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Calcareous nannofossil biostratigraphy of the Lower–Middle Pleistocene boundary of the GSSP, Chiba composite section in the Kokumoto Formation, Kazusa Group, central Japan, and implications for sea-surface environmental changes

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Abstract

The Chiba composite section (CbCS), in the middle of the Boso Peninsula in central Japan, was ratified as the Global Boundary Stratotype Section and Point (GSSP) for the Lower–Middle Pleistocene boundary, accompanied by the Matuyama–Brunhes (M–B) paleomagnetic polarity boundary in January 2020. This study examined the calcareous nannofossil biostratigraphy of the CbCS to describe potential nannofossil events and discuss sea-surface environments around the M–B paleomagnetic polarity boundary. There are no clear biohorizons at the M–B paleomagnetic polarity boundary, although a temporary disappearance of *Gephyrocapsa* specimens ($\geq 5 \mu\text{m}$ in diameter), an important calcareous nannofossil genus in the Pleistocene, occurs just above the Lower–Middle Pleistocene boundary. Although this is a characteristic event around the M–B paleomagnetic polarity boundary, it is unclear whether the event is globally traceable.

Changes in the environmental proxy taxa of calcareous nannofossils in the CbCS revealed that sea-surface environments were driven by glacial-interglacial and millennial-scale climate forces. The time-transgressive change of the Tn value, a calcareous nannofossil temperature index, is mostly concordant with the planktonic foraminiferal oxygen isotope fluctuation. Abundant occurrences of a warm-water species, *Umbilicosphaera* spp., indicate that the Kuroshio Current was strong after ~ 783 ka. Even the strong influence of the Kuroshio Current, cooling events related to southward movements of the Kuroshio Front occurred every 10,000 years based on the presence of a cold-water taxon, *Coccolithus pelagicus*. Additionally, the inflow of coastal waters strengthened after ~ 778 ka because of abundant occurrences of *Helicosphaera* spp. Millennial-scale sea-surface changes were also inferred from detected floral fluctuations of less than 10,000 years.

Keywords: Calcareous nannofossils, Chiba composite section, Lower–Middle Pleistocene boundary, M–B paleomagnetic polarity boundary, *Gephyrocapsa*, Kuroshio Current

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Introduction

Calcareous nannofossils are major phytoplankton fossils that are used to determine the geologic age of strata and to infer past marine environmental changes. Many calcareous nannofossil biohorizons, corresponding to the appearance and disappearance of species, are known because calcareous nannofossils have rapidly evolved since the Late Triassic (e.g., Bown et al. 2004). Comparative studies between these biohorizons and other chronostratigraphic data have been used to construct a biochronological framework. The framework of the Neogene–Quaternary biohorizons exists in the eastern equatorial Pacific, the western equatorial Atlantic, and the Mediterranean (summarized by Raffi et al. 2006). However, useful biohorizons and their relationship to marine isotope stages have not yet been established in the North Pacific deep-sea cores because of the rarity of calcareous sediments caused by a shallow calcite compensation depth (CCD) (e.g., Pälike et al. 2012) from the Neogene to the Quaternary.

The marine Kazusa Group is a Japanese Pleistocene unit on the Boso Peninsula (central Pacific Japanese coast; Fig. 1) that yields abundant microfossils including pollen and spores, planktonic and benthic foraminifers, calcareous nannofossils, diatoms, and radiolarians (e.g., Oda 1977; Sato et al. 1988). These microfossils have been used to determine the age of the Group and the paleoceanographic conditions. However, the time resolution of these studies was relatively low (i.e., a minimum of tens of kyrs). Therefore, further biochronostratigraphic analyses of the formations in the Group are required to obtain suitable Quaternary age models and to discuss past climatic changes around the NW Pacific.

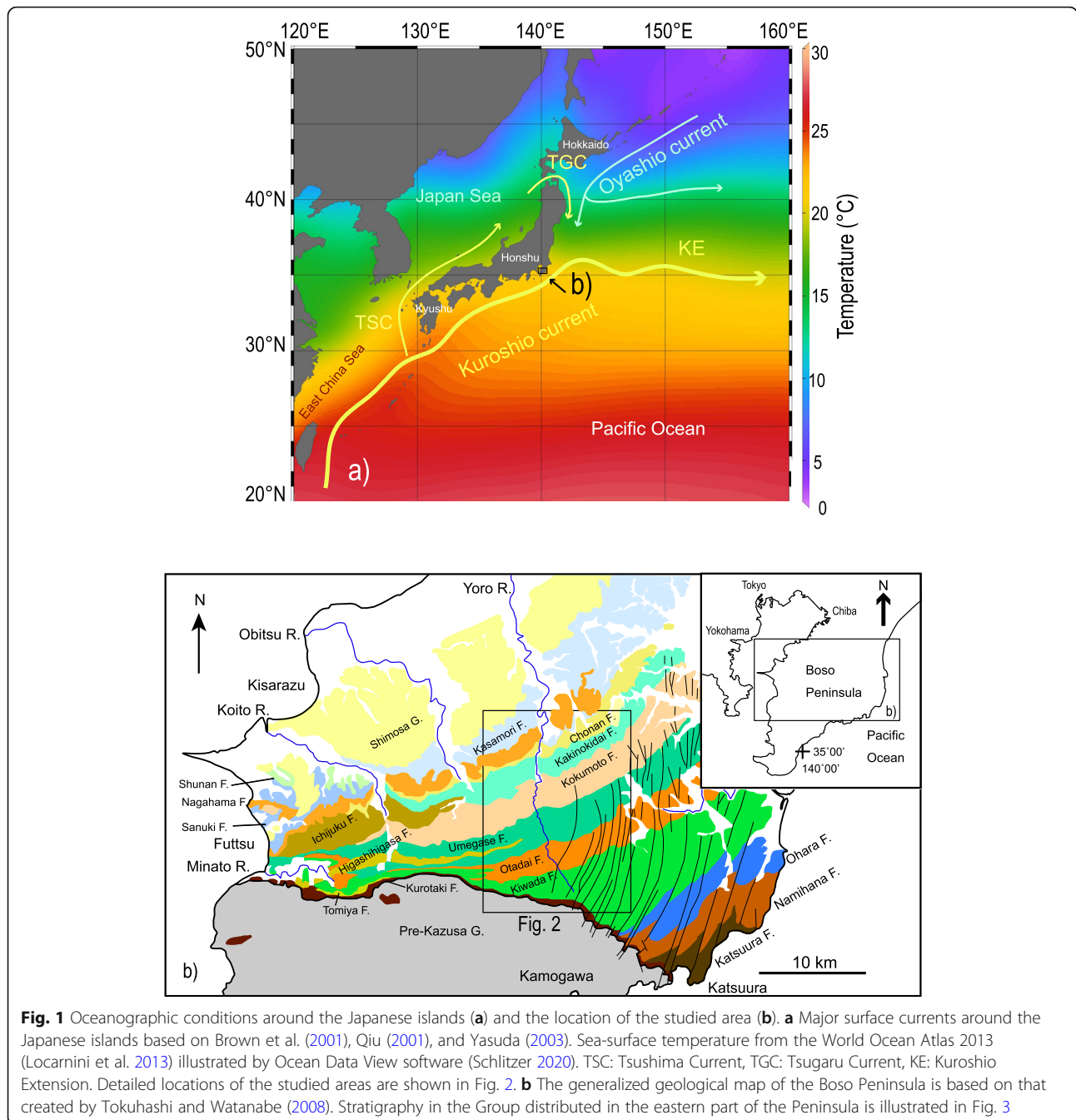
This paper reviews previous studies of the calcareous nannofossil biostratigraphy of the Kazusa Group and discusses the calcareous nannofossil assemblages in the Chiba composite section (CbCS), which is the ratified Global Boundary Stratotype Section and Point (GSSP) for the Lower–Middle Pleistocene boundary. Furthermore, detailed assemblage data of the calcareous nannofossils across the Matuyama–Brunhes (M–B) paleomagnetic polarity boundary are described, and the variability of calcareous nannofossils related to paleoceanographic changes in sea-surface waters is discussed. It is expected that the GSSP for the Lower–Middle Pleistocene boundary should provide good climatic information for understanding recent climatic changes because the boundary is situated within the interglacial Marine Isotope Stage (MIS) 19 (e.g., Head and Gibbard 2005). The orbital configuration in MIS 19 is considered to be similar to the current interglacial MIS 1 (e.g., Tzedakis et al. 2012); thus, orbitally induced climatic and

paleoceanographic changes within MIS 19 should be investigated to clarify their effects on the recent marine biosphere. Calcareous nannoplankton, one of the most important marine primary producers, is a suitable tracer for environmental changes which occurred at the sea surface, especially within the photic zone.

Geological setting and chronostratigraphic analyses of the Kazusa Group

The Lower to Middle Pleistocene Kazusa Group is composed of thick siliciclastic sediments in the Boso Peninsula on the Pacific side of the Japanese islands (e.g., Ito 1998; Kazaoka et al. 2015; Ito et al. 2016). The basin where the Kazusa Group was deposited developed as a forearc basin in response to the northward or northward subduction of the Pacific Plate against the Japanese islands (e.g., Seno and Takano 1989). The Group consists of deep-sea to shallow-shelf sediments and is divided into ten formations on the eastern part of the Peninsula; namely, in chronological order from oldest to youngest: the Kurotaki, Katsuura, Namihana, Ohara, Kiwada, Otadai, Umegase, Kokumoto, Kakinokidai, Chonan, and Kasamori Formations (Fig. 1; e.g., Suzuki et al. 1995; Kazaoka et al. 2015). Shallowing-upward successions and deepening successions eastward of the basin are recognized in the Group, suggesting a northeastward paleocurrent direction (e.g., Ito et al. 2016). Generally, all formations are composed of mostly continuous, undeformed sediments; however, in the eastern part of the Boso Peninsula, the sequence is disrupted by NNE–SSW-trending faults.

On the Yoro River, in the middle part of the Boso Peninsula, a thick succession of the Kazusa Group is present (Figs. 1 and 2). Several chronostratigraphic and chronological studies have been carried out in this sequence. Planktonic foraminifera (Oda 1977), calcareous nannofossils (Takayama 1973; Sato et al. 1988), diatoms (Cherepanova et al. 2002), magnetostratigraphic (Niitsuma 1971; Niitsuma 1976), and $\delta^{18}\text{O}$ (Okada and Niitsuma 1989; Pickering et al. 1999; Tsuji et al. 2005) studies estimate the age of the Group to span ca. 2.4–0.45 Ma (see summary by Ito et al. 2016). Many interbedded tephra layers allow the correlation of different facies among the formations not only within the Group but also in other formations in Japan (e.g., Satoguchi and Nagahashi 2012). Sedimentological analyses revealed the depositional environments of the formations, and sequence stratigraphic analysis was applied to clarify their formation processes and relationship to sea-level changes (e.g., Ito and Katsura 1992). As a result, glacioeustatic variability during the Quaternary has primarily controlled the deposition of the formations of the Kazusa Group, even in the active margin setting (Ito 1992).



The Chiba Composite Section (CbCS) is in the middle part of the Kokumoto Formation, which is the upper formation of the Group (e.g., Suzuki et al. 1995). This formation is mainly composed of massive mudstones interbedded with sandstones, indicating deposition in shelf-edge and slope environments (e.g., Ito 1992). No evidence of hiatuses or unconformities is present in the CbCS (Nishida et al. 2016).

