Neogene radiolarian biostratigraphy and faunal evolution rates in the eastern equatorial Pacific ODP Sites 845 and 1241

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Radiolarians from Sites 845 and 1241 in the eastern equatorial Pacific were examined in order to evaluate the role of paleoceanographic perturbations upon the general faunal evolutionary pattern of tropical planktonic organisms during the last 17 Ma. Radiolarian appearance and extinction rates indicate no periods of mass extinctions during the past 17 Ma. However, a relatively rapid replacement of the species in the radiolarian assemblages occurs near the middle–late Miocene boundary. This replacement event represents the gradual extinction of a number of radiolarian species and their gradual replacement by evolving new species. The modern equatorial circulation system was formed near the middle–late Miocene boundary due to the closure of the Indonesian seaway. The minor faunal turnover appears to be associated with the formation of the modern equatorial circulation system near the middle–late Miocene boundary. Diatom assemblages in the equatorial Pacific became more provincial in character after about 9 Ma. The appearance and extinction rates of planktic foraminifers were relatively high near the middle–late Miocene boundary, and those of calcareous nannoplankton reached high values in the early late Miocene in the equatorial Pacific Ocean. Thus, faunal evolution from the middle Miocene type to late Miocene types occurred first, being followed by floral evolution. The middle–late Miocene boundary is not a sharp boundary for planktonic microfossils, but marks a time of transition critical for faunal and floral evolution in both siliceous and calcareous microfossil assemblages in the equatorial Pacific Ocean.

Key words: Radiolaria, biostratigraphy, faunal evolution, middle–late Miocene boundary, eastern equatorial Pacific.

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Introduction

Various evidences support minor faunal and floral turnover at the early middle Miocene, early late Miocene, latest Miocene, and late Pliocene but none of these was described as a mass extinction event. So far documented faunal/florar turnovers seem to operate in conjuction with increasing high-latitude cooling and/or reorganization of oceanic circulation associated with the closure of oceanic gateways (e.g., Thomas 1985; McGowran 1986; Wei and Kennett 1986; Chaisson and Leckie 1993; Takayama 1993; Barron 1992, 2003; Barron and Baldauf 1995). Although these numerous studies of faunal and floral evolution and paleoceanographic relations have been published using planktonic organisms such as planktonic foraminifera and diatoms, evolutionary studies of radiolarians in a paleoceanographic context are rare. Because radiolarians inhabit a wider range of water depths and occupy a broader range of water niches than planktonic foraminifera and diatoms (e.g., Renz 1976; Kling 1979; Anderson 1993; Casey 1993; Kling and Boltovskoy 1995; Yamashita et al. 2002), a paleontologic examination of radiolarian assemblages through time can help clarify the nature of evolutionary turnover.

Environmental control of diversity and evolutionary rates in the Neogene radiolarian fauna has been investigated by Lazarus (2002) and Johnson and Nigrini (1985). Lazarus (2002) reconstructed the diversity and faunal turnover history of Antarctic Neogene radiolarians based on the range-chart data of three authors (Caulet 1991; Abelmann 1992; Lazarus 1992), and compared the patterns to environmental change such as paleotemperature, sea level, and marine productivity, which are the primary controlling factors of evolution. His results suggested that radiolarian faunal turnover is associated with the enhanced glaciation and increased productivity shifts in the middle Miocene (ca. 15–13 Ma) and latest Miocene (ca. 7–4 Ma) on or around Antarctica. Johnson and Nigrini (1985) correlated fifty Neogene radiolarian appearance and extinction events in an east–west transect of the equatorial Indian and Pacific oceans, and showed that

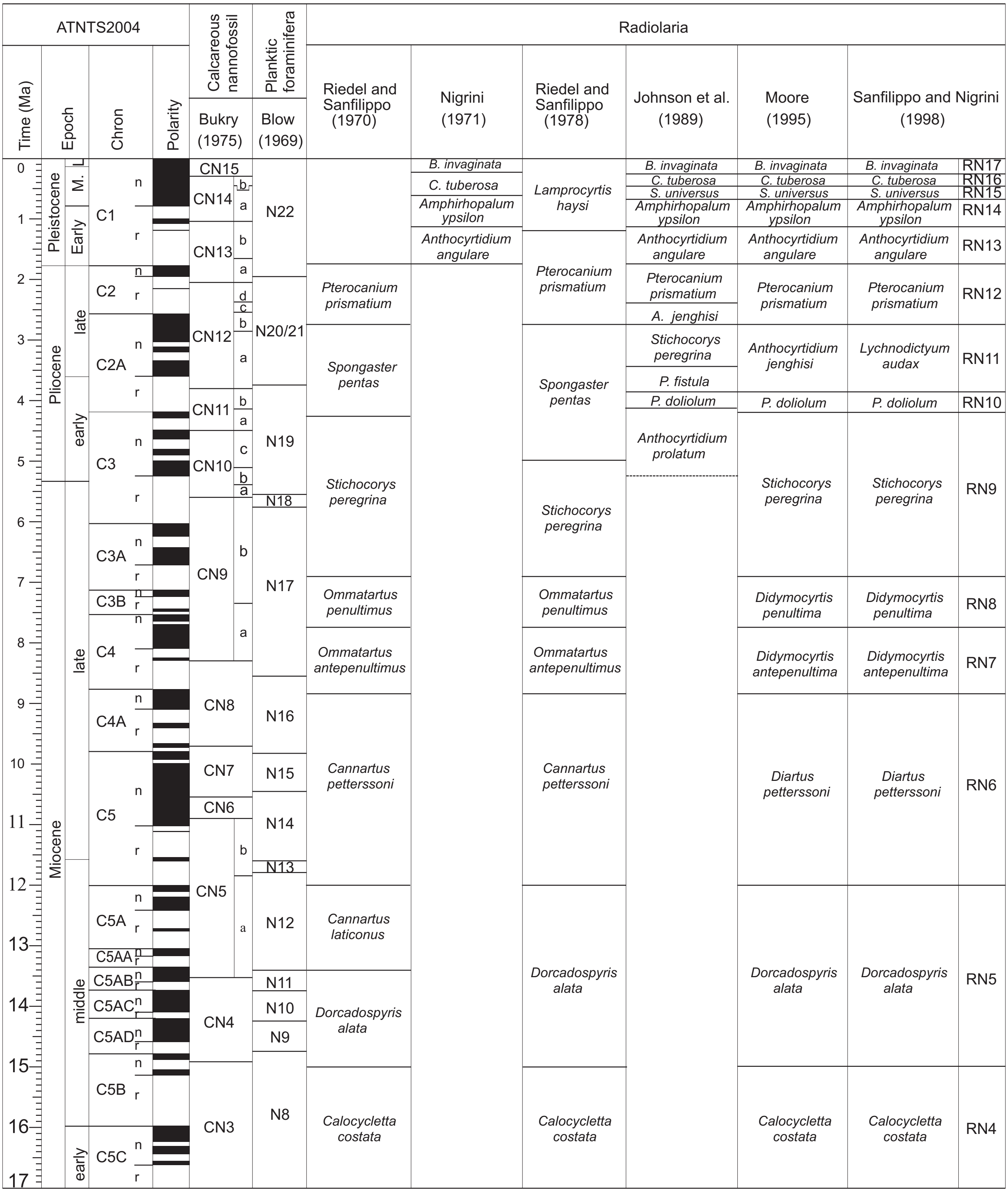

Fig. 1. Correlation of Neogene calcareous nannoplankton, planktic foraminifera and radiolarian zones. ATNTS, astromically tuned Neogene time scale (Ogg and Smith, 2004).

most of the studied radiolarian species first evolved in the Indian ocean and subsequently in the western and eastern Pacific ocean. However, it has not been examined whether radiolarian appearances and disappearances are concentrated during short time intervals, because they studied a limited number of species. Thus, the detailed history of radiolarian faunal change in the tropics remains to be investigated.

Radiolarians are abundant with high diversity in the tropical Pacific, where they have been widely used primarily as a biostratigraphic tool for dating and correlating Neogene marine sediments (Fig. 1). This progress of radiolarian biostratigraphy was achieved through biostratigraphic studies of numerous continuous sequences of deep sea cores, as well as by detailed taxonomic studies (e.g., Riedel and Sanfilippo 1970, 1971, 1978; Moore 1971, 1995; Nigrini 1971; Foreman 1973; Caulet 1979; Sanfilippo et al. 1985; Johnson et al. 1989; Lazarus et al. 1995; Sanfilippo and Nigrini 1998; Nigrini et al. 2006). Lazarus et al. (1995) and Sanfilippo and Nigrini (1998) provided paleomagnetically dated radiolarian events for the Neogene in the tropics. Despite these advances, many radiolarian events have yet not been paleomagnetically dated.

Here we will document radiolarian species appearance and extinction events for the past 17 Ma in the eastern equatorial Pacific and discuss their timing and relationship to global climatic and regional oceanographic changes to evaluate the influence of environmental change on the long-term evolution of the tropical planktonic fauna. For this purpose, we have documented the stratigraphic occurrences of 115 radiolarian species and recognized 152 radiolarian events at Ocean Drilling Program (ODP) Sites 845 and 1241 in the tropical Pacific Ocean. These events have been tied to the geomagnetic polarity time scale of Ogg and Smith (2004) through direct and indirect correlation.

Institutional abbreviation.—MPC, Micropaleontology Collection, National Museum of Nature and Science, Tokyo, Japan.

Other abbreviation.—mcd, meters composite depth.

Oceanographic setting

The modern Pacific equatorial circulation consists of three primary currents, the westward flowing North and South Equatorial Currents, and the eastward flowing Equatorial Countercurrent (Fig. 2). There were large differences in past tropical circulation patterns, when the Indonesian and Central American seaways were open to surface water circulation. During the early and middle Miocene, westward equatorial currents flowed continuously from the Atlantic, through the Pacific, and into the Indian Ocean through the Central American and Indonesian seaways. The modern equatorial circulation system was formed near the middle–late Miocene boundary due to the closure of the Indonesian Seaway (Kennett et al. 1985; Jian et al. 2006; Li et al. 2006). The surface-water exchange between the equatorial Atlantic and the Pacific continued until the late Pliocene (Cannariato and Ravelo 1997; Chaisson and Ravelo 2000).

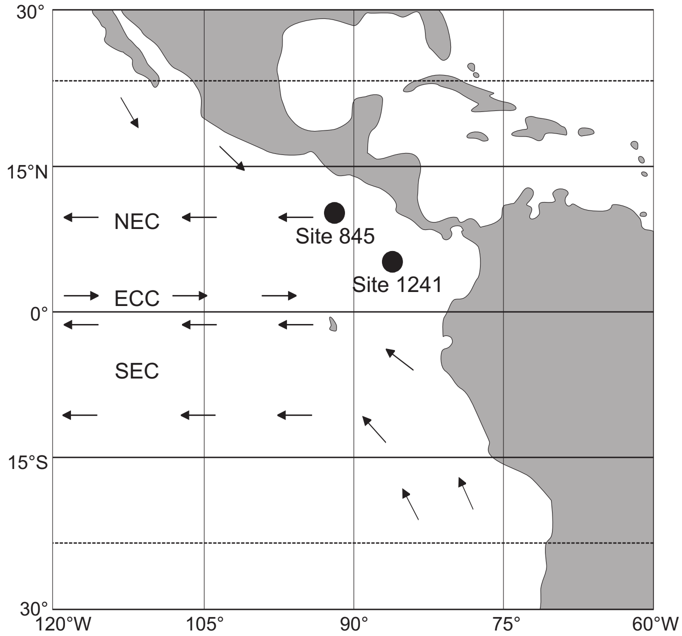

Fig. 2. Modern surface water circulation and location of ODP Sites 845 and 1241 used to determine stratigraphic ranges of radiolarian species in the eastern equatorial Pacific Ocean. NEC, North Equatorial Current; ECC, Equatorial Countercurrent; SEC, South Equatorial Current.

Material and methods

Samples were obtained from ODP Leg 138 Site 845 (9°34.95’N, 94°35.45’W, water depth 3704 m) and ODP Leg 202 Site 1241 (5°50.570’N, 86°26.676’W, water depth 2027 m) in the eastern equatorial Pacific (Fig. 2). The sediments recovered from the two sites consist mainly of calcareous nannofossil ooze with foraminifers, diatom and well-preserved radiolarians.

We analyzed 54 samples from Site 845 and 116 samples from Site 1241. Freeze-dried and weighed sediment samples were placed into a beaker with a 3–5% solution of hydrochloric acid (HCl) to remove the calcareous fine fraction from the sediment before H_2O_2 treatment, because the calcareous fraction sometimes breaks the radiolarian shells during the intense effervescence of the hydrogen peroxide (H_2O_2) solution. Disaggregated particles were sieved through a 63-μm mesh sieve, and returned to a beaker. A solution of 5% H_2O_2 with a little sodium diphosphate decahydrate was added to the beaker and then boiled for 20 min. Wet residues, sieved through a 63-μm mesh, were dried in an oven at 40°C overnight. The clean sample was divided equally, using a plankton splitter, into subsamples big enough to obtain several thousand specimens per sample. One portion of the divided sample was scattered randomly on a glass slide on which a thin layer of gum tragacanth had been spread. Material was mounted using Canada balsam and a 24 × 40 mm cover glass. We counted radiolarian specimens to the end of the transverse line at which 500 specimens was exceeded. All specimens mounted on a slide were ob-

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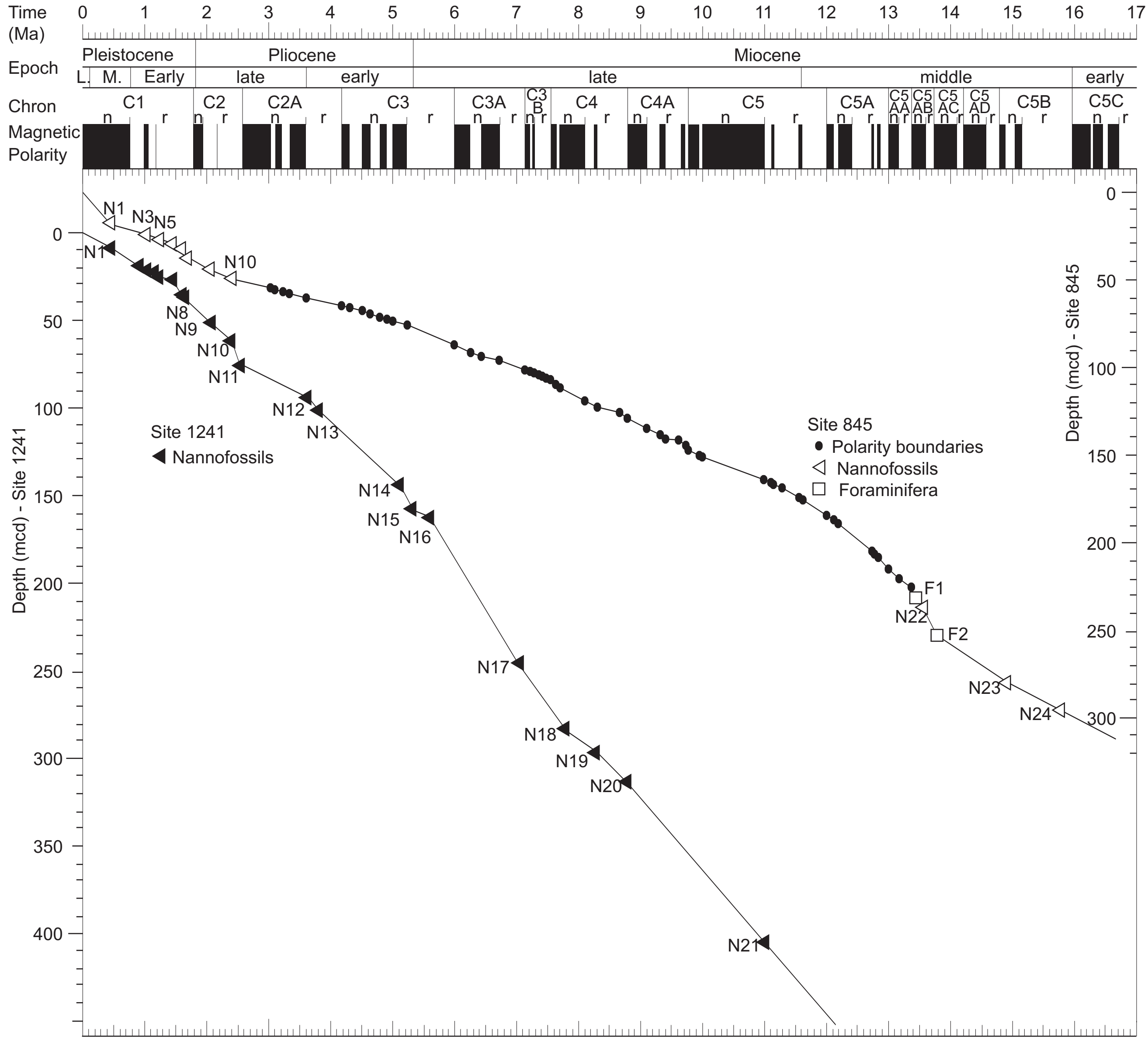

Fig. 3. Age-depth plot of Sites 845 and 1241. Geomagnetic polarity time scale is after Ogg and Smith (2004). The symbols "N1" to "N24", "F1" and "F2" for the control correspond to those in Tables 1 and 2.

served to confirm the occurrence of stratigraphic marker species. The studied slides are deposited in the micropaleontological reference collection of the National Science Museum, Tokyo, Japan: MPC 3277–3390, 4834–4889.

Age model

The ages of the radiolarian events are estimated using the sediment accumulation rate diagram for ODP Sites 845 and 1241 (Fig. 3). For the construction of the age-depth models for the middle Miocene to upper Pliocene sequence at Site 845, we plotted paleomagnetic data (Schneider 1995) and a few planktic foraminifer (Vincent and Toumarkine 1995) and calcareous nannoplankton events (Raffi and Flores 1995) from the intervals with poor paleomagnitic polarity records (Table 1). The diagram for the middle Miocene to Pleistocene sequence of Site 1241 is constructed based on marker calcareous nannoplankton biohorizons (Mix et al. 2003; Table 2 in the present study). The ages of planktic foraminifer and calcareous nannoplankton datum events recalibrated by Lourens et al. (2004) to the geomagnetic polarity time scale of Ogg and Smith (2004) are used in this study.

Radiolarian biostratigraphy

The low latitude radiolarian biostratigraphy and the code numbers of radiolarian zones as defined by Sanfilippo and Nigrini (1998) were used in this study (Fig. 1). The strati-

Table 1. Magnetostratigraphic and biostratigraphic events (Raffi and Flores 1995; Schneider 1995; Vincent and Toumarkine 1995) used for the construction of the age-depth plots of Site 845. Abbreviations: F, planktic foraminifera; FO, first occurrence; LO, last occurrence; N, calcareous nannofossils.

		Datum	Age (Ma)	Depth (mcd)
N_1	LO	*Pseudoemiliania lacunosa*	0.44	18.09/18.38
N_3		Reentry medium *Gephyrocapsa* spp.	1.04	22.88/24.38
N_5	LO	large *Gephyrocapsa* spp.	1.24	27.38/27.85
N_6	FO	large *Gephyrocapsa* spp.	1.46	29.15/30.65
N_7	LO	*Calcidiscus macintyrei*	1.6	32.15/33.65
N_8	FO	medium *Gephyrocapsa* spp.	1.67	36.66/38.15
N_9	LO	*Discoaster brouweri*	2.06	43.03/44.38
N_{10}	LO	*Discoaster pentaradiatus*	2.39	49.11/49.6
	Top	C2An.1r	3.032	53.88
	Top	C2An.2n	3.116	54.98
	Top	C2An.2r	3.207	55.98
	Top	C2An.3n	3.33	57.38
	Top	C2Ar	3.596	59.88
	Top	C3n.1n	4.187	65.56
	Top	C3n.1r	4.3	67.06
	Top	C3n.2n	4.493	68.46
	Top	C3n.2r	4.631	69.76
	Top	C3n.3n	4.799	71.6
	Top	C3n.3r	4.896	72.05
	Top	C3n.4n	4.997	73.3
	Top	C3r	5.235	76
	Top	C3An.1n	6.033	87.51
	Top	C3An.1r	6.252	90.21
	Top	C3An.2n	6.436	92.51
	Top	C3Ar	6.733	96.28
	Top	C3Bn	7.14	101.18
	Top	C3Br.1r	7.212	103.18
	Top	C3Br.1n	7.251	103.71
	Top	C3Br.2r	7.285	104.46
	Top	C3Br.2n	7.454	106.86
	Top	C3Br.3r	7.489	107.46
	Top	C4n.1n	7.528	108.06
	Top	C4n.1r	7.642	110.11
	Top	C4n.2n	7.695	111.01
	Top	C4r.1r	8.108	119.28
	Top	C4r.1n	8.254	121.83
	Top	C4r.2r	8.3	122.13
	Top	C4r.2r-1	8.661	127.96
	Base	C4r.2r-1	8.699	128.66
	Top	C4An	8.769	129.71
	Top	C4Ar.1r	9.098	136.68
	Top	C4Ar.1n	9.312	139.98
	Top	C4Ar.2r	9.409	141.43
	Top	C4Ar.2n	9.656	145.08
	Top	C4Ar.3r	9.717	146.7
	Top	C5n.1n	9.779	147.86
	Top	C5n.1r	9.934	150.21
	Top	C5n.2n	9.987	150.76
	Top	C5r.1r	11.04	164.93
	Top	C5r.1n	11.118	166.01
	Top	C5r.2r	11.154	166.6
	Top	C5r.2r-1	11.267	168.16
	Base	C5r.2r-1	11.298	168.95
	Top	C5r.2n	11.554	174.17
	Top	C5r.3r	11.614	175.77
	Top	C5An.1n	12.014	183.73
	Top	C5An.1r	12.116	187.14
	Top	C5An.2n	12.207	189.55
	Top	C5Ar.1n	12.73	204.9
	Top	C5Ar.2r	12.765	206.29
	Top	C5Ar.2n	12.82	208.08
	Top	C5Ar.3r	12.878	209.74
	Top	C5AAn	13.015	215.73
	Top	C5AAr	13.183	219.98
	Top	C5ABn	13.369	226.62
F_1	FO	*Fohsella fohsi*	13.41	231.76/232.26
N_{22}	LO	*Sphenolithus heteromorphus*	13.53	237.29/237.69
F_2	FO	*Fohsella praefohsi*	13.77	251.73/252.54
N_{23}	LO	*Helicosphaera ampliaperta*	14.91	278.95/279.71
N_{24}	LO	acme *Discoaster deflandrei*	15.8	295.53/297.03

graphic distribution of radiolarians is presented in Figs. 4, 5, and 6. The studied sequence was divided into eleven radiolarian biozones from RN15 to RN4 at Site 845 and from Zones RN16 to RN6 at Site 1241 (Table 3, Figs. 4, 5). The radiolarian biostratigraphy of Site 845 was originally examined by Moore (1995), and subsequently herein. That of Site 1241 was established for the first time in this study. In this study, 115 morphotypes of radiolarians are identified, and 152 radiolarian events are recognized at the two sites (Appendix 1, Figs. 7–14).

