

REVIEW

Open Access



Transitional changes in microfossil assemblages in the Japan Sea from the Late Pliocene to Early Pleistocene related to global climatic and local tectonic events

Takuya Itaki

Abstract

Many micropaleontological studies based on data from on-land sections, oil wells, and deep-sea drilling cores have provided important information about environmental changes in the Japan Sea that are related to the global climate and the local tectonics of the Japanese Islands. Here, major changes in the microfossil assemblages during the Late Pliocene to Early Pleistocene are reviewed. Late Pliocene (3.5–2.7 Ma) surface-water assemblages were characterized mainly by cold-temperate planktonic flora and fauna (nannofossils, diatoms, radiolarians, and planktonic foraminifera), suggesting that nutrient-rich North Pacific surface waters entered the Japan Sea via northern straits. The common occurrence of Pacific-type deep-water radiolarians during this period also suggests that deep water from the North Pacific entered the Japan Sea via the northern straits, indicating a sill depth >500 m. A weak warm-water influence is recognized along the Japanese coast, suggesting a small inflow of warm water via a southern strait. Nannofossil and sublittoral ostracod assemblages record an abrupt cooling event at 2.75 Ma that correlates with the onset of the Northern Hemisphere glaciation. Subsequently, cold intermediate- and deep-water assemblages of ostracods and radiolarians increased in abundance, suggesting active ventilation and the formation of the Japan Sea Proper Water, associated with a strengthened winter monsoon. Pacific-type deep-water radiolarians also disappeared around 2.75 Ma, which is attributed to the intermittent occurrence of deep anoxic environments and limited migration from the North Pacific, resulting from the near-closure or shallowing of the northern strait by a eustatic fall in sea level and tectonic uplift of northeastern Japan. A notable reduction in primary productivity from 2.3 to 1.3 Ma also suggests that the nutrient supply from the North Pacific was restricted by the near-closure of the northern strait. An increase in the abundance of subtropical surface fauna suggests that the inflow of the Tsushima Warm Current into the Japan Sea via a southern strait began at 1.7 Ma. The opening of the southern strait may have occurred after the subsidence of southwestern Japan.

Keywords: Radiolaria, Diatom, Calcareous nannofossil, Foraminifera, Ostracoda, Productivity, Paleoceanography, Northern Hemisphere glaciation, Tectonics, Tsushima Warm Current

Correspondence: t-itaki@aist.go.jp
AIST, Geological Survey of Japan, Higashi 1-1-1, Tsukuba Central 7, Ibaraki
305-8567, Japan



© 2016 Itaki. **Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Review

The Japan Sea is a marginal sea in the northwestern Pacific Ocean bounded by the Eurasian continent, the Japanese Islands, and Sakhalin Island (Fig. 1). Although this sea has deep basins with depths to 3700 m, it is connected to adjacent marginal seas and the Pacific Ocean by only four shallow straits, with sill depths of 130 m or less. The Tsushima Strait (sill depth, 130 m) connects it to the East China Sea, the Tsugaru Strait (130 m)

connects it to the Pacific, and the Soya (55 m) and Mamiya (12 m) Straits connect it to the Sea of Okhotsk.

The circulation of oceanic water in this marginal sea is driven by the inflow of the Tsushima Warm Current (TWC), which enters from the south via the Tsushima Strait (Fig. 1). The TWC, which branches from the Kuroshio Current and the Taiwan Current in the East China Sea, carries heat and nutrients into the Japan Sea (e.g., Morimoto and Yanagi 2001; Kodama et al. 2015)

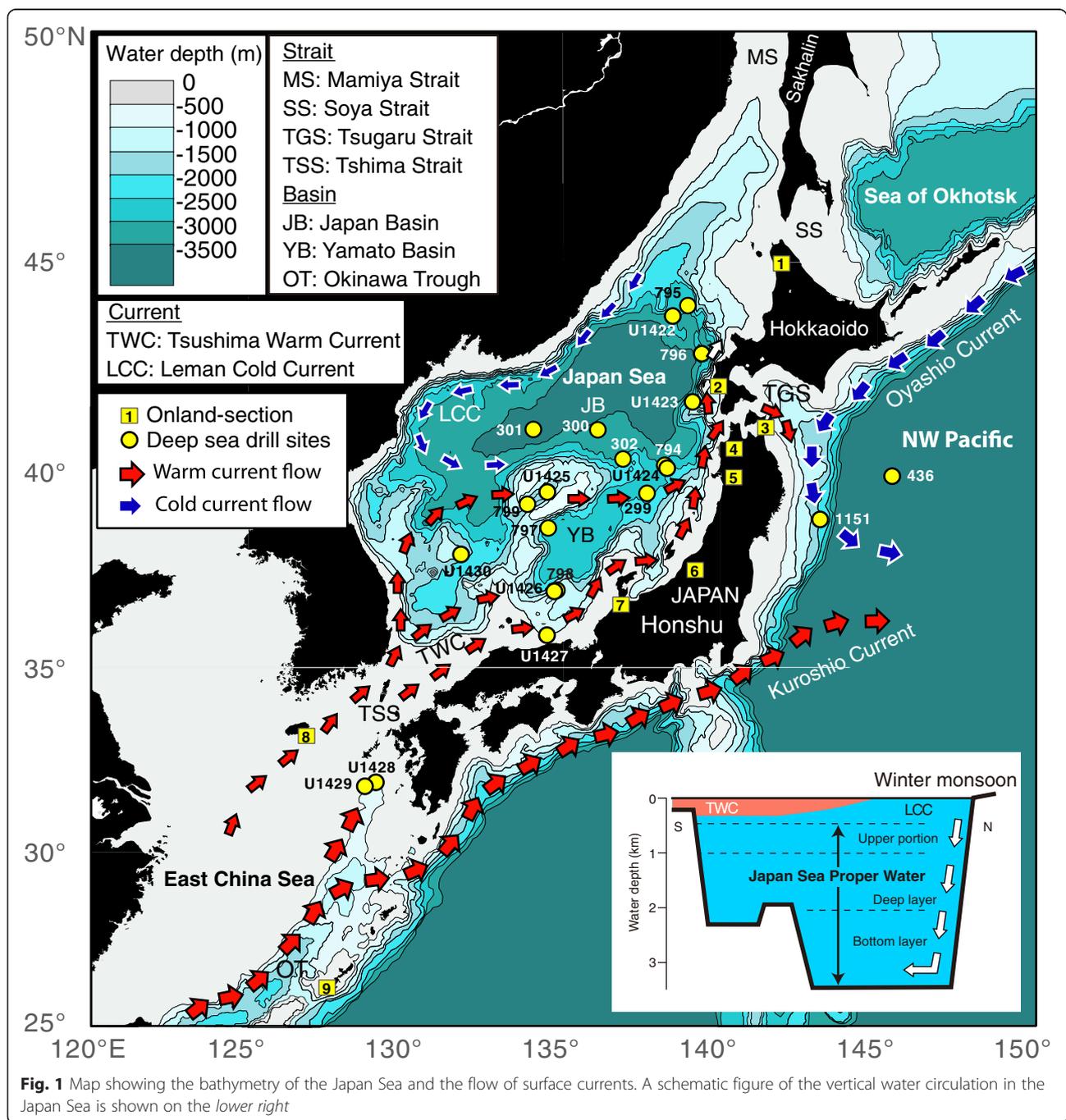


Fig. 1 Map showing the bathymetry of the Japan Sea and the flow of surface currents. A schematic figure of the vertical water circulation in the Japan Sea is shown on the lower right

and thus importantly affects the climate and ecosystems of the sea (e.g., Naganuma 2000). Seasonal variations in the sea surface temperature (SST) of the TWC range between 13 and 27 °C in the southern part of the sea and between 3 and 18 °C in the northern part. Part of the TWC flows northwestward and then sinks as its density increases in response to the cooling and sea-ice formation caused by the strong winter monsoon (Talley et al. 2003). As a result, a uniform deep-water mass characterized by a low temperature (0–0.5 °C) and a high dissolved oxygen content (5 ml/l) forms at depths below 300 m, the so-called “Japan Sea Proper Water” (JSPW) (Fig. 1; e.g., Gamo et al. 1986; Senju and Sudo 1994; Talley et al. 2003). Therefore, the deep-water biofacies in the JSPW are isolated from the open Pacific Ocean (e.g., Naganuma 2000).

In contrast to the well-ventilated deep water of the present day, the bottom conditions are known to have been anoxic during the last glacial period, associated with a covering of low-salinity surface water (e.g., Oba et al. 1991). Tada (1994) demonstrated that such large fluctuations between oxic and anoxic bottom conditions occurred since the Late Pliocene (2.6 Ma) and were probably related to the onset of the Northern Hemisphere glaciation (NHG) with the global cooling trend and to the uplift of the northeastern Japanese Islands.

Microfossils, used as index and facies fossils, are a powerful tool for reconstructing the paleogeographic and paleoenvironmental histories of the Japan Sea. A huge amount of micropaleontological data is available from on-land sections, oil wells, and deep-sea drilling cores obtained during cruises such as Deep Sea Drilling Project (DSDP) Leg 31 (sites 299–302) and Ocean Drilling Program (ODP) Leg 127/128 (sites 794–799). In particular, Expedition 346 of the Integrated Ocean Drilling Program (IODP) recently collected deep-sea drilling cores from seven sites in the Japan Sea and two sites in the northern East China Sea (Tada et al. 2015).

The aim of this article is to review the literature on the microfossil assemblages in the Japan Sea, focusing on calcareous nannofossils, diatoms, radiolarians, foraminifera, and ostracods during the Late Pliocene to Early Pleistocene transition (3.5–0.8 Ma), and to discuss the relationships between the changes in these assemblages and both global climatic changes and local or regional tectonics. Different microfossil groups provide different environmental information according to their ecological preferences, such as habitat depth, and the water masses with which they are associated (Table 1). A comprehensive interpretation of the microfossil assemblages in the Japan Sea during the Pliocene–Pleistocene transition is expected to improve our understanding of the oceanographic changes in the sea and their relationships to both variations in

the global climate and the topographic changes caused by regional and local tectonic activities.

Many important publications written in Japanese, in addition to those written in English, are included in this review, so that the information they contain might become accessible to a larger group of readers. However, because space is restricted, it is unrealistic to show all the publications dealing with microfossils in the Japan Sea because they are too many. Therefore, papers describing quantitative or semiquantitative data, such as fossil abundances and/or percentages of specific species, have been included, whereas others are only noted in an overview. Most abstracts and reports addressed to closed communities are not included.

The geological ages of each section of on-land and deep-sea cores are basically referred to the biozones listed in Table 2. All ages in this review have been converted from those of the original publications to the GTS2012 time scale (Gradstein et al. 2012), usually to within 0.1 million years. However, the ages of nannofossil bioevents are given to within 0.01 million years, because they are well documented and their age estimates have been correlated with the magnetostratigraphy of the North Atlantic Ocean and the Japan Sea (e.g., Takayama and Sato 1987, Takayama et al. 1988; Sato et al. 1988a, 2009; Watanabe et al. 2003).

Geological and geographic settings

The Japan Sea is a back-arc basin opened during the Early to Middle Miocene (ca. 25–13 Ma) as a result of continental rifting throughout the back-arc margin with the extension of regional tectonic stress (e.g., Sato 1994). The Japan Basin is underlain by an oceanic-type crust, dated at around 24–17 Ma at the basaltic basement at ODP site 795, whereas the Yamato Basin, which is younger (21–18 Ma), is unlikely to be an oceanic-type crust (Tamaki et al. 1992; Kaneoka et al. 1992). The tectonic stress changed to compression after 3.5 Ma, causing the uplift of northeast Japan (e.g., Nakajima et al. 2006). In the southwestern Japan Sea, a tectonic event, such as intra-arc folding under N–S compressive stress, resulted in the closure of the Tsushima Strait during the Late Miocene, and the attenuation of the N–S compression in southwest Japan seems to have been related to the reopening of the Tsushima Strait in the Late Pliocene (Itoh et al. 1997).

On-land sections that include Pliocene and Early Pleistocene marine deposits are widely distributed from Hokkaido Island southward to central Honshu Island in southwestern Japan (Figs. 1 and 2; Table 2). The Pliocene geography of the Japan Sea has been reconstructed using data from these on-land sections and wells, together with data from ocean drilling cores (Iijima and Tada 1990; Chinzei 1991; Ogasawara 1994;

