Quaternary radiolarian biostratigraphy in the subarctic northeastern Pacific (IODP Expedition 341 Site U1417) and synchroneity of bioevents across the North Pacific

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Abstract. Expedition 341 of the Integrated Ocean Drilling Program (IODP) retrieved sediment cores spanning the time interval between the Pleistocene and Miocene from the southern Gulf of Alaska. Onboard Pleistocene radiolarian biostratigraphy is hereby refined by increasing the sampling resolution. The 178 core samples from the upper 190 m CCSF-B (Composite Core Depth Scale F-B) of Site U1417 contained faunal elements similar to the northwestern Pacific; for example, the three biozones in the northwestern Pacific (i.e., *Eucyrtidium matuyamai*, *Stylatractus universus* and *Botryostrobus aquilonaris*) were also recognized in the Gulf of Alaska, spanning 1.80–1.13 Ma, 1.13–0.45 Ma, and the last 0.45 Myr, respectively. Based on the age model that we used in this study and the shipboard paleomagnetic reversal events, the first occurrences (FOs) of *Amphimelissa setosa* and *Schizodiscus japonicus* in the northeastern Pacific were preliminarily determined to be 1.48 and 1.30 Ma, respectively. The last occurrence (LO) of *Eucyrtidium matuyamai* and the FO of *Lychnocanoma sakaii*, both well-established bioevents in the northwestern Pacific, were dated at 0.80 and 1.13 Ma, respectively. The LO of *E. matuyamai* is a synchronous event at 1.05 ± 0.1 Ma in the North Pacific, while the FOs of *A. setosa* and *S. japonicus* at 1.48 and 1.30 Ma, respectively, are significantly older than what has been found elsewhere.

1 Introduction

In order to clarify the relationship between tectonic and climate changes during the Neogene, Expedition 341 of the Integrated Ocean Drilling Program (IODP) retrieved sediment cores at five sites off the southern Gulf of Alaska (northeastern Pacific) between 29 May and 29 July 2013 (sites U1417 to U1421) (Jaeger et al., 2014; Gulick et al., 2015). The deep-sea sediments collected at Site U1417 span the time interval from the Pleistocene to the Miocene (Jaeger et al., 2014). Of particular interest in the retrieved cores are polycystine radiolarians, which are siliceous microorganisms that inhabit shallow, intermediate and deep waters (e.g., Renz, 1976; Anderson, 1983; Kling, 1979; Kling

and Boltovskoy, 1995; Nimmergut and Abelmann, 2002; Okazaki et al., 2004; Suzuki and Not, 2015; Matsuzaki et al., 2016). Their skeletons composed of amorphous silica are generally well-preserved and abundant in the seafloor of the North Pacific, and the high levels of radiolarian preservation and abundance in deep-sea sediments of this region have facilitated numerous paleoceanographic and biostratigraphic studies (e.g., Hays, 1970; Kling, 1973; Foreman, 1975; Morley et al., 1982; Motoyama, 1996; Pisias et al., 1997; Matul et al., 2002; Kamikuri et al., 2004, 2007; Matul and Abelmann, 2005; Itaki et al., 2012; Matsuzaki et al., 2014a–c, 2015a; Kamikuri, 2017). According to onboard data, radiolarians were very rare in the Pliocene–Miocene sediments collected at Site U1417 (Jaeger et al., 2014). Of the few radi-

olarians that were present, the Pleistocene radiolarians were better preserved and more abundant (Jaeger et al., 2014). Preliminary biostratigraphic analysis at low resolution (> 10 m sampling interval) conducted during Expedition 341 revealed the existence of numerous barren intervals in cores retrieved from the site (Jaeger et al., 2014). We reexamined these core data and propose a refined Pleistocene radiolarian biostratigraphy for the northeastern Pacific using a markedly higher sampling resolution.

Therefore, widely distributed bioevents in the North Pacific were examined in this study. The last occurrences (LOs) of *Amphimelissa setosa* (Cleve, 1899) and *Schizodiscus japonicus* Matsuzaki and Suzuki, 2014 (*Spongodiscus* sp. in Matul et al., 2002), are all well-known, recorded at 0.07 and 0.29 Ma, respectively, in the Sea of Okhotsk (Matul et al., 2002). However, their first occurrences (FOs) in the North Pacific are poorly understood; Matul and Abelmann (2005) recorded the FO of *A. setosa* in the Sea of Okhotsk at 1.03 Ma, and Ikenoue et al. (2016) assigned the ages of the FOs of *A. setosa* and *S. japonicus* in the Bering Sea to be 0.99 Ma. Clarifying these bioevents in other regions is very important in facilitating discussions on bioevent synchroneity and/or diachroneity. During Expedition 341, Jaeger et al. (2014) identified several clearly defined Pleistocene paleomagnetic reversal events at Site U1417. Specifically, these included the reversal events of C1n (bottom, B), C1r.1n (top, T), C1r.1n (B), C1r.2n (middle, M) and the C2n (T), indicating 0.78, 0.98, 1.07, 1.17 and 1.78 Ma, respectively (Ogg, 2012). Assuming that the sedimentation rates are linear between reversal events, these paleomagnetic reversal events can be used to estimate the preliminary ages of the FOs of *A. setosa* and *S. japonicus* in the northeastern Pacific. After refining the radiolarian biostratigraphy for the Pleistocene, we estimated the preliminary age of the FOs for *A. setosa* and *S. japonicus* for the first time in the northeastern Pacific and discussed the synchroneity and potential suitability of these bioevents as biostratigraphic proxies.

2   Material and methods

We analyzed samples collected from Site U1417 on Expedition 341 of the IODP at 56°57.59 N and 147°6.59 W (Jaeger et al., 2014). The seafloor at the site, which is located in the Surveyor Fan of the Gulf of Alaska (Fig. 1; Jaeger et al., 2014), was calculated to be 4198 m below sea level (Jaeger et al., 2014). The sampling site is close to Site 178 of the Deep-Sea Drilling Project (ca. 1.5 km) (Jaeger et al., 2014). According to Jaeger et al. (2014), the upper 190 m of the Composite Core Depth Scale F-B (CCSF-B) timescale covers the last 1.8 Myr. The details concerning the establishment of the CCSF-B are explained Jaeger et al. (2014). The lithology of this interval can be divided into three facies. The upper 70 m CCSF-B is composed of dark gray mud with localized intervals of diatom oozes; similar facies exist between 70 and
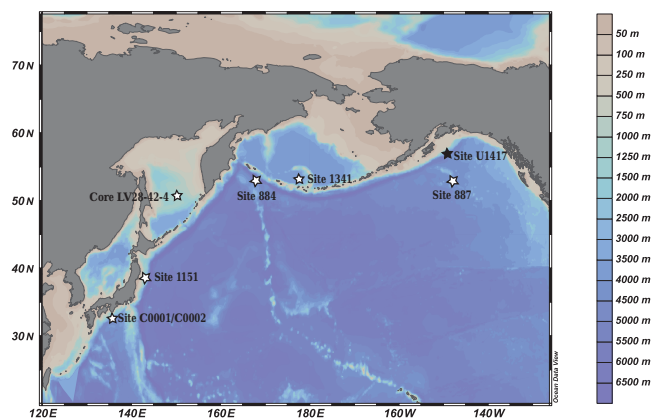

Figure 1. Location of the study site. Map from Ocean Data View (ver. 4) (Schlitzer, 2016).

