Late Neogene Radiolarian Biostratigraphy of the Eastern North Pacific ODP Sites 1020/1021

Author: Kamikuri, Shin-Ichi

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Late Neogene radiolarian biostratigraphy of the eastern North Pacific ODP Sites 1020/1021

SHIN-ICHI KAMIKURI

Faculty of Education, Ibaraki University, Bunkyo 2-1-1, Mito, Ibaraki 310-8512, Japan (e-mail: shin-ichi.kamikuri.millefeuille@vc.ibaraki.ac.jp)

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Abstract. During Ocean Drilling Program Leg 167, Sites 1020/1021 were drilled to assess the paleoceanographic conditions within the northern region of the California Current. Radiolarian records from the upper middle Miocene to Pleistocene were obtained at Sites 1020/1021 cores in order to develop a correlation between Neogene biostratigraphic data and paleomagnetic chronostratigraphy. Of 66 radiolarian events identified during this study, 26 Pleistocene to late Miocene events were directly tied to the paleomagnetic stratigraphy, and 40 middle to late Miocene events were correlated with that result by second-order methods based on the diatom biostratigraphy. The updated ages of radiolarian bioevents were estimated based on the geologic time scale of Ogg (2012). Of these events, 12 bioevents that define low-latitude tropical radiolarian zones were either missing at Sites 1020/1021, or proved to have different ranges from those in the tropics. Using selected bioevents of the temperate and subarctic species, the studied sequences of Sites 1020/1021 were divided into fifteen radiolarian zones/subzones from the *Eucyrtidium inflatum* Zone to *Botryostrobus aquilonaris* Zone. Six new subzones were described: *Hexacontium parviakitaense*, *Lamprocyclas hannai*, *Lithelius klingi*, *Dictyophimus splendens*, *Cycladophora cabrilloensis*, and *Collosphaera reynoldsi* subzones. The *Cycladophora funakawai* Zone was proposed for the subarctic Northwest Pacific.

Key words: North Pacific, northern California, radiolarians, temperate to subarctic, zonations

Introduction

Deep-sea sediments in the North Pacific are characterized by widespread biosiliceous components, with age spans from the Pleistocene to middle Miocene (Keller and Barron, 1983; Barron, 1998; Cortese *et al*., 2004). During the Ocean Drilling Program (ODP) Leg 167, thirteen sites were drilled from about 30°N to 42°N along the California continental margin in the eastern North Pacific Ocean. Biosiliceous sediments present an ideal record for reconstructing paleoceanographic and paleoclimatic variability along the California margin, for all time scales. The sites were positioned so as to provide a latitudinal transect of cores along the California margin, in order to explore the evolution of the California Current system, and to investigate how the North Pacific Ocean interacted with the global climate system from about 13 Ma to the present (Lyle *et al*., 2000).

A nearly continuous sequence dating from the middle Miocene onwards was drilled at ODP Leg 167 Sites 1020/1021, in order to assess paleoceanographic conditions within the northern region of the California Current (Figure 1). Another primary drilling purpose was to develop a correlation between Neogene biostratigraphic data from the eastern North Pacific and paleomagnetic chronostratigraphy, in order to reconstruct the evolution of the California Current system. All sediments contain biogenic assemblages, mainly calcareous nannofossils, foraminifers, diatoms, and radiolarians. Excellent biostratigraphic records on calcareous nannofossils, planktonic foraminifers and diatoms since the middle Miocene, were obtained at Sites 1020/1021 and published in the *ODP Scientific Results*, Vol. 167 (Fornaciari, 2000; Kennett *et al*., 2000; Maruyama, 2000).

Radiolarians, one of the siliceous microfossils, are diverse and abundant in the deep-sea sediments of the North Pacific (e.g. Campbell and Clark, 1944; Nakaseko, 1954; Casey, 1972; Ling, 1980; Weaver *et al*., 1981; Runeva, 1984; Perez-Guzman, 1985; Akers *et al*., 1987; Tochilina *et al*., 1988; Vitukhin, 1993; Sono *et al*., 2009; Lazarus *et al*., 2015; Matsuzaki *et al*., 2015; Yanchenko and Gorbarenko, 2015; Ikenoue *et al*., 2016), and have been widely used as a biostratigraphic tool for dating and correlating Neogene sequences in middle- to high-

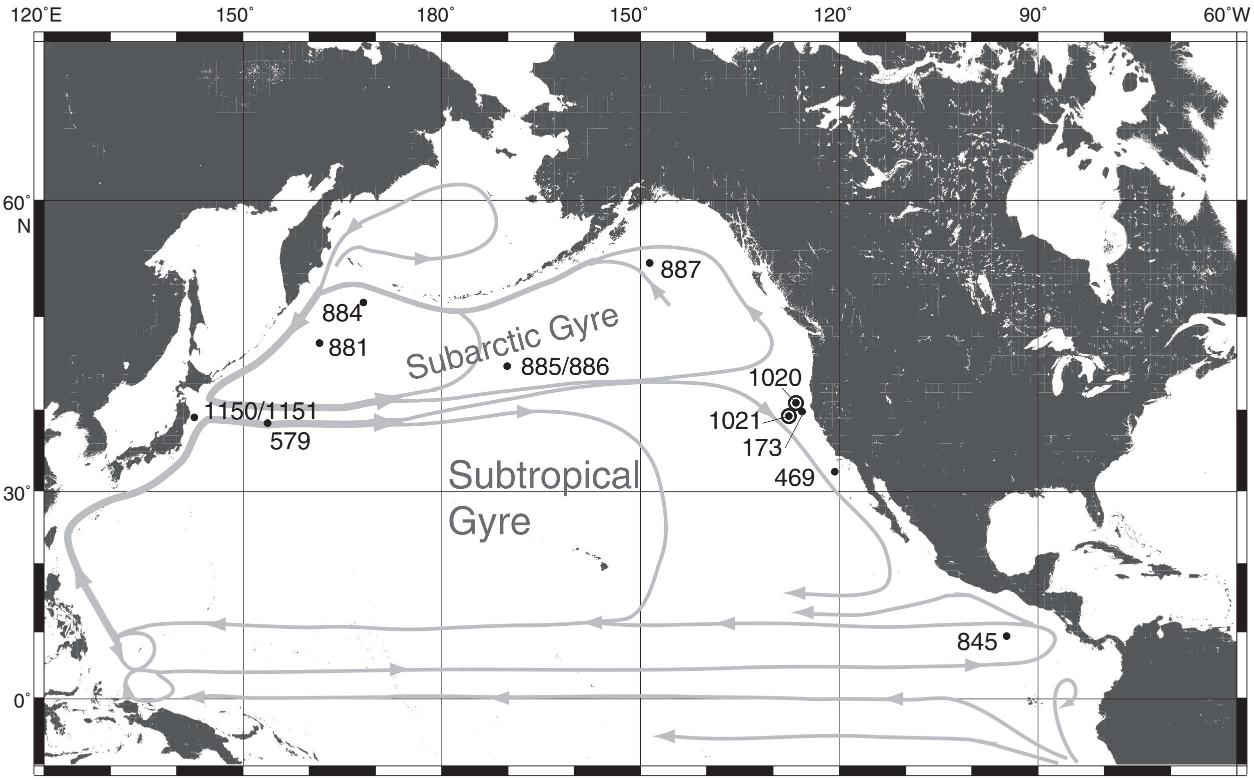

Figure 1. Location map of Deep Sea Drilling Project and Ocean Drilling Program sites and oceanic currents (Lyle *et al*., 2000).

latitude zones. However, radiolarian studies were not conducted beyond those in the *Initial Reports* volume (Lyle *et al*., 1997). The objectives of this paper are to record the biostratigraphic distribution of radiolarians at Sites 1020/1021 in order to establish a radiolarian zonation for the late Neogene in the eastern North Pacific.

Previous studies

The radiolarian zones in the North Pacific, used to date Pleistocene sediments, were first introduced by Hays (1970), on the basis of studies of sediments from piston core samples. Later, radiolarian zones for the Pliocene succession were described by Foreman (1975). Several authors accepted their zonal schemes as a reliable sequence for the Pliocene and Pleistocene, and also introduced the radiolarian zonations of Riedel and Sanfilippo (1970, 1978) for the upper Miocene and lower Pliocene in the North Pacific (Kling, 1973; Reynolds, 1980; Sakai, 1980; Wolfart, 1981; Morley, 1985). Reynolds (1980) extended the zonation back to the lower Miocene, and proposed eight new zones for the middle latitudes of the North Pacific (Figure 2). Funayama (1988) revised Reynolds's *Eucyrtidium inflatum* Zone, and further distinguished two new zones in the middle Miocene, based on on-shore sections from the Japanese Islands. Spencer-Cervato *et al*. (1993) calibrated 28 important radiolarian biostratigraphic events based on previously published siliceous and calcareous biostratigraphy and magnetostratigraphy. Using five sites drilled during ODP Leg 145, Morley and Nigrini (1995) found 50 radiolarian biostratigraphic events, and tied these directly to the paleomagnetic time scale, providing a comprehensive tabulation of radiolarian datum levels in the high latitudes of the North Pacific. They suggested that the radiolarian biostratigraphy in high latitudes differs from that of the tropical to subtropical region by the absence of tropical-subtropical markers and diachronous bioevents. Shilov (1995) developed a radiolarian stratigraphy based on the same Leg 145 material, and established 11 radiolarian zones including eight new zones for high latitudes, from the lower Miocene to the upper Pliocene (Figure 2). Motoyama (1996), and Motoyama and Maruyama (1998) distinguished 13 zones for the western North Pacific, from the middle Miocene to the Pleistocene, including three upper zones similar to those of Hays (1970), three new Pliocene zones, four new upper Miocene zones, and three zones similar to those of Funayama (1988). Subsequently, Motoyama's zonal scheme was applied from the middle Miocene to Pleistocene sedimentary sequences of ODP Sites 884,

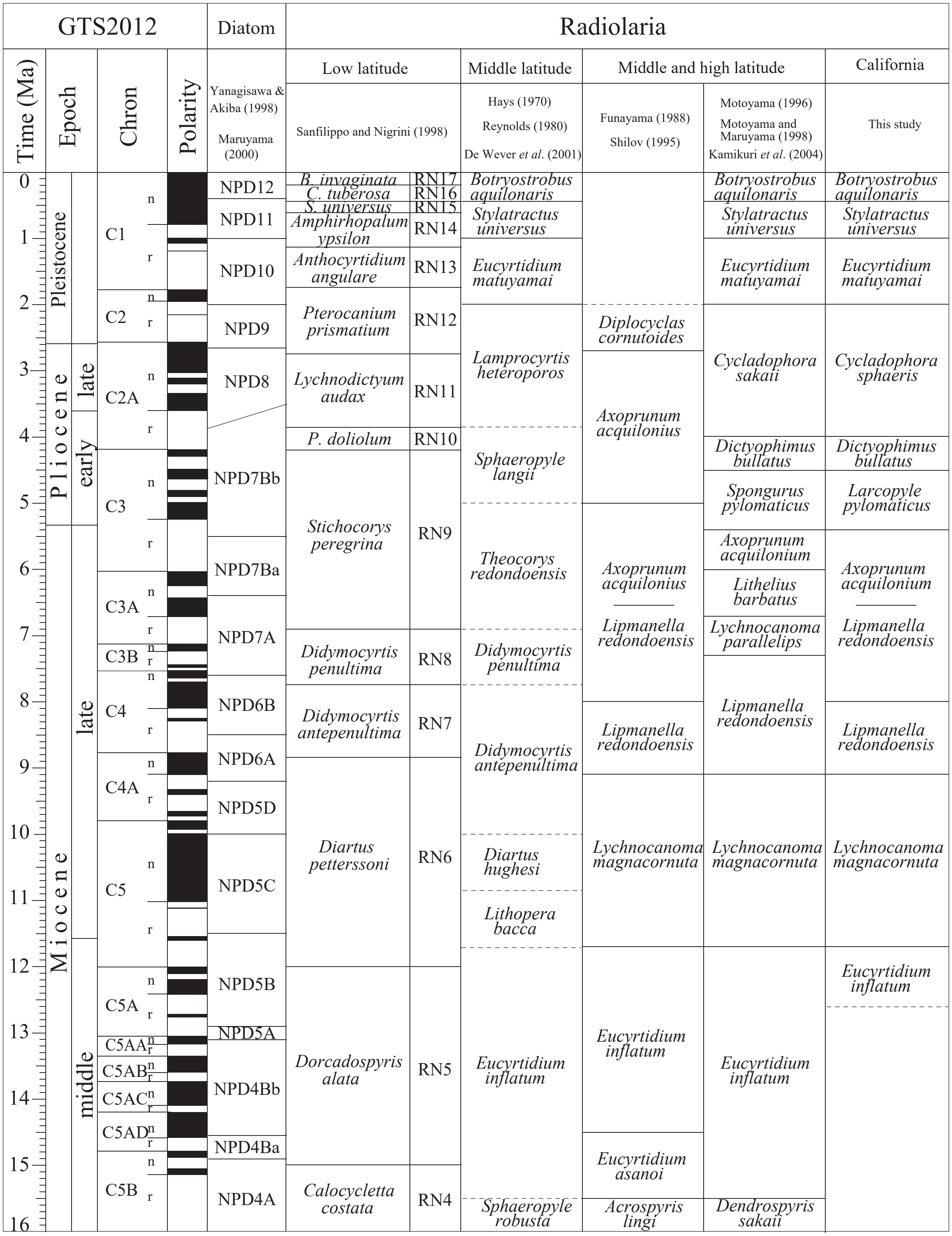

Figure 2. Correlation of Neogene diatom and radiolarian zones from the middle to high latitudes of the North Pacific.

887, 1150, and 1151 in the high latitudes of the North Pacific (Kamikuri *et al*., 2004, 2007) (Figures 1, 2).

Perez-Guzman (1985) and Perez-Guzman and Casey (1986) studied radiolarian biostratigraphy from the middle to upper Miocene in Baja California (32° to 22°N) and the Tres Marías Islands (21°30'N), and distinguished five radiolarian zones for low latitude. Rowell (1981) identified only the range of *Stichocorys peregrina* in the Palos Verdes Hills of California (33°50'N), and did not distinguish the radiolarian zones for low latitude. Poore *et al.* (1981) showed the stratigraphic distributions of radiolarians with other microfossills from the lower to middle Miocene of California (35°30'N), and commented that standard tropical or extratropical zones could not be recognized for California. Weaver *et al*. (1981) identified radiolarian assemblage biofacies with several datum planes in the Newport Back Bay (33°40'N) and the Centerville Beach (40°60'N). The radiolarian biofacies indicated the temperate to subarctic conditions since the middle Miocene in these areas. These studies indicated many tropical zonal markers lacking north of 33°N in the northeastern Pacific. In spite of these efforts, radiolarian zonal schemes for the temperate and subarctic regions (middle- to high-latitudes) have not been applied to the deep-sea sediments off California.

Material and methods

Radiolarians were examined from ODP Sites 1020 (41°0.051´N, 126°26.064´W, water depth of 3038.4 m), and 1021 (39°5.248´N, 127°46.985´W, water depth of 4211.5 m) off California in the eastern North Pacific (Figure 1). Samples were prepared following procedures similar to those described in Sanfilippo *et al*. (1985). Dried and weighed sediment samples were placed in a beaker with 15% H_2O_2 to remove organic material, and a 3–5% solution of hydrochloric acid (HCl) to remove the calcareous fraction from the sediment. Samples were washed and sieved through a 63-μm mesh. Sediments that were not disaggregated were treated again. A dried sample was scattered randomly on a glass slide. The samples were mounted with Norland Optical Adhesive #61 as a mounting medium, and subsequently covered by a 24 × 36 mm cover glass.

Preservation of the radiolarian shells was assessed on the following criteria: G (good), only minor fragmentation; M (moderate), obvious fragmentation, but identification of species not impaired; and P (poor), individual taxa exhibited considerable fragmentation, and identification of some species was not possible. The relative abundances of individual taxa were based on systematic examination of 500 radiolarians per sample: abundant (A) > 10%, common (C) > 5–10%, few (F) 1–5%, rare (R) < 1%, and (*) indicates suspected reworking. The total abundance of the radiolarian assemblage on a slide was estimated as abundant (A) > 10000, common (C) 5001–10000, few (F) 1001–5000, rare (R) 11–1000, very rare (VR) 1–10, and barren (B).