Zone RN17 *Buccinosphaera invaginata* Range Zone (Nigrini 1971)

Definition: This zone is defined as the total range *Buccinosphaera invaginata* Haeckel, 1887.

Remarks: This zone was not sampled, because the core sampling began at a depth of 7.1 mcd at Site 1241 (0.33 Ma).

Zone RN16 *Collosphaera tuberosa* Interval Zone (Nigrini 1971 emended by Caulet 1979).

Definition: This zone corresponds to the stratigraphic interval from the first occurrence of *Buccinosphaera invaginata* (top) to the last occurrence of *Stylatractus universus* Hays, 1970 (Fig. 9O) (base).

Base interval: Sample 1241A-2H-3, 75–76 cm (8.6 mcd) through sample 1241A-2H-5, 75–76 cm (11.6 mcd).

Correlation and age: The basal datum of this zone (last occurrence of *Stylatractus universus*) corresponds to the upper part of calcareous nannoplankton Zone CN14 at Site 1241. The age of this zone is the Middle Pleistocene (0.18–0.42 Ma).

Zone RN15 *Stylatractus universus* Concurrent Range Zone (Caulet 1979 renamed by Johnson et al. 1989)

Definition: This zone corresponds to the stratigraphic interval from the last occurrence of *Stylatractus universus* (Fig. 9O) (top) to the first occurrence of *Collosphaera tuberosa* Haeckel, 1887 (Fig. 9N) (base).

Base interval: Sample 1241A-2H-5, 75–76 cm (11.6 mcd) through sample 1241A-2H-6, 75–76 cm (13.1 mcd).

Correlation and age: This zone is located with the middle part of calcareous nannoplankton Zone CN14. This zone spans a short interval from 0.42 to 0.60 Ma within the Middle Pleistocene.

Zone RN14 *Amphirhopalum ypsilon* Interval Zone (Nigrini 1971)

Definition: This zone corresponds to the stratigraphic interval between the first occurrence of *Collosphaera tuberosa* (Fig. 9N) (top) and the last occurrence of *Anthocyrtidium angulare* Nigrini, 1971 (Fig. 11C) (base).

Base interval: Sample 845B-2H-CC (25.0 mcd) through sample 845C-1H-CC (30.8 mcd), sample 1241A-3H-5, 75–77 cm (21.9 mcd) through sample 1241A-3H-6, 75–76 cm (23.4 mcd).

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Table 2. Biostratigraphic events (Mix et al. 2003) used for the construction of the age-depth plots of Site 1241. Abbreviations: FO, first occurrence; LO, last occurrence; N, calcareous nannofossils.

		Datum	Age (Ma)	Core, section interval	Depth (mcd)	Av. (mcd)
N_{1}	LO	*Pseudoemiliania lacunosa*	0.44	2H-3, 75/2H-4, 75	8.60/10.10	9.35
N_{2}	LO	*Reticulofenestra asanoi*	0.91	3H-3, 75/3H-4, 75	18.91/20.41	19.66
N_{3}		Reentry medium *Gephyrocapsa*	1.04	3H-4, 75/3H-5, 75	20.41/21.91	21.16
N_{4}	FO	*Reticulofenestra asanoi*	1.14	3H-5, 75/3H-CC	21.91/24.76	22.67
N_{5}	LO	*Gephyrocapsa* (large)	1.24	3H-CC/4H-1, 75	24.76/27.59	26.18
N_{6}	FO	*Gephyrocapsa* (large)	1.46	4H-1, 75/4H-2, 75	27.59/29.09	28.34
N_{7}	LO	*Calcidiscus macintyrei*	1.60	4H-CC/5H-1, 75	36.51/37.87	37.19
N_{8}	FO	*Gephyrocapsa* (medium)	1.67	5H-1, 75/5H-2, 75	37.87/39.39	38.63
N_{9}	LO	*Discoaster brouweri*	2.06	6H-1, 75/6H-2, 75	48.82/50.33	49.58
N_{10}	LO	*Discoaster pentaradiatus*	2.39	7H-2, 75/7H-3, 75	60.69/62.2	61.45
N_{11}	LO	*Discoaster surculus*	2.52	8H-4, 75/8H-5, 75	74.87/76.38	75.63
N_{12}	LO	*Sphenolithus* spp.	3.65	10H-2, 75/10H-3, 75	92.87/94.37	93.62
N_{13}	LO	*Reticulofenestra pseudoumbilicus*	3.79	10H-CC/11H-1, 75	100.68/101.95	101.32
N_{14}	FO	*Ceratolithus cristatus*	5.12	15H-2, 75/15H-3, 75	144.38/145.89	145.14
N_{15}	FO	*Ceratolithus armatus*	5.32	16H-3, 75/16H-4, 75	156.93/158.44	157.69
N_{16}	LO	*Discoaster quinqueramus*	5.59	16H-6, 75/16H-7, 40	161.46/162.61	162.04
N_{17}	LO	paracme *Reticulofenestra pseudoumbilicus*	7.08	24H-4, 75/24H-5, 75	245.33/246.84	246.09
N_{18}	FO	*Discoaster surculus*	7.79	27H-CC/28H-1, 75	282.36/284.1	283.23
N_{19}	FO	*Discoaster berggrenii*	8.29	29H-2, 75/29H-3, 75	295.85/297.35	296.6
N_{20}	FO	paracme *Reticulofenestra pseudoumbilicus*	8.79	30H-7, 40/30H-CC	313.69/314.33	314.01
N_{21}	LO	*Coccolithus miopelagicus*	11.02	39X-4, 75/39X-5, 75	405.61/407.11	406.36

Table 3. Radiolarian events at Ocean Drilling Program (ODP) Sites 845 and 1241 with ages calibrated at each site. The ages after Lazarus (1995) and Sanfilippo and Nigrini (1998) have been updated to the ATNTS 2004 (Ogg and Smith, 2004). Abbreviations: FO, first occurrence; LO, last occurrence; ET, evolutionary transition.

	Zone		Radiolarian events	Fig.	Age* (Ma)	Age**	Site1241	Depth (mcd)	Age (Ma)	Site 845	Depth (mcd)	Age (Ma)
0	RN17	FO	*Buccinosphaera invaginata* Haeckel, 1887		0.18	0.30	no data			no data		
1	RN16	LO	*Stylatractus universus* Hays, 1970	9O	0.42	0.45	2H-3, 75–76/ 2H-5, 75–76	8.6/ 11.6	0.40/ 0.54	no data		
2	RN15	FO	*Collosphaera tuberosa* Haeckel, 1887	9N	0.60	0.73	2H-5, 75–76/ 2H6, 75–76	11.6/ 13.1	0.54/ 0.61	no data		
3	RN14	FO	*Axoprunum stauraxonium* Haeckel, 1887	9P			2H-6, 75–76/ 3H-2, 77–79	13.1/ 17.4	0.61/ 0.81	no data		
4	RN14	LO	*Didymocyrtis avita* (Riedel, 1953)	9K			3H-2, 77–79/ 3H-3, 77–79	17.4/ 18.9	0.81/ 0.88	no data		
5	RN14	FO	*Pterocorys hertwigii* (Haeckel, 1887)	11Q			3H-5, 75–77/ 3H-6, 75–76	21.9/ 23.4	1.09/ 1.16	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
6	RN14	LO	*Pterocorys campanula* Haeckel, 1887	11P			3H-5, 75–77/ 3H-6, 75–76	21.9/ 23.4	1.09/ 1.16	no data		
7	RN14	LO	*Anthocyrtidium angulare* Nigrini, 1971	11C	1.12	1.14	3H-5, 75–77/ 3H-6, 75–76	21.9/ 23.4	1.09/ 1.16	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
8	RN13	FO	*Lamprocyrtis nigriniae* (Caulet, 1971)	11E		1.30	3H-6, 75–76/ 4H-1, 76–78	23.4/ 27.6	1.16/ 1.38	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
9	RN13	FO	*Pterocanium praetextum praetextum* (Ehrenberg, 1872)	12N		4.20	3H-6, 75–76/ 4H-1, 76–78	23.4/ 27.6	1.16/ 1.38	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
10	RN13	LO	*Anthocyrtidium nosicaae* Caulet, 1979	11N			3H-6, 75–76/ 4H-1, 76–78	23.4/ 27.6	1.16/ 1.38	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
11	RN13	LO	*Theocorythium vetulum* Nigrini, 1971	11S		1.30	3H-6, 75–76/ 4H-1, 76–78	23.4/ 27.6	1.16/ 1.38	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
12	RN13	FO	*Pterocanium praetextum eucolpum* Haeckel, 1887	12O			4H-1, 76–78/ 4H-2, 76–78	27.6/ 29.1	1.38/ 1.47	B-2HCC/ C-1HCC	25.0/ 30.8	1.11/ 1.50
13	RN13	LO	*Lamprocyrtis neoheteroporos* Kling, 1973	11F			4H-2, 76–78/ 4H-3, 75–77	29.1/ 30.6	1.47/ 1.50	C-1HCC/ B-3HCC	30.8/ 32.3/	1.50/ 1.57
14	RN13	FO	*Pterocorys minythorax* (Nigrini, 1968)	11M			4H-4, 75–77/ 4H-5, 75–77	32.1/ 33.6	1.52/ 1.54	C-1HCC/ B-3HCC	30.8/ 32.3/	1.50/ 1.57
15	RN13	LO	*Lamprocyrtis heteroporos* (Hays, 1965)	11G			4H-4, 75–77/ 4H-5, 75–77	32.1/ 33.6	1.52/ 1.54	C-1HCC/ B-3HCC	30.8/ 32.3/	1.50/ 1.57
16	RN13	FO	*Theocorythium trachelium dianae* (Haeckel, 1887)	11L			4H-6, 75–77/ 6H-1, 75–77	35.1/ 48.8	1.57/ 2.03	B-3HCC/ A-4HCC	32.3/ 38.6	1.57/ 1.75
17	RN13	FO	*Theocorythium trachelium trachelium* (Ehrenberg, 1872)	11K		1.61	4H-6, 75–77/ 6H-1, 75–77	35.1/ 48.8	1.57/ 2.03	B-3HCC/ A-4HCC	32.3/ 38.6	1.57/ 1.75

	Zone		Radiolarian events	Fig.	Age* (Ma)	Age**	Site1241	Depth (mcd)	Age (Ma)	Site 845	Depth (mcd)	Age (Ma)
18	RN13	FO	*Anthocyrtidium angulare* Nigrini, 1971	11C		1.80	4H-6, 75–77/ 6H-1, 75–77	35.1/ 48.8	1.57/ 2.03	B-3HCC/ A-4HCC	32.3/ 38.6	1.57/ 1.75
19	RN13	LO	*Pterocanium prismatium* Riedel, 1957	12B	1.75	1.71	4H-6, 75–77/ 6H-1, 75–77	35.1/ 48.8	1.57/ 2.03	A-4HCC/ C-2HCC	38.6/ 41.4	1.75/ 1.92
20	RN12	FO	*Pterocorys zancleus* (Müller, 1855)	11R			6H-3, 75–77/ 6H-4, 77–79	51.8/ 53.4	2.12/ 2.16	B-4HCC/ B-5HCC	45.1/ 49.6	2.08/ 2.42
21	RN12	LO	*Anthocyrtidium jenghisi* Streeter, 1988	11A			6H-4, 77–79/ 6H-5, 76–77	53.4/ 54.8	2.16/ 2.21	B-4HCC/ A-5HCC	45.1/ 49.6	2.08/ 2.42
22	RN12	FO	*Cycladophora davisiana* Ehrenberg, 1861	12K			7H-6, 62–64/ 9H-3, 62–64	66.6/ 83.7	2.44/ 3.03	A-5HCC/ C-3HCC	49.6/ 51.9	2.42/ 2.76
23	RN12	LO	*Lithelius klingi* Kamikuri, 2009	9R			7H-6, 62–64/ 9H-3, 62–64	66.6/ 83.7	2.44/ 3.03	A-5HCC/ C-3HCC	49.6/ 51.9	2.42/ 2.76
24	RN12	LO	*Larcospira moschkovskii* Kruglikova, 1978	8E			7H-6, 62–64/ 9H-3, 62–64	66.6/ 83.7	2.44/ 3.03	A-5HCC/ C-3HCC	49.6/ 51.9	2.42/ 2.76
25	RN12	LO	*Stichocorys delmontensis* (Campbell and Clark, 1944)	10Q			7H-6, 62–64/ 9H-3, 62–64	66.6/ 83.7	2.44/ 3.03	C-3HCC/ B-5HCC	51.9/ 53.8	2.76/ 3.02
26	RN12	LO	*Stichocorys peregrina* (Riedel, 1953)	10P	2.74	2.71	7H-6, 62–64/ 9H-3, 62–64	66.6/ 83.7	2.44/ 3.03	C-3HCC/ B-5HCC	51.9/ 53.8	2.76/ 3.02
27	RN11	FO	*Lamprocyrtis neoheteroporos* Kling, 1973	11F			9H-3, 62–64/ 9H-5, 62–64	83.7/ 86.7	3.03/ 3.21	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
28	RN11	FO	*Lamprocyrtis heteroporos* (Hays, 1965)	11G			9H-3, 62–64/ 9H-5, 62–64	83.7/ 86.7	3.03/ 3.21	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
29	RN11	FO	*Dictyophimus crisiae* Ehrenberg, 1854	12C			9H-5, 62–64/ 10H-3, 62–64	86.7/ 94.2	3.21/ 3.66	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
30	RN11	LO	*Anthocyrtidium pliocenica* (Seguenza, 1880)	11I			9H-5, 62–64/ 10H-3, 62–64	86.7/ 94.2	3.21/ 3.66	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
31	RN11	LO	*Anthocyrtidium ehrenbergi* (Stöhr, 1880)	11D			9H-5, 62–64/ 10H-3, 62–64	86.7/ 94.2	3.21/ 3.66	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
32	RN11	LO	*Phormostichoartus fistula* Nigrini, 1977	10C		3.47	9H-5, 62–64/ 10H-3, 62–64	86.7/ 94.2	3.21/ 3.66	B-5HCC/ A-6HCC	53.8/ 59.7	3.02/ 3.58
33	RN11	LO	*Lychnodictyum audax* Riedel, 1953	12A		3.59	9H-5, 62–64/ 10H-3, 62–64	86.7/ 94.2	3.21/ 3.66	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
34	RN11	FO	*Lamprocyclas maritalis polypora* Nigrini, 1967	11J			10H-5, 62–64/ 11H-3, 62–64	97.2/ 104.8	3.72/ 3.90	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
35	RN11	FO	*Amphirhopalum ypsilon* Haeckel, 1887	8G		3.83	10H-5, 62–64/ 11H-3, 62–64	97.2/ 104.8	3.72/ 3.90	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
36	RN11	LO	*Spongaster pentas* Riedel and Sanfilippo, 1970	8B		3.47	10H-5, 62–64/ 11H-3, 62–64	97.2/ 104.8	3.72/ 3.90	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
37	RN11	LO	*Phormostichoartus doliolum* (Riedel and Sanfilippo, 1971)	10I	3.87	3.71	10H-5, 62–64/ 11H-3, 62–64	97.2/ 104.8	3.72/ 3.90	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
38	RN10	ET	*Spongaster pentas*– *Spongaster tetras tetras*	8B, C			11H-4, 62–64/ 11H-5, 62–64	106.4/ 107.9	3.94/ 3.99	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
39	RN10	FO	*Spongaster tetras tetras* Ehrenberg, 1860	8C		3.96	11H-5, 62–64/ 12H-3, 62–64	107.9/ 115.7	3.99/ 4.23	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
40	RN10	LO	*Didymocyrtis penultima* (Riedel, 1957)	9G	4.19	3.96	11H-5, 62–64/ 12H-3, 62–64	107.9/ 115.7	3.99/ 4.23	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
41	RN9	ET	*Didymocyrtis avita*– *Didymocyrtis tetrathalamus*	9K, L			12H-3, 62–64/ 12H-4, 62–64	115.7/ 117.3	4.23/ 4.27	A-6HCC/ B-6HCC	59.7/ 66.7	3.58/ 4.27
42	RN9	FO	*Pterocanium prismatium* Riedel, 1957	12B		5.38	12H-3, 62–64/ 12H-4, 62–64	115.7/ 117.3	4.23/ 4.27	B-6HCC/ A-7HCC	66.7/ 69.8	4.27/ 4.63
43	RN9	FO	*Anthocyrtidium nosicaae* Caulet, 1979	11N			12H-5, 62–64/ 13H-3, 62–64	118.8/ 125.6	4.32/ 4.53	B-6HCC/ A-7HCC	66.7/ 69.8	4.27/ 4.63
44	RN9	FO	*Liriospyris reticulata* (Ehrenberg, 1872)	14F			12H-5, 62–64/ 13H-3, 62–64	118.8/ 125.6	4.32/ 4.53	B-6HCC/ A-7HCC	66.7/ 69.8	4.27/ 4.63
45	RN9	LO	*Botryostrobus bramlettei* (Campbell and Clark, 1944)	10G		4.58	13H-3, 62–64/ 13H-4, 62–64	125.6/ 127.1	4.53/ 4.57	too rare		
46	RN9	FO	*Pterocorys campanula* Haeckel, 1887	11P			13H-4, 62–64/ 13H-5, 62–64	127.1/ 128.6	4.57/ 4.62	B-6HCC/ A-7HCC	66.7/ 69.8	4.27/ 4.63
47	RN9	FO	*Nephrospyris renilla* Haeckel, 1887	13E			14H-1, 62–64/ 14H-3, 62–64	132.7/ 135.7	4.74/ 4.83	B-6HCC/ A-7HCC	66.7/ 69.8	4.27/ 4.63
48	RN9	FO	*Anthocyrtidium jenghisi* Streeter, 1988	11A			15H-5, 62–64/ 16H-4, 62–64	148.8/ 158.3	5.18/ 5.36	A-7HCC/ B-7HCC	69.8/ 76.5	4.63/ 5.27
49	RN9	LO	*Dictyophimus splendens* (Campbell and Clark, 1944)	12F			15H-5, 62–64/ 16H-4, 62–64	148.8/ 158.3	5.18/ 5.36	A-7HCC/ B-7HCC	69.8/ 76.5	4.63/ 5.27
50	RN9	FO	*Theocorythium vetulum* Nigrini, 1971	11S			16H-4, 62–64/ 16H-5, 62–64	158.3/ 159.8	5.36/ 5.45	B-7HCC/ B-8HCC	76.5/ 88.0	5.27/ 6.07
51	RN9	LO	*Spongaster berminghami* (Campbell and Clark, 1944)	8A		4.58	16H-6, 62–64/ 17H-4, 62–64	161.3/ 168.4	5.55/ 5.70	B-7HCC/ B-8HCC	76.5/ 88.0	5.27/ 6.07
52	RN9	LO	*Solenosphaera omnitubus procera* Sanfilippo and Riedel, 1974	9S			17H-4, 62–64/ 17H-5, 62–64	168.4/ 169.9	5.70/ 5.73	B-7HCC/ B-8HCC	76.5/ 88.0	5.27/ 6.07
53	RN9	LO	*Solenosphaera omnitubus omnitubus* Riedel and Sanfilippo, 1971	9T		5.14	17H-4, 62–64/ 17H-5, 62–64	168.4/ 169.9	5.70/ 5.73	B-7HCC/ B-8HCC	76.5/ 88.0	5.27/ 6.07