160 m of CCSF-B, but intervals of diatom oozes are common (Jaeger et al., 2014). Between 160 and 260 m CCSF-B, the lithology is composed of gray to greenish-gray mud with interbeds of sand and silt (Jaeger et al., 2014). For radiolarian analysis, a total of 178 samples covering the upper 190 m CCSF-B from Site U1417 were freeze-dried and then treated with diluted hydrogen peroxide (15 %) and hydrochloric acid (15 %) to remove organic and calcareous matter. Undissolved residues sieved over a 45 μm screen were then mounted on 22×40 mm cover glasses for microscopic analysis. These samples contain such rare radiolarians that we were only able to examine an average of 296 radiolarian specimens per sample. We then calculated the relative abundance of biostratigraphically important radiolarian species to clarify the radiolarian biostratigraphy at this site for the Pleistocene.

3   Bioevents and age model

We carefully examined several well-known bioevents identified by previous studies in the North Pacific (Matul et al., 2002; Kamikuri et al., 2004, 2007; Matsuzaki et al., 2014a, b; Ikenoue et al., 2016; Kamikuri, 2017). Of these, seven radiolarian species were considered to be well suited for use as biostratigraphic markers: *Lychnocanoma sakaii* Morley and Nigrini, 1995; *A. setosa*, *S. japonicus* and *Axoprunum acquilonium* Hays, 1970; *Stylatractus universus* Hays, 1970; *Eucyrtidium matuyamai* Hays, 1970; and *Actinomma robustum* (Kling, 1973) (Table 1). In this study (Site U1417), we recognized the following seven radiolarian LO bioevents for the Pleistocene defined in the northwestern Pacific: *L. sakaii* (0.03 Ma at a median depth of 19.10 m CCSF-B), *A. setosa* (0.075 Ma at 25.39 m CCSF-B), *S. japonicus* (0.29 Ma at 60.39 m CCSF-B), *A. acquilonium* (0.35 Ma at 62.39 m CCSF-B), *S. universus* (0.45 Ma at 87.81 m CCSF-B), *E. matuyamai* (1.25 Ma at 145.51 m CCSF-B) and *A. robustum* (1.50 Ma at 170.60 m CCSF-B) (Fig. 2, Table 2). An abundance peak (acme) of *L. sakaii* (0.06 Ma at 23.00 m CCSF-
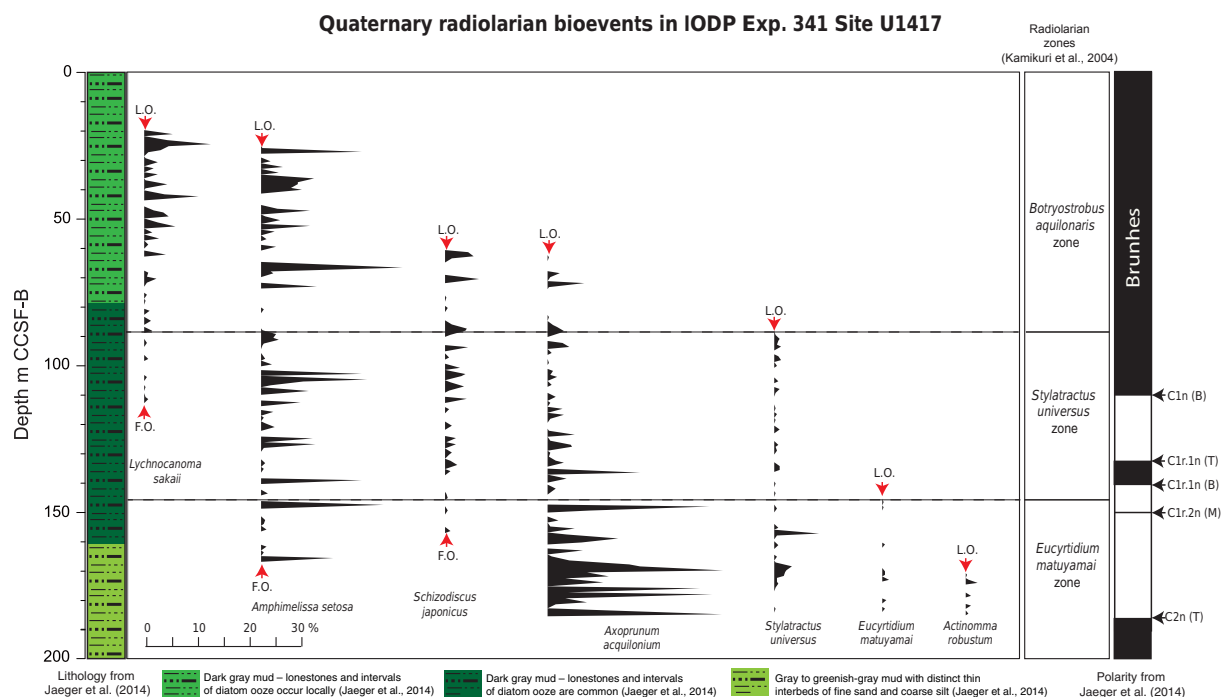
Figure 2. Radiolarian biostratigraphy at Site U1417 calibrated to paleomagnetic reversal events (Jaeger et al., 2014; Ogg, 2012) and the radiolarian zonation of Kamikuri et al. (2004). L.O.: last occurrence; F.O.: first occurrence.

B) was also found in this core (Table 2). These data are shown by Matsuzaki and Suzuki (2017) available at https: //doi.pangaea.de/10.1594/PANGAEA.877703.