Table 1 Ecological locations of each microfossil group

Calcareous nannofossil	Phytoplankton	Calcareous	Surface water	<p>Subtropical water</p> <p><i>Discoaster</i> spp. (extincted)</p> <p>Warm and high-nutrient water</p> <p><i>Reticulofenestra</i> spp. (small type)</p> <p>Cold water</p> <p><i>Coccolithus pelagicus</i></p>
Diatom	Phytoplankton	Opal	Surface water	<p>Warm water</p> <p><i>Actinocyclus ellipticus</i>, <i>A. elongatus</i>, <i>Alveus marinus</i>, <i>Asterolampra marylandica</i>, <i>Asteromphalus arachne</i>, <i>A. flabellatus</i>, <i>A. imbricatus</i>, <i>A. petterssonii</i>, <i>A. sarcophagus</i>, <i>Azpeitia africanus</i>, <i>A. nodulifera</i>, <i>A. tabularis</i>, <i>Fragilariopsis doliolus</i>, <i>Hemidiscus cuneiformis</i>, <i>Nitzschia interruptestriata</i>, <i>N. kolaczekii</i>, <i>Planktoniella sol</i>, <i>Pseudosolenia calcar-avis</i>, <i>Rhizosolenia acuminata</i>, <i>R. bergonii</i>, <i>R. hebetata f. semispina</i>, <i>R. imbricata</i>, <i>Roperia tessellata</i>, <i>Thalassiosira leptopus</i>, <i>T. oestrupii</i></p> <p>Cold water</p> <p><i>Actinocyclus curvatus</i>, <i>A. ochotensis</i>, <i>Asteromphalus hyalinus</i>, <i>A. robustus</i>, <i>Bacterosira fragilis</i>, <i>Chaetoceros furcellatus</i>, <i>Coscinodiscus marginatus</i>, <i>C. oculus-iridis</i>, <i>Fragilariopsis cylindrus</i>, <i>F. oceanica</i>, <i>Neodenticula seminae</i>, <i>Porosira glacilis</i>, <i>Rhizosolenia hebetata</i>, <i>Thalassiosira gravida</i>, <i>T. hyalina</i>, <i>T. kryophila</i>, <i>T. nordenskioldii</i>, <i>T. trifulta</i> Td' = warm/(warm + cold)</p> <p>Brackish water</p> <p><i>Paralia sulcata</i></p>
Radiolaria	Protista	Opal	Surface to deep water	<p>Warm water</p> <p><i>Tetrapyle octacantha</i> group, <i>Dictocoryne profunda</i>, <i>Dictocoryne truncatum</i>, <i>Didymocorytis tetrathalamus</i>, <i>Euchitonia flucata</i></p> <p>Temperate water</p> <p><i>Actinomma medianum</i> group, <i>Lithelius minor</i></p> <p>Deep water</p> <p><i>Cornutella profunda</i>, <i>Bathropyramis woodringi</i> (Pacific); <i>Cycladophora davisiana</i>, <i>Actinomma boreale</i> group (JSPW)</p>
Planktonic foraminifera	Protista	Calcareous	Surface to intermediate water	<p>Subtropical water</p> <p><i>Globigerinoides ruber</i>, <i>Pulleniatina</i> spp. group</p> <p>Temperate intermediate water</p> <p><i>Globorotalia inflata</i></p> <p>Cold water</p> <p><i>Neogloboquadrina pachyderma</i></p>
Benthic foraminifera	Protista	Calcareous agglutinated	Sublittoral to abyssal seafloor	<p>Littoral-sublittoral</p> <p><i>Cassidulina yabei</i>, <i>Hanzawaia nipponica</i>, <i>Elphidium</i> spp., <i>Buccella</i> spp.</p> <p>Bathyal</p> <p><i>Uvigerina subperegriana</i>, <i>Epistominella pacifica</i>, <i>Angulogerina ikebei</i>, <i>Uvigerina yabei</i></p> <p>Abyssal</p> <p><i>Miliammina echigoensis</i>, <i>Martinottiella communis</i>, <i>Cribrostomoides subglobosus</i>, <i>Guppyella miocenica</i>, <i>Cyclammina japonica</i></p>

Table 1 Ecological locations of each microfossil group (*Continued*)

Ostracoda	Copepoda	Calcareous	Sublittoral to bathyal seafloor	Warm sublittoral
				<i>Cornucoquimba moniwenensis</i> , <i>Cytheropteron miurense</i>
				Cold sublittoral
				<i>Baffinicythere subkatoraforma</i> , <i>Schizocythere okhotskensis</i> , <i>Johnnealella nopporensis</i> , <i>Semicytherura mainensis</i>
				Warm upper bathyal
				<i>Krithe</i> spp.
				Cold upper bathyal
				<i>Acanthocythereis dunelmensis</i>

Kitamuta 2008). Figure 2 is a reconstructed geographic map of the Late Pliocene, compiled from these previous works. During the Late Pliocene, a wide strait between southwestern Hokkaido and northern Honshu, corresponding to the modern Tsugaru Strait, connected the Japan Sea with the North Pacific Ocean (Fig. 2). In contrast, the area around the present Tsushima Strait, at the southern end of the sea, was probably occupied by a land bridge or at most, a narrow strait, indicated by the lack of Pliocene marine deposits on southwestern Honshu and the northern Kyushu islands.

In on-land stratigraphic sections, the Pliocene sequence is mainly composed of diatom-bearing mudstone, which is covered by sandy, shallow-water Pleistocene deposits, sometimes unconformably (Fig. 3; Table 2). Based on the benthic foraminiferal assemblages in these sequences, the lithological change from mud to sand has been interpreted as reflecting a change from a bathyal (ca. 1000 m) to a sublittoral (<100 m) depositional environment during the Early Pleistocene (Matoba 1984). This large-scale shallowing of the depositional depth cannot be explained simply by the eustatic fall in sea level (about 100 m) but probably also reflects the uplift of northeastern Honshu Island with intensified compression (Sato 1994; Nakajima et al. 2006), which occurred between 3.5 and 1.7 Ma (Sato et al. 2012).

Figure 3 shows schematically the lithofacies in a deep-sea core obtained during ODP Leg 127 (Tada 1994) and their correlations with typical on-land sections obtained in various districts of Japan. Unit 2 of the deep-sea core, which consists of Pliocene diatomaceous mudstone, can also be identified in the various on-land sections. Unit 1 in the deep-sea core, which is characterized by alternating dark and light layers of hemipelagic mud, tends to correlate with sandy sequences in the on-land sections. The dark–light alternations in the deep-sea core imply that the bottom water became anoxic periodically (Tada 1994).

Changes in the microfossil groups

Figure 4 is a compilation of the Pliocene and Pleistocene biostratigraphic zones of the microfossil groups usually used in the Japan Sea. Although most bioevents originally proposed based on data from the North Pacific can also be identified in the Japan Sea, the results from the DSDP and ODP cores indicate that some Pleistocene radiolarian events are missing from the Japan Sea or occur with a large time lag (Ling 1992; Alexandrovich 1992). For this reason, the boundaries of the Pleistocene radiolarian zones in Fig. 4 are indicated with dashed lines, reflecting their uncertainty (Tada et al. 2015). In contrast, the planktonic and benthic foraminiferal zones are unique to the Japan Sea, probably because the Japan Sea was isolated from the adjacent seas.

In this section, the floral and faunal changes in the diatoms, calcareous nannofossils, radiolarians, planktonic foraminifera, benthic foraminifera, and ostracods in the Japan Sea are described. The temporal changes in the absolute abundance of each microfossil group and in the relative abundances of several important species are shown in Figs. 5 and 6, respectively.

Biogeographic distribution patterns are closely related to climatic zonation, such as the tropical, subtropical, transition, subarctic, and arctic zones. Warm- and cold-water species, terms often used in the paper previously published, include the tropical–subtropical groups and the subarctic–arctic groups, respectively. Around Japan, warm-water species are usually distributed in the subtropical waters influenced by the Tsushima and Kuroshio Currents, whereas the cold-water species mainly occur in the subarctic waters of the Oyashio Current.

Diatoms

Pioneer work on the biostratigraphy of Neogene diatoms has been carried out on on-land sections from the Tsugaru district (Koizumi 1966), Akita district (Oga Peninsula) (Koizumi 1968), and DSDP–ODP

Table 2 Typical on-land sections along the Japanese coast and records of microfossils from these areas

District	Formation	Lithology	Microfossils	Biozone	Bathymetry
1. Hokkaido (north)	Yuchi/Mochikubetsu	Fine sandstone	Diatom (Akiba, 2001; Sagayama, 2003)	NPD9 (younger than 2.4 Ma) (Akiba, 2001) NPD8 (Sagayama, 2003)	
	Koetoi/Enbetsu	Diatomaceous mudstone	Diatom (Akiba, 2001)	NPD7B–NPD8 (Akiba, 2001)	
2. Hokkaido (southwest)	Setana/Urura	Medium–coarse sandstone	Foraminifera (Nojo et al., 1999; Nemoto and Oikawa, 2006), nannofossil (Nojo et al., 1999)	CN13b–CN14a, PF8 (Nojo et al., 1999)	Sublittoral to upper bathyal (Nemoto and Oikawa, 2006)
	Kuromatsunai (type locality)	Medium sand–siltstone	Foraminifera (Masatani and Ohkura, 1980; Tsubakihara et al., 1989), diatom (Masatani and Ohkura, 1980; Tsubakihara et al., 1989)	NPD9 (Tsubakihara et al., 1989)	Lower sublittoral to middle bathyal (Masatani and Ohkura, 1980)
	Tate	Diatomaceous siltstone	Foraminifera (Masatani and Ohkura, 1980), diatom (Masatani and Ohkura, 1980)	NPD7B–NPD8 (Masatani and Ohkura, 1980)	Sublittoral to bathyal (Masatani and Ohkura, 1980)
3. Shimokita Peninsula	Hamada	Sandstone–siltstone	Foraminifera (Sugawara et al., 1997; Nemoto and Yoshimoto, 2001), Ostracoda (Ozawa and Domitsu, 2010)	CN13 (ca. 1.2–1.5 Ma, Sugawara et al., 1997) PF7 (Sugawara et al., 1997)	Upper shelf to inner bay (Ozawa and Domitsu, 2010), inner sublittoral to upper bathyal (Nemoto and Yoshimoto, 2001)
4. Tsugaru	Daishaka	Fine–medium sandstone	Foraminifera (Hata and Nemoto, 2005), Ostracoda (Ozawa, 2007)	PF8/PF9 (Hata and Nemoto, 2005)	Sublittoral to upper bathyal (Hata and Nemoto, 2005)
	Tsukushimoriyama	Fine sandstone–siltstone	Foraminifera (Hata and Nemoto, 2005)	PF7 (Hata and Nemoto, 2005)	Upper bathyal (Hata and Nemoto, 2005)
	Narusawa	Fine sandstone	Nannofossil (Okada, 1988), Foraminifera (Matoba, 1988), diatom (Maruyama, 1988; Akiba and Hiramatsu, 1988)	CN12 (Okada, 1988) NPD8 (Akiba and Hiramatsu, 1988) NPD9 (according to present of <i>N. seminae</i> in occurrence list of Maruyama, 1988)	Upper bathyal (Matoba, 1988)
	Maido	Diatomaceous, siltstone	Foraminifera (Nemoto 1990), Radiolaria (Hanagata and Miwa, 2002), diatom (Maruyama, 1988; Akiba and Hiramatsu, 1988)	PF6–PF7 (Nemoto 1990) NPD7B–NPD8 (Maruyama, 1988; Akiba and Hiramatsu, 1988) <i>L. pylomaticus</i> – <i>C. sakaii</i> zone (Hanagata and Miwa, 2002)	Middle/lower bathyal (lower part: Matoba, 1988) to upper bathyal (upper part: Nemoto 1990)
5. Akita (Oga Peninsula)	Kitaura	Alternations of fine sandstone and siltstone	Foraminifera (Sato et al., 1988a), nannofossil (Sato et al., 1988a)	PF7 (Sato et al., 1988a) <i>U. subperegrina</i> zone (Sato et al., 1988a) CN13 including datum 12 to 6 of Sato et al. (2009), (Sato et al., 1988a)	Upper bathyal (according to the <i>U. subperegrina</i> assemblage)
	Funakawa	Diatomaceous mudstone–siltstone	Foraminifera (Sato et al., 1988a), nannofossil (Sato et al., 1988a), Radiolaria (Hanagata et al. 2001b)	<i>M. echigoensis</i> zone (Sato et al., 1988a; Hanagata et al. 2001b) <i>L. pylomaticus</i> – <i>C. sakaii</i> zone (Hanagata et al. 2001b)	Middle bathyal (according to the <i>M. echigoensis</i> assemblage)

Table 2 Typical on-land sections along the Japanese coast and records of microfossils from these areas (Continued)

5. Akita (Sasaoka area)	Sasaoka	Fine sandstone–siltstone	Foraminifera (Sato et al., 1988a), nannofossil (Sato et al., 1988a), Ostracoda (Yamada et al., 2002; Irizuki and Ishida, 2007)	<i>C. yabei</i> zone (Sato et al., 1988a)	Sublittoral (according to the <i>C. yabei</i> assemblage)
	Tentokuji	Siltstone–mudstone	Foraminifera (Sato et al., 1988a; Hanagata and Watanabe, 2001), nannofossil (Sato et al., 1988a; Hanagata and Watanabe, 2001)	PF6–PF7 (Hanagata and Watanabe, 2001) CN12 including Datum A (Sato et al., 1988a; Hanagata and Watanabe, 2001) <i>M. echigoensis</i> to <i>U. subperegrina</i> zone (Sato et al., 1988a; Hanagata and Watanabe, 2001)	Upper bathyal (Hanagata and Watanabe, 2001)
6. Niigata	Haizume	Sandy siltstone–sandstone	Foraminifera (Sato et al., 1987), nannofossil (Sato et al., 1987)	PF8 (Sato et al., 1987) <i>C. yabei</i> zone (Sato et al., 1987)	Sublittoral (according to the <i>C. yabei</i> assemblage)
	Nishiyama	Siltstone–mudstone	Foraminifera (Sato et al., 1987), nannofossil (Sato et al., 1987)	PF7 (Sato et al., 1987) <i>U. subperegrina</i> zone (Sato et al., 1987) CN13 including datum 10 to 8 of Sato et al. (2009, 1987)	Upper bathyal (according to the <i>U. subperegrina</i> assemblage)
	Tanihama	Siltstone	Foraminifera (Watanabe, 1976), diatom (Yanagisawa and Amano 2003)	NPD9 (Yanagisawa and Amano 2003) <i>U. subperegrina</i> zone (Watanabe, 1976)	Upper bathyal (according to the <i>U. subperegrina</i> assemblage)
	Nadachi	Mudstone	Foraminifera (Watanabe, 1976), diatom (Yanagisawa and Amano 2003)	NPD8 (Yanagisawa and Amano 2003) <i>U. subperegrina</i> zone (Watanabe, 1976)	Upper bathyal (according to the <i>U. subperegrina</i> assemblage)
	Kuwae	Siltstone–sandy siltstone	Foraminifera (Miwa et al., 2004a), diatom (Watanabe et al., 2003), nannofossil (Watanabe et al., 2003), Ostracoda (Yamada et al., 2005; Irizuki and Ishida, 2007; Irizuki et al., 2007)	PF7 (Miwa et al., 2004a) NPD8–NPD9 (Watanabe et al., 2003)	Lower sublittoral to upper bathyal (Yamada et al. 2005)
	Shiia	Alternation of sandstone and mudstone	Foraminifera (Hanagata et al., 2001a), Radiolaria (Hanagata et al., 2001a)	<i>L. pylomaticus</i> – <i>C. sakaii</i> zone before 2.7 Ma (Hanagata et al. 2001a) <i>M. echigoensis</i> zone (Hanagata et al. 2001a)	Middle bathyal (according to the <i>M. echigoensis</i> assemblage)
7. Hokuriku	Omma	Fine sand–very fine sand	Foraminifera (Hasegawa, 1979; Takayama et al., 1988; Kitamura et al., 2001; Takata, 2000), nannofossil (Takayama et al., 1988), Ostracoda (Ozawa and Kamiya, 2001; 2005)	CN13–CN14 (Takayama et al., 1988; Takata, 2000)	Outer–inner sublittoral (Takata, 2000)
	Junicho	Silty sandstone–sandy siltstone	Foraminifera (Hasegawa, 1979; Takayama et al., 1988), nannofossil (Hasegawa, 1979; Takayama et al., 1988)	CN13 including datum 12 to 11 of Sato et al. (2009) (Takayama et al., 1988)	Sublittoral (Takayama et al., 1988)
	Yabuta	Fine sandstone–siltstone	Foraminifera (Hasegawa, 1979; Takayama et al., 1988; Miwa et al., 2004b), diatom (Watanabe, 2002), nannofossil (Takayama et al., 1988), Ostracoda (Cronin et al., 1994)	NPD7B–NPD9 (Watanabe, 2002) PF6–PF 7 (Miwa et al., 2004b)	Sublittoral to upper bathyal (Takayama et al., 1988; Cronin et al., 1994)

