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

SHIN-ICHI KAMIKURI¹

¹ Faculty of Education, Ibaraki University, Bunkyo 2-1-1, Ibaraki 310-8512, Japan

(e-mail: shin-ichi.kamikuri.millefeuille@vc.ibaraki.ac.jp)

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 upper Miocene events were directly tied to the paleomagnetic stratigraphy, and 40 middle to upper Miocene events were correlated with that 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 parviakitaensis*, *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: radiolarians, temperate to subarctic, zonations, northern California, North Pacific

Introduction

Deep-sea sediments in the North Pacific is characterized by widespread biosiliceous components, which ages 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 the biostratigraphic tool for dating and correlating Neogene sequences in middle- to high-latitude zones. However, radiolarian studies were not studied beyond those that reported 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 radiolarian zonations 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 radiolarian zonations of Riedel and Sanfilippo (1970; 1978) for the late Miocene and early Pliocene in the North Pacific (Kling, 1973; Reynolds, 1980; Sakai, 1980; Wolfart, 1981; Morley, 1985). Reynolds (1980) extended the zonation back to the early Miocene, and proposed eight new zones for the middle latitude 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-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 during ODP Leg 145, Morley and Nigrini (1995) found fifty 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-latitude differs from those 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 early Miocene to the late Pliocene (Figure 2). Motoyama (1996), and Motoyama and Maruyama (1998) distinguished thirteen 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 late 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, 887, 1150, and 1151 in the high latitudes of the North Pacific (Kamikuri *et al.*, 2004, 2007) (Figures 1 and 2).

Perez-Guzman (1985) and Perez-Guzman and Casey (1986) studied radiolarian biostratigraphy from the middle to late Miocene in Baja California (32° to 22° N) and Tres Marías Islands ($21^{\circ}30'$ 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 ($33^{\circ}50'$ N), and did not distinguish the radiolarian zones for low latitude. Poore *et al.* (1981) showed the stratigraphic distributions of radiolarians with other microfossils from the lower to middle Miocene of California ($35^{\circ}30'$ 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 ($33^{\circ}40'N$) and the Centerville Beach ($40^{\circ}60'N$). The radiolarian biofacies indicated the temperate to subarctic conditions since the middle Miocene in these areas. These studies indicated lacking many tropical zonal markers at north of $33^{\circ}N$ in the northeastern Pacific. In spite of these efforts, radiolarian zonal schemes for the temperate and subarctic regions (middle- to high-latitudes), has not been applied to the deep-sea sediments off California.

Materials and methods

Radiolarians were examined from ODP Sites 1020 ($41^{\circ}0.051'N$, $126^{\circ}26.064'W$, water depth of 3038.4 m), and 1021 ($39^{\circ}5.248'N$, $127^{\circ}46.985'W$, 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 latest Miocene can be directly correlated with the paleomagnetic stratigraphy, while that from the middle to late 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 age 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 latest Miocene were directly correlated with the 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 latitude 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 and 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).

***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 Holocene (0.4 to 0 Ma).

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

Remarks: The LO of *S. universus*, that defines the base of the *B. 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. The *B. aquilonaris* Zone is correlated with the interval from the *A. vinculata* Zone to the upper part of *Cyrtidospaera reticulata* Zone, proposed by Matsuzaki *et al.* (2014).

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

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

Top: LO of *Stylatractus universus*.

Base: LO of *Eucyrtidium matuyamai*.

Magnetochronologic calibration: The top of this zone is placed within the middle of C1n, and the base within the C1r.1n (Jaramillo).

Age: Early to middle Pleistocene (1.0 to 0.4 Ma).

Remarks: The LO of *E. matuyamai*, that defines the base of *S. 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: *A. acqilonium*, *B. aquilonaris*, *C. borealis*, *C. davisiana*, *L. pylomaticus*, and *S. universus*.

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

Top: LO of *Eucyrtidium matuyamai*.

Base: FO of *Eucyrtidium matuyamai*.

Magnetochronologic 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 *Lamprocyrts heteroporos*, and *L. neoheteroporos*.

Remarks: The FO of *E. 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 *L. 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: *A. acqilonium*, *B. aquilonaris*, *C. borealis*, *C. davisiana*, *E. matuyamai*, *L. pylomaticus*, and *S. universus*.

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

Top: FO of *Eucyrtidium matuyamai*.

Base: LO of *Dictyophimus bullatus*.

Magnetochronologic 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 *E. matuyamai* (top) to LO of *D. bullatus* (=*D. robustus* in the original paper) (base). Because *C. sakaii* Motoyama is regarded as a junior synonym of *Cycladophora sphaeris* (Popova), I renamed the *C. sakaii* Zone to *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 *C. davisiana*.

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

Top: FO of *Eucyrtidium matuyamai*.

Base: FCO of *Cycladophora davisiana*.

Magnetochronologic 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 *L. sakaii*.

Remarks: Shilov (1995) first defined the *Cycladophora cornutooides* (=*Diplocyclas cornutooides*) Zone as an interval from the FO of *E. matuyamai* (top) to the FO of *C. davisiana* (base) (Figure 4). Because the species name of *C. cornutooides* has been already used for a zone of 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 *C. 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 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 *H. dionysus* Interval Subzone in the high-latitude North Pacific. However, the ET from *C. sphaeris* to *C. davisiana* 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 *H. 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 *C. 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: *A. acqilonium*, *B. aquilonaris*, *C. borealis*, *C. davisiana*, *L. pylomaticus*, *L. heteroporus*, *L. neoheteroporus*, and *S. universus*.

***Hexacontium parviakitaensis* Interval Subzone (herein)**

Top: FCO of *Cycladophora davisiana*.

Base: LO of *Dictyophimus bullatus*.

Magnetochronologic 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 *L. neoheteroporus*.

Remarks: The *H. parviakitaensis* subzone is correlated with the upper part of the *Axoprunum acquilonium* Zone of Shilov (1995), that is the interval from the FO of *C. davisiana* (top) to the LO of *Lipmanella redondoensis* (base) (Figure 4). *H. parviakitaensis* (=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: *A. acquilonium*, *C. sphaeris*, *H. parviakitaensis*, *L. pylomaticus*, *L. heteroporus*, and *S. universus*.

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

Top: LO of *Dictyophimus bullatus*.

Base: FO of *Dictyophimus bullatus*.

Magnetochronologic 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: *D. bullatus* is generally rare throughout this zone (Appendix). Its taxon range appears to be diachronous across latitude in the North Pacific. *D. 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 latitude of the central North Pacific, with an age of 5.6-4.2 Ma (Morley and Nigrini, 1995); Site 1021 is in the middle latitude 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 bioevents, and that reversal records were not well identified from the Subchronozne 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 *A. acqilonium* Zone of Shilov (1995).

This zone contains the following species: *A. acqilonium*, *C. sphaeris*, *D. bullatus*, *L. pylomaticus*, *L. heteroporus*, and *S. universus*.

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

Top: FO of *Dictyophimus bullatus*.

Base: FO of *Larcopyle pylomaticus*.

Magnetochronologic 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 *L. 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 *A. acqilonium* Zone to the upper part of the *A. acqilonium-L. redondoensis* Zone of Shilov (1995) (Figure 4). The FO of *Lamprocyclis heteroporus* is near the FO of *L. pylomaticus* in the middle latitude of 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. heteroporus* at Sites 884 and 887 in the high latitude of 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 *E. matuyamai* Zone (*ca.* 1.5 Ma) at Sites 884 and 887 in the high latitudes of the North Pacific (Kamikuri, 2010), and the *Pterocanium prismatum* 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 *L. redondoensis*.

***Lamprocyclas hannai* Interval Subzone (herein)**

Top: FO of *Dictyophimus bullatus*.

Base: LO of *Lipmanella redondoensis*.

Magnetochronologic 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 *C. davisiana* (top) to LO of *L. redondoensis* (base) as the *A. acqilonium* 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 *A. acqilonium* Zone of Shilov (1995).

This subzone contains the following species: *A. acqilonium*, *C. sphaeris*, *L. pylomaticus*, *L. heteroporos*, *S. delmontensis*, *S. peregrina*, and *S. universus*.

***Lithelius klingi* Interval Subzone (herein)**

Top: LO of *Lipmanella redondoensis*.

Base: FO of *Larcopyle pylomaticus*.

Magnetochronologic 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 *L. redondoensis* (top), and FO of *A. acqilonium* (base) as the *A. acqilonium-L. redondoensis* Zone (Figure 4). The *L. klingi* Subzone is correlated with the interval from the upper part of the *A. acqilonium-L. redondoensis* Zone of Shilov (1995).

This subzone contains the following species: *A. acqilonium*, *C. sphaeris*, *L.*

pylomaticus, *L. heteroporos*, *L. redondoensis*, *L. klingi*, *S. 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*.

Magnetostratigraphic 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 *L. redondoensis* (top) to the FO of *A. 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. acquilonium*, 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 *S. 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 *A. acquilonium-L. redondoensis* Zone is correlated with the interval from the *A. acquilonium* Zone to the *Lipmanella redondoensis* Zone, that were proposed by Motoyama (1996) and Kamikuri *et al.* (2004) for the high latitudes of the North Pacific.

Lychnocanoma parallelopipes 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*.

Magnetochronologic 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 *L. heteroporus*, LOs of *Dictyophimus splendens* and *Larcospira moschkovskii*, and LCO of *L. redondoensis*.

Remarks: The LO of *Lychnocanoma nipponica*, that defines 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 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: *A. acqilonium*, *C. sphaeris*, *L. klingi*, *L. redondoensis*, *S. peregrina*, and *S. universus*.