The sedimentation rates for the depth interval between 111 and 186 m CCSF-B at Site U1417 were constrained relying only on the paleomagnetic reversal events (Jaeger et al., 2014) (Fig. 3, Table 3). Assuming that sedimentation rates are linear between the paleomagnetic reversal events reported by Jaeger et al. (2014), the sedimentation rates range from 7.0 to 10 cm kyr^{-1} from 111 to 150 m CCSF-B, decreasing to 5.9 cm kyr^{-1} from 150 to 186 m CCSF-B (Table 3). For this time interval, the LOs of *E. matuyamai* (1.25 ± 0.15 Ma) and *A. robustum* (1.25 ± 0.1 Ma) are consistent with the sedimentation rates defined based on the paleomagnetic reversal events (Fig. 3, Tables 2 and 3). Since there were no paleomagnetic reversal events for the depth interval between 0 and 111 m CCSF-B, the sedimentation rates were based only on radiolarian bioevents (this study) (Fig. 3, Table 3). Based on these bioevents, the sedimentation rate of 63.6 cm kyr^{-1} is considered to be exceptionally high during the last 0.03 Mky. For older intervals, the sedimentation rates ranged between 12.9 and 27.5 cm kyr^{-1}, except between 60 and 62 m CCSF-B, when a very low sedimentation rate of 2.0 cm kyr^{-1} was recorded.
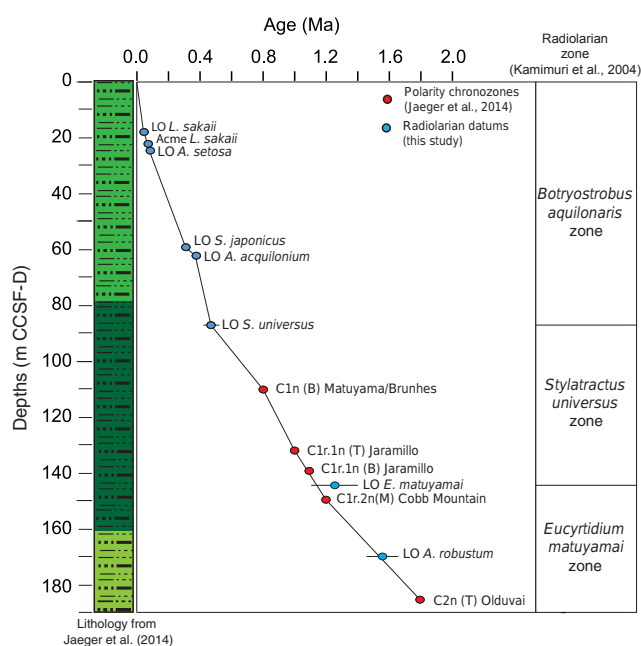
Figure 3. Depth–age model of Site U1417 based on shipboard measurements of paleomagnetic reversal events by Jaeger et al. (2014), enabling the age estimation of the FOs of *Amphimelissa setosa* and *Schizodiscus japonicus*, the LO of *Eucyrtidium matuyamai*, and radiolarian bioevents defined in this study for the upper 111 m CCSF-B.

Table 1. Taxonomic references of the biostratigraphic taxa mentioned in this study.

Species names	Figure(s)	Reference
Actinomma robustum (Kling, 1973)	pl. 1, fig. 11	Ikenoue et al., 2016, p. 40, pl. 1, figs. 9a–13b.
Amphimelissa setosa (Cleve, 1899)	pl. 1, figs. 5–6	Cleve, 1899, p. 27, pl. 1, fig. 10a, 10b.
Axoprunum acquilonium (Hays, 1970)	pl. 1, figs. 7–8	Matsuzaki et al., 2015b, p. 17, figs. 5.1–5.3.
Eucyrtidium matuyamai Hays, 1970	pl. 1, figs. 2–4	Hays, 1970, p. 213, pl. 1, figs. 7–9.
Lychnocanoma sakaii Morley and Nigrini, 1995	pl. 1, fig. 1	Matsuzaki et al., 2015b, p. 50, figs. 8.31–8.32.
Schizodiscus japonicus Matsuzaki and Suzuki, 2014	pl. 1, fig. 12	Matsuzaki et al., 2014a, p. 209, pl. 2, fig. 27–30.
Stylatractus universus Hays, 1970	pl. 1, figs. 9–10	Hays, 1970, p. 215, pl. 1, figs. 1–2.

Table 2. Radiolarian bioevents recognized at Site U1417 and paleomagnetic reversal events defined by Jaeger et al. (2014).

Datums	Age (Ma)	Core, section, interval (cm) Top	Bottom	Depth (m CCSF-B) Top (middle)	Bottom (middle)	Median	±m CCSF-B	Reference:
LO *L. sakaii*	0.03	341-U1417A, 2H-7, 50–52 cm	341-U1417C, 4H-1, 50–52 cm	17.36	20.84	19.10	1.74	Matsuzaki et al. (2014a)
Acme *L. sakaii*	0.06	341-U1417A, 3H-3, 50–52 cm		23.00		23.00	0.00	Matsuzaki et al. (2014a)
LO *A. setosa*	0.075	341-U1417A, 4H-4, 50–52 cm	341-U1417C, 4H-5, 50–52 cm	24.74	26.03	25.39	0.65	Matul et al. (2002)
LO *S. japonicus*	0.29	341-U1417C, 8H-2, 50–52 cm	341-U1417C, 8H-3, 50–52 cm	59.74	61.04	60.39	0.65	Matul et al. (2002)
LO *A. acquilonium*	0.35	341-U1417C, 8H-4, 50–52 cm	341-U1417C, 8H-5, 52–54 cm	62.33	63.63	62.98	0.65	Matsuzaki et al. (2014a)
LO *S. universus*	0.45 ± 0.05	341-U1417C, 11H-1, 40–42 cm	341-U1417C, 11H-2, 50–52 cm	87.16	88.45	87.81	0.64	Kamikuri et al. (2007)
C1n (B) Matuyama/Brunhes	0.781					111.00	1.00	Ogg (2012)
C1r.1n (T) Jaramillo	0.988					133.00	1.50	Ogg (2012)
C1r.1n (B) Jaramillo	1.072					140.00	1.00	Ogg (2012)
C1r.2n (M) Cobb Mountain	1.179					150.5	1.5	Ogg (2012)
LO *E. matuyamai*	1.25 ± 0.15	341-U1417A, 17H-1, 126–128 cm	341-U1417C, 17H-3, 48–50 cm	145.38	145.65	145.51	0.13	Kamikuri et al. (2007)
LO *A. robustum*	1.50 ± 0.1	341-U1417A, 19H-5, 50–52 cm	341-U1417C, 20H-6, 50–52 cm	169.82	170.29	170.06	0.23	Kamikuri et al. (2007)
C2n (T) Olduvai	1.778					186.00	2.00	Ogg (2012)

4   Radiolarian zones

Based on the recorded radiolarian taxa (illustrated in Plate 1) and their bioevents, we were able to apply the biostratigraphic scheme proposed by Kamikuri et al. (2004) and identify three radiolarian interval zones: the *Eucyrtidium matuyamai* interval zone, the *Stylatractus universus* interval zone and the *Botryostrobus aquilonaris* interval zone (Fig. 2).

Eucyrtidium matuyamai interval zone, Hays (1970)

Definition: The base of this zone could not be determined due to barren intervals from 186 m CCSF-B. The top of this zone is defined by the LO of *E. matuyamai* (Fig. 2 and Table 2).

Interval: The stratigraphic interval between samples 341-U1417C, 22H-5, 50–51 cm (186.35 m CCSF-B) and 341-U1417A, 17H-1, 126–128 cm (145.51 m CCSF-B) (Table 2).

Important datums: Three other important bioevents were identified in this zone. The LO of *A. robustum* (1.55 ± 0.1 Ma), defined by Kamikuri et al. (2004, 2007), was identified. This bioevent was situated between samples 341-U1417A, 19H-5, 50–52 cm and U1417C, 20H-6, 50–52 cm at a median depth of 170.29 m CCSF-B (Fig. 2 and Table 2). The FO of *A. setosa* was identified at

1.48 ± 0.01 Ma between samples 341-U1417A, 19H-3, 50–52 cm and U1417C, 20H-4, 50–52 cm and at a median depth of 167.22 m CCSF-B (Fig. 3 and Table 4). The FO of *S. japonicus*, which is indicative of 1.3 ± 0.01 Ma, was found between samples 341-U1417A, 18H-4, 50–52 cm and U1417C, 18H-5, 50–52 cm (Table 4).