Table 2 Typical on-land sections along the Japanese coast and records of microfossils from these areas (*Continued*)

8. Jeju Island	Sogwipo	Fine-coarse sandstone	Foraminifera (Kang et al., 2010), nannofossil (Yi et al. 1998), Ostracoda (Lee, 2014)	CN13a–CN14a (Yi et al. 1998)	Foreshore–inner shelf (Kang, 1995)
9. Okinawa	Ryukyu Group	Bioclastic limestone/siltstone	Foraminifera (Yamamoto et al., 2003), nannofossil (Yamamoto et al., 2005)	CN13b–CN14a (Yamamoto et al., 2005)	Reef–shelf (Yamamoto et al., 2003)
	Shimajiri Group	Siltstone	Foraminifera (Ujiié and Kaneko, 2006), nannofossil (Tanaka and Ujiié 1984)	N16–N22 (Ujiié and Kaneko, 2006) CN9a–CN13a (Tanaka and Ujiié 1984)	Upper bathyal (Ujiié and Kaneko, 2006)

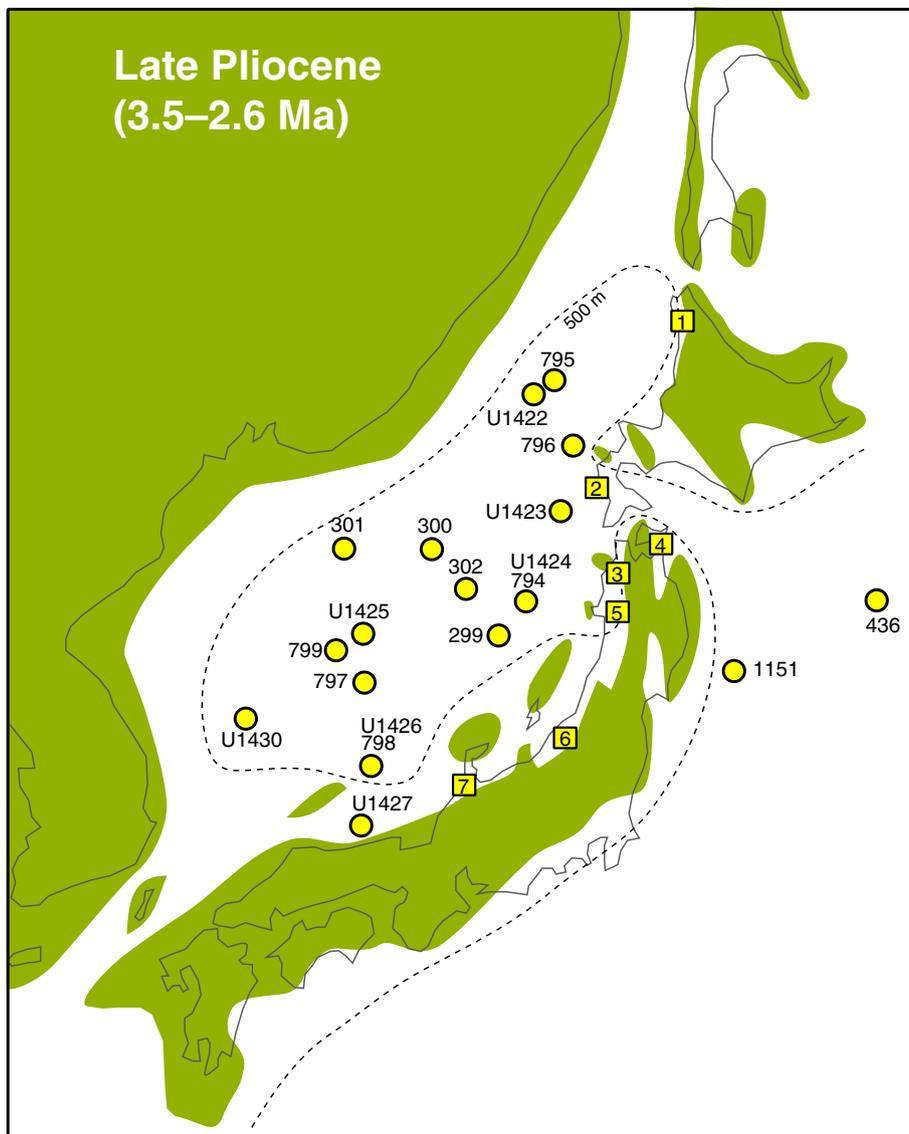
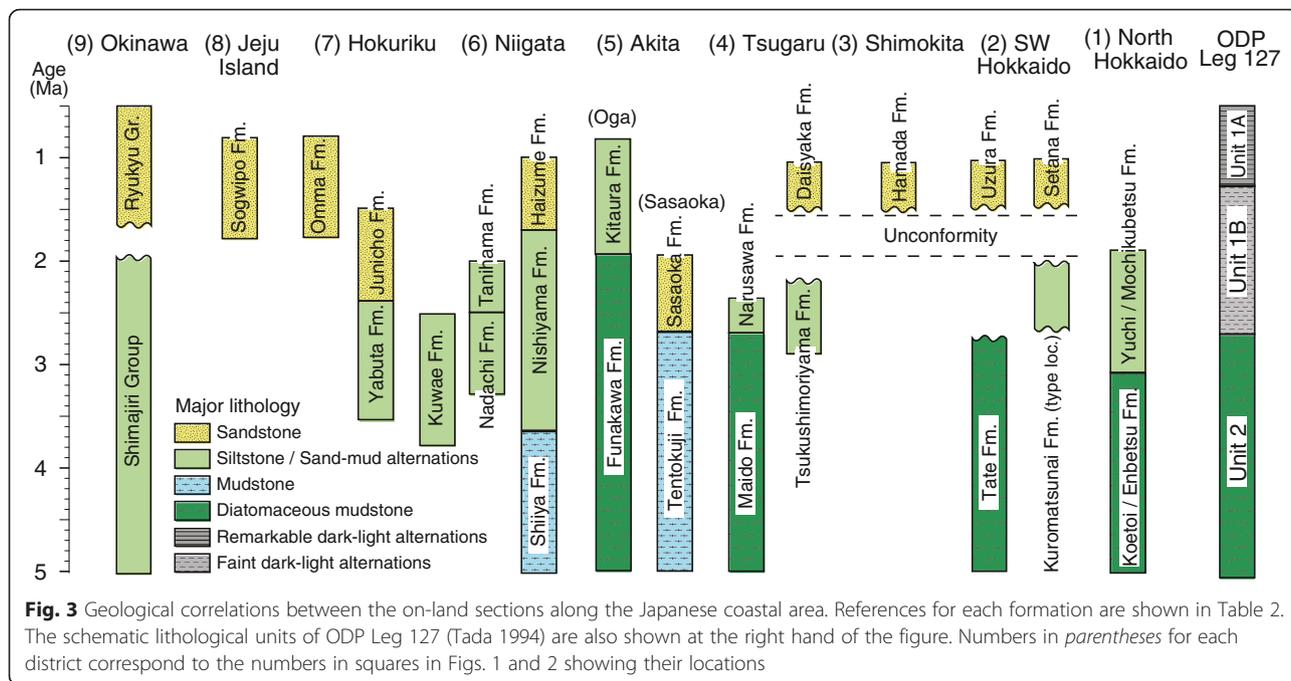


Fig. 2 Reconstructed paleogeography of the late Pliocene, modified from Iijima and Tada (1990) and Ogasawara (1994). The locations of the on-land geological sections and drill sites of the DSDP, ODP, and IODP expeditions are shown

sites in the Japan Sea (Koizumi 1975, 1992a). These studies have reported that the widely distributed Pliocene diatomaceous deposits are mainly composed of marine diatoms, suggesting the presence of nutrient-rich seawater. However, the preservation of siliceous microfossils deteriorated from 2.9 to 2.3 Ma (White and Alexandrovich 1992), and diatom abundances decreased thereafter, most notably from ca. 2.3 Ma until ca. 1.3 Ma at ODP Leg 127 sites 794–797 (Koizumi 1992a; Koizumi and Yamamoto in press; Fig. 5). This reduction can be interpreted as reflecting a reduced nutrient supply from the Pacific, resulting from the shallowing of the Tsugaru Strait (White and Alexandrovich 1992). After ca. 1.3 Ma, the diatom abundance

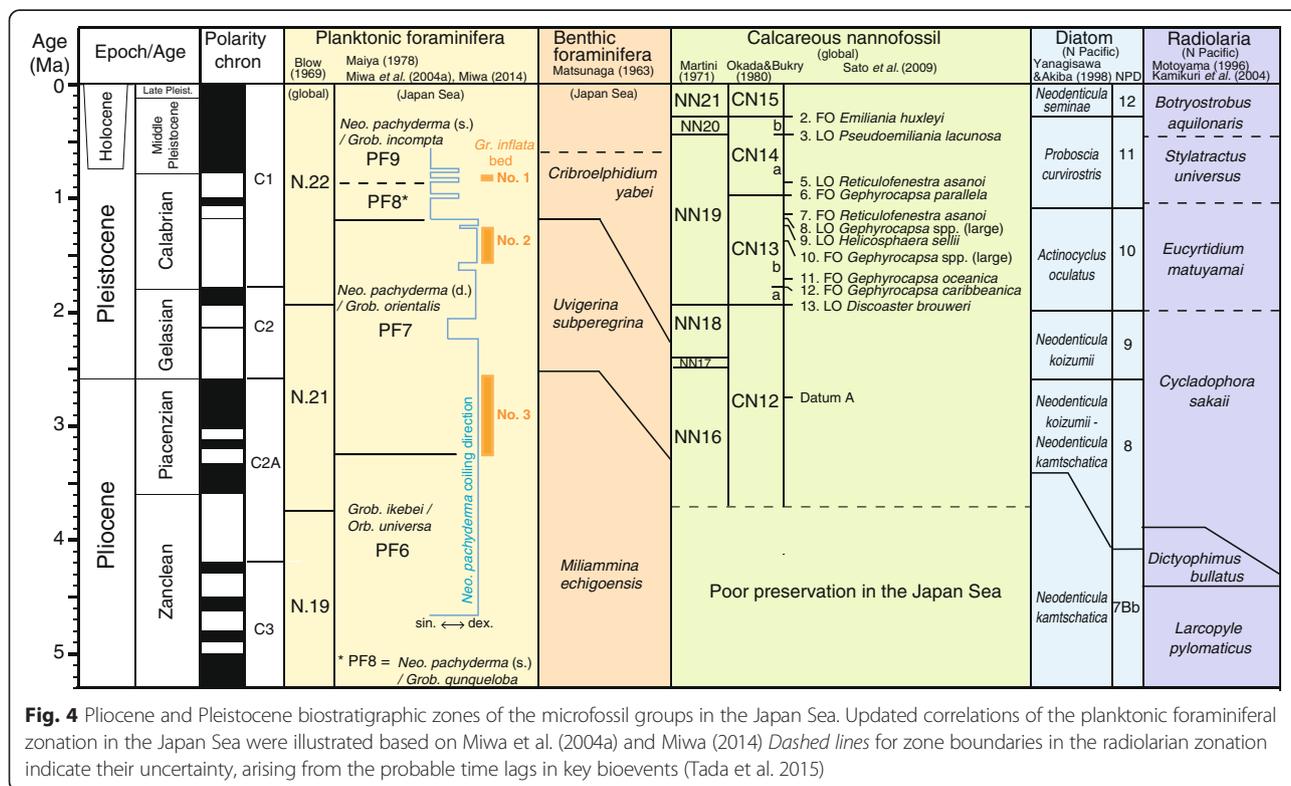
fluctuated greatly with the glacial and interglacial cycles (Koizumi 1992a, 1992b). Although the diatom abundance data for the Pliocene to Pleistocene have not been reported at Leg 128 ODP site 798 (980 m water depth in the southern Japan Sea), the biogenic opal content, consisting mainly of diatom skeletons, was higher during 2.6–1.3 Ma at this site (Dunbar et al. 1992), a pattern opposite that of the diatom abundance at the ODP Leg 127 sites in more northerly and deeper waters (Fig. 5).

