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History of the inflow of the warm Tsushima Current into the Sea of Japan at 3.5-0.8 Ma

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Abstract

Warm-water molluscs and planktonic foraminifers sporadically entered the southern Sea of Japan from the East China Sea via the Tsushima Current at 3.2, 2.9, 2.4 and 1.9 Ma. In contrast, warm-water diatoms already appeared at 3.5 Ma (the first occurrence of *Neodenticula koizumi*) and have occurred continuously to the present. This discrepancy implies that warm-water diatoms could tolerate environments lower in salinity and temperature than could warm-water molluscs and planktonic foraminifers. If this interpretation is correct, then East China Sea coastal water has periodically entered the Sea of Japan since 3.5 Ma, prior to the entry of mollusks and planktonic foraminifers. Except for these periods, there was no connection between the Sea of Japan and East China Sea. However, the stratigraphic distribution of warm-water molluscs and planktonic foraminifers shows that the Tsushima Current flowed in at every interglacial highstand, except for MIS 25, 23 and 21.3, at 1.71 to 0.8 Ma (MIS 59 to 20).

Key words: Sea of Japan, Tsushima Current, Pleistocene, Pliocene, stratigraphy, planktonic foraminifera, molluscs, diatoms

1. Introduction

The Sea of Japan is a semi-enclosed marginal sea with an area of approximately 1,000,000 km^2 and an average depth of 1350 m. It is connected southward to the East China Sea through Tsushima Strait, to the Pacific Ocean through Tsugaru Strait, and northward to the Sea of Okhotsk through Soya and Mamiya Straits, all of which are narrow and shallower than 130 m (Fig. 1). The only current that flows into the Sea of Japan today is the Tsushima Current, a branch of the warm Kuroshio Current, which enters through Tsushima Strait and flows northward along the western coast of Honshu Island (Fig. 1). This current supplies a large quantity of heat, and transports marine organisms, into the Sea of Japan. When present, this current isolated the terrestrial organisms of Japan from those of eastern Asia, and profoundly influenced the Neogene palaeoenvironments, ecosystems and evolution of organisms within and around the Sea of Japan (e.g., Yasuda, 1982; Kitamura and Kondo, 1990; Oba et al., 1991; Dunber et al., 1992; Tada, 1994; Kitamura et al., 1994, 1997, 2000; Ishiwatari et al., 1999, Tada et al., 1999; Koizumi et al., 2003).

The history of the Tsushima Current is reflected in the stratigraphic distribution of warm-water taxa. Koizumi (1992) examined the stratigraphic distribution of diatoms at ODP Sites 794 and 797 of the Sea of Japan (Fig. 1) and noted that warm-water species appeared at 3.5 Ma. Based on Koizumi's (1992) data, Tada (1994) inferred that the periodic inflow of warm surface water into the Sea of Japan began at that time. However, warm-water diatoms are an anomalous proxy for the Tsushima Current, because they first occurred during the later part of marine oxygen isotope stage (MIS) 2 (Tada et al., 1999). According to Ishiwatari et al. (1999), the alkenone-based sea-surface temperature in sediment cores from the Oki Ridge (Fig. 1) was 18°C at 17.5 ka, which is similar to the modern value (19°C) and likely was caused by stable stratification of the water column due to fresh water input. Kitamura et al. (2001) inferred that this warming of surface water led to a proliferation of warm-water diatoms that was a relict of prior warm interglacial periods. In contrast, warm-water planktonic foraminifers and molluscs have not been reported from the last glacial period (e.g., Habe & Kosuge, 1970; Emery et al., 1971; Oba et al., 1991), which implies that they are more accurate proxies for the warm Tsushima Current than are diatoms.

Kheradyar (1992) examined the stratigraphic distribution of planktonic foraminifers at ODP Site 798 (Fig. 1) and found many intervals barren of calcareous fossils. The calcium carbonate compensation depth was shallower than 1000 m deep during deglacial periods (Oba et al., 1991), so deep-sea sediments are not suitable for recording temporal changes of the Tsushima Current. To overcome this problem, a number of workers have examined the stratigraphic distribution of late Pliocene-early Pleistocene warm-water molluscs and planktonic foraminifera at numerous sites along the Sea of Japan coast in central Japan. Kitamura et al. (2001), from the stratigraphic distribution and abundance of molluscs and planktonic foraminifera within sixth-order (41-k.y.) depositional sequences of the early Pleistocene Omma Formation, inferred that the paleoceanographic history of the Sea of Japan is divisible into three substages: cold surface water prevailed when the southern channel was closed during substage I (2.5-1.71 Ma (MIS 60/59); the warm Tsushima Current flowed into the sea during interglacial highstands of substage II (1.71-1.52 Ma (MIS 51)); and, geographic isolation was exacerbated due to the narrowing and/or shallowing of northern straits in substage III (1.52-0 Ma).