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

herein)

Top: LO of *Lychnocanoma nipponica*.

Base: LO of *Cycladophora cabrilloensis*.

Magnetochronologic 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 amphistylum* and *Didymocyrtis penultima*.

Remarks: The *L. 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: *A. acqilonium*, *C. sphaeris*, *D. splendens*, *L. klingi*, *L. nipponica*, *L. redondoensis*, *S. peregrina*, and *S. universus*.

Cycladophora cabrilloensis Interval Subzone (herein)

Top: LO of *Cycladophora cabrilloensis*.

Base: FO of *Axoprunum acqilonius*.

Magnetochronologic 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: *C. 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; Lombardi and Lazarus, 1988). This subzone contains the following species: *A. acqilonius*, *A. amphistylum*, *C. cabrilloensis*, *D. penultima*, *D. splendens*, *L. klingi*, *L. nipponica*, *L. redondoensis*, *S. delmontensis*, and *S. universus*.

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

Top: FO of *Axoprunum acquilonium*.

Base: LO of *Lychnocanoma magnacornuta*.

Magnetochronologic 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 FO of *C. 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 *L. redondoensis* for a biofacies, this biofacies is different from the zone proposed by Shilov (1995).

This zone contains the following species: *L. klingi*, *L. moschkovskii*, *L. redondoensis*, and *S. universus*.

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

Top: LO of *Lychnocanoma magnacornuta*.

Base: FO of *Lychnocanoma magnacornuta*.

Magnetochronologic 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 *L. 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*.

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

Age: Late Miocene (10.2 to 9.1 Ma).

Radiolarian events: FOs of *D. antepenultima*, *D. 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 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 *L. 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 latitude of the eastern North Pacific.

This subzone contains the following species: *C. cabrilloensis*, *C. reynoldsi*, *Dendrospyris* aff. *bursa*, *L. klingi*, *L. magnacornuta*, *L. nipponica*, *L. moschkovskii*, *L. redondoensis*, and *S. universus*.

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

Top: LO of *Cyrtocapsella japonica*.

Base: FO of *Lychnocanoma magnacornuta*.

Magnetochronologic calibration: The top of this zone is placed the upper part of C5n.2n, and 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 *Albatrossidium* sp. C, *Collosphaera glebulenta*, *Collosphaera pyloma*, *Cyrtocapsella cornuta*, *Cyrtocapsella tetrapera*, *Eucyrtidium yatsuoense*, *Lamprocyclas margatensis*, *Lipmanella hister*, and *Lithopera renzae*.

Remarks: The LO of *C. 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*, *L. 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: *C. cabrilloensis*, *C. japonica*, *C. pyloma*, *C. reynoldsi*, *Dendrospyris* aff. *bursa*, *L. klingi*, *L. magnacornuta*, *L. nipponica*, *L. redondoensis*, and *S. universus*.

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

Top: FO of *Lychnocanoma magnacornuta*.

Base: FO of *Eucyrtidium inflatum*.

Magnetochronologic calibration: The top of this zone is placed he C5r.3r (this study), and 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 *Albatrossidium* 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: *C. cabrilloensis*, *C. japonica*, *C. reynoldsi*, *E. inflatum*,

L. nipponica, *L. klingi*, *L. redondoensis*, and *S. 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*, *Collospshaera tuberosa*, *Anthocyrtidium angulare*, *Pterocanium prismatum*, and *Phormostichoartus dololum* (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. prismatum* 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 year 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 *Didymocyrtis 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 and Kling, 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, that are the *C. sphaeris* (=*C. sakaii*), *D. bullatus* (=*D. robustus*) and *L. 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, that are 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 cornutooides* Zone of Motoyama (1996)

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

Top: FO of *Lychnocanoma parallelipes*.

Base: LO of *Lychnocanoma magnacornuta*.

Magnetochronologic calibration: The top of this zone is placed the C3Br.2r, and 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 *L. parallelipes* (top) to LCO of *L. magnacornuta* (base) for the subarctic Northwest Pacific. Later, Kamikuri *et al.* (2004) changed the zonal name (*C. cornutoides* Zone) to *L. 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 *A. acqilonium* 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) 66 radiolarian bioevents were recognized since the middle Miocene at Sites 1020/1021.
- 2) 26 radiolarian datum levels, since the latest Miocene, were directly correlated with paleomagnetic stratigraphy. 40 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, that are the *C. sphaeris* (=*C. sakaii*), *D. bullatus* (=*D. robustus*), and *L. 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 *C. funakawai* Zone was proposed for the subarctic Northwest Pacific.

Faunal references (Figures 6, 7, 8, 9)

Amphymenium amphistylum 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, figs. 1a–1d.

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.

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

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

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

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

Diarthus petterssoni (Riedel and Sanfilippo, 1970). Sanfilippo *et al.*, 1985, p. 657, figs. 8.10a, 10b.

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, figs. 8.5a, 5b.

Didymocyrtis penultima (Riedel, 1957). Sanfilippo *et al.*, 1985, p. 658, figs. 8.7a, 7b.

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, figs. 6a, 6b.

Lamprocyclas margatensis (Campbell and Clark, 1944). Sugiyama and Furutani, 1992, p. 207, pl. 18, fig. 7.

Lamprocyrtsis heteroporus (Hays, 1970). Kling, 1973, p. 639, pl. 5, figs. 19–21, pl. 15, fig. 6.

Lamprocyrtsis neoheteroporus 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, figs. 6a–6c, 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, figs. 16.5a, 5b.

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, figs. 16.3a, 3b.

Lychnocanoma magnacornuta Sakai, 1980. Motoyama, 1996, p. 248, pl. 5, figs. 10a–11.

Lychnocanoma nipponica (Nakaseko, 1963) type A: *Lychnocanium nipponicum* Nakaseko, 1963, p. 168, text-fig. 2, pl. 1, figs. 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 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 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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References

- Akers, W. H., Marolt, R. E. and Navarette, R. J., 1987: Late Miocene and early Pliocene siliceous microfossils from the upper Monterey and lower Siaquoc formations, Sweeny Road, Santa Barbara Country, California. *Tulane Studies in Geology and Paleontology*, vol. 20, p. 1–112.
- Barron, J. A., 1998: Late Neogene changes in diatom sedimentation in the North Pacific. *Journal of Asian Earth Sciences*, vol. 16, p. 85–95.
- Barron, J. A. and Baldauf, J. G., 1995: Cenozoic marine diatom biostratigraphy and applications to paleoclimatology and paleoceanography. *Siliceous Microfossils. Paleontological Society, Short Courses in Paleontology*, vol. 8, p. 107–118.
- Barron, J. A. and Gladenkov, A. Y., 1995: Early Miocene to Pleistocene diatom stratigraphy of Leg 145. In, Rea, D. K., Basov, I. A., Scholl, D. W. and Allan, J. F. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 145, p. 3–19. Ocean Drilling Program, College Station, TX.
- Bjørklund, K. R. and Goll, M. R., 1979: Internal skeletal structures of *Collospshaera* and *Trisolenia*: a case of repetitive evolution in the Collosphaeridae (Radiolaria). *Journal of Paleontology*, vol. 53, p. 1293–1326.
- Campbell, A. S. and Clark, B. L., 1944: Miocene radiolarian faunas from Southern California. *Geological Society of America, Special Paper*, vol. 51, p. 1–76.
- Casey, R. E., 1972: Neogene radiolarian biostratigraphy and paleotemperatures: Southern California, the experimental Mohole, and Antarctic Core 14-8. *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 12, p. 115–130.
- Cortese, G., Gersonde, R., Hillenbrand, C.-D. and Kuhn, G., 2004: Opal sedimentation shifts in the World Ocean over the last 15 Myr. *Earth and Planetary Science Letters* vol. 224, p. 509–527.
- Foreman, H. P., 1975: Radiolaria from the North Pacific, Deep Sea Drilling Project, Leg 32. In, Larson, R. L., Moberly, R. et al., *Initial Reports of the Deep Sea Drilling Project*, vol. 32, p. 579–676. U. S. Government Printing Office, Washington, DC.

- Fornaciari, E., 2000: Calcareous nannofossil biostratigraphy of the California margin. In, Lyle, M., Koizumi, I., Richter C. and Moore, T. C., Jr. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 167, p. 3–40. Ocean Drilling Program, College Station, TX.
- Funakawa, S., 1993: Late Miocene radiolarian fossils from eastern Hokkaido, Japan. *News of Osaka Micropaleontologists (NOM), Special Volume*, no. 9, p. 293–311. (in Japanese with English abstract)
- Funakawa, S., 2000: Internal skeletal structures of the Cenozoic genera *Gondwanaria*, *Lipmanella* and *Lithomelissa* (Plagiocanthidae, Nassellaria) and their taxonomy. *Micropaleontology*, vol. 46, p. 97–121.
- Funayama, M., 1988: Miocene radiolarian stratigraphy of the Suza area, northwestern part of the Noto Peninsula, Japan. *Contributions of the Institute of Geology and Paleontology, Tohoku University*, vol. 91, p. 15–41. (in Japanese with English abstract)
- Hays, J. D., 1970: Stratigraphy and evolutionary trends of Radiolaria in North Pacific deep-sea sediments. *Geological Society of America, Memoir*, vol. 126, p. 185–218.
- Hays, J. D. and Shackleton, N. J., 1976: Globally synchronous extinction of the radiolarian *Stylatractus universus*. *Geology*, vol. 4, p. 649–652.
- Ikenoue, T., Takahashi, K., Sakamoto, T., Sakai, S. and Iijima, K., 2011: Occurrences of radiolarian biostratigraphic markers *Lychnocanoma nipponica sakaii* and *Amphimelissa setosa* in Core YK07-12 PC3B from the Okhotsk Sea. *Memoirs of the Faculty of Science, Kyushu University, Series D, Earth and Planetary Sciences*, vol. 32, p. 1–10.
- Johnson, D. A. and Nigrini, C. A., 1980: Radiolarian biogeography in surface of the western Indian Ocean. *Marine Micropaleontology*, vol. 5, p. 111–152.
- Kamikuri, S., 2010: New late Neogene radiolarian species from the middle to high latitudes of the North Pacific. *Revue de Micropaleontologie*, vol. 53, p. 85–106.

