Paleoceanographic Changes of the Sea of Japan During 3.5-0.8 Ma

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ABSTRACT

On the basis of fossil record from marine deposits in and around the Sea of Japan, the environment during 3.5–0.8 Ma is divided into two stages. During the old stage (3.5–1.71 Ma (stage 60/59)), cold surface water prevailed, except for the short term inflow (< 41 ky duration) of warm Tsushima Current at 3.5, 3.2, 2.9, 2.4 and 1.9 Ma. During the young stage (1.71–0.8 Ma), the Tsushima Current flowed into the sea at every interglacial highstand. This change was caused by opening of the southern channel due to crustal stretching in the northern Okinawa Trough. The onset of inflow of the Tsushima Current caused intrusion of warm-water organisms into the Sea of Japan during interglacial stages and barrier to migration of land organisms between East Asia and Japan. In summary, the environments and organisms in and around the Sea of Japan since 3.5 Ma have been strongly controlled by the development of southern channel (1.71 and 1.35 Ma) and global climate changes (glacial/interglacial cycles).

Keywords: Sea of Japan, Warm Tsushima current, Fossil record, Shallow-marine deposits, Pliocene, Pleistocene

INTRODUCTION

The warm Tsushima Current supplies a large quantity of heat to the Sea of Japan as well as Indo-Pacific marine organisms. The current also acts to isolate the terrestrial organisms of Japan from those of Asia. Therefore, it probably had a strong influence on the Pliocene-Pleistocene paleoclimate, paleoenvironment, and ecosystem within and around the Sea of Japan. In this paper, I review paleoceanographic changes within the Sea of Japan during the period from 3.5 to 0.8 Ma. First, I will introduce "the recent oceanographic condition of the Sea of Japan". Second, I discuss a "proxy for the warm Tsushima Current"; third, "cyclic changes in shallow marine environments during the early Pleistocene"; and, fourth, "paleoceanographic changes within the Sea of Japan during the period from 3.5 to 0.8 Ma.

OCEANOGRAPHIC CONDITION OF THE SEA OF JAPAN

The Sea of Japan is a semi-enclosed marginal sea and is connected to the East China Sea to the south via the Tsushima Strait, to the Pacific Ocean through the Tsugaru Strait, and to the Sea of Okhotsk to the north via the Soya and Mamiya straits. All of these straits have water depths of less than 140 m, similar to the sea level at the last glacial maximum at 20,000 years ago, when the Sea of Japan was isolated from the Pacific Ocean. Consequently, at this time the salinity of the surface water was relatively low because of the more precipitation relative to

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evaporation over the sea [1].

The warm Tsushima Current, a branch of the warm Kuroshio Current, flows into the Sea of Japan today. Based on the stratigraphic data of warm-water planktonic foraminifers, the Tsushima Current first began to flow into the Sea of Japan in this way at about 9,000 years before present [1, 2]. The current enters the sea via Tsushima Strait and flows northward along the western coast of Honshu Island, with the majority of the current flowing out to the Pacific Ocean via the Tsugaru Strait. The remainder of the current reaches the northern shores of the Sea of Japan and becomes dense enough to sink to the bottom due to cooling and freezing during winter. This sunken water mass is the Japan Sea Proper Water (JSPW), which has a low temperature and high concentration of dissolved oxygen. The water temperature within the intermediate zone of the Sea of Japan is significantly lower than that of the Pacific. This remarkable zone of low temperature is due to the JSPW.

PROXY FOR THE WARM TSUSHIMA CURRENT

The history of the Tsushima Current is recorded in the stratigraphic distribution of warm-water taxa within the Sea of Japan. On the basis of the stratigraphic distribution of diatoms from deep-sea sediment cores, warm-water species appeared at 3.5 Ma [3]. However, warm-water diatoms are not a good proxy for the Tsushima Current because they occurred during the late stage of the last glacial period, oxygen isotope stage 2 [4]. As noted above, surface water salinity was very low within the Sea of Japan during the last glacial period [1]. Such a low salinity has an influence on foraminiferal $\delta^{18}O$ values and alkenone thermometry [1, 5]. However, we do not yet understand the degree of this effect because we have yet to determine the salinity at this time. Consequently, there is some debate regarding estimates of the sea surface temperature during the last glacial period. Many recent studies have estimated the sea surface temperatures in the northwestern Pacific and the East China Sea, reporting that temperatures during the last glacial period were about 4°C lower than those of the present day [6, 7]. Thus many workers thought that the sea surface temperature within the Sea of Japan during the last glacial period was significantly lower than current-day temperatures. In summary, there is problem in using diatoms as a proxy for the warm Tsushima Current.