More recently, Kitamura and Kimoto (2004) reconstructed the history of the Tsushima Current at 3.9 to 1.72 Ma from fossil records and reached the following conclusions: 1) there is no direct evidence for inflow of the Tsushima Current from 3.9

to 3.1-3.0 Ma; 2) this current flowed into the Sea of Japan only rarely between 3.1-3.0 and 2.0 Ma; and, 3) incomplete fossil records for the 2.0 to 1.72 Ma interval (MIS 60) show no evidence of warm-water molluscs and planktonic foraminifers, except in MIS 69.

In the present study, we combine the new fossil records of Miwa et al. (2004a, b) and Kitamura and Kawagoe (in press) with previous work to more accurately reconstruct the history of the Tsushima Current at 3.5 to 0.8 Ma (Figs. 2 and 3). Kitamura and Kimoto (2004) cited 3.9 Ma as the first occurrence (FO) of the diatom *Neodenticula koizumi*, but herein we use the revised age of 3.5 Ma that is based on the diatom biostratigraphy of Watanabe (2002) and Watanabe et al. (2003).

2. Data sources

The stratigraphic distribution of warm-water molluscs can be directly traced in the field, which is useful for initial paleoceanographic interpretations. The modern distribution of benthic organisms shows that the present thickness of the Tsushima Current in the Sea of Japan is 150-160 m, with cold-water taxa dwelling in the underlying bottom faunas. Kitamura et al. (1997) inferred a maximum thickness of 100 m in MIS 47. Even at times when the Tsushima Current flowed into the Sea of Japan, it was possible for warm-water molluscs to be missing from sediments on the continental shelf. In contrast, planktonic foraminifers are strongly controlled by surface sea-water temperature, plus they are short-lived and respond rapidly to environmental changes, compared to adult molluscs that are relatively long-lived and which may lag behind environmental changes. Unfortunately, microfossils cannot be examined in these outcrops, so an archive containing stratigraphic data for both molluscs and planktonic foraminifers is most suitable for reconstructing the history of the Tsushima Current.

Such archives currently exist for a few strata, including the late Pliocene Yabuta Formation (Cronin et al., 1994; Miwa et al., 2004b), the Plio-Pleistocene Junicho Formation (Arai et al., 1991, 1997), and the early Pleistocene Omma Formation (Kitamura and Kondo, 1990; Kitamura, 1991a, b, 1994; Kitamura et al., 1994; Kitamura and Kawagoe, in press). In order to help fill the data gap, we are adding molluscan records from Plio-Pleistocene strata in the Joetsu area and the late Pliocene Kuwae Formation (Figs. 1 and 2). However, we did not obtain fossils records from the last occurrence (LO) of *Neodenticula koizumi* (2.0 Ma) to base of the Olduvai Subchron (1.95 Ma).

3. Stratigraphic occurrences of warm-water species

Yabuta Formation

The Yabuta Formation (Fig. 1) consists mainly of massive siltstone up to 200 m thick with abundant calcareous and siliceous microfossil and molluscs. Watanabe (1990) cited the LO of *Neodenticula kamtschatica* (2.7-2.6 Ma) just below the UN volcanic ash bed, and more recently Watanabe (2002) identified the FO of *N. koizumi* (3.5 Ma) near the base of the formation (Fig. 2). The top of the formation is estimated to be 2.4 Ma in age, based on the sediment accumulation-rate curve of Watanabe (2002). Cronin et al. (1994) assigned molluscs in the upper part of the formation an age of 2.9 to 2.4 Ma, and showed that the molluscan assemblage is characterized by the bivalves *Conchocele bisecta* and *Lucinoma acutilineata*, which have symbiotic sulfide-oxidizing bacteria in their gills. Warm-water molluscs are not present in this formation, although Miwa et al. (2004b) identified one individual of the warm-water planktonic foraminifera *Globigerinoides ruber* in one horizon (sample number: YBF 52, total number of counted foraminifera is 367) (Fig. 4). This represents a new record for the inflow of the Tsushima Current and is inferred to have an age of 3.2 Ma, based on the sediment accumulation rate curve of Miwa et al. (2004b).

Kuwae Formation

The Kuwae Formation (Fig. 1) is about 210 m thick and consists mainly of siltstone. Amano et al. (2000) reported that warm-water molluscs occur on at least two horizons located between the LO of *Reticulofenestra pseudoumbilicus* (3.85 Ma) and Datum A (2.75 Ma; Sato and Kameo (1996)) (Fig. 2). The precise stratigraphic positions of these datum planes were not identified, so more detailed ages cannot be inferred.