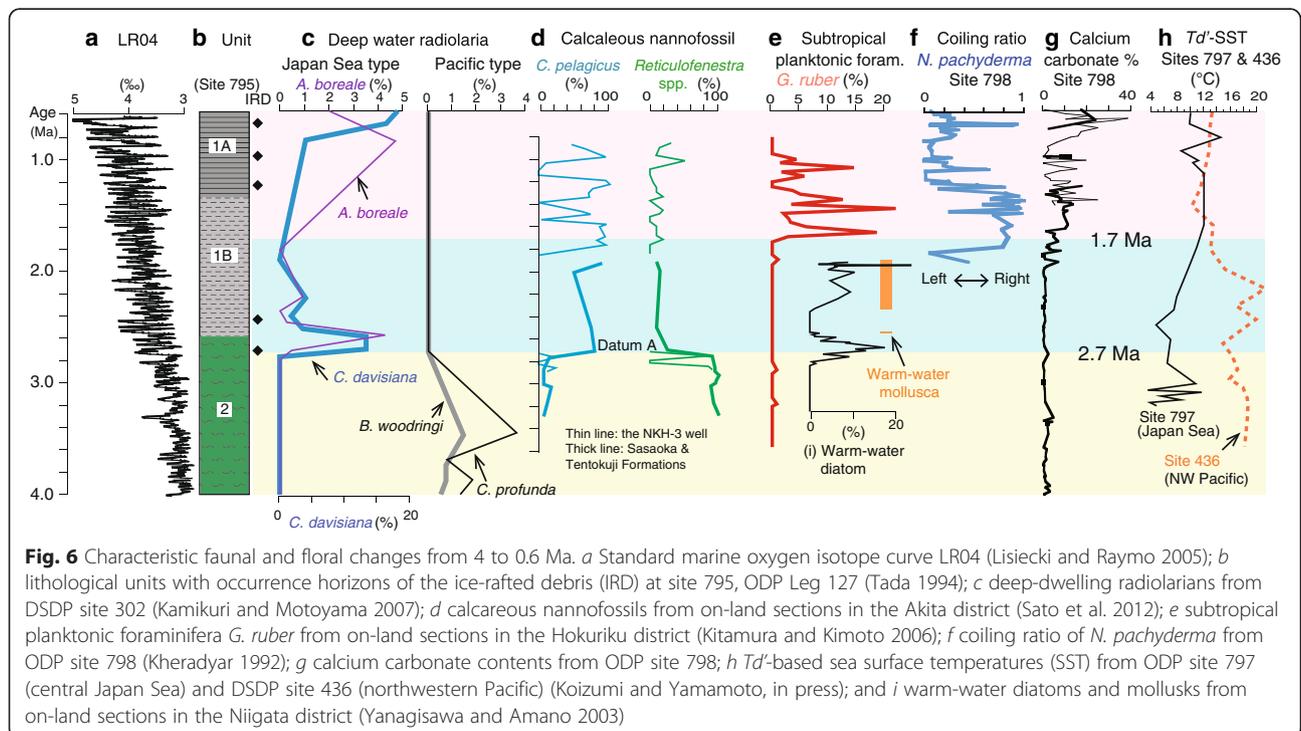
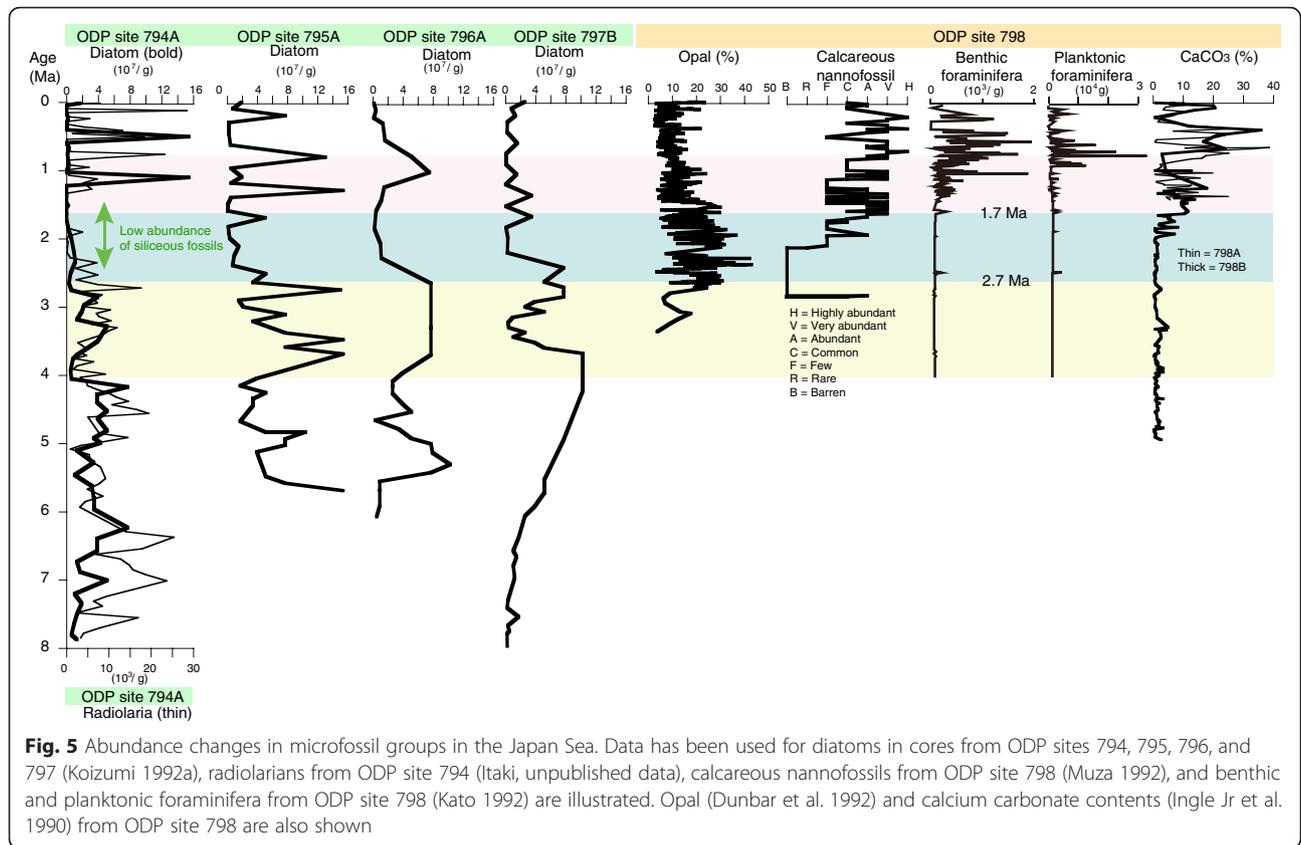
Koizumi (1992b) noted that the Miocene to Pliocene diatom assemblages collected during ODP Leg 127 were dominated by cold-water species, such as *Coscinodiscus marginatus* and *Neodenticula kamtschatica*, and



were not significantly influenced by warm water entering from the southern strait. He also reported that *Paralia sulcata* was more abundant after 3.5 Ma at southern sites (797 and 794) and after 2 Ma at northern sites (795 and 796), which he attributed to the inflow of

brackish water from the Yellow Sea via the southern strait. Yanagisawa and Amano (2003) noted that in the diatom assemblages from the Nadachi and Tanihama formations in the Niigata district (Fig. 3; Table 2), which correspond to the period from 3.9/3.6 to 2.0/





2.1 Ma, warm-water species existed alongside the cold-water assemblage at 3.2–2.7 Ma and 2.4–2.0 Ma, suggesting the presence of mixed cold and warm water during those intervals (Fig. 6 (i)).

Koizumi and Yamamoto (in press) recently reconstructed the SST changes during the Pliocene to Pleistocene based on Td' values, a temperature index of diatom fossil assemblages, from ODP site 797 (central Japan Sea, from 3 Ma), site 798 (southern Japan Sea, from 1.3 Ma), and DSDP site 436 (Northwest Pacific off northern Honshu, from 3.6 Ma) (Fig. 6 (h)). In the Japan Sea (site 797), the SST dropped at 2.6 Ma and increased toward 2 Ma. In contrast, on the Pacific side (site 436), the SST was nearly 20 °C during the Late Pliocene but decreased thereafter from 21.7 °C at 2.1 Ma to 10 °C at 1.4 Ma. As shown in Fig. 6 (h), the difference in SST between sites 797 and 436 was larger during the Late Pliocene but declined after 1.7 Ma.

Calcareous nannofossils

Calcareous nannofossils were reported from the deep-sea cores of ODP Leg 127 (Rahman 1992) and Leg 128 (Muza 1992). At site 798, nannofossils occur at well-defined intervals, separated by equally well-defined barren intervals, from 1.7 Ma onward, but they occur only sporadically and very sparsely before 2.0 Ma (Muza 1992). Their occurrence patterns are closely related to the patterns of CaCO₃ content (Fig. 5). However, the nannofossil abundances are much lower at deeper sites (794, 2825 m; 795, 3374 m; 796, 2223 m; 797, 2945 m; and 799, 2073 m) (Muza 1992; Rahman 1992) than at site 798 (980 m). Well-preserved nannofossil records during the late Pliocene to Pleistocene (after 3.85 Ma) are also available in on-land sections (e.g., Takayama et al. 1988; Sato et al. 1988a, Sato et al. 2012), which were deposited at shallower water depths than at the ODP sites. These results suggest that the calcite compensation depth (CCD) was less than 1000 m before 1.7 Ma and increased to 2000 m thereafter, as it is in the present day (Ujiie and Ichikura 1973).

High-resolution biostratigraphic data collected in the North Atlantic Ocean (Takayama and Sato 1987) have been applied to the Late Pliocene–Pleistocene on-land sections and oil-well data from the Japan Sea side of the Japanese Islands (Fig. 4) (e.g., Takayama et al. 1988; Sato et al. 1988a, 2004). The bioevent known as “Datum A” in the subarctic area of the North Pacific Ocean, defined as a dramatic floral change from a *Reticulofenestra*-dominant assemblage to a *Coccolithus pelagicus*-dominant assemblage at 2.75 Ma, has also been identified in the Japan Sea (Fig. 6 (d)) (Sato et al. 2002, 2012). This dramatic floral change probably indicates a change in paleoceanographic conditions. The high abundance of *Reticulofenestra* spp. (small type) before 2.75 Ma in the Japan Sea (Sato et al. 2002, 2012) can be explained by the presence of high-nutrient water (Tanaka and

Takahashi 2001), whereas the rapid increase in the abundance of the cold-water species *C. pelagicus* after 2.75 Ma is interpreted as a result of global cooling, known as the onset of the NHG (Sato et al. 2002, 2012).

In the middle- to low-latitude areas on the Pacific side of the central Japanese Islands, the nannofossil assemblages were dominated by the subtropical group *Discoaster* spp. in ca. 4–2 Ma, without the “Datum A” event at 2.75 Ma, but no such subtropical group is found on the Japan Sea side (Sato et al. 2002). This finding suggests that the biotic province in the Japan Sea was derived from the boreal Pacific province, rather than from the subtropical Pacific province.

Radiolarians

The assemblages of radiolarian fossils preserved in marine deposits in on-land sections along the Japan Sea have been divided into zones and used since the 1950s for the stratigraphic correlation of the geological succession (e.g., Nakaseko 1959, 1960; Nakaseko et al. 1972; Nakaseko and Sugano 1973). More recently, the standard radiolarian biostratigraphy for the mid- to high-latitude North Pacific has been applied to the marine deposits of the Japan Sea (e.g., Motoyama 1996; Motoyama and Maruyama 1996). However, some Pleistocene data could not be applied to the Japan Sea because of the large time lag between their occurrence at the DSDP and ODP sites and their occurrence in the Pacific (Ling 1992; Alexandrovich 1992; Motoyama 1996). For example, the last occurrence of *Stylocostium aquilonaris*, which is widely recognized in the Pacific at 0.33 Ma (Matsuzaki et al. 2015b), is substantially earlier in the Japan Sea. Moreover, the occurrence of *Eucyrtidium matsuyamai* between 1.05 and 1.80 Ma in the Pacific (Matsuzaki et al. 2015a) is difficult to identify at all in the Japan Sea. Therefore, it may be necessary to establish a separate radiolarian biostratigraphy for the Japan Sea.

At ODP site 794, radiolarians occurred abundantly during the Miocene to Pliocene and decreased significantly from 2.3 to 1.3 Ma (Fig. 5). Thereafter, their abundance fluctuated greatly. This fluctuating pattern, which is similar to that in the diatom abundance, reflects productivity changes in the siliceous plankton in surface waters.

Kamikuri and Motoyama (2007) analyzed the radiolarian assemblages in the period 8–0.6 Ma from DSDP site 302 (Fig. 1) and compared them with the assemblages at ODP site 1151, located at almost the same latitude in the northwestern Pacific, and at ODP site 884, in the subarctic Pacific. The species diversity index was almost the same in the Japan Sea and the North Pacific until 3.5 Ma but decreased

significantly in the Japan Sea after 3.5 Ma, probably reflecting the isolation of the Japan Sea from the Pacific at that time. Moreover, typical deep-water species that are common in the modern world ocean, such as *Cornutella profunda* and *Bathropyramis woodringi* (Casey 1977), disappeared from the Japan Sea after 2.6 Ma and were replaced by the *Cycladophora davisiana* and *Actinomma boreale* group (Fig. 6 (c)), which is found in the JSPW today (Itaki 2003).

The distributions of tropical and subtropical species, such as the *Tetrapyle octacantha* group, *Dictocoryne profunda*, *Dictocoryne truncatum*, *Didymocorytis tetrathalamus*, and *Euchitonina flucata*, are closely related to the TWC in the Japan Sea (Motoyama et al. in press). The occurrence of warm-water fauna in all samples younger than approximately 1.8 Ma containing preserved radiolarians from ODP site 797 indicates that the TWC probably began to flow into the Japan Sea at that time (Alexandrovich 1992). According to Kamikuri and Motoyama (2007), who analyzed the radiolarian assemblages from DSDP site 302, the Pliocene radiolarian assemblages contained temperate-water species, such as the *Actinomma medianum* group and *Lithelius minor*, which are minor species during the Pleistocene, whereas the subtropical species appeared after 2.2 Ma. These results suggest that in the Early Pleistocene, the temperate surface water entering the Japan Sea via the northern strait was replaced by subtropical water entering via the southern strait.