Oceanographic conditions on the Pacific side of the Japanese islands

Oceanic waters flowing around the Pacific side of Japanese islands are composed of two main surface currents, the warm Kuroshio and the cold Oyashio currents, which are northeast- and southwest-flowing surface currents, respectively (Fig. 1). The Kuroshio Current is warm, with high-salinity surface water. It is the western boundary current of the subtropical

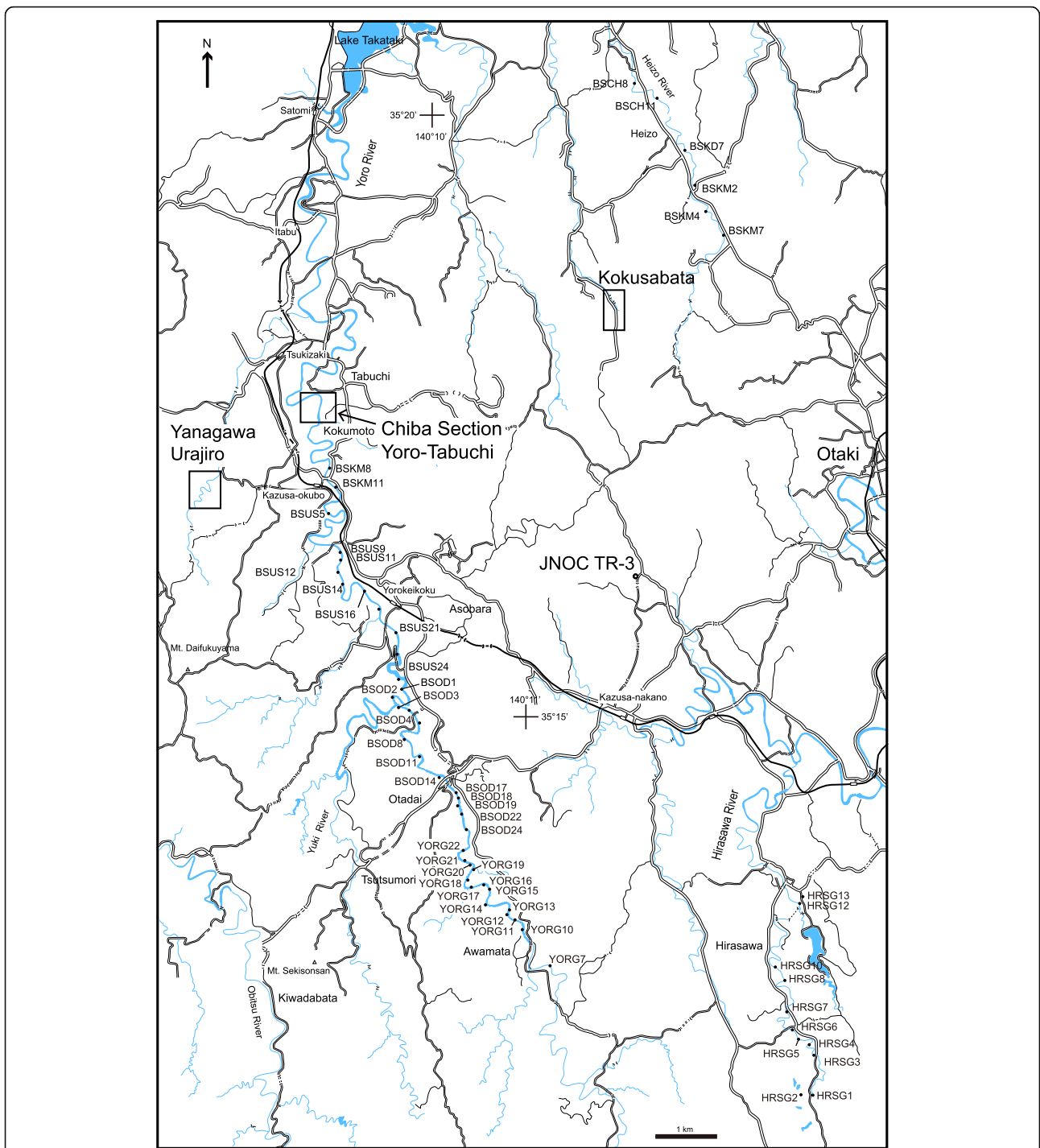


Fig. 2 Locations of the studied areas, along the Yoro River, Yanagawa, Urajiro, Chiba section, and Kokusabara construct the Chiba composite section (CbCS). The basemap is from 1:50,000 “Ootaki” topographic map published by the Geospatial Information Authority of Japan (GSI). Detailed locations are shown in Suganuma et al. (2018). Samples shown in BSCH, BSKD, BSKM, BSUS, BSOD, YORG, and HRSG were used by Sato et al. (1988) and Sato (1989). The location of “the JNOC TR-3” is also shown

gyre in the North Pacific Ocean (e.g., Qiu 2001; Yasuda 2003) and flows northward from the western equatorial Pacific region. This current is less than 100 km wide and approximately 1000-m deep

(Gallagher et al. 2015) and flows along the Pacific coast of the western part of the Japanese islands and becomes an eastward flow—the Kuroshio Extension—after separating from the coast (Fig. 1).

The Oyashio Current is the southwestern extension of the East Kamchatka Current, which is itself the western extension of the Western Subarctic Gyre from the North Pacific (e.g., Qiu 2001; Yasuda 2003). The Oyashio Current originates in the subarctic region. A mixed water regime between the Kuroshio and Oyashio currents is present off the coast of northeastern Japan, and the boundary between the two currents is either the Kuroshio Front or the Subarctic Front (Qiu 2001). In the mixed water region, the Oyashio Current generally flows beneath the warmer Kuroshio Current; generating complex warm and cold eddies in the surface waters (e.g., Unoki and Kubota 1996; Yasuda 2003). These eddies bring eutrophic surface waters to the mixed water region, whereas the Kuroshio Current is oligotrophic. Regional variations in both currents strongly influence the marine environments and organisms around the NW Pacific because physical and chemical conditions, such as sea-surface temperature, salinity, and nutrient richness, are strongly controlled by the strength of both currents (e.g., Kimura et al. 2000).

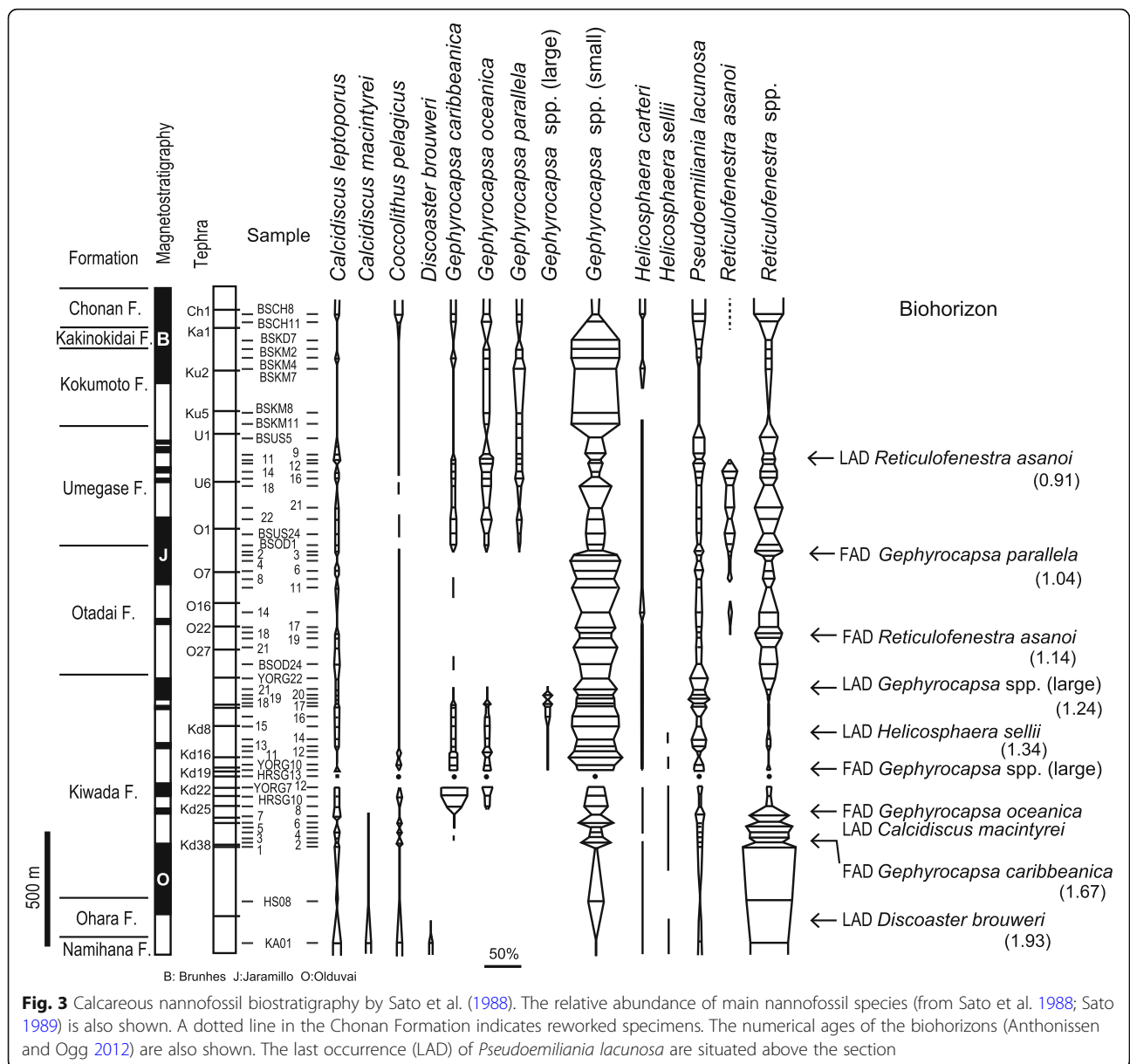
The Tsugaru Current is another surface water mass along the Pacific coast of Japan, which is a southward current flowing along the NE Japanese coast (Fig. 1; e.g., Qiu 2001; Gallagher et al. 2018; Yasuda 2003). This current flows between the coast and the Oyashio Current and originates in the Japan Sea as the Tsushima Current, which branches from the Kuroshio Current around the eastern part of the East China Sea off the west coast of the Tokara Islands, small islands to the south of Kyushu (Fig. 1). The Tsushima Current enters the Japan Sea through the shallow (< 140 m) Tsushima Strait (Fig. 1). It then passes through the Tsugaru Strait—a shallow (< 130 m) strait between Hokkaido and Honshu, and finally flows southward along the Pacific side of the Japanese islands (Gallagher et al. 2018; Yasuda 2003).

Previous studies on calcareous nannofossil biostratigraphy of the Kazusa Group

Several biostratigraphic studies on calcareous nannofossils from Japanese strata have been conducted since Takayama (1967) first described calcareous nannofossils from the Neogene and Quaternary sections in the southern Kanto region of Japan. In the Boso Peninsula, Takayama (1973) studied the calcareous microfossil biostratigraphy of the uppermost Cenozoic formations on the Japanese islands and from a sediment core taken near the northwestern region of the Pacific Ocean and described the biohorizons of planktonic foraminifera and calcareous nannofossils. In 1987, Takayama and Sato established 11 calcareous nannofossil datums (biohorizons) composed of the first and last occurrences of calcareous nannofossil taxa using the North Atlantic

Quaternary sediment cores (Takayama and Sato 1987; Sato and Takayama 1992). Around the same time, similar Quaternary nannofossil biohorizons have been proposed by several authors, such as Raffi et al. (1993) and Matsuoka and Okada (1989). Sato et al. (1988) and Sato (1989) dated the formations in the Kazusa Group along the Yoro River in order to locate the Plio-Pleistocene boundary in the uppermost Japanese Quaternary sequences (Table S1). Subsequently, Sato et al. (1999) revised the calcareous nannofossil biostratigraphy detected in the Kazusa Group. Samples used in these papers were obtained along the Yoro, Heizo, and Hirasawa Rivers (Fig. 2), and the eastern part of the Boso Peninsula. Tsuji et al. (2005) established a high-resolution chronostratigraphy based on oxygen isotope stratigraphy, magnetostratigraphy, and calcareous nannofossil biostratigraphy in portions of the Otadai and Umegase Formations in the JNOC TR-3 sediment core (Fig. 2). Based on these studies, the following ten datums (= biohorizons) are recognized in the Kazusa Group (Fig. 3):