Miwa et al. (2004a) identified five datum planes in exposures along the Tainai River, including the FO of *N. koizumi* (3.5 Ma), a rapid increase (RI) of *N. koizumi* (3.1-3.0 Ma), Datum A, the LO of *N. kamtschatica* (2.7-2.6 Ma), and the Gauss-Matuyama boundary (2.58 Ma) (Fig. 2). One individual of the warm-water planktonic foraminifer *Gds. ruber* was found in one horizon (sample number: 156, total number of counted foraminifera is 367) and has an inferred age of 2.9 Ma, using the sediment accumulation rate curve of Miwa et al. (2004a) (Fig. 4). This warm period is not evidenced in the Yabuta Formation, probably owing to a lack of sampling; conversely, the warm period at 3.2 Ma identified in the Yabuta Formation was not recognized in the Kuwae Formation.

Plio-Pleistocene strata near Joetsu

The 2-km thick Plio-Pleistocene marine strata in the western part of Joetsu City (Fig. 1) have been divided into the Kawazume, Nadachi and Tanihama Formations, in ascending order. The molluscs in these formations have been extensively studied (e.g., Amano et al., 1987, 1988, 1990; Amano and Kanno, 1991) and consist predominantly of cold-water taxa, but with a few warm-water molluscs in some horizons.

Amano and Kanno (1991) reported warm-water molluscs from the middle part of the Nadachi Formation (Loc. 23). This horizon is located between the RI of *N. koizumi* (3.1-3.0 Ma) and the LO of *N. kamtschatica* (2.7-2.6 Ma) (Yanagisawa and Amano, 2003), so it evidently correlates with the horizon yielding *Gds. ruber* in the Kuwae Formation (2.9 Ma).

Amano et al. (1988) found warm-water molluscs in the uppermost beds of the Nadachi Formation, in a horizon with an inferred age of 2.4 Ma (Kurokawa, 1999; Yanagisawa and Amano, 2003) (Fig. 4). Warm-water molluscs occur in at least three horizons in the Tanihama Formation (Amano et al., 1987) that lie between the FO of *N. seminae* (2.4 Ma) and the LO of *N. koizumi* (2.0 Ma) (Yanagisawa and Amano, 2003) (Fig. 3). Unfortunately, more detailed ages for these horizons cannot be inferred, because the precise stratigraphic position of the LO of *N. koizumi* was not identified.

Junicho Formation

The Junicho Formation (Fig. 1) has been divided lithologically into lower, middle and upper parts (Arai et al., 1991). The middle part is 50-80 m thick and composed of at least three depositional sequences within the Olduvai Subchron (Arai et al., 1991) that mainly contain fine, calcareous sandstone with abundant cold-water molluscs such as *Acila nakazimai* and *Astarte alaskensis*. Warm-water molluscs are absent (Arai et al., 1991). However, Arai et al. (1998) found one individual of the warm-water planktonic foraminifer *Gds. ruber* from each of two horizons in the upper portion of the lowest sequence (C120 and C121; total number of counted foraminifera are 286 and 199, respectively). Kitamura and Kimoto (2004) assigned these horizons to

MIS 69 (1.9 Ma) (Fig. 4), based on a combination of cycle stratigraphic and chronological data (Arai et al., 1997, 1998; Okubo et al., 2000).

Omma Formation

The early Pleistocene Omma Formation (Fig. 1) is up to 220 m thick and has been divided into lower, middle and upper parts (Kitamura and Kondo, 1990). Its lower and middle parts are composed of fourteen sixth-order (41-ka) depositional sequences that were deposited in inner- to outer-shelf depths during MIS 56 to 28 (Kitamura et al., 1994, 2001; Kitamura and Kimoto, 2004). Warm-water molluscs and planktonic foraminifers are found in all sequences (Fig. 3). Recently, Kitamura and Kawagoe (in press) have identified five depositional sequences (U1 to 5) in the upper part of this formation (Fig. 3), the three lower ones of which correlate with MIS 28-26, 26-24 and 24-22; the upper two depositional sequences correspond to MIS 22-20. Kitamura and Kawagoe (in press) conclude that the horizons with maximum water depth in depositional sequences U4 and U5 correspond to MIS 21.5 and 21.3, respectively. Warm-water molluscs were present during MIS 27 and 21.5 (Fig. 3). As for the other interglacial periods (MIS 25, 23 and 21.3), molluscs are not identifiable, owing to shell dissolution.