Planktonic foraminifera

The biostratigraphic zonation of planktonic foraminifera established by Maiya (1978) for petroleum exploration is unique to the Japan Sea and independent of the standard zonation used in the Pacific Ocean (e.g., Blow 1969). A unique set of bioevents, called the No. 1, No. 2, and No. 3 *Globorotalia inflata* beds, defined by the abundant occurrence of *G. inflata*, date to 0.8, 1.2–1.4, and 2.7–3.3 Ma, respectively (Fig. 4). A high abundance of *G. inflata* is known to indicate the presence of warm water (e.g., Maiya et al. 1976; Kitamura et al. 2001). Although the subtropical planktonic foraminifer *Globigerinoides ruber* also occurs in the No. 1 and No. 2 *G. inflata* beds, it is not found in the No. 3 *G. inflata* bed (e.g., Kitamura and Kimoto 2006). Similarly, the *Pulleniatina* group, which is characteristic of Kuroshio water, is also absent from the No. 3 *G. inflata* bed (Miwa et al. 2004a, 2004b). In the northwestern Pacific, *G. ruber* is a subtropical surface-water species, whereas *G. inflata* is distributed in temperate to subtropical waters between 20° and 40° N, at depths shallower than 200 m (Thompson 1981; Tsuchihashi and Oda 2001). In the No. 1 and No. 2 *G. inflata* beds, *G. inflata* is accompanied by *G. ruber*, so *G. inflata* probably entered the Japan Sea via the

southern strait. In contrast, the occurrence of abundant *G. inflata* without *G. ruber* or other Kuroshio indicators in the No. 3 *G. inflata* bed suggests that the plankton assemblage entered the Japan Sea with temperate water via the northern strait (Hanagata and Watanabe 2001; Miwa et al. 2004a, 2004b; Kitamura and Kimoto 2006; Hanagata 2007). During the Late Pliocene interval corresponding to the No. 3 *G. inflata* bed (2.7–3.3 Ma), the alkenone-based SST at ODP site 1208 in the northwestern Pacific was 20–24 °C, which is warmer than the Late Pleistocene SST range (15–20 °C) (LaRiviere et al. 2012). This warmer Pliocene SST probably allowed a northward shift in the *G. inflata* distribution, resulting in its higher abundance around the mouth of the northern strait.

Kitamura and Kimoto (2006) reconstructed the history of the TWC from the occurrences of the subtropical species *G. ruber* and other warm-water fossils from 3.5 to 0.8 Ma in on-land sections along the western coast of Honshu Island. Because *G. ruber* occurred only sporadically during the interglacial periods before 1.7 Ma, they inferred its very limited transport by the TWC before that date. However, after 1.7 Ma, a significant inflow of subtropical water occurred during each interglacial period, as indicated by corresponding increases in *G. ruber* (Fig. 6 (e)). The initial increase in the TWC inflow coincided with an increase in the CaCO₃ content of the Japan Sea sediments (Fig. 6 (g)). The TWC inflow was probably initiated by the opening of the southern strait and the migration of the Kuroshio water into the East China Sea, which almost coincided with the formation of the Okinawa Trough (Shinjo 1999).

In the subpolar species *Neogloboquadrina pachyderma*, the left-coiling (sinistral) variant is associated with cold-water masses, and this variant was dominant, although with large fluctuations, after 1.2 Ma in the Japan Sea (Fig. 6 (f)) (e.g., Kheradyar 1992), suggesting that large climatic changes accompanied the amplified glacial cycles during the Mid-Pleistocene transition. The proportion of the right-coiling (dextral) variant increases dramatically at SSTs between 6 and 10 °C (Darling et al. 2006).

Benthic foraminifera

The benthic foraminiferal zones in the Japan Sea are mainly based on the characteristic faunal compositions of on-land sections. Three biozones, the *Miliammina echigoensis*, *Uvigerina subperegrina*, and *Cassidulina yabei* zones (in ascending order through the Pliocene to Pleistocene sequences), were established by Matsunaga (1963) (Fig. 4). As inferred from the depth distribution of modern foraminifera, the agglutinated fauna of the *M. echigoensis* zone (= *M. echigoensis*–*M. nodulosa*

zone of Matoba 1990) indicates an abyssal assemblage, usually distributed below the CCD, and the calcareous fauna of the *U. subperegrina* and *C. yabei* zones (= *C. norcrossi*–*U. akitaensis* zone of Matoba 1990) is a lower–upper bathyal assemblage (Matoba 1990). Therefore, the faunal change from the *M. echigoensis* zone to the *U. subperegrina* zone probably resulted from a shallowing of the water depth, reflecting the uplift of the northern Japanese islands (e.g., Sato et al. 1988b; Matoba 1990). Although the boundary between the agglutinated and calcareous assemblages is generally recognized around the Pliocene–Pleistocene transition (Fig. 4), the exact timing of the transition varies among sections, according to the water depth at which each was deposited (e.g., Sato et al. 1988b; Matoba 1992; Kato 1992; Hanagata 2007).

The shallowing of the water depth of benthic foraminiferal deposition from the Late Pliocene to the Early Pleistocene has also been observed in assemblages in on-land sections from the Tsugaru Peninsula (northern Honshu Island) and southwestern Hokkaido Island, where a northern strait was probably located. The upper bathyal assemblage is recognized in the Pliocene Tsukushimoriyama Formation (2.9–2.4 Ma) on the Tsugaru Peninsula (Hata and Nemoto 2005), and lower sublittoral Pleistocene assemblages (1.5–1.1 Ma) are recognized in the Daisyaka Formation on northern Honshu Island (Hata and Nemoto 2005) and in the Setana Formation on southwestern Hokkaido Island (Nojo et al. 1999). The latter two formations unconformably contact the underlying strata (Fig. 3). The widespread distribution of these lower sublittoral assemblages implies the existence of a shallow, wide northern strait from 1.5 to 1.1 Ma.

Ostracods

Shallow-water ostracods from the Sasaoka Formation show a reduction in warm-water species and an increase in temperate–subarctic species at 2.75 Ma (Irizuki and Ishida 2007) as a result of cooling at the NHG (e.g., Sato et al. 2002). This change is consistent with the observation of ice-rafted debris (IRD) in the northern Japan Sea beginning in ca. 2.6 Ma (Fig. 6; Tada 1994).

In the Kuwae Formation, the lower sublittoral–upper bathyal assemblages from 3.5 to 2.6 Ma show cyclic changes with a 41-kyr periodicity, related to eustatic sea level changes (Yamada et al. 2005; Irizuki et al. 2007; Irizuki and Ishida 2007). During the interglacial periods between 3.1 and 2.8 Ma, the assemblage included temperate intermediate-water species, such as *Krithe* spp., which suggests water temperatures between 6 and 20 °C and a muddy seafloor at depths of 100–800 m (Irizuki et al. 2007). The intermediate water was probably warmer than it is today, especially from 3.0 to 2.9 Ma. Because

these species are presently distributed in the East China Sea, their occurrence in the Pliocene Japan Sea is interpreted as indicating their migration via the southern strait (Irizuki et al. 2007). From 2.8 to 2.6 Ma, temperate intermediate-water species were rare, and cold intermediate-water species increased in abundance (Yamada et al. 2005). These results suggest that cold intermediate water, similar to JSPW, formed in association with the global cooling episode at that time.

The ostracod analysis indicates that the sea level in the Japan Sea fell during the NHG. In the Yabuta Formation (3.4–2.3 Ma), the ostracod assemblages suggest an environmental change from upper bathyal to sublittoral, an estimated sea level fall of 50–60 m, at 2.7 Ma (Cronin et al. 1994). Yamada et al. (2005) also inferred a faunal change from an upper bathyal assemblage to a lower sublittoral assemblage at 2.7 Ma in the Kuwae Formation.

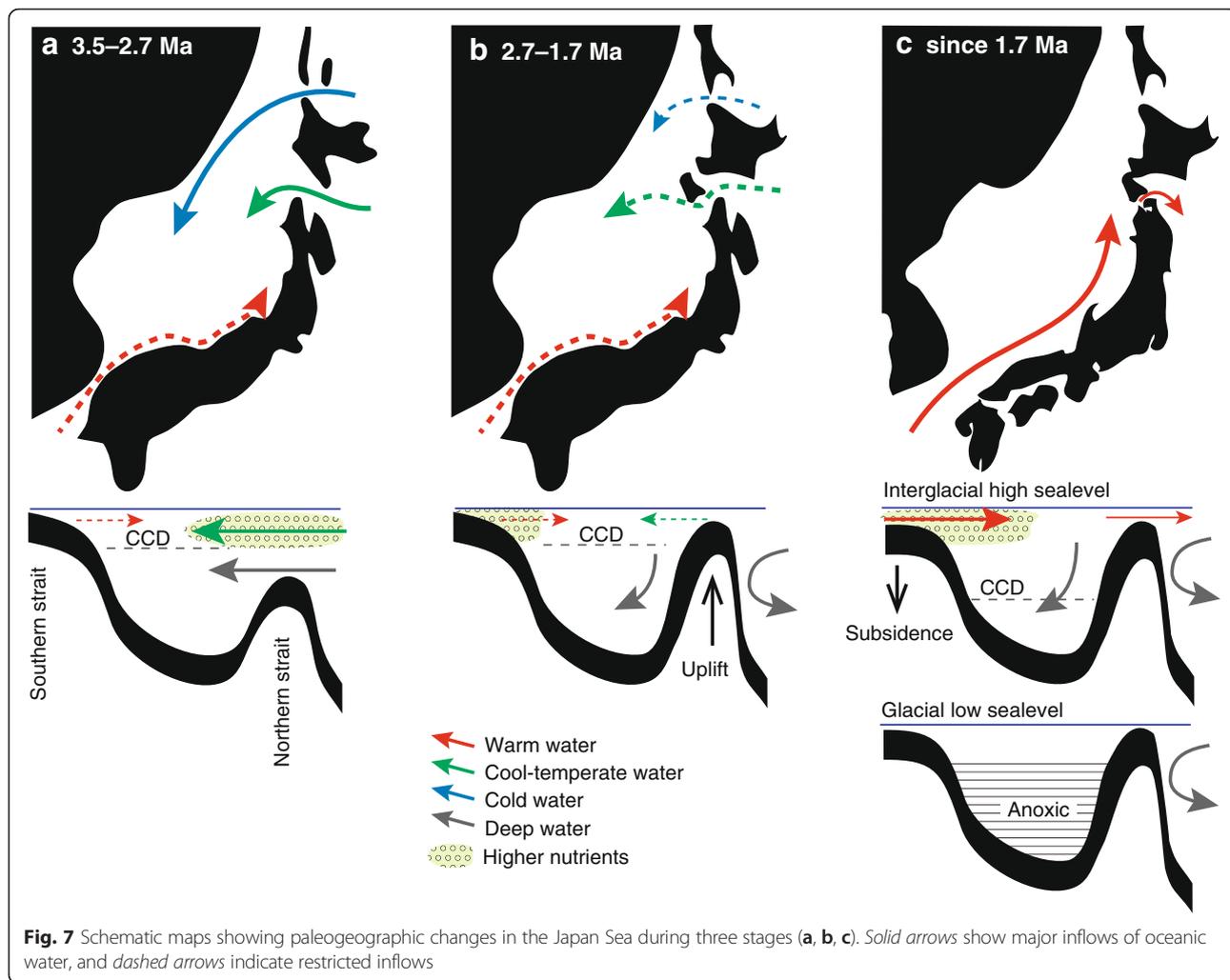
Ozawa and Kamiya (2001) reported cyclic changes in the ostracod assemblages in the Omma Formation from 1.5 to 1.3 Ma. During this period, warm-water species increased in abundance during each interglacial period, probably reflecting an increased volume of TWC inflow. A warm-water assemblage was also reported in this period in the Hamada Formation on the Shimokita Peninsula located on the Pacific side of the Tsugaru Strait (Ozawa and Domitsu 2010).

Discussion

The results presented here show that remarkable changes occurred in the faunal and floral assemblages in the Japan Sea during the Late Pliocene to Early Pleistocene. The occurrences of microfossil assemblages during three periods are discussed: the Late Pliocene (3.5–2.7 Ma), early Early Pleistocene (2.7–1.7 Ma) and late Early Pleistocene (1.7–0.8 Ma). These three intervals were bounded by remarkable assemblage changes: from the *Reticulofenestra* to *C. pelagicus* assemblages of nannofossils (Fig. 6 (d)) and from the Pacific type to Japan Sea type of deep-dwelling radiolarians (Fig. 6 (c)) at 2.7 Ma, and the first increase in subtropical *G. ruber* at 1.7 Ma (Fig. 6 (e)). The paleogeographic changes in the Japan Sea inferred from the micropaleontological record are shown schematically in Fig. 7.

Late Pliocene (3.5–2.7 Ma)

The Late Pliocene climate was globally warmer by 2–3 °C than today's climate (e.g., Dowsett et al. 2009). In the northwestern Pacific, the Late Pliocene SST has been estimated from the alkenone record at ODP site 1208 to have been 20–24 °C, which is about 4 °C warmer than the present SST (LaRiviere et al. 2012). Koizumi and Yamamoto (in press) also reported similar results for the diatom-based SST at



DSDP site 436 in the Pacific off Honshu Island, central Japan (Fig. 6 (h)). Despite these warm SSTs in the northwestern Pacific, the Late Pliocene microfossil assemblages in the Japan Sea are characterized by cold- or temperate-water species, with very few warm-water species. Two possible sources of water have been proposed as influencing the Pliocene biota in the Japan Sea, based on the biogeographic distribution of fossils: North Pacific water entering via the northern strait and subtropical water entering via the southern strait. The occurrence of warm-water species suggests inflow from the southern strait, like the present Tsushima Current, and inflow via the northern strait explains the predominance of cold-temperate species.

The dominance of calcareous nannofossils, diatoms, planktonic foraminifera, and radiolarians of cold-temperate species in the fossil assemblages, together with the near absence of warm-water species, suggests that

the source water entered via the northern strait (Fig. 7a). A northern source is also consistent with the known Pliocene geography of the Japan Sea (Iijima and Tada 1990; Chinzei 1991). A wide strait was located near the present Tsugaru Strait in northern Japan, whereas in the south, where the Tsushima Strait is today, only a narrow waterway existed at most.

If the North Pacific water flowed into the Japan Sea through the northern strait near the present Tsugaru Strait during the Pliocene, it is expected that the difference in the SST of the North Pacific and Japan Sea would be small because of the influence of the warm Pacific water. However, the Td' -based differences in SST between sites 436 (North Pacific) and 797 (Japan Sea) were large during the Pliocene and Early Pleistocene and became small after 1.7 Ma (Fig. 6 (h)). These large differences in SST explain the greater occurrence of cold-water species in the Japan Sea. It is also plausible that the Okhotsk Sea was another

source of this cold surface water, flowing into the Japan Sea via another northern strait, which probably opened around northern Hokkaido Island.