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	Zone		Radiolarian events	Fig.	Age* (Ma)	Age**	Site1241	Depth (mcd)	Age (Ma)	Site 845	Depth (mcd)	Age (Ma)
54	RN9	FO	*Spongaster pentas* Riedel and Sanfilippo, 1970	8B			17H-5, 62–64/ 17H-6, 62–64	169.9/ 171.4	5.73/ 5.76	B-7HCC/ B-8HCC	76.5/ 88.0	5.27/ 6.07
55	RN9	FO	*Botryostrobus aquilonaris* (Bailey, 1856)	10F			20H-5, 62–64/ 21H-2, 62–64	202.4/ 208.7	6.31/ 6.42	A-9H-5, 0–2/ A-9HCC	88.1/ 92.1	6.07/ 6.40
56	RN9	FO	*Spirocyrtis scalaris* Haeckel, 1887	10A			20H-5, 62–64/ 21H-2, 62–64	202.4/ 208.7	6.31/ 6.42	A-9H-5, 0–2/ A-9HCC	88.1/ 92.1	6.07/ 6.40
57	RN9	FO	*Pterocorys macroceras* (Popofsky, 1913)	11O			21H-4, 62–64/ 21H-5, 62–64	211.7/ 213.2	6.47/ 6.50	A-9H-5, 0–2/ A-9HCC	88.1/ 92.1	6.07/ 6.40
58	RN9	LO	*Siphostichartus corona* (Haeckel, 1887)	10J		5.61	21H-5, 62–64/ 22H-3, 62–64	213.2/ 220.7	6.50/ 6.63	A-10H-2, 0–2/ B-9HCC	93.6/ 97.7	6.52/ 6.85
59	RN9	LO	*Stichocorys johnsoni* Caulet, 1986	10R		6.44	21H-5, 62–64/ 22H-3, 62–64	213.2/ 220.7	6.50/ 6.63	A-10H-2, 0–2/ B-9HCC	93.6/ 97.7	6.52/ 6.85
60	RN9	LO	*Acrobotrys tritubus* Riedel, 1957	12Q		5.84	22H-5, 62–64/ 23H-3, 62–64	223.8/ 232.4	6.69/ 6.84	A-10H-2, 0–2/ B-9HCC	93.6/ 97.7	6.52/ 6.85
61	RN9	FO	*Didymocyrtis avita* (Riedel, 1953)	9K			23H-3, 62–64/ 23H-5, 62–64	232.4/ 236.5	6.84/ 6.91	A-10H-2, 0–2/ B-9HCC	93.6/ 97.7	6.52/ 6.85
62	RN9	LO	*Calocycletta cladara* Sanfilippo and Riedel, 1992	14D			too rare			A-10H-2, 0–2/ B-9HCC	93.6/ 97.7	6.52/ 6.85
63	RN9	LO	*Calocycletta caepa* Moore, 1972	14E		6.44	23H-5, 62–64/ 24H-3, 62–64	236.5/ 243.7	6.91/ 7.04	A-10H-5, 0–2/ A-10HCC	98.1/ 102.1	6.88/ 7.17
64	RN9	ET	*Stichocorys delmontensis*–*Stichocorys peregrina*	10P, Q	6.89	6.81	23H-5, 62–64/ 24H-3, 62–64	236.5/ 243.7	6.91/ 7.04	A-10H-5, 0–2/ A-10HCC	98.1/ 102.1	6.88/ 7.17
65	RN8	FO	*Botryostrobus auritus/australis* (Ehrenberg, 1884)	10D			25H-5, 62–64/ 26H-3, 62–64	257.9/ 265.6	7.31/ 7.45	A-10HCC/ B-10HCC	102.1/ 108.9	7.17/ 7.57
66	RN8	FO	*Solenosphaera omnitubus procera* Sanfilippo and Riedel, 1974	9S			25H-5, 62–64/ 26H-3, 62–64	257.9/ 265.6	7.31/ 7.45	A-10HCC/ B-10HCC	102.1/ 108.9	7.17/ 7.57
67	RN8	FO	*Solenosphaera omnitubus omnitubus* Riedel and Sanfilippo, 1971	9T		6.94	25H-5, 62–64/ 26H-3, 62–64	257.9/ 265.6	7.31/ 7.45	A-10HCC/ B-10HCC	102.1/ 108.9	7.17/ 7.57
68	RN8	LO	*Didymocyrtis laticonus* (Riedel, 1959)	9E		8.34	26H-3, 62–64/ 27H-3, 62–64	265.6/ 276.1	7.45/ 7.65	A-10HCC/ B-10HCC	102.1/ 108.9	7.17/ 7.57
69	RN8	FO	*Anthocyrtidium ophirense* (Ehrenberg, 1872)	11B			27H-3, 62–64/ 27H-5, 62–64	276.1/ 279.1	7.65/ 7.71	B-10HCC/ A-11HCC	108.9/ 113.0	7.57/ 7.79
70	RN8	FO	*Spirocyrtis gyroscalaris* Nigrini, 1977	10E			27H-3, 62–64/ 27H-5, 62–64	276.1/ 279.1	7.65/ 7.71	B-10HCC/ A-11HCC	108.9/ 113.0	7.57/ 7.79
71	RN8	ET	*Didymocyrtis antepenultima*–*Didymocyrtis penultima*	9F, G			27H-5, 62–64/ 28H-3, 62–64	279.1/ 287.0	7.71/ 7.93	B-10HCC/ A-11HCC	108.9/ 113.0	7.57/ 7.79
72	RN8	LO	*Diartus hughesi* (Campbell and Clark, 1944)	9I	7.74	7.80	27H-5, 62–64/ 28H-3, 62–64	279.1/ 287.0	7.71/ 7.93	B-10HCC/ A-11HCC	108.9/ 113.0	7.57/ 7.79
73	RN7	FO	*Acrobotrys tritubus* Riedel, 1957	12Q		8.34	28H-5, 62–64/ 29H-3, 62–64	290/ 297.2	8.04/ 8.31	A-11HCC/ B-11H-CC	113.0/ 120.1	7.79/ 8.15
74	RN7	FO	*Spongaster berminghami* (Campbell and Clark, 1944)	8A		8.61	28H-5, 62–64/ 29H-3, 62–64	290/ 297.2	8.04/ 8.31	A-11HCC/ B-11H-CC	113.0/ 120.1	7.79/ 8.15
75	RN7	LO	*Dictyocoryne ontongensis* Riedel and Sanfilippo, 1971	8F			too rare			A-11HCC/ B-11H-CC	113.0/ 120.1	7.79/ 8.15
76	RN7	LO	*Lophocyrtis tanythorax* (Sanfilippo and Riedel, 1970)	13C			28H-5, 62–64/ 29H-3, 62–64	290/ 297.2	8.04/ 8.31	A-11HCC/ B-11H-CC	113.0/ 120.1	7.79/ 8.15
77	RN7	LO	*Lophocyrtis brachythorax* (Sanfilippo and Riedel, 1970)	13D			28H-5, 62–64/ 29H-3, 62–64	290/ 297.2	8.04/ 8.31	A-11HCC/ B-11H-CC	113.0/ 120.1	7.79/ 8.15
78	RN7	FO	*Lophocyrtis neatum* (Sanfilippo and Riedel, 1970)	13B			29H-3, 62–64/ 29H-5, 62–64	297.2/ 300.2	8.31/ 8.39	B-11HCC/ A-12HCC	120.1/ 123.7	8.15/ 8.40
79	RN7	LO	*Phormostichoartus marylandicus* (Martin, 1904)	10H			29H-3, 62–64/ 29H-5, 62–64	297.2/ 300.2	8.31/ 8.39	B-11HCC/ A-12HCC	120.1/ 123.7	8.15/ 8.40
80	RN7	FO	*Pterocanium korotnevi* (Dogiel, 1952)	12G			29H-5, 62–64/ 30H-1, 62–64	300.2/ 304.9	8.39/ 8.53	A-12HCC/ B-12HCC	123.7/ 130.6	8.40/ 8.81
81	RN7	LO	*Botryostrobus miralestensis* (Campbell and Clark, 1944)	10B		8.80	29H-5, 62–64/ 30H-1, 62–64	300.2/ 304.9	8.39/ 8.53	A-12HCC/ B-12HCC	123.7/ 130.6	8.40/ 8.81
82	RN7	LO	*Diartus petterssoni* (Riedel and Sanfilippo, 1970)	9J		8.80	30H-1, 62–64/ 30H-3, 62–64	304.9/ 307.9	8.53/ 8.61	A-12HCC/ B-12HCC	123.7/ 130.6	8.40/ 8.81
83	RN7	LO	*Lithopera neotera* Sanfilippo and Riedel, 1970	10AC		9.57	30H-3, 62–64/ 30H-5, 62–64	307.9/ 310.9	8.61/ 8.70	A-12HCC/ B-12HCC	123.7/ 130.6	8.40/ 8.81
84	RN7	FO	*Larcospira quadrangula* Haeckel, 1887	8D			30H-7, 62–64/ 31H-1, 62–64	313.9/ 315.3	8.79/ 8.82	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
85	RN7	FO	*Stichocorys johnsoni* Caulet, 1986	10R			30H-7, 62–64/ 31H-1, 62–64	313.9/ 315.3	8.79/ 8.82	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
86	RN7	ET	*Lithopera neotera* –*Lithopera bacca*	10AC, AD			31H-1, 62–64/ 31H-3, 62–64	315.3/ 318.3	8.82/ 8.89	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
87	RN7	FO	*Phormostichoartus doliolum* (Riedel and Sanfilippo, 1971)	10I			31H-3, 62–64/ 31H-5, 62–64	318.3/ 321.3	8.89/ 8.97	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
88	RN7	ET	*Didymocyrtis laticonus*–*Didymocyrtis antepenultima*	9E, F			31H-3, 62–64/ 31H-5, 62–64	318.3/ 321.3	8.89/ 8.97	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
89	RN7	ET	*Diartus petterssoni*–*Diartus hughesi*	9I, J	8.84		31H-3, 62–64/ 31H-5, 62–64	318.3/ 321.3	8.89/ 8.97	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00

	Zone		Radiolarian events	Fig.	Age* (Ma)	Age**	Site1241	Depth (mcd)	Age (Ma)	Site 845	Depth (mcd)	Age (Ma)
90	RN6	FO	*Anthocyrtidium zanguebaricum* (Ehrenberg, 1872)	11H			31H-7, 62–64/ 32H-1, 62–64	324.3/ 327.9	9.04/ 9.12	B-11HCC/ A-12HCC	120.1/ 123.7	8.15/ 8.40
91	RN6	FO	*Diartus hughesi* (Campbell and Clark, 1944)	9I		9.01	32H-3, 62–64/ 32H-5, 62–64	330.9/ 333.9	9.20/ 9.27	A-13HCC/ B-13HCC	134.7/ 140.6	9.00/ 9.53
92	RN6	FO	*Lithopera bacca* Ehrenberg, 1872	10AD			33H-1, 62–64/ 33H-3, 62–64	340.4/ 343.4	9.43/ 9.50	A-13HCC/ B-13HCC	134.7/ 140.6	9.00/ 9.53
93	RN6	FO	*Anthocyrtidium pliocenica* (Seguenza, 1880)	11I			33H-5, 62–64/ 34H-1, 62–64	346.4/ 351.1	9.57/ 9.69	A-10HCC/ B-10HCC	102.1/ 108.9	7.17/ 7.57
94	RN6	LO	*Trisolenia megalactis megalactis* Ehrenberg, 1872	8J			35X-1, 62–64/ 35X-3, 62–64	358.3/ 361.3	9.86/ 9.93	B-13HCC/ A-14HCC	142.4/ 145.7	9.53/ 9.61
95	RN6	LO	*Trisolenia megalactis costlowi* Bjørklund and Goll, 1979	8K			35X-1, 62–64/ 35X-3, 62–64	358.3/ 361.3	9.86/ 9.93	B-13HCC/ A-14HCC	142.4/ 145.7	9.53/ 9.61
96	RN6	LO	*Spirocyrtis subtilis* Petrushevskaya, 1972	10L			35X-3, 62–64/ 35X-5, 62–64	361.3/ 364.3	9.93/ 10.00	too rare		
97	RN6	FO	*Botryostrobus bramlettei* (Campbell and Clark, 1944)	10G		10.62	35X-5, 62–64/ 36X-1, 62–64	364.3/ 368.4	10.00/ 10.10	too rare		
98	RN6	LO	*Stichocorys wolffii* Haeckel, 1887	10N		8.91	36X-1, 62–64/ 36X-3, 62–64	368.4/ 371.4	10.10/ 10.18	B-12HCC/ A-13HCC	130.6/ 134.7	8.81/ 9.00
99	RN6	LO	*Cyrtocapsella japonica* (Nakaseko, 1963)	10Y		10.00	37X-1,62–64/ 37X-3, 62–64	379.4/ 382.4	10.37/ 10.45	B-14HCC/ A-15HCC	153.0/ 157.0	10.15/ 10.45
100	RN6	LO	*Collosphaera brattstroemi* Bjørklund and Goll, 1979	8I			40X-3, 62–64/ 40X-5, 62–64	415.5/ 418.5	11.24/ 11.31	A-16HCC/ B-16HCC	168.4/ 175.3	11.28/ 11.60
101	RN6	LO	*Lithopera thornburgi* Sanfilippo and Riedel, 1970	10AE			40X-3, 62–64/ 40X-5, 62–64	415.5/ 418.5	11.24/ 11.31	B-16HCC/ A-17HCC	175.3/ 178.8	11.60/ 11.77
102	RN6	FO	*Diartus petterssoni* (Riedel and Sanfilippo, 1970)	9J	12.02		no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
103	RN5	LO	*Cyrtocapsella cornuta* Haeckel, 1887	10X		11.98	no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
104	RN5	LO	*Cyrtocapsella tetrapera* (Haeckel, 1887)	10Z		12.22	no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
105	RN5	LO	*Tholospyris anthopora* (Haeckel, 1887)	12I			no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
106	RN5	LO	*Pterocanium* sp. TX	12M			no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
107	RN5	LO	*Giraffospyris toxaria* (Haeckel, 1887)	12P			no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
108	RN5	LO	*Lithopera renzae* Sanfilippo and Riedel, 1970	10T		12.22	no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
109	RN5	LO	*Dorcadospyris alata* (Riedel, 1959)	13F			no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
110	RN5	LO	*Theocorys*? sp. Y	10AA			no data			A-17HCC/ B-17HCC	178.8/ 184.5	11.77/ 12.04
111	RN5	LO	*Didymocyrtis mammifera* (Haeckel, 1887)	9D			no data			B-18H-2, 0–2/ A-18HCC	186.0/ 189.0	12.08/ 12.17
112	RN5	FO	*Dictyophimus splendens* (Campbell and Clark, 1944)	12F			no data			B-18HCC/ B-19HCC	194.8/ 204.2	12.39/ 12.71
113	RN5	FO	*Cyrtocapsella japonica* (Nakaseko, 1963)	10Y			no data			B-18HCC/ B-19HCC	194.8/ 204.2	12.39/ 12.71
114	RN5	LO	*Calocycletta robusta* Moore, 1971	14B			no data			B-18HCC/ B-19HCC	194.8/ 204.2	12.39/ 12.71
115	RN5	FO	*Calocycletta cladara* Sanfilippo and Riedel, 1992	14D			no data			B-19HCC/ A-20HCC	204.2/ 211.1	12.71/ 12.91
116	RN5	ET	*Lithopera renzae*– *Lithopera neotera*	10T, AC			no data			B-19HCC/ A-20HCC	204.2/ 211.1	12.71/ 12.91
117	RN5	LO	*Lithomelissa* sp. B	12J			no data			B-19HCC/ A-20HCC	204.2/ 211.1	12.71/ 12.91
118	RN5	ET	*Didymocyrtis mammifera*– *Didymocyrtis laticonus*	9D, E			no data			A-20HCC/ B-20HCC	211.1/ 213.8	12.91/ 12.97
119	RN5	FO	*Didymocyrtis laticonus* (Riedel, 1959)	9E			no data			B-20HCC/ A-21HCC	213.8/ 221.4	12.97/ 13.22
120	RN5	LO	*Didymocyrtis tubaria* (Haeckel, 1887)	9B		14.74	no data			A-21HCC/ A-22HCC	221.4/ 232.8	13.22/ 13.43
121	RN5	LO	*Didymocyrtis violina* (Haeckel, 1887)	9C		15.05	no data			A-21HCC/ A-22HCC	221.4/ 232.8	13.22/ 13.43
122	RN5	FO	*Lithopera neotera* Sanfilippo and Riedel, 1970	10AC		14.46	no data			A-21HCC/ A-22HCC	221.4/ 232.8	13.22/ 13.43
123	RN5	FO	*Larcospira moschkovskii* Kruglikova, 1978	8E			no data			A-21HCC/ A-22HCC	221.4/ 232.8	13.22/ 13.43
124	RN5	FO	*Calocycletta caepa* Moore, 1972	14E			no data			A-22HCC/ A-23XCC	232.8/ 241.8	13.43/ 13.60
125	RN5	LO	*Didymocyrtis bassanii* (Carnevale, 1908)	9H			no data			A-22HCC/ A-23XCC	232.8/ 241.8	13.43/ 13.60

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	Zone		Radiolarian events	Fig.	Age* (Ma)	Age**	Site1241	Depth (mcd)	Age (Ma)	Site 845	Depth (mcd)	Age (Ma)
126	RN5	LO	*Eucyrtidium* sp. Q	10S			no data			A-22HCC/ A-23XCC	232.8/ 241.8	13.43/ 13.60
127	RN5	LO	*Stichocorys armata* Haeckel, 1887	10O			no data			A-22HCC/ A-23XCC	232.8/ 241.8	13.43/ 13.60
128	RN5	FO	*Lithopera thornburgi* Sanfilippo and Riedel, 1970	10AE			no data			A-23XCC/ A-24XCC	241.8/ 243.7	13.60/ 13.63
129	RN5	LO	*Carpocanium rubyae* O'Connor, 1997	10V			no data			A-23XCC/ A-24XCC	241.8/ 243.7	13.60/ 13.63
130	RN5	LO	*Carpocanium* sp. X	10U			no data			A-23XCC/ A-24XCC	241.8/ 243.7	13.60/ 13.63
131	RN5	LO	*Lophocyrtis leptetrum* (Sanfilippo and Riedel, 1970)	13A			no data			A-23XCC/ A-24XCC	241.8/ 243.7	13.60/ 13.63
132	RN5	FO	*Dictyocoryne ontongensis* Riedel and Sanfilippo, 1971	8F			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
133	RN5	LO	*Valkyria pukapuka* O'Connor, 1997	12D			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
134	RN5	LO	*Liriospyris parkerae* Riedel and Sanfilippo, 1971	12E			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
135	RN5	LO	*Carpocanopsis bramlettei* Riedel and Sanfilippo, 1971	10W			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
136	RN5	LO	*Acrocubus octopylus* Haeckel, 1887	12H			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
137	RN5	LO	*Calocycletta virginis* (Haeckel, 1887)	14C		14.46	no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
138	RN5	LO	*Calocycletta costata* (Riedel, 1959)	14A		14.74	no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
139	RN5	LO	*Dendrospyris bursa* Sanfilippo and Riedel, 1973	14G			no data			A-24XCC/ A-25XCC	243.7/ 261.3	13.63/ 14.70
140	RN5	FO	*Dorcadospyris alata* (Riedel, 1959)	13F		15.36	no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
141	RN5	ET	*Dorcadospyris dentata–Dorcadospyris alata*	13F, G	14.98		no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
142	RN4	LO	*Dorcadospyris dentata* Haeckel, 1887	13G		15.18	no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
143	RN4	LO	*Carpocanopsis favosa* (Haeckel, 1887)	10AF			no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
144	RN4	FO	*Liriospyris parkerae* Riedel and Sanfilippo, 1971	12E		15.13	no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
145	RN4	FO	*Phormostichoartus corbula* (Harting, 1863)	10K			no data			A-26XCC/ A-27XCC	270.8/ 280.8	14.83/ 14.99
146	RN4	LO	*Amphisphaera* ? sp. D	9Q			no data			A-27XCC/ A-28XCC	280.8/ 289.8	14.99/ 15.46
147	RN4	LO	*Periphaena decora* Ehrenberg, 1873	9M			no data			A-27XCC/ A-28XCC	280.8/ 289.8	14.99/ 15.46
148	RN4	LO	*Spongodiscus klingi* Caulet, 1986	8H			no data			A-27XCC/ A-28XCC	280.8/ 289.8	14.99/ 15.46
149	RN4	LO	*Eucyrtidium diaphanes* Sanfilippo and Riedel, 1973	10M			no data			A-27XCC/ A-28XCC	280.8/ 289.8	14.99/ 15.46
150	RN4	FO	*Acrocubus octopylus* Haeckel, 1887	12H			no data			A-29XCC/ A-30XCC	299.6/ 309.1	15.97/ 16.17
151	RN4	LO	*Didymocyrtis prismatica* (Haeckel, 1887)	9A		15.63	no data			A-29XCC/ A-30XCC	299.6/ 309.1	15.97/ 16.17
152	RN4	LO	*Carpocanopsis cingulata* Riedel and Sanfilippo, 1971	10AB			no data			A-29XCC/ A-30XCC	299.6/ 309.1	15.97/ 16.17

*, eastern equatorial Pacific (Sanfilippo and Nigrini 1995); **, eastern equatorial Pacific (Lazarus et al. 1995).

