FCO, first continuous occurrence.

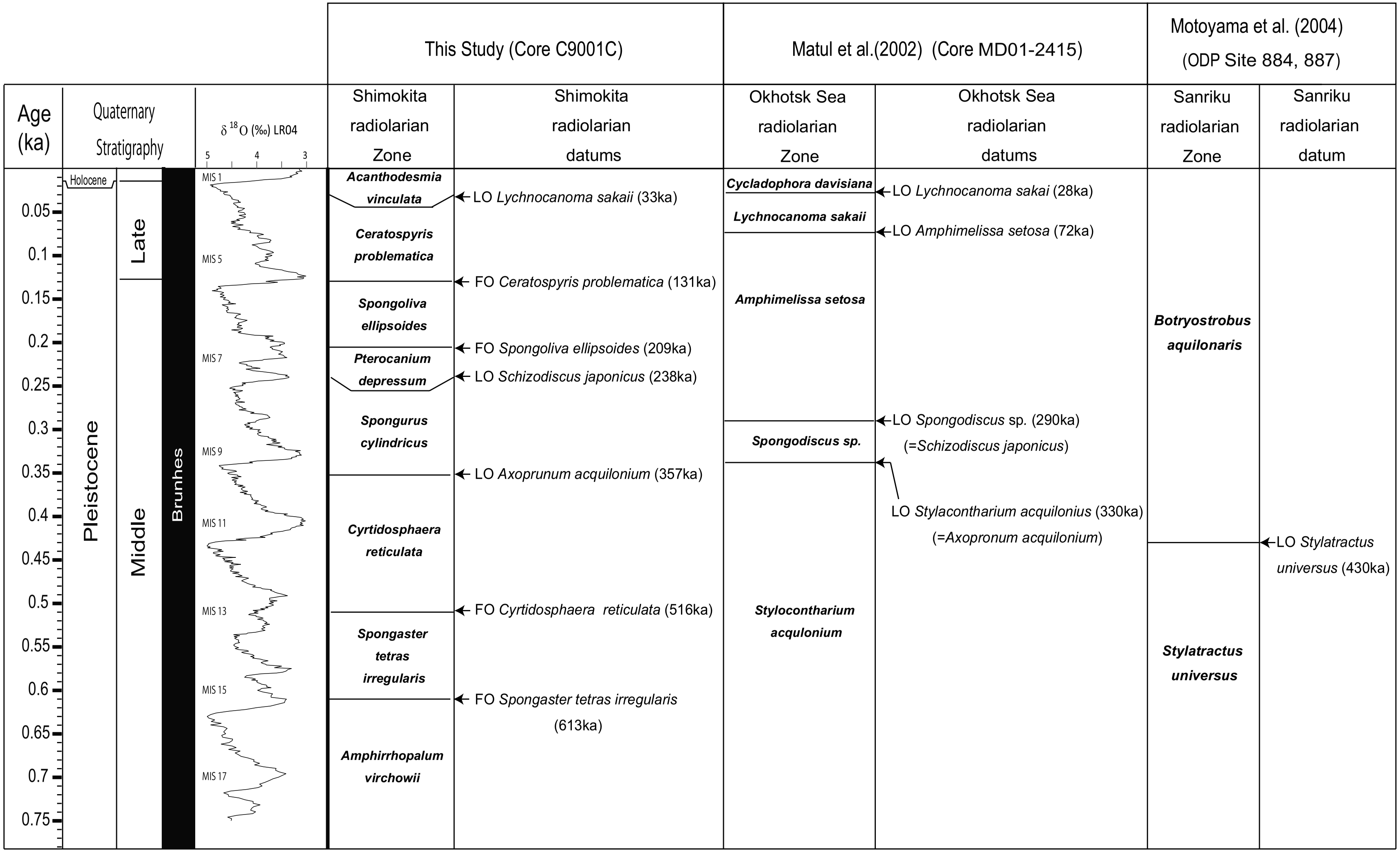

Fig. 5. Updated Middle to Upper Pleistocene Quaternary radiolarian biostratigraphic schemes in the northwestern Pacific based on comparisons between radiolarian biostratigraphic schemes determined in the present study (Shimokita) and those identified in the Sea of Okhkost (Matul *et al.* 2002) and the East Japan Sanriku region (Motoyama *et al.* 2004). FO, first occurrence datum; LO, last occurrence datum.

Table 3. *Lychnocanoma sakaii* events – rapid increase (RI), rapid decrease (RD) and abundance peaks (AP) serving as alternative stratigraphic proxies within the northwestern Pacific Middle to late Pleistocene.

Radiolarian event	Core section, interval (cm)	Depth (mbsf)	Age (ka)	Position in the chemostratigraphy (MIS)
Lychocanoma sakaii RD	5H-1, 45.5–54.5	35.86	55	late MIS 4
Lychocanoma sakaii AP3	5H-4, 45.5–54.5	39.74	61	middle MIS 4
Lychocanoma sakaii AP2	13H-4, 45.5–54.5	115.8	207	late MIS 7
Lychocanoma sakaii AP1	16H-2, 10–16	140.33	229	early MIS 7
Lychocanoma sakaii RI	17H-4, 37–43	152.47	240	MIS 8/MIS 7 boundary

Sea of Okhotsk. The *A. acquilonium* Zone correlated with three of the radiolarian zones identified in the present study. An *A. virchowii* Zone (*c*. 613 ka), which would cover the lower part of the *A. acquilonium* Zone, as defined by Matul *et al.* (2002), could serve to cover this interval. The middle part of the *A. acquilonium* Zone established by Matul *et al.* (2002) correlates with the *S. tetras irregularis* Zone (613–516 ka) herein (Fig. 5). The *C. reticulata* Zone (516–357 ka) covers the top of the *A. acquilonium* Zone of Matul *et al.* (2002). The LO of *A. acquilonium* determined at our study site (357 ka) was relatively synchronous with the LO of the same species observed in the Sea of Okhotsk (330 ka).