Result and discussion

Radiolarian datum levels and zonations since the middle Miocene, at Sites 1020/1021 in the eastern North Pacific

A summary of the most significant radiolarian bioevents at Sites 1020/1021 is presented in Table 1. Most of the selected radiolarian species have been described in the North Pacific sediments, by other scientists (e.g. Hays, 1970; Kling, 1973; Ling, 1973; Foreman, 1975; Reynolds, 1980; Sakai, 1980; Weaver *et al*., 1981; Wolfart, 1981; Morley, 1985; Funayama, 1988; Morley and Nigrini, 1995; Shilov, 1995; Motoyama, 1996; Kamikuri *et al*., 2004). Sites 1020/1021 provided excellent magnetostratigraphic records of the last 6.3 m.y. (Lyle *et al*., 2000). Radiolarian datum levels since the uppermost Miocene can be directly correlated with the paleomagnetic stratigraphy, while those from the middle to upper Miocene can be correlated by second-order methods using age-depth plots based on diatom stratigraphy (Maruyama, 2000) (Figure 3, Table 2). Diatoms are a group contributing to Neogene biochronology from the middle- to high- latitude North Pacific, being highly refined biostratigraphic tools (e.g. Koizumi, 1985; Barron and Gladenkov, 1995; Yanagisawa and Akiba, 1998; Maruyama, 2000). This study uses the ages of biohorizons that are updated based on the geologic time scale (GTS) of Ogg (2012) by extrapolation of each horizon within each magnetic chron.

Twenty-six radiolarian datum levels from the uppermost Miocene were directly correlated with the paleomagnetic stratigraphy. Forty bioevent horizons from middle to upper Miocene were correlated with the paleomagnetic stratigraphy by second-order correlation at the Sites 1021/1021 in the middle latitudes of the eastern North Pacific (Table 1).

Using selected bioevents of temperate and subarctic species, the studied sequence of ODP Sites 1020/1021 was divided into fifteen radiolarian zones/subzones from the *Botryostrobus aquilonaris* Zone to the *Eucyrtidium inflatum* Zone (Figures 2, 4). The following abbreviations were used in this study to express events: FO, first occurrence; LO, last occurrence; FCO, first consistent occurrence; LCO, last consistent occurrence; ET, evolutionary transition. The concept of evolutionary transition (ET) follows that of Sanfilippo and Nigrini (1998).

Table 1. Age of selected late Neogene radiolarian bioevents.

		Radiolarian events	Hole, core, section, interval (cm)	Depth (mbsf)	Depth (mcd)	Age (Ma)
1	LO	*Lychnocanoma sakaii*	1020B-1H-2, 20-22/2H-2, 20-22	1.70/9.50	1.73/9.43	0.01/0.06
2	LO	*Axoprunum acquilonium*	1020B-4H-2, 20-22/5H-2, 20-22	28.50/38.00	30.77/41.47	0.21/0.28
3	**LO**	***Stylatractus universus***	1020B-5H-2, 20-22/6H-2, 20-22	38.00/47.50	41.47/52.60	0.28/0.48
4	LO	***Eucyrtidium matuyamai***	1020B-10H-2, 20-22/11H-2, 20-22	85.50/95.00	97.41/106.48	0.95/1.05
5	LO	*Lamprocyrtis heteroporos*	1021B-5H-4, 70-72/5H-6, 20-22	41.71/44.21	46.14/48.83	1.45/1.55
6	LO	*Lamprocyrtis neoheteroporos*	1021B-5H-4, 70-72/5H-6, 20-22	41.71/44.21	46.14/48.83	1.45/1.55
7	**FO**	***Eucyrtidium matuyamai***	1021B-6H-6, 20-22/7H-1, 20-22	53.71/55.71	59.22/61.42	1.88/1.94
8	FO	*Lychnocanoma sakaii*	1021B-7H-2, 120-122/7H-4, 70-72	58.21/60.71	64.15/66.87	2.01/2.08
9	FO	*Botryostrobus aquilonaris*	1021B-9H-2, 120-122/9H-4, 70-72	77.21/79.71	87.07/90.64	2.61/2.69
10	FO	*Ceratospyris borealis*	1021B-9H-2, 120-122/9H-4, 70-72	77.21/79.71	87.07/90.64	2.61/2.69
11	**FCO**	***Cycladophora davisiana***	1021B-9H-2, 120-122/9H-4, 70-72	77.21/79.71	87.07/90.64	2.61/2.69
12	FO	*Cycladophora davisiana*	1021B-9H-2, 120-122/9H-4, 70-72	77.21/79.71	87.07/90.64	2.61/2.69
13	FO	*Lamprocyrtis neoheteroporos*	1021B-10H-2, 120-122/10H-4, 70-72	86.71/89.21	99.57/102.18	2.90/2.96
14	**LO**	***Dictyuphimus bullatus***	1021B-13H-4, 70-72/13H-6, 20-22	117.71/120.21	131.53/133.80	3.99/4.08
15	**FO**	***Dictyuphimus bullatus***	1021B-14H-6, 20-22/15H-1, 20-22	129.71/131.71	143.71/145.86	4.51/4.56
16	LO	*Stichocorys peregrina*	1021B-15H-1, 20-22/15H-2, 120-122	131.71/134.21	145.86/148.57	4.56/4.63
17	LO	*Stichocorys delmontensis*	1021B-15H-1, 20-22/15H-2, 120-122	131.71/134.21	145.86/148.57	4.56/4.63
18	LO	*Lithelius klingi*	1021B-15H-2, 120-122/15H-4, 70-72	134.21/136.71	148.57/151.29	4.63/4.69
19	**LO**	***Lipmanella redondoensis***	1021B-16H-6, 20-22/17H-1, 20-22	148.71/150.71	164.13/166.24	5.08/5.15
20	**FO**	***Larcopyle pylomaticus***	1021B-18H-1, 20-22/18H-2, 120-122	160.21/162.71	175.62/178.12	5.39/5.44
21	FO	*Lamprocyrtis heteroporos*	1021B-18H-4, 70-72/18H-6, 20-22	165.21/167.71	180.62/183.12	5.50/5.56
22	LO	*Larcospira moschkovskii*	1021B-18H-6, 20-22/19X-1, 20-22	167.71/169.71	183.12/185.12	5.56/5.60
23	LO	*Dictyophimus splendens*	1021B-21X-1, 20-22/21X-2, 120-122	185.21/187.71	200.62/203.12	5.96/6.02
24	LCO	*Lipmanella redondoensis*	1021B-22X-1, 20-22/22X-2, 120-122	194.41/197.41	210.32/212.82	6.14/6.19
25	**LO**	***Lychnocanoma nipponica*** (type B)	1021B-22X-1, 20-22/22X-2, 120-122	194.41/197.41	210.32/212.82	6.14/6.19
26	LO	*Amphymenium amphistylium*	1021B-22X-2, 120-122/22X-4, 70-72	197.41/199.91	212.82/215.32	6.19/6.25
27	LO	*Didymocyrtis penultima*	1021B-23X-4, 70-72/23X-6, 20-22	209.51/212.01	224.92/227.42	6.73/7.18
28	**LO**	***Cycladophora cabrilloensis***	1021B-23X-4, 70-72/23X-6, 20-22	209.51/212.01	224.92/227.42	6.73/7.18
29	FO	*Cycladophora sphaeris*	1021B-23X-6, 20-22/24X-1, 20-22	212.01/214.21	227.42/229.62	7.18/7.58
30	ET	*Stichocorys delmontensis-peregrina*	1021B-24X-1, 20-22/24X-2, 120-122	214.21/216.71	229.62/232.12	7.58/7.78
31	**FO**	***Axoprunum acquilonium***	1021B-24X-4, 70-72/24X-6, 20-22	219.21/221.71	234.62/237.12	7.89/8.00
32	LO	*Anthocyrtoma*? sp. A	1021B-24X-4, 70-72/24X-6, 20-22	219.21/221.71	234.62/237.12	7.89/8.00
33	LO	*Diartus hughesi*	1021B-26X-1, 20-22/26X-2, 120-122	233.41/235.91	248.82/251.32	8.51/8.61
34	LO	*Didymocyrtis antepenultima*	1021B-26X-1, 20-22/26X-2, 120-122	233.41/235.91	248.82/251.32	8.51/8.61
35	LO	*Didymocyrtis* sp. D	1021B-26X-1, 20-22/26X-2, 120-122	233.41/235.91	248.82/251.32	8.51/8.61
36	FO	*Anthocyrtoma*? sp. A	1021B-26X-6, 20-22/27X-1, 20-22	240.91/243.01	256.32/258.42	8.91/9.05
37	LO	*Dendrospyris* aff. *bursa*	1021B-26X-6, 20-22/27X-1, 20-22	240.91/243.01	256.32/258.42	8.91/9.05
38	LO	*Lithopera neotera*	1021B-26X-6, 20-22/27X-1, 20-22	240.91/243.01	256.32/258.42	8.91/9.05
39	FO	*Lithopera bacca*	1021B-27X-1, 20-22/27X-2, 120-122	243.01/245.51	258.42/260.92	9.05/9.22
40	LO	*Lychnocanoma nipponica* (type A)	1021B-27X-1, 20-22/27X-2, 120-122	243.01/245.51	258.42/260.92	9.05/9.22
41	**LO**	***Lychnocanoma magnacornuta***	1021B-27X-1, 20-22/27X-2, 120-122	243.01/245.51	258.42/260.92	9.05/9.22
42	FO	*Lychnocanoma nipponica* (type B)	1021B-27X-4, 70-72/27X-6, 20-22	248.01/250.51	263.42/265.92	9.36/9.47
43	LO	*Didymocyrtis laticonus*	1021B-28X-2, 120-122/28X-4, 70-72	255.11/257.61	270.55/273.07	9.67/9.77
44	FO	*Diartus hughesi*	1021B-29X-1, 20-22/29X-2, 120-122	262.31/264.81	277.82/280.29	9.98/10.11
45	FO	*Didymocyrtis antepenultima*	1021B-29X-1, 20-22/29X-2, 120-122	262.31/264.81	277.82/280.29	9.98/10.11
46	**LO**	***Cyrtocapsella japonica***	1021B-29X-2, 120-122/29X-4, 70-72	264.81/267.31	280.29/282.77	10.11/10.24
47	LO	*Diartus petterssoni*	1021B-29X-4, 70-72/29X-6, 20-22	267.31/282.77	282.77/285.24	10.24/10.37
48	FO	*Didymocyrtis* sp. D	1021B-30X-4, 70-72/30X-6, 20-22	276.91/279.41	292.32/294.82	10.75/10.88
49	FO	*Larcospira moschkovskii*	1021B-30X-4, 70-72/30X-6, 20-22	276.91/279.41	292.32/294.82	10.75/10.88
50	LO	*Collosphaera glebulenta*	1021B-30X-6, 20-22/31X-1, 20-22	279.41/281.51	294.82/296.92	10.88/10.99
51	LO	*Albatrossidum* sp. C	1021B-30X-6, 20-22/31X-1, 20-22	279.41/281.51	294.82/296.92	10.88/10.99
52	LO	*Eucyrtidium yatsuoense*	1021B-31X-1, 20-22/31X-2, 120-122	281.51/284.01	296.92/299.42	10.99/11.12
53	LO	*Collosphaera pyloma*	1021B-31X-1, 20-22/31X-2, 120-122	281.51/284.01	296.92/299.42	10.99/11.12
54	LO	*Lamprocyclas margatensis (*type B)	1021B-31X-2, 120-122/31X-4, 70-72	284.01/286.51	299.42/301.92	11.12/11.26
55	LO	*Cyrtocapsella cornuta*	1021B-31X-6, 20-22/32X-1, 20-22	289.01/291.11	304.42/306.52	11.39/11.52
56	LO	*Cyrtocapsella tetrapera*	1021B-31X-6, 20-22/32X-1, 20-22	289.01/291.11	304.42/306.52	11.39/11.52
57	LO	*Lamprocyclas margatensis (*type A)	1021B-31X-6, 20-22/32X-1, 20-22	289.01/291.11	304.42/306.52	11.39/11.52
58	LO	*Lithopera renzae*	1021B-31X-6, 20-22/32X-1, 20-22	289.01/291.11	304.42/306.52	11.39/11.52
59	FO	*Dendrospyris* aff. *bursa*	1021B-32X-1, 20-22/32X-2, 120-122	291.11/293.61	306.52/309.02	11.52/11.67
60	LO	*Lipmanella hister*	1021B-32X-2, 120-122/32X-4, 70-72	293.61/296.11	309.02/311.52	11.67/11.83
61	**FO**	***Lychnocanoma magnacornuta***	1021B-32X-4, 70-72/32X-6, 20-22	296.11/298.61	311.52/314.02	11.83/11.98
62	LO	*Albatrossidium* sp. A	1021B-32X-4, 70-72/32X-6, 20-22	296.11/298.61	311.52/314.02	11.83/11.98
63	LO	*Lithopera thornburgi*	1021B-32X-4, 70-72/32X-6, 20-22	296.11/298.61	311.52/314.02	11.83/11.98
64	LO	*Eucyrtidium inflatum*	1021B-32X-4, 70-72/32X-6, 20-22	296.11/298.61	311.52/314.02	11.83/11.98
65	FCO	*Cyrtocapsella japonica*	1021B-32X-6, 20-22/33X-1, 20-22	298.61/300.71	314.02/316.12	11.98/12.11
66	FO	*Diartus petterssoni*	1021B-32X-6, 20-22/33X-1, 20-22	298.61/300.71	314.02/316.12	11.98/12.11

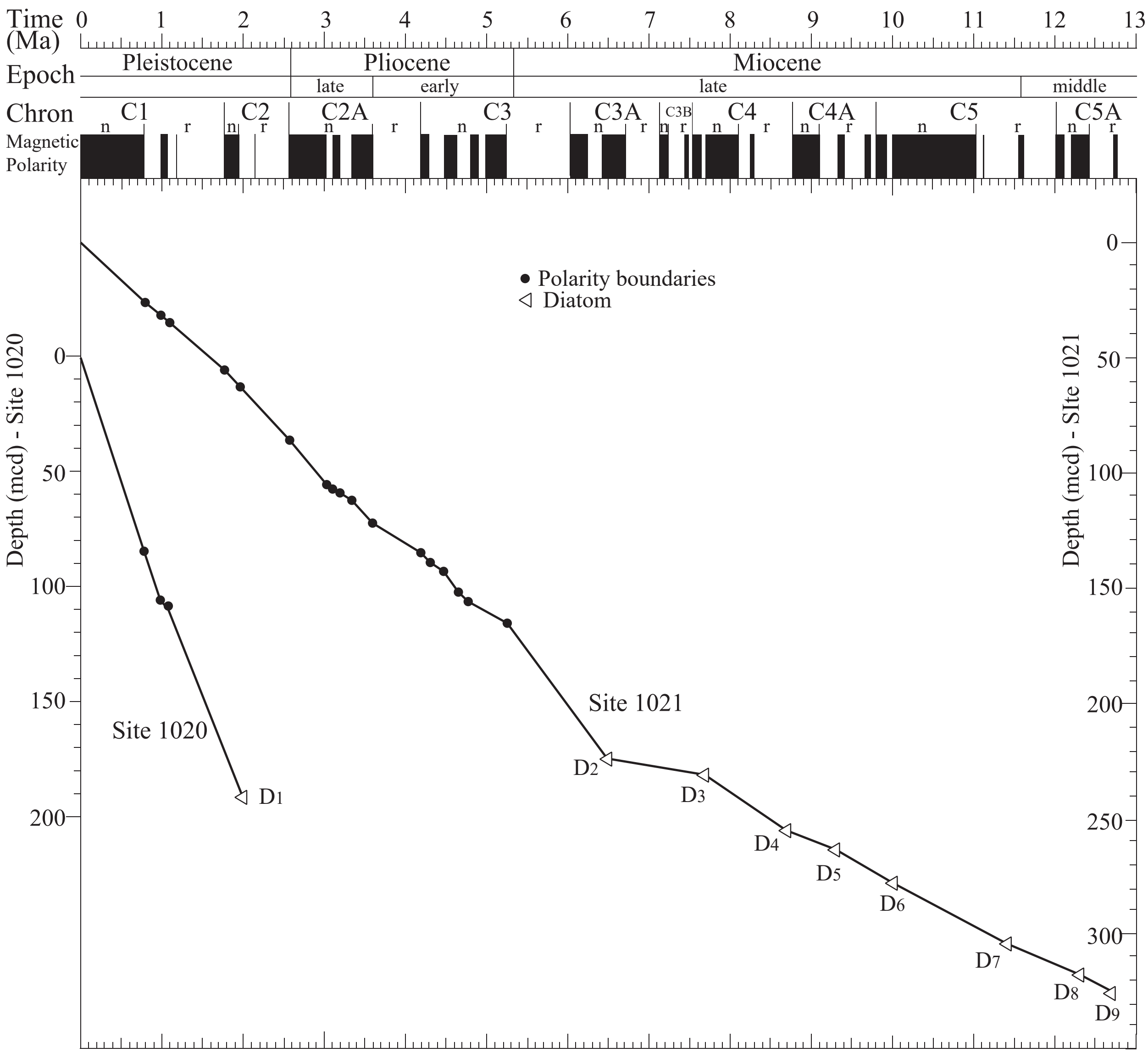

Figure 3. Age-depth plot of Sites 1020 and 1021. Geomagnetic polarity time scale is after Ogg (2012). Biohorizon numbers for the age control points correspond to those in Table 2.