Radiolarian events: The last occurrences of *Axoprunum stauraxonium* Haeckel, 1887, *Didymocyrtis avita* (Riedel, 1953), and *Pterocorys campanula* Haeckel, 1887 and the first occurrence of *Pterocorys hertwigii* (Haeckel, 1887) are recognized within this zone.

Correlation and age: This zone is approximately equivalent to the lower part of calcareous nannoplankton Zone CN14. The age of this zone is assigned to the Early to Middle Pleistocene (0.60–1.12 Ma).

Zone RN13 *Anthocyrtidium angulare* Interval Zone (Nigrini 1971)

Definition: This zone is defined as the interval from the last occurrence of *Anthocyrtidium angulare* (Fig. 11C) (top) to the last occurrence of *Pterocanium prismatium* Riedel, 1957 (Fig. 12B) (base).

Base interval: Sample 845A-4H-CC (38.6 mcd) through sample 845C-2H-CC (41.4 mcd), sample 1241A-4H-6, 75–77 cm (35.1 mcd) through sample 1241A-6H-1, 75–77 cm (48.8 mcd).

Radiolarian events: The following bioevents are recognized in this zone: seven first occurrences of *Lamprocyrtis nigriniae* (Caulet, 1971), *Pterocanium praetextum praetextum* (Ehren-

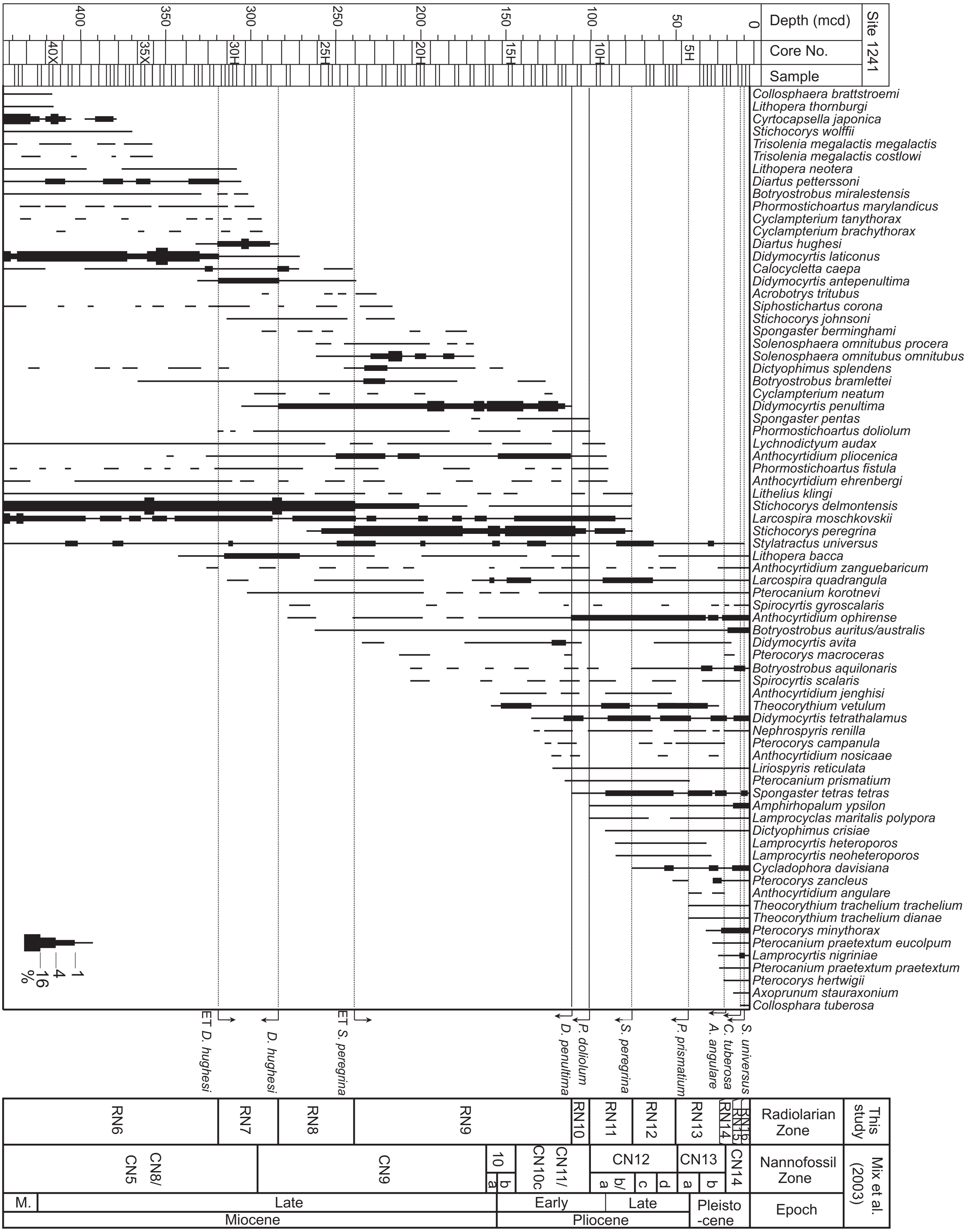

Fig. 4. Stratigraphic distribution of selected radiolarian species at Site 1241.

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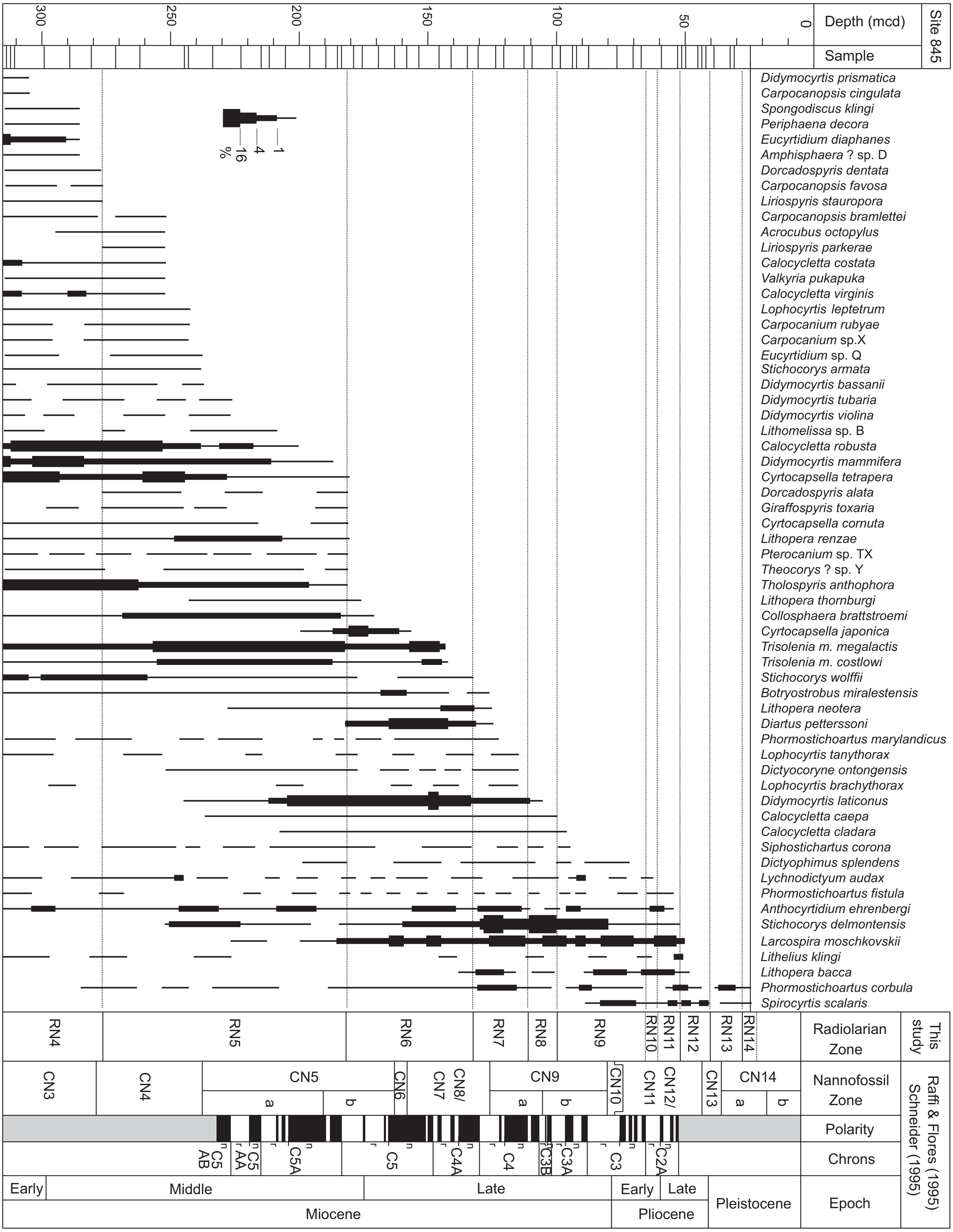
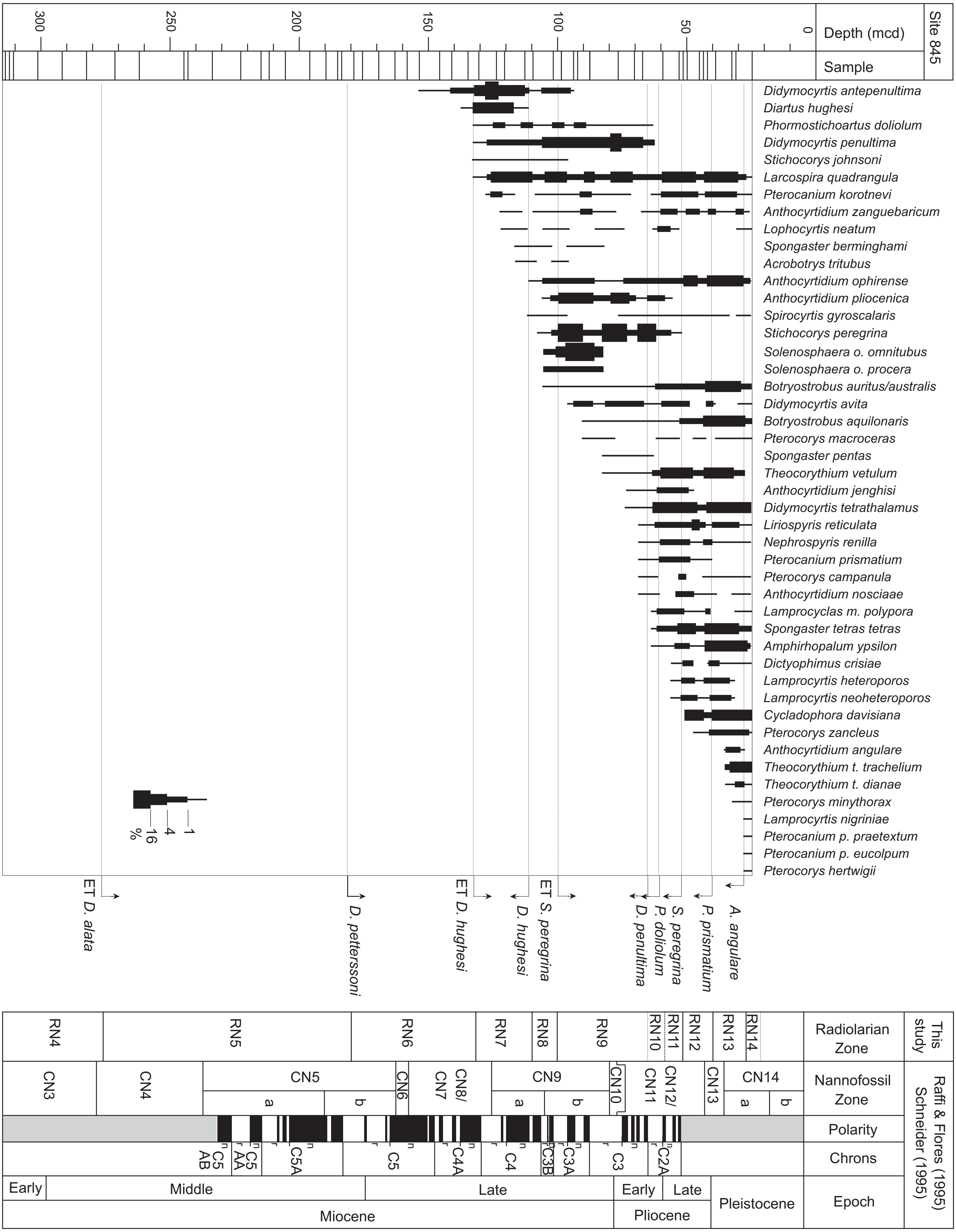


Fig. 5. Stratigraphic distribution of selected radiolarian species at Site 845.



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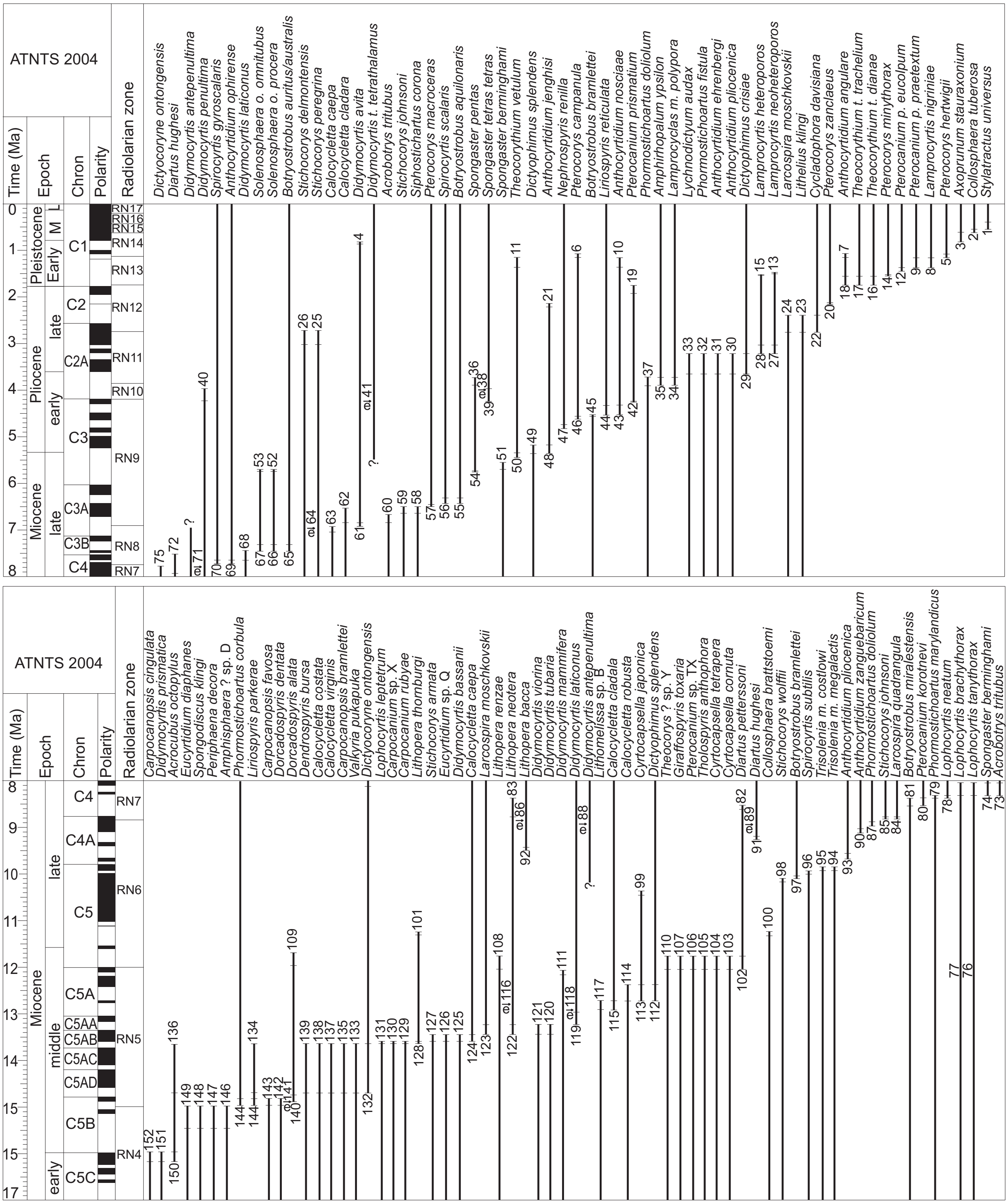

Fig. 6. Radiolarian zones and ranges of stratigraphic valuable species at Sites 884 and 1241. Top and bottom lines mark the lower and upper limits of the location of datum levels, respectively. Even numbers shown in Table 3. Abbreviation: e, evolutionary transition.

berg, 1872), *Pterocanium praetextum eucolpum* Haeckel, 1887, *Pterocorys minythorax* (Nigrini, 1968), *Theocorythium trachelium trachelium* (Ehrenberg, 1872), *Theocorythium trachelium dianae* (Haeckel, 1887), and *Anthocyrtidium angulare*, and four last occurrences of *Anthocyrtidium nosicaae* Caulet, 1979, *Theocorythium vetulum* Nigrini, 1971, *Lamprocyrtis neoheteroporos* Kling, 1973, and *Lamprocyrtis heteroporos* (Hays, 1965).

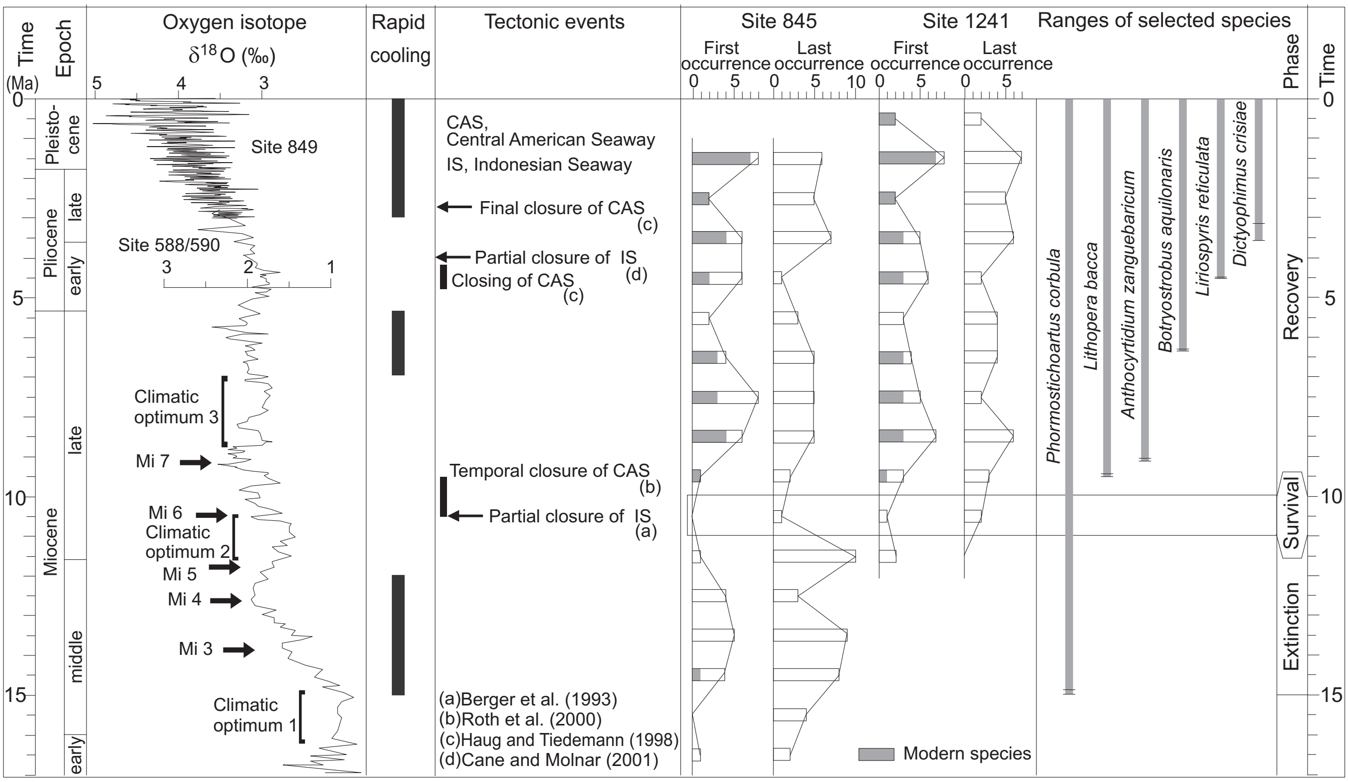

Fig. 7. Comparison of the appearance and extinction rates of radiolarians in the eastern equatorial Pacific during the last 17 Ma with a generalized benthic foraminiferal oxygen isotope curve and tectonic events. The isotope curve is after Mix et al. (1995) for the interval between 0 and 2.5 Ma and after Kennett (1986) for the interval between 2.5 and 17 Ma. The isotope curve has been updated to the ATNTS 2004 (Ogg and Smith, 2004) through paleomagnetic correlation provided by Barton and Bloemendal (1986). The isotope events are after Miller et al. (1991) and Barron and Baldauf (1990).