- (1) The LAD (last appearance datum: equivalent to the last occurrence or highest occurrence) of *Discoaster brouweri* in the middle part of the Ohara Formation (Sato et al. 1988). The numerical age for this biohorizon is 1.93 Ma by GTS2012 scaling (Anthonissen and Ogg 2012 in Gradstein et al. 2012). This biohorizon is in the eastern part of the Boso Peninsula; however, it is not in the Yoro River.
- (2) The FAD (first appearance datum: equivalent to the first occurrence or lowest occurrence) of *Gephyrocapsa caribbeanica* above the Kd38 tephra in the lower part of the Kiwada Formation (Sato et al. 1988). The biohorizon is situated just above the magnetochron C2n, the Olduvai Subchronozone (Niitsuma 1976). This biohorizon corresponds to the first occurrence of medium *Gephyrocapsa* spp. The biohorizon is correlated with MIS 59 (Wei 1993; Berger et al. 1994) or a transition of MIS 58/59 (Lourens et al. 2004; Anthonissen and Ogg 2012). The numerical age is 1.73 Ma (Anthonissen and Ogg 2012).
- (3) The FAD of *Gephyrocapsa oceanica* is just below the Kd25 tephra in the Kiwada Formation (Sato et al. 1988, 1999). The LAD of *Calcidiscus macintyreii* also occurs in the same horizon. The FAD of *G. oceanica* was defined by Takayama and Sato (1988) and Sato and Takayama (1992) and is situated into MIS 57 in the Ontong Java Plateau (Berger et al., 1994). No age data by GTS2012 scaling for the biohorizon has been calculated.
- (4) Large forms of *Gephyrocapsa* specimens first appear close to the Kd19 tephra in the Kiwada Formation (Sato et al. 1988, 1999). They are composed of large



specimens, which are over 6 μm in diameter with an oblique bridge to the short axis (Takayama and Sato, 1987). On the other hand, some authors treated large specimens over 5.5 μm in diameter as large *Gephyrocapsa* (e.g., Raffi et al. 1993). The first occurrence of *Gephyrocapsa* over 6 μm in diameter corresponds to MIS 50 in the Ontong Java Plateau (Berger et al. 1994) and MIS 45 in the North Atlantic Ocean (Sato et al. 2009). Its first occurrence seems to be slightly diachronous as same as that of specimens over 5.5 μm in diameter (e.g., Wei 1993; Raffi et al. 2006). The numerical age of the biohorizon based on the GTS2012 scaling has not been estimated.

(5) *Helicosphaera sellii* disappears prior to the Kd8 tephra in the upper part of the Kiwada Formation (Sato et al. 1988, 1999). Lourens et al. (2004) and Anthonissen and Ogg (2012) indicated that the biohorizon corresponds to MIS 49 in the eastern equatorial Pacific. This biohorizon is also situated into MIS 47 in the Ontong Java Plateau (Berger et al. 1994). However, it seems to be diachronous (e.g., Lourens et al. 2004) because the biohorizon is situated in MIS 37/38 boundary in the North Atlantic (Sato et al. 2009). The numerical age of this biohorizon is calculated at 1.34 Ma (Anthonissen and Ogg 2012).

- (6) The LAD of large forms of *Gephyrocapsa* is in the upper part of the Kiwada Formation (Sato et al. 1988, 1999). The stratigraphic position of the biohorizon, however, could shift due to the relatively low-resolution analysis of nannofossils across the Kiwada and Otadai Formation boundary. Corresponding oxygen isotope stage is MIS 37 (e.g., Berger et al. 1994; Lourens et al. 2004; Anthonissen and Ogg, 2012). However, the biohorizon is slightly later in the North Atlantic, in MIS 35 (Sato et al. 2009). Its numerical age is 1.24 Ma (Anthonissen and Ogg 2012).
- (7) The FAD of *Reticulofenestra asanoi* was initially described below the O22 tephra in the Otadai Formation (Sato et al. 1988). Later, its stratigraphic range was extended below the O23 tephra (Sato et al. 1999). The biohorizon is correlated with MIS 35 (e.g., Wei 1993; Berger et al. 1994; Raffi et al. 2002) or MIS 34 in the North Atlantic (Sato et al. 2009). The age of this biohorizon is 1.14 Ma (Anthonissen and Ogg 2012).
- (8) *Gephyrocapsa parallela* first appears in the uppermost Otadai Formation. The first occurrence of this species is considered to be the reentrance of medium *Gephyrocapsa* specimens, usually over 4 μm in diameter (Raffi 2002), with a parallel bridge to the short axis. Larger forms (> 5.5 or \geq 6 μm in diameter) of this species are sometimes found above its first occurrence, but they differ from large forms of *Gephyrocapsa* due to having a parallel bridge to the short axis. The biohorizon is between the tephtras O1 and O7. A high-resolution chronological analysis of the JNOC TR-3 core—near Kamishiki, Otaki, in the north of Kazusa-Nakano (Fig. 2), by Tsuji et al. (2005) revealed that this biohorizon is in the middle part of the core, between tephtras TR-3B and TR-3C. The first occurrence corresponds to MIS 29 (Anthonissen and Ogg 2012) or MIS 30 (Berger et al. 1994; Tsuji et al. 2005) but slightly later stages in the North Atlantic (e.g., Sato et al. 2009; Wei 1993). This biohorizon was also recognized within the magnetochron C1r.1n (Jaramillo Subchronozone) (Berger et al. 1994; Tsuji et al. 2005). The age of this biohorizon is 1.04 Ma (Anthonissen and Ogg 2012).
- (9) The LAD of *R. asanoi* is below the tephra U4 in the Umegase Formation (Sato et al. 1999). This biohorizon can be correlated with MIS 22 and/or MIS 23 (e.g., Wei 1993; Berger et al. 1994; Raffi et al. 2002). The numerical age is 0.91 Ma (Anthonissen and Ogg 2012).

Based on Sato et al. (1988), the Chonan Formation, an uppermost formation of the Kazusa Group, can be

situated below the LAD of *Pseudoemiliana lacunosa* (0.44 Ma; Anthonissen and Ogg 2012).

Biogeography of modern calcareous nanoplanktons from the Japanese islands

The ecological preferences of several nannofossil taxa in the CbCS were mainly interpreted from previous ecological and biogeographic studies of calcareous nanoplankton around the Japanese islands (e.g., Tanaka 1991; Hagino 1997). Tanaka (1991) examined calcareous nannofossil species in 437 surface sediments from the Pacific Ocean, the Japan Sea, and the East China Sea, and clarified 10 biotopes based on the Q-mode cluster analysis of nannofossil assemblages. The distribution patterns of coccolith thanatocoenosis follow changes in the environmental conditions of surface currents around the Japanese islands, and several diagnostic nanoplankton taxa are recognized in specific surface currents and within oceanic areas. Aizawa et al. (2004) summarized the ecology and biogeography of the main Quaternary calcareous nanoplankton species in order to evaluate calcareous nannofossil assemblages during the last 144 ka in a piston core off the Kashima coast, north of the Boso Peninsula. Ecological information on these modern calcareous nanoplankton species in other oceans enables us to discuss paleoceanographic changes based on calcareous nannofossils.

A nannofossil tracer of the Kuroshio Current (Fig. 1) is *Umbilicosphaera* spp. because extant *Umbilicosphaera sibogae* is dominant in the main route of the Kuroshio Current (Tanaka 1991). Recently, Pleistocene *Umbilicosphaera* was classified into several species (e.g., Young et al. 2017). *U. sibogae* consists of two species, *U. sibogae*, and *Umbilicosphaera foliosa*; however, this study follows the definition used by Tanaka (1991) and treats them uniformly as *U. sibogae*.

Common *Coccolithus pelagicus* in thanatocoenosis is associated with cooler surface waters from the Kuroshio (Subarctic) Front and the mixed water region off the northeastern coast of the Japanese islands (Tanaka 1991). This taxon may include *C. pelagicus pelagicus* and *C. pelagicus braarudii*. Based on their ecological preferences in the Atlantic Ocean (e.g., Cachão and Moita 2000), *C. pelagicus pelagicus* corresponds to colder conditions than *C. pelagicus braarudii* (Narciso et al. 2006). *C. pelagicus braarudii* is common in Atlantic upwelling areas, where surface waters are cool and eutrophic. Based on Aizawa et al. (2004), *C. pelagicus* is abundant in surface waters under low-temperature and high-nutrient conditions.

Tanaka (1991) suggested that the dominance of *Heli-cosphaera* spp. in thanatocoenosis is typical of coastal water from the East China Sea. This taxon is present from the East China Sea to off the Boso Peninsula,

which is off the southwestern coast of the Japanese islands. Tanaka (1997) indicated that this taxon occurred abundantly in sediment trap samples from the continental shelf slope in the East China Sea. Aizawa et al. (2004) summarized that the presence of this taxon may presumably be affected by nutrient levels.

A lower photic taxon, *Florisphaera profunda*, has been utilized to reconstruct nutrient dynamics around the equatorial regions (e.g., Molfino and McIntyre 1990), water transparency, and/or turbidity (surface stratification) in the NW Pacific (Ahagon et al., 1993). According to Tanaka (1991), *F. profunda* occurs in more stable, stratified, warm offshore waters and gradually increases in number farther from the Japanese coast (Tanaka 1991). Another offshore taxon, *Calcidiscus leptoporus*, is more abundant to the east of the Izu-Ogasawara Ridge, in the northeastern part of the Pacific Ocean (Tanaka 1991). There has been no relationship established between the occurrence of this species and the Kuroshio and/or Oyashio currents.

Rhabdosphaera clavigera, *Syracosphaera* spp., *Calciosolenia* spp., and *Umbellosphaera* spp. are observed mainly south of the Kuroshio Front (Tanaka 1991), although these are considered as very rare taxa in the nanoplankton thanatocoenosis.

Materials and methods

We used mudstone samples from Suganuma et al. (2018) from the CbCS of the Kokumoto Formation on the Yoro River (Fig. 2) to investigate potential bioevents of calcareous nannofossils across the M–B paleomagnetic polarity boundary and environmental changes in detail. Previous studies (Sato et al. 1988, 1999) suggest that there is no characteristic change in the occurrence of nannofossil species across this boundary (Fig. 3). The interval is between the last occurrences of *Reticulofenestra asanoi* and *Pseudoemiliana lacunosa*, and previous studies in other oceans (e.g., Raffi et al. 2006) have no apparent diagnostic biohorizons.

The analyzed intervals, including the tephra Byk-E (Takeshita et al., 2016), are in the middle part of the Kokumoto Formation. The formation mainly contains massive mudstones with thin sandstones and occasional mudstone/sandstone interbeds. This study adds 12 samples to those presented by Suganuma et al. (2018); the total number of samples was 75. The time resolution in this study is less than one thousand years, on average.

Typical smear slides and permanent slides were prepared and observed using a light-polarized microscope (Olympus BX51) at $\times 1500$ magnification. Smear slides were used to estimate the relative abundance of each calcareous nannofossil species based on the count of 200 specimens per slide. Additional transects of each smear slide were observed to detect rare species outside 200

counts. According to Suganuma et al. (2018), specimens of *Gephyrocapsa*, *Pseudoemiliana*, and *Florisphaera* comprise approximately 90% of the total flora in the section. Thus, the frequencies of other rare taxa related to sea-surface conditions are obscured. In this study, we applied additional counting of subordinate taxa (Okada and Wells 1997) after 200 counts. The subordinate taxa in this study are nannofossil specimens except for major taxa (*Gephyrocapsa*, *Pseudoemiliana*, and *Florisphaera*). Permanent slides were made following the simplified method of Flores and Sierro (1997) to obtain the count data for subordinate taxa. The overall preservation of calcareous nannofossils in each sample was visually evaluated using the following criteria modified after that of Takayama and Sato (1987): good (i.e., most fossils have little or no evidence of dissolution and/or overgrowth), moderate (i.e., fossil specimens are partly etched, but all taxa can be identified), and poor (i.e., most specimens are etched, and it can be difficult to identify each species).

To avoid taxonomic problems, *Gephyrocapsa* specimens were subdivided into several morphotypes based on the maximum diameter of the coccolith. At the same time, a bridge angle to the diameter was also observed. The maximum diameter of a specimen was measured at 1 μm intervals using an eyepiece graticule under a light microscope. Based on the measurements, *Gephyrocapsa* specimens were subdivided into four categories ($< 3 \mu\text{m}$, 3–4 μm , 4–5 μm , and $\geq 5 \mu\text{m}$). Most *Gephyrocapsa* species over 4 μm in diameter in the CbCS are likely to be *Gephyrocapsa parallela* or *Gephyrocapsa omega*, with a parallel bridge to the short axis.