Botryostrobus aquilonaris **Interval Zone** (Hays, 1970; *rename*. Reynolds, 1980)

Top.—Present.

Base.—LO of *Stylatractus universus*.

Magnetochronological calibration.—The base of this zone is placed within the middle of C1n (Brunhes).

Age.—Middle Pleistocene to Holocen e (0.4 to 0 Ma).

Radiolarian events.—LOs of *Axoprunum acquilonium* and *Lychnocanoma sakaii* juvenile form.

Remarks.—The LO of *Stylatractus universus*, that defines the base of the *Botryostrobus aquilonaris* Zone, is synchronous within the middle part of Brunhes in the North Pacific (Hays and Shackleton, 1976; Morley and Shackleton, 1978; Spencer-Cervato *et al*., 1993; Moore, 1995; Morley and Nigrini, 1995; Kamikuri *et al*., 2007). The LO of *Axoprunum acquilonium,* recognized in the middle part of this zone, is also a good marker in the North Pacific (Kling, 1973; Robertson, 1975; Morley and Nigrini, 1995; Ikenoue *et al*., 2011; Matsuzaki *et al*., 2014). Recently, Matsuzaki *et al*. (2014) established eight new radiolarian zones from the *Acanthodesmia vinculata* Zone to the *Amphirrhopalum virchowii* Zone since the Middle Pleistocene off the northeastern Japanese islands.

Table 2. Biostratigraphic and magneto-stratigraphic events used for the construction of the age-depth plots.

		Magneto-biostratigraphic events	Age(Ma) GTS2012	Site 1021 depth (mcd)	Site 1020 depth (mcd)
	bottom	C1n	0.781	27.16	84.83
	top	C1r.1n	0.988	33.23	100.68
	bottom	C1r.1n	1.072	36.22	108.81
	top	C2n	1.778	55.33	–
	bottom	C2n	1.945	61.63	–
D_1	LO	*Neodenticula koizumii*	2.0	–	191.61
	top	C2An.1n	2.581	86.03	
	bottom	C2An.1n	3.032	105.18	
	top	C2An.2n	3.116	107.16	
	bottom	C2An.2n	3.207	109.62	
	top	C2An.3n	3.330	113.14	
	bottom	C2An.3n	3.596	121.80	
	top	C3n.1n	4.187	136.50	
	bottom	C3n.1n	4.300	140.00	
	top	C3n.2n	4.493	143.15	
	bottom	C3n.2n	4.631	151.39	
	top	C3n.3n	4.799	155.67	
	bottom	C3n.3n	4.896	–	
	top	C3n.4n	4.997	–	
	bottom	C3n.4n	5.235	168.84	
D_2	LCO	*Rouxia californica*	6.5	223.66	
D_3	LCO	*Thalassionema schraderi*	7.7	230.26	
D_4	LCO	*Denticulopsis simonsenii*	8.7	253.29	
D_5	LO	*Denticulopsis dimorpha*	9.3	262.08	
D_6	FO	*Denticulopsis dimorpha*	10.0	278.29	
D_7	LCO	*Denticulopsis praedimorpha*	11.4	304.61	
D_8	LO	*Crucidenticula nicobarica*	12.3	319.84	
D_9	FO	*Denticulopsis praedimorpha*	12.7	<325.61	

The *B. aquilonaris* Zone is correlated with the interval from the *A. vinculata* Zone to the upper part of *Cyrtidosphaera reticulata* Zone, proposed by Matsuzaki *et al*. (2014).

This zone contains the following species: *Botryostrobus aquilonaris*, *Ceratospyris borealis*, *Cycladophora davisiana*, and *Larcopyle pylomaticus*.

***Stylatractus universus* Interval Zone** (Hays, 1970)

Top.—LO of *Stylatractus universus*.
Base.—LO of *Eucyrtidium matuyamai*.
Magnetochronological calibration.—The top of this zone is placed within the middle of C1n, and the base within the C1r.1n (Jaramillo).

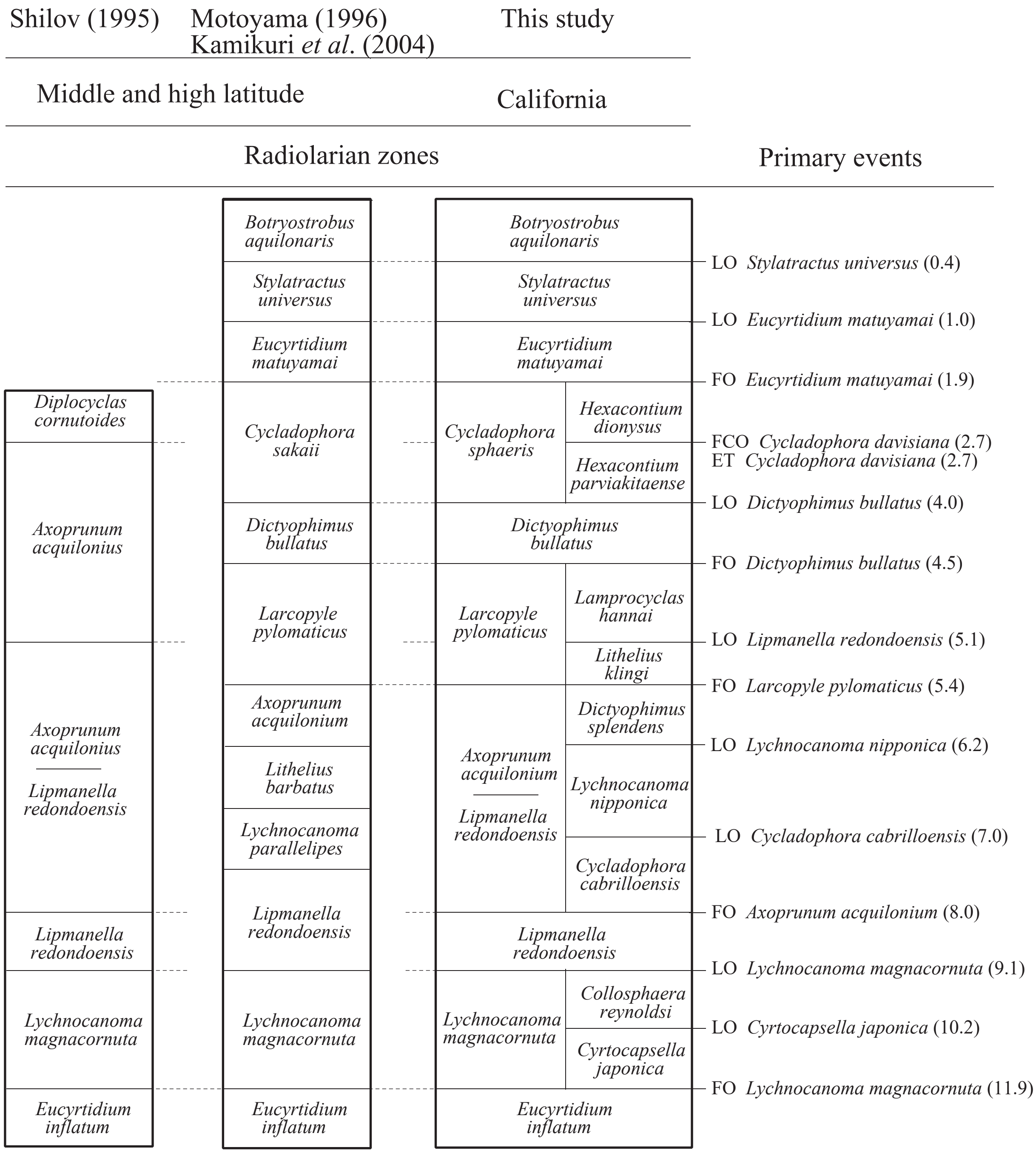

Figure 4. Intercorrelation of late Neogene radiolarian zonations for the middle to high latitudes of the North Pacific (Shilov, 1995; Motoyama, 1996; Kamikuri *et al*., 2004; this study).

Age.—Early to Middle Pleistocene (1.0 to 0.4 Ma).

Remarks.—The LO of *Eucyrtidium matuyamai*, that defines the base of *Stylatractus universus* Zone, is synchronous in the North Pacific, and a very good marker horizon for correlation (Hays, 1970; Kling, 1973; Reynolds, 1980; Weaver *et al*., 1981; Morley, 1985; Morley and Nigrini, 1995; Motoyama, 1996; Kamikuri *et al*., 2004).

This zone contains the following species: *Axoprunum acquilonium*, *Botryostrobus aquilonaris*, *Ceratospyris borealis*, *Cycladophora davisiana*, *Larcopyle pylomaticus*, and *Stylatractus universus*.

Eucyrtidium matuyamai Taxon Range Zone
(Hays, 1970; *emend*. Foreman, 1975)

Top.—LO of *Eucyrtidium matuyamai*.
Base.—FO of *Eucyrtidium matuyamai*.
Magnetochronological calibration.—The top of this zone is placed within the C1r.1n, and the base within the C2n (Olduvai).
Age.—Early Pleistocene (1.9 to 1.0 Ma).
Radiolarian events.—LOs of *Lamprocyrtis heteroporos* and *L. neoheteroporos*.
Remarks.—The FO of *Eucyrtidium matuyamai*, that defines the base of this zone, appears to be a synchronous reliable biostratigraphic event throughout the North Pacific (Foreman, 1975; Sakai, 1980; Wolfart, 1981; Spencer-Cervato *et al*., 1993; Morley and Nigrini, 1995; Motoyama, 1996; Kamikuri *et al*., 2004). However, it is difficult to recognize this bioevent in several sections due to a gradual evolutionary change in morphology from *Eucyrtidium calvertense* to *E. matuyamai* (Hays, 1970; Kling, 1973). This zone was originally defined by Hays (1970) as the interval from the LO of *E. matuyamai* (top) to the LO of *Lamprocyrtis heteroporos* (base). It was later modified by Foreman (1975) to the taxon range zone of *E. matuyamai*. The LO of *L. heteroporos* is diachronous in the North Pacific (Hays, 1970; Kling, 1973; Weaver *et al*., 1981; Moore, 1995; Morley and Nigrini, 1995; Motoyama, 1996; Kamikuri *et al*., 2004), and appears not to be a good marker for correlation (Figure 5). However it is possible that the diachroneity is due to a different taxonomic concept (Tochilina, 1996).

This zone contains the following species: *Axoprunum acquilonium*, *Botryostrobus aquilonaris*, *Ceratospyris borealis*, *Cycladophora davisiana*, *Eucyrtidium matuyamai*, *Larcopyle pylomaticus*, and *Stylatractus universus*.

Cycladophora sphaeris Interval Zone (Motoyama, 1996; *rename*. herein)

Top.—FO of *Eucyrtidium matuyamai*.
Base.—LO of *Dictyophimus bullatus*.
Magnetochronological calibration.—The top of this zone is placed within the C2n, and the base within the lower part of C2Ar.
Age.—Early Pliocene to early Pleistocene (4.0 to 1.9 Ma).
Remarks.—Motoyama (1996) originally defined the *Cycladophora sakaii* Zone as an interval from the FO of *Eucyrtidium matuyamai* (top) to LO of *Dictyophimus bullatus* (= *D. robustus* in the original paper) (base). Because *C. sakaii* Motoyama is regarded as a junior synonym of *C. sphaeris* (Popova), I renamed the *C. sakaii* Zone the *C. sphaeris* Zone. According to Kamikuri *et al*. (2007), *C. sphaeris* (= *C. sakaii* in the original paper) occurs commonly in this zone at ODP Sites 884 and 1151 in the western North Pacific, and at Site 887 in the high latitudes of the eastern North Pacific (Figure 1). However, this species has a fairly sporadic occurrence at Site 1021 in off-shore sections off California (Appendix). This sporadic occurrence is probably because *C. sphaeris* is basically a subarctic species in its geographic distribution (Motoyama, 1997; Kamikuri *et al*., 2007; Oseki and Suzuki, 2009).

This zone is subdivided into two subzones based on the FCO of *Cycladophora davisiana*.

Hexacontium dionysus Interval Subzone (Shilov, 1995; *emend*. herein)

Top.—FO of *Eucyrtidium matuyamai*.
Base.—FCO of *Cycladophora davisiana*.
Magnetochronological calibration.—The top of this zone is placed within the C2n, and the base within the upper part of C2An.1n.
Age.—Late Pliocene to early Pleistocene (2.7 to 1.9 Ma).
Radiolarian events.—FOs of *Botryostrobus aquilonaris*, *Ceratospyris borealis*, and *Lychnocanoma sakaii*.
Remarks.—Shilov (1995) first defined the *Cycladophora cornutoides* (= *Diplocyclas cornutoides*) Zone as an interval from the FO of *Eucyrtidium matuyamai* (top) to the FO of *C. davisiana* (base) (Figure 4). Because the species name of *C. cornutoides* has been already used for a zone of a different region (Goll and Bjørklund, 1989), I have changed the zonal name. *Hexacontium dionysus* occurs commonly within this subzone in the North Pacific (Kamikuri, 2010).