The diatomaceous deposits and the predominance of the high-nutrient indicator *Reticulofenestra* spp. (small type) (Fig. 6 (d)) indicate that the primary productivity of the water mass derived from the northern strait during the Pliocene was high. The *Reticulofenestra* spp. (small type) distribution (Sato et al. 2002) also suggests that nutrient-rich water was widespread in the subarctic North Pacific. Based on biogenic opal and nitrogen isotope data from ODP site 882 in the subarctic Pacific, Haug et al. (1999) demonstrated that nutrient-rich deep water was transported into the euphotic zone during the Pliocene but decreased abruptly at 2.73 Ma with the development of the halocline coincident with the onset of the NHG.

According to the benthic foraminiferal assemblage of the Tate and Mado formations, composed of diatomaceous mudstone, the depth of the northern strait around the present Tsugaru Strait was upper–lower bathyal, which is deeper than it is today (Table 2). Furthermore, another northern strait around northern Hokkaido might have been even deeper, because the hemipelagic diatomaceous mudstone of the Koitoi and Enbetsu formations is widely distributed on both sides of the Japan Sea and the Sea of Okhotsk in northern Hokkaido. The deep-water-dwelling radiolarians *C. profunda* and *B. woodringi*, which live today at depths >500 m in the North Pacific (e.g., Casey 1977), were present in the Japan Sea during the Miocene and Pliocene. They may have migrated from the North Pacific via the northern strait when migration via the southern strait was blocked, even to surface dwellers, by the restricted water exchange through an almost-closed channel. The occurrence of these deep-water dwellers implies that the sill depth of the northern strait was >500 m, which is consistent with the results for the benthic foraminifera in the Tate and Mado formations. The low CaCO₃ contents during the Pliocene probably resulted from the reduced carbonate preservation in deep-sea water, with high nutrients and dissolved CO₂ derived from the North Pacific. It has been suggested that the CCD in the Japan Sea was shallower than in the present day, similar to the situation in the North Pacific (e.g., Rea et al. 1995).

However, some evidence of warm-water intrusion from the southern strait has been proposed, based on the fossil records of diatoms, mollusks, and ostracods in on-land sections.

Yanagisawa and Amano (2003) reported that in the Nadachi and Tanihama formations, warm-water diatoms were present in two intervals, 3.2–2.6 and 2.4–2.0 Ma,

whereas warm-water mollusks were only present during the latter period (Fig. 6 (i)). Because diatoms and mollusks reflect the environments of their habitats, such as the sea surface and seafloor, respectively, this result suggests that the cold bottom water was covered with a thin layer of warm surface water during the warmer interval of the Late Pliocene (3.2–2.7 Ma), and that the seafloor was influenced by a thick warm-water mass during the warmer Early Pleistocene interval (2.4–2.0 Ma). Therefore, the warm surface-water layer was thinner during the Pliocene than during the Pleistocene, as suggested by Amano et al. (2000).

The occurrence of the temperate intermediate-water ostracod group *Krithe* spp. in sublittoral–bathyal assemblages from the Kuwae Formation has been interpreted as the result of the inflow of warm water into the Japan Sea via the southern strait. This is based on the modern distribution of this species group and its similarity to the occurrence pattern of the planktonic foraminifer *G. inflata*, which indicates the presence of temperate–subtropical waters shallower than 200 m (Irizuki et al. 2007). The similar occurrence patterns of *Krithe* spp. and *G. inflata* suggest that the abundance changes in both groups reflect the temperature of the same water mass. As mentioned above in the planktonic foraminifera section, the No. 3 *G. inflata* bed (3.3–2.7 Ma) in the Japan Sea is probably a result of the migration of this species from the northern strait, with a northward shift in their distribution on the Pacific side during the warm Pliocene period (Hanagata and Watanabe 2001; Miwa et al. 2004a, 2004b; Kitamura and Kimoto 2006; Hanagata 2007). If this scenario is correct, the occurrence of *Krithe* spp. in the Kuwae Formation is also probably related to the intrusion of temperate intermediate water into the Japan Sea from the Pacific via the northern strait.

It can be concluded from this evidence that the major part of the Japan Sea, from its surface layer to depth, was influenced by nutrient-rich cold–temperate water that originated in the North Pacific and entered the Japan Sea via northern straits, although a small volume of subtropical water probably flowed into the sea via the southern strait and then along the Japanese coast.

Earliest Pleistocene (2.7–1.7 Ma)

From 3.5 to 1.7 Ma, a regression resulting from a significant local uplift led to a shallowing of the water around northeastern Japan (Sato et al. 2012). The growth of high-latitude ice sheets in the Northern Hemisphere, a consequence of the global cooling after 3.2 Ma and significantly at 2.7 Ma, also caused the sea level to fall, in the event known as the NHG (Lisiecki and Raymo 2005) and the first major glaciation at

2.15 Ma (Rohling et al. 2014). This drop in sea level has been documented along the central Japanese coast by the changes in the ostracod assemblages, from upper bathyal to sublittoral (Cronin et al. 1994; Yamada et al. 2005). Based on the modern analog technique for ostracods, Cronin et al. (1994) estimated that the sea level dropped 50–60 m. As a result, the northern straits became shallower and the Japan Sea was almost isolated from the Pacific, as it is at present (Fig. 7b).

Calcareous nanofossils (e.g., Sato et al. 2012) and sublittoral ostracods (Irizuki and Ishida 2007) indicate remarkable cooling in the Japan Sea at 2.75 Ma, with an abrupt change from warm Pliocene to cold Pleistocene assemblages. Furthermore, the upper bathyal ostracod and deep-water radiolarian assemblages related to the cold JSPW are first observed near the Pliocene–Pleistocene boundary (Yamada et al. 2005; Irizuki et al. 2007; Kamikuri and Motoyama 2007). A reduction in the planktonic foraminifera *G. inflata* indicates related cooling at intermediate depths (Kitamura 2009). After 2.8 Ma, an intensified winter monsoon and sea-ice expansion, indicated by the Chinese eolian loess (Xiong et al. 2003) and IRD at ODP site 795 in the northern Japan Sea (Tada 1994), probably caused increased ventilation during the interglacial periods, as in the present day, as suggested by an increase in the JSPW-related radiolarian and ostracod fauna at that time.

In contrast, the intermittent development of low-oxygen conditions in the deep water, probably during the glacial periods, is indicated by the alternations of dark and light layers shown as Unit 1 of the Pleistocene deep-sea deposits (Fig. 6 (b)) (Tada 1994). Such low-oxygen conditions would have prevented the survival of the deep-dwelling radiolarian species *C. profunda* and *B. woodlingi*, which were common during the Pliocene. Moreover, as a result of the uplift of northeastern Japan, the northern straits probably became too shallow for these deep-sea dwellers to pass into the Japan Sea, and any that managed to enter the Japan Sea would not have survived the low-oxygen conditions in the deep water. Although the JSPW-related radiolarians, the *A. boreale* group and *C. davisiana*, are associated with low temperatures and high dissolved oxygen contents, their habitation depths in the high-latitude oceans are usually shallow or intermediate (e.g., Itaki et al. 2003). Therefore, if low-oxygen conditions prevailed in deep water, these species could have moved to shallower habitats or could have migrated from the North Pacific during each high-stand interglacial period.

The shallower northern strait was a barrier to nutrient input from the North Pacific. The high abundances of diatoms and radiolarians during the Pliocene were possibly related to the inflow of high-nutrient surface water from the North Pacific. However, these abundances

decreased significantly during the Early Pleistocene (ca. 2.3–1.3 Ma) at the ODP 127 sites (Fig. 5). The sedimentological record of the Early Pleistocene (2–1.5 Ma) is very limited in the coastal areas of northeastern Japan because of a widespread unconformity (Fig. 3), suggesting that erosion occurred widely after marine regression. As a result, the northern straits probably became very narrow or closed, even during interglacial sea level high stands, which probably restricted the nutrient supply from the North Pacific during this period.

However, the concentration of opal (composed mainly of diatoms and radiolarians) increased during 2.7–1.5 Ma at ODP site 798 in the southern Japan Sea. This pattern is contrary to that seen in the diatom and radiolarian abundances at the other ODP 127 sites (Fig. 5), and its cause is still unknown. It may be a small dissolution effect at the shallow-water depth of site 798, or the nutrient supply may have only been sufficient in the southern Japan Sea because it was supplied by the southern strait.

Late Early Pleistocene (1.7–0.8 Ma)

The global sea level dropped continuously as the Northern Hemisphere ice sheets developed. Nevertheless, the occurrence of subtropical planktonic foraminifera and radiolarians implies that a significant intrusion of the TWC via the southern strait began around 1.8–1.7 Ma. The widening of the southern strait is attributed to active subsidence, which exceeded the reduction in sea level. This active subsidence was probably related to the genesis of the Okinawa Trough in the East China Sea, at ca. 2 Ma (Shinjo 1999). It also coincided with the start of reefal sediment deposition (Ryukyu Group) in Okinawa, southern Japan (Fig. 3), which implies that the intrusion of the Kuroshio Current into the East China Sea also began around this time (Yamamoto et al. 2006). Therefore, both the active subsidence around the southern strait and the intrusion of the Kuroshio Current into the East China Sea could have allowed the TWC to intrude into the Japan Sea. Interestingly, the abundance of calcareous microfossils and the CaCO₃ content increased after the TWC intrusion around 1.7 Ma (Fig. 6 (g)).

The surface and intermediate depths in the Japan Sea were warmer during the period 1.46–1.3 Ma, according to the high occurrence of *G. ruber* and *G. inflata*, which was related to the TWC inflow (Kitamura 2009). During this period, the occurrence of warm-water ostracods in the Hamada Formation (ca. 1.5–1.2 Ma) on the Shimokita Peninsula (Ozawa and Domitsu 2010) implies that the assemblage on the Pacific side of the Tsugaru Strait was influenced by a water mass from the

Japan Sea, suggesting the outflow of the TWC via the Tsugaru Strait (Fig. 7c).

Conclusions

Micropaleontological studies of the Late Pliocene to Early Pleistocene Japan Sea have been comprehensively reviewed, and the relationships between the major changes in the microfossil assemblages and both global climate and local tectonics in the Japanese Islands have been discussed.

Late Pliocene (3.5–2.7 Ma): Although the Late Pliocene was globally warm, cold–temperate surface and deep waters with high-nutrient levels delivered from the North Pacific via the northern straits occupied most of the Japan Sea. The weak influence of warm water, identified along the Japanese coast, suggests a small inflow of warm water via the southern strait.

Early Early Pleistocene (2.8–1.7 Ma): An abrupt cooling event at 2.75 Ma, recorded in both nannofossil and ostracod assemblages, can be correlated with global cooling, especially in the Northern Hemisphere. After this period, intermediate- and deep-water assemblages of ostracods and radiolarians were intermittently characterized by cold-water dwellers, possibly related to well-ventilated water formations, such as the JSPW, associated with the development of a strong winter monsoon, despite the insignificant inflow of saline TWC water. As a result of the uplift of northeastern Japan and a eustatic fall in sea level in response to the NHG, the northern strait probably became very narrow and very shallow. Consequently, the nutrient supply from the North Pacific was restricted and primary productivity decreased significantly.

Late Early Pleistocene (1.7–0.8 Ma): Subtropical surface faunal assemblages were continuously present after 1.7 Ma, when the inflow of the TWC via the southern strait began. This inflow was facilitated by the subsidence of southwestern Japan. At about the same time, the Kuroshio Current began to intrude into the East China Sea.

Although many important papers have described the microfossils in the Japan Sea, only selected papers could be included in this review. Nevertheless, it is clear that the microfossil assemblages in the Japan Sea changed significantly during the Pliocene to Pleistocene transition. Recently, the analysis of materials collected by IODP Expedition 346 is still ongoing, and this work is expected to provide much more detailed information about the temporal and spatial changes in the microfossil assemblages here.

Abbreviations

JSPW: Japan Sea Proper Water; NHG: Northern Hemisphere glaciation; TWC: Tsushima Warm Current.

Competing interests

The author declares that he has no competing interests.

Acknowledgements

The author expresses his gratitude to Prof. Ryuji Tada of the University of Tokyo for providing the opportunity to submit this paper. Most of the ideas in this paper are based on discussions with many paleontologists. Thanks are also due to two anonymous reviewers for their critical review. This work was financially supported by the Japan Society for the Promotion of Science (JSPS), grant numbers 25400504 and 23221022.