- Kamikuri, S., 2012: Evolutionary changes in the biometry of the fossil radiolarian *Stichocorys peregrina* lineage in the eastern equatorial and eastern North Pacific. *Marine Micropaleontology*, vol. 90, p. 13–28.
- Kamikuri, S., Motoyama, I., Nishi, H. and Iwai, M., 2009: Neogene radiolarian biostratigraphy ad faunal evolution rates in the eastern equatorial Pacific ODP Sites 845 and 1241. *Acta Palaeontologica Polonica*, vol. 54, p. 713–742.
- Kamikuri, S., Nishi, H. and Motoyama, I., 2007: Effects of late Neogene climatic cooling on North Pacific radiolarian assemblages and oceanographic conditions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 249, p. 370–392.
- Kamikuri, S., Nishi, H., Motoyama, I. and Saito, S., 2004: Middle Miocene to Pleistocene radiolarian biostratigraphy in the Northwest Pacific Ocean, ODP Leg 186. *Island Arc*, vol. 13, p. 191–226.
- Keller, G. and Barron, J. A., 1983: Paleoceanographic implications of Miocene deep-sea hiatuses. *Geological Society of America Bulletin*, vol. 94, p. 590–613.
- Kennett, J. P., Rozo-Vera, G. A. and Castillo, M., 2000: Latest Neogene planktonic foraminiferal biostratigraphy of the California margin. In, Lyle, M., Koizumi, I., Richter, C. and Moore, T. C., Jr. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 167, p. 41–62. Ocean Drilling Program, College Station, TX.
- Kling, S. A., 1973: Radiolaria from the eastern North Pacific, Deep Sea Drilling Project Leg 18. In, Kulm, L. D., von Huene, R., et al., *Initial Reports of Deep Sea Drilling Project*, vol. 18, p. 617–671. U. S. Government Printing Office, Washington, DC.
- Koizumi, I., 1985: Diatom biochronology for late Cenozoic Northwest Pacific. *Journal of the Geological Society of Japan*, vol. 91, p. 195–211.
- Kruglikova, S. B., 1978: New radiolarian species from the Miocene to Holocene in the equatorial Pacific. In, Zhuze, A. P. ed., *Marine Micropaleontology (Diatoms, Radiolarians, Silicoflagellates, Foraminifers and Calcareous Nannoplanktons)*, p. 87–90 and p. 214–215, pls. 21–27. Akademiya Nauk SSSR, Okeanograficheskaya

Komissiya, Nauka, Moskva. (*in Russian; original title translated*)

- Lazarus, D., Faust, K. and Popova-Goll, I., 2005: New species of prunoid radiolarians from the Antarctic Neogene. *Journal of Micropaleontology*, vol. 24, p. 97–121.
- Ling, H. Y., 1973: Radiolaria: Leg 19 of the Deep Sea Drilling Project. In, Creager, J. S., Scholl D. W. *et al.*, *Initial Reports of the Deep Sea Drilling Project*, vol. 19, p. 777–797. U. S. Government Printing Office, Washington, DC.
- Ling, H. Y., 1980: Radiolarians from the Emperor Seamounts of the Northwest Pacific: Leg 55 of the Deep Sea Drilling Project. In, Jackson, E. D., Koizumi, I. *et al.*, *Initial Reports of the Deep Sea Drilling Project*, vol. 55, p. 365–373. U. S. Government Printing Office, Washington, DC.
- Ikenoue, T., Okazaki, Y., Takahashi, K. and Sakamoto, T., 2016: Bering Sea radiolarian biostratigraphy and paleoceanography at IODP Site U1341 during the last four million years. *Deep-Sea Research II*, vol. 125/126, p. 38–55.
- Lazarus, D., Suzuki, N., Caulet, J.-P., Nigrini, C., Goll, I., Goll, R., Dolven, J. K., Diver, P. and Sanfilippo, A., 2015: An evaluated list of Cenozoic-Recent radiolarian species names (Polycystinea), based on those used in the DSDP, ODP and IODP deep-sea drilling programs. *Zootaxa*, vol. 3999, p. 301–333.
- Lombardi, G. and Lazarus, D. B., 1988: Neogene cycladophorid radiolarians from North Atlantic, Antarctic, and North Pacific deep-sea sediments. *Micropaleontology*, vol. 34, p. 97–135.
- Lyle, M., Koizumi, I., Delaney, M. L. and Barron, J. A., 2000: Sedimentary record of the California current system, middle Miocene to Holocene: A synthesis of Leg 167 results. In, Lyle, M., Koizumi, I., Richter C. and Moore, T. C., Jr. *eds.*, *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 167, p. 341–376. Ocean Drilling Program, College Station, TX.
- Lyle, M., Koizumi, I., Richter, C. *et al.*, 1997: *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 167, p. 1–1378. Ocean Drilling Program, College

Station, TX.

- Maruyama, T., 2000: Middle Miocene to Pleistocene diatom stratigraphy of Leg 167. In, Lyle, M., Koizumi, I., Richter C. and Moore, T. C., Jr. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 167, p. 63–110. Ocean Drilling Program, College Station, TX.
- Matsuzaki, K., Suzuki, N., Nishi, H., Takashima, R., Kawate, Y. and Sakai, T., 2014: 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). *Journal of Micropalaeontology*, vol. 33, p. 205–222.
- Matsuzaki, K., Suzuki, N., Nishi, H., Hayashi, H., Gyawali, B. R., Takashima, R. and Ikebara, M., 2015: Early to Middle Pleistocene paleoceanographic history of southern Japan based on radiolarian data from IODP Exp. 314/315 Sites C0001 and C0002. *Marine Micropalaeontology*, vol. 118, p. 17–33.
- Moore, T. C., Jr., 1995: Radiolarian stratigraphy, Leg 138. In, Pisias, N. G. et al., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 138, p. 191–232. Ocean Drilling Program, College Station, TX.
- Morley, J. J., 1985: Radiolarians from the Northwest Pacific, Deep Sea Drilling Project Leg 86. In, Heath, G. R., Burckle L. H. et al., *Initial Reports of the Deep Sea Drilling Project*, vol. 86, p. 399–422. U. S. Government Printing Office, Washington, DC.
- Morley, J. J. and Nigrini, C., 1995: Miocene to Pleistocene radiolarian biostratigraphy of North Pacific sites 881, 884, 885, 886 and 887. In, Rea, D. K. Basov, I. A., Scholl, D. W. and Allan, J. F. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 145, p. 55–91. Ocean Drilling Program, College Station, TX.
- Morley, J. J. and Shackleton, N. J., 1978: Extension of the radiolarian *Stylatractus universus* as a biostratigraphic datum to the Atlantic Ocean. *Geology*, vol. 6, p. 309–311.

- Motoyama, I., 1996: Late Neogene radiolarian biostratigraphy in the subarctic Northwest Pacific. *Micropaleontology*, vol. 42, p. 221–262.
- Motoyama, I., 1997: Origin and evolution of *Cycladophora davisiana* Ehrenberg (Radiolaria) in DSDP Site 192, Northwest Pacific. *Marine Micropaleontology*, vol. 30, p. 45–63.
- Motoyama, I. and Maruyama, T., 1996: Integrated radiolarian and diatom biostratigraphy of the Neogene strata in the Tsugaru Peninsula, Aomori Prefecture, northern Honshu, Japan. *Journal of the Geological Society of Japan*, vol. 102, 481–499. (in Japanese with English abstract)
- Motoyama, I. and Maruyama, T., 1998: Neogene diatom and radiolarian biochronology for the middle-to-high latitudes of the Northwest Pacific region: Calibration to the Cande and Kent's geomagnetic polarity time scales (CK 92 and CK 95). *Journal of the Geological Society of Japan*, vol. 104, p. 171–183. (in Japanese with English abstract)
- Motoyama, I., Niitsuma, N., Maruyama, T., Hayashi, H., Kamikuri, S., Shiono, M., Kanamatsu, T., Aoki, K., Morishita, C., Hagino, K., Nishi, H. and Oda, M., 2004: Middle Miocene to Pleistocene magneto-biostratigraphy of ODP Sites 1150 and 1151, northwest Pacific: Sedimentation rate and updated regional geological timescale. *Island Arc*, vol. 13, p. 289–305.
- Mullineaux, L. S. and Westberg-Smith, M. J., 1986: Radiolarians as paleoceanographic indicators in the Miocene Monterey Formation, Upper Newport Bay, California. *Micropaleontology*, vol. 32, p. 48–71.
- Nakaseko, K., 1954: Preliminary report of Miocene radiolarian faunas from southern Toyama Prefecture (Micro-biostratigraphic study of the Cenozoic strata in Japan, part 5). *Science Reports, South and North College, Osaka University*, vol. 3, p. 107–124.