This study basically follows the age model of the CbCS established by Suganuma et al. (2018), which combines oxygen isotope stratigraphy and magnetostratigraphy. Oxygen isotope data of planktonic and benthic foraminifera revised by Haneda et al. (2020) were also used in this study. Marine isotope stages MIS 20 to MIS 18 were recognized, and high-resolution oxygen isotope records enabled us to identify three substages within MIS 19 (MIS 19c–19a). A chronologic uncertainty of the age model is approximately 4 kyr (Haneda et al. 2020).

In order to estimate sea-surface temperatures during the deposition of the CbCS, we calculated the nannofossil temperature index (Tn value) proposed by Aizawa et al. (2004). Tn values were estimated by using the relative abundances of subordinate counts, as mentioned above. Tn was estimated as follows:

$$\text{Tn} = \text{warm taxa} / (\text{warm taxa} + \text{cold taxa}) \times 100$$

Originally, warm taxa were considered as Kuroshio taxa (Aizawa et al. 2004). These are composed of *Umbellosphaera* spp., *Rhabdosphaera clavigera*, *Oolithotus* spp., *Syracosphaera* spp., and *Umbellosphaera* spp., which are all recognized in the Kuroshio region (Tanaka

1991). On the other hand, cold nannofossil taxa consist of *Coccolithus pelagicus pelagicus* and *C. pelagicus braarudii*. As mentioned above, Tanaka (1991) did not divide *C. pelagicus* into two subspecies and considered *C. pelagicus* as an Oyashio taxon. However, a few occurrences of this species were recognized just south of the Kuroshio Front, indicating the presence of locally low-temperature and nutrient-rich areas near the Front. Considering geographic distributions and ecological preferences in other oceans, they are likely to be *C. pelagicus braarudii*.

Results

Calcareous nannofossil assemblages of the Chiba composite section

The middle part of the Kokumoto Formation generally contained well preserved, abundant calcareous nannofossils, while some samples yielded fewer nannofossil specimens in the upper part of the section. Dominant *Gephyrocapsa*, *Pseudoemiliana*, and *Florisphaera* characterized the calcareous nannofossil assemblages (Figs. 4

and 5, Table S2); comprising 90% of the total flora in the section. Small forms of *Gephyrocapsa* (< 3 μm in longer diameter) commonly reached over 70% of the total flora below sample TB3-43 in the lower part. This taxon, however, decreased from samples TB3-38 to TB14 and reached an average abundance of 45% above sample TB10.

In contrast, *Gephyrocapsa* specimens (from 3 to 4 μm in diameter) slightly increased above sample TB3-38 and replaced the smaller forms. The specimens over 5 μm in diameter were sporadically observed in the section; however, they were absent, in TB2-44 to KG30 samples between tephra Byk-A and an unnamed tephra layer in the middle of the Kokusabata section (Fig. 4). Within the lower part of this interval (TB2-44 to KG34), specimens from 4 to 5 μm in diameter were less numerous than those in other intervals. The interval with minor *Gephyrocapsa* (4–5 μm in diameter) and absent *Gephyrocapsa* over 5 μm in diameter corresponded to ~ 770–760 ka (Fig. 6). Most of the *Gephyrocapsa* (≥ 4 μm in diameter) specimens in the CbCS had a bridge parallel to the short

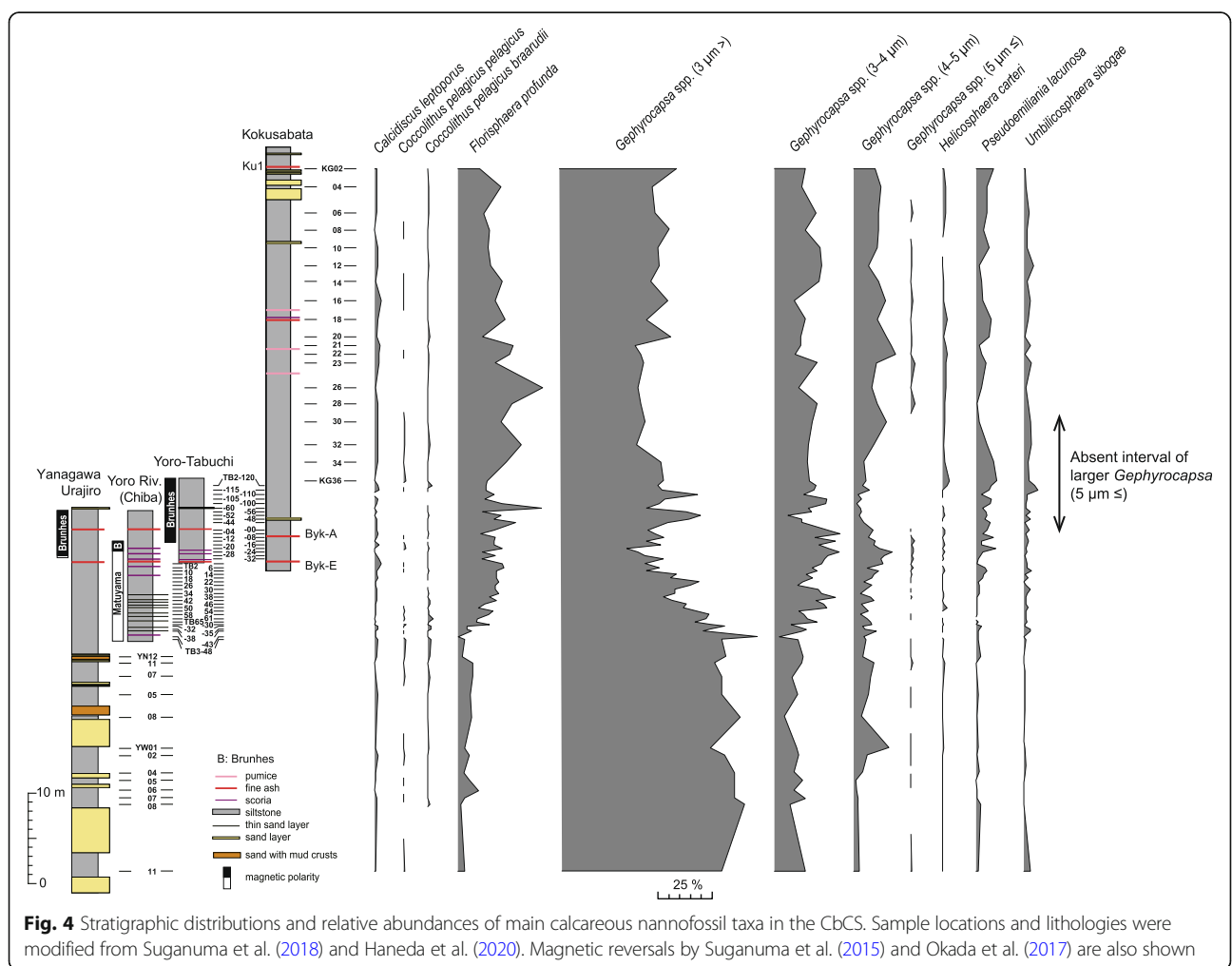


Fig. 4 Stratigraphic distributions and relative abundances of main calcareous nannofossil taxa in the CbCS. Sample locations and lithologies were modified from Suganuma et al. (2018) and Haneda et al. (2020). Magnetic reversals by Suganuma et al. (2015) and Okada et al. (2017) are also shown

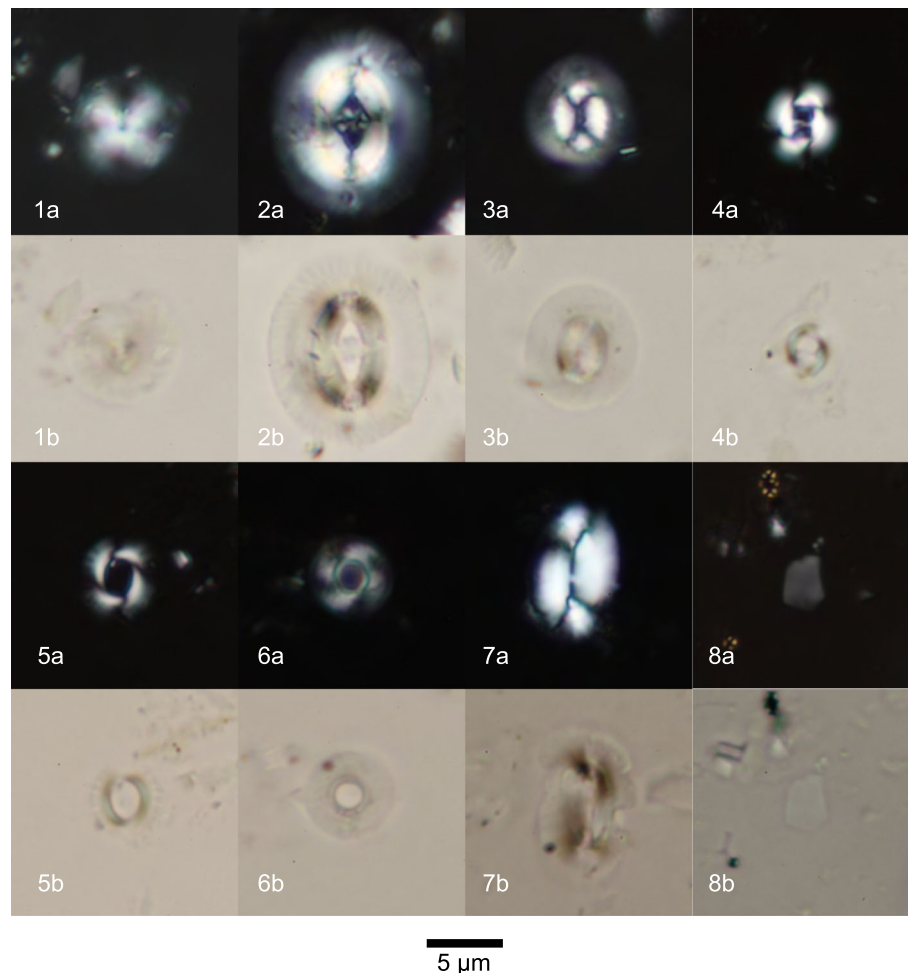


Fig. 5 Main calcareous nannofossils in the CbCS. **a** crossed nicols. **b** Without nicols. (1) *Calcidiscus leptoporus* (Murray & Blackman) Loeblich & Tappan, Sample TB2-16. (2) *Coccolithus pelagicus braarudii* (Gaarder) Geisen et al., Sample TB2-16. 3. *Coccolithus pelagicus pelagicus* (Wallich) Schiller, Sample TB2-16. (4) *Gephyrocapsa parallela* Hay & Beaudry or *Gephyrocapsa omega* Bukry, Sample TB3-15. (5) *Pseudoemiliana lacunosa* Kamptner ex Gartner, Sample TB3-15. (6) *Umbilicosphaera sibogae* (Weber-van Bosse) Gaarder, Sample TB2-16. (7) *Helicosphaera carteri* (Wallich) Kamptner, Sample TB3-15. (8) *Florisphaera profunda* Okada & Honjo, Sample TB3-15. Scale bar is 5 µm