Received: 6 April 2015 Accepted: 14 April 2016

Published online: 05 May 2016

References

- Akiba F (2001) Fossil diatom assemblages from the Mochikubetsu Formation in the Tenpoku-Haboro areas, northwestern Hokkaido, and their geological implications. *Bull Technol Lab JAPEX* 15:27–51 (in Japanese with English abstract)
- Akiba F, Hiramatsu C (1988) Neogene diatom biostratigraphy in Ajiga-sawa, Gosyogawara, and Shimokita area of Aomori Prefecture. In: Iijima A (ed) Comprehensive study of Tertiary siliceous shale –Reports of Grant-in-Aid for Scientific Research during 1987 fiscal year–, pp 35–52, in Japanese
- Alexandrovich J (1992) Radiolarians from sites 794, 795, 796, and 797 (Japan Sea). In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 291–307
- Amano K, Suzuki M, Sato T (2000) Warm-water influx into Japan Sea in the middle Pliocene—molluscan fauna from the Tentokujii Formation around Mt. Taihei in Akita Prefecture. *J Geol Soc Jpn* 106:299–307
- Blow WH (1969) Late Middle Eocene to recent planktonic foraminiferal biostratigraphy. In Bronimann P and Renz HR (eds) Proc. 1st Internat. Conf. Planktonic Microfossils, Gcnvca, 1967, 1, 199–422, E.J. Brill, Leiden
- Casey RE (1977) Distribution of polycystine Radiolaria in the oceans in relation to physical and chemical conditions. In: Funnell BM, Riedel WR (eds) The Micropaleontology of the Oceans. Cambridge University Press, Cambridge, pp 151–159
- Chinzei K (1991) Late Cenozoic zoogeography of the Sea of Japan area. *Episodes* 14:231–235
- Darling KF, Kucera M, Kroon D, Wade CM (2006) A resolution for the coiling direction paradox in *Neogloboquadrina pachyderma*. *Paleoceanography* 21: PA2011. doi:10.1029/2005PA001189
- Dowsett HJ, Robinson MM, Foley KM (2009) Pliocene three-dimensional global ocean temperature reconstruction. *Clim Past* Vol 5:769–783
- Cronin T, Kitamura A, Ikeya N, et al (1994) Late Pliocene climate-change 3.4–2.3 Ma—paleoceanographic record from the Yabuta Formation, Sea of Japan. *Palaeogeogr Palaeoclimatol Palaeoecol* 108:437–455
- Dunbar RB, deMenocal PB, Burckle L (1992) Late Pliocene-Quaternary biosiliceous sedimentation at site 798, Japan Sea. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 439–455
- Gamo T, Nozaki Y, Sakai H, Nakai T, Tsubota H (1986) Spatial and temporal variations of water characteristics in the Japan Sea bottom layer. *J Mar Res* 44:781–793
- Gradstein F, Ogg J, Schmitz M, Ogg G (eds) (2012) The geologic time scale 2012: Elsevier, Amsterdam, 1144 pp
- Hanagata S (2007) Historical changes in the Pliocene foraminiferal fauna in the Japan Sea oil-field region and its paleoceanographic implications. *Fossils* 82: 29–34 (in Japanese with English abstract)
- Hanagata S, Miwa M (2002) Miocene-Pliocene microfossil biostratigraphy and paleoenvironment in the Fukaura district, Aomori Prefecture, northern Japan. *J Geol Soc Jpn* 108:767–780 (in Japanese with English abstract)
- Hanagata S, Watanabe K (2001) Pliocene foraminifera and calcareous nannofossils from the well “Kainosawa Osen” in the eastern part of Akita City, Akita Prefecture, northern Japan: their biostratigraphy and paleoenvironmental implications. *J Geol Soc Jpn* 107:620–639 (in Japanese with English abstract)
- Hanagata S, Motoyama I, Hiramatsu C, Watanabe K, Tsuji T (2001a) Biostratigraphy of the Miocene/Pliocene boundary sections in the Jouetsu-Chuetsu district, Niigata Prefecture, northeastern Japan. *J Geol Soc Jpn* 107: 565–584

- Hanagata S, Motoyama I, Miwa M (2001b) Geologic ages of the last occurrence of *Milliammina echigoensis* (benthic foraminifera), and their paleoceanographic implications—response to the latest Miocene—earliest Pliocene sea level changes—J Geol Soc Jpn 107: 101-116 (in Japanese with English abstract)
- Hasegawa S (1979) Foraminifera of the Himi group Hokuriku province central Japan. *Sci Rep Tohoku Univ Second Ser (Geology)* 49:89–164
- Hata M, Nemoto N (2005) Pliocene to Lower Pleistocene foraminiferal assemblages from the southeastern Tsugaru Peninsula, Northeast Japan. *Fossils* 78:21–31 (in Japanese with English abstract)
- Haug GH, Sigman DM, Tiedemann R, Pedersen TF, Sarnthein M (1999) Onset of permanent stratification in the subarctic Pacific Ocean. *Nature* 401:779–782
- Iijima A, Tada R (1990) Evolution of Tertiary sedimentary basins of Japan. In reference to opening of the Japan Sea. *J Fac Sci Univ Tokyo Section II Geol Mineral Geogr Geophys* 22:121–171
- Ingle JC Jr, Suyehiro K, von Breyman MT, et al (1990) Proceedings of Ocean Drilling Program, Initial Reports, Vol. 128: College Station, TX (Ocean Drilling Program), doi:10.2973/odp.proc.ir.128.1990.
- Irizuki T, Ishida K (2007) Relationship between Pliocene ostracode assemblages and marine environments along the Japan Sea side regions in Japan. *Fossils* 82:13–20 (in Japanese with English abstract)
- Irizuki T, Kusumoto M, Ishida K, Tanaka Y (2007) Sea-level changes and water structures between 3.5 and 2.8 Ma in the central part of the Japan Sea Borderland: analyses of fossil Ostracoda from the Pliocene Kuwae Formation, central Japan. *Palaeogeogr Palaeoclimatol Palaeoecol* 245:421–443
- Itaki T (2003) Depth-related radiolarian assemblage in the watercolumn and surface sediments of the Japan Sea. *Mar Micropaleontol* 47:253–270
- Itaki T, Ito M, Narita H, Ahagon N, Sakai H (2003) Depth distribution of radiolarians from the Chukchi and Beaufort Seas, western Arctic. *Deep-Sea Res* 50:1507–1522
- Itoh Y, Nakajima T, Takemura A (1997) Neogene deformation of the back-arc shelf of Southwest Japan and its impact on the palaeoenvironments of the Japan Sea. *Tectonophysics* 281:71–82
- Kang S (1995) Sedimentary facies and palaeoenvironment of the Lower Pleistocene Sogwipo Formation, Cheju Island, Korea. *Quatern Res* 34:19–38
- Kang S, Lim D, Kim SY (2010) Benthic foraminiferal assemblage of Seogwipo Formation in Jeju Island, South Sea of Korea: implication for Late Pliocene to Early Pleistocene cold episode in the northwestern Pacific margin. *Quatern Int* 225:138–146
- Kamikuri S, Motoyama I (2007) Radiolarian assemblage and environmental changes in the Japan Sea since the Late Miocene. *Fossils* 82:35–42 (in Japanese with English abstract)
- Kaneoka I, Takigami Y, Takaoka N, Yamashita S, Tamaki K (1992) ^{40}Ar – ^{39}Ar analysis of volcanic rocks recovered from the Japan Sea floor: constraint of the formation of the Japan Sea. In: Tamaki K, Suehiro K, Allan J, McWilliams M, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 2, 819-836
- Kato M (1992) Benthic foraminifera from the Japan Sea: Leg 128. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 365-392
- Kitamura A (2008) Paleocceanographic changes of the Sea of Japan during 3.5–0.8 Ma. In: Okada H, Mawatari SF, Suzuki N and Gautam P (eds) Origin and Evolution of Natural Diversity, Proceedings of International Symposium "The Origin and Evolution of Natural Diversity", 1–5 October 2007, Sapporo, pp. 187–194
- Kitamura A (2009) Early Pleistocene evolution of the Japan Sea intermediate water. *J Quatern Sci* 24:880–889
- Kitamura A, Kimoto K (2006) History of the inflow of the warm Tsushima Current into the Sea of Japan between 3.5 and 0.8 Ma. *Palaeogeogr Palaeoclimatol Palaeoecol* 236:355–366
- Kitamura A, Takano O, Takata H, et al (2001) Late Pliocene-early Pleistocene paleoceanographic evolution of the Sea of Japan. *Palaeogeogr Palaeoclimatol Palaeoecol* 172:81–98
- Kodama T, Morimoto H, Igeta Y, Ichikawa T (2015) Macroscale-wide nutrient inversions in the subsurface layer of the Japan Sea during summer. *J Geophys Res Oceans* 120:7476–7492. doi:10.1002/2015JC010845
- Koizumi I (1966) Tertiary stratigraphy and diatom flora of the Ajigasawa District, Aomori Prefecture, Northeast Japan. *Contrib Inst Geol Paleontol Tohoku Univ* 62:1–34 (in Japanese with English Abstract)
- Koizumi I (1968) Tertiary diatom flora of Oga peninsula, Akita Prefecture, Northeast Japan. *Sci Rep Tohoku Univ 2nd Ser (Geology)* 40:171–240
- Koizumi I (1975) Neogene diatoms from the western margin of the Pacific Ocean Leg 31, Deep Sea Drilling Project. In Karig DE, Ingle JC Jr, et al, Init. Repts. DSDP, 31: Washington (U.S. Govt. Printing Office), 779-819
- Koizumi I (1992a) Diatom biostratigraphy of the Japan Sea: Leg 127. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 249-289
- Koizumi I (1992b) Biostratigraphy and paleoceanography of the Japan Sea based on diatoms—ODP Leg 127. Pacific Neogene: environment, evolution, and events: 15-24, Univ Tokyo press
- Koizumi I, Yamamoto H (in press) Diatom records in the Quaternary marine sequences around the Japanese Islands. *Quaternary Int*
- Kheradvar T (1992) Pleistocene planktonic foraminiferal assemblages and paleotemperature fluctuations in Japan Sea, site 798. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 457-470
- LaRiviere JP, Ravelo AC, Crimmins A, Dekens PS, Ford HL, Lyle M, Wara MW (2012) Late Miocene decoupling of oceanic warmth and atmospheric carbon dioxide forcing. *Nature* 486:97–100
- Lee EH (2014) New cytheracean ostracod fossils from the Plio-Pleistocene Seogwipo Formation of the Jeju Island, Korea. *Geosci J* 18:281–293
- Ling HY (1992) Radiolarians from the Sea of Japan: Leg 128. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1, 225-236
- Lisiecki LE, Raymo ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20:PA1003. doi:10.1029/2004PA001071
- Maiya S (1978) Late Cenozoic planktonic foraminiferal biostratigraphy of the oil-field region of northeast Japan. Huzita K, Ichikawa K, Ichihara M, et al (Eds) Cenozoic Geology of Japan: Professor Nobuo Ikebe Memorial Volume: 35-60, Ikebe Nobuo Kyoju Taikan Kinen Jigyo-Kai, Osaka (in Japanese with English abstract)
- Maiya S, Saito T, Sato T (1976) Late Cenozoic planktonic foraminiferal biostratigraphy of north west Pacific sedimentary sequences. In Takayanagi Y, Saito T eds, Progress in Micropaleontology (Selected papers in honor of Prof. Kiyoshi Asano), Micropaleontology Press, New York, 395-422
- Maruyama T (1988) Neogene diatom biostratigraphy in Aomori Prefecture. In: Iijima A (ed) Comprehensive study of Tertiary siliceous shale –Reports of Grant-in-Aid for Scientific Research during 1987 fiscal year–, pp 13–34 (in Japanese)
- Masatani K, Ohkura T (1980) Neogene biostratigraphy in Oshima Peninsula, Hokkaido, Japan—in particular relation between "Operculina-Miogypsina Zone" and planktonic foraminifera. *J Jpn Assoc Pet Technol* 23:32–52 (in Japanese with English abstract)
- Matoba Y (1984) Paleoenvironment of the Sea of Japan. In Oertli HJ (Ed), Benthos '83: 2nd Int. Symp. Benthic foraminifera, 409-414
- Matoba Y (1990) Neogene and Quaternary sedimentary sequences in the Oga Peninsula. In Benthos '90: 4th Int. Symp. Benthic foraminifera: Guidebook for Field Trip No. 2, Oga Peninsula, B1-B62
- Matoba Y (1992) Late Cenozoic benthic foraminiferal assemblages in the Japan Sea coastal region of northeast Honshu, Japan. *Mem Geol Soc Jpn* 37: 125–138 (in Japanese with English abstract)
- Matoba Y (1988) Foraminiferal fossils from Ajiga-sawa and Tsugaru Peninsula area of Aomori Prefecture. In: Iijima A (ed) Comprehensive study of Tertiary siliceous shale –Reports of Grant-in-Aid for Scientific Research during 1987 fiscal year–, pp 87–94 (in Japanese)
- Matsuzaki K, Nishi H, Hayashi H, Suzuki N, Gyawali BR, Ikehara M, Tanaka T, Takashima R (2015a) Radiolarian biostratigraphic scheme and stable oxygen isotope stratigraphy in southern Japan (IODP Expedition 315 Sute C0001). *Newsl Stratigr* 47: 107-130
- Matsuzaki K, Suzuki N, Nishi H, Takashima R, Kawate Y, Sakai T (2015b) 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 Micropaleontol* 33: 205-222
- Matsunaga T (1963) Benthonic smaller foraminifera from the oilfields of northern Japan. *Sci Repts Tohoku Univ 2nd Ser (Geol)* 35:67–122
- Miwa M (2014) Foraminifera. In Petroleum Technology Handbook 2013 (Jpn. Assoc. Pet. Technol.), 223-227. (in Japanese)
- Miwa M, Yanagisawa Y, Yamada K, et al (2004a) Planktonic foraminiferal biostratigraphy of the Pliocene Kuwae Formation in the Tainai River section, Niigata Prefecture and the age of the base of the No. 3 *Globorotalia inflata* bed. *J Japanese Assoc Pet Technol* 69: 272-283