Remarks: After Jaeger et al. (2014), the paleomagnetic reversal event of C1r.2n (M) (Cobb Mountain: 1.179 Ma) was identified at Site U1417 (Ogg, 2012) (see Table 2). We were therefore able to accurately recalculate the age of the LO of *E. matuyamai* following the sedimentation rates described above (Fig. 3, Tables 3 and 4). The revised age of the LO of *E. matuyamai* for the northeastern Pacific is thus 1.13 ± 0.01 Ma.

Correlation and ages: The base of this zone is defined by the FO of *E. matuyamai*, which is typically located near the C2n (Olduvai) paleomagnetic reversal event (e.g., Kamikuri et al., 2004, 2007; Matsuzaki et al., 2014b). The top of this zone is defined by the LO of *E. matuyamai* placed between paleomagnetic reversal event C1r.2n (M) (Cobb Mountain) and the top of C1r.1n (T) (Jaramillo). Considering the revised age of the LO of *E. matuyamai*, this zone spans from 1.8 to 1.13 Ma.

Table 3. Sedimentation rates estimated based on the paleomagnetic reversal events of Jaeger et al. (2014) and radiolarian bioevents defined in this study.

Radiolarian bioevents and polarity chronozones	Age (Ma)	Depths (m CCSF-B)	Sedimentation rates (cm kyr^{-1})
Top of U1417	0	0	
			63.67
LO *L. sakaii*	0.03	19.10	
			12.99
Acme *L. sakaii*	0.06	23.00	
			15.91
LO *A. setosa*	0.075	25.39	
			21.21
LO *S. japonicus*	0.24	60.39	
			2.16
LO *A. acquilonium*	0.36	62.98	
			27.58
LO *S. universus*	0.45	87.81	
			7.01
C1n (B) Matuyama/Brunhes	0.781	111.00	
			10.63
C1r.1n (T) Jaramillo	0.988	133.00	
			8.33
C1r.1n (B) Jaramillo	1.072	140.00	
			9.81
C1r.2n (M) Cobb Mountain	1.179	150.50	
LO *E. matuyamai*	1.25 ± 0.15	145.51 ± 0.13	
LO *A. robustum*	1.50 ± 0.1	170.06 ± 0.23	
			5.93
C2n (T) Olduvai	1.778	186.00	
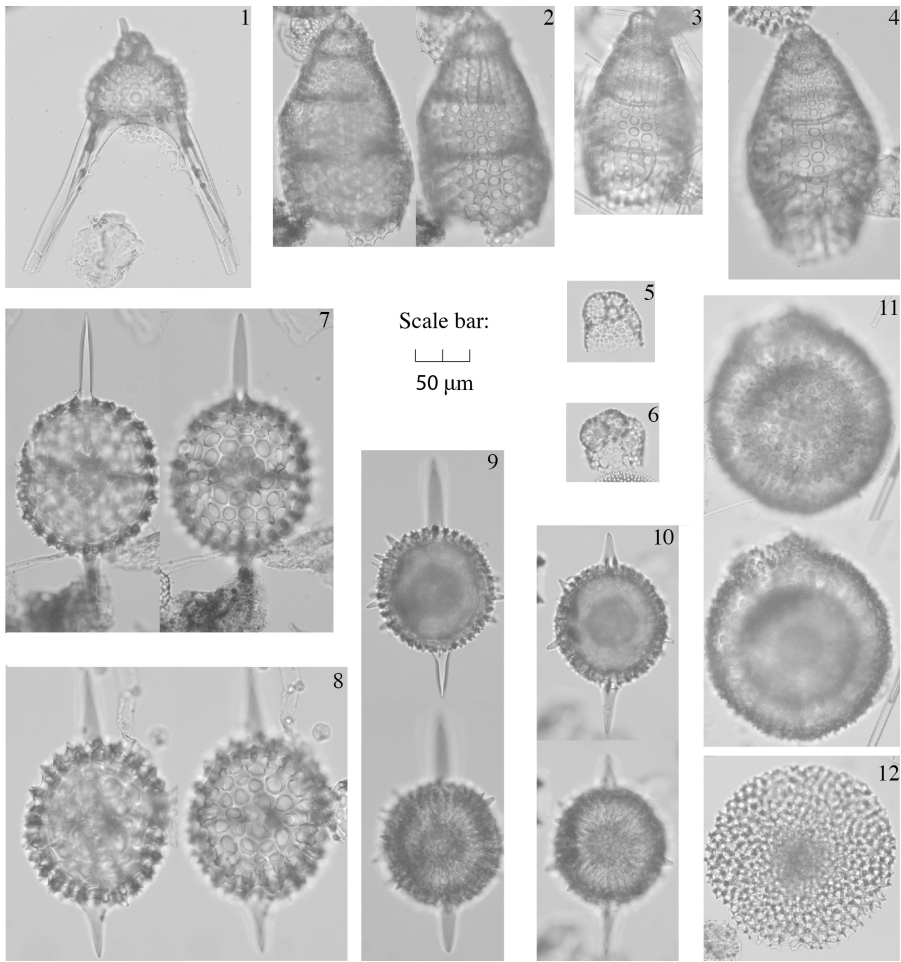
Plate 1. Photomicrographs of selected radiolarians (biostratigraphic markers) from Site U1417. 1. *Lychnocanoma sakaii* Morley and Nigrini; 2, 3, 4. *Eucyrtidium matuyamai* Hays; 5–6. *Amphimelissa setosa* (Cleve); 7–8. *Axoprunum acquilonium* Hays; 9–10. *Stylatractus universus* Hays; 11. *Actinomma robustum* (Kling); 12. *Schizodiscus japonicus* Matsuzaki and Suzuki.

Table 4. Age estimation of the LO of *Eucyrtidium matuyamai* and FOs of *Amphimelissa setosa* and *Schizodiscus japonicus*.

| Bioevents | Age (Ma) | Core, section, interval (cm) | | Depth (m CCSF-B) | | | |
		Top	Bottom	Top (middle)	Bottom (middle)	Median	± m CCSF-B
FO *Lychnocanoma sakaii*	0.8 ± 0.01	341-U1417A, 13H-2, 50–52 cm	341-U1417C, 14H-1, 50–52 cm	112.35	114.00	113.18	0.83
LO *Eucyrtidium matuyamai*	1.13	341-U1417A, 17H-1, 126–128 cm	341-U1417C, 17H-3, 48–50 cm	145.38	145.65	145.51	0.13
FO *Schizodiscus japonicus*	1.3 ± 0.01	341-U1417A, 18H-4, 28–30 cm	341-U1417A,18H-5, 50–52 cm	157.38	158.31	157.85	0.47
FO *Amphimelissa setosa*	1.48	341-U1417A, 19H-3, 50–52 cm	341-U1417C, 20H-4, 50–52 cm	167.22	167.78	167.50	0.28

Estimation of *L. sakaii*, *S. japonicus* and *A. setosa* FOs and *E. matuyamai* LO at Site U1417 based on shipboard polarity chronozones (Jaeger et al., 2014)

Stylatractus universus interval zone, Hays (1970)

Definition: The base of this zone is defined by the LO of *E. matuyamai* and the top is defined by the LO of *S. universus* (Fig. 2 and Table 2).