Spencer-Cervato *et al*. (1993) estimated an average age of 2.7 Ma for the FO of *Cycladophora davisiana* in the North Pacific. Morley and Nigrini (1995) also reported that *C. davisiana* first occurred in the North Pacific between 2.75 and 3.0 Ma. According to Motoyama (1997), *C. davisiana* evolved from *C. sphaeris* (= *C. sakaii*) through a series of intermediates in the western North Pacific, followed by fairly rapid migration into other oceans. The morphotypic first occurrence of *C. davisiana* is placed at about 4.2 Ma, and the earliest occurrence of a typical *C. davisiana* is recorded at 2.75 Ma at Site 192 in the western North Pacific (Motoyama, 1997). The rare to sporadic occurrences of this species are recorded prior to its first common occurrence in samples below approximately 2.7 Ma in the high-latitude North Pacific (Reynolds, 1980; Motoyama, 1996; Kamikuri *et al*., 2007). Hence, it is difficult to define the FO of *C. davisiana* in the high-latitude North Pacific, where *C. sphaeris* and *C. davisiana* are

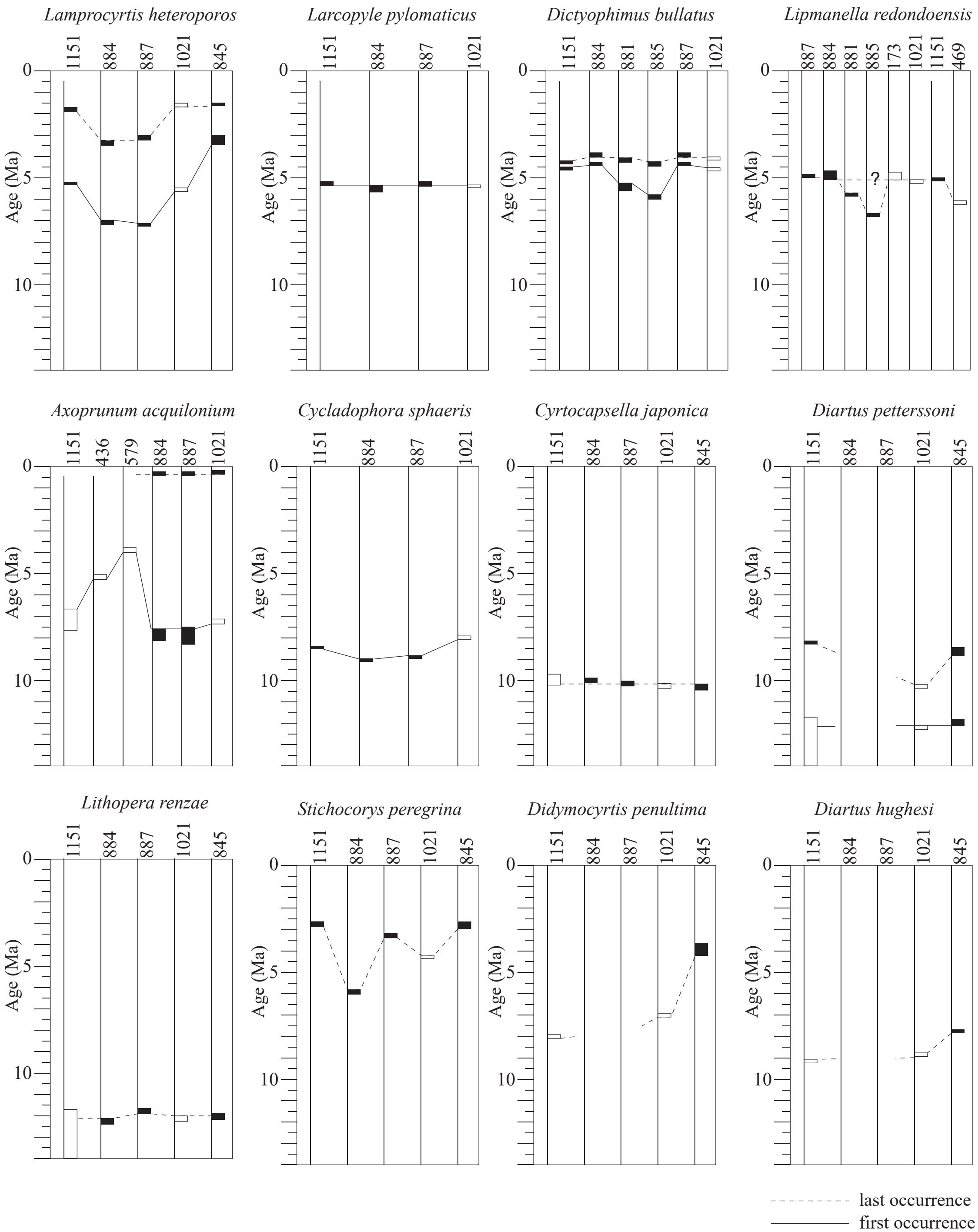

Figure 5. Radiolarian datum levels of Sites 1150 and 1151 in the middle latitudes of the Northwest Pacific (Kamikuri *et al*., 2004), Sites 884 and 887 in the high latitudes of the North Pacific (Kamikuri *et al*., 2007), Site 885 in the central Pacific (Morley and Nigrini, 1995), and Site 845 in the equatorial Pacific (Kamikuri *et al*., 2009).

fairly co-occurrent, as the smallest specimens of *C. sphaeris* are similar in morphology to *C. davisiana*. Here, I propose that the ET from *C. sphaeris* to *C. davisiana* should replace the FO of *C. davisiana* as the base of the *H. dionysus* Interval Subzone in the high-latitude North Pacific. However, the ET from *C. sphaeris* to *C. davi-*

siana is not also easy to recognize in the eastern North Pacific, as *C. sphaeris* is sporadic, and *C. davisiana* is generally few at Sites 1020/1021 in the off-shore sections off California. Instead, the FCO of *C. davisiana* can be employed as a primary biohorizon to recognize the base of the *H. dionysus* Subzone in the eastern North Pacific. Because the FCO and ET of *C. davisiana* are not always at the same horizon, I lowered the *Hexacontium dionysus* Zone (= Shilov's *D. cornutoides* Zone) to a subzone.

The Pliocene/Pleistocene boundary occurs at the C2r/C2An (Gauss/Matuyama) boundary (Ogg, 2012). Hence, the ET from *Cycladophora sphaeris* to *C. davisiana*, and the FCO of *C. davisiana* that defines the base of *C. cornutoides* Subzone are approximately correlated with this boundary.

This subzone contains the following species: *Axoprunum acquilonium*, *Botryostrobus aquilonaris*, *Ceratospyris borealis*, *Cycladophora davisiana*, *Larcopyle pylomaticus*, *Lamprocyrtis heteroporos*, *L. neoheteroporus*, and *Stylatractus universus*.

***Hexacontium parviakitaense* Interval Subzone** (herein)

Top.—FCO of *Cycladophora davisiana*.

Base.—LO of *Dictyophimus bullatus*.

Magnetochronological calibration.—The top of this zone is placed within the upper part of C2An.1n., and the base within the lower part of C2Ar.

Age.—Early to late Pliocene (4.0 to 2.7 Ma).

Radiolarian events.—FO of *Lamprocyrtis neoheteroporos*.

Remarks.—The *H. parviakitaense* subzone is correlated with the upper part of the *Axoprunum acquilonium* Zone of Shilov (1995), that is the interval from the FO of *Cycladophora davisiana* (top) to the LO of *Lipmanella redondoensis* (base) (Figure 4). *Hexacontium parviakitaense* (= identified as *Thecosphaera akitaensis* in the original paper) is common to rare in Pliocene sediments of the high-latitude North Pacific, and its FO and LO are good markers for the top and base of this subzone (Motoyama and Maruyama, 1998; Kamikuri, 2010). However, these biohorizons are difficult to recognize at Site 1021 in the middle latitude of the eastern North Pacific, owing to their rare and sporadic occurrence.

This subzone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Hexacontium parviakitaense*, *Larcopyle pylomaticus*, *Lamprocyrtis heteroporos*, and *Stylatractus universus*.

***Dictyophimus bullatus* Taxon Range Zone** (Motoyama, 1996; *rename*. Kamikuri *et al*., 2004)

Top.—LO of *Dictyophimus bullatus*.

Base.—FO of *Dictyophimus bullatus*.

Magnetochronological calibration.—The top of this zone is placed within the lower part of C2Ar, and the base within the C3n.2n.

Age.—Early Pliocene (4.5 to 4.0 Ma).

Remarks.—*Dictyophimus bullatus* is generally rare throughout this zone (Appendix). Its taxon range appears to be diachronous across latitude in the North Pacific. *Dictyophimus bullatus* has a short range, and its calibrated age is 4.4–3.9 Ma at Sites 884 and 887 in the high latitudes of the North Pacific (Kamikuri *et al*., 2007). Sites 1150 and 1151 lie in the middle latitudes of the western North Pacific with an age of 4.5–4.3 Ma (Kamikuri *et al*., 2004); Site 885 is in the middle latitudes of the central North Pacific, with an age of 5.6–4.2 Ma (Morley and Nigrini, 1995); Site 1021 is in the middle latitudes of the eastern North Pacific with an age of 4.5–4.0 Ma (this study) (Figure 5). The range of the estimated age for the FO of this species, is between 5.6 and 4.4 Ma, and that for the LO is between 4.3 and 3.9 Ma in the North Pacific. The FO of this species was placed within the C3r at Sites 885/886 in the central North Pacific; the C3n.2n at Sites 1150, 1151, and 1021 in the middle-latitude North Pacific; the C3n.1r at Sites 884 and 887 in the high-latitude North Pacific. On the other hand, the LO was within the C3n.1n/1r boundary at Sites 1150 and 1151 at middle latitudes of the western North Pacific; the C3n.1n at Sites 885/886; the C2Ar at Sites 884, 887, and 1121 in the high-latitude North Pacific and California margins. Kamikuri *et al*. (2004) and Motoyama *et al*. (2004) discussed that such discrepancy among ages estimated from different sections, might be caused by misinterpretation of bio-events, and that reversal records were not well identified from the Sibchronzone C3n.1n through to C3n.4n at Sites 885/886. Although the usefulness and reliability of these events has not been fully proven in the North Pacific, they appear to be a good marker at least for the eastern North Pacific. This zone is located with the middle part of the *Axoprunum acquilonium* Zone of Shilov (1995).

This zone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Dictyophimus bullatus*, *Larcopyle pylomaticus*, *Lamprocyrtis heteroporos*, and *Stylatractus universus*.

***Larcopyle pylomaticus* Interval Zone** (Motoyama, 1996)

Top.—FO of *Dictyophimus bullatus*.

Base.—FO of *Larcopyle pylomaticus*.

Magnetochronological calibration.—The top of this zone is placed within the C3n.2n., and the base within the upper part of C3r.

Age.—Late Miocene to early Pliocene (5.4 to 4.5 Ma).

Remarks.—The Miocene/Pliocene boundary lies within the uppermost part of C3r (Ogg, 2012). Hence, the FO of *Larcopyle pylomaticus*, that defines the base of *L. pylomaticus* Zone, is approximately correlated with the Miocene/Pliocene boundary. The *L. pylomaticus* Zone is correlated with the interval from the lower part of the *Axoprunum acquilonium* Zone to the upper part of the *A. acquilonium-L. redondoensis* Zone of Shilov (1995) (Figure 4). The FO of *Lamprocyrtis heteroporos* is near the FO of *L. pylomaticus* in the middle latitudes of the North Pacific (Foreman, 1975; Reynolds, 1980; Weaver *et al*., 1981; Wolfart, 1981; Kamikuri *et al*., 2004; this study), and serves as another guide to recognize the latter biohorizon. However Morley and Nigrini (1995) and Kamikuri *et al*. (2007) reported an older age of 7.3 Ma for the FO of *L. heteroporos* at Sites 884 and 887 in the high latitudes of the North Pacific, whereas Moore (1995) and Kamikuri *et al*. (2009) gave a younger age of 3.3 Ma for this event at Site 845 in the low latitudes of the North Pacific (Figure 5). The LO of *L. klingi* was located within the *L. pylomaticus* Zone (*ca*. 4.7 Ma) at Site 1151 and 1021 in the middle latitudes of the North Pacific (Kamikuri, 2010; this study), the *Eucyrtidium matuyamai* Zone (*ca*. 1.5 Ma) at Sites 884 and 887 in the high latitudes of the North Pacific (Kamikuri, 2010), and the *Pterocanium prismatium* Zone (*ca*. 2.7 Ma) at Site 845 in the low latitudes of the North Pacific (Kamikuri *et al*., 2009) (Figure 5).

This zone is subdivided into two subzones based on the LO of *Lipmanella redondoensis*.

Lamprocyclas hannai **Interval Subzone** (herein)

Top.—FO of *Dictyophimus bullatus*.

Base.—LO of *Lipmanella redondoensis*.

Magnetochronological calibration.—The top of this zone is placed within the C3n.2n., and the base within the C3n.4n.

Age.—Early Pliocene (5.1 to 4.5 Ma).

Radiolarian events.—LOs of *Lithelius klingi*, *Stichocorys delmontensis*, and *S. peregrina*.

Remarks.—Shilov (1995) proposed the interval zone from the FO of *Cycladophora davisiana* (top) to LO of *Lipmanella redondoensis* (base) as the *Axoprunum acquilonium* Zone (Figure 4). The LO of *L. redondoensis* is calibrated at an age of 5.0 Ma at Site 887 (54°N) (Kamikuri *et al*., 2007); 4.9 Ma at Site 884 (51°N); 4.9 Ma (for GTS2012) at Site 173 (40°N) (Spencer-Cervato *et al*., 1993); 5.1 Ma at Site 1021 (39°N); 5.1 Ma at Site 1151 (38°N) (Kamikuri *et al*., 2004); and 6.2 Ma (for GTS2012) at Site 469 (32°N) (Spencer-Cervato *et al*., 1993). Mullineaux and Westberg-Smith (1986) found that this event was positioned below the FO of *L. heteroporos* in the Newport section of the Monterey Formation (33°N). It appears to be a very good marker useful in latitudes higher than 38°N of the North Pacific. However, an older age was reported at only two sites. The LO of this species showed an age of 5.8 Ma at Site 881 (47°N), and 6.7 Ma (44°N) at Site 885 (Morley and Nigrini, 1995). Hence, I used the LO of *L. redondoensis* as a marker for this subzone (not zone), and subdivided the *L. pylomaticus* Zone into two subzones. The *L. hannai* Subzone is correlated with the interval from the lower part of the *A. acquilonium* Zone of Shilov (1995).

This subzone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Larcopyle pylomaticus*, *Lamprocyrtis heteroporos*, *Stichocorys delmontensis*, *S. peregrina*, and *S. universus*.

Lithelius klingi **Interval Subzone** (herein)

Top.—LO of *Lipmanella redondoensis.*

Base.—FO of *Larcopyle pylomaticus*.

Magnetochronological calibration.—The top of this zone is placed within the C3n.4n, and the base within the upper part of C3r.

Age.—Late Miocene to early Pliocene (5.4 to 5.1 Ma).

Remarks.—Shilov (1995) proposed the interval zone between the LO of *Lipmanella redondoensis* (top) and FO of *Axoprunum acquilonium* (base) as the *A. acquilonium-L. redondoensis* Zone (Figure 4). The *Lithelius klingi* Subzone is correlated with the interval from the upper part of the *A. acquilonium-L. redondoensis* Zone of Shilov (1995).

This subzone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Larcopyle pylomaticus*, *Lamprocyrtis heteroporos*, *Lipmanella redondoensis*, *Lithelius klingi*, *Stichocorys delmontensis*, *S. peregrina*, and *S. universus*.

Axoprunum acquilonium-Lipmanella redondoensis **Interval Zone** (Shilov, 1995; *emend*. herein)

Top.—FO of *Larcopyle pylomaticus*.

Base.—FO of *Axoprunum acquilonium*.

Magnetochronological calibration.—The top of this zone is placed within the upper part of C3r, and base within the C4n.2n.

Age.—Late Miocene (8.0 to 5.4 Ma).

Remarks.—This zone was originally defined as an interval from the LO of *Lipmanella redondoensis* (top) to the FO of *Axoprunum acquilonium* (base) by Shilov (1995) (Figure 4). The upper limit of this zone is herein refined as determined by the FO of *L. pylomaticus,* rather than the LO of *L. redondoensis*. The FO of *L. pylomaticus*, that is the top of this zone, is synchronous in the North Pacific (Figure 5). However, the FO of *A. acquilo-*

nium, that is the base of this zone, is diachronous in the North Pacific as discussed by Morley and Nigrini (1995) and Kamikuri *et al*. (2004). This event was placed within C4n.2n in the high latitudes of the North Pacific, and the middle latitudes of the eastern North Pacific (Morley and Nigrini, 1995; this study), whereas it is diachronous at lower latitudes, with clearly younger ages of *ca.* 7.0 Ma at Sites 438 and 1151 (Motoyama, 1996; Kamikuri *et al*., 2004); 5.1 Ma at Site 436, and 3.8 Ma at Site 579 (Spencer-Cervato *et al*., 1993). The FO of *A. acquilonium* approximately coincides with the ET from *Stichocorys delmontensis* to *S. peregrina* at the present sites (Table 1), and ODP 145 sites in the high latitudes of the North Pacific (Morley and Nigrini, 1995).

The *Axoprunum acquilonium-Lipmanella redondoensis* Zone is correlated with the interval from the *A. acquilonium* Zone to the *L. redondoenis* Zone, that were proposed by Motoyama (1996) and Kamikuri *et al*. (2004) for the high latitudes of the North Pacific. *Lychnocanoma parallelipes* and *Lithelius barbatus* appear to serve as a very useful biostratigraphic marker species in the high latitudes of the North Pacific (Motoyama, 1996; Kamikuri *et al*., 2007). However, it has limited usefulness in the western North Pacific and the high latitudes of the eastern North Pacific, because the species is basically subarctic in its geographic distribution.