The *B. aquilonaris* Zone of Motoyama *et al.* (2004) and defined by the LO of *S. universus* at 430 ka correlates with four radiolarian zones in the Sea of Okhotsk (Matul *et al.* 2002); in the present study the *B. acquilonaris* Zone correlates with five radiolarian zones. The base of the *B. acquilonaris* Zone correlated with the *Spongodiscus* sp. Zone established by Matul *et al.* (2002), which was defined by the LO of *A. acquilonium* (330 ka) (Base) and the LO of *Spongodiscus* sp. (*Schizodiscus japonica* sp. nov.) at 290 ka (Top). The *Spongodiscus* sp. Zone of Matul *et al.* (2002) correlates with the *Spongurus cyclindrica* Zone (357–259 ka) newly established in the present study, which was defined by the interval between the LO of *A. acquilonium* (357 ka) and the base of the *P. depressum* Zone (238 ka) (Fig. 5). The middle part of the *B. acquilonaris* Zone correlates with the *Amphimelissa setosa* Zone established by Matul *et al.* (2002) in the Sea of Okhotsk as defined by the LO of *Spongodiscus* sp. at 290 ka and the LO of *A. setosa* at 72 ka (Fig. 5). This only correlated with the zones identified in the present study in an indirect manner, as *A. setosa* was not included in our analysis due to its small size (<60 µm). Based on the numerical ages of Domitsu *et al.* (2011), it was determined that the *A. setosa* Zone would correlate with the *P. depressum* Zone (238–209 ka) in C9001C. The base of the *P. depressum* Zone was defined by the LO of *Schizodiscus japonicus* (238 ka). A time gap of nearly 50 ka existed between the LOs of *S. japonicus* sp. nov. (*Spongodiscus* sp. in Matul *et al.* 2002) determined at the present study site and in the Sea of Okhotsk (Matul *et al.* 2002). This time gap demonstrates that the LOs of *S. japonicus* sp. nov. at these two sites were not synchronous. The middle part of the *A. setosa* Zone in the Sea of Okhotsk was correlated with the *S. ellipsoides* Zone (209–131 ka) identified in the present study as defined by the FO of *S. ellipsoides* (209 ka).

The upper part of the *B. acquilonaris* Zone (Motoyama *et al.* 2004) correlates with the *L. sakaii* Zone in the Sea of Okhotsk, which was defined by the LOs of *A. setosa* at 72 ka and *L. sakaii* at 28 ka (Matul *et al.* 2002),. This zone also correlates with the upper part of the *C. problematica* Zone (131–33 ka), which was defined in the present study by the FO of *C. problematica* at 131 ka and LO of *L. sakaii* at 33 ka. These results demonstrate that the LO of *L. sakaii* appears to be synchronous in both the Shimokita region and the Sea of Okhotsk within a time gap of 5 ka.

CONCLUSIONS

In the present study, a high-resolution Middle to Upper Pleistocene radiolarian biostratigraphical scheme is established for the northwestern Pacific. We confirmed continuous stratigraphical occurrences of 74 radiolarian species and identified 38 of these as useful for biostratigraphical purposes. Furthermore, three new species were described (*Amphisphaera tanzhiyuani* sp. nov., *Schizodiscus japonicus* sp. nov. and *Siphonosphaera*? *paraphoros* sp. nov.). A total of 12 bioevents were identified during the past 740 ka and were used in the establishment of eight new Pleistocene radiolarian zones. Dates were based on the age model of Domitsu *et al.* (2011). Of the 12 events identified, 12 had never been previously identified in the northwestern Pacific. The newly established radiolarian zones were compared with zonations previously proposed in the northwestern Pacific and the Sea of Okhotsk by Matul *et al.* (2002), Motoyama *et al.* (2004) and Kamikuri *et al.* (2007). It was noted that the well-known *Stylatractus universus* LO, which has served as one of the most synchronous datum levels throughout the North Pacific, could not be used, as the species was absent in both the Shimokita site and the Sea of Okhotsk. This suggested that these sites were located outside the northwestern distribution limit of *S. universus*. Therefore, it was determined that the LO of *S. universus* was not a suitable datum for use in the western margin of the northwestern Pacific in North Japan and the Sea of Okhotsk. Instead of the LO of *S. universus*, the following three datums were determined to be important with respect to the Pleistocene: the LOs of *A. aquilonium* (357 ka), *S. japonicus* (238 ka) and *L. sakaii* (33 ka). Additionally, the abundance curve of *L. sakaii* was identified as a potentially useful stratigraphical tool within Middle Pleistocene sediments in the northwestern Pacific due to its rapid decrease datum (RD; 55 ka), rapid increase datum (RI; 240 ka) and three abundance peaks (229 ka (AP1), 207 ka (AP2) and 61 ka (AP3)), which could serve as synchronous events within the region.

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