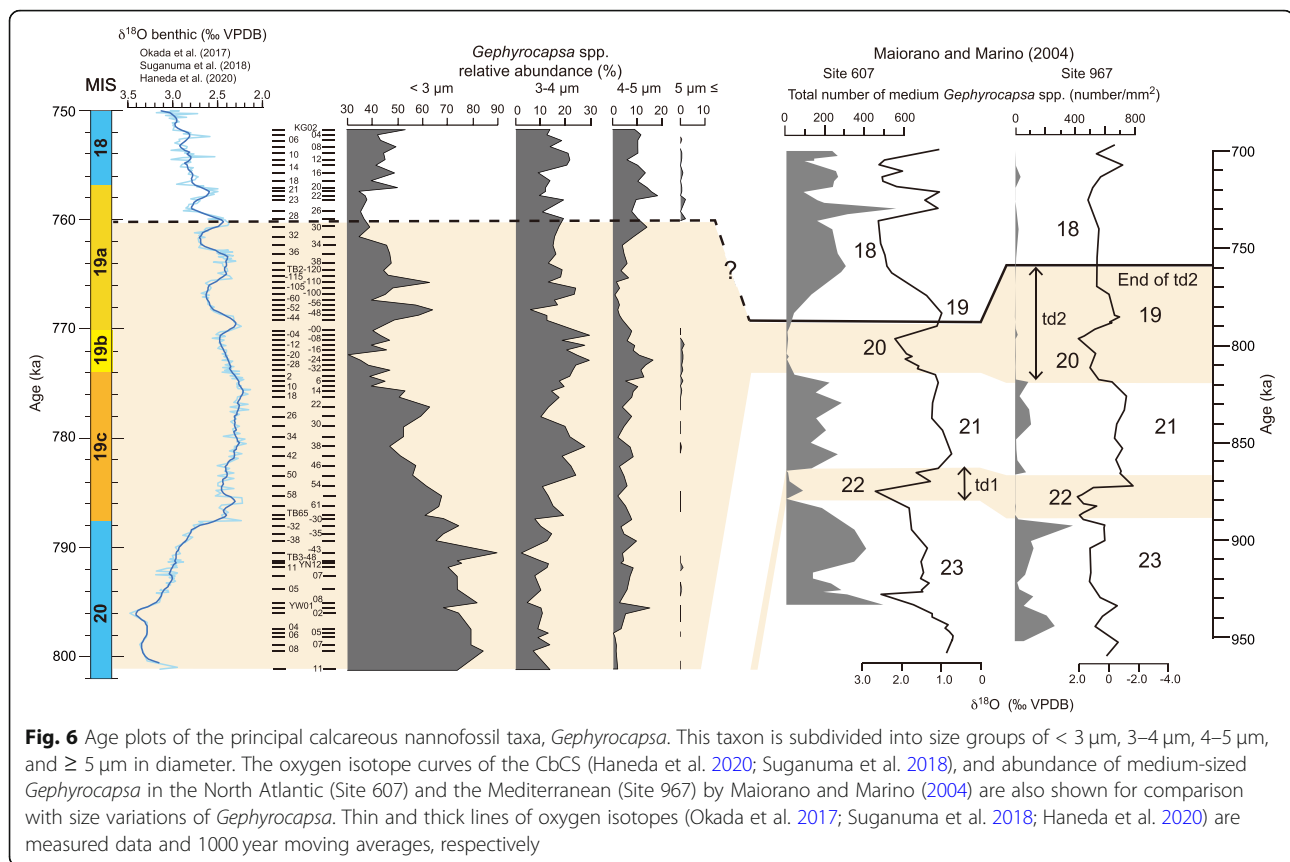
axis of the specimen; thus, they were named *Gephyrocapsa parallela* or *Gephyrocapsa omega*.

Florisphaera profunda, another common species, typically replaced small forms of *Gephyrocapsa* above samples TB3-38 (Fig. 4). Here, the relative abundance of the taxon was over 15%, whereas its abundance was 5% or less below this level. *Pseudoemiliana lacunosa*, a common species in the Pliocene–Pleistocene sediments, was present throughout this section and became more abundant above TB18 (approximately 4% on average). *Umbilicosphaera sibogae* increased in samples above TB3-38, although its average percentage was approximately 2% of the total flora. *Helicosphaera* spp., *Calcidiscus leptoporus*, and *Coccolithus pelagicus* are considered key taxa typical of the uppermost part of the Neogene and Quaternary and were also present in the CbCS with an average continuous presence of ~ 1–

2%. Thus, their variability in abundance was not revealed in standard counts.

Occurrence of environmental indicators

F. profunda, one of the most common species in the nannofossil assemblages, is a lower photic taxon in low- to middle-latitude oceans (Fig. 4). This taxon became abundant above sample TB3-30, ~ 787 ka (Fig. 7). As a possible Kuroshio water taxon, *Umbilicosphaera* spp. (mostly *U. sibogae*) was also abundant within subordinate taxa at almost the same time when its average abundance changed from ~ 20 to 40 % (Table S3). This taxon was most abundant from ~ 787 to ~ 776 ka (TB65–TB18) (Fig. 7). Subsequently, its abundance slightly decreased until ~ 769 ka (TB2-48), before increasing again. Short-term variabilities of this taxon from ten thousand to a



few thousand years were also present. As a temperate and offshore taxon, *C. leptopus* had a relative abundance within subordinate taxa of 9–40%. This taxon occurred prior to ~ 787 ka (TB65) and rapidly decreased at ~ 786 ka (TB61). Subsequently, a gradual increase of this taxon was observed after ~ 776 ka (TB14). Fluctuations in the abundance of this taxon with different cycles were recognized on the scale of twenty thousand and a few thousand years.

C. pelagicus braarudii, a cool and nutrient-rich water taxon, was abundant before ~ 783 ka (TB50) and from ~ 764 to ~ 762 ka (KG38–KG32). This subspecies predominated when *Umbilicosphaera* spp. decreased, except for the period from ~ 787–784 ka (TB3–38–TB54) and reached a 29% maximum within subordinate counts at 791 ka (YN12). At the same time, *C. pelagicus pelagicus* (a colder-water taxon) was also recognized but generally had fewer occurrences than *C. pelagicus braarudii*. *C. pelagicus pelagicus* was occasionally present approximately every ten thousand years (~ 801–795, ~ 787–783, ~ 772, ~ 764–761, and ~ 753 ka) (Fig. 7) and was most abundant around ~ 772 ka (TB2–16).

Helicosphaera spp., another abundant and characteristic taxon within the subordinate species, increased before ~ 787 ka (TB3–30) and after ~ 778 ka (TB26) (Fig. 7). *Helicosphaera* spp. mainly consisted of *Helicosphaera carteri*, *Helicosphaera hyalina*, and *Helicosphaera pavimentum* with rare

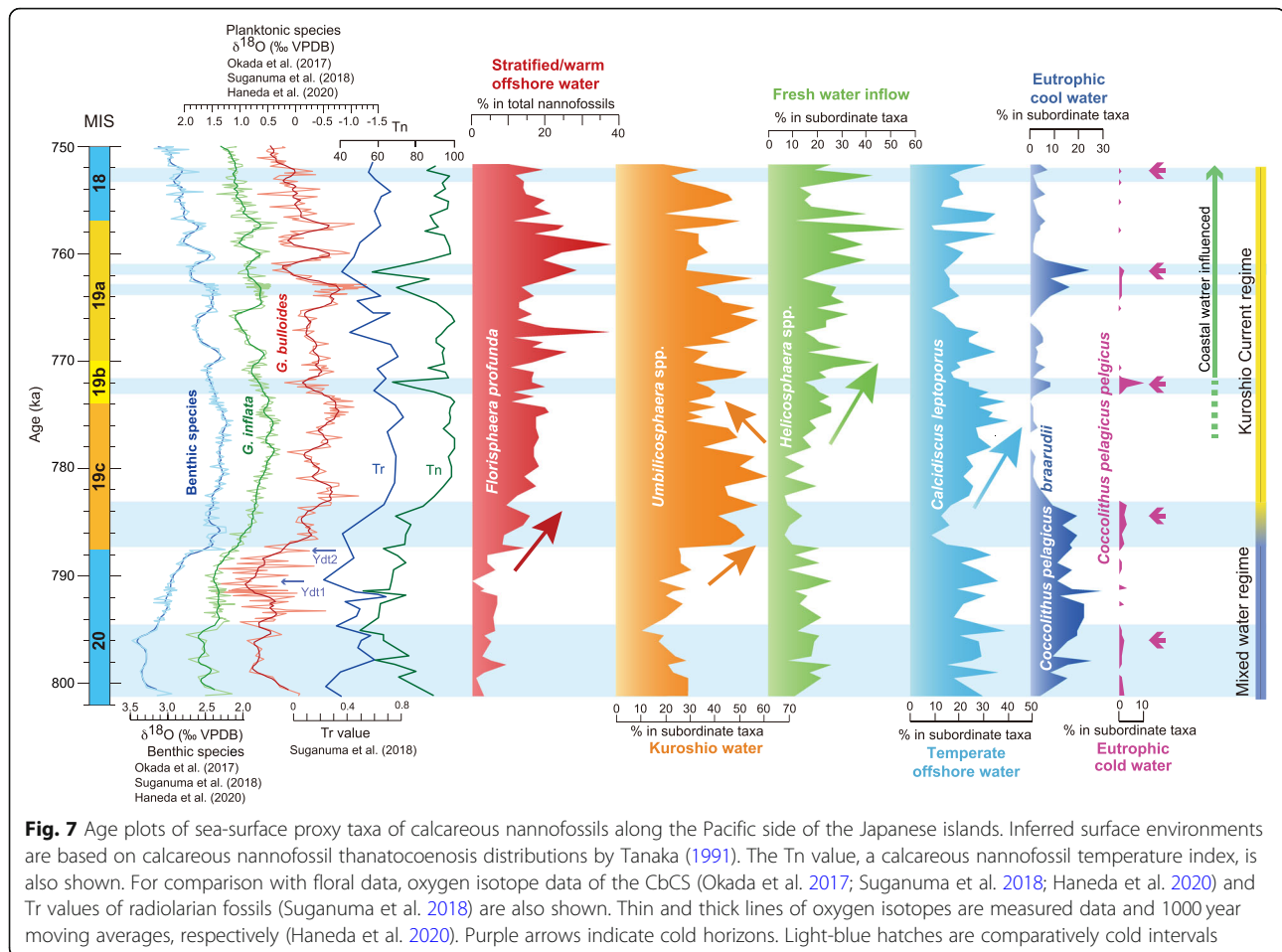
Helicosphaera wallichii. Average values before ~ 787 ka and after ~ 778 ka were 16% and 24% in the subordinate taxon, respectively. Between these intervals, corresponding to the early part of MIS 19c, fewer occurrences—approximately 10% on average—were recorded. The sequential pattern of this taxon was dissimilar to that of other calcareous nannofossil specimens. Small fluctuations with a duration of several thousand years of this taxon were also observed throughout the studied intervals. Other nannofossil taxa in subordinate counts included *Rhabdosphaera clavigera*, *Syracosphaera pulchra*, *Oolithotus fragilis*, and other minor and extremely rare species (see Table S3).

The Tn value, which is the calcareous nannofossil temperature index, shows warm-cold fluctuation within the CbCS (Fig. 7). Tn values were relatively low before ~ 783 ka, after which higher values were recorded. The fluctuation of Tn values was similar to that of the oxygen isotope of a planktonic species, *Globigerina bulloides*, in that Tn values were characteristically low at ~ 772 and ~ 763–761 ka.

Discussion

Possible bioevent around the M–B paleomagnetic polarity boundary at the Chiba composite section

There are no apparent useful nannofossil bioevents in the CbCS across the M–B paleomagnetic polarity



boundary (e.g., Raffi et al. 1993; Takayama and Sato 1987). This makes it difficult to constrain the M–B paleomagnetic polarity boundary with calcareous nannofossils.

In the Quaternary strata, the significance of size variations of *Gephyrocapsa* has been recognized elsewhere around the world (e.g., Rio et al. 1990). Appearances and disappearances of *Gephyrocapsa* of different sizes and morphologic characters can be correlated globally and used to date marine sediments. Matsuoka and Okada (1990) demonstrated the size and morphological changes of *Gephyrocapsa* species in the Quaternary strata of the Indian Ocean and recognized several morphotypes. The first and last occurrences of these morphotypes are global and have been utilized as biohorizons. Across the M–B boundary, *Gephyrocapsa* specimens are typified by abundant smaller forms (< 4 μm) and medium to large-sized specimens with a higher bridge angle (nearly parallel to the short axis) called *Gephyrocapsa omega* (Bukry 1973), *Gephyrocapsa parallela* (Hay and Beaudry, 1973), *Gephyrocapsa* sp. 3 (Rio 1982), and/or *Gephyrocapsa* sp. C (Matsuoka and Okada, 1990; Hagino et al. 2011). In the CbCS, specimens over 4 μm in diameter correspond

to these forms. In the middle part of the section, fewer medium-sized specimens (4–5 μm) and no specimens over 5 μm in diameter occurred (Figs. 4 and 6), which represents characteristic changes of *Gephyrocapsa* in the CbCS.