This zone is subdivided into three subzones based on the LOs of *Cycladophora cabrilloensis* and *Lychnocanoma nipponica*.

Dictyophimus splendens **Interval Subzone** (herein)

Top.—FO of *Larcopyle pylomaticus.*

Base.—LO of *Lychnocanoma nipponica*.

*Magnetochronological calibration.—*The top of this zone is placed within the upper part of C3r, and the base within the C3An.1n.

Age.—Late Miocene (6.2 to 5.4 Ma).

Radiolarian events.—FO of *Lamprocyrtis heteroporos*, LOs of *Dictyophimus splendens* and *Larcospira moschkovskii*, and LCO of *L. redondoensis*.

Remarks.—The LO of *Lychnocanoma nipponica*, that defines the base of this subzone, was calibrated at an age of 6.4 Ma (for GTS2012) within the top of C3An.2n at Sites 436 and 881 in the western North Pacific and at Site 885 in the central Pacific (Sakai, 1980; Morley and Nigrini, 1995). This bioevent is nearly synchronous in the middle latitudes of the North Pacific, and appears to be used for this correlation. The LO of *L. nipponica* was older with a range between 9.3 and 10.0 Ma at Sites 884 and 887 in the high latitudes of the North Pacific (Morley and Nigrini, 1995).

This subzone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Lithelius klingi*, *Lipmanella redondoensis*, *Stichocorys peregrina*, and *S. universus*.

Lychnocanoma nipponica **Interval Subzone** (Nakaseko and Sugano, 1972; *emend*. herein)

Top.—LO of *Lychnocanoma nipponica.*

Base.—LO of *Cycladophora cabrilloensis*.

*Magnetochronological calibration.—*The top of this zone is placed within the C3An.1n, and the base within the C3Ar.

Age.—Late Miocene (7.0 to 6.2 Ma).

Radiolarian events.—LOs of *Amphymenium amphistylium* and *Didymocyrtis penultima*.

Remarks.—The *Lychnocanoma nipponica* Assemblage Zone of Nakaseko and Sugano (1973) was revised herein as an interval subzone. This assemblage zone is different from the proposed subzone herein. This subzone contains the following species: *Axoprunum acquilonium*, *Cycladophora sphaeris*, *Dictyophimus splendens*, *Lithelius klingi*, *Lychnocanoma nipponica*, *Lipmanella redondoensis*, *Stichocorys peregrina*, and *S. universus*.

Cycladophora cabrilloensis **Interval Subzone** (herein)

Top.—LO of *Cycladophora cabrilloensis.*

Base.—FO of *Axoprunum acquilonius*.

*Magnetochronological calibration.—*The top of this zone is placed within the C3Ar, and the base within the C4n.2n.

Age.—Late Miocene (8.0 to 7.0 Ma).

Radiolarian events.—FO of *Cycladophora sphaeris* and ET from *S. delmontensis* to *S. peregrina.*

Remarks.—*Cycladophora cabrilloensis* is distributed mainly in the eastern North Pacific, and is restricted to the late Miocene (Campbell and Clark, 1944; Kling, 1973; Weaver *et al*., 1981; Lombari and Lazarus, 1988). This subzone contains the following species: *Axoprunum acquilonium*, *Amphymenium amphistylium*, *Cycladophora cabrilloensis*, *Didymocyrtis penultima*, *Dictyophimus splendens*, *Lithelius klingi*, *Lychnocanoma nipponica*, *Lipmanella redondoensis*, *Stichocorys delmontensis*, and *S. universus*.

Lipmanella redondoensis **Interval Zone** (Shilov, 1995)

Top.—FO of *Axoprunum acquilonium*.

Base.—LO of *Lychnocanoma magnacornuta*.

*Magnetochronological calibration.—*The top of this zone is placed with the C4n.2n, and base within the C4An.

Age.—Late Miocene (9.1 to 8.0 Ma).

Radiolarian events.—FOs of *Anthocyrtoma*? sp. A and

Lithopera bacca, LOs of *Anthocyrtoma*? sp. A, *Dendrospyris* aff. *bursa*, *Diartus hughesi*, *Didymocyrtis antepenultima*, *Didymocyrtis* sp. D, and *Lithopera neotera*.

Remarks.—The FOs of *Cycladophora sphaeris* seem to appear earlier in the higher latitudes (Sites 884 and 887) than in the lower latitudes (Sites 1151 and 1021) within this zone (Figure 5). This indicates that this species evolved first in the high latitudes of the western North Pacific, and subsequently migrated to the middle latitudes. Although Weaver *et al.* (1981) used the species name of *Lipmanella redondoensis* for a biofacies, this biofacies is different from the zone proposed by Shilov (1995).

This zone contains the following species: *Lithelius klingi*, *Larcospira moschkovskii*, *Lipmanella redondoensis*, and *Stichocorys universus*.

***Lychnocanoma magnacornuta* Taxon Range Zone** (Funayama, 1988)

Top.—LO of *Lychnocanoma magnacornuta*.

Base.—FO of *Lychnocanoma magnacornuta*.

Magnetochronological calibration.—The top of this zone is placed the C4An, and base within the C5r.3r.

Age.—Middle to late Miocene (11.9 to 9.1 Ma).

Remarks.—Funayama (1998) proposed the *Lychnocanoma magnacornuta* Zone as a taxon range zone of *L. magnacornuta*. This species has a sporadic occurrence following its last continuous occurrence in the western North Pacific (Sakai, 1980; Funakawa, 1993; Motoyama and Maruyama, 1996; Motoyama, 1996; Kamikuri *et al*., 2004). Later, Motoyama (1996) acknowledged this problem, and indicated both the last consistent occurrence (LCO) and the last occurrence (LO) for *L. magnacornuta*, and redefined the top of this zone by the LCO of *L. magnacornuta*. However, to identify the LCO of *L. magnacornuta* is difficult at several on-shore sections (Sawada *et al*., 2009; Shinzawa *et al*., 2009), and off California (this study), as this species occurs sporadically throughout this zone. The LCO of *L. magnacornuta* in the western North Pacific appears to be synchronous with the LO of *L. magnacornuta* at ODP Site 1021 in off-shore sections of California. The discontinuous occurrence of *L. magnacornuta* between the LCO and LO in the western North Pacific may have been affected by reworking. I take the LCO of *L. magnacornuta* to be its LO. Hence, the definition of Funayama (1988) is used for this zone in this paper.

This zone is subdivided into two subzones based on the LO of *Cyrtocapsella japonica*.

***Collosphaera reynoldsi* Interval Subzone** (herein)

Top.—LO of *Lychnocanoma magnacornuta*.

Base.—LO of *Cyrtocapsella japonica*.

Magnetochronological calibration.—The top of this zone is placed within the C4An, and its base within the upper part of the C5n.2n.

Age.—Late Miocene (10.2 to 9.1 Ma).

Radiolarian events.—FOs of *Didymocyrtis antepenultima*, *Diartus hughesi* and *Lychnocanoma nipponica* type B, LOs of *Didymocyrtis laticonus* and *Lychnocanoma nipponica* type A.

Remarks.—*Collosphaera reynoldsi* has fairly common to rare occurrences within this subzone. The LO of *Cyrtocapsella japonica*, that defines the base of this subzone, is placed within the C5n.2n. This event is calibrated at an age of *ca*. 10.0 Ma, and is a synchronous reliable biostratigraphic event throughout the North Pacific (Morley and Nigrini, 1995; Motoyama, 1996; Kamikuri *et al*., 2004, 2007; Kamikuri, 2010) (Figure 5). In the western North Pacific and Japan Sea, abundant occurrences of *Cycladophora nakasekoi* also characterize assemblages of this subzone (Motoyama, 1996; Kamikuri *et al*., 2007). However it is difficult to recognize the LO of *C. japonica* at several on-shore sections, because *C. japonica* occurred frequently as derived fossils for redeposition (e.g. Sugano, 1986; Sawada *et al.*, 2009). Hence, I used the LO of *C. japonica* as a marker for this subzone (not zone), and subdivided the *Lychnocanoma magnacornuta* Zone into two subzones. The FO of *C. nakasekoi* coincides with the LO of *C. japonica*, and is also a useful marker in on-shore or near shore sediments in Japan (Motoyama, 1996; Kamikuri *et al*., 2004). However, this species did not occur at Site 1021 in the middle latitudes of the eastern North Pacific.

This subzone contains the following species: *Cycladophora cabrilloensis*, *Collosphaera reynoldsi*, *Dendrospyris* aff. *bursa*, *Lithelius klingi*, *Lychnocanoma magnacornuta*, *L. nipponica*, *Larcospira moschkovskii*, *Lipmanella redondoensis*, and *Stichocorys universus*.

***Cyrtocapsella japonica* Interval Subzone** (Nakaseko and Sugano, 1972; *emend*. herein)

Top.—LO of *Cyrtocapsella japonica*.

Base.—FO of *Lychnocanoma magnacornuta*.

Magnetochronological calibration.—The top of this zone is placed in the upper part of C5n.2n, and its base within the C5r.3r.

Age.—Middle to late Miocene (11.9 to 10.2 Ma).

Radiolarian events.—FOs of *Dendrospyris* aff. *bursa*, *Didymocyrtis* sp. D, and *Larcospira moschkovskii*, and LOs of *Albatrossidum* sp. C, *Collosphaera glebulenta*, *Collosphaera pyloma*, *Cyrtocapsella cornuta*, *Cyrtocapsella tetrapera*, *Eucyrtidium yatsuoense*, *Lamprocyclas* *margatensis*, *Lipmanella hister*, and *Lithopera renzae*.

Remarks.—The LO of *Collosphaera pyloma* is estimated at 11.0 Ma in age, and is a good secondary marker for the middle horizon in the *C. japonica* Subzone in the North Pacific (Kamikuri *et al*., 2007; this study) (Figure 5). The base of the *C. japonica* Subzone approximates the FO of *Diartus petterssoni*, and LOs of *C. tetrapera*, *Eucyrtidium inflatum*, *Lipmanella hister*, *Lithopera thornburgi*, and *L. renzae*. Although *Thecosphaera akitaensis* is a short-ranging marker species for the middle part of this subzone in the western North Pacific (Kamikuri, 2010), this species did not occur at Site 1021. The middle/late Miocene boundary lies within the C5r.2n (Ogg, 2012). The lower part of this subzone is correlated with the middle/late Miocene boundary. Although Nakaseko and Sugano (1972) used the species name of *C. japonica* for an assemblage zone, this assemblage zone is different from the proposed subzone herein. The *C. japonica* Assemblage Zone of Nakaseko and Sugano (1973) was redefined herein as an interval subzone.

This subzone contains the following species: *Cycladophora cabrilloensis*, *Cyrtocapsella japonica*, *Collosphaera pyloma*, *C. reynoldsi*, *Dendrospyris* aff. *bursa*, *Lithelius klingi*, *Lychnocanoma magnacornuta*, *L. nipponica*, *Lipmanella redondoensis*, and *Stichocorys universus*.

***Eucyrtidium inflatum* Interval Zone** (Reynolds, 1980; *emend*. Funayama, 1988)

Top.—FO of *Lychnocanoma magnacornuta*.

Base.—FO of *Eucyrtidium inflatum*.

Magnetochronological calibration.—The top of this zone is placed in the C5r.3r (this study), and its base within the C5Br (Kamikuri *et al*., 2007).

Age.—Middle Miocene (15.4 to 11.9 Ma).

Secondary biohorizons.—FO of *Diartus petterssoni*, FCO of *C. japonica*, and LOs of *Albatrossidum* sp. A, *E. inflatum* and *Lithopera thornburgi*.

Remarks.—The base of this zone was not encountered in this study. This zone contains the following species: *Cycladophora cabrilloensis*, *Cyrtocapsella japonica*, *Collosphaera reynoldsi*, *Eucyrtidium inflatum*, *Lychnocanoma nipponica*, *Lithelius klingi*, *Lipmanella redondoensis*, and *Stichocorys universus*.

Radiolarian zonal correlations

At Sites 1020/1021 in the eastern North Pacific, many first and last occurrences of species that define low-latitude tropical radiolarian zones (Sanfilippo and Nigrini, 1998) were either missing, or proved to have different ranges from those in the tropics. The following species for the Pliocene-Pleistocene zonation were missing at Sites 1020/1021: *Buccinosphaera invaginata*, *Collosphaera tuberosa*, *Anthocyrtidium angulare*, *Pterocanium prismatium*, and *Phormostichoartus doliolum* (Table 1). The latitudinal distributions of selected radiolarian events from the tropical to subarctic North Pacific are shown in Figure 5. The LO of *Stichocorys peregrina* that defines the base of the *P. prismatium* Zone in the low latitudes had an age of 4.2 Ma at Site 1021 (Figure 5). The calibrated age for the equatorial Pacific (Site 845) is 2.7 Ma (Moore, 1995; Kamikuri *et al*., 2009). In the high latitudes of the western North Pacific (Site 884), an age of 5.8 Ma is assigned to this event (Kamikuri *et al*., 2007). The LO of *Diartus penultima* was placed at 7.0 Ma at Site 1021, three million years before the low-latitude age. The LO of *Diartus hughesi* occurred at 8.6 Ma at Site 1021. In the low latitudes, it occurred one million years later (7.7 Ma; Kamikuri *et al*., 2009). The evolutionary transition from *Stichocorys delmontensis* to *S. peregrina,* that defines the base of the *S. peregrina* Zone in the low latitudes, was calibrated with an age of 8.0 Ma at Site 1021. The corresponding low-latitude calibration of 6.5 Ma (Kamikuri, 2012) is diachronous with the estimated North Pacific age. The ETs from *Didymocyrtis antepenultima* to *D. penultima* and from *D. laticonus* to *D. antepenultima* were not defined at Site 1021, as these species have fairly rare to sporadic occurrences. The time-transgressive nature of the FO of *Actinomma langii* (= *Sphaeropyle langii* in the original paper) for middle-latitude zonation was discussed by Spencer-Cervato *et al*. (1993). Hence, the tropical radiolarian zonation of Sanfilippo and Nigrini (1998) is difficult to apply to the deep-sea sediments off northern California as several studies have already proved (Rowell, 1981; Poore *et al.*, 1981; Weaver *et al*., 1981; Perez-Guzman, 1985). The radiolarian zonation for the temperate and subarctic regions is required at Sites 1020/1021, in the middle latitudes of the eastern North Pacific.

Figure 4 indicates the correlations of 15 radiolarian zones/subzones in this paper, with the middle-high latitudes radiolarian zonation by Shilov (1995) and Motoyama (1996). Motoyama (1996) improved radiolarian biostratigraphy for the western North Pacific, and provided new zonations based on locally characteristic species from the Pliocene to the late Miocene. Motoyama's zonal scheme was also applied at Site 887 in the high latitudes of the eastern North Pacific (Kamikuri *et al*., 2007). In the present study, an attempt was made to use the zonation developed by Motoyama (1996) at Site 1020/1021 in the northern California margin of the eastern North Pacific. Of all the zones proposed by Motoyama (1996), three zones, namely the *Cycladophora sphaeris* (= *C. sakaii*), *Dictyophimus bullatus* (= *D. robustus*) and *Larcopyle pylomaticus* zones, can be employed from the Pliocene to the latest Miocene at Sites 1020/1021 in the middle latitudes of the eastern North Pacific. However, three zones during the late Miocene, the *Axoprunum acquilonium* (= *Stylacontarium acquilonium*), *Lithelius barbatus*, and *Lychnocanoma parallelipes* zones, cannot be used owing to the absence of *L. barbatus* and *L. parallelipes* in the middle latitudes of the eastern North Pacific. Instead, the *Axoprunum acquilonium-Lipmanella redondoensis* Zone, proposed by Shilov (1995), was modified and employed for the late Miocene zonation in the northern California margin. The radiolarian zonation of Shilov (1995) for the temperate-subarctic North Pacific sequences was readily recognized with the broadest geographical application.

Redefinition of the *Cycladophora cornutoides* Zone of Motoyama (1996)

***Cycladophora funakawai* Interval Zone** (Motoyama, 1996; *emend*. herein)

Top.—FO of *Lychnocanoma parallelipes*.

Base.—LO of *Lychnocanoma magnacornuta*.