- Nakaseko, K., 1963: Neogene Cyrtoidia (Radiolaria) from the Isozaki Formation in Ibaraki Prefecture, Japan. *Science Reports, College of General Education, Osaka University*, vol. 12, p. 165–198.
- Nakaseko, K. and Sugano, K., 1972: Radiolarian biostratigraphy in the oil bearing regions of Honshu, Japan. *Journal of the Japanese Association for Petroleum Technology*, vol. 37, p. 375–384. (in Japanese)
- Nakaseko, K. and Sugano, K., 1973: Neogene radiolarian zonation in Japan. *The memoirs of the Geological Society of Japan*, no. 8, p. 23–34. (in Japanese with English abstract)
- Nigrini, C., 1977: Tropical Cenozoic Artostrobiidae (Radiolaria). *Micropaleontology*, vol. 23, p. 241–269.
- Nigrini, C. and Moore, T. C. Jr., 1979: A guide to modern Radiolaria. *Cushman Foundation Foraminiferal Research, Special Publication*, vol. 16, p. S1–S142 and N1–N106.
- Ogg, J. G., 2012: Geomagnetic polarity time scale. In, Gradstein, F. M., Ogg, J. G., Schmitz, M., Ogg, G. eds., *The Geologic Time Scale 2012*, p. 85–113. Elsevier, BV.
- Oseki, S. and Suzuki, N., 2009: Miocene to Pleistocene paleogeographic distributions of polycystine radiolarians in the North Pacific. *News of Osaka Micropaleontologists (NOM), Special Volume*, no. 14, p. 183–238.
- Perez-Guzman, A. M., 1985: Radiolarian biostratigraphy of the late Miocene in Baja California and the Tres Marias Islands, Mexico. *Micropaleontology*, vol. 31, p. 320–334.
- Perez-Guzman, A. M. and Casey, R. E., 1986: Paleoceanographic reconstructions from radiolarian-bearing Baja California and adjacent sections. *The Monterey Formation and Related Siliceous Rocks of California: Society of Economic Paleontologist and Mineralogists, Special Publication*, vol. 45, p. 55–68.

- Poore, R. Z., McDougall J. A., Barron, J. A., Brabb, E. E. and Kling, S. A., 1981: Microfossil biostratigraphy and biochronology of the type Relizian and Luisian stages of California. In, Garrison, R. E. and Douglas, R. G. eds., *The Monterey Formation and Related Siliceous Rocks of California: Society of Economic Paleontologist and Mineralogists, Special Publication*, vol. 15, p. 15–41.
- Popova, I., 1989: New insight on the systematics of some Theopiliinae (Radiolaria). In, Anonymous ed., *Paleontologo-Stratigraphicheskie Issledovaniya Fanerozooya, Dal'nego Vostoka*, p. 68–77, p. 131, and p. 143–145. Dal'nevostochniy Otdel Akademii Nauk SSSR, Vladivostok. (in Russian; original title translated)
- Reynolds, R. A., 1980: Radiolarians from the western North Pacific, Leg 57, Deep Sea Drilling Project. In, Scientific Party, *Initial Reports of the Deep Sea Drilling Project*, vols. 56–57, p. 735–769. U. S. Government Printing Office, Washington, DC.
- Riedel, W. R. and Sanfilippo, A., 1970: Radiolaria, Leg 4, Deep Sea Drilling Project. In, Bader, R. G., Gerard, R. D. et al., *Initial Reports of Deep Sea Drilling Project*, vol. 4, p. 503–575. U. S. Government Printing Office, Washington, DC.
- Riedel, W. R. and Sanfilippo, A., 1978: Stratigraphy and evolution of tropical Cenozoic radiolarians. *Micropaleontology*, vol. 24, p. 61–96.
- Robertson, J. H., 1975: Glacial to interglacial Oceanographic changes in the northwest Pacific, including a continuous record of the last 400,000 years [Ph.D. thesis], p. 1–355. Columbia University, New York.
- Rowell, H. C., 1981: Diatom biostratigraphy of the Monterey Formation, Palos Verdes Hills, California. In, Garrison, R. E. and Douglas, R. G. eds., *The Monterey Formation and Related Siliceous Rocks of California: Society of Economic Paleontologist and Mineralogists, Special Publication*, vol. 15, p. 55–70.
- Runeva, N. P., 1984: Late Cenozoic radiolarians from the Northern Sakhalin. In, Petrushevskaya, M. G. and Stepanjants, S. D. eds., *Morphology, Ecology and Evolution of Radiolarians*, p. 223–233. Leningrad (Nauka).

- Sakai, T., 1980: Radiolarians from Sites 434, 435, and 436, Northwest Pacific, Leg 56, Deep Sea Drilling Project. In, Scientific Party, *Initial Reports of the Deep Sea Drilling Project*, vols. 56–57, p. 695–733. U. S. Government Printing Office, Washington, DC.
- Sanfilippo, A. and Nigrini, C., 1998: Code numbers for Cenozoic low latitude radiolarian biostratigraphic zones and GPTS conversion tables. *Marine Micropaleontology*, vol. 33, p. 109–156.
- Sanfilippo, A. and Riedel, W. R., 1970: Post-Eocene “closed” theoperid radiolarians. *Micropaleontology*, vol. 16, p. 446–462.
- Sanfilippo, A., Westberg-Smith, M. J. and Riedel, W. R., 1985: Cenozoic radiolaria. In, Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K. eds., *Plankton Stratigraphy*, p. 631–712. Cambridge University Press, Cambridge, UK.
- Sawada, T., Shindo, R., Motoyama, I. and Kameo, K., 2009: Geology and radiolarian biostratigraphy of the Miocene and Pliocene Series exposed along the Koitogawa River, Boso Peninsula, Japan. *Journal of Geological Society of Japan*, vol. 115, p. 206–222.
- Shilov, V. V., 1995: Miocene - Pleistocene radiolarians from Leg 145, North Pacific. In, Rea, D. K. Basov, I. A., Scholl, D. W. and Allan, J. F. eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 145, p. 93–116. Ocean Drilling Program, College Station, TX.
- Shinzawa, M., Kamikuri, S. and Motoyama, I., 2009: Radiolarian fossils from the Miocene Series in the Hobetsu area, southern central Hokkaido, Japan. *News of Osaka Micropaleontologists (NOM), Special Volume*, no. 14, p. 117–141.
- Sono, A., Suzuki, N., Yoshimura, E., Kano, H. and Takeda, K., 2009: Radiolarian faunal changes in the mid-latitudinal North Pacific over the past 6.4 m.y. (ODP Leg 198 Site 1210, Shatsky Rise). *News of Osaka Micropaleontologists (NOM), Special Volume*, no. 14, p. 143–181.

- Spencer-Cervato, C., Lazarus, D. B., Beckmann, J. -P., von Salis Perch-Nielsen, K. and Biolzi, M., 1993: New calibration of Neogene radiolarian events in the North Pacific. *Marine Micropaleontology*, vol. 21, p. 261–293.
- Sugano, K., 1986: On the reposition of radiolarian fossil. *News of Osaka Micropaleontologists (NOM), Special Volume*, no. 7, p. 131–139.
- Sugiyama, K. and Furutani, H., 1992: Middle Miocene radiolarians from the Oidawara Formation, Mizunami Group, Gifu Prefecture, central Japan. *Bulletin of the Mizunami Fossil Museum*, vol. 19, p. 199–213.
- Tochilina, S. V., Bagina, N. K., Popova, I. M. and Remizovskiy, V. I., 1988: *The Upper Cenozoic in South Sakhalin. IGCP Project 246*, 76 p. Akademiya Nauka SSSR, Dal'nevostochnoe Otdelenie, Tikhookeanskiy Okeanologicheskiy Institut i Dal'nevostochniy Geologicheskiy Institut, Vladivostok. (in Russian; original title translated)
- Tochilina, S. V., 1996: On the problem of the systematics of Nassellaria (Radiolaria). Biochemical Peculiarities. *Evolution*, 51p. Far Eastern Branch of Russian Academy of Sciences, Oceanological Institute, Vladivostok.
- Vitukhin, D. I., 1993: Raschlenenie kainozoya Dalnego Bostoka Rossii po radiolariyam. *Geologicheskii Institut, Rossiskaya Akademiya Nauk, Trudi*, vol. 485, p. 1–104. (in Russian with English abstract)
- Weaver, F. M., Casey, R. E. and Perez, A. M., 1981: Stratigraphic and paleoceanographic significance of early Pliocene to middle Miocene radiolarian assemblages from Northern to Baja California. In, Garrison, G. and Douglas, R. E. eds., *The Monterey Formation and related siliceous rocks of California*, p. 71–86. Society of Economic Paleontologists and Mineralogists, Los Angeles, California.
- Wolfart, R., 1981: Neogene radiolarians from the eastern North Pacific (off Alta and Baja California), Deep Sea Drilling Project Leg 63. In, Yeats, R. S., Haq, B. U. et

- al.*, *Initial Reports of the Deep Sea Drilling Project*, vol. 63, p. 473–506. U. S. Government Printing Office, Washington, DC.
- Yanagisawa, Y. and Akiba, F., 1998: Refined diatom biostratigraphy for the northwest Pacific around Japan, with an introduction of code numbers for selected diatom biohorizons. *Journal of the Geological Society of Japan*, vol. 104, p. 395–414.
- Yanchenko, E. and Gorbarenko, S., 2015: Radiolarian responses of the central Okhotsk Sea to the global orbital and millennial scale climate oscillations over last 90 kyr. *Journal of Asian Earth Sciences*, vol. 114, p. 601–610.