Maiorano et al. (2004) described the calcareous nannofossil biostratigraphy of the Lower to Middle Pleistocene in the Montalbano Jonico section and a Mediterranean Ocean Drilling Project (ODP) site (Site 964). Maiorano and Marino (2004) also provided quantitative data on the temporal and spatial distributions of *Gephyrocapsa* and *Reticulofenestra* from the Early to Middle Pleistocene, including across the M–B paleomagnetic polarity boundary in the North Atlantic Ocean (Site 607) and the Mediterranean (Sites 964, 967, and 977). These studies revealed temporal disappearances of medium-sized *Gephyrocapsa* (4–5.5 μm in size) around MIS 22 (td1) and MIS 20–19 (td2). Based on these patterns, both temporal disappearances are characteristic, but they seem to be diachronous (Maiorano and Marino 2004). In the CbCS, no intervals with a complete absence of medium-sized specimens (4–5 μm) were observed. However, there is a characteristic interval with fewer

occurrences of medium-sized *Gephyrocapsa* (4–5 μm) and a temporal disappearance of *Gephyrocapsa* specimens over 5 μm in diameter. This interval in the CbCS may correspond to a later part of td2 (Maiorano and Marino 2004). One possibility is that the end of td2 might be correlated with the top of the absent interval of *Gephyrocapsa* over 5 μm in diameter at ~ 760 ka because of re-occurrence of them at the same time (Fig. 6).

The presence of *Gephyrocapsa* over 5 μm in diameter in the CbCS suggests that this horizon corresponds to the latest occurrence of *Gephyrocapsa* sp. C identified by Matsuoka and Okada (1990) and Hagino et al. (2011). Across the M–B paleomagnetic polarity boundary, between the tops of *Reticulofenestra asanoi* (0.889 Ma) and *Pseudoemiliania lanunosa* (0.443 Ma), *Gephyrocapsa* sp. C (a medium to large *Gephyrocapsa* specimen with a comparatively high angle bridge nearly parallel to the shorter axis), disappeared. Although the exact timing of the last occurrence of *Gephyrocapsa* sp. C has not been determined, *Gephyrocapsa* specimens ($\geq 5 \mu\text{m}$) only occurred just prior to the disappearance of *Gephyrocapsa* sp. C in the upper part of the Pleistocene of the Indian Ocean (Hagino et al. 2011). *Gephyrocapsa* specimens over 5 μm in diameter in the lower CbCS may correlate with the uppermost occurrence of *Gephyrocapsa* sp. C. To correlate these *Gephyrocapsa* events identified in the CbCS with other oceans, studies on size variations and morphologic changes of *Gephyrocapsa* must be conducted across the M–B paleomagnetic polarity boundary.

Sea-surface environmental changes based on calcareous nannofossils

The stratigraphic distribution of certain major nannofossil taxa and their time-series variability revealed that sea-surface conditions, including surface currents, changed during the deposition (Fig. 7).

Prior to 788 ka, during MIS 20, warm-water taxa, *Florisphaera profunda*, and *Umbilicosphaera* spp., were not common. Instead, the abundance of *Coccolithus pelagicus braarudii* with *C. pelagicus pelagicus*, a colder, subarctic taxon (e.g., Cachão and Moita 2000), suggests cold and eutrophic surface conditions (Fig. 7). *C. pelagicus* deposited within surface sediments around the Japanese islands may include both subspecies (Tanaka 1991), and the dominant area of *C. pelagicus* coincides with the distribution areas of the cool mixed water region and the cold Oyashio Current from Sanriku to Hokkaido coast. The continuous occurrence of *C. pelagicus* suggests that the influence of Kuroshio water was weak during MIS 20 and that cold and eutrophic waters from the north of the Kuroshio Front invaded the Kazusa Basin. Tn values are low during this interval, indicating low sea-surface temperatures. The presence of small forms of

Gephyrocapsa during MIS 20 (Figs. 4 and 6) also supports this interpretation, as an abundance of smaller forms generally demonstrates a high nutrient supply in the upper photic zone (e.g., Okada and Wells 1997; Chiyonobu et al. 2012).

Around 790 ka, extreme decreases in a lower photic taxon, *F. profunda*, indicate the collapse of sea-surface stratification (Fig. 7) because this species is more likely to be abundant in stable surface conditions. At the same time, increases in small *Gephyrocapsa* ($< 3 \mu\text{m}$) (Fig. 4) and *C. pelagicus braarudii* also indicate a turbulent photic zone, resulting in cool and nutrient-rich sea surface conditions. This suddenly disturbed horizon corresponds to the Ydt1 (Younger Dryas-type event 1: Suganuma et al. 2018; Haneda et al., 2020) which is a characteristic cooling event at the latest MIS 20. Another cooling event, called Ydt2, was not clearly detected, even though there was a small reduction in the Tn value around 788 Ka (Fig. 7).

Umbilicosphaera spp. became abundant around 787 ka and persisted until 776 ka, suggesting that the strong incursion of the Kuroshio Current during MIS 19 was associated with a northward retreat of the Kuroshio Front. This interval almost corresponds to the full-interglacial conditions in MIS 19 (785.0–775.1 ka; Suganuma et al. 2018) when the Boso Peninsula was strongly influenced by southern surface waters and the Kuroshio Current. However, Tn values suggest the beginning of warming of sea-surface waters was during early MIS 19c, around ~ 783 ka. The Tr value, a sea-surface temperature index calculated by radiolarians (Suganuma et al. 2018), also supports the timing of warming. During 787–783 ka, co-occurrences of Kuroshio water taxa and cool-water taxa (Fig. 7) suggest that the study area was possibly situated around the Kuroshio Front and seasonal movements of the Front around the CbCS may have largely fluctuated.

In the early MIS 19c, *F. profunda* and *C. leptoporus* increased in abundance, although *F. profunda* began to increase earlier than *C. leptoporus*. Recently, *F. profunda* was found to have mainly lived outside the Kuroshio Current, to the south of 32–34° N (Tanaka 1991). Conversely, *C. leptoporus* is relatively abundant in the eastern part of the offshore areas, from 142° E. Thus, a gradual increase in both species signifies the stronger influence of offshore waters and the relative deepening of the basin.

After ~ 783 ka, the Kuroshio Current was common throughout the study area because of the abundant occurrences of warm-water taxa. Moreover, the gradual increase and common occurrences of *Helicosphaera* spp. after ~ 778 ka suggest the influence of coastal waters. This taxon is abundant in the East China Sea and coastal areas along the Pacific side of Japanese islands (Tanaka 1991; Tanaka 1997) and may relate to the inflow of fresh

coastal waters (Tanaka 1991). In the CbCS, however, *Umbilicosphaera* spp. and *F. profunda* were still common (Fig. 7) at the same time. Their occurrences suggest that the influence of coastal water near the coast of the Japanese islands may have increased along with the Kuroshio Current after the full interglacial during MIS 19. In Japan Sea, subtropical Tsushima Warm Current radiolarian species were rapidly decreased in Hole U1427 (Sagawa et al. 2018). Sagawa et al. (2018) suggested that shallowing the Tsushima strait due to lowering sea-level prevented the Tsushima Warm Current from flowing into Japan Sea after interglacial maxima. It has possibly influenced on common occurrences of the Kuroshio Current nannofossil taxa and increases of a coastal nannofossil taxon at the CbCS.

Although the study area has been under the strong Kuroshio Current regime, climatic fluctuations shorter than the glacial-interglacial cycle were found for each taxon. In particular, strong Kuroshio Current and comparatively cooler water regimes were regularly repeated (Fig. 7). *C. pelagicus pelagicus* and *C. pelagicus braarudii* seem to occur approximately every 10,000 years at ~ 801–795 ka, ~ 787–783 ka, ~ 772 ka, ~ 764–761 ka, and ~ 753 ka. Preliminary spectrum analysis of *C. pelagicus* (Fig. S1) also shows approximately 10,000 periodicity throughout the section, indicating cyclic southward invasions of the Kuroshio Front. These cold invasions mostly coincide with the larger oxygen isotope values of surface-dwelling *Globigerina bulloides*. On the basis of the occurrences of *C. pelagicus pelagicus*, the durations and influences of cold waters seem to be shorter and weaker, respectively. Haneda et al. (2020) suggested millennial-scale oceanographic variations, possibly influenced by North Atlantic climate variability and tropical insolation. They indicated that the millennial-scale oscillation during MIS 19b–19a corresponds to four stadial-interstadial cycles (Fig. 7; Haneda et al. 2020). These patterns indicate that the oscillatory movement of the Kuroshio Front may have controlled abrupt, millennial-scale increases and decreases in surface temperature. Two stadial periods (S1 and S3 by Haneda et al., 2020) correspond to these cooler intervals indicated by calcareous nannofossils at ~ 772 ka and ~ 764–761 ka, respectively. However, other climatic changes (stadial periods S2 and S4) indicated by oxygen isotope data were only shown by small reductions in Tn values (Fig. 7). Further examination of a higher-resolution analysis of calcareous nannofossils would be needed in order to discuss millennial-scale changes in surface waters.

Conclusions

This study examined calcareous nannofossil assemblages of the CbCS of the Kokumoto Formation of the Kazusa Group in order to extract the calcareous

nannofossil index for the Lower–Middle Pleistocene boundary and to consider environmental changes in sea surface conditions along the southwest Pacific side of the Japanese islands around the M–B paleomagnetic polarity boundary. This paper reviews previous calcareous nannofossil investigations and introduces the detailed calcareous nannofossil biostratigraphy of the CbCS, as follows. In addition, local bioevents and floral changes associated with oceanographic conditions were found using high-resolution analysis of calcareous nannofossils:

1. Previous results of the calcareous nannofossil biostratigraphy of the Kazusa Group (e.g., Sato et al. 1988, 1999) and resultant nannofossil biohorizons (datums) were summarized. Quaternary calcareous nannofossil biohorizons established in the North Atlantic (Takayama and Sato 1987; Sato and Takayama 1992) were applied in the Group. Similar biohorizons were also found in other Quaternary sequences (e.g., Raffi et al. 1993), and thus, the worldwide utility of the nannofossil biohorizons was demonstrated.
2. Based on high-resolution calcareous nannofossil biostratigraphy of the CbCS, there are no apparent bioevents of calcareous nannofossil species around the M–B paleomagnetic polarity boundary. *Gephyrocapsa* specimen ($\geq 5 \mu\text{m}$ in diameter), with a higher bridge angle (nearly parallel to the short axis), may have temporarily disappeared from ~ 770–760 ka, just after the M–B paleomagnetic polarity boundary appears in the sequence. This event could be related to the temporary disappearance of medium-sized *Gephyrocapsa* in MIS 20–19 (td2: Maiorano and Marino 2004). Moreover, the presence of large specimens of *Gephyrocapsa* corresponds to the latest occurrence of *Gephyrocapsa* sp. C (Matsuoka and Okada, 1990). Further investigation of calcareous nannofossils around the M–B paleomagnetic polarity boundary will be needed because it is unclear if this event can be traceable to other areas.
3. Floral changes in the environmental proxy taxa of calcareous nannofossils enable us to infer changes in surface currents around the M–B paleomagnetic polarity boundary. Before 787 ka, the influence of the Kuroshio Current was weak around the Kazusa Basin, and cool and eutrophic conditions were inferred because of the presence of *Coccolithus pelagicus*. Generally, abundant occurrences of *Umbilicosphaera* spp. and *Florisphaera profunda* indicate that the Kuroshio Current affected the Kazusa Basin after 787 ka.

After ~ 783 ka, the Kuroshio Current was common until MIS 18, but sea-surface temperatures fluctuate shorter than the glacial-interglacial cycle. Moreover, periodic southward invasions of the Kuroshio Front occurred approximately every 10,000 years based on the presence of a cold-water species. Shorter-term fluctuations of flora were also observed and correspond to millennial-scale environmental changes.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s40645-020-00355-x>.

Additional file 1: Table S1. Counts of calcareous nannofossils of the Kazusa Group by Sato (1989).

Additional file 2: Table S2. Counts of overall calcareous nannofossils of the Chiba composite section (This study and Suganuma et al. 2018).

Additional file 3: Table S3. Counts of subordinate taxa of calcareous nannofossils of the Chiba composite section.