Correlation and age: This zone is placed within the calcareous nannoplankton Zone CN13. The age of this zone is the early Early Pleistocene (1.12–1.75 Ma).

Zone RN12 *Pterocanium prismatium* Interval Zone (Riedel and Sanfilippo 1970)

Definition: This zone corresponds to the stratigraphic interval from the last occurrence of *Pterocanium prismatium* (Fig. 12B) (top) to the last occurrence of *Stichocorys peregrina* (Riedel, 1953) (Fig. 10P) (base).

Base interval: Sample 845C-43H-CC (51.9 mcd) through sample 845B-5H-CC (53.8 mcd), sample 1241A-7H-6, 62–64 cm (66.6 mcd) through sample 1241A-9H-3, 62–64 cm (83.7 mcd).

Radiolarian events: Two first occurrences *Pterocorys zancleus* (Müller, 1855) and *Cycladophora davisiana* Ehrenberg, 1861, and four last occurrences *Anthocyrtidium jenghisi* Streeter, 1988, *Lithelius klingi* Kamikuri, 2009, *Larcospira moschkovskii* Kruglikova, 1978 and *Stichocorys delmontensis* (Campbell and Clark, 1944) are found in this zone.

Correlation and age: This zone corresponds to the interval from the lower part of calcareous nannoplankton Zone CN13 to the upper part of CN12. The age of this zone is assigned to the late late Pliocene (1.75–2.74 Ma). The Pliocene–Pleistocene boundary is located within the uppermost part of RN12.

Zone RN11 *Lychnodictyum audax* Interval Zone (Moore 1995 renamed by Sanfilippo and Nigrini 1998)

Definition: This zone corresponds to the interval from the last occurrence of *Stichocorys peregrina* (Fig. 10P) (top) to the last occurrence of *Phormostichoartus doliolum* (Riedel and Sanfilippo, 1971) (Fig. 10I) (base).

Base interval: Sample 845A-6H-CC (59.7 mcd) through sample 845B-6H-CC (66.7 mcd), sample 1241A-10H-5, 62–64 cm (97.2 mcd) through sample 1241A-11H-3, 62–64 cm (104.8 mcd).

Radiolarian events: Five first occurrences *Lamprocyrtis neoheteroporos, Lamprocyrtis heteroporos, Dictyophimus crisiae* Ehrenberg, 1854, *Lamprocyclas maritalis polypora* Nigrini, 1967 and *Amphirhopalum ypsilon* Haeckel, 1887, and five last occurrences *Anthocyrtidium pliocenica* (Seguenza, 1880), *Anthocyrtidium ehrenbergi* (Stöhr, 1880), *Phormostichoartus fistula* Nigrini, 1977, *Lychnodictyum audax* Riedel, 1953, and *Spongaster pentas* Riedel and Sanfilippo, 1970 are recognized in this zone.

Correlation and age: This zone is approximately equivalent to the lower part of Zone CN12. The basal datum of this zone (last occurrence of *Phormostichoartus doliolum*) has been recorded within the Chron C2A.r. This zone spans the Early

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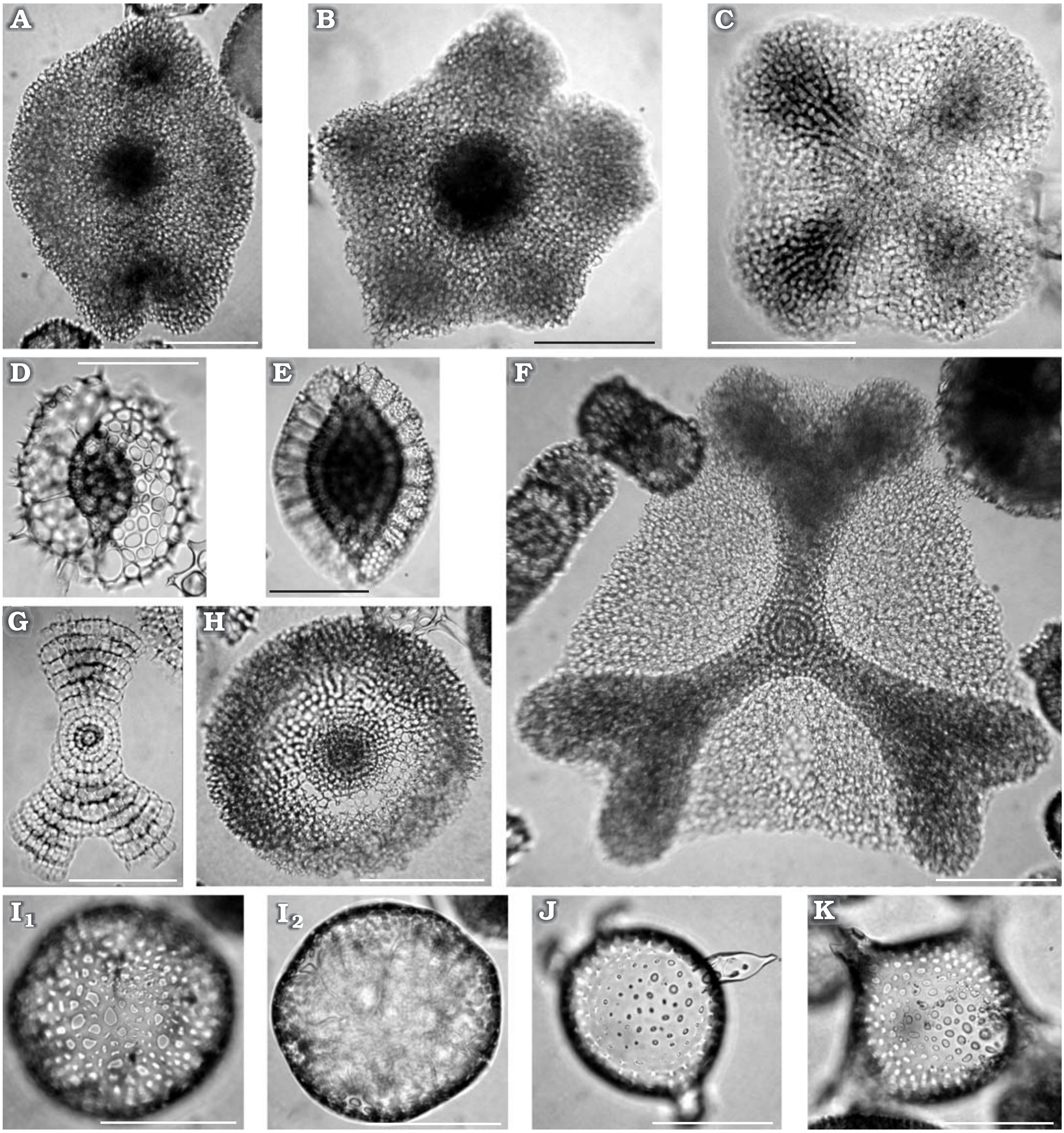

Fig. 8. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Spongaster berminghami* (Campbell and Clark, 1944). MPC-4845; 1241A-28H-03, 62–64 cm, T51/2; Zone RN7. **B**. *Spongaster pentas* Riedel and Sanfilippo, 1970. MPC-3363; 1241A-12H-03, 62–64 cm, W33/0; Zone RN9. **C**. *Spongaster tetras tetras* Ehrenberg, 1860. MPC-3332; 1241A-2H-03, 75–77 cm, Q52/3; Zone RN16. **D**. *Larcospira quadrangula* Haeckel, 1887. MPC-3357; 1241A-9H-05, 62–64 cm, E51/0; Zone RN11. **E**. *Larcospira moschkovskii* Kruglikova, 1978. MPC-4847; 1241A-29H-03, 62–64 cm, G47/0; Zone RN7. **F**. *Dictyocoryne ontongensis* Riedel and Sanfilippo, 1971. MPC-3303; 845A-13HCC, X31/2; Zone RN6. **G**. *Amphirhopalum ypsilon* Haeckel, 1887. MPC-3332; 1241A-2H-03, 75–77 cm, T45/0; Zone RN16. **H**. *Spongodiscus klingi* Caulet, 1986. MPC-3336; 1241A-3H-03, 77–79 cm, X26/1; Zone RN14. **I**. *Collosphaera brattstroemi* Bjørklund and Goll, 1979. MPC-3317; 845A-20HCC, K51/1; Zone RN5. **J**. *Trisolenia megalactis megalactis* Ehrenberg, 1872. MPC-3317; 845A-20HCC, Q53/0; Zone RN5. **K**. *Trisolenia megalactis costlowi* Bjørklund and Goll, 1979. MPC-3324; 845A-26XCC, G37/4; Zone RN5. Scale bars 100 µm.

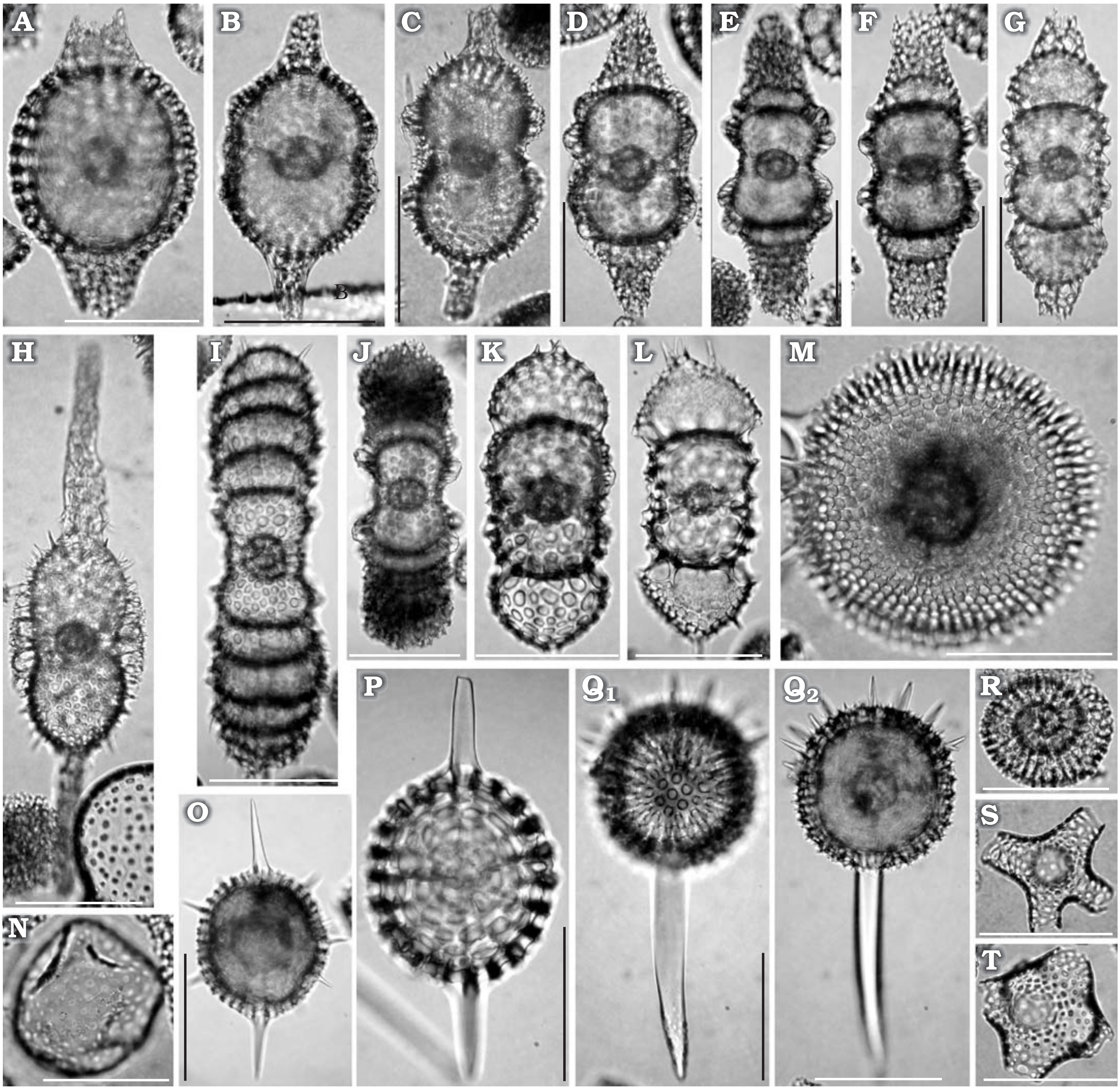

Fig. 9. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Didymocyrtis prismatica* (Haeckel, 1887). MPC-3328; 845A-30XCC, J23/2; Zone RN4. **B**. *Didymocyrtis tubaria* (Haeckel, 1887). MPC-3328; 845A-30XCC, P23/0; Zone RN4. **C**. *Didymocyrtis violina* (Haeckel, 1887). MPC-3330; 845A-31X-03, 0–2 cm, K36/0; Zone RN4. **D**. *Didymocyrtis mammifera* (Haeckel, 1887). MPC-3320; 845A-22HCC, S46/3; Zone RN5. **E**. *Didymocyrtis laticonus* (Riedel, 1959). MPC-4855; 1241A-31H-05, 62–64 cm, R49/2; Zone RN6. **F**. *Didymocyrtis antepenultima* (Riedel and Sanfilippo, 1970). MPC-4849; 1241A-30H-01, 62–64 cm, J26/3; Zone RN7. **G**. *Didymocyrtis penultima* (Riedel, 1957). MPC-3373; 1241A-15H-05, 62–64 cm, U31/0; Zone RN9. **H**. *Didymocyrtis bassanii* (Carnevale, 1908). MPC-3322; 845A-24XCC, S48/4; Zone RN5. **I**. *Diartus hughesi* (Campbell and Clark, 1944). MPC-4847; 1241A-29H-03, 62–64 cm, T25/1; Zone RN7. **J**. *Diartus petterssoni* (Riedel and Sanfilippo, 1970). MPC-4863; 1241A-34H-01, 62–64 cm, R32/4; Zone RN6. **K**. *Didymocyrtis avita* (Riedel, 1953). MPC-3373; 1241A-15H-05, 62–64 cm, V51/0; Zone RN9. **L**. *Didymocyrtis tetrathalamus* (Haeckel, 1887). MPC-3332; 1241A-2H-03, 75–76 cm, X43/0; Zone RN16. **M**. *Periphaena decora* Ehrenberg, 1873. MPC-3326; 845A-28XCC, S37/0; Zone RN4. **N**. *Collosphaera tuberosa* Haeckel, 1887. MPC-3331; 1241A-2H-02, 75–76 cm, K23/0; Zone RN16. **O**. *Stylatractus universus* Hays, 1970. MPC-3331; 1241A-2H-05, 75–77 cm, U32/0; Zone RN15. **P**. *Axoprunum stauraxonium* Haeckel, 1887. MPC-3331; 1241A-2H-02, 75–77 cm, W25/0; Zone RN16. **Q**. *Amphisphaera*? sp. D. MPC-3326; 845A-28XCC, K18/4; Zone RN4. **R**. *Lithelius klingi* Kamikuri, 2009. MPC-3324; 845A-26XCC, W34/0; Zone RN5. **S**. *Solenosphaera omnitubus procera* Sanfilippo and Riedel, 1974. MPC-3383; 1241A-19H-05, 62–64 cm, U51/3; Zone RN9. **T**. *Solenosphaera omnitubus omnitubus* Riedel and Sanfilippo, 1971. MPC-4834; 1241A-22H-05, 62–64 cm, F36/0; Zone RN9. Scale bars 100 μm.

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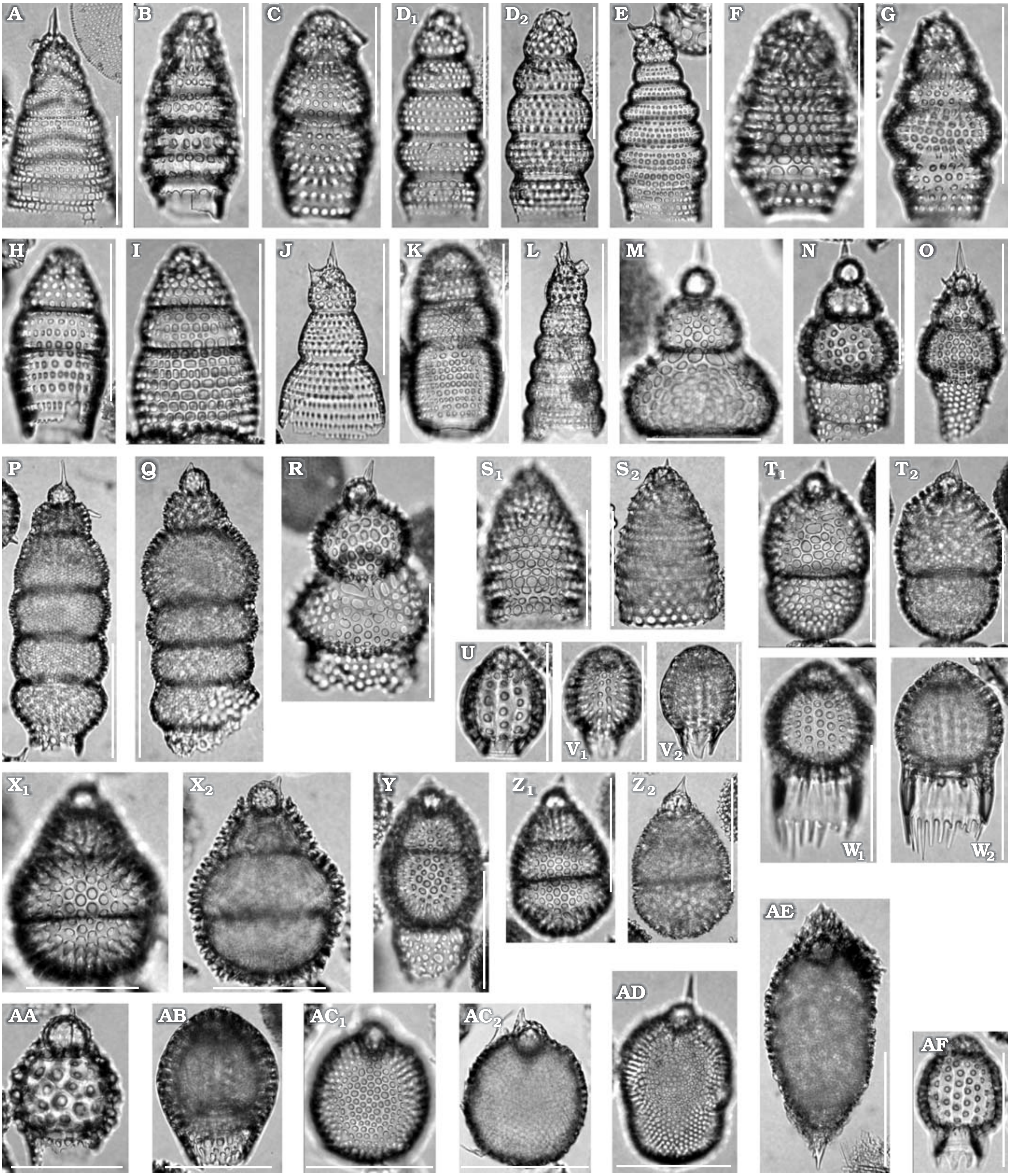

Fig.10. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Spirocyrtis scalaris* Haeckel, 1887. MPC-3337; 1241A-3H-04, 75–77 cm, M41/3; Zone RN14. **B**. *Botryostrobus miralestensis* (Campbell and Clark, 1944). MPC-4863; 1241A-34H-01, 62–64 cm, K43/3; Zone RN6. **C**. *Phormostichoartus fistula* Nigrini, 1977. MPC-4846; 1241A-28H-05, 62–64 cm, S46/0; Zone RN7. **D**. *Botryostrobus auritus/australis* (Ehrenberg, 1884). MPC-3333; 1241A-2H-05, 75–77 cm, H43/2; Zone RN15. **E**. *Spirocyrtis gyroscalaris* Nigrini, 1977. MPC-4843; 1241A-27H-03, 62–64 cm, R43/4; Zone RN8. **F**. *Botryostrobus aquilonaris* (Bailey, 1856). MPC-3333; 1241A-2H-05, 75–77 cm, K43/4; Zone RN16. **G**. *Botryostrobus bramlettei* (Campbell and Clark, 1944). MPC-4839; 1241A-25H-01, 62–64 cm, W37/2; Zone RN8. **H**. *Phormostichoartus marylandicus* (Martin, 1904). →

to late Pliocene (2.74–3.87 Ma). The early–late Pliocene boundary is located within the lower part of RN11.

Zone RN10 *Phormostichoartus doliolum* Interval Zone (Johnson et al. 1989 emended by Moore 1995)

Definition: This zone is defined as the stratigraphic interval from the last occurrence of *Phormostichoartus doliolum* (Fig. 10I) (top) to the last occurrence of *Didymocyrtis penultima* (Riedel, 1957) (Fig. 9G) (base).