Magnetochronological calibration.—The top of this zone is placed in the C3Br.2r, and its base within the C4An (Kamikuri *et al*., 2007).

Age.—Late Miocene (9.1 to 7.3 Ma).

Remarks.—Motoyama (1996) originally defined the *Cycladophora cornutoides* Zone as an interval zone from the FO of *Lychnocanoma parallelipes* (top) to the LCO of *L. magnacornuta* (base) for the subarctic Northwest Pacific. Later, Kamikuri *et al*. (2004) changed the zonal name (*C. cornutoides* Zone) to the *Lipmanella redondoensis* Zone. They used the definition of Motoyama (1996) and the zonal name of Shilov (1995) for the *L. redondoensis* Zone, as the species name of *C. cornutoides* was already used for a zone of a different region and time interval (Goll and Bjørklund, 1989), and as the FO of *Axoprunum acquilonium* is clearly diachronous in the North Pacific. However, the *L. redondoensis* Zone of Shilov (1995) was applied at Sites 1020/1021 in the temperate North Pacific (Figure 4). The *L. redondoensis* Zone (= *C. cornutoides* Zone of Motoyama, 1996) should be redefined, as two radiolarian zones of the same name exist in the North Pacific, but with different definitions.

Conclusions

Radiolarians were examined from ODP Sites 1020/1021 off California, in the eastern North Pacific, in order to record their biostratigraphic distribution, and to establish radiolarian zonations for the late Neogene.

1) Sixty-six radiolarian bioevents were recognized since the middle Miocene at Sites 1020/1021.

2) Twenty-six radiolarian datum levels since the latest Miocene were directly correlated with paleomagnetic stratigraphy. Forty bioevents from the middle to late Miocene were correlated with the paleomagnetic stratigraphy by second-order correlation at the Sites 1021/1021 in the middle latitudes of the eastern North Pacific.

3) Twelve radiolarian bioevents that define low-latitude tropical radiolarian zones were either missing at Sites 1020/1021, or proved to have different ranges from those in the tropics.

4) The radiolarian zonation of Shilov (1995) for the temperate-subarctic North Pacific sequences was readily recognized, with the broadest geographical application.

5) Of all the zones proposed by Motoyama (1996), three zones, namely the *Cycladophora sphaeris* (= *C. sakaii*), *Dictyophimus bullatus* (= *D. robustus*), and *Larcopyle pylomaticus* Zones, can be used from the Pliocene to the latest Miocene at Sites 1020/1021, in the middle latitudes of the eastern North Pacific.

6) The studied sequence was divided into ten radiolarian zones using selected bioevents of the temperate and subarctic species, from the *Botryostrobus aquilonaris* Zone to *Eucyrtidium inflatum* Zone, including nine subzones. Six new subzones are described: *Hexacontium parviakitaensis*, *Lamprocyclas hannai*, *Lithelius klingi, Dictyophimus splendens*, *Cycladophora cabrilloensis*, and *Collosphaera reynoldsi* Subzones.

7) The *Cycladophora funakawai* Zone was proposed for the subarctic Northwest Pacific.

Faunal references (Figures 6–9)

Amphymenium amphistylium Haeckel, 1887. Morley and Nigrini, 1995, p. 78, pl. 1, figs. 8, 9.

Axoprunum acquilonium (Hays, 1970): *Druppatructus acquilonius* Hays, 1970. Hays, 1970, p. 214, pl. 1, figs. 4, 5.

Axoprunum bispiculum (Popofsky, 1912). Takemura, 1992, p. 741, pl. 1, figs. 1, 2.

Botryostrobus aquilonaris (Bailey, 1856). Nigrini, 1977, p. 246, pl. 1, fig. 1.

Ceratospyris borealis Bailey, 1856. Nigrini and Moore, 1979, p. N9, pl. 19, fig. 1a–d.

Collosphaera glebulenta Bjørklund and Goll, 1979. Bjørklund and Goll, 1979, p. 1316, pl. 2, figs. 9–25.

Collosphaera pyloma Reynolds, 1980. Reynolds, 1980, p. 761, pl. 1, figs. 5–9.

Cycladophora cabrilloensis (Campbell and Clark, 1944). Akers *et al*., 1987, p. 22, pl. 5, fig. 3.

Cycladophora davisiana Ehrenberg, 1862. Motoyama, 1997, p. 60, pl. 1, figs. 4–10.

Cycladophora sphaeris (Popova, 1989): *Spuroclathrocyclas sphaeris* Popova, 1989, p. 73, pl. 11, fig. 17, pl. 12, fig. 3; *Cycladophora sakaii* Motoyama, 1996, p. 246, pl. 4, figs. 4a–6b. *Spuroclathrocyclas sphaeris* Popova is synonymized with *Cycladophora sakaii* Motoyama. The species is translated from *Spuroclathrocyclas* to *Cycladophora*, because it is similar to *Cycladophora davisiana* Ehrenberg.

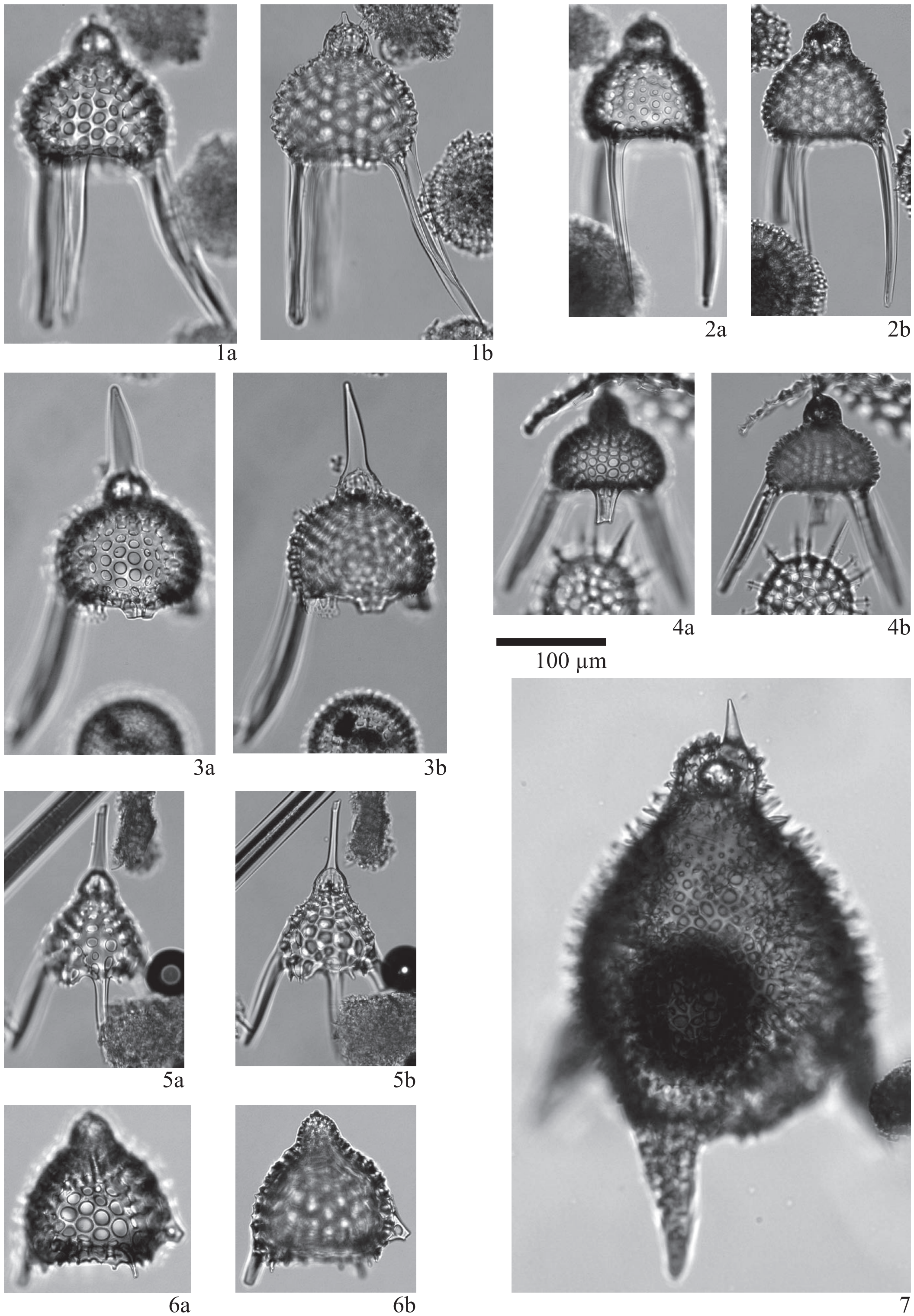

Figure 6. Photographs of selected radiolarian species identified during this study. **1,** *Lychnocanoma nipponica* (Nakaseko) type A, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, Z47/2; **2,** *Lychnocanoma nipponica* (Nakaseko) type B, Sample 165-1021B-26X-4, 70–72 cm, sl. 1, J50/2; **3,** *Lychnocanoma magnacornuta* Sakai, Sample 165-1021B-28X-6, 20–22 cm, sl. 1, H19/4; **4,** *Lychnocanoma sakaii* Morley and Nigrini (juvenile form), Sample 165-1020B-2H-2, 20–22 cm, sl. 1, N31/0; **5,** *Dictyophimus splendens* (Campbell and Clark), Sample 165-1021B-32X-6, 20–22 cm, sl. 1, H47/0; **6,** *Dictyophimus bullatus* Morley and Nigrini, Sample 165-1021B-14H-1, 20–22 cm, sl. 1, O30/0; **7,** *Anthocyrtoma* ? sp. A, Sample 165-1021B-24X-6, 20–22 cm, sl. 1, S44/3.

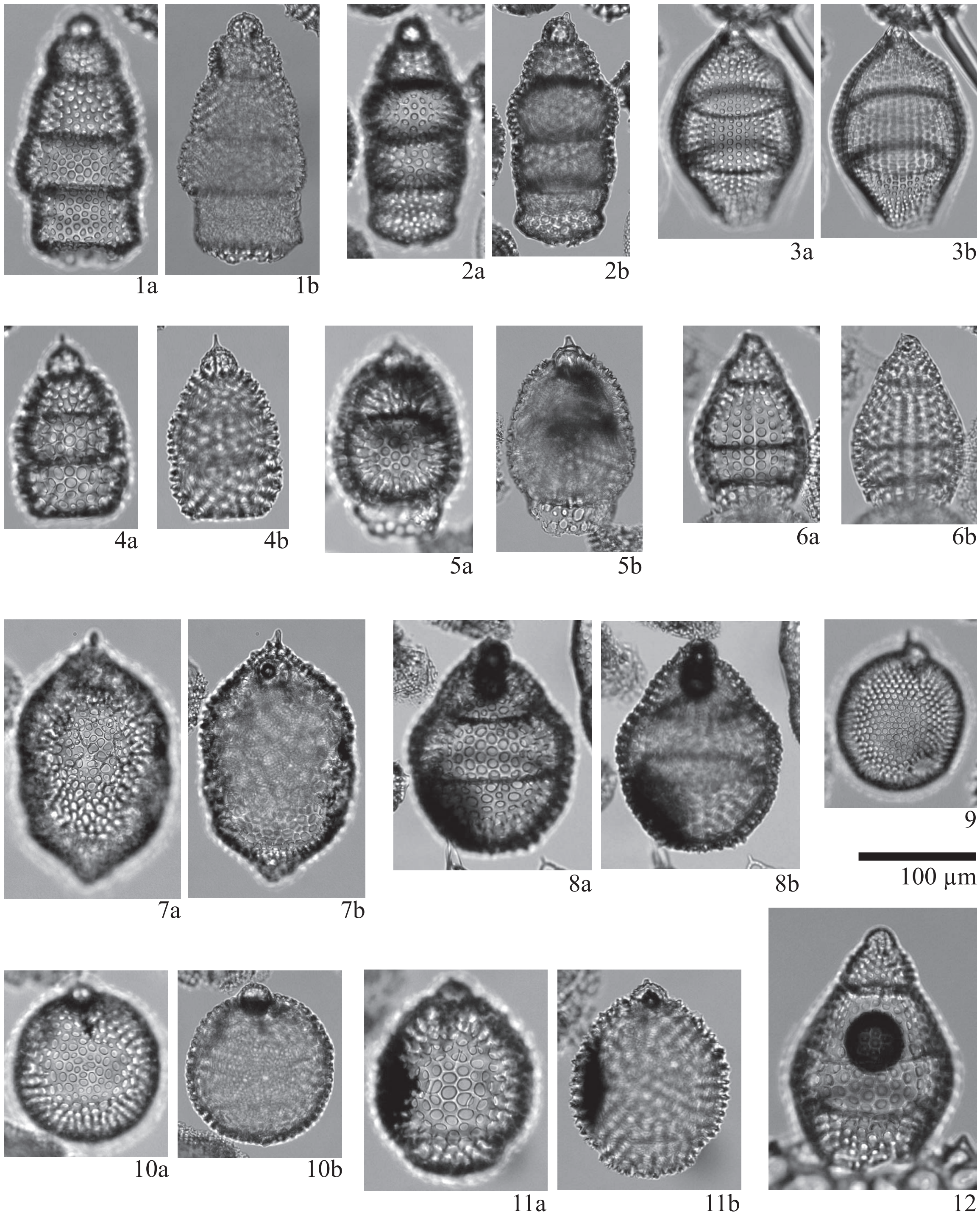

Figure 7. Photographs of selected radiolarian species identified during this study. **1,** *Stichocorys peregrina* (Riedel), Sample 165-1021B-28X-6, 20–22 cm, sl. 1, W43/3; **2,** *Stichocorys delmontensis* (Campbell and Clark), Sample 165-1021B-26X-4, 70–72 cm, sl. 1, O43/1; **3,** *Eucyrtidium yatsuoense* Nakaseko, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, V32/0; **4,** *Cyrtocapsella tetrapera* Haeckel, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, X37/4; **5,** *Cyrtocapsella japonica* (Nakaseko), Sample 165-1021B-33X-2, 120–122 cm, sl. 1, X46/2; **6,** *Eucyrtidium inflatum* Kling, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, K28/3; **7,** *Lithopera thornburgi* Sanfilippo and Riedel, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, Z50/2; **8,** *Cyrtocapsella cornuta* (Haeckel), Sample 165-1021B-32X-6, 20–22 cm, sl. 1, T17/0; **9,** *Lithopera bacca* Ehrenberg, Sample 165-1021B-28X-6, 20–22 cm, sl. 1, H45/1; **10,** *Lithopera neotera* Sanfilippo and Riedel, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, Q50/0; **11,** *Lithopera renzae* Sanfilippo and Riedel, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, P51/0; **12,** *Eucyrtidium matuyamai* Hays, Sample 165-1021B-6H-6, 20–22 cm, sl. 1, Y34/1.