Takata (2000) studied planktonic foraminiferal assemblages in five sixth-order (41-k.y.) depositional sequences in the early Pleistocene Omma Formation in Toyama Prefecture (the Oyabe section) (Fig. 1). The FO of *Gephyrocapsa oceanica* and *G.* (large) are in the middle portion of Cycle 2 and at the base of Cycle 5, respectively. Using the FO of *G.* (large) as a datum plane, the three depositional sequences in the lower part of the Omma Formation at Okuwa correlate with Cycles 3 to 5 in the Oyabe area. The warm-water planktonic foraminifer *Gds. ruber* was recognized in Cycles 1, 2 and 3, which suggests that warm-water organisms entered the Sea of Japan at every interglacial highstand since the FO of *G. oceanica* (MIS 59) (Fig. 4). The absence of warm-water planktonic foraminifera in Cycles 4 and 5 at Oyabe is due to erosion (Kitamura et al., 2001).

Discussion

The history of the warm Tsushima Current at 3.5 to 0.8 Ma is divisible into two intervals. In the interval from 3.5 to 1.71 Ma, it periodically flowed into the Sea of Japan at 3.2, 2.9, 2.4 and 1.9 Ma (MIS 69) (Fig. 4). Comparing these ages with $\delta^{18}O$ stratigraphy (Shackleton et al., 1995), the older three events may correlate with KM5 or 3, G17 or 15 and MIS 95 or 93, respectively. On the other hand, at 1.71-0.8 Ma (MIS 59-20), the Tsushima Current flowed into the Sea of Japan at every interglacial highstand, except for MIS 25, 23 and 21.3 (Fig. 4).

It is noteworthy that the values of the relative abundance of *Gds. ruber* in the early interval (0.3-0.6%) are significant lower than those in the latter (1.4-21.8%) (Fig. 4). Although there are a few data on the relative abundance of *Gds. ruber* in modern surface sediments of the Sea of Japan, its values decrease northward. According to Tsukawaki et al. (2001), the relative abundances of *Gds. ruber* are 0-0.5% and 0.6-4.1% off of the Matsumae Peninsula of Hokkaido and off Niigata in central Japan, respectively (Fig. 1). Ujiie and Ujiie (2000) reported its relative-abundance range to be 8.4 to 15.9% in sediment samples from the Danjo Basin in the northeastern East China Sea (Fig. 1). Thus we inferred that the relative abundance of *Gds. ruber* is an index for the early Pleistocene marine climate of Sea of Japan (Kitamura and Kimoto, in prep.). The abundance values for the early interval come from Niigata (Kuwae Formation) and the east side of the Noto Peninsula (Yabuta and Junicho Formations), while the values for the later interval come from the west side of the Noto Peninsula (Omma Formation) (Fig. 1). As a result, the geographic positions of the fossil records result in a difference in the relative abundance of *Gds. ruber* between the two intervals. However, we think it worth considering the possibility that the volume of inflow of the Tsushima Current in the early interval was smaller than in the later interval. The reason for this is that there was a channel, some 10-20 km-wide and 40-km long, that connected the west and east sides of the Noto Peninsula in the late Pliocene and early Pleistocene (Chinzei, 1986) (Fig. 1). The Yabuta, Junicho and Omma Formations are sedimentary fill within this channel. *Gds. ruber* evidently dwell in surface water throughout its life cycle (Fairbanks et al., 1982), so its distribution is relatively unconstrained by water depth compared to other species. It is unlikely that a significant decrease in the relative abundance of *Gds. ruber* took place when the Tsushima Current flowed through the channel. From this, we believe that its inflow volumes during the early interval, especially at 3.2 and 1.9 Ma (these data are from the Yabuta and Junicho Formations), were smaller than during the later one. If this interpretation is correct, then the late Pliocene elevation of the southern part of the Sea of Japan was up to 50 m above present-day sea level, because sea levels in the interglacial periods at 3.3 to 2.5 Ma were up to 50m higher than the present-day level (Dwyer et al., 1995).

At the end of the early interval, the altitude of the southern part of the Sea of Japan might have rapidly decreased due to crustal stretching in the northern Okinawa Trough after 2 Ma (Kitamura et al., 2001). Consequently, the present-day southern channel had formed by MIS 59 (1.71 Ma) when the Tsushima Current began to flow during each interglacial period. Large numbers of the planktonic foraminifer *Globorotalia inflata*, a species which indicates that the southern channel had a water depth greater than at present (>200 m), occur in MIS 57, 47, 45, 43, 41 and 29, along with warm-water planktonic foraminifers (Kitamura et al., 2001; Kitamura and Kimoto, 2004). The contemporaneous southern channel seems to have been narrower than the modern one, because the thickness of the Tsushima Current at MIS 47 (100 m) was two thirds that of today (150-160 m) (Kitamura et al., 1997).