Base interval: Sample 845A-6H-CC (59.7 mcd) through sample 845B-6H-CC (66.7 mcd), sample 1241A-11H-5, 62–64 cm (107.9 mcd) through sample 1241A-12H-3, 62–64 cm (115.7 mcd).

Radiolarian events: This zone contains the first occurrence of *Spongaster tetras tetras* Ehrenberg, 1860 and the evolutionary transition from *Spongaster pentas* to *Spongaster tetras tetras*.

Correlation and age: This zone is correlated within Zone CN11. The base of this zone is placed within the middle part of the Chron C3Ar. The age of this zone is equivalent to the late early Pliocene (3.87–4.19 Ma) (Sanfilippo and Nigrini 1998).

Zone RN9 *Stichocorys peregrina* Interval Zone (Riedel and Sanfilippo 1970 emended by Moore 1995)

Definition: This zone is the interval from the last occurrence of *Didymocyrtis penultima* (Fig. 9G) (top) to the evolutionary transition from *Stichocorys delmontensis* (Fig. 10Q) to *Stichocorys peregrina* (Fig. 10P) (base).

Base interval: Sample 845A-10H-5, 0–2 cm (98.1 mcd) through sample 845A-10H-CC (102.1 mcd), sample 1241A--23H-5, 62–64 cm (236.5 mcd) through sample 1241A--24H-3, 62–64 cm (243.7 mcd).

Radiolarian events: The following bioevents are observed in this zone: twelve first occurrences of *Pterocanium prismatium*, *Anthocyrtidium nosicaae*, *Liriospyris reticulata* (Ehrenberg, 1872), *Pterocorys campanula*, *Nephrospyris renilla* Haeckel, 1887, *Anthocyrtidium jenghisi*, *Theocorythium vetulum*, *Spongaster pentas*, *Botryostrobus aquilonaris* (Bailey, 1856), *Spirocyrtis scalaris* Haeckel, 1887, *Pterocorys macroceras* (Popofsky, 1913) and *Didymocyrtis avita*, and ten last occurrences of *Botryostrobus bramlettei* (Campbell and Clark, 1944), *Dictyophimus splendens* (Campbell and Clark, 1944), *Spongaster berminghami* (Campbell and Clark, 1944), *Solenosphaera omnitubus omnitubus* Riedel and Sanfilippo, 1971, *Solenosphaera omnitubus procera* Sanfilippo and Riedel, 1974, *Siphostichartus corona* (Haeckel, 1887), *Stichocorys johnsoni* Caulet, 1986, *Acrobotrys tritubus* Riedel, 1957, *Calocycletta cladara* Sanfilippo and Riedel, 1992, and *Calocycletta caepa* Moore, 1972 and an evolutionary transition from *Didymocyrtis avita* to *Didymocyrtis tetrathalamus* (Haeckel, 1887).

Correlation and age: This zone is correlated with the stratigraphic interval between the Zone CN9b and CN11. The base of this zone is placed within the middle part of the Chron C3Ar. The Miocene–Pliocene boundary is thought to be placed within the middle part of RN9. This zone ranges in age from the late Miocene to the early Pliocene (6.89–4.19 Ma).

Zone RN8 *Didymocyrtis penultima* Interval Zone (Riedel and Sanfilippo 1970 emended by Riedel and Sanfilippo 1978)

Definition: This zone is defined as the interval zone from the evolutionary transition from *Stichocorys delmontensis* (Fig. 10Q) to *Stichocorys peregrina* (Fig. 10P) (top) to the last occurrence of *Diartus hughesi* (Campbell and Clark, 1944) (Fig. 9I) (base).

Base interval: Sample 845B-10H-CC (108.9 mcd) through sample 845A-11H-CC (113.0 mcd), sample 1241A-27H-5, 62–64 cm (279.1 mcd) through sample 1241A-28H-3, 62–64 cm (287.0 mcd).

Radiolarian events: The following bioevents occurred in this zone: five first occurrences of *Botryostrobus auritus/australis* (Ehrenberg, 1884), *Solenosphaera omnitubus omnitubus*, *Solenosphaera omnitubus procera*, *Anthocyrtidium ophirense* (Ehrenberg, 1872) and *Spirocyrtis gyroscalaris* Nigrini, 1977, the last occurrence of *Didymocyrtis laticonus* (Riedel, 1959), and the evolutionary transition from *Didymocyrtis antepenultima* (Riedel and Sanfilippo, 1970) to *Didymocyrtis penultima*.

MPC-4852; 1241A-31H-07, 62–64 cm, K50/4; Zone RN6. **I**. *Phormostichoartus doliolum* (Riedel and Sanfilippo, 1971). MPC-3374; 1241A-16H-04, 62–64 cm, V24/3; Zone RN9. **J**. *Siphostichartus corona* (Haeckel, 1887). MPC-4836; 1241A-23H-05, 62–64 cm, G47/0; Zone RN9. **K**. *Phormostichoartus corbula* (Harting, 1863). MPC-4854; 1241A-31H-03, 62–64 cm, H44/2; Zone RN7. **L**. *Spirocyrtis subtilis* Petrushevskaya, 1972. MPC-3326; 845A-28XCC, X19/0; Zone RN4. **M**. *Eucyrtidium diaphanes* Sanfilippo and Riedel, 1973. MPC-3326; 845A-28XCC, K35/3; Zone RN4. **N**. *Stichocorys wolffii* Haeckel, 1887. MPC-3328; 845A-30XCC, L18/0; Zone RN4. **O**. *Stichocorys armata* Haeckel, 1887. MPC-3326; 845A-28XCC, K52/0; Zone RN4. **P**. *Stichocorys peregrina* (Riedel, 1953). MPC-4834; 1241A-22H-05, 62–64 cm, U49/0; Zone RN9. **Q**. *Stichocorys delmontensis* (Campbell and Clark, 1944). MPC-4851; 1241A-30H-05, 62–64 cm, M40/0; Zone RN7. **R**. *Stichocorys johnsoni* Caulet, 1986. MPC-4851; 1241A-30H-05, 62–64 cm, P42/0; Zone RN7. **S**. *Eucyrtidium* sp. Q. MPC-3325; 845A-27XCC, P40/1; Zone RN4. **T**. *Lithopera renzae* Sanfilippo and Riedel, 1970. MPC-3322; 845A-24XCC, W34/1; Zone RN5. **U**. *Carpocanium* sp. X. MPC-3324; 845A-26XCC, V42/4; Zone RN5. **V**. *Carpocanium rubyae* O'Connor, 1997. MPC-3323; 845A-25XCC, J44/2; Zone RN5. **W**. *Carpocanopsis bramlettei* Riedel and Sanfilippo, 1971. MPC-3328; 845A-30XCC, K44/1; Zone RN4. **X**. *Cyrtocapsella cornuta* Haeckel, 1887. MPC-3324; 845A-26XCC, P44/3; Zone RN5. **Y**. *Cyrtocapsella japonica* (Nakaseko, 1963). MPC-4885; 1241A-41X-03, 62–64 cm, O50/0; Zone RN6. **Z**. *Cyrtocapsella tetrapera* (Haeckel, 1887). MPC-3320; 845A-22HCC, P49/0; Zone RN5. **AA**. *Theocorys* ? sp. Y. MPC-3323; 845A-25XCC, U45/3; Zone RN5. **AB**. *Carpocanopsis cingulata* Riedel and Sanfilippo, 1971. MPC-3328; 845A-30XCC, X25/3; Zone RN4. **AC**. *Lithopera neotera* Sanfilippo and Riedel, 1970. MPC-4870; 1241A-36X-03, 62–64 cm, L49/2; Zone RN6. **AD**. *Lithopera bacca* Ehrenberg, 1872. MPC-3343; 1241A-4H-04, 75–77 cm, Q25/3; Zone RN13. **AE**. *Lithopera thornburgi* Sanfilippo and Riedel, 1970. MPC-4885; 1241A-41X-03, 62–64 cm, K36/4; Zone RN6. **AF**. *Carpocanopsis favosa* (Haeckel, 1887). MPC-3325; 845A-27XCC, R27/3; Zone RN4. Scale bars 100 µm.

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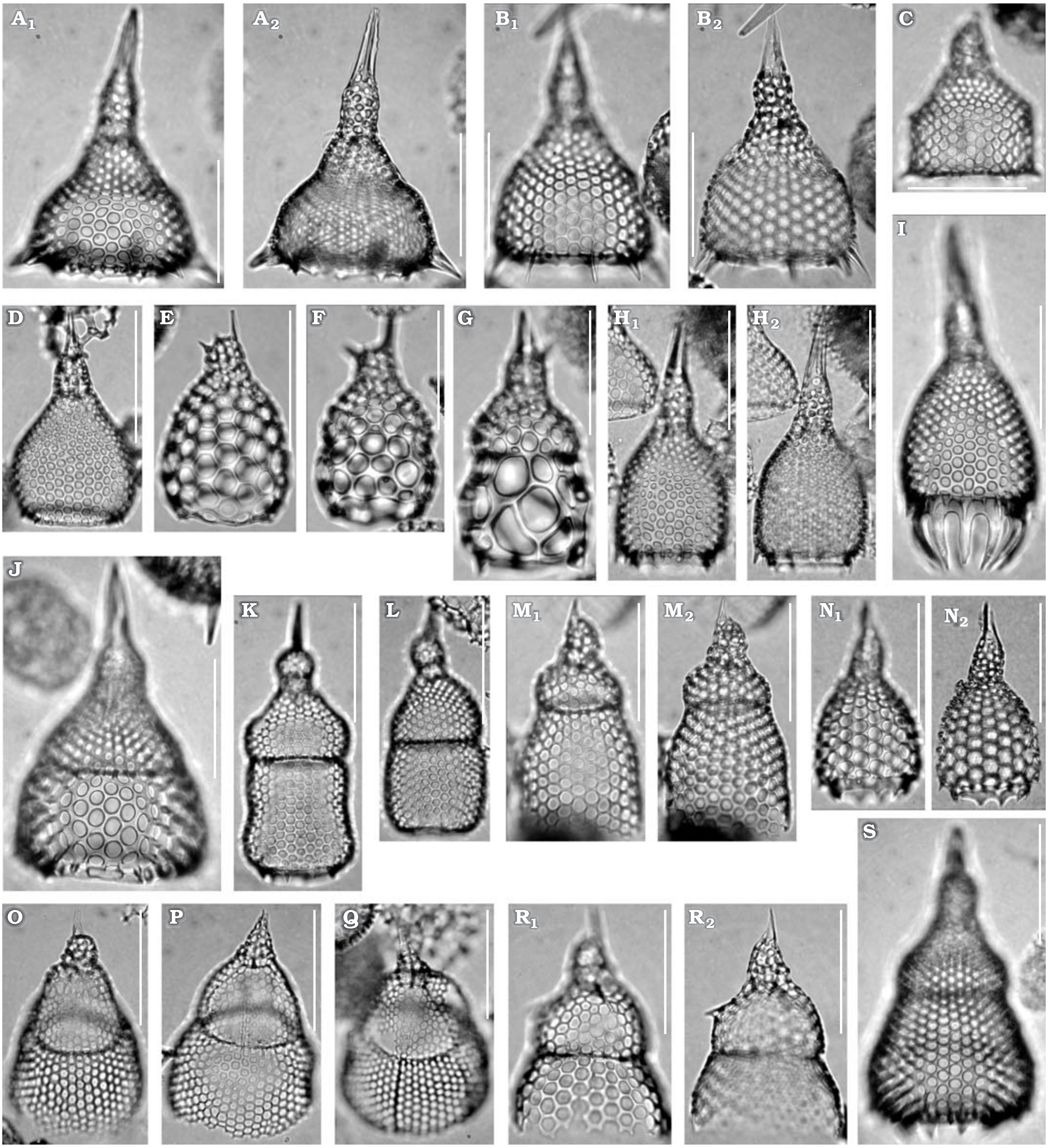

Fig. 11. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Anthocyrtidium jenghisi* Streeter, 1988. MPC-3358; 1241A-10H-03, 62–64 cm, H56/0; Zone RN11. **B**. *Anthocyrtidium ophirense* (Ehrenberg, 1872). MPC-3333; 1241A-2H-05, 75–77 cm, M52/4; Zone RN15. **C**. *Anthocyrtidium angulare* Nigrini, 1971. MPC-3345; 1241A-4H-06, 75–77 cm, J45/0; Zone RN13. **D**. *Anthocyrtidium ehrenbergi* (Stöhr, 1880). MPC-3372; 1241A-15H-03, 62–65 cm, G21/0; Zone RN9. **E**. *Lamprocyrtis nigriniae* (Caulet, 1971). MPC-3333; 1241A-2H-05, 75–77 cm, Q17/2; Zone RN15. **F**. *Lamprocyrtis neoheteroporos* Kling, 1973. MPC-3345; 1241A-4H-06, 75–77 cm, G26/0; Zone RN13. **G**. *Lamprocyrtis heteroporos* (Hays, 1965). MPC-3349; 1241A-6H-04, 77–79 cm, W35/3; Zone RN12. **H**. *Anthocyrtidium zanguebaricum* (Ehrenberg, 1872). MPC-3361; 1241A-11H-04, 62–64 cm, O20/2; Zone RN10. **I**. *Anthocyrtidium pliocenica* (Seguenza, 1880). MPC-3371; 1241A-14H-05, 62–64 cm, A14/3; Zone RN9. **J**. *Lamprocyclas maritalis polypora* Nigrini, 1967. MPC-3333; 1241A-2H-05, 75–77 cm, G53/2; Zone RN15. **K**. *Theocorythium trachelium trachelium* (Ehrenberg, 1872). MPC-3332; 1241A-2H-03, 75–77 cm, L19/0; Zone RN16. **L**. *Theocorythium trachelium dianae* (Haeckel, 1887). MPC-3338; 1241A-3H-05, 75–77 cm, P26/0; Zone RN14. →

Correlation and age: This zone is located within the lower part of CN9. The basal datum of this zone was recorded within C4n.1r. The age of this zone is the middle late Miocene (7.74–6.89 Ma).

Zone RN7 *Didymocyrtis antepenultima* Interval Zone (Riedel and Sanfilippo 1970 emended by Riedel and Sanfilippo 1978)

Definition: This zone is the stratigraphic interval between the last occurrence of *Diartus hughesi* (Fig. 9I) (top) and the evolutionary transition from *Diartus petterssoni* (Riedel and Sanfilippo, 1970) (Fig. 9J) to *Diartus hughesi* (Fig. 9I) (base).

Base interval: Sample 845B-12H-CC (130.6 mcd) through sample 845A-13H-CC (134.7 mcd), sample 1241A-31H-3, 62–64 cm (318.3 mcd) through sample 1241A-31H-5, 62–64 cm (321.3 mcd).

Radiolarian events: The following bioevents are found in this zone: seven first occurrences of *Acrobotrys tritubus*, *Spongaster berminghami*, *Lophocyrtis neatum* (Sanfilippo and Riedel, 1970), *Pterocanium korotnevi* (Dogiel, 1952), *Larcospira quadrangula* Haeckel, 1887, *Stichocorys johnsoni* and *Phormostichoartus doliolum*, seven last occurrences of *Dictyocoryne ontongensis* Riedel and Sanfilippo, 1971, *Lophocyrtis tanythorax* (Sanfilippo and Riedel, 1970), *Lophocyrtis brachythorax* (Sanfilippo and Riedel, 1970), *Phormostichoartus marylandicus* (Martin, 1904), *Botryostrobus miralestensis* (Campbell and Clark, 1944), *Diartus petterssoni* and *Lithopera neotera* Sanfilippo and Riedel, 1970, and two evolutionary transitions from *Lithopera neotera* to *Lithopera bacca* Ehrenberg, 1872 and from *Didymocyrtis laticonus* to *Didymocyrtis antepenultima*.

Correlation and age: This zone is located in the interval from the lower part of Zone CN9 to the upper part of CN8 and between Chrons C4n and C4An. The age of this zone corresponds to the middle late Miocene (8.84–7.74 Ma).

Zone RN6 *Diartus petterssoni* Interval Zone (Riedel and Sanfilippo 1970 emended by Riedel and Sanfilippo 1978)

Definition: This zone is defined as an interval between the evolutionary transition from *Diartus petterssoni* (Fig. 9J) to *Diartus hughesi* (Fig. 9I) (top) and the first occurrence of *Diartus petterssoni* (Fig. 9J) (base).

Base interval: Sample 845A-17H-CC (178.8 mcd) through sample 845B-17H-CC (184.5 mcd).

Radiolarian events: The following bioevents are observed in this study: five first occurrences *Anthocyrtidium zanguebaricum* (Ehrenberg, 1872), *Diartus hughesi*, *Lithopera bacca*, *Anthocyrtidium pliocenica* and *Botryostrobus bramlettei*, and seven last occurrences *Trisolenia megalactis megalactis* Ehrenberg, 1872, *Trisolenia megalactis costowi* Bjørklund and Goll, 1979, *Spirocyrtis subtilis* Petrushevskaya, 1972, *Stichocorys wolffii* Haeckel, 1887, *Cyrtocapsella japonica* (Nakaseko, 1963), *Collosphaera brattstroemi* Bjørklund and Goll, 1979, and *Lithopera thornburgi* Sanfilippo and Riedel, 1970.

Correlation and age: This zone is placed within the interval from the lower part of Zone CN8 to the upper part of Zone CN5a. The base of this zone is correlated with the boundary bewteen Chron C5r-C5An. This zone ranges in age from the latest middle Miocene to early late Miocene (12.02–8.84 Ma). The middle–late Miocene boundary is located within the lowermost part of RN6.

Zone RN5 *Dorcadospyris alata* Interval Zone (Riedel and Sanfilippo 1970 emended by Riedel and Sanfilippo 1978)

Definition: This zone is the interval between the first occurrence of *Diartus petterssoni* (Fig. 9J) (top) and the evolutionary transition from *Dorcadospyris dentata* Haeckel, 1887 (Fig. 13G) to *Dorcadospyris alata* (Riedel, 1959) (Fig. 13F) (base).

Base interval: Sample 845A-26H-CC (270.8 mcd) through sample 845A-27H-CC (280.8 mcd).

Radiolarian events: This zone includes 26 last occurrences (e.g., *Cyrtocapsella tetrapera* Haeckel, 1887, *Dorcadospyris alata*, *Didymocyrtis bassanii* (Carnevale, 1908), *Lophocyrtis leptetrum* (Sanfilippo and Riedel, 1970), *Calocycletta virginis* (Haeckel, 1887) (see Table 3), 10 first occurrences (*Dictyophimus splendens*, *Cyrtocapsella japonica*, *Calocycletta cladara*, *Didymocyrtis laticonus*, *Lithopera neotera*, *Larcospira moschkovskii*, *Calocycletta caepa*, *Lithopera thornburgi*, *Dictyocoryne ontongensis*, *Dorcadospyris alata*) and two evolutionary transitions (*Lithopera renzae* to *Lithopera neotera* and *Didymocyrtis mammifera* (Haeckel, 1887) to *Didymocyrtis laticonus*).

Correlation and age: The basal datum approximately coincides with the upper limit of Zone CN3. The age of this zone is equivalent to the middle Miocene (14.98–12.02 Ma).

Zone RN4 *Calocycletta costata* Interval Zone (Riedel and Sanfilippo 1970 emended by Riedel and Sanfilippo 1978)

Definition: This zone is defined as the interval from the evolutionary transition from *Dorcadospyris dentata* (Fig. 13G) to

M. *Pterocorys minythorax* (Nigrini, 1968). MPC-3333; 1241A-2H-05, 75–77 cm, M35/2; Zone RN15. **N**. *Anthocyrtidium nosicaae* Caulet, 1979. MPC-3361; 1241A-11H-04, 62–64 cm, V33/1; Zone RN10. **O**. *Pterocorys macroceras* (Popofsky, 1913). MPC-3339; 1241A-3H-06, 75–77 cm, L32/3; Zone RN13. **P**. *Pterocorys campanula* Haeckel, 1887. MPC-3341; 1241A-4H-02, 76–78 cm, V36/4; Zone RN13. **Q**. *Pterocorys hertwigii* (Haeckel, 1887). MPC-3335; 1241A-3H-02, 77–79 cm, S22/0; Zone RN14. **R**. *Pterocorys zancleus* (Müller, 1855). MPC-3332; 1241A-2H-03, 75–77 cm, G35/3; Zone RN16. **S**. *Theocorythium vetulum* Nigrini, 1971. MPC-3349; 1241A-6H-04, 77–79 cm, T44/4; Zone RN12.