Additional file 4: Fig. S1. Spectral power of *Coccolithus pelagicus* based on REDFIT method (Schulz and Mudelsee 2002) using the PAST4 software (Hammer et al. 2001). A blue dotted line shows 95% confidence level and a red dotted line indicates the first-order autoregressive (AR1) red noise model fit. A periodic change of 11 kyr is characteristically extracted from sequential occurrence of *C. pelagicus* in the CbCS.

Abbreviations

CbCS: Chiba composite section; FAD: First appearance datum; GSSP: Global Boundary Stratotype Section and Point; LAD: Last appearance datum; M-B paleomagnetic polarity boundary; Matuyama–Brunhes paleomagnetic polarity boundary

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Authors' contributions

KK conducted an overall investigation of calcareous nannofossils including sample treatments, counting, interpretation of data, writing of the manuscript, drawing of figures and tables, and creation of other additional files. YK, YH, YS, and MO assisted with the data interpretation for paleoceanography. YH and MO also take responsibility for the lithostratigraphy, the identification of samples, and their stratigraphic locations. YH supported the drawing of the figures related to magnetostratigraphy and oxygen isotopes. The authors read and approved the final manuscript.

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Availability of data and materials

The counting data of calcareous nannofossils of this article are included within the article and its additional files.

Competing interests

The authors have no competing interests to declare.

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References

- Ahagon N, Tanaka Y, Ujiie H (1993) *Florisphaera profunda*, a possible nanoplankton indicator of late Quaternary changes in sea-water turbidity at the northwestern margin of the Pacific. *Mar Micropaleontol* 22:255–273. [https://doi.org/10.1016/0377-8398\(93\)90047-2](https://doi.org/10.1016/0377-8398(93)90047-2)
- Aizawa C, Oba T, Okada H (2004) Late Quaternary paleoceanography deduced from coccolith assemblages in a piston core recovered off the central Japan coast. *Mar Micropaleontol* 52:277–297. <https://doi.org/10.1016/j.marmicro.2004.05.005>
- Anthonissen DE, Ogg JG (2012) Appendix 3 Cenozoic and Cretaceous biochronology of planktonic foraminifera and calcareous nannofossils. In: Gradstein FM, Ogg JG, Schmitz M, Ogg G (eds) *The Geologic Time Scale 2012*. Elsevier, Boston, USA 2:1083–1124
- Berger WH, Yasuda MK, Bickert T, Wefer G, Takayama T (1994) Quaternary time scale for the Ontong Java Plateau: Milankovitch template for Ocean Drilling Program Site 806. *Geology* 22:463–467. [https://doi.org/10.1130/0091-7613\(1994\)022<0463:QTSFTO>2.3.CO;2](https://doi.org/10.1130/0091-7613(1994)022<0463:QTSFTO>2.3.CO;2)
- Bown PR, Lees JA, Young JR (2004) Calcareous nanoplankton evolution and diversity through time. In: Thierstein HR, Young JR (eds) *Coccolithophores*. Springer, Berlin, Heidelberg, pp 481–508
- Brown E, Colling A, Park D, Phillips J, Rothery D, Wright J (2001) Chapter 3-Ocean Currents, Ocean Circulation (Second Edition). Butterworth-Heinemann, Oxford, pp 37–78
- Bukry D (1973) Low-latitude coccolith biostratigraphic zonation. In: Edgar NT, Saunders JB, et al. *Initial Reports DSDP 15*, Washington (U.S. Govt. Printing Office), 685–703. <https://doi.org/10.2973/dsdp.proc.15.116.1973>
- Cachão M, Moita MT (2000) *Coccolithus pelagicus*, a productivity proxy related to moderate fronts off Western Iberia. *Mar Micropaleontol* 39:131–155. [https://doi.org/10.1016/S0377-8398\(00\)00018-9](https://doi.org/10.1016/S0377-8398(00)00018-9)
- Cherepanova MV, Pushkar VS, Razjigaeva N, Kumai H, Koizumi I (2002) Diatom biostratigraphy of the Kazusa Group, Boso Peninsula, Honshu, Japan. *Quat Res (Daiyonki Kenkyu)* 41:1–10. <https://doi.org/10.4116/jaqua.41.1>
- Chiyonobu S, Mori Y, Oda M (2012) Reconstruction of paleoceanographic conditions in the northwestern Pacific Ocean over the last 500 kyr based on calcareous nannofossil and planktic foraminiferal assemblages. *Mar Micropaleontol* 96(97):29–37. <https://doi.org/10.1016/j.marmicro.2012.07.002>
- Flores JA, Sierro FJ (1997) Revised technique for calculation of calcareous nannofossil accumulation rates. *Micropaleontol* 43:321–324
- Gallagher SJ, Kitamura A, Iryu Y, Itaki T, Koizumi I, Hoiles PW (2015) The Pliocene to recent history of the Kuroshio and Tsushima warm currents: a multi-proxy approach. *Prog Earth Planet Sci* 2:1–17. <https://doi.org/10.1186/s40645-015-0045-6>
- Gallagher SJ, Sagawa T, Henderson ACG, Saavedra-Pellitero M, De Vleeschouwer D, Black H, Itaki T, Toucanne S, Bassetti M-A, Clemens S, Anderson W, Alvarez-Zarikian C, Tada R (2018) East Asian monsoon history and paleoceanography of the Japan Sea over the last 460,000 years. *Paleoceanogr. Paleoclimatol.* 33: 683–702. <https://doi.org/10.1029/2018PA003331>
- Gradstein FM, Ogg JG, Schmitz M, Ogg G (2012) *The Geologic Time Scale 2012*. Elsevier, Boston, USA. <https://doi.org/10.1016/C2011-1-08249-8>
- Hagino K (1997) Distribution of living coccolithophores in the western Pacific Ocean off the coast of Northwest Japan. *Fossil.* 63:1–19 (in Japanese with English abstract)
- Hagino K, Horiguchi T, Takano Y, Matsuoka H (2011) Geological and biological approaches of speciation with size variation in coccolithophores. *Bull. Plank. Soc. Japan.* 58:73–80 (in Japanese with English abstract)

- Hammer Ø, Harper DAT, Ryan PD (2001) PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica* 4:9 pp http://palaeo-electronica.org/2001_1/past/issue1_01.htm
- Haneda Y, Okada M, Kubota Y, Suganuma Y (2020) Millennial-scale hydrographic changes in the northwestern Pacific during marine isotope stage 19: teleconnections with ice melt in the North Atlantic. *Earth Planet Sci Lett* 531. <https://doi.org/10.1016/j.epsl.2019.115936>
- Hay WW, Beaudry FM (1973) Calcareous nanofossils-Leg 15. In: Edgar NT, Saunders JB, et al. Initial Reports DSDP 15, Washington (U.S. Govt. Printing Office), 625–683 <https://doi.org/10.2973/dsdp.proc.15.116.1973>
- Head MJ, Gibbard PL (2005) Early–Middle Pleistocene transitions: an overview and recommendation for the defining boundary. In: Head MJ, Gibbard PL (eds) Early–Middle Pleistocene Transitions: The Land–Ocean Evidence. Geological Society, London, Special Publications 247:1–18. <https://doi.org/10.1144/GSL.SP.2005.247.01.01>
- Ito M (1992) High-frequency depositional sequences of the upper part of the Kazusa Group, a middle Pleistocene forearc basin fill in Boso Peninsula, Japan. *Sedimentary Geology* 76:155–175. [https://doi.org/10.1016/0037-0738\(92\)90081-2](https://doi.org/10.1016/0037-0738(92)90081-2)
- Ito M (1998) Submarine fan sequences of the lower Kazusa Group, a Plio-Pleistocene forearc basin fill in the Boso Peninsula, Japan. *Sedimentary Geology* 122:69–93. [https://doi.org/10.1016/S0037-0738\(98\)00099-2](https://doi.org/10.1016/S0037-0738(98)00099-2)
- Ito M, Kameo K, Satoguchi Y, Masuda F, Hiroki Y, Takano O, Nakajima T, Suzuki N (2016) Neogene–Quaternary sedimentary successions. In: Moreno T, Wallis S, Kojima T, Gibbons W (eds) The Geology of Japan, Geological Society, London, Geology of Series, 309–337
- Ito M, Katsura Y (1992) Inferred glacio-eustatic control for high-frequency depositional sequences of the Plio-Pleistocene Kazusa Group, a forearc basin fill in Boso Peninsula, Japan. *Sedimentary Geology* 80:67–75. [https://doi.org/10.1016/0037-0738\(92\)90032-M](https://doi.org/10.1016/0037-0738(92)90032-M)
- Kazaoka O, Suganuma Y, Okada M, Kameo K, Head MJ, Yoshida T, Kameyama S, Nirei H, Aida N, Kumai H (2015) Stratigraphy of the Kazusa Group, Central Japan: a high-resolution marine sedimentary sequence from the Lower to Middle Pleistocene. *Quat Int* 383:116–135. <https://doi.org/10.1016/j.quaint.2015.02.065>
- Kimura S, Nakata H, Okazaki Y (2000) Biological production in meso-scale eddies caused by frontal disturbances of the Kuroshio Extension. *ICES Journal of Marine Science* 57:133–142. <https://doi.org/10.1006/jmsc.1999.0564>
- Locarnini RA, Mishonov AV, Antonov JJ, Boyer TP, Garcia HE, Baranova OK, Zweng MM, Paver CR, Reagan JR, Johnson DR, Hamilton M, Seidov D (2013) World Ocean Atlas 2013, Volume 1: Temperature. In: Levitus S, Mishonov A, (Technical ed) NOAA Atlas NESDIS 73: p 40
- Lourens L, Hilgen F, Shackleton NJ, Lasker J, Wilson D. (2004) 21 The Neogene Period. In: Gradstein FM, Ogg JG, Smith AG (eds) A Geologic Time Scale 2004. Cambridge University Press, Cambridge, 409–440.
- Maiorano P, Marino M (2004) Calcareous nanofossil bioevent and environmental control on temporal and spatial patterns at the early-middle Pleistocene. *Mar Micropaleontol* 53:405–422. <https://doi.org/10.1016/j.marmicro.2004.08.003>
- Maiorano P, Marino M, Di Stefano E, Ciaranfi N (2004) Calcareous nanofossil events in the lower–middle Pleistocene transition at the Montalbano Jonico section and ODP Site 964: calibration with isotope and sapropel stratigraphy. *Riv Ital Paleontol Stratigr* 110:547–556. <https://doi.org/10.13130/2039-4942/5823>
- Matsuoka H, Okada H (1989) Quantitative analysis of Quaternary nannoplankton in the subtropical northwestern Pacific Ocean. *Mar Micropaleontol* 14:97–118. [https://doi.org/10.1016/0377-8398\(89\)90033-9](https://doi.org/10.1016/0377-8398(89)90033-9)
- Matsuoka H, Okada H (1990) Time-progressive morphometric changes of the genus *Gephyrocapsa* in the Quaternary sequence of the tropical Indian Ocean, Site 709. In: Duncan RA, Backman J, Peterson LC et al. Proc ODP, Sci Results, 115: College Station, TX (Ocean Drilling Program), 255–270. <https://doi.org/10.2973/odp.proc.sr.115.155.1990>
- Molifino B, McIntyre A (1990) Precessional forcing of nutricline dynamics in the Equatorial Atlantic. *Science* 249:766–769. <https://doi.org/10.1126/science.249.4970.766>
- Narciso A, Cachão M, de Abreu L (2006) *Coccolithus pelagicus* subsp. *pelagicus* versus *Coccolithus pelagicus* subsp. *braarudii* (Coccolithophore, Haptophyta): a proxy for surface subarctic Atlantic waters off Iberia during the last 200 kyr. *Mar Micropaleontol* 59:15–34. <https://doi.org/10.1016/j.marmicro.2005.12.001>
- Niitsuma N (1971) Detailed study of the sediments recording the Matuyama–Brunhes geomagnetic reversal. *Tohoku Univ Sci Rep 2nd Ser (Geol)* 43: 1–39
- Niitsuma N (1976) Magnetic stratigraphy in the Boso Peninsula. *Jour Geol Soc Japan* 82:163–181 (in Japanese with English abstract)
- Nishida N, Kazaoka O, Izumi K, Suganuma Y, Okada M, Yoshida T, Ogitsu I, Nakazato H, Kameyama S, Kagawa A, Morisaki M, Nirei H (2016) Sedimentary processes and depositional environments of a continuous marine succession across the Lower–Middle Pleistocene boundary: Kokumoto Formation, Kazusa Group, central Japan. *Quat Int* 397:3–15. <https://doi.org/10.1016/j.quaint.2015.06.045>
- Oda M (1977) Planktonic foraminiferal biostratigraphy of the late Cenozoic sedimentary sequence, Central Honshu, Japan. *Tohoku Univ Sci Rep 2nd Ser (Geol)* 48: 1–76
- Okada H, Wells P (1997) Late Quaternary nanofossil indicators of climate change in two deep-sea cores associated with the Leeuwin Current off Western Australia. *Palaeogeogr Palaeoclimatol Palaeoecol* 131:413–432. [https://doi.org/10.1016/S0031-0182\(97\)00014-X](https://doi.org/10.1016/S0031-0182(97)00014-X)
- Okada M, Niitsuma N (1989) Detailed paleomagnetic records during the Brunhes–Matuyama geomagnetic reversal and a direct determination of depth lag for magnetization in marine sediments. *Phys Earth Planet Inter* 56: 133–150. [https://doi.org/10.1016/0031-9201\(89\)90043-5](https://doi.org/10.1016/0031-9201(89)90043-5)
- Okada M, Suganuma Y, Haneda Y, Kazaoka O (2017) Paleomagnetic direction and paleointensity variations during the Matuyama–Brunhes polarity transition from a marine succession in the Chiba composite section of the Boso Peninsula, central Japan. *Earth, Planets, Space* 69(45). <https://doi.org/10.1186/s40623-017-0627-1>
- Pälike H, Lyle MW, Nishi H, Raffi I, Ridgwell A, Gamage K, Klaus A, Acton G, Anderson L, Backman J, Baldauf J, Beltran C, Bohaty SM, Bown P, Busch W, Channell JET, Chun COJ, Delaney M, Dewangan P, Jones TD, Edgar KM, Evans H, Fitch P, Foster GL, Gussone N, Hasegawa H, Hathorne ED, Hayashi H, Herrle JO, Holbourn A, Hovan S, Hyeong K, Iijima K, Ito T, Kamikuri S, Kimoto K, Kuroda J, Leon-Rodriguez L, Malinverno A, Moore TC Jr, Murphy BH, Murphy DP, Nakamura H, Ogane K, Ohneiser C, Richter C, Robinson R, Rohling EJ, Romero O, Sawada K, Scher H, Schneider L, Sliuis A, Takata H, Tian J, Tsujimoto A, Wade BS, Westerhold T, Wilkens R, Williams T, Wilson PA, Yamamoto Y, Yamamoto S, Yamazaki T, Zeebe RE (2012) A Cenozoic record of the equatorial Pacific carbonate compensation depth. *Nature* 488:609–614. <https://doi.org/10.1038/nature11360>
- Pickering KT, Souter C, Oba T, Taira A, Schaaf M, Platzman E (1999) Glacio-eustatic control on deep-marine clastic forearc sedimentation, Pliocene–mid-Pleistocene (ca 1180–600 ka) Kazusa Group SE Japan. *Jour Geol Soc London* 156:125–136. <https://doi.org/10.1144/gsjgs.156.1.0125>
- Qiu B (2001) Kuroshio and Oyashio currents. In: Steele JH, Thorpe SA, Turekian KK (eds) Encyclopedia of Ocean Sciences, London, Academic Press, pp 1413–1425. <https://doi.org/10.1006/rwos.2001.0350>
- Raffi I (2002) Revision of the early-middle Pleistocene calcareous nanofossil biochronology (1.75–0.85 Ma). *Mar Micropaleontol* 45:25–55. [https://doi.org/10.1016/S0377-8398\(01\)00044-5](https://doi.org/10.1016/S0377-8398(01)00044-5)
- Raffi I, Backman J, Fornaciari E, Pälike H, Rio D, Lourens L, Hilgen F (2006) A review of calcareous nanofossil astrobiochronology encompassing the past 25 million years. *Quat Sci Rev* 25:3113–3137. <https://doi.org/10.1016/j.quascirev.2006.07.007>
- Raffi I, Backman J, Rio D, Shackleton NJ (1993) Plio-Pleistocene nanofossil biostratigraphy and calibration to oxygen isotope stratigraphies from Deep Sea Drilling Project Site 607 and Ocean Drilling Program Site 677. *Paleoceanography* 8:387–408. <https://doi.org/10.1029/93PA00755>
- Rio D (1982) The fossil distribution of coccolithophore genus *Gephyrocapsa* Kamptner and related Plio-Pleistocene chronostratigraphic problems. In: Prell WL, Gardner JV, et al. Init Repts DSDP 68, Washington (U.S. Govt. Printing Office), 325–343. <https://doi.org/10.2973/dsdp.proc.68.109.1982>
- Rio D, Fornaciari E, Raffi I (1990) Late Oligocene through early Pleistocene calcareous nanofossils from western equatorial Indian Ocean (Leg 115). In: Duncan RA, Backman J, Peterson LC, et al, Proc ODP, Sci Res 115, College Station, TX (Ocean Drilling Program), 175–235. <https://doi.org/10.2973/odp.proc.sr.115.152.1990>
- Sato T (1989) Uppermost Cenozoic calcareous nanofossil biostratigraphy of Japan. Institute of Geology and Paleontology, Faculty of Science, Tohoku University, Doctoral dissertation, p 117 (in Japanese)
- Sato T, Chiyonobu S, Hodell DA (2009) Data report: Quaternary calcareous nanofossil datums and biochronology in the North Atlantic Ocean, IODP Site U1308. In: Channell JET, Kanamatsu T, Sato T, Stein R, Alvarez Zarikian CA, Malone MJ, the Expedition 303/306 Scientists, Proc IODP, 303/306: College Station, TX (Integrated Ocean Drilling Program Management International, Inc), <https://doi.org/10.2204/iodp.proc.303306.210.2009>
- Sato T, Kameo K, Mita I (1999) Validity of the latest Cenozoic calcareous nanofossil datums and its application to the tephrochronology. *Earth*