Interval: The stratigraphic interval between samples 341-U1417A, 17H-1, 126–128 cm (145. 51 m CCSF-B) and U1417C, 11H-1, 40–42 cm (87. 81 m CCSF-B) (Table 2).

Important datums: We identified the FO of *L. sakaii* in this zone as being between samples 341-U1417A, 13H-2, 50–52 cm and U1417C, 14H-1, 50–52 cm at a median depth of 113.18 m CCSF-B (Fig. 3 and Table 4). Based on the sedimentation rates shown in Fig. 3, the FO of *L. sakaii* is dated at 0.8 ± 0.1 Ma, in Site U1417.

Correlation and ages: The base of this zone is defined by the LO of *E. matuyamai* at 1.13 Ma. According to Kamikuri et al. (2004), the top of this zone is defined by the LO of *S. universus* (0.45 Ma), which is placed into the diatom *Proboscia curvirostris* zone of Barron et al. (1995), and within the C1n (Brunhes) normal polarity epoch. Therefore, this zone spans from 1.13 to 0.45 Ma.

Botryostrobus aquilonaris interval zone, Hays (1970)

Definition: The base and top of this zone are defined by the LO of *S. universus* and the top of the core, respectively (Fig. 2 and Table 2).

Interval: The stratigraphic interval between samples 341-U1417A, 17H-1, 126–128 cm (87.81 m CCSF-B) and U1417A, 1H-1, 49–51 cm (0.47 m CCSF-B) (Table 2).

Important datums: Five important bioevents were recognized in this zone: the LO of *L. sakaii* recorded between samples 341-U1417A, 2H-7, 50–52 cm and U1417C, 4H-1, 50–52 cm (at a median depth of 19.10 m CCSF-B); the abundance peak (acme) of *L. sakaii* recorded in sample 341-U1417A, 3H-3, 50–52 cm (at a median depth of 23.00 m CCSF-B); the LO of *A. setosa* recorded between

samples 341-U1417A, 4H-4, 50–52 cm and U1417C, 4H-5, 50–52 cm (at a median depth of 25.39 m CCSF-B); the LO of *S. japonicus* recorded between samples 341-U1417C, 8H-2, 50–52 cm and U1417C, 8H-3, 50–52 cm (at a median depth of 60.39 m CCSF-B); the LO of *A. acquilonium* recorded between Samples 341-U1417C, 8H-4, 50–52 cm and U1417C, 8H-5, 52–54 cm (at a median depth of 62.98 m CCSF-B) (Fig. 2 and Table 2).

Correlation and ages: The base of this zone as described above is defined by the LO of *S. universus*. According to Kamikuri et al. (2004), this zone corresponds to the *Neodenticula seminae* zone (diatom biostratigraphy) and spans the last 0.45 Myr.

5 Discussion

The ages of formerly known radiolarian bioevents were estimated using different geochronologic proxies, including biostratigraphy (e.g., diatoms and calcareous nannofossils), paleomagnetic reversal events and/or chemostratigraphy. In this study, for the bioevents recorded in the *Botryostrobus aquilonaris* interval zone, we do not have a geochronologic proxy suitable for temporal calibration of the recorded bioevents (LOs of *A. acquilonium*, *A. setosa*, *L. sakaii*, *S. japonicus* and an abundance peak of *L. sakaii*). However, five paleomagnetic reversal events were identified in both the *Stylatractus universus* and *Eucyrtidium matuyamai* zones (Jaeger et al., 2014) (Fig. 3). These reversal events enable us to calculate the ages of the LO of *E. matuyamai* as 1.13 Ma, and the FOs of *A. setosa*, *S. japonicus*, and *L. sakaii* as 1.48 Ma, 1.30 Ma, and 0.80 Ma, respectively. These ages estimated for the *S. universus* and *E. matuyamai* zones allow us to clarify the synchroneity and diachroneity of bioevents between the northwestern and northeastern Pacific.

5.1 Synchroneity and diachroneity of bioevents associated with *Eucyrtidium matuyamai*

The FO and LO of *E. matuyamai* are considered to be robust biostratigraphic markers for the lower Pleistocene in the North Pacific (Hays, 1970; Motoyama, 1996; Motoyama and Murayama, 1998; Kamikuri et al., 2004, 2007). The age of

these bioevents in the North Pacific has been accurately calibrated (Hays, 1970; Morley, 1985; Morley and Nigrini, 1995; Kamikuri et al., 2004, 2007; Matsuzaki et al., 2014b; Ikenoue et al., 2016).

The FO and LO of *E. matuyamai*, as well as the taxonomic description of this species, were first reported by Hays (1970), who proposed that *E. matuyamai* evolved from *Eucyrtidium calvertense* Martin (1904) near the paleomagnetic reversal event of C2n (T) (1.778 Ma; Ogg, 2012). The distribution of the ancestor *E. calvertense* was south of 40° N in the North Pacific, which differs from the more northern distribution of *E. matuyamai* (Hays, 1970). The appearance of *E. matuyamai* can be attributed to allopatric speciation resulting from the invasion of water masses into the subarctic North Pacific region at the C2n (T), which resulted in isolation of some *E. calvertense* populations and the evolution of *E. matuyamai* (Hays, 1970). The FO of *E. matuyamai* has been placed close to C2n (T) at various locations in the northwestern Pacific (e.g., Hays, 1970; Motoyama, 1996; Kamikuri et al., 2004, 2007; Matsuzaki et al., 2014b), implying that levels of synchronicity were high from a stratigraphic point of view, with the event dated at ca. 1.8 Ma in most of the literature cited above. Although the core examined in the present study covers the C2n (T), the FO of *E. matuyamai* was not recorded at this site due to the presence of barren intervals.

The LO of *E. matuyamai* was first observed near the base of the C1r.1n (Jaramillo: 0.98–1.07 Ma in Ogg, 2012) paleomagnetic reversal event by Hays (1970). To the best of our knowledge, this stratigraphic relationship has been corroborated in all subsequent published papers: the estimated ages exhibit little variability, mainly due to the sampling intervals used. In the northeastern Pacific (Ocean Drilling Program (ODP) Leg 145 Site 887, located close to Site U1417), Kamikuri et al. (2007) placed the LO of *E. matuyamai* between 1.1 and 1.4 Ma using the dating model of Barron et al. (1995), which was developed based on data from the same site (Fig. 1). The LO of *E. matuyamai* assigned at 1.13 Ma in this study is in agreement with the age ranges provided by Kamikuri et al. (2007). The difference in the dating accuracy between sites 887 and U1417 is likely due to sampling resolution rather than variation attributed to true diachroneity. In the northwestern Pacific, Matsuzaki et al. (2014b) chemostratigraphically calibrated the LO of *E. matuyamai* as 0.94 Ma at IODP Site C0001/C0002 (southern Japan). At ODP Site 1151 (northeastern Japan), the LO of *E. matuyamai* is placed between 1.0 and 1.1 Ma (Fig. 1; Kamikuri et al., 2004). The age range, which was estimated using the paleomagnetic reversal events as well as diatom biostratigraphy defined at the same site by Maruyama and Shiono (2003) and Kanamatsu and Niitsuma (2004), is considered to be well constrained. The LO of *E. matuyamai* is also recognized in the Bering Sea, a marginal sea north of the Kuril Islands. Kamikuri et al. (2007) placed the LO of *E. matuyamai* between 0.9 and 1.1 Ma at ODP Site 884 based on paleomag-