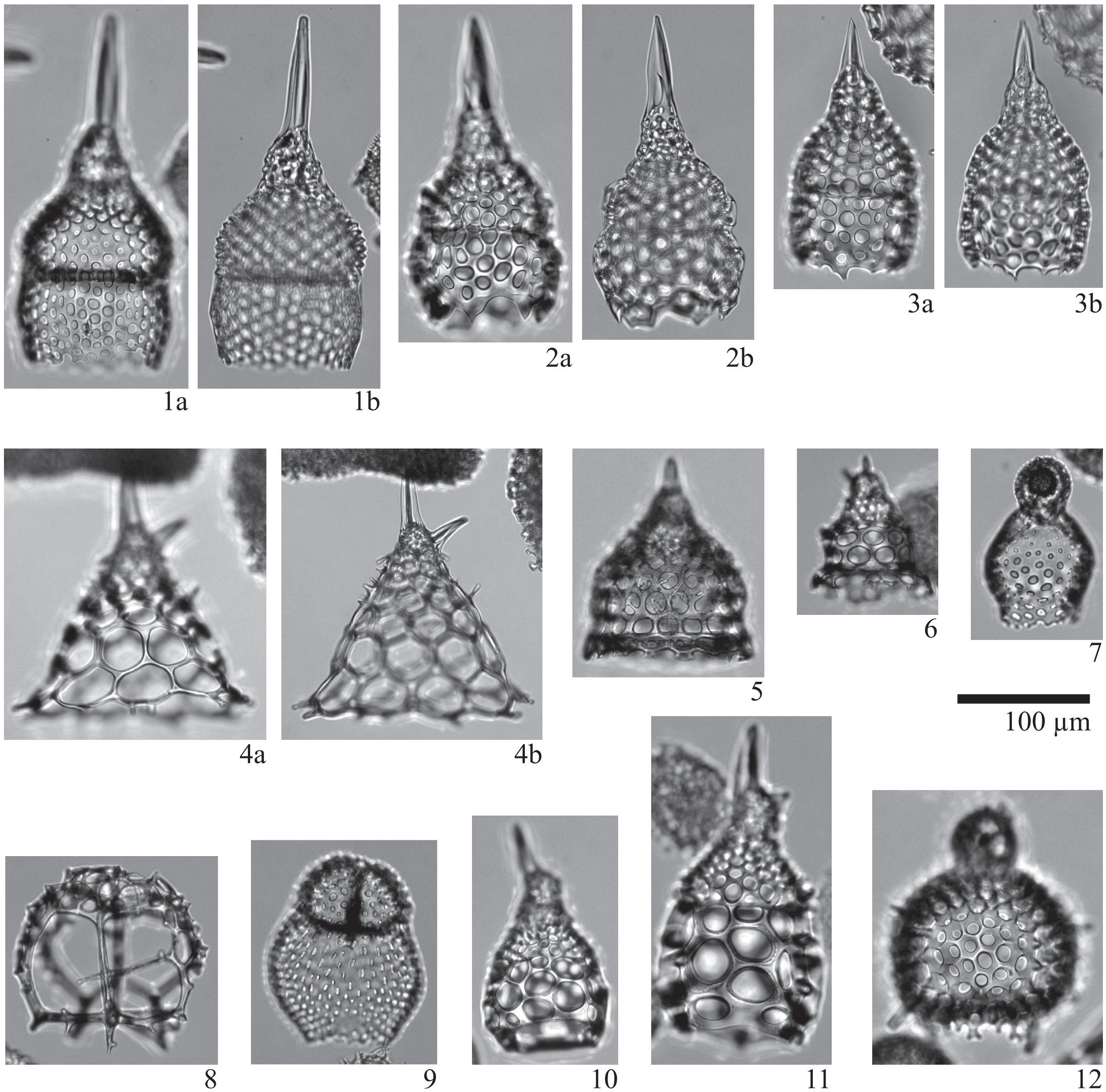

Figure 8. Photographs of selected radiolarian species identified during this study. **1,** *Albatrossidium* sp. A, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, R51/0; **2,** *Lamprocyclas margatensis* (Campbell and Clark) type B, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, Y35/2; **3,** *Lamprocyclas margatensis* (Campbell and Clark) type A, Sample 165-1021B-32X-6, 20–22 cm, sl. 1, N41/0; **4,** *Cycladophora cabrilloensis* (Campbell and Clark), Sample 165-1021B-26X-4, 70–72 cm, sl. 1, D43/0; **5,** *Cycladophora sphaeris* (Popova), Sample 165-1021B-22X-6, 20–22 cm, sl. 1, Q36/0; **6,** *Cycladophora davisiana* Ehrenberg, Sample 165-1020B-7H-2, 20–22 cm, sl. 1, U50/2; **7,** *Lipmanella hister* (Petrushevskaya). Sample 165-1021B-33X-4, 70–72 cm, sl. 1, E36/0; **8,** *Ceratospyris borealis* Bailey, Sample 165-1020B-2H-2, 20–22 cm, sl. 1, F42/0; **9,** *Dendrospyris* aff. *bursa* (Sanfilippo and Riedel), Sample 165-1021B-28X-6, 20–22 cm, sl. 1, R35/4; **10,** *Lamprocyrtis neoheteroporos* Kling, Sample 165-1021B-9H-2, 20–22 cm, sl. 1, P21/0; **11,** *Lamprocyrtis heteroporos* (Hays), Sample 165-1021B-10H-2, 20–22 cm, sl. 1, S43/0; **12,** *Lipmanella redondoensis* (Campbell and Clark), Sample 165-1021B-28X-6, 20–22 cm, sl. 1, J20/0.

Cyrtocapsella cornuta (Haeckel, 1887). Sakai, 1980, p. 709, pl. 8, fig. 8a, b.

Cyrtocapsella japonica (Nakaseko, 1963). Sakai, 1980, p. 709, pl. 8, fig. 7a, b.

Cyrtocapsella tetrapera Haeckel, 1887. Sakai, 1980, p. 709, pl. 8, figs. 5, 6.

Diartus hughesi (Campbell and Clark, 1944). Sanfilippo *et al*., 1985, p. 655, fig. 8.11.

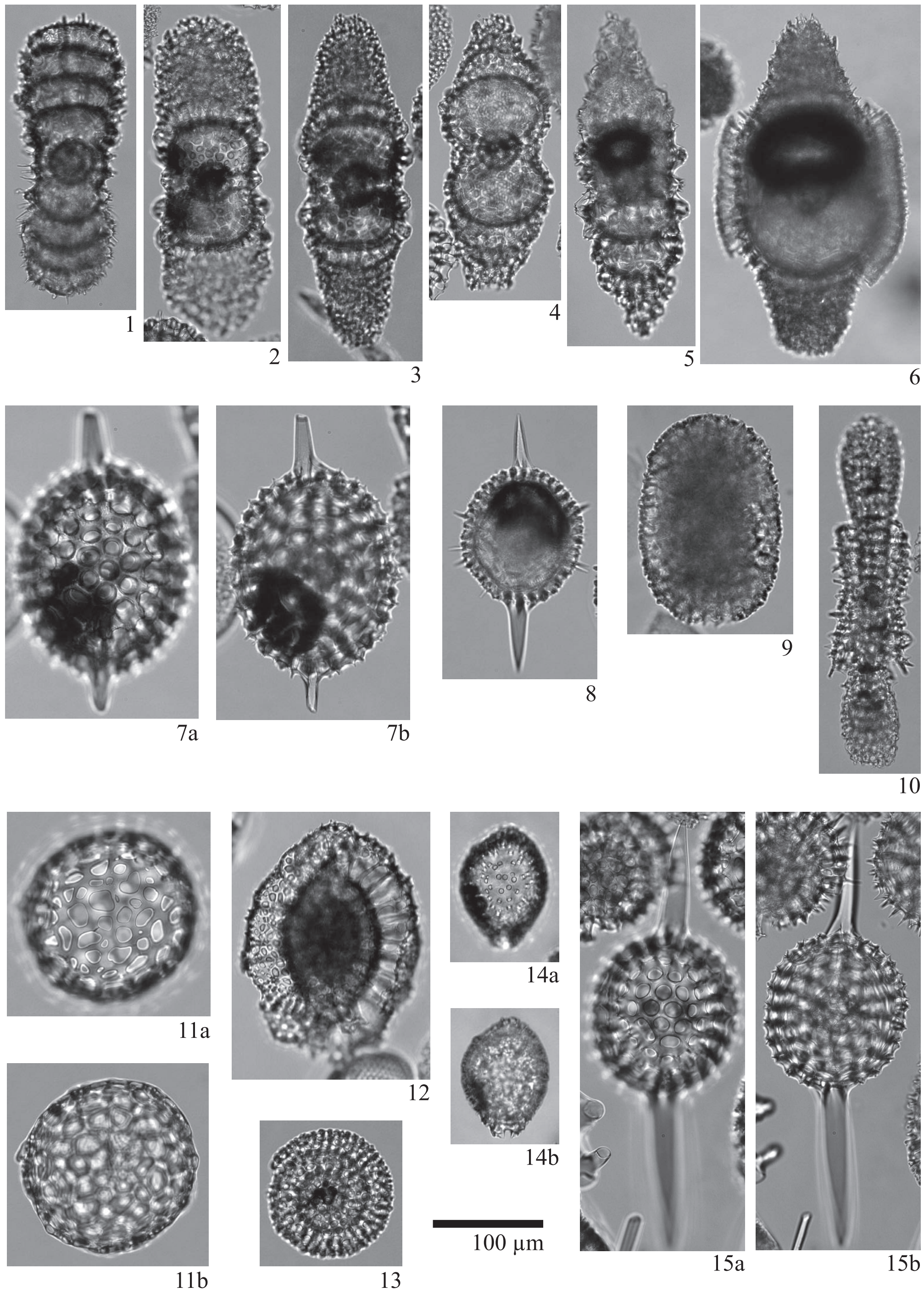

Figure 9. Photographs of selected radiolarian species identified during this study. **1,** *Diartus hughesi* (Campbell and Clark), Sample 165-1021B-26X-2, 120–122 cm, sl. 1, E29/0; **2,** *Diartus petterssoni* (Riedel and Sanfilippo), Sample 165-1021B-32X-6, 20–22 cm, sl. 1, J36/0; **3,** *Didymocyrtis laticonus* (Riedel), Sample 165-1021B-33X-2, 120–122 cm, sl. 1, Y22/4; **4,** *Didymocyrtis antepenultima* (Riedel and Sanfilippo), Sample 165-1021B-28X-6, 20–22 cm, sl. 1, V47/2; **5,** *Didymocyrtis penultima* (Riedel), Sample 165-1021B-23X-6, 20–22 cm, sl. 1, N28/3; **6,** *Dydymocyrtis* sp. D, Sample 165-1021B-26X-6, 20–22 cm, sl. 1, U41/0; **7,** *Axoprunum acquilonium* (Hays), Sample 165-1021B-10H-2, 20–22 cm, sl. 1, J28/2; **8,** *Stylatractus universus* Hays, 1970, Sample 165-1020B-7H-2, 20–22 cm, sl. 1, R36/4; **9,** *Larcopyle*? *pylomaticus* (Riedel), Sample 165-1021B-9H-2, 120–122 cm, sl. 1, M33/0; **10,** *Amphymenium amphistylium* Haeckel, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, C40/4; **11,** *Collosphaera glebulenta* Bjørklund and Goll, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, X45/0; **12,** *Larcospira moschkovskii* Kruglikova, Sample 165-1021B-26X-2, 120–122 cm, sl. 1, E33/0; **13,** *Lithelius klingi* Kamikuri, Sample 165-1021B-33X-2, 120–122 cm, sl. 1, H40/3; **14,** *Collosphaera pyloma* Reynolds, Sample 165-1021B-32X-4, 20–22 cm, sl. 1, O28/2; **15,** *Axoprunum bispiculum* (Popofsky), Sample 165-1021B-28X-6, 20–22 cm, sl. 1, H23/3.

Diartus petterssoni (Riedel and Sanfilippo, 1970). Sanfilippo *et al*., 1985, p. 657, fig. 8.10a, b.
Dictyophimus bullatus Morley and Nigrini, 1995. Morley and Nigrini, 1995, p. 79, pl. 4, figs. 5, 9, 10; *Dictyophimus robustus* Motoyama, 1996, p. 246, pl. 6, figs. 1a–2c; *Dictyophimus marujamai* Tochilina? in Tochilina *et al*., 1988, p. 49, pl. 3, fig. 11.
Dictyophimus splendens (Campbell and Clark, 1944). Morley and Nigrini, 1995, p. 79, pl. 7, figs. 3, 4.
Didymocyrtis antepenultima (Riedel and Sanfilippo, 1970). Sanfilippo *et al*., 1985, p. 657, fig. 8.6.
Didymocyrtis laticonus (Riedel, 1959). Sanfilippo *et al*., 1985, p. 658, fig. 8.5a, b.
Didymocyrtis penultima (Riedel, 1957). Sanfilippo *et al*., 1985, p. 658, fig. 8.7a, b.
Eucyrtidium inflatum Kling, 1973. Kling, 1973, p. 636, pl. 11, figs. 7, 8, pl. 15, figs. 7–10.
Eucyrtidium matuyamai Hays, 1970. Hays, 1970, p. 213, pl. 1, figs. 7–9.
Eucyrtidium yatsuoense Nakaseko, 1963. Nakaseko, 1963, p. 189, pl. 3, fig. 6a, b.
Lamprocyclas margatensis (Campbell and Clark, 1944). Sugiyama and Furutani, 1992, p. 207, pl. 18, fig. 7.
Lamprocyrtis heteroporos (Hays, 1970). Kling, 1973, p. 639, pl. 5, figs. 19–21, pl. 15, fig. 6.
Lamprocyrtis neoheteroporos Kling, 1973. Kling, 1973, p. 639, pl. 5, figs. 17, 18, pl. 15, figs. 4, 5.
Larcopyle pylomaticus (Riedel, 1958). Lazarus *et al*., 2005, p. 115, pl. 9, figs. 1–3, 6, 10?, 12? (not 4, 5, 7–9, 11).
Larcospira moschkovskii Kruglikova, 1978. Kruglikova, 1978, p. 88, pl. 27, figs. 3–6.
Lipmanella hister (Petrushevskaya, 1975). Sugiyama and Furutani, 1992, p. 209, pl. 13, figs. 7, 8.
Lipmanella redondoensis (Campbell and Clark, 1944). Funakawa, 2000, p. 108, pl. 4, figs. 2a–3c, pl. 7, fig. 6a–c, text-fig. 8.
Lithelius klingi Kamikuri, 2010. Kamikuri, 2010, p. 95, pl. 4, figs. 9–14.
Lithopera bacca Ehrenberg, 1873. Johnson and Nigrini, 1980, p. 127, pl. 3, fig. 8.
Lithopera neotera Sanfilippo and Riedel, 1970. Sanfilippo *et al*., 1985, p. 675, fig. 16.5a, b.
Lithopera renzae Sanfilippo and Riedel, 1970. Sanfilippo and Riedel, 1970, p. 454, pl. 1, figs. 21–23, 27.
Lithopera thornburgi Sanfilippo and Riedel, 1970. Sanfilippo *et al*., 1985, p. 676, fig. 16.3a, b.
Lychnocanoma magnacornuta Sakai, 1980. Motoyama, 1996, p. 248, pl. 5, figs. 10, 11.
Lychnocanoma nipponica (Nakaseko, 1963) type A: *Lychnocanium nipponicum* Nakaseko, 1963, p. 168, text-fig. 2, pl. 1, fig. 1a, b; *Lychnocanium grande* (Campbell and Clark) in Kling, 1973, p. 637, pl. 10, figs. 10–14; *Lychnocanoma nipponica nipponica* (Nakaseko) in Morley and Nigrini, 1995, p. 81, pl. 5, fig. 4 (not fig. 5). *L. nipponica* type A differs from *L. grande* Campbell and Clark by having a hemispherical thorax. In the present study, I did not encounter the species described by Campbell and Clark (1944) as *L. grande*.
Lychnocanoma nipponica (Nakaseko, 1963) type B: *Lychnocanoma nipponica nipponica* (Nakaseko) in Morley and Nigrini, 1995, p. 81, pl. 5, fig. 5 (not fig. 4). *L. nipponica* type B differs from *L. nipponica* type A by its slightly convergent feet, and from *Lychnocanoma parallelipes* Motoyama by its thin thorax wall without spine.
Lychnocanoma sakaii Morley and Nigrini, 1995 (juvenile form). Matsuzaki *et al.*, 2015, p. 50, figs. 8.28, 8.33.
Stichocorys delmontensis (Campbell and Clark, 1944). Sanfilippo and Riedel, 1970, p. 451, pl. 1, fig. 9.
Stichocorys peregrina (Riedel, 1953). Sanfilippo and Riedel, 1970, p. 451, pl. 1, fig. 10.
Stylatractus universus Hays, 1970. Hays, 1970, p. 215, pl. 1, figs. 1, 2.

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Appendix 1.