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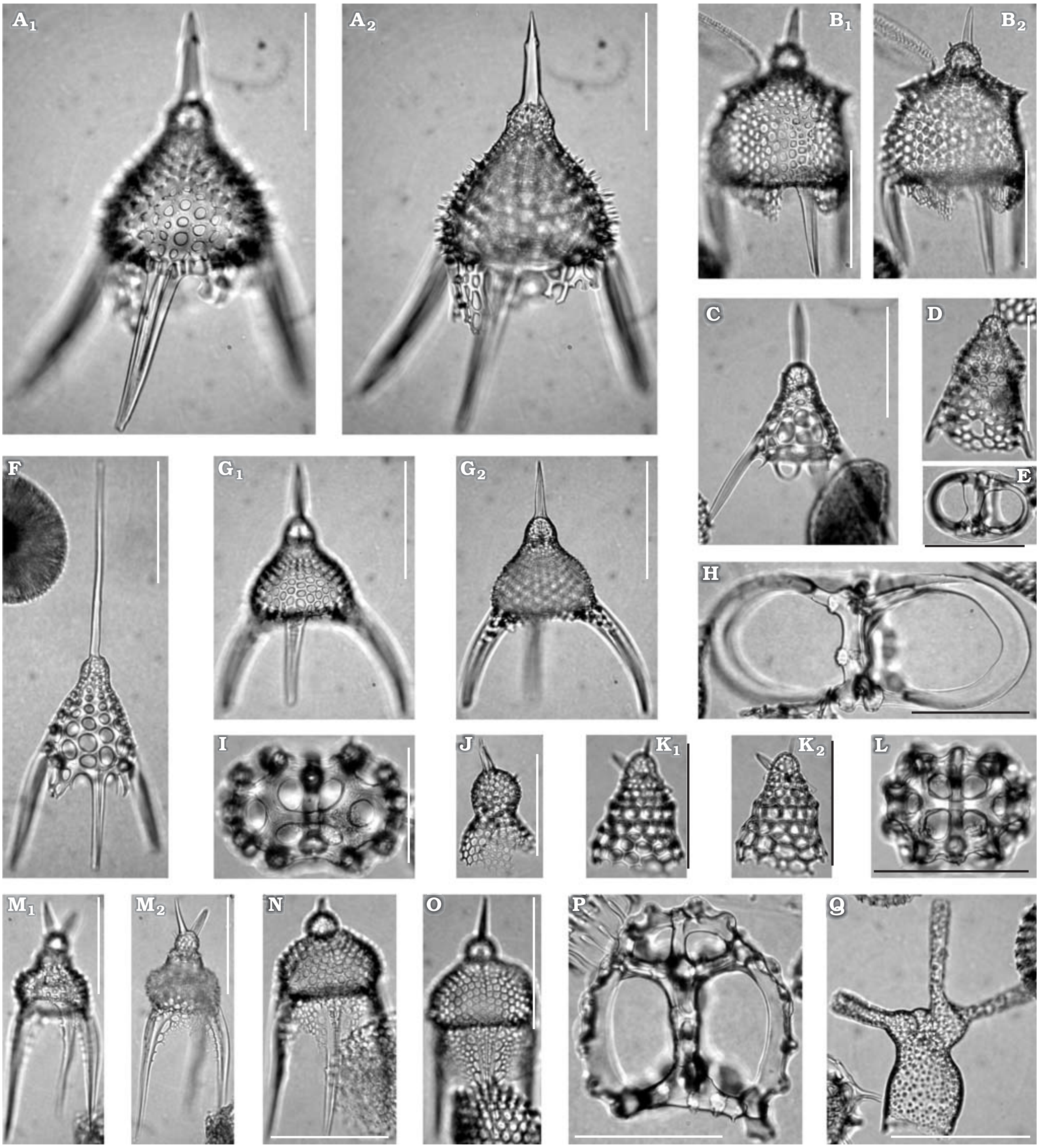

Fig. 12. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Lychnodictyum audax* Riedel, 1953. MPC-3388; 1241A-21H-04, 62–64 cm, W15/1; Zone RN9. **B**. *Pterocanium prismatium* Riedel, 1957. MPC-3280; 845A-4HCC, R47/0; Zone RN13. **C**. *Dictyophimus crisiae* Ehrenberg, 1854. MPC-3333; 1241A-2H-05, 75–77 cm, U31/4; Zone RN15. **D**. *Valkyria pukapuka* O'Connor, 1997. MPC-3326; 845A-28XCC, O20/0; Zone RN4. **E**. *Liriospyris parkerae* Riedel and Sanfilippo, 1971. MPC-3324; 845A-26XCC, R39/0; Zone RN5. **F**. *Dictyophimus splendens* (Campbell and Clark, 1944). MPC-4835; 1241A-23H-03, 62–64 cm, K40/2; Zone RN9. **G**. *Pterocanium korotnevi* (Dogiel, 1952). MPC-3386; 1241A-20H-05, 62–64 cm, G24/0; Zone RN9. **H**. *Acrocubus octopylus* Haeckel, 1887. MPC-3326; 845A-28XCC, R39/4; Zone RN4. **I**. *Tholospyris anthopora* (Haeckel, 1887). MPC-3328; 845A-30XCC, P53/3; Zone RN4. **J**. *Lithomelissa* sp. B. MPC-3318; 845A-20HCC, P23/3; Zone RN5. **K**. *Cycladophora davisiana* Ehrenberg, 1861. MPC-3333; 1241A-2H-05, 75–77 cm, P28/2; Zone RN15. **L**. *Tholospyris kantiana* (Haeckel, 1887). MPC-3324; 845A-26XCC, X28/4; Zone RN5. **M**. *Pterocanium* sp. TX. MPC-3319; 845A-21HCC, X47/0; Zone RN5. **N**. *Pterocanium praetextum praetextum* (Ehrenberg, 1872). MPC-3357; 1241A-9H-05, 62–64 cm, E51/0; Zone RN11. **O**. *Pterocanium praetextum eucolpum* Haeckel, 1887. MPC-3338; 1241A-3H-05, 75–77 cm, R22/2; Zone RN14. **P**. *Giraffospyris toxaria* (Haeckel, 1887). MPC-3326; 845A-28XCC, R27/2; Zone RN4. **Q**. *Acrobotrys tritubus* Riedel, 1957. MPC-3299; 845A-11HCC, H48/2; Zone RN7. Scale bars 100 µm.

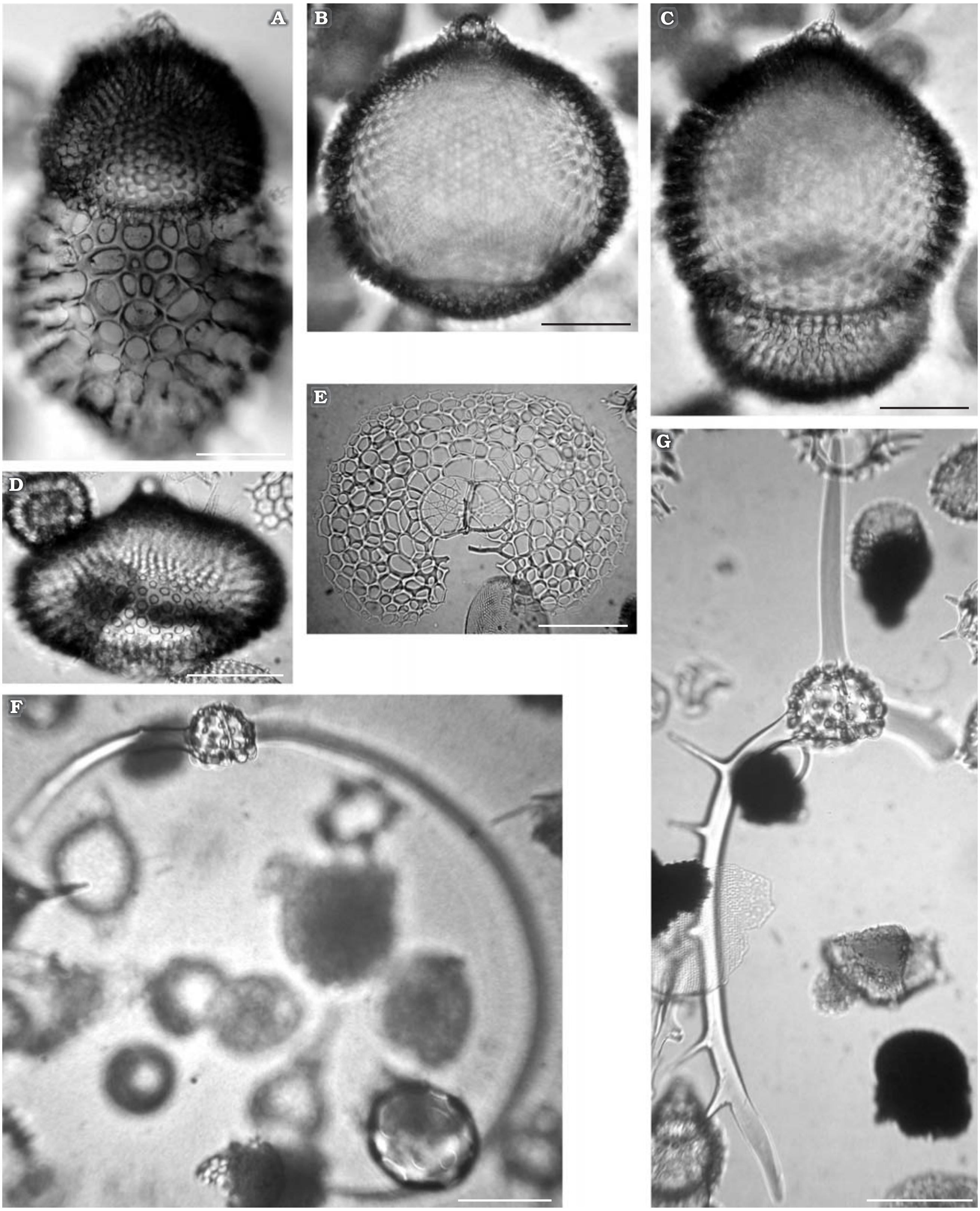

Fig. 13. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Lophocyrtis* (*Cyclampterium*) *leptetrum* (Sanfilippo and Riedel, 1970). MPC-3322; 845A-24XCC, R43/3; Zone RN5. **B**. *Lophocyrtis* (*Cyclampterium*) *neatum* (Sanfilippo and Riedel, 1970). MPC-4847; 1241A-29H-03, 62–64 cm, O14/0; Zone RN7. **C**. *Lophocyrtis* (*Cyclampterium*) *tanythorax* (Sanfilippo and Riedel, 1970). MPC-4854; 1241A-31H-03, 62–64 cm, L40/0; Zone RN7. **D**. *Lophocyrtis* (*Cyclampterium*) *brachythorax* (Sanfilippo and Riedel, 1970). MPC-4870; 1241A-36X-03, 62–64 cm, S32/3; Zone RN6. **E**. *Nephrospyris renilla* Haeckel, 1887. MPC-3337; 1241A-3H-04, 75–77 cm, T37/0; Zone RN14. **F**. *Dorcadospyris alata* (Riedel, 1959). MPC-3322; 845A-24XCC, R45/0; Zone RN5. **G**. *Dorcadospyris dentata* Haeckel, 1887. MPC-3328; 845A-30XCC, G39/0; Zone RN4. Scale bars 100 µm.

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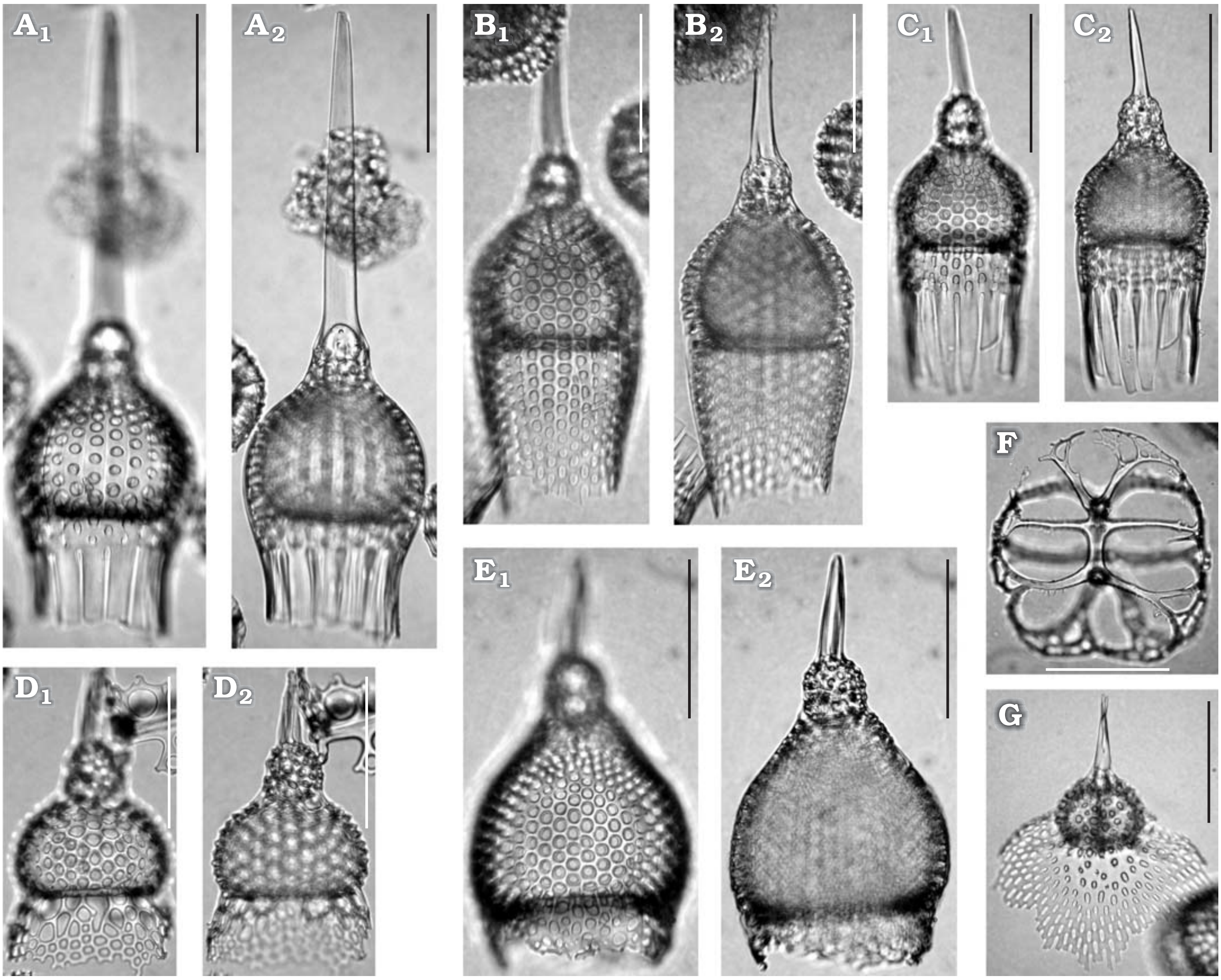

Fig. 14. Radiolarians from the early Miocene to Pleistocene of the eastern equatorial Pacific. **A**. *Calocycletta* (*Calocyclissima*) *costata* (Riedel, 1959). MPC-3324; 845A-26XCC, R19/4; Zone RN5. **B**. *Calocycletta* (*Calocycletta*) *robusta* Moore, 1971. MPC-3326; 845A-28XCC, Q40/3; Zone RN4. **C**. *Calocycletta* (*Calocycletta*) *virginis* (Haeckel, 1887). MPC-3326; 845A-28XCC, V46/3; Zone RN4. **D**. *Calocycletta* (*Calocycletta*) *cladara* Sanfilippo and Riedel, 1992. MPC-3299; 845A-11HCC, K47/4; Zone RN7. **E**. *Calocycletta* (*Calocyclior*) *caepa* Moore, 1972. MPC-4852; 1241A-30H-07, 62–64 cm, R51/4; Zone RN7. **F**. *Liriospyris reticulata* (Ehrenberg, 1872). MPC-3337; 1241A-3H-04, 75–77 cm, Q49/3; Zone RN14. **G**. *Dendrospyris bursa* Sanfilippo and Riedel, 1973. MPC-3325; 845A-27XCC, N27/0; Zone RN4. Scale bars 100 μm.

Dorcadospyris alata (Fig. 13F) (top) to the first occurrence of *Calocycletta costata* (Riedel, 1959) (Fig. 14A) (base).

Radiolarian events: The following bioevents occur in this zone: Eight last occurrences of *Dorcadospyris dentata*, *Carpocanopsis favosa* (Haeckel, 1887), *Amphisphaera* ? sp. D, *Periphaena decora* Ehrenberg, 1873, *Spongodiscus klingi* Caulet, 1986, *Eucyrtidium diaphanes* Sanfilippo and Riedel, 1973, *Didymocyrtis prismatica* (Haeckel, 1887) and *Carpocanopsis cingulata* Riedel and Sanfilippo, 1971, and three first occurrences of *Liriospyris parkerae* Riedel and Sanfilippo, 1971, *Phormostichoartus corbula* (Harting, 1863), and *Acrocubus octopylus*.

Correlation and age: This zone is correlated with the upper part of calcareous nannoplankton Zone CN3 (Sanfilippo and Nigrini, 1998). This zone ranges in age from the latest early Miocene to early middle Miocene (14.98–17.03 Ma).

Discussion

Radiolarian events in the tropics.—We recognize 61 first occurrences, 81 last occurrences and 10 evolutionary transitions at the two sites (Table 3, Fig. 6). Most of the radiolarian events encountered in our study indicate high synchroneity between the two sites. Moore et al. (1993) found 39 radiolarian events since the late Miocene in the eastern equatorial Pacific. These events are also identified at Sites 845 and 1241, and are approximately synchronous. Johnson and

Nigrini (1985) recognized 50 radiolarian events through the Neogene in the equatorial Indo-Pacific and documented the degree of synchroneity or diachroneity. They identified and dated 29 radiolarian events at DSDP Site 503 in the eastern equatorial Pacific. Most of the 29 events are also identified at Sites 845 and 1241 in this study, and there is a good agreement with their ages between the three sites, although large differences are recognized in a few events including the first occurrence of *Botryostrobus aquilonaris* (Fig. 10F) and the last occurrence of *Dendrospyris bursa* (Fig. 14G), *Eucyrtidium diaphanes* (Fig. 10M), and *Dorcadospyris alata* (Fig. 13F). This indicates that the majority of the events identified by Johnson and Nigrini (1985) are synchronous within the restricted eastern equatorial Pacific region. However, among the 152 events that are identified in this study, the majority (123 out of 152) have not been well dated in the other sections, so we cannot discuss the degree of synchroneity of those datum levels over the tropical oceans. To provide a more refined high-resolution radiolarian biostratigraphy for more precise dating and correlation in the tropics, it will be important to examine more complete radiolarian sequences in other regions to determine the degree of synchroneity between regions and to select a number of useful secondary radiolarian biohorizons.

Radiolarian evolutionary patterns.—The ages of appearance and extinction events of 115 radiolarian species were determined for the eastern equatorial Pacific during the past 17 Ma. These data have allowed us to discuss the relationship between the evolutionary turnover of radiolarian species and paleoceanographic changes in the equatorial Pacific. The number of appearances and extinctions of radiolarians in one million year increments in the equatorial Pacific from 17.0 Ma to the present is plotted in Fig. 7. This figure suggests no periods of mass extinctions of radiolarians during the past 17 Ma. As discussed below, a relatively rapid replacement of radiolarian species in the assemblages occurred near the middle–late Miocene boundary. This turnover event represents the gradual extinction of a number of radiolarian species and their gradual replacement by newly evolved species.

During the middle Miocene (17.0 to 11.0 Ma), the appearance rate of tropical radiolarians did not exceed five events per one million year. Among the species that evolved during the middle Miocene, *Phormostichoartus corbula* (Fig. 10K) is the only extant radiolarian species. This species is distributed in the lower part of the intermediate water (500 to 1000 m of water depth) of the modern ocean (Kling and Boltovskoy 1995; see also Table 3 and Fig. 7 herein). The environmental character of intermediate water may be relatively stable since the middle Miocene in the equatorial Pacific. The rate of extinction of radiolarians during the middle Miocene is generally high. Between 15.0 and 11.0 Ma, extinction peaks of eight to ten events per one million year occurred in two intervals (15.0 to 13.0 Ma and 12.0 to 11.0 Ma). Therefore, the middle Miocene can be generally referred to as a minor extinction phase for radiolarians of the equatorial Pacific. These gradual extinctions during the middle Miocene may be indicating either that the number of niches was decreasing or that the environmental character of those niches was unstable in the eastern equatorial Pacific.

Reduced rates of radiolarian appearance and extinction (# two events per one million year) are found at the earliest late Miocene (11.0 to 10.0 Ma). This faunal stagnation was probably related to less environmental perturbation in the region and/or more environmentally tolerant taxa.