As noted above, there is an apparent discrepancy in stratigraphic distribution between warm-water planktonic foraminifers and diatoms during the later part of MIS 2 (Tada et al., 1999). A similar discrepancy exists within late Pliocene fossil records. Koizumi (1992) showed that warm-water diatoms (*Hemidiscus cuneiformis*) appeared between the LO of *N. kamtschatica* (2.7-2.6 Ma) and the FO of *N. koizumi* (2.0 Ma), while Yanagisawa and Amano (2003) observed that many warm-water diatoms (*Thalassiosira convexa*, *Nitzschia fossilis*, *N. reinholdii* and *Rhizosolenia praebergonii*) occur continuously in the lower Nadachi Formation and the main part of the Tanihama Formation (3.2-2.0 Ma). In the case of the Kuwae and Yabuta Formations (Watanabe, 2002; Watanabe et al., 2003; Miwa et al., 2004a, b), the stratigraphic distribution of diatoms at 3.5 and 2.6 Ma correlates directly with the planktonic foraminifers. These records show that warm-water diatoms had appeared by 3.5 Ma, after which they occurred continuously in both formations (Fig. 4).

This discordance may be explained by differences in the salinity and temperature tolerances between warm-water diatoms and *Gds. ruber*, since the latter tolerates salinities between 22 and 49 ‰ (Bijima et al., 1990). Warm-water diatoms tolerate salinities below 22 ‰, and were transported by the inflow of low-salinity coastal water through the southern channel during short warm periods. The appearance of warm-water diatoms may be significant older than that of *Gds. ruber*, which occurred sporadically at 3.2 and 2.9 Ma (Miwa et al., 2004a, b), whereas warm-water diatoms occurred continuously. This may be explained by the assumption that the lower temperature limits of warm-water diatoms were lower than 19°C, which is the lower temperature limit of *Gds. ruber*. Koizumi (1992) and Tada (1994) noted that the periodic inflow of warm surface water restarted at 3.5 Ma. If my assumption is correct, this warm surface water was probably coastal water having salinities less than 22 ‰. At present, the East China Sea coastal water is characterized by a slightly lower salinity and by enrichment in nutrients regenerated from bottom sediments of the sea (Hong et al., 1995). Tada et al. (1999) inferred that the influx of this water subdued the production of deep water in the Sea of Japan and enhanced surface productivity at periods of low sea level in the late Quaternary. It is possible that similar phenomena reoccurred in the Sea of Japan at 3.5-1.7 Ma (Fig. 4).

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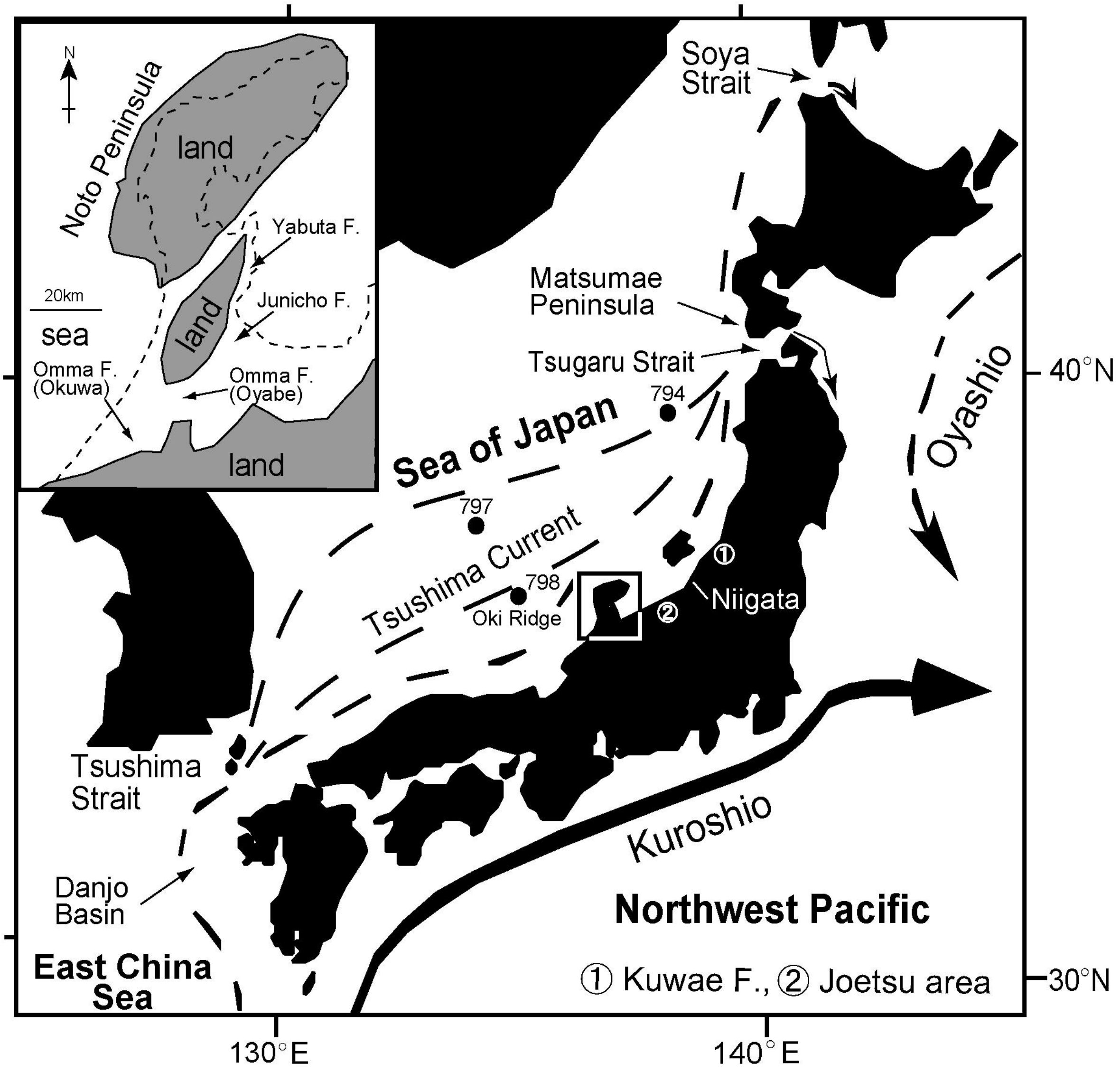
Figure captions