In contrast, warm-water planktonic foraminifers and molluscs have not been described from the last glacial period [1, 5], suggesting that they are more accurate proxies for the warm Tsushima Current than diatoms. But further research is required to demonstrate the utility of these species as proxies for the current. As noted above, the cool JSPW occupies the deeper part of the Sea of Japan, below the Tsushima Current. In the area off southwestern Japan, the thermocline between the two water masses is located at about 150 m water depth. The depth of the thermocline exerts a strong control on the bathymetric range of warm-water benthos [8]. Even during times when the Tsushima Current flowed into the Sea of Japan, it was possible that warm-water molluscs were absent from a given sediment if it was deposited below the thermocline. The depth of the thermocline becomes shallower northward. Thus, the number of species of Indo-Pacific molluscs decreases gradually northward, with no species at all observed off Oshima Peninsula, Hokkaido. In terms of identifying the stratigraphic distribution of warm-water molluscs, the sedimentary records preserved in southern areas of the Sea of Japan and in shallow water are suitable for detailed examinations of temporal changes in the Tsushima Current. Warm-water planktonic foraminifera are also useful in this regard.

The distribution of planktonic foraminifera is strongly controlled by the surface sea-water temperature. Moreover, they are short-lived and respond rapidly to environmental change; in comparison, adult molluscs are relatively long-lived. Co-workers and I proposed that warm-water *Globigerinoides ruber* is the most suitable planktonic foraminifera species as a proxy for the warm Tsushima Current [9]. This is because it is the shallowest dwelling species and it remains in surface waters throughout its entire life cycle [10]. The lower limit of the temperature tolerance of *G. ruber* is 19°C, meaning that the present-day population is unlikely to survive winter within the Sea of Japan.

Recently, planktonic foraminiferal assemblages from 51 surface sediment samples were described [11]. I and co-worker examined their data and identified two patterns in terms of the distribution of *G. ruber* [12]. The first pattern is that the species decreases in abundance from inshore to offshore areas (Fig. 1). The second pattern is that its relative abundance decreases northward, being absent in the area off northern Hokkaido. This pattern is very clear when considering sediment samples collected from water depths shallower than two hundred meters