- Science (Chikyū Kagaku) 53:265–274 (in Japanese with English abstract). https://doi.org/10.15080/agcjchikyukagaku.53.4_265
- Sato T, Takayama T (1992) A stratigraphically significant new species of the calcareous nannofossil *Reticulofenestra asanoi*. In: Ishizaki K, Saito T (eds) Centenary of Japanese Micropaleontology. Terra Scientific Publishing Company, Tokyo, pp 457–460
- Sato T, Takayama T, Kato M, Kudo T, Kameo K (1988) Calcareous microfossil biostratigraphy of the uppermost Cenozoic formations distributed in the coast of the Japan Sea, Part 4: Conclusion. *Jour Jap Assoc Petr Tech* 53:474–491 (in Japanese with English abstract). <https://doi.org/10.3720/japt.53.475>
- Satoguchi Y, Nagahashi Y (2012) Tephrostratigraphy of the Pliocene to Middle Pleistocene Series in Honshu and Kyushu Islands, Japan. *Island Arc* 21:149–169. <https://doi.org/10.1111/j.1440-1738.2012.00816.x>
- Schlitzer R (2020) Ocean Data view. <http://odv.awi.de>
- Schulz M, Mudelsee M (2002) REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. *Comput. Geosci.* 28:421–426
- Seno T, Takano T (1989) Seismotectonics at the Trench-Trench-Trench Triple Junction off Central Honshu. *Pure and Applied Geophysics* 129:27–40
- Suganuma Y, Haneda Y, Kameo K, Kubota Y, Hayashi H, Itaki T, Okuda M, Head MJ, Sugaya M, Nakazato H, Igarashi A, Shikoku K, Hongo M, Watanabe M, Satoguchi Y, Takeshita Y, Nishida N, Izumi K, Kawamura K, Kawamata M, Okuno J, Yoshida T, Ogitsu I, Yabusaki H, Okada M (2018) Paleoclimatic and paleoceanographic records of Marine Isotope Stage 19 at the Chiba composite section, central Japan: a reference for the Early–Middle Pleistocene boundary. *Quat Sci Rev* 191:406–430. <https://doi.org/10.1016/j.quascirev.2018.04.022>
- Suganuma Y, Okada M, Horie K, Kaiden H, Takehara M, Senda R, Kimura J, Kawamura K, Haneda Y, Kazaoka O, Head MJ (2015) Age of Matuyama–Brunhes boundary constrained by U–Pb zircon dating of a widespread tephra. *Geology* 43(6):491–494. <https://doi.org/10.1130/G36625.1>
- Suzuki Y, Kodama K, Mitsunashi T, Oka S, Urabe A, Endo T, Horiguchi M, Eto T, Kikuchi T, Yamauchi S, Nakajima T, Tokuhashi S, Nirei H, Hara Y, Nakayama T, Nasu N, Kagami H, Kimura M, Honza E (1995) Explanatory text of geological map of Tokyo Bay and adjacent areas (2nd ed), scale 1:100,000 Miscellaneous Map series (20). *Geol Surv Japan*, p 109 (in Japanese with English abstract)
- Takayama T (1967) First report on nannoplankton of the Upper Tertiary and Quaternary of the Southern Kwanto region, Japan. *Jahrb Geol Bundesanst Wien* 110:169–198
- Takayama T (1973) On the distribution of calcareous nannoplankton in the youngest Cenozoic of Japan, *Memoirs of the Geological Society of Japan. Neogene Biostratigraphy and Radiometric Dating of Japan* 8:45–63
- Takayama T, Sato T (1987) Coccolith Biostratigraphy of the North Atlantic Ocean, Deep Sea Drilling Project Leg 94. In: Ruddiman WF, Kidd RB, Thomas E et al. *Init Repts DSDP, 94: Washington (U.S. Govt. Printing Office)* 651–702. <https://doi.org/10.2973/dsdp.proc.94.113.1987>
- Takeshita Y, Matsushima N, Teradaira H, Uchiyama T, Kumai H (2016) A marker tephra bed close to the Lower–Middle Pleistocene boundary: Distribution of the Ontake–Byakubi Tephra Bed in central Japan. *Quat Int* 397:27–38. <https://doi.org/10.1016/j.quaint.2015.03.054>
- Tanaka Y (1991) Calcareous nannoplankton thanatocoenoses in surface sediments from seas around Japan. *Tohoku Univ Sci Rep 2nd Ser (Geol)* 61(2):127–198
- Tanaka Y (1997) Sedimentary processes from the shelf edge to the Okinawa Trough in the East China Sea based on the coccolith assemblages. *Jour Sedimentol Soc Japan* 44:33–41 (in Japanese with English abstract)
- Tokuhashi S, Watanabe M (2008) 4.2 Kazusa Group and its corresponding formations. In: Amano K et al (eds) Sato M, Asakura, Kanto District, pp 281–292 (in Japanese)
- Tsuji T, Miyata Y, Okada M, Mita I, Nakagawa H, Sato Y, Nakamizu M (2005) High-resolution chronology of the lower Pleistocene Otadai and Umegase Formations of the Kazusa Group, Boso Peninsula, central Japan—Chronostratigraphy of the JNOC TR-3 cores based on oxygen isotope, magnetostratigraphy and calcareous nannofossil—. *Jour Geol Soc Japan*, 111: 1–20 (in Japanese with English abstract) <https://doi.org/10.5575/geosoc.111.1>
- Tzedakis PC, Channell JET, Hodell DA, Kleiven HF, Skinner LC (2012) Determining the natural length of the current interglacial. *Nat. Geosci.* 5:138–141. <https://doi.org/10.1038/ngeo1358>
- Unoki S, Kubota M (1996) Waves and currents in the ocean. Tokai University Press, p 356
- Wei W (1993) Calibration of upper Pliocene–lower Pleistocene nannofossil events with oxygen isotope stratigraphy. *Paleoceanography* 8:85–99. <https://doi.org/10.1029/92PA02504>
- Yasuda I (2003) Hydrographic structure and variability in the Kuroshio–Oyashio transition areas. *Jour Oceanography* 59:389–402. <https://doi.org/10.1023/A:1025580313836>
- Young JR, Bown PR, Lees JA (2017) Nannotax3 website International Nannoplankton Association Accessed 21 Apr 2017. <http://www.mikrotax.org/Nannotax3>

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