Fig. 1 Location of fossils records used in this study. The inset map shows late Pliocene to Early Pleistocene paleogeography in the Hokuriku district.

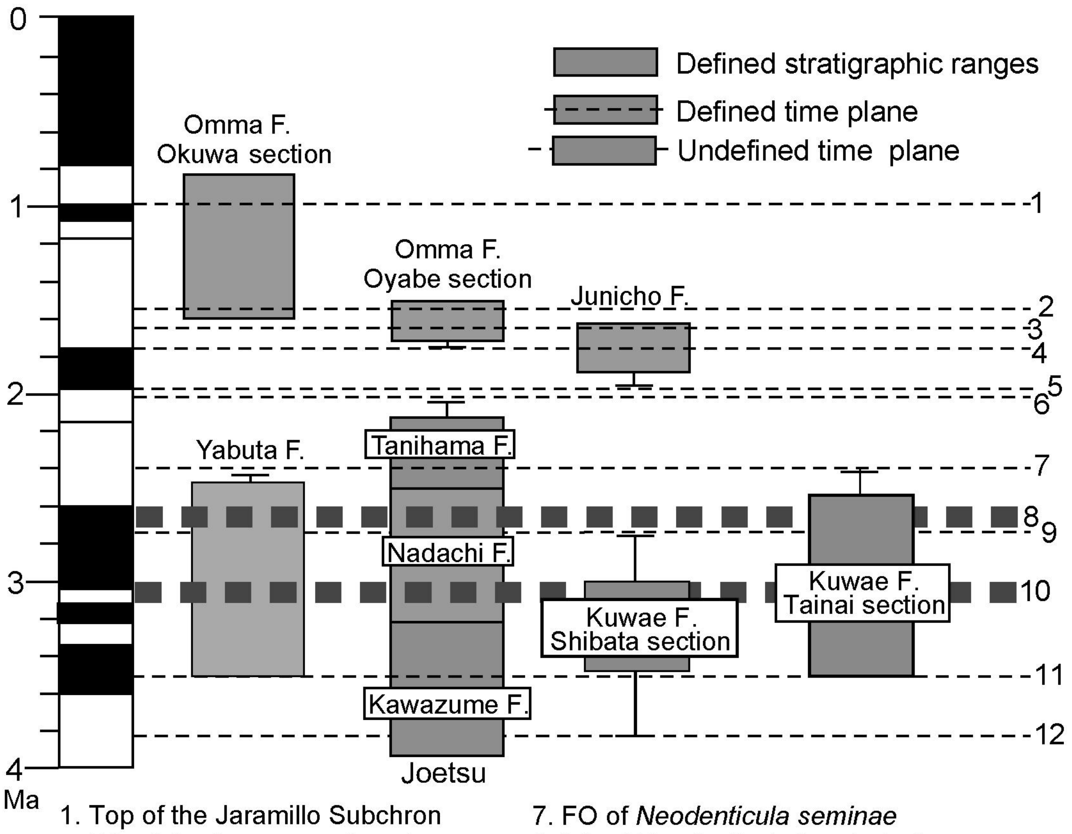
Fig. 2 Correlation of fossil records in the late Pliocene to early Pleistocene sediments along the western coast of Honshu Island.