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Captions.

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

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

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.

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

Figure 5. Radiolarian datum levels of Sites 1150 and 1151 in the middle latitude of Northwest Pacific (Kamikuri *et al.*, 2004), Sites 884 and 887 in the high latitude of 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).

Figure 6. Photographs of selected radiolarian species identified during this study. **1a, b**, *Lychnocanoma nipponica* (Nakaseko) type A, Sample 165-1021B-32X-6, 20-22 cm, sl. 1, Z47/2; **2a, b**, *Lychnocanoma nipponica* (Nakaseko) type B, Sample 165-1021B-26X-4, 70-72 cm, sl. 1, J50/2; **3a, b**, *Lychnocanoma magnacornuta* Sakai, Sample 165-1021B-28X-6, 20-22 cm, sl. 1, H19/4; **4a, b**, *Lychnocanoma sakaii* Morley and Nigrini (juvenile form), Sample 165-1020B-2H-2, 20-22 cm, sl. 1, N31/0; **5a, b**, *Dictyophimus splendens* (Campbell and Clark), Sample 165-1021B-32X-6, 20-22 cm, sl. 1, H47/0; **6a, b**, *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. **1a, b**, *Stichocorys peregrina* (Riedel), Sample 165-1021B-28X-6, 20-22 cm, sl. 1, W43/3;

2a, b, *Stichocorys delmontensis* (Campbell and Clark), Sample 165-1021B-26X-4, 70-72 cm, sl. 1, O43/1; **3a, b**, *Eucyrtidium yatsuoense* Nakaseko, Sample 165-1021B-33X-2, 120-122 cm, sl. 1, V32/0; **4a, b**, *Cyrtocapsella tetraperata* Haeckel, Sample 165-1021B-33X-2, 120-122 cm, sl. 1, X37/4; **5a, 5b**, *Cyrtocapsella japonica* (Nakaseko), Sample 165-1021B-33X-2, 120-122 cm, sl. 1, X46/2; **6a, 6b**, *Eucyrtidium inflatum* Kling, Sample 165-1021B-33X-2, 120-122 cm, sl. 1, K28/3; **7a, b**, *Lithopera thornburgi* Sanfilippo and Riedel, Sample 165-1021B-32X-6, 20-22 cm, sl. 1, Z50/2; **8a, b**, *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; **10a, b**, *Lithopera neotera* Sanfilippo and Riedel, Sample 165-1021B-32X-6, 20-22 cm, sl. 1, Q50/0; **11a, b**, *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. **1a, b**, *Albatrossidium* sp. A, Sample 165-1021B-32X-6, 20-22 cm, sl. 1, R51/0; **2a, b**, *Lamprocyclas margatensis* (Campbell and Clark) type B, Sample 165-1021B-33X-2, 120-122 cm, sl. 1, Y35/2; **3a, b**, *Lamprocyclas margatensis* (Campbell and Clark) type A, Sample 165-1021B-32X-6, 20-22 cm, sl. 1, N41/0; **4a, b**, *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.

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**, *Dydyomocyrtis* sp. D, Sample 165-1021B-26X-6, 20-22 cm, sl. 1, U41/0; **7a, b**, *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 amphistylum* Haeckel, Sample 165-1021B-33X-2, 120-122 cm, sl. 1, C40/4; **11a, b**, *Collospshaera 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; **14a, b**, *Collospshaera pyloma* Reynolds, Sample 165-1021B-32X-4, 20-22 cm, sl. 1, O28/2; **15a, b**, *Axoprunum bispiculum* (Popofsky), Sample 165-1021B-28X-6, 20-22 cm, sl. 1, H23/3.

Table 1. Age of selected late Neogene radiolarian bioevents.

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

Appendix. Stratigraphic distribution of selected radiolarian taxa at Sites 1020/1021.