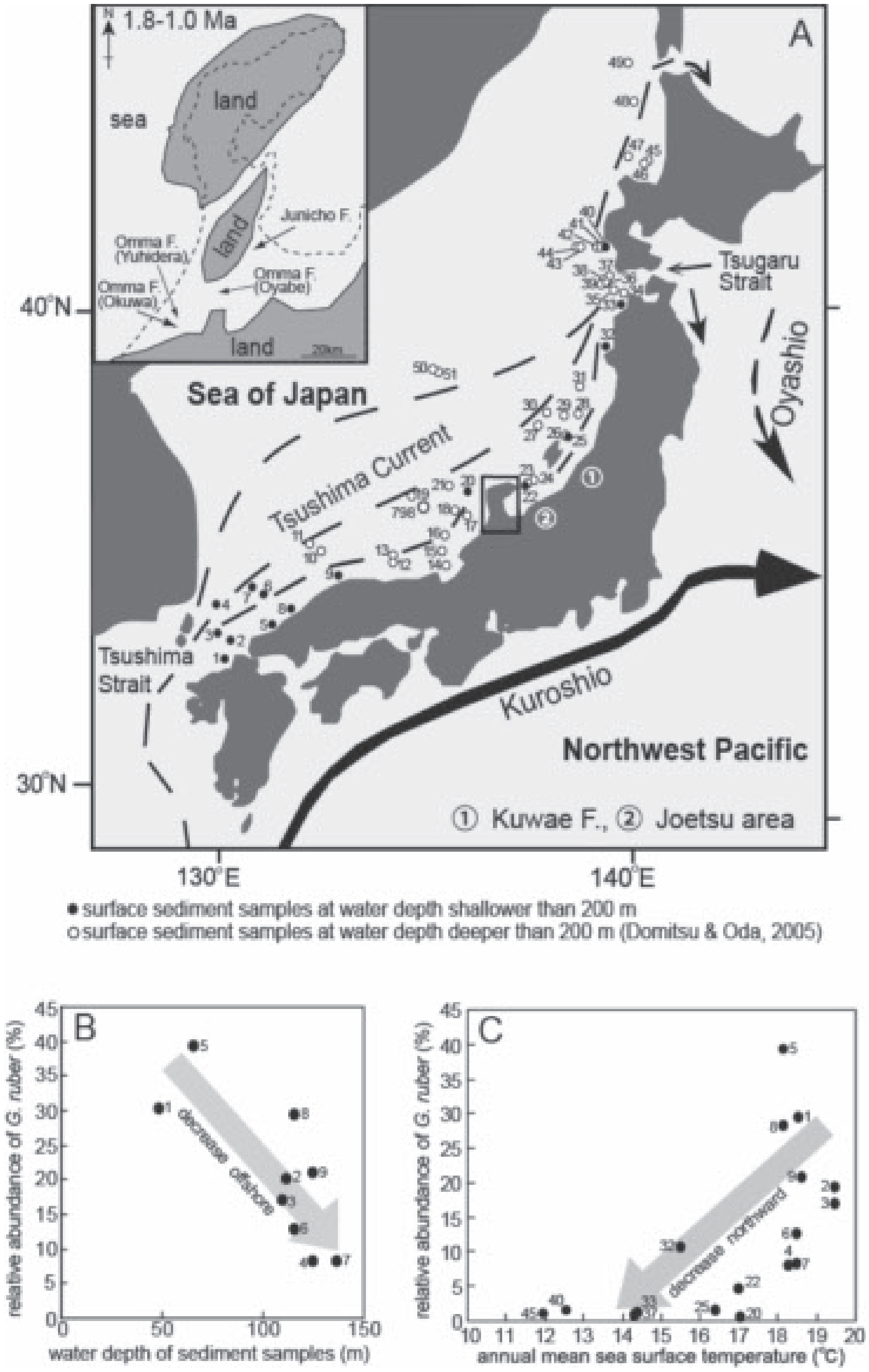


Fig. 1 (A) Locality map of fossil records and the sampling location of planktonic foraminiferal assemblages reported by Domitsu and Oda (2005). (B) Relationship between relative abundance of planktonic foraminifera *Globigerinoides ruber* and water depth of the sampling points. (C) Relationship between relative abundance of *G. ruber* and annual mean sea surface temperature (Japan Oceanographic Data Center; http://www.jodc.go.jp/service_j.htm). The relative abundance of *G. ruber* was calculated from data presented by Domitsu and Oda (2005). Numbers are the sampling location numbers.

(Fig. 1). Thus, the utility of *G. ruber* as the proxy for the Tsushima Current requires the same attention as that required by warm-water molluscs. There exists an additional special problem encountered in examining the stratigraphic distribution of *G. rube*r. Because their size is less than one millimeter, they are too small to be examined in outcrop with the naked eye. Consequently, sampling effects must be taken into account when evaluating the stratigraphic distribution of the species.

CYCLIC CHANGES IN SHALLOW MARINE ENVIRONMENTS DURING THE EARLY PLEISTOCENE

In this chapter, I review cyclic changes in both molluscs and planktonic foraminifer within depositional sequences in the early Pleistocene Omma Formation. At its type section, the Omma Formation is up to 220 m thick, and has been divided into lower, middle, and upper parts (Fig. 2) [13, 14]. The lower and middle parts are composed of fourteen depositional sequences that were deposited at inner- to outer-shelf depths. Five depositional sequences are identified in the upper part, deposited at alluvial plain to inner-shelf depths [15]. The basement of basal shell beds corresponds to sequence boundary.

In each depositional sequence, the lithofacies present are, in ascending order, a basal shell bed, a well-sorted fine sandstone, a muddy fine- to very-fine sandstone, and a well-sorted fine sandstone. The depositional sequences contain in situ molluscan fossils, although X-ray diffraction studies reveal diagenetic calcite derived from the aragonite shells. It is highly likely that this diagenetic alteration also affected planktonic foraminifers. Thus we did not geochemically analyze fossils within the Omma Formation.