During the late Miocene to the present (10.0 to 0 Ma), some of the evolving radiolarian species have survived up to the present time (Fig. 7). The appearances of surface-intermediate dwelling species [0–750 m; *Anthocyrtidium zanguebaricum* (Fig. 11H) and *Lithopera bacca* (Fig. 10A–D)] occurred first and were followed by that of surface dwelling species [0–300 m; e.g., *Larcospira quadrangula* (Fig. 8D), *Pterocanium korotnevi* (Fig. 12G), *Lophocyrtis neatum* (Fig. 13B) and *Anthocyrtidium ophirense* (Fig. 11B)]. Some intermediate-deep dwelling species, *Botryostrobus aquilonaris* (Fig. 10F), *Liriospyris reticulata* (Fig. 14F) and *Dictyophimus crisiae* (Fig. 12C), appeared at the latest Miocene and early Pliocene (Appendix 1). All of the radiolarian species that appeared after 3.0 Ma except for *Anthocyrtidium angulare* (Fig. 11C), *Lamprocyrtis heteroporos* (Fig. 11G) and *Lamprocyrtis neoheteroporos* (Fig. 11F), are still in existence (Table 3, Fig. 7). Thus, the late Miocene to Quaternary seems to have been characterized by a recovery phase for radiolarians of the equatorial Pacific. The rapid appearance (≥ five events per one million year) occurred in three intervals (9.0 to 7.0 Ma, 5.0 to 3.0 Ma, and 2.0 to 1.0 Ma), roughly every three million years. After 1.0 Ma, the appearance and extinction of equatorial Pacific radiolarians did not exceed two events per one million year.

As mentioned above, the evolution of Neogene radiolarian species is marked by three phases: the extinction phase (15.0 to 11.0 Ma, middle Miocene to earliest late Miocene), the survival phase (11.0 to 10.0 Ma, earliest late Miocene), and the recovery phase (10.0 to 0 Ma, late Miocene to Quaternary). This indicates that the minor faunal turnover of radiolarians occurred at the base of late Miocene (11.0 to 10.0 Ma).

In the Southern Ocean, the evolutionary turnover rates of radiolarians were relatively high during the middle Miocene (15 to 13 Ma) (Lazarus 2002). However, the increases of the turnover rates were not recognized at the base of late Miocene in the Southern Ocean. This is interpreted as an indication of global control of paleoceanographic changes during the middle Miocene and regional control during the early late Miocene upon the evolution of radiolarians.

The middle Miocene $\delta^{18}O$ increase (ca. 15 to 12 Ma) was a major step in the progression toward a cold polar climate which is interpreted as the expansion of the East Antarctic ice sheet and following cooling both surface and deep water (Miller et al. 1991; Zachos et al. 2001). Many radiolarian species that could not adapt to the low temperature water masses became extinct between 15.0 and 11.0 Ma. During this interval, the drop in chert abundance occurred in the Pacific Ocean (Moore 2008).

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The oceanic circulation system of the equatorial Pacific changed stepwise during the early late Miocene and early Pliocene. The surface-water exchange between the Indian and the Pacific Oceans through the narrowing Indonesian seaway remained efficient during the late Miocene. As a result, an early western Pacific warm pool, Equatorial Undercurrent and Equatorial Countercurrent system were formed in the tropical Pacific Ocean at about 10 Ma (Kennett et al. 1985; Jian et al. 2006; Li et al. 2006). The strengthening of the Equatorial Undercurrent effected the large increases in siliceous biogenic productivity along the equator (van Andel et al. 1975; Theyer et al. 1985; Farrell et al. 1995: fig 27). The modern east-west gradient in equatorial Pacific surface hydrography appeared between 4.5 and 4.0 Ma (Cannariato and Ravelo 1997; Chaisson and Ravelo 2000). This hydrographic change was related to the closing of the Central American Seaway and subsequent changes in meridional temperature gradients and/or changes in air-sea interactions that modified the tropical winds. The increasing appearance of modern radiolarian species after 10.0 Ma encountered in our study seems to have resulted from the stepwise development of a modern circulation system and the subdivision of surface water masses.

Diatom assemblages in the equatorial and North Pacific became more provincial in character after about 9 Ma, because water mass barriers to the migration of North Pacific diatoms into the equatorial Pacific were strengthened due to the development of the modern circulation system in the equatorial Pacific (Barron 2003). The appearance and extinction rates of planktic foraminifers were relatively high near the Middle–late Miocene boundary (12 to 10 Ma; Wei and Kennett 1986), and those of calcareous nannoplankton reached high values in the early late Miocene (about 9 Ma) in the equatorial Pacific Ocean (Pujos 1985). Thus, faunal evolution (radiolarians and planktic foraminifers) from the middle Miocene type to late Miocene types occurred first, being followed by floral evolution (diatoms and calcareous nannoplankton). The middle–late Miocene boundary is not a sharp boundary for planktonic microfossils, but marks a time of transition critical for faunal and floral evolution in both siliceous and calcareous microfossil assemblages in the equatorial Pacific Ocean.

Conclusions

Identified 115 morphotypes of radiolarians at the ODP Sites 845 and 1241 (Figs. 8–14).

The studied sequence is divided into eleven zones from RN15 to RN4 at Site 845 and from Zones RN16 to RN6 at Site 1241.

The updated ages of 152 radiolarian events are estimated using the sediment accumulation rates for ODP Sites 845 and 1241. Paleomagnetic data, planktic foraminifer and calcareous nannoplankton events are used for the construction of the age-depth models at Site 845. The diagram for the middle Miocene to Pleistocene sequence of Site 1241 was constructed based on calcareous nannoplankton marker biohorizons.

The general faunal evolutionary and extinction rates of tropical radiolarians were reconstructed and discussed in the context of global and regional environmental changes. The evolution of Neogene radiolarian species is marked by three stages: extinction stage (15.0 to 11.0 Ma), survival stage (11.0 to 10.0 Ma) and recovery stage (10.0 Ma to the present). The middle Miocene extinction was in response to an expansion of Antarctic ice sheets. Many species presented in the recent sediments have appeared since ca. 10 Ma. The increasing appearance of modern radiolarian species since the middle Miocene seems to have resulted from the stepwise development of the modern circulation system.

The middle–late Miocene boundary is not a sharp boundary for planktonic microfossils, but marks a time of transition critical for faunal and floral evolution in both siliceous and calcareous microfossil assemblages in the equatorial Pacific Ocean.

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Appendix 1

Species list.

Acrobotrys tritubus Riedel, 1957: 80, pl. 1: 5. (Fig. 12Q)
Acrocubus octopylus Haeckel, 1887: 993, pl. 82: fig. 9. (Fig. 12H)
Amphirhopalum ypsilon Haeckel, 1887; Nigrini 1967: 35, pl. 3: 3a–d. (Fig. 8G)
Anthocyrtidium angulare Nigrini, 1971; Nigrini and Caulet 1988: 343, pl. 1: 1, 2. (Fig. 11C)
Anthocyrtidium ehrenbergi (Stöhr, 1880); Nigrini and Caulet 1988: 345, pl. 1: 3, 4. (Fig. 11D)
Anthocyrtidium jenghisi Streeter, 1988; Nigrini and Caulet 1988: 350, pl. 1: 9–12. (Fig. 11A)
Anthocyrtidium nosicaae Caulet, 1979; Nigrini and Caulet 1988: 351, pl. 1: 15–17. (Fig. 11N)
Anthocyrtidium ophirense (Ehrenberg, 1872); Nigrini and Moore 1979: N67, pl. 25: 1. (Fig. 11B)
Anthocyrtidium pliocenica (Seguenza, 1880); Nigrini and Caulet 1988: 355, pl. 2: 5, 6. (Fig. 11I)
Anthocyrtidium zanguebaricum (Ehrenberg, 1872); Nigrini and Caulet 1988: 355, pl. 2: 11. (Fig. 11H)
Axoprunum stauraxonium Haeckel, 1887; Nigrini and Moore 1979: N57, pl. 7: 2, 3. (Fig. 9P)
Botryostrobus aquilonaris (Bailey, 1856); Nigrini 1977: 246, pl. 1: 1. (Fig. 10F)
Botryostrobus auritus/australis (Ehrenberg, 1884) group; Nigrini 1977: 246, pl. 1: 2–5. (Fig. 10D)
Botryostrobus bramlettei (Campbell and Clark, 1944); Nigrini 1977: 248, pl. 1: 7, 8. (Fig. 10G)
Botryostrobus miralestensis (Campbell and Clark, 1944); Nigrini 1977: 249, pl. 1: (Fig. 10B)
Calocycletta (*Calocyclior*) *caepa* Moore, 1972: 150, pl. 2: 4–7; Sanfilippo and Riedel 1992: 31. (Fig. 14E)
Calocycletta (*Calocycletta*) *cladara* Sanfilippo and Riedel, 1992: 30, pl. 2: 12–16. (Fig. 14D)
Calocycletta (*Calocyclissima*) *costata* (Riedel, 1959); Nigrini and Lombari 1984: N155, pl. 28: 2; Sanfilippo and Riedel 1992: 30. (Fig. 14A)
Calocycletta (*Calocycletta*) *robusta* Moore, 1971: 743, pl. 10: 5, 6; Sanfilippo and Riedel 1992: 28. (Fig. 14B)
Calocycletta (*Calocycletta*) *virginis* (Haeckel, 1887); Nigrini and Lombari 1984: N161, pl. 29: 2; Sanfilippo and Riedel 1992: 28. (Fig. 14C)
Carpocanium rubyae O'Connor, 1997b: 107, pl. 2: 1–4, pl. 5: 5–8. (Fig. 10V)
Carpocanopsis bramlettei Riedel and Sanfilippo, 1971; Nigrini and Lombari 1984: N85, pl. 21: 3. (Fig. 10W)
Carpocanopsis cingulata Riedel and Sanfilippo, 1971; Nigrini and Lombari 1984: N87, pl. 21: 4. (Fig. 10AB)
Carpocanopsis favosa (Haeckel, 1887); Nigrini and Lombari 1984: N91, pl. 21: 6a–c. (Fig. 10AF)
Collosphaera brattstroemi Bjørklund and Goll, 1979: 1315, pl. 3: 10–26, pl. 4: 13–16. (Fig. 8I)
Collosphaera tuberosa Haeckel, 1887; Nigrini 1971: 445, pl. 34.1: 1. (Fig. 9N)
Cycladophora davisiana Ehrenberg, 1861; Motoyama 1997: 60, pl. 1: 4–10. (Fig. 12K)
Cyrtocapsella cornuta Haeckel, 1887; Nigrini and Lombari 1984: N101, pl. 23: 1. (Fig. 10X)
Cyrtocapsella japonica (Nakaseko, 1963); Nigrini and Lombari 1984: N107, pl. 23: 4a–c. (Fig. 10Y)
Cyrtocapsella tetrapera (Haeckel, 1887); Nigrini and Lombari 1984: N109, pl. 23: 5. (Fig. 10Z)
Dendrospyris bursa Sanfilippo and Riedel, 1973; Nigrini and Lombari 1984: N19, pl. 16: 1a–f. (Fig. 14G)
Diartus hughesi (Campbell and Clark, 1944); Nigrini and Lombari 1984: S43, pl. 6: 2. (Fig. 9I)
Diartus petterssoni (Riedel and Sanfilippo, 1970); Nigrini and Lombari 1984: S41, pl. 6: 1. (Fig. 9J)
Dictyocoryne ontongensis Riedel and Sanfilippo, 1971: 1588, pl. 1E: 1, 2, pl. 4: 9–11. (Fig. 8F)
Dictyophimus crisiae Ehrenberg, 1854: Nigrini and Moore 1979: N33, pl. 22: 1a, b. (Fig. 12C)
Dictyophimus splendens (Campbell and Clark, 1944); Morley and Nigrini 1995: 79, pl. 7: 3, 4. (Fig. 12F)
Didymocyrtis antepenultima (Riedel and Sanfilippo, 1970); Nigrini and Lombari 1984: S55, pl. 7: 2a, b. (Fig. 9F)
Didymocyrtis avita (Riedel, 1953); Sanfilippo et al. 1985: 657, figs. 8.8a, b. (Fig. 9K)
Didymocyrtis bassanii (Carnevale, 1908); Nigrini et al. 2006: 32, pl. P1: 5. (Fig. 9H)
Didymocyrtis laticonus (Riedel, 1959); Nigrini and Lombari 1984: S53, pl. 7: 1a–c. (Fig. 9E)
Didymocyrtis mammifera (Haeckel, 1887); Nigrini and Lombari 1984: S51, pl. 6: 6. (Fig. 9D)
Didymocyrtis penultima (Riedel, 1957); Nigrini and Lombari 1984: S57, pl. 7: 3a–c. (Fig. 9G)
Didymocyrtis prismatica (Haeckel, 1887); Nigrini and Lombari 1984: S45, pl. 6: 3a, b. (Fig. 9A)
Didymocyrtis tetrathalamus (Haeckel, 1887); Sanfilippo et al. 1985: 659, figs. 8.9a, b. (Fig. 9L)
Didymocyrtis tubaria (Haeckel, 1887); Nigrini and Lombari 1984: S47, pl. 6: 4. (Fig. 9B)
Didymocyrtis violina (Haeckel, 1887); Nigrini and Lombari 1984: S49, pl. 6: 5. (Fig. 9C)
Dorcadospyris alata (Riedel, 1959); Sanfilippo et al. 1985: 661, fig. 10.7. (Fig. 13F)
Dorcadospyris dentata Haeckel, 1887; Nigrini and Lombari 1984: N29, pl. 17: 2. (Fig. 13G)
Eucyrtidium diaphanes Sanfilippo and Riedel, 1973; Sanfilippo et al. 1973: 221, pl. 5: 12–14. (Fig. 10M)
Giraffospyris toxaria (Haeckel, 1887); Goll 1969: 335, pl. 56: 1, 2, 4, 7, text-fig. 2. (Fig. 12P)
Lamprocyclas maritalis polypora Nigrini, 1967; Nigrini and Moore 1979: N77, pl. 25: 5. (Fig. 11J)
Lamprocyrtis heteroporos (Hays, 1965); Kling 1973: 639, pl. 5: 19–21, pl. 15: 6. (Fig. 11G)
Lamprocyrtis neoheteroporos Kling, 1973: 639, pl. 5: 17, pl. 15: 4, 5. (Fig. 11F)
Lamprocyrtis nigriniae (Caulet, 1971); Nigrini and Moore 1979: N81, pl. 25: 7. (Fig. 11E)
Larcospira moschkovskii Kruglikova, 1978; Nigrini and Lombari 1984: S91, pl. 13: 2a, b. (Fig. 8E)
Larcospira quadrangula Haeckel, 1887 group; Nigrini and Lombari 1984: S93, pl. 13: 3a–c. (Fig. 8D)
Liriospyris parkerae Riedel and Sanfilippo, 1971: 1590, pl. 2C: 15, pl. 5: 4. (Fig. 12E)
Liriospyris reticulata Ehrenberg, 1872; Nigrini and Moore 1979: N13, pl. 19: 4a, b. (Fig. 14F)
Lithelius klingi Kamikuri, 2009 (Fig. 9R)
Lithopera bacca Ehrenberg, 1872; Sanfilippo and Riedel 1970: 455, pl. 1: 29. (Fig. 10AD)

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Lithopera neotera Sanfilippo and Riedel, 1970: 454, pl. 1: 24–26, 28. (Fig. 10AC)
Lithopera renzae Sanfilippo and Riedel, 1970: 454, pl. 1: 21–23, 27. (Fig. 10T)
Lithopera thornburgi Sanfilippo and Riedel, 1970: 455, pl. 2: 4–6. (Fig. 10AE)
Lophocyrtis (*Cyclampterium*) *brachythorax* (Sanfilippo and Riedel, 1970); Sanfilippo1990: 304, pl. 4: 4–6. (Fig. 13D)
Lophocyrtis (*Cyclampterium*) *leptetrum* (Sanfilippo and Riedel, 1970); Sanfilippo 1990: 306, pl. 2: 6–9. (Fig. 13A)
Lophocyrtis (*Cyclampterium*) *neatum* (Sanfilippo and Riedel, 1970): Sanfilippo 1990: 307, pl. IV: 1–3. (Fig. 13B)
Lophocyrtis (*Cyclampterium*) *tanythorax* (Sanfilippo and Riedel, 1970); Sanfilippo 1990: 307, pl. 4: 7–10. (Fig. 13C)
Lychnodictyum audax Riedel, 1953; Sanfilippo and Riedel 1974: 1022, pl. 2: 8. (Fig. 12A)
Nephrospyris renilla Haeckel, 1887: 1101, pl. 90: 9. (Fig. 13E)
Periphaena decora Ehrenberg, 1873; Sanfilippo and Riedel 1973: 523, pl. 8: 8–10. (Fig. 9M)
Phormostichoartus corbula (Harting, 1863); Nigrini 1977: 252, pl. 1: 10. (Fig. 10K)
Phormostichoartus doliolum (Riedel and Sanfilippo, 1971); Nigrini 1977: 252, pl. 1: 14. (Fig. 10I)
Phormostichoartus fistula Nigrini, 1977: 253, pl. 1: 11–13. (Fig. 10C)
Phormostichoartus marylandicus (Martin, 1904); Nigrini 1977: 253, pl. 2: 1–4. (Fig. 10H)
Pterocanium korotnevi (Dogiel, 1952); Nigrini and Moore 1979: N39, pl. 23: 1a, b. (Fig. 12G)
Pterocanium praetextum eucolpum Haeckel, 1887; Nigrini and Moore 1979: N43, pl. 23: 3. (Fig. 12O)
Pterocanium praetextum praetextum (Ehrenberg, 1872); Nigrini and Moore 1979: N41, pl. 23: 2. (Fig. 12N)
Pterocanium prismatium Riedel, 1957; Lazarus et al. 1985: 200, figs. 17.1–17.4. (Fig. 12B)
Pterocorys campanula Haeckel, 1887; Caulet and Nigrini 1988: 226, pl. 1: 2–5. (Fig. 11P)
Pterocorys hertwigii (Haeckel, 1887); Caulet and Nigrini 1988: 229, pl. 1: 11, 12. (Fig. 11Q)
Pterocorys macroceras (Popofsky, 1913); Caulet and Nigrini 1988: 230, pl. 2: 1–5. (Fig. 11O)
Pterocorys minythorax (Nigrini, 1968); Caulet and Nigrini 1988: 231, pl. 2: 6. (Fig. 11M)
Pterocorys zancleus (Müller, 1855); Caulet and Nigrini 1988: 232, pl. 2: 10, 11. (Fig. 11R)
Siphostichartus corona (Haeckel, 1887); Nigrini 1977: 257, pl. 2: 5–7. (Fig. 10J)
Solenosphaera omnitubus omnitubus Riedel and Sanfilippo, 1971; Nigrini and Lombari 1984: S7, pl. 1: 4. (Fig. 9T)
Solenosphaera omnitubus procera Sanfilippo and Riedel, 1974: 1024, pl. 1: 2–5. (Fig. 9S)
Spirocyrtis gyroscalaris Nigrini, 1977: 258, pl. 2: 10, 11. (Fig. 10E)
Spirocyrtis scalaris Haeckel, 1887; Nigrini 1977: 259, pl. 2: 12, 13. (Fig. 10A)
Spirocyrtis subtilis Petrushevskaya, 1972; Nigrini 1977: 260, pl. 3: 3. (Fig. 10L)
Spongaster berminghami (Campbell and Clark, 1944); Nigrini and Lombari 1984: S63, pl. 9: 1a, b. (Fig. 8A)
Spongaster pentas Riedel and Sanfilippo, 1970: 523, pl. 15: 3. (Fig. 8B)
Spongaster tetras tetras Ehrenberg, 1860; Riedel and Sanfilippo 1978: 74, pl. 2: 2, 3. (Fig. 8C)
Spongodiscus klingi Caulet, 1986: 849, pl. 2: 2, 3. (Fig. 8H)
Stichocorys armata Haeckel, 1887; Riedel and Sanfilippo 1971: 1595, pl. 2E: 13–15. (Fig. 10O)
Stichocorys delmontensis (Campbell and Clark, 1944); Nigrini and Lombari 1984: N129, pl. 25: 4. (Fig. 10Q)
Stichocorys johnsoni Caulet, 1986: 851, pl. 6: 5, 6. (Fig. 10R)
Stichocorys peregrina (Riedel, 1953); Nigrini and Lombari 1984: N133, pl. 25: 6. (Fig. 10P)
Stichocorys wolffii Haeckel, 1887; Nigrini and Lombari 1984: N135, pl. 25: 7. (Fig. 10N)
Stylatractus universus Hays, 1970: 215, pl. 1: 1, 2. (Fig. 9O)
Theocorythium trachelium dianae (Haeckel, 1887); Nigrini and Moore 1979: N97, pl. 26: 3a, b. (Fig. 11L)
Theocorythium trachelium trachelium (Ehrenberg, 1872); Nigrini and Moore 1979: N93, pl. 26: 2. (Fig. 11K)
Theocorythium vetulum Nigrini, 1971: 447, pl. 34.1: 6a, b. (Fig. 11S)
Tholospyris anthopora (Haeckel, 1887); Nigrini and Lombari 1984: N69, pl. 20: 1. (Fig. 12I)
Tholospyris kantiana (Haeckel, 1887); Nigrini and Lombari 1984: N71, pl. 20: 2a–c. (Fig. 12L)
Trisolenia megalactis costlowi Bjørklund and Goll, 1979: 1322, pl. 4: 5, 6, 9–12, pl. 6: 1–11. (Fig. 8K)
Trisolenia megalactis megalactis Ehrenberg, 1872; Bjørklund and Goll 1979: 1321, pl. 5: 1–21. (Fig. 8J)
Valkyria pukapuka O'Connor, 1997a: 74, pl. 2: 15, 16, pl. 3: 1, 2, pl. 7: 11, 12, pl. 8: 1, 2. (Fig. 12D)