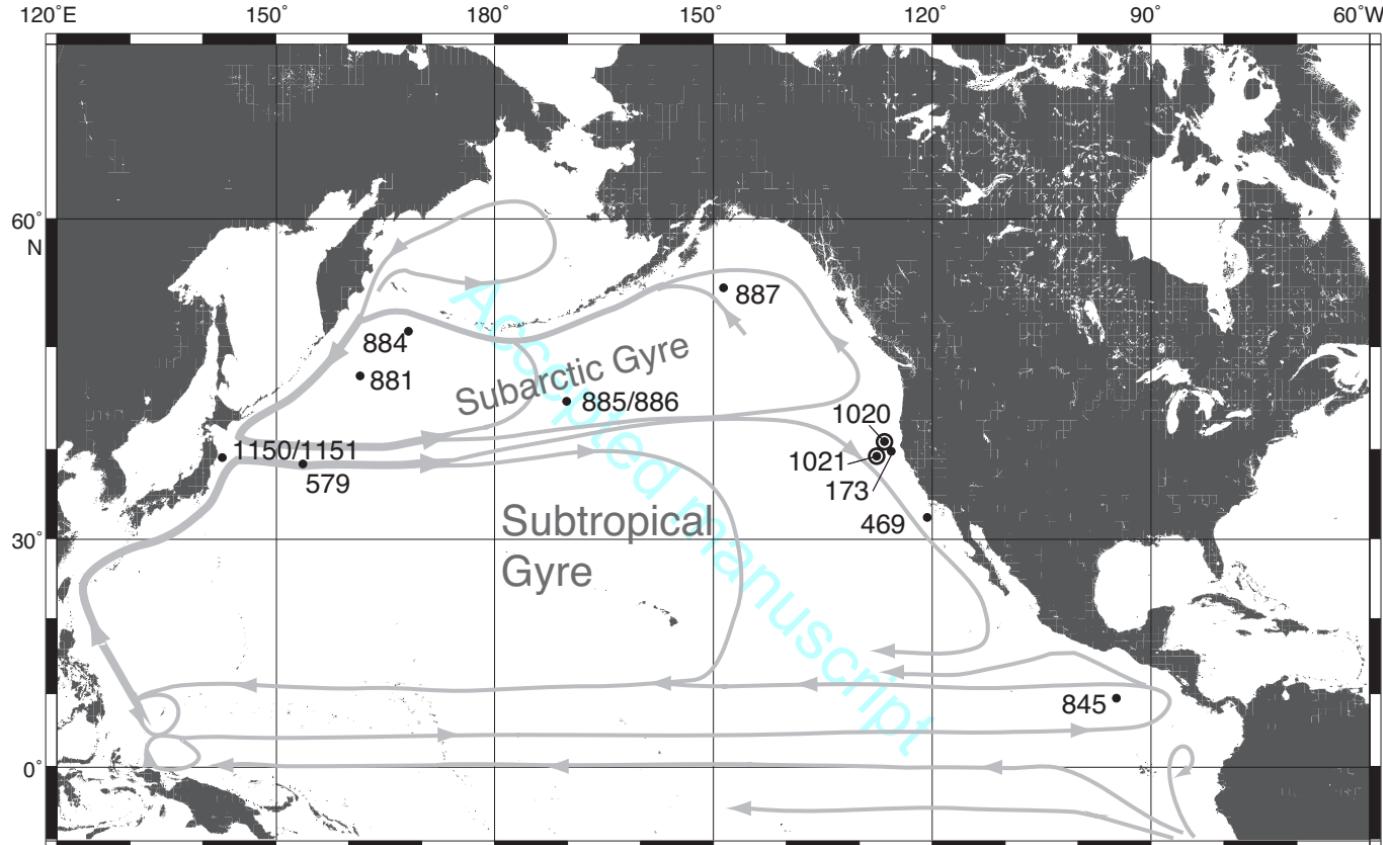


Fig. 1 Kamikuri

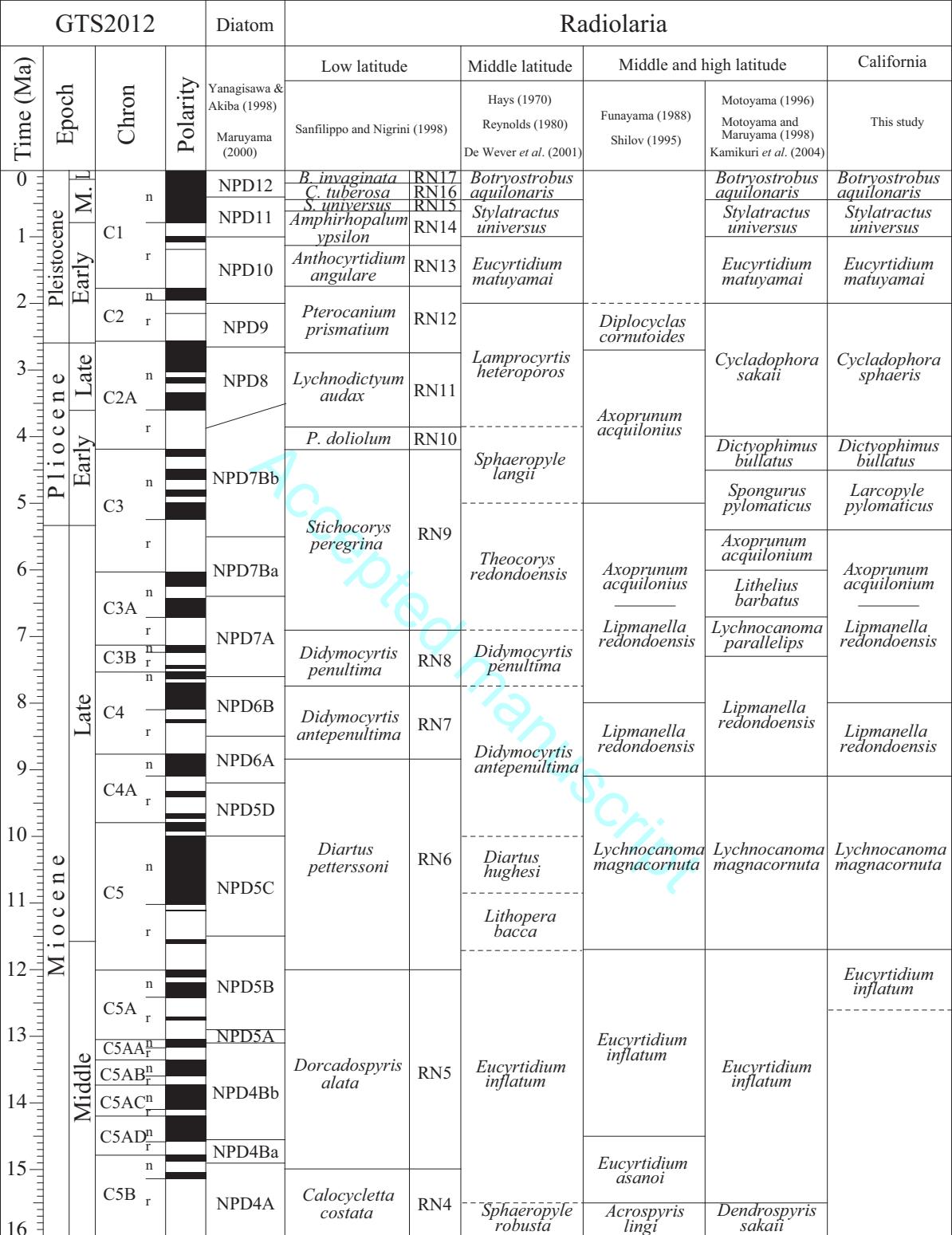


Fig. 2 Kamikuri

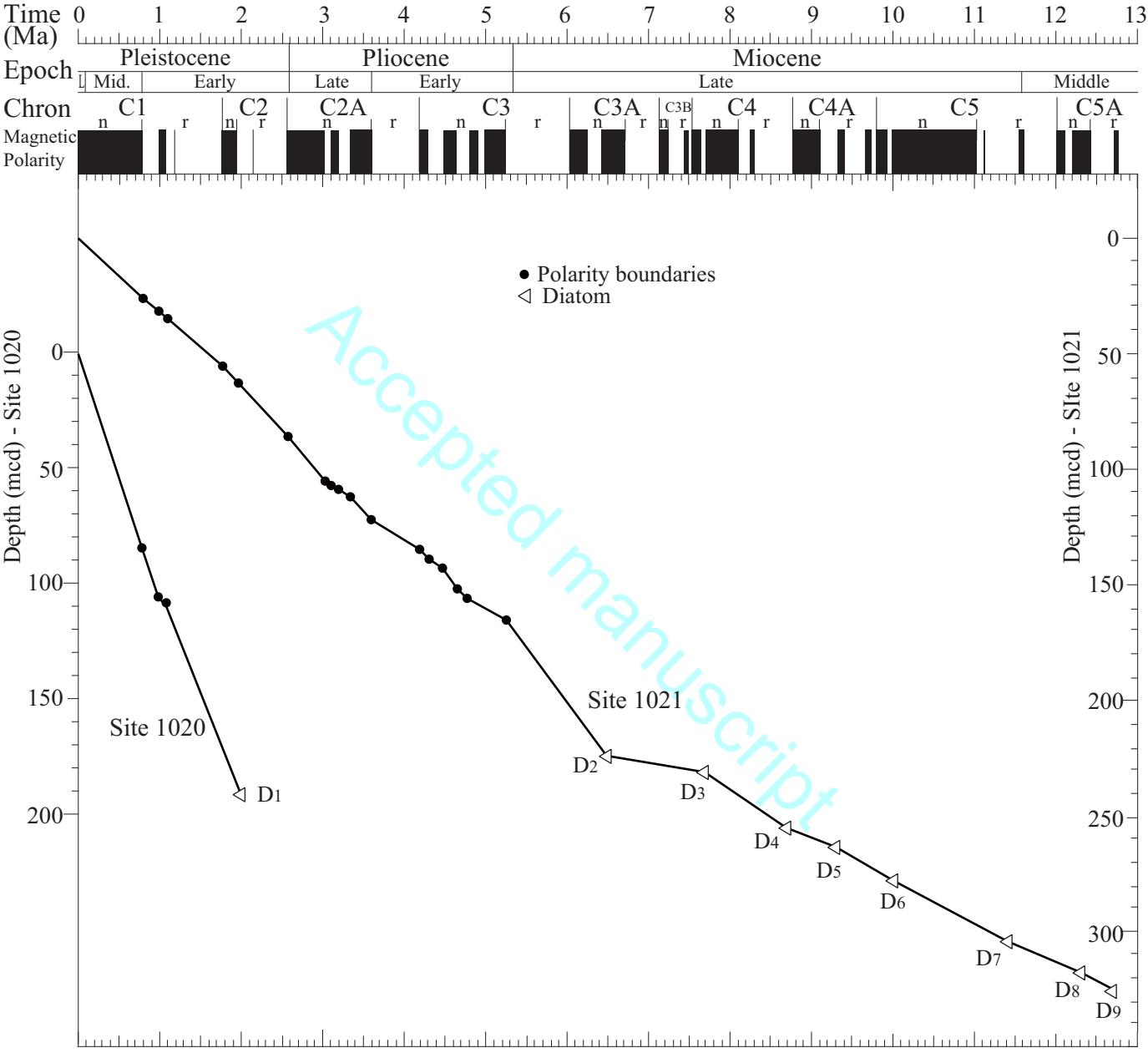


Fig. 3 Kamikuri

Middle and high latitude

California

Radiolarian zones

Primary events

<i>Diplocyclas cornutoides</i>	<i>Botryostrobus aquilonaris</i>	<i>Botryostrobus aquilonaris</i>	LO <i>Stylatractus universus</i> (0.4)
	<i>Stylatractus universus</i>	<i>Stylatractus universus</i>	LO <i>Eucyrtidium matuyamai</i> (1.0)
	<i>Eucyrtidium matuyamai</i>	<i>Eucyrtidium matuyamai</i>	FO <i>Eucyrtidium matuyamai</i> (1.9)
<i>Axoprunum acquilonius</i>	<i>Cycladophora sakaii</i>	<i>Cycladophora sphaeris</i>	FCO <i>Cycladophora davisiana</i> (2.7)
		<i>Hexacontium dionysus</i>	ET <i>Cycladophora davisiana</i> (2.7)
	<i>Dictyophimus bullatus</i>	<i>Dictyophimus bullatus</i>	LO <i>Dictyophimus bullatus</i> (4.0)
	<i>Larcopyle pylomaticus</i>	<i>Larcopyle pylomaticus</i>	FO <i>Dictyophimus bullatus</i> (4.5)
<i>Axoprunum acquilonius</i>	<i>Axoprunum acquilonium</i>	<i>Lamprocyclas hannai</i>	LO <i>Lipmanella redondoensis</i> (5.1)
<i>Lipmanella redondoensis</i>	<i>Lithelius barbatus</i>	<i>Lithelius klingi</i>	FO <i>Larcopyle pylomaticus</i> (5.4)
	<i>Lychnocanoma parallelipipes</i>	<i>Dictyophimus splendens</i>	LO <i>Lychnocanoma nipponica</i> (6.2)
	<i>Lipmanella redondoensis</i>	<i>Axoprunum acquilonium</i>	LO <i>Cycladophora cabrilloensis</i> (7.0)
		<i>Lipmanella redondoensis</i>	FO <i>Axoprunum acquilonium</i> (8.0)
<i>Lipmanella redondoensis</i>		<i>Lychnocanoma magnacornuta</i>	LO <i>Lychnocanoma magnacornuta</i> (9.1)
<i>Lychnocanoma magnacornuta</i>	<i>Lychnocanoma magnacornuta</i>	<i>Collosphaera reynoldsi</i>	LO <i>Cyrtocapsella japonica</i> (10.2)
<i>Eucyrtidium inflatum</i>	<i>Eucyrtidium inflatum</i>	<i>Cyrtocapsella japonica</i>	FO <i>Lychnocanoma magnacornuta</i> (11.9)