Hole	Core	section	Interval (cm)	Depth (mbsf)	Depth (mcd)	Age (Ma)	Preservation	Abundance	*Albatrossidium* sp. A	*Albatrossidium* sp. C	*Amphymenium amphistylium*	*Anthocyrtoma*? sp. A	*Axoprunum acquilonius*	*Axoprunum bispiculum*	*Botryostrobus aquilonaris*	*Ceratospyris borealis*	*Collosphaera glebulenta*	*Collosphaera pyloma*	*Cycladophora cabrilloensis*	*Cycladophora davisiana*	*Cycladophora sphaeris*	*Cyrtocapsella cornuta*	*Cyrtocapsella japonica*	*Cyrtocapsella tetrapera*	*Dendrospyris* aff. *bursa*	*Diartus hughesi*	*Diartus petterssoni*	*Dictyophimus splendens*	*Dictyophimus bullatus*	*Didymocyrtis antepenultima*	*Didymocyrtis laticonus*	*Didymocyrtis penultima*	*Didymocyrtis* sp. D	*Eucyrtidium inflatum*	*Eucyrtidium matuyamai*	*Eucyrtidium yatsuoense*	*Lamprocyclas margatensis* type A	*Lamprocyclas margatensis* type B	*Lamprocyrtis heteroporos*	*Lamprocyrtis neoheteroporos*	*Larcopyle pylomaticus*	*Larcospira moschkovskii*	*Lipmanella hister*	*Lipmanella redondoensis*	*Lithelius klingi*	*Lithopera bacca*	*Lithopera neotera*	*Lithopera renzae*	*Lithopera thornburgi*	*Lychnocanoma magnacornuta*	*Lychnocanoma nipponica* type A	*Lychnocanoma nipponica* type B	*Lychnocanoma sakaii*	*Stichocorys delmontensis*	*Stichocorys peregrina*	*Stylatractus universus*
1020B	1H	2	20–22	1.70	1.73	0.01	M	R						F	F	R				R																																								
1020B	2H	2	20–22	9.50	9.43	0.06	G	F						F	F	F				F																					R					R							F			
1020B	3H	2	20–22	19.00	19.59	0.13	G	C						R	F	R				F																					R												F			
1020B	4H	2	20–22	28.50	30.77	0.21	P	R						R																																												
1020B	5H	2	20–22	38.00	41.47	0.28	G	F					R	R	R	F				A																					R												F			
1020B	6H	2	20–22	47.50	52.60	0.48	G	F					R	R	C	R				F																					R															R
1020B	7H	2	20–22	57.00	63.24	0.58	G	C						R	C	R				C																					R												R			F
1020B	8H	2	20–22	66.50	74.65	0.69	G	F					R	R	C	R				C																					R															F
1020B	9H	2	20–22	76.00	86.52	0.80	G	F					R	R	F	R				C																					R												R			F
1020B	10H	2	20–22	85.50	97.41	0.95	M	R					R	R	R	R				R																																					F
1020B	11H	2	20–22	95.00	106.48	1.05	P	R					R	R	R					R																R																					F
1020B	12H	2	20–22	104.50	117.38	1.11	P	R					R	R	R					R																																					F
1021B	5H	1	20–22	36.71	40.75	1.26	M	R					A	R	R					R																																					R
1021B	5H	2	120–122	39.21	43.44	1.35	P	vR																																																
1021B	5H	4	70–72	41.71	46.14	1.45	P	vR																																																
1021B	5H	6	20–22	44.21	48.83	1.55	M	R					A	C	R					R																			R	R																	A
1021B	6H	1	20–22	46.21	50.99	1.62	M	R					R	R	R	R				R																																					F
1021B	6H	2	120–122	48.71	53.74	1.72	P	R					F	R	R					R																																					R
1021B	6H	4	70–72	51.21	56.48	1.81	G	F					R	R	R	R				F																																					F
1021B	6H	6	20–22	53.71	59.22	1.88	G	F					R	R	R	R				F																R																					F
1021B	7H	1	20–22	55.71	61.42	1.94	G	F					R	R	R	R				F																																					R
1021B	7H	2	120–122	58.21	64.15	2.01	G	F					R	R	R	R				C	R																	F	R	R					R							R			R
1021B	7H	4	70–72	60.71	66.87	2.08	M	R					R	R	R	R				F																																					R
1021B	7H	6	20–22	63.21	69.60	2.15	M	R					R	R	R	R				F																																					R
1021B	8H	1	20–22	65.21	71.81	2.21	M	R					R	R	R	R				F																																					R
1021B	8H	2	120–122	67.71	74.88	2.29	G	C					R	R	R	R				F	R																	F	R	R					R											R
1021B	8H	4	70–72	70.21	77.94	2.37	M	R					R	R	R	R				F																																					R
1021B	8H	6	20–22	72.71	81.01	2.45	M	R					R	R	R	R				R																																					R
1021B	9H	1	20–22	74.71	83.51	2.52	M	R					R	R	R	R				R																																					R
1021B	9H	2	120–122	77.21	87.07	2.61	G	C					R	R	R	R				F	R																	F	R	R					R											R
1021B	9H	4	70–72	79.71	90.64	2.69	G	F					R	R																																											R
1021B	9H	6	20–22	82.21	94.20	2.77	G	F					R	R																																											R
1021B	10H	1	20–22	84.21	96.97	2.84	G	F					R	R																																											
1021B	10H	2	120–122	86.71	99.57	2.90	G	C					F	R							R																	C	C	R														F
1021B	10H	4	70–72	89.21	102.18	2.96	G	F					R	R																																											
1021B	10H	6	20–22	91.71	104.78	3.02	G	F						R																																											
1021B	11H	1	20–22	93.71	106.89	3.10	M	F					R	R																									F		R														R
1021B	11H	2	120–122	96.21	109.69	3.22	M	F					A	C																									R																R
1021B	11H	4	70–72	98.71	112.50	3.31	P	R					C																																								?			
1021B	11H	6	20–22	101.21	115.30	3.40	G	C					F	F																									C		R														R
1021B	12H	1	20–22	103.21	117.52	3.46	P	R					R																										C																		
1021B	12H	2	120–122	105.71	120.01	3.54	P	R					F	R																									A																R
1021B	12H	4	70–72	108.21	122.51	3.62	P	vR																																																
1021B	12H	6	20–22	110.71	125.00	3.72	P	R					A																																											C
1021B	13H	1	20–22	112.71	126.98	3.80	M	C					F	R							R																																			F
1021B	13H	2	120–122	115.21	129.25	3.90	P	R					F	F																																											F
1021B	13H	4	70–72	117.71	131.53	3.99	P	R					R																																											R
1021B	13H	6	20–22	120.21	133.80	4.08	M	C					F	R															F																											F
1021B	14H	1	20–22	122.21	135.66	4.15	M	R					R	R															F																											R
1021B	14H	2	120–122	124.71	138.34	4.27	M	F					C	A															R																											R
1021B	14H	4	70–72	127.21	141.02	4.40	M	R					F	A															R																											R
1021B	14H	6	20–22	129.71	143.71	4.51	M	F					F	F															R									R		R														R
1021B	15H	1	20–22	131.71	145.86	4.56	G	R					R	C																																											C
1021B	15H	2	120–122	134.21	148.57	4.63	M	C					R	R																									C		R					R							R	F	R
1021B	15H	4	70–72	136.71	151.29	4.69	G	C					F	F																									F		R				R								R	F	F
1021B	15H	6	20–22	139.21	154.01	4.76	G	A					R	R																									C		R				R								R	F	F
1021B	16H	1	20–22	141.21	156.17	4.82	G	C					F	R																									F		R													R	R	F
1021B	16H	2	120–122	143.71	158.83	4.90	G	C					R	R																									F		R				R									R	F
1021B	16H	4	70–72	146.21	161.48	4.99	G	F					R	R																									F														R	R	R
1021B	16H	6	20–22	148.71	164.13	5.08	G	F					F	R																									F														R	F	F
1021B	17H	1	20–22	150.71	166.24	5.15	G	F					R	F																									F		R			R	R										R	R
1021B	17H	2	120–122	153.21	168.71	5.23	G	F					R	R																									F															R	F
1021B	17H	4	70–72	155.71	171.17	5.29	G	F					R	R																									F					R										R	F
1021B	17H	6	20–22	158.21	173.64	5.34	G	C					R	F																									F		R			R	R	R									R	F
1021B	18H	1	20–22	160.21	175.62	5.39	G	F					R	R																											R															R	A
1021B	18H	2	120–122	162.71	178.12	5.44	G	F					R	F																									R															R	R
1021B	18H	4	70–72	165.21	180.62	5.50	G	F						R																									R																F
1021B	18H	6	20–22	167.71	183.12	5.56	G	F						R																				*											R											R	R
1021B	19X	1	20–22	169.71	185.12	5.60	G	F						R										*																			R		R										R	F	F
1021B	19X	2	120–122	172.21	187.62	5.66	G	F					R	R							R			*																			R		R										R	F	R
1021B	19X	4	70–72	174.71	190.12	5.71	G	F						R																																									F	R
1021B	19X	6	20–22	177.21	192.62	5.77	G	F						R																													R			R												R
1021B	20X	1	20–22	175.61	191.02	5.74	G	F					R	R																																											R
1021B	20X	2	120–122	178.11	193.52	5.79	G	F						R																													R			R												R
1021B	20X	4	70–72	180.61	196.02	5.85	G	A						R																													R		R													R
1021B	20X	6	20–22	183.11	198.52	5.91	G	A						R																													R		R													R
1021B	21X	1	20–22	185.21	200.62	5.96	G	R						R																															R												R
1021B	21X	2	120–122	187.71	203.12	6.02	M	R						R														R																													R
1021B	21X	4	70–72	190.21	205.62	6.08	M	R						R														R																	R												R
1021B	21X	6	20–22	192.71	208.12	6.14	M	R						R														R																	R												R
1021B	22X	1	20–22	194.91	210.32	6.19	G	F						R														R															R			R												R
1021B	22X	2	120–122	197.41	212.82	6.25	G	C						R														R															R		R	R								R		R	F	R
1021B	22X	4	70–72	199.91	215.32	6.30	G	C			R		R	F														R															R		R	F								R		R	C	C
1021B	22X	6	20–22	202.41	217.82	6.36	G	C			R			F														R															R		R	R								R		F	C	F
1021B	23X	1	20–22	204.51	219.92	6.41	G	C			R			R														R															R		R	R								R		F	A	F
1021B	23X	2	120–122	207.01	222.42	6.47	G	A			R			R														R																		R	R								R		F	C	F
1021B	23X	4	70–72	209.51	224.92	6.73	G	A			R			R														R															R		R	R								R		F	C	F
1021B	23X	6	20–22	212.01	227.42	7.18	G	A			R		R	R				R		R						R				R														R	R	R							R		R	C	F
1021B	24X	1	20–22	214.21	229.62	7.58	G	A			R			R				R										R															R		R	R	R							R		R	C	R
1021B	24X	2	120–122	216.71	232.12	7.78	G	A					R	R				R										R																		R	R	R							R		F	F	F
1021B	24X	4	70–72	219.21	234.62	7.89	G	A			R		R	R				R										R				R														R	R								R		F	F	F
1021B	24X	6	20–22	221.71	237.12	8.00	G	A				R		R				R										R															R		R	R								R		C	F	F
1021B	25X	1	20–22	223.81	239.22	8.09	G	A			R	R		R				R										R															F		R	R								R		C	F	R
1021B	25X	2	120–122	226.31	241.72	8.20	G	A			R	R		R				R										R															F		R	R								R		C	F	F
1021B	25X	4	70–72	228.81	244.22	8.31	G	A			R	R		R				R										R				R												R		R									R		F	R	F
1021B	25X	6	20–22	231.31	246.72	8.41	G	A			R	R		R				R										R															R		R									R		F	R	F
1021B	26X	1	20–22	233.41	248.82	8.51	G	C			R	R		R				R										R																		R									R		F	F	F
1021B	26X	2	120–122	235.91	251.32	8.61	G	C			R	R		R				F						R		R		R			R														R	R	R							F		F	F	F
1021B	26X	4	70–72	238.41	253.82	8.74	G	C			R	R		R				F						R		R				R													*	R	R	R							F		F	R	R
1021B	26X	6	20–22	240.91	256.32	8.91	G	C			R	R		R				R								R		R			R														R	R								R		C	F	F
1021B	27X	1	20–22	243.01	258.42	9.05	G	C			R			R				R						R	R		R		R	*		R									R		R	R	R	R					R		C	F	F
1021B	27X	2	120–122	245.51	260.92	9.22	G	C						R				R						R	R							R									F		R	F		R				R	R	R		C	F	F
1021B	27X	4	70–72	248.01	263.42	9.36	G	C			R			R				R						R			R					R									F		R	R		R					R	R		C	F	F
1021B	27X	6	20–22	250.51	265.92	9.47	G	A						R				R						R	R		R		R			R									F		R							R			F	F	F
1021B	28X	1	20–22	252.61	268.02	9.56	G	A			R			R				R							R							R									F		R			R			F	R			F	F	F
1021B	28X	2	120–122	255.11	270.55	9.67	G	A			R			R				R						R								R									F		R			R			F	R			F	F	F
1021B	28X	4	70–72	257.61	273.07	9.77	G	A			R			R				R			*			R	R		R		R	R		R									R		R	R		R				R			C	F	R
1021B	28X	6	20–22	260.11	275.60	9.88	G	A			R			F				R			*			F	R		R			R		R									R		R	R		R			R	R			C	F	R
1021B	29X	1	20–22	262.31	277.82	9.98	G	A						R				R						R	R				R	R		R									R		R	R					F	R			F	R	R
1021B	29X	2	120–122	264.81	280.29	10.11	G	A			R			R				R						R			R			R		R									R		R	R		R			F	F			F	F	R
1021B	29X	4	70–72	267.31	282.77	10.24	G	A						R				R				R		F			R			R		R									F		R	F					F	F			F	F	R
1021B	29X	6	20–22	269.81	285.24	10.37	G	F			R			R				R				R		R		R	R			R		R									R		R	F		R			F	F			R	F	F
1021B	30X	1	20–22	271.91	287.32	10.48	G	C		R	R			F				R				C		R		R	R			R		R												R	R		R			F	R			R		R
1021B	30X	2	120–122	274.41	289.82	10.61	G	C		R	R			R				R				A				R			R		R									R		R	R		R				R			R		F
1021B	30X	4	70–72	276.91	292.32	10.75	G	C		R	R			R				R				A		R		R	R			R		R									R		R			R			R	R			R		F
1021B	30X	6	20–22	279.41	294.82	10.88	G	C		R	R			R				R				A		R			R			F														R	R		R			R	R			R		F
1021B	31X	1	20–22	281.51	296.92	10.99	G	C		R	R			R			R		R				A		R		R				F														R	R					R	R			R		F
1021B	31X	2	120–122	284.01	299.42	11.12	G	C		F				R			R	R	R				A				R	R			F					R									R	R		R			R	R			F	R	R
1021B	31X	4	70–72	286.51	301.92	11.26	G	C		F	R			R			R		R				C		R		R				F					R		R							R	F		R				R			F	R	R
1021B	31X	6	20–22	289.01	304.42	11.39	G	C		F	R			R				R	R				C		R			R			F					R		R							R	R		R			F	R			F	R	R
1021B	32X	1	20–22	291.11	306.52	11.52	G	A		R	R			R			R	R	R			R	A	R	R		R				F					R	R	R							R	R		R	R		F	R			C	R	R
1021B	32X	2	120–122	293.61	309.02	11.67	G	F		R	R			R				R	R			R	C	R				R			R														R	R			R		R	F			C	R	R
1021B	32X	4	70–72	296.11	311.52	11.83	G	A		R	R			R			R	R	R			R	F	R			R	R			R					R	R	R					R	R	R		R	R		R	C			A	R	
1021B	32X	6	20–22	298.61	314.02	11.98	G	A	F	R	R			R			R	R	R			R	F	R			R	R			R		F		R	R	R					R	R	R			R		R		C			C	R	
1021B	33X	1	20–22	300.71	316.12	12.11	G	A	F	R	R			R			R	R	R			R		C				R			R			R		R	R	R					R	R				R	R		C			F	R	
1021B	33X	2	120–122	303.21	318.62	12.27	G	A	R	R	R			R			R	R	R			R		A				R			F			R			R	R					R	R	R			R	R		F			R		
1021B	33X	4	70–72	305.71	321.12	12.42	G	A	R	R	R			R			R	R	R			R	R	C				R			F			R		R	R	R					R	R			R	F	R		R			F		
1021B	33X	6	20–22	308.21	323.62	12.58	G	A	R	R	R			R			F	R	R			R		F				R			F			R		R	R	R					R	R	R		R	C	R		R			F		