netic stratigraphy and the diatom biostratigraphy of Barron et al. (1995). Ikenoue et al. (2016) assigned the LO of *E. matuyamai* to 0.95 Ma at IODP Site U1341 in the Bering Sea using a dating model based on an astronomically tuned model combined with the Si / Al ratio proposed by Takahashi et al. (2011). Although the highly constrained ages seem to be variable (0.94 Ma in the northwestern Pacific, 0.95 Ma in the Bering Sea and 1.13 Ma in the northeastern Pacific, this study), the LO of *E. matuyamai* is considered to be relatively synchronous across the North Pacific at 1.05 Ma with a total error range of 0.1 Myr.

5.2 Synchroneity and diachroneity of FOs of *Amphimelissa setosa* and *Schizodiscus japonicus*

One of the most important questions regarding the age of bioevents in the North Pacific is the estimation of FOs for *A. setosa* and *S. japonicus*, currently placed at 1.48 and 1.30 Ma, respectively. *A. setosa* is an extant species in Arctic to subarctic area of the North Atlantic Ocean (Bjørklund et al., 2015; Matul and Abelmann, 2005). It seems that *A. setosa* has existed in the subarctic North Atlantic Ocean since the end of Marine Isotopic Stage 11 (MIS 11) (Bjørklund et al., 2015), and this species has disappeared from the North Pacific between the MIS 4 and MIS 5 (0.06–0.07 Ma) (Kruglikova, 1976; Matul and Abelmann, 2005; Matul et al., 2002, 2009). The FO of *A. setosa* was recorded at 1.03 Ma in the Sea of Okhotsk at Core LV28-42-4 (Matul and Abelmann, 2005) and the first continuous occurrence (FCO) of the representative species in the Bering Sea is 0.99 Ma (Ikenoue et al., 2016). The FO of *A. setosa* at 1.48 Ma (this study) in the northeastern Pacific (Fig. 3 and Table 4) is significantly older than in these two marginal seas.

The biostratigraphic importance of *S. japonicus* was first pointed out by Ling (1973). The LO of *S. japonicus* was dated at 0.287 Ma in the Sea of Okhotsk (Matul et al., 2002) and at 0.37 Ma in the Bering Sea (Ikenoue et al., 2016); however, the FCO of *S. japonicus* was determined to be 0.99 Ma in the Bering Sea (Ikenoue et al., 2016). Since the FO of *S. japonicus* at Site U1417 is placed at 1.30 Ma (this study), these age differences might imply the existence of a diachroneity between the Bering Sea and the southern Gulf of Alaska.

Concerning both taxa (*A. setosa* and *S. japonicus*), an earlier FO is recorded in the subarctic North Pacific than those recorded in the Sea of Okhotsk and Bering Sea, which are marginal seas. This would suggest that the FO of both taxa occurred later in the marginal seas because of a hydrographical semi-isolation from the open ocean. However, a few concerns remain. Concerning the Sea of Okhotsk, the cores studied by Matul et al. (2002, 2009) cover the time interval of 1.1 Ma at its maximum. Therefore, the situation for time older than 1.1 Ma is unknown. In the Bering Sea, Ikenoue et al. (2016) define their datum as FCO, which infers that sporadic occurrence of both taxa may have occurred for time

intervals older than 0.99 Ma. Conversely, we do not have a report of *A. setosa* and *S. japonicus* FOs in the Japan Sea, the other marginal sea of the North Pacific. Reports of both taxa FOs in the Japan Sea would potentially elucidate this issue.

5.3 Synchroneity and diachroneity of bioevents associated with *Lychnocanoma sakaii*

With its characteristic three long, bladed feet, *Lychnocanoma sakaii* is easily identified from similar species in the Pleistocene (Sakai, 1980; Morley and Nigrini, 1995; Matsuzaki et al., 2015b). This species was widely distributed in the North Pacific, particularly in the Bering Sea (Blueford, 1983; Itaki et al., 2012; Ikenoue et al., 2016), Japan Sea (Alexandrovich, 1992; Itaki et al., 2007), Sea of Okhotsk (Matul et al., 2002), the arctic North Pacific above 50° N (Morley and Nigrini, 1995; Kamikuri et al., 2007) and off northeastern Japan in the northwestern Pacific (Sakai, 1980; Kamikuri et al., 2004; Matsuzaki et al., 2014a). The synchroneity of the LO and abundance peak (acme in the original paper) for *L. sakaii* was previously reported by Matul et al. (2002) and Matsuzaki et al. (2014a). Relatively little is known regarding the FO of this taxon, but it has variously been estimated at 0.95 Ma off northeastern Japan (Kamikuri et al., 2004), 1.4–1.7 Ma in the south Bering Sea (Kamikuri et al., 2007) and 1.8–1.9 Ma in the northeastern Pacific (Kamikuri et al., 2007). The FCO of this species is 0.45 Ma in the Bering Sea (Ikenoue et al., 2016). This study places the FO of this taxon from Site U1417 in the northeastern Pacific at 0.80 Ma. The differences in these ages are not considered to be due to taxonomic uncertainty, preservation state or dating accuracy. To evaluate this diachroneity, the presence or absence of the congeneric ancestor to *L. sakaii* is considered to play a key role in the mode of speciation for this species. However, such evaluations are difficult because most of the studies published to date did not state whether other *Lychnocanoma* spp., such as *L. nipponica*, were present or absent.

6 Conclusions

Examination of the Pleistocene radiolarian biostratigraphy at IODP Site U1417 (Gulf of Alaska, northeastern Pacific) verified the applicability of the northwestern Pacific radiolarian zonal scheme from the *Eucyrtidium matuyamai* zone (1.80–1.13 Ma), through the *Stylatractus universus* (1.13–0.45 Ma) to the *Botryostrobus aquilonaris* zone (0.45 Ma and later). Among the bioevents recognized in the northwestern Pacific, eight LOs were recognized at Site U1417: *Lychnocanoma sakaii*, *Amphimelissa setosa*, *Schizodiscus japonicus*, *Axoprunum acquilonium*, *S. universus*, *E. matuyamai* and *Actinomma robustum*. Recognition of these events indicates that they are well suited for application as biostratigraphic events across the northeastern and northwestern Pacific. This is the first study to identify the FOs of *Amphimelissa setosa* and

Schizodiscus japonicus in the northeastern Pacific, which were preliminary dated at 1.48 and 1.30 Ma, respectively.