- Miwa M, Watanabe M, Yamada K, et al (2004b) Planktonic foraminiferal assemblages from the Pliocene Yabuta Formation, Nadaura, Himi City, Toyama Prefecture, with special reference to the base of the No. 3 *Globorotalia inflata* bed. *J Jpn Assoc Petrol Technol* 69: 668-678
- Morimoto A, Yanagi T (2001) Variability of sea surface circulation in the Japan Sea. *J Oceanogr* 57:1-13
- Motoyama I (1996) Late Neogene radiolarian biostratigraphy in the subarctic Northwest Pacific. *Micropaleontology* 42:221-262
- Motoyama I, Maruyama T (1996) Integrated radiolarian and diatom biostratigraphy of the Neogene strata in the Tsugaru Peninsula, Aomori Prefecture, northern Honshu, Japan. *J Geol Soc Jpn* 102:481-499 (in Japanese with English abstract)
- Motoyama I, Yamada Y, Hoshiba M, Itaki T (in press) Radiolarian assemblages in surface sediments of the Japan Sea. *Paleontol Res*
- Muza JP (1992) Calcareous nannofossil biostratigraphy from the Japan Sea, sites 798 and 799: evidence for an oscillating Pleistocene oceanographic frontal boundary. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1*, 171-186
- Nakajima T, Danhara T, Iwano H, Chinzei K (2006) Uplift of the Ou Backbone Range in Northeast Japan at around 10 Ma and its implication for the tectonic evolution of the eastern margin of Asia. *Palaeogeogr Palaeoclimatol Palaeoecol* 241:28-48
- Nakaseko K (1959) Applied micropaleontological research by means of radiolarian fossil in the oil bearing Tertiary, Japan (mainly in Akita and Yamagata sedimentary basins) Part I. Method, geological note and radiolarian assemblage in Akita sedimentary basin. *Sci Rept Osaka Univ South North Coll* 8:113-193
- Nakaseko K (1960) Applied micropaleontological research by means of radiolarian fossil in the oil bearing Tertiary, Japan (mainly in Akita and Yamagata sedimentary basins) Part II. Radiolarian assemblage in Yamagata basin, discussion and conclusion. *Sci Rept Osaka Univ Coll Gen Educ* 9:1493-185
- Nakaseko K, Sugano K (1973) Neogene radiolarian zonation in Japan. *Mem Geol Soc Jpn* 8:23-33 (in Japanese with English abstract)
- Nakaseko K, Sugano K, Ieda K (1972) Some problems concerning the radiolarian-stratigraphy in the Niigata sedimentary basin, Japan (Studies of fossil radiolarian-stratigraphy of the Neogene formation in Niigata Prefecture, Japan, part 4). *J Japanese Assoc Petroleum Technol* 37:7-22 (in Japanese with English abstract)
- Naganuma K (2000) The Sea of Japan as the natural environment of marine organisms. *Bull Jpn Sea Natl Fish Res Inst* 50:1-42
- Nemoto N (1990) Foraminifera of the Maïdo Formation in Aijigasawa District, Aomori Prefecture, Northeast Japan. *Fossils* 48:17-33, in Japanese with English abstract
- Nemoto N, Oikawa Y (2006) Foraminiferal fossils from the Lower Pleistocene Setana Formation in Yamakoshi district, Southwestern Hokkaido, North Japan. *Bull Fac Sci Tech Hirosaki Univ* 9:29-40
- Nemoto N, Yoshimoto N (2001) Foraminiferal fossils from the Pleistocene Hamada Formation in the Chikagawa area, eastern Shimokita Peninsula, Northeast Japan. *Fossils* 69:1-24 (in Japanese with English abstract)
- Nojo A, Hasegawa S, Okada H, Togo Y, Suzuki A, Matsuda T (1999) Interregional lithostratigraphy and biostratigraphy of the Pleistocene Setana Formation, southwestern Hokkaido, Japan. *J Geol Soc Jpn* 105:370-388 (in Japanese with English abstract)
- Oba T, Kato M, Kitazato H, Koizumi I, Omura A, Sakai T, Takayama T (1991) Paleoenvironmental changes in the Japan Sea during last 85,000 years. *Paleoceanogr* 6:499-518
- Ogasawara K (1994) Neogene paleogeography and marine climate of the Japanese Islands based on shallow-marine molluscs. *Palaeogeogr Palaeoclimatol Palaeoecol* 108:335-351
- Okada H (1988) Neogene calcareous nannofossil biostratigraphy in northern NE Japan. In: Iijima A (ed) *Comprehensive study of Tertiary siliceous shale - Reports of Grant-in-Aid for Scientific Research during 1987 fiscal year-*, pp 81-86, in Japanese
- Ozawa H (2007) Faunal changes of cryophilic ostracods (Crustacea) in the Japan Sea, in relation to oceanographic environment: an overview. *Fossils* 82: 21-28 (in Japanese with English abstract)
- Ozawa H, Domitsu H (2010) Early Pleistocene Ostracods from the Hamada Formation in the Shimokita Peninsula, Northeastern Japan: the palaeobiogeographic significance of their occurrence for the shallow-water fauna. *Paleontol Res* 14(1):1-18
- Ozawa H, Kamiya T (2001) Palaeoceanographic records related to glacio-eustatic fluctuations in the Pleistocene Japan Sea coast, based on ostracods from the Omma Formation. *Palaeogeogr Palaeoclimatol Palaeoecol* 170:27-48
- Ozawa H, Kamiya T (2005) The effects of glacio-eustatic sea-level change on Pleistocene cold-water ostracod assemblages from the Japan Sea. *Mar Micropaleontol* 54:167-189
- Rahman A (1992) Calcareous nannofossil biostratigraphy of Leg 127 in the Japan Sea. In: Pisciotta KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1*, 171-186
- Rea DK, Basov IA, Krissek LA, the Leg 145 Scientific Party (1995) Scientific results of drilling the north Pacific transect. In: Rea DK, Basov IA, Scholl DW, Allan JF (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, vol 145, Vol.*, pp 171-186
- Rohling EJ, Foster GK, Grant KM, Marino G, Roberts AP, Tamisiea ME, Williams F (2014) Sea-level and deep-sea-temperature variability over the past 5.3 million years. *Nature* 508:477-482
- Sagayama T (2003) Geologic age of the boundary part between the Embetsu Formation-Koetoi Formation and the Yuchi Formation, northern Hokkaido, Japan—Rubeshube River and Kaminukanan River routes. *J Geol Soc Japan* 109:310-323 (in Japanese with English abstract)
- Sato H (1994) The relationship between late Cenozoic tectonic events and stress field and basin development in northeast Japan. *J Geophysical Res* 99(B11): 22261-22274
- Sato T, Takayama T, Kato M, Kudo T (1987) Calcareous microfossil biostratigraphy of the upper most Cenozoic Formations distributed in the coast of the Japan Sea. Part 1. Niigata area. *J Jpn Assoc Petrol Technol* 52:231-242 (in Japanese with English abstract)
- Sato T, Takayama T, Kato M, Kudo T (1988a) Calcareous microfossil biostratigraphy of the uppermost Cenozoic formations distributed in the coast of the Japan Sea. Part 3: Akita area and Oga Peninsula. *J Jpn Assoc Pet Technol* 53: 1-14 (in Japanese with English abstract)
- Sato T, Takayama T, Kato M, Kudo T, Kameo K (1988b) Calcareous microfossil biostratigraphy of the uppermost Cenozoic formations distributed in the coast of the Japan Sea. Pt. 4: Conclusion. *Japan. Assoc. Pet. Tech., J.* 53: 475-491 (in Japanese with English abstract)
- Sato T, Saito T, Yuguchi S, Nakagawa H, Kameo K, Takayama T (2002) Late Pliocene calcareous nannofossil paleobiogeography of the Pacific Ocean: evidence for glaciation at 2.75 Ma. *Rev Mex Cienc Geológica* 19:175-189
- Sato T, Chiyonobu S, Hodell DA (2009) Quaternary calcareous nannofossil 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, *Proceedings of the Integrated Ocean Drilling Program, Vol. 303/306*, College Station, TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.303306.210.2009
- Sato T, Sato N, Yamasaki M, Ogawa Y, Kaneko M (2012) Late Neogene to Quaternary paleoenvironmental changes in the Akita area, Northeastern Japan. *J Geol Soc Jpn* 118:62-73, in Japanese with English abstract
- Senjyu T, Sudo H (1994) The upper portion of the Japan Sea Proper Water: its source and circulation as deduced from isopycnal analysis. *J Oceanogr* 50:663-690
- Shinjo R (1999) Geochemistry of high Mg andesites and the tectonic evolution of the Okinawa Trough-Ryukyu arc system. *Chem Geol* 157:69-88
- Sugawara H, Yamaguchi T, Kawabe T (1997) Geological age of the Hamada Formation in the eastern Shimokita Peninsula, Aomori Prefecture. *Fossils* 62: 15-23 (in Japanese with English abstract)
- Tada R (1994) Paleoceanographic evolution of the Japan Sea. *Palaeogeogr Palaeoclimatol Palaeoecol* 108:487-508
- Tada R, Murray RW, Alvarez Zarikian CA, the Expedition 346 Scientists (2015) *Proc. IODP, 346*: College Station, TX (Integrated Ocean Drilling Program). doi:10.2204/iodp.proc.346.2015
- Takata H (2000) Paleoenvironmental changes during the deposition of the Omma Formation (late Pliocene to early Pleistocene) in Oyabe area, Toyama Prefecture based on the analysis of benthic and planktonic foraminiferal assemblages. *Fossils* 67:1-18 (in Japanese with English abstract)
- 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 (eds), *Initial Reports of Deep Sea Drilling Project: United States, Washington, U.S. Govt. Printing Office, 94*, 651-702

- Takayama T, Kato M, Kudo T, et al (1988) Calcareous microfossil biostratigraphy of the uppermost Cenozoic formations distributed in the coast of the Japan Sea. Part 2: Hokuriku sedimentary basin. *J Japanese Assoc Petroleum Technol* 53:9–27 (in Japanese with English abstract)
- Talley LD, Lobanov V, Ponomarev V, Salyuk A, Tishchenko P, Zhabin I, Riser S (2003) Deep convection and brine rejection in the Japan Sea. *Geophys Res Lett* 30, doi:10.1029/2002GL016451
- Tamaki K, Suehiro K, Allan J, Ingle Jr JC, Pisciotto KA (1992) Tectonic synthesis and implication of Japan Sea ODP Drilling. In: Tamaki K, Suehiro K, Allan J, McWilliams M, et al (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 2*, 1333–1348
- Tanaka Y, Takahashi M (2001) Stratigraphic change in size distribution pattern of calcareous nannofossil genus *Reticulofenestra* in the lower part of the Miocene Arakawa Group in the Karasuyama area, Tochigi Prefecture, central Japan. *J Geol Soc Jpn* 107:557–564, in Japanese with English abstract
- Tanaka Y, Ujiie H (1984) A standard late Cenozoic microbiostratigraphy in southern Okinawajima, Japan. Part 1. Calcareous nannoplankton zones and their correlation to the planktonic foraminiferal zones. *Bull Natl Sci Mus Tokyo Ser C* 10:141–168
- Thompson PR (1981) Planktonic foraminifera in the western North Pacific during the past 150 000 years: comparison of modern and fossil assemblages. *Palaeogeogr Palaeoclimatol Palaeoecol* 35:241–279
- Tsubakihara S, Hasegawa S, Maruyama T (1989) Upper Cenozoic in Kurumatsunai area, southwestern Hokkaido—stratigraphy and biochronology of the Kurumatsunai Formation. *Jpr Geol Soc Japan* 95:423–438 (in Japanese with English abstract)
- Tsuchihashi M, Oda M (2001) Seasonal changes of the vertical distribution of living planktic foraminifera at the main axis of the Kuroshio off Honshu, Japan. *Fossils* 70:1–17 (in Japanese with English abstract)
- Ujiie H, Ichikura M (1973) Holocene to upper-most Pleistocene plankton foraminifera in a piston core from off San'in district, Sea of Japan. *Trans Proc Paleontol Soc Jpn NS* 91:137–150
- Ujiie H, Kaneko N (2006) Geology of the Naha and Okinawashi-Nambu district. *Quadrangle Series, 1:50,000, Geological Survey of Japan, AIST*, 48 p. (in Japanese with English abstract 3 p.)
- Watanabe K (1976) The foraminiferal biostratigraphy of oil-bearing Neogene system in the Kubiki District, Niigata Prefecture, Japan. *Contrib Dep Geol Mineral Niigata Univ* 4:179–190 (in Japanese with English abstract)
- Watanabe M (2002) Revised diatom biostratigraphy and chronostratigraphy of the Pliocene sequence in the Himi-Nadaura area, Toyama Prefecture, central Japan: with special reference to ages of widespread volcanic ash beds and No. 3 Globorotalia inflata bed of planktonic foraminiferal biostratigraphy. *J Geol Soc Jpn* 108:499–509 (in Japanese with English abstract)
- Watanabe M, Yanagisawa Y, Tanaka Y, et al (2003) Diatom and calcareous nannofossil biostratigraphy of the Pliocene Kuwae Formation along the Tainai River, Kitakanbara area, Niigata Prefecture, central Japan. *J Japanese Assoc Pet Technol* 68:561–569 (in Japanese with English abstract)
- White LD, Alexandrovich JM (1992) Pliocene and Pleistocene abundance and preservation of siliceous microfossil assemblages from sites 794, 795, and 797: implications for circulation and productivity in the Japan Sea. In: Pisciotto KA, Ingle JC Jr, von Breyman MT, Barron J, et al (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 1*, 341–357
- Xiong SF, Ding ZL, Jiang WY, Yang SL, and Liu TS (2003) Initial intensification of East Asian winter monsoon at about 2.75 Ma as seen in the Chinese eolian loess-red clay deposit. *Geophys Res Lett* 30: 1524, doi:10.1029/2003GL017059
- Yamada K, Irizuki T, Tanaka Y (2002) Cyclic sea-level changes based on fossil ostracode faunas from the upper Pliocene Sasaoka Formation, Akita Prefecture, central Japan. *Palaeogeogr Palaeoclimatol Palaeoecol* 185:115–132
- Yamada K, Tanaka Y, Irizuki T (2005) Paleooceanographic shifts and global events recorded in late Pliocene shallow marine deposits (2.80–2.55 Ma) of the Sea of Japan. *Palaeogeogr Palaeoclimatol Palaeoecol* 220:255–271
- Yamamoto K, Iryu Y, Nakagawa H, Sato T, Matsuda H (2003) Stratigraphy of the Upper Cenozoic Deposits on the Neck of Motobu Peninsula, Okinawa-jima, Ryukyu Islands, Japan. *Quatern Res* 42:279–294 (in Japanese with English abstract)
- Yamamoto K, Iryu Y, Sato T, Abe E (2005) Stratigraphy of the Ryukyu Group on northern Motobu Peninsula, Okinawa-jima, Ryukyu Islands, Japan. *J Geol Soc Japan* 111:527–546 (in Japanese with English abstract)
- Yamamoto K, Iryu Y, Sato T, Chiyinobu S, Sagae K, Abe E (2006) Responses of coral reefs to increased amplitude of sea-level changes at the Mid-Pleistocene climate transition. *Palaeogeogr Palaeoclimatol Palaeoecol* 241:160–175
- Yanagisawa Y, Amano K (2003) Diatom biostratigraphy and paleoceanography of the Pliocene sequence in the western part of Joetsu City, Niigata Prefecture, central Japan. *Bull Geol Surv Jpn* 54:63–93, in Japanese with English abstract
- Yi S, Yun H, Yoon S (1998) Calcareous nannoplankton from the Seogwipo Formation of Cheju Island, Korea and its paleoceanographic implications. *Paleontol Res* 2:253–265

Submit your manuscript to a SpringerOpen® journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Immediate publication on acceptance
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com