Fig. 3 Columnar section of the Omma Formation at its type section. Biostratigraphic datum horizons are after Takayama et al. (1988) and Sato and Takayama (1992); magnetostratigraphic data from Kitamura et al. (1994); time scale for the oxygen isotope record at DSDP Site 607 (Ruddiman et al., 1989) and ages of biostratigraphic datum horizons and magnetic polarity changes are based on chronology of Berger et al. (1994). SB: Sequence boundary. L-1 to 3, 1-11, U1-U5: depositional sequence numbers.

Fig. 4 (A) Stratigraphic distribution of maximum relative abundance of *Globigerinoides ruber* at each interglacial stage. Also shown in the figure is the stratigraphic position of the first occurrence of warm-water diatoms, after Watanabe (2002) and Watanabe et al. (2003). (B) Reconstruction of the southern part of the Sea of Japan during interglacial periods after 1.7 Ma. (C) Reconstruction of the southern part during interglacial periods before 1.7 Ma.

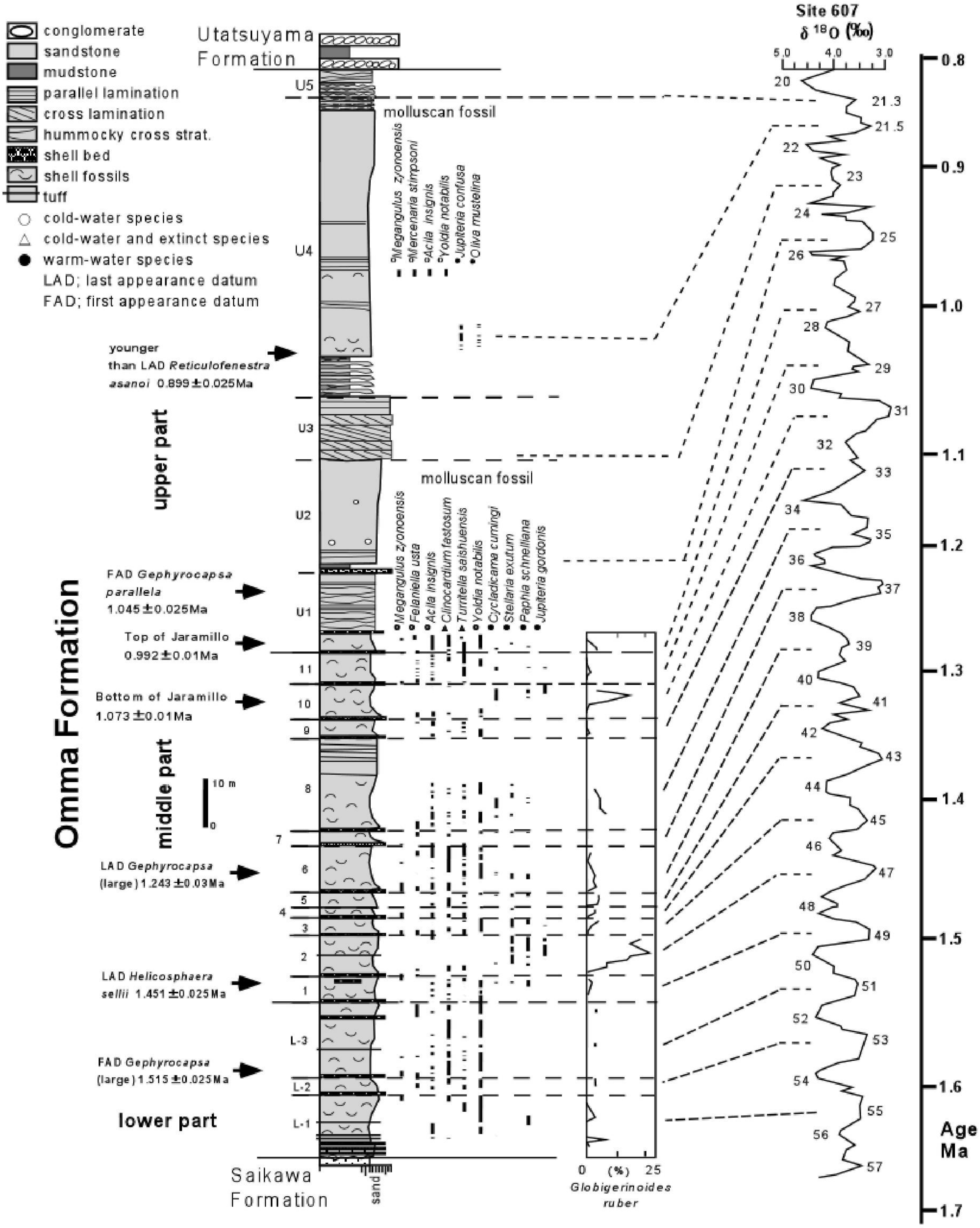


Kitamura and Kimoto Fig. 1

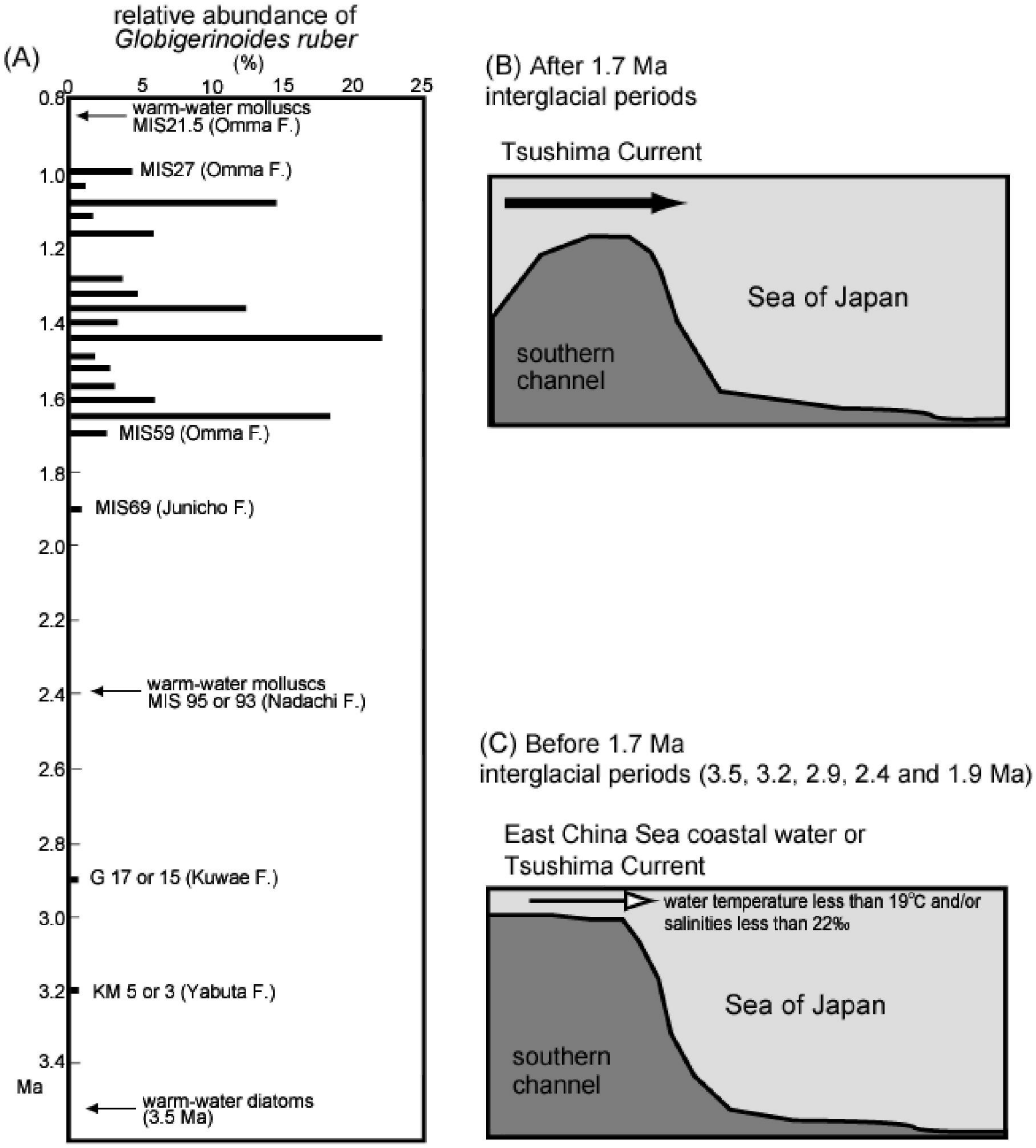


1. Top of the Jaramillo Subchron
2. FO of *Gephyrocapsa* (large)
3. FO of *Gephyrocapsa oceanica*
4. Top of the Olduvai Subchron
5. Base of the Olduvai Subchron
6. LO of *Neodenticula koizumii*
7. FO of *Neodenticula seminae*
8. LO of *Neodenticula kamtschatica*
9. Datum plane A
10. RI of *Neodenticula koizumii*
11. FO of *Neodenticula koizumii*
12. LO of *Reticulofenestra pseudoumbilicus*

Kitamura and Kimoto Fig. 2



Kitamura and Kimoto Fig. 3



Kitamura and Kimoto Fig. 4