However, in terms of synchroneity, slight differences were observed between the seven bioevents. Based on the shipboard paleomagnetic polarity reversal data, the LO of *E. matuyamai* was a synchronous event in the northeastern and northwestern Pacific, occurring at ca. 1.05 ± 0.1 Ma. However, the FO of *A. setosa* was placed at 1.48 Ma at Site U1417, which is 0.49 Myr older than the oldest age of this bioevent in the Bering Sea. Similarly, the FO of *S. japonicus* was dated as 1.30 Ma, 0.31 Myr older than its oldest known age in the Bering Sea.

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References

Alexandrovich, J. M.: Radiolarians from Sites 794, 795, and 797 (Japan Sea), in: Proceedings of the Ocean Drilling Program, Scientific Results, edited by: Tamaki, K., Ingle, J. C., et al. , 127–128, Ocean Drilling Program, College Station, 291–307, 1992.

Anderson, O. R.: Radiolaria, Springer-Verlag, New York, 1–355, 1983.

Barron, J. A., Basov, I. A., Beaufort, L., Dubuisson, G., Gladenkov, A. Y., Morley, J. J., Okada, M., Ólafsson, D. K., Pak, D. K., Roberts, A. P., Shilov, V. V., and Weeks, R. J. Biostratigraphic

and magnetostratigraphic summary, in: Proceedings of the Ocean Drilling Program, Scientific Results, edited by: Rea, D. K., Basov, I. A., Scholl, D. W., and Allan, J. F., 145, Ocean Drilling Program, College Station, 559–575, 1995.

Bjørklund, K. R., Hatakeda, K., Kruglikova, S., and Matul, A. G.: *Amphimelissa setosa* (Cleve) (Polycystina, Nassellaria) – a stratigraphic and paleoecological marker of migrating polar environments in the northern hemisphere during the Quaternary, Stratigraphy, 12, 23–37, 2015.

Blueford, J. R.: Distribution of Quaternary Radiolaria in the Navarin Basin geologic province, Bering Sea, Deep-Sea Res., 30, 763–781, 1983.

Cleve, T. P.: Plankton collected by the Swedish Expedition to Spitzbergen in 1898, Kongliga Svenska Vetenskaps-Akademiens Handlingar, 32, 1–51, 1899.

Foreman, H. P.: Radiolaria from the North Pacific, Deep Sea Drilling Project, Leg. 32, in: Initial Reports of the Deep Sea Drilling Project, edited by: Larson, R. L., Moberly, R., Bukry, D., Foreman, H. P., Gardner, J. V., Keene, J. B., Lancelot, Y., Luterbacher, H., Marshall, M. C., and Matter, A., 32, US Government Printing Office, Washington, DC, 579–676, 1975.

Gulick, S. P. S., Jaeger, J. M., Mix, A. C., Asahi, H., Bahlburg, H., Belanger, C., Berbel, G. B. B., Childress, L., Cowan, E., Drab, L., Forwick, M., Fukumura, A., Ge, S., Gupta, S., Kioka, A., Konno, S., LeVay, L. J., März, C., Matsuzaki, K. M., McClymont, E., Moy, C., Müller, J., Nakamura, A., Ojima, T., Ribeiro, F. R., Ridgway, K. D., Romero, O., Slagle, A., Stoner, J., St-Onge, G., Suto, I., Walczak, M. D., Worthington, L., Bailey, I., Enkelmann, E., Reece, R., and Swartz, J.: Mid-Pleistocene climate transition drives net mass loss from rapidly uplifting St. Elias Mountains, Alaska, P. Natl. Acad. Sci. USA, 112, 15042–15047, 2015.

Hays, J. D.: The stratigraphy and evolutionary trends of radiolaria in north Pacific deep-sea sediments, Geol. Soc. Am. Mem., 126, 185–218, 1970.

Ikenoue, T., Okazaki, Y., Takahashi, K., and Sakamoto, T.: Bering Sea radiolarian biostratigraphy and paleoceanography at IODP Site U1341 during the last four million years, Deep-Sea Res. Pt. II, 125, 38–55, 2016.

Itaki, T., Komatsu, N. and Motoyama, I.: Orbital- and millennial-scale changes of radiolarian assemblages during the last 220 kyrs in the Japan Sea, Palaeogeogr. Palaeocl., 247, 115–130, 2007.

Itaki, T., Kim, S.-G., Rella, S. F., Uchida, M., Tada, R., and Khim, B.-K.: Millennial-scale variations of late Pleistocene radiolarian assemblages in the Bering Sea related to environments in shallow and deep waters, Deep-Sea Res. Pt. II, 61–64, 127–144, 2012.

Jaeger, J. M., Gulick, S. P. S., LeVay, L. J., and Expedition 341 Scientist: Southern Alaska Margin: interactions of tectonics, climate, and sedimentation, Proceedings of the Integrated Ocean Drilling Program, 341, https://doi.org/10.2204/iodp.proc.341.2014, 2014.

Jøregensen, E.: The protist plankton and diatoms in bottom samples: Radiolaria, in: Hydrographical and Biological Investigation in Norwegian Fjords, edited by: Nurdgaard, O., Bergens Museum Skrifter, Ser. 1, 7, 114–142, 1905.

Kamikuri, S.: Late Neogene radiolarian biostratigraphy of the eastern North Pacific ODP Sites 1020/1021, Paleontol. Res., 21, 230–255, 2017.

Kamikuri, S., Nishi, H., Motoyama, I., and Saito, S.: Middle Miocene to Pleistocene radiolarian biostratigraphy in the North-

west Pacific Ocean, ODP Leg 186, The Island Arc, 13, 191–226, 2004.

Kamikuri, S., Nishi, H., and Motoyama, I.: Effects of late Neogene climatic cooling on North Pacific radiolarian assemblages and oceanographic conditions, Palaeogeogr. Palaeocl., 249, 370–392, 2007.

Kanamatsu, T. and Niitsuma, J.: Rock magnetism and paleomagnetic stratigraphy of forearc sediments of the Japan Trench, ODP Sites 1150 and 1151, The Island Arc, 13, 180–190, 2004.

Kling, S. A.: Radiolaria from the eastern North Pacific, Deep Sea Drilling Project, Leg 18, in: Initial Reports of the Deep Sea Drilling Project, edited by: Kulm, L. D. and von Huene, R., 18, US Government Printing Office, Washington, DC, 617–671, 1973.

Kling, S. A.: Vertical distribution of polycystine radiolarians in the central North Pacific, Mar. Micropaleontol., 4, 295–318, 1979.

Kling, S. A. and Boltovskoy, D.: Radiolarian vertical distribution patterns across the southern California current, Deep-Sea Res., 42, 191–231, 1995.

Kruglikova, S. B.: Radiolarians in the Upper Pleistocene sediments of the boreal and northern subtropical zones of the Pacific Ocean, Oceanology, 16, 61–64, 1976.

Ling, H. Y.: Radiolaria: Leg 19 of the Deep Sea Drilling Project, in: Initial Reports of the Deep Sea Drilling Project, edited by: Creager, J. C., Scholl, D. W., Boyce, R. E., Echols, R. J., Fullam, T. J., Grow, J. A., Koizumi, I., Lee, H. J., Ling, H. Y., Stewart, R. J., Supko, P. R., and Worsley, T. R., 19, US Governmental Printing Office, Washington, DC, 777–797, 1973.