Fig. 4 Kamikuri

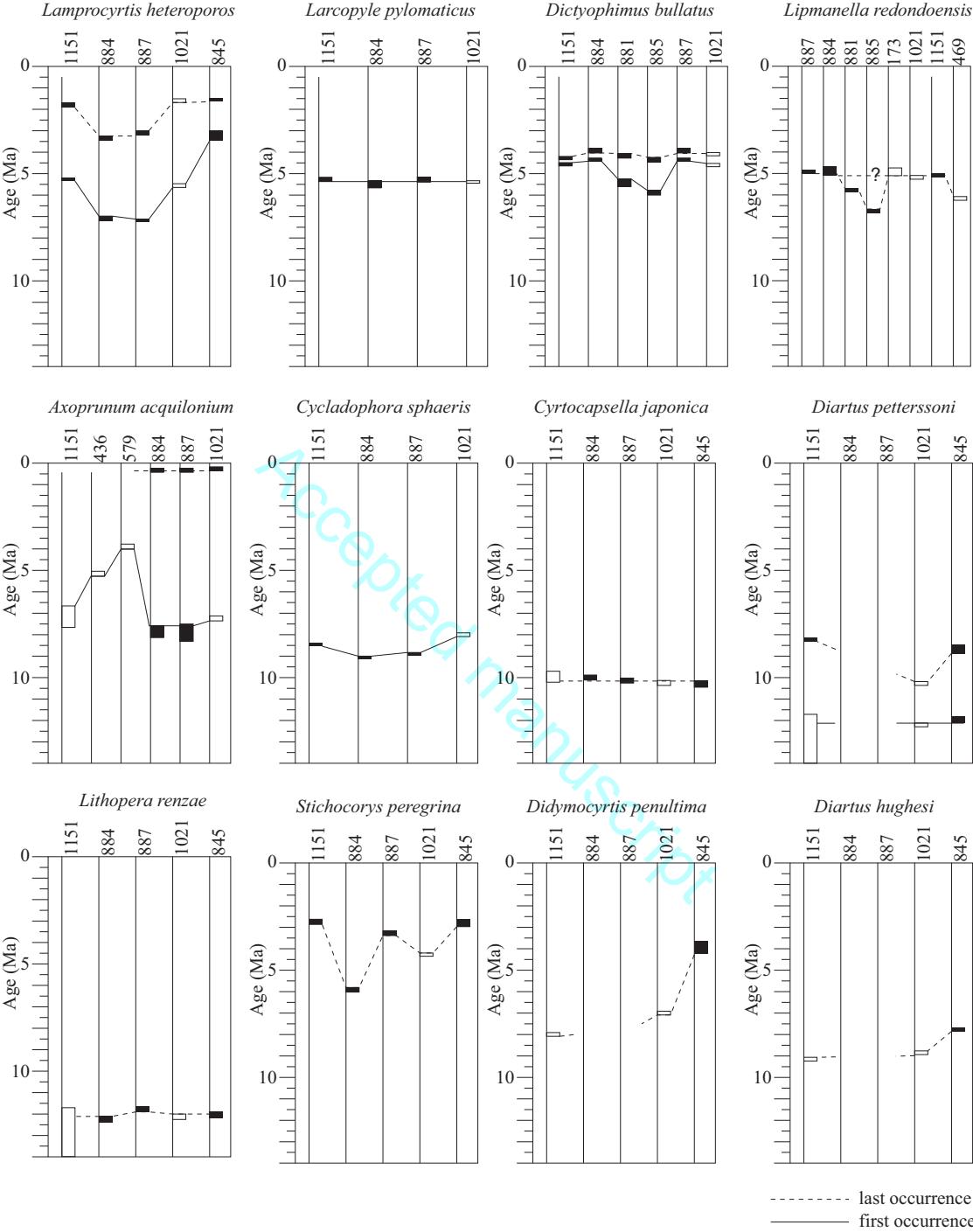


Fig. 5 Kamikuri

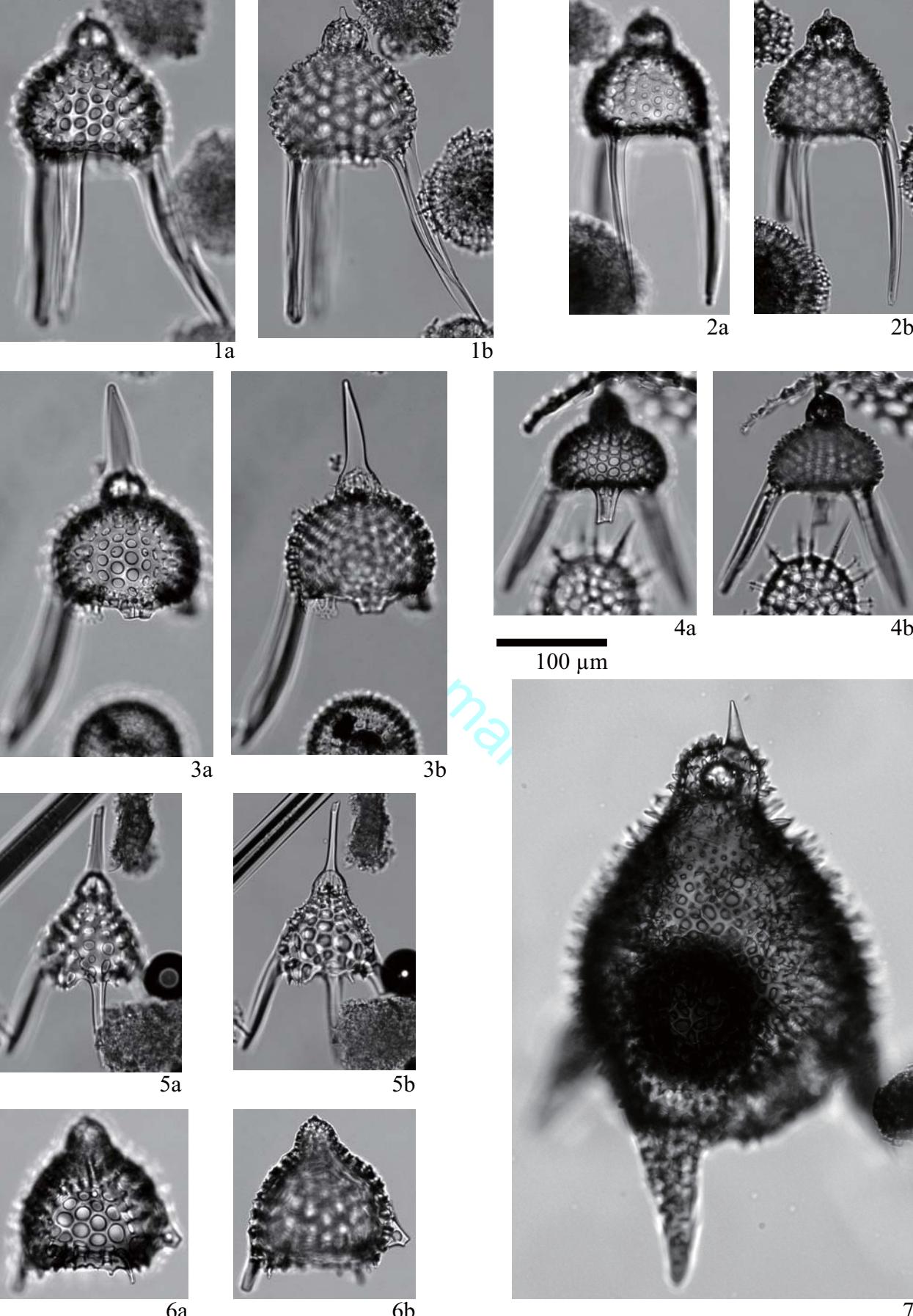


Fig. 6 Kamikuri

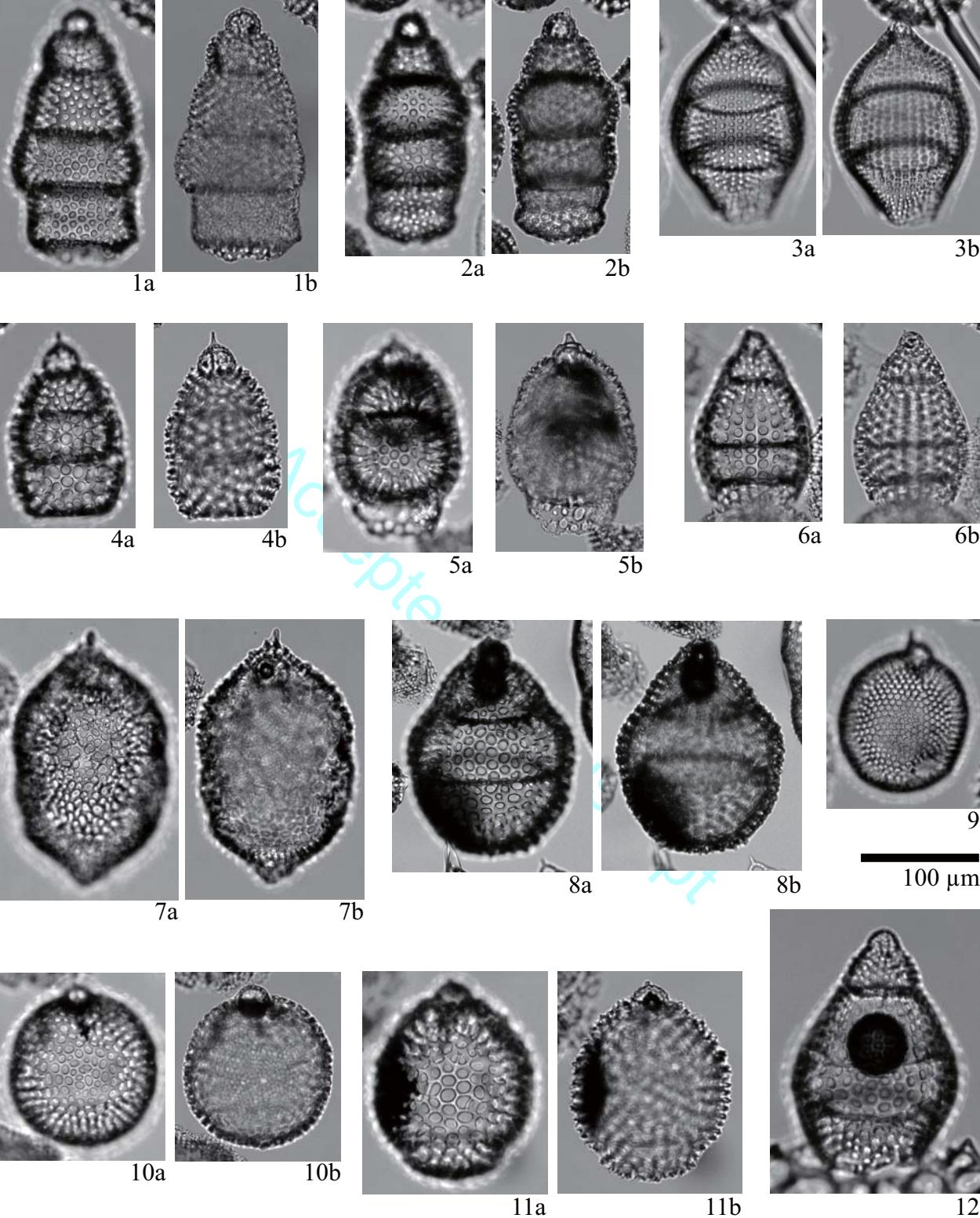


Fig. 7 Kamikuri

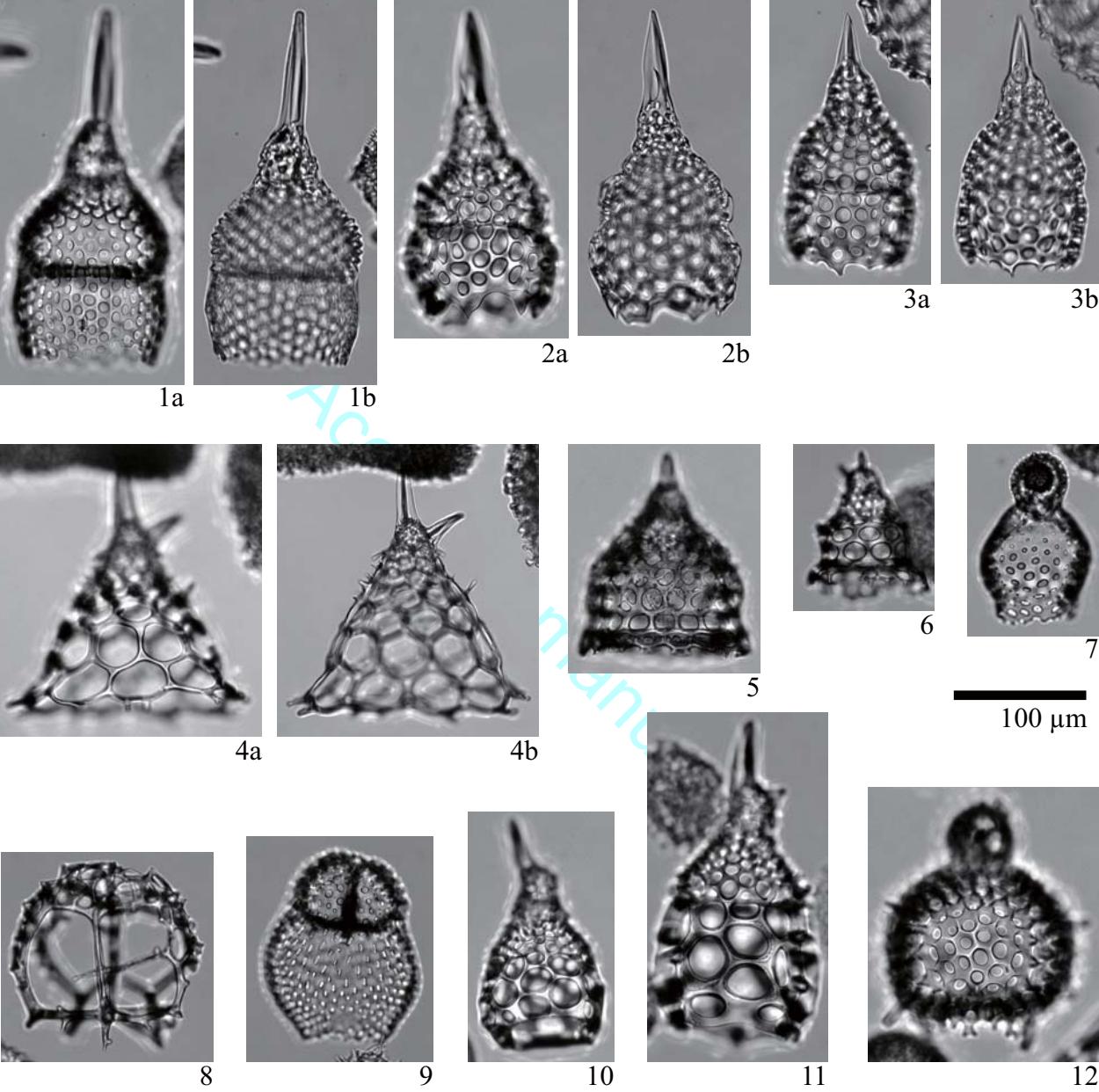


Fig. 8 Kamikuri

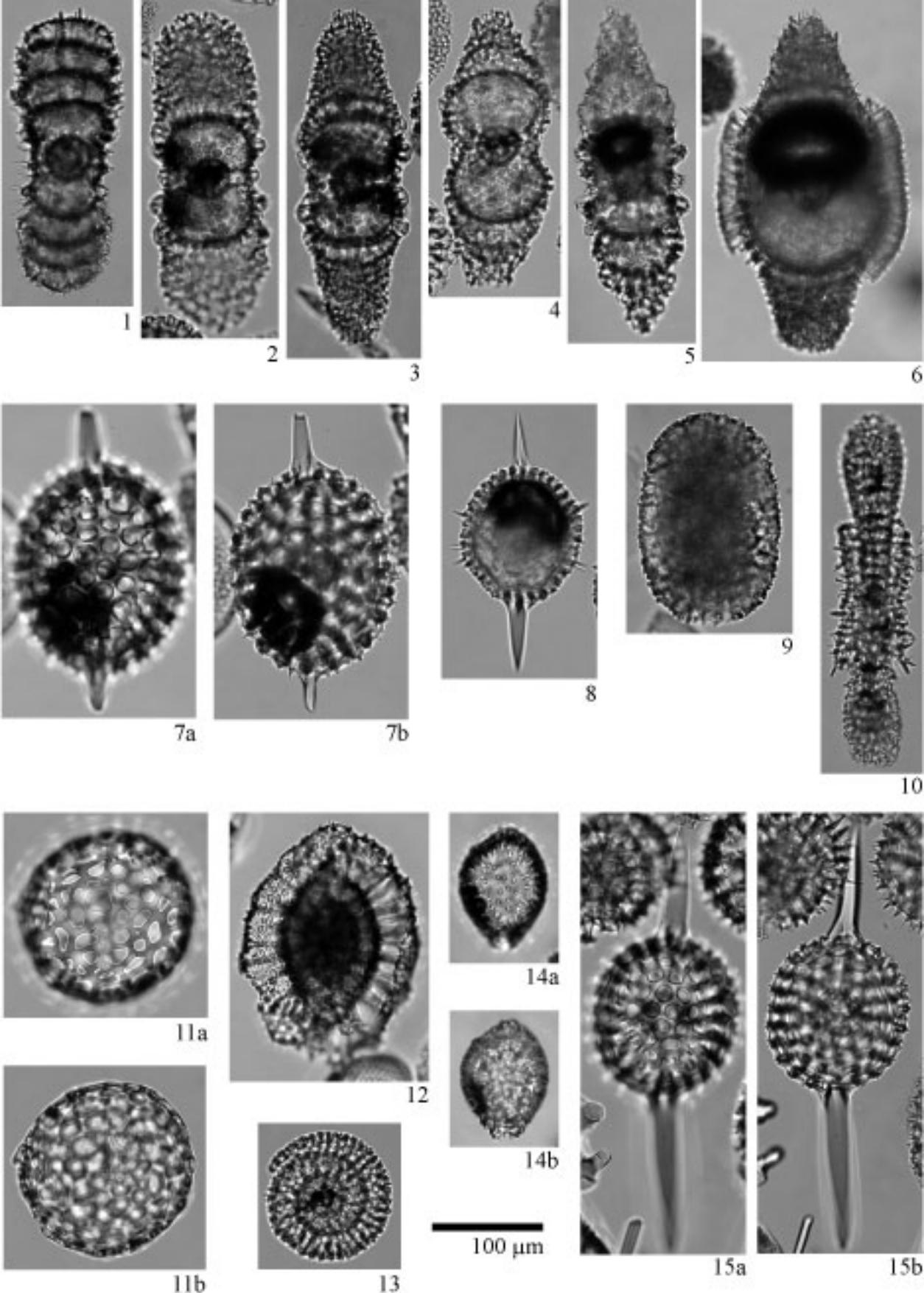


Fig. 9 Kamikuri

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

Magneto–biostratigraphic events		Age(Ma)	Site 1021 GTS2012 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 <i>Neodenticula koizumii</i>	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 <i>Rouxia californica</i>	6.5	223.66	
D ₃	LCO <i>Thalassionema schraderi</i>	7.7	230.26	
D ₄	LCO <i>Denticulopsis simonsenii</i>	8.7	253.29	
D ₅	LO <i>Denticulopsis dimorpha</i>	9.3	262.08	
D ₆	FO <i>Denticulopsis dimorpha</i>	10.0	278.29	
D ₇	LCO <i>Denticulopsis praedimorpha</i>	11.4	304.61	
D ₈	LO <i>Crucidenticula nicobarica</i>	12.3	319.84	
D ₉	FO <i>Denticulopsis praedimorpha</i>	12.7	<325.61	