Martin, G. C.: Radiolaria, in: Systematic Paleontology of the Miocene Deposits of Maryland, edited by: Clark, W. B., Eastman, C. R., Glenn, L. C., Bagg, R. M., Bassler, R. S., Boyer, C. S., Case, E. C., and Hollick, C. A., Baltimore, Maryland Geological Survey, Johns Hopkins Press, 447–459, 1904.

Maruyama, T. and Shiono, M.: Middle Miocene to Pleistocene diatom stratigraphy of the northwest Pacific at Sites 1150 and 1151, in: Proceeding of the Ocean Drilling Program Scientific Results, edited by: Suyehiro, K., Sacks, I. S., Acton, G. D., and Oda, M., 186, US Governmental Printing Office, Washington, DC, 1–38, 2003.

Matsuzaki, K. M., Suzuki, N., Nishi, H., Takashima, R., Kawate, Y. and Sakai, T.: 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), J. Micropalaeontol., 33, 205–222, 2014a.

Matsuzaki, K. M., Nishi, H., Hayashi, H., Suzuki, N., Ikehara, M., Gyawali, B. R., Tanaka, T., and Takashima, R.: Radiolarian biostratigraphic scheme and stable oxygen isotope stratigraphy in southern Japan (IODP Expedition 315 Site C0001), Newsl. Stratigr., 47, 107–130, 2014b.

Matsuzaki, K. M., Nishi, H., Suzuki, N., Cortese, G., Eynaud, F., Takashima, R., Kawate, Y., and Sakai, T.: Paleoceanographic history of the Northwest Pacific Ocean over the past 740 kyr, discerned from radiolarian fauna, Palaeogeogr. Palaeocl., 396, 26–40, 2014c.

Matsuzaki, K. M., Suzuki, N., Nishi, H., Hayashi, H., Gyawali, B. R., Takashima, R., and Ikehara, M.: Early to Middle Pleistocene paleoceanographic history of the southern Japan based on radiolarian data from IODP Exp. 314/315 Sites C0001 and C0002, Mar. Micropaleontol., 118, 17–33, 2015a.

Matsuzaki, K. M., Suzuki, N., and Nishi, H.: Middle to Upper Pleistocene polycystine radiolarians from Hole 902-C9001C, northwestern Pacific, Paleontol. Res., Supplement, 19, 1–77, 2015b.

Matsuzaki, K. M., Itaki, T., and Kimoto, K.: Vertical distribution of polycystine radiolarians in the north-eastern China Sea, Mar. Micropaleontol., 125, 66–84, 2016.

Matsuzaki, K. M. and Suzuki, N.: Quaternary radiolarian biostratigraphy of IODP Site 341-U1417A. PANGAEA, Dataset #877703, Supplement to: Matsuzaki, K. M. and Suzuki, N. (in press): Quaternary radiolarian biostratigraphy in the subarctic northeastern Pacific (IODP Expedition 341 Site U1417) and synchroneity of bioevents across the North Pacific, J. Micropalaeontol., 2017.

Matul, A. and Abelmann, A.: Pleistocene and Holocene distribution of the radiolarian *Amphimelissa setosa* Cleve in the North Pacific and North Atlantic: Evidence for water mass movement, Deep-Sea Res. Pt. II, 52, 2351–2364, 2005.

Matul, A., Abelmann, A., Tiedemann, R., Kaiser, A., and Nürnberg, D.: Late Quaternary polycystine radiolarian datum events in the Sea of Okhotsk, Geo-Mar. Lett., 22, 25–32, 2002.

Matul, A. G., Abelmann, A., Nürnberg, D., and Tiedemann, R.: Stratigraphy and major paleoenvironmental changes in the Sea of Okhotsk during the last million years inferred from radiolarian data, Oceanology, 49, 93–100, 2009.

Morley, J. J.: Radiolarians from the northwest Pacific, in: *Initial Reports of the Deep Sea Drilling Project*, edited by: Heath, G. R., Burckle, L. H., D'Agostino, A. E., Bleil, U., Horai, K., Jacobi, R. D., Janecek, T. R., Koizumi, I., Krissek, L. A., Monechi, S., Lenotre, N., Morley, J. J., Schultheiss, P., and Wright, A. A., 86, US Government Printing Office, Washington, DC, 399–422, 1985.

Morley, J. J. and Nigrini, C.: Miocene to Pleistocene radiolarian biostratigraphy of North Pacific Sites 881, 884, 885, 886 and 887, in: Proceedings of the Ocean Drilling Program, Scientific Results, edited by: Rea, D. K., Basov, I. A., Scholl, D. W., and Allan, J. F., 145, Ocean Drilling Program, College Station, 55–91, 1995.

Morley, J. J., Hays, J. D., and Robertson, J. H.: Stratigraphic framework for the late Pleistocene in the northwest Pacific Ocean, Deep-Sea Res., 29, 1485–1499, 1982.

Motoyama, I.: Late Neogene radiolarian biostratigraphy in the subarctic northwest Pacific, Micropaleontology, 42, 221–262, 1996.

Motoyama, I. and Maruyama, T.: 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 scale (CK92 and CK95), J. Geol. Soc. Jpn., 104, 171–183, 1998 (in Japanese with English Abstract).

Nimmergut, A. and Abelmann, A.: Spatial and seasonal changes of radiolarian standing stocks in the Sea of Okhotsk, Deep-Sea Res. Pt. I, 49, 463–493, 2002.

Ogg, J. G.: Geomagnetic polarity time scale, in: The Geological Time Scale, edited by: Gradstein, F. M., Ogg. J. G., Schmitz, M. D., and Ogg, G. M., Elseiver, BV, 85–113, 2012.

Okazaki, Y., Takahashi, K., Itaki, T., and Kawasaki, Y.: Comparison of radiolarian vertical distributions in the Okhotsk Sea near the Kuril Island and in the northwestern North Pacific off Hokkaido Island, Mar. Micropaleontol., 51, 257–284, 2004.

Pisias, N. G., Roelofs, A., and Weber, M.: Radiolarian-based transfer function for estimating mean surface ocean temperatures and seasonal range, Paleoceanography, 12, 365–379, 1997.

Renz, G. W.: The distribution and ecology of radiolaria in the central Pacific: Plankton and surface sediments, Bulletin of the Scripps Institution of Oceanography, University of California, 22, 1–267, 1976.

Sakai, T.: 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, 56–57, US Government Printing Office, Washington, DC, 695–733, 1980.

Schlitzer, R.: Ocean Data View, http://odv.awi.de, last access: May 2016.

Suzuki, N. and Not, F.: Biology and ecology of radiolaria, in: Marine Protists: Diversity and Dynamic, edited by: Ohtsuka, S., Suzaki, T., Horiguchi, T., Suzuki, N., and Not, F., 179–222, 2015.

Takahashi, K., Ravelo, A. C., Alvarez Zarikian, C. A., and the Expedition 323 Scientists: Bering Sea Paleoceanography, Proceedings of the Integrated Ocean Drilling Program, 323, https://doi.org/10.2204/iodp.proc.323.2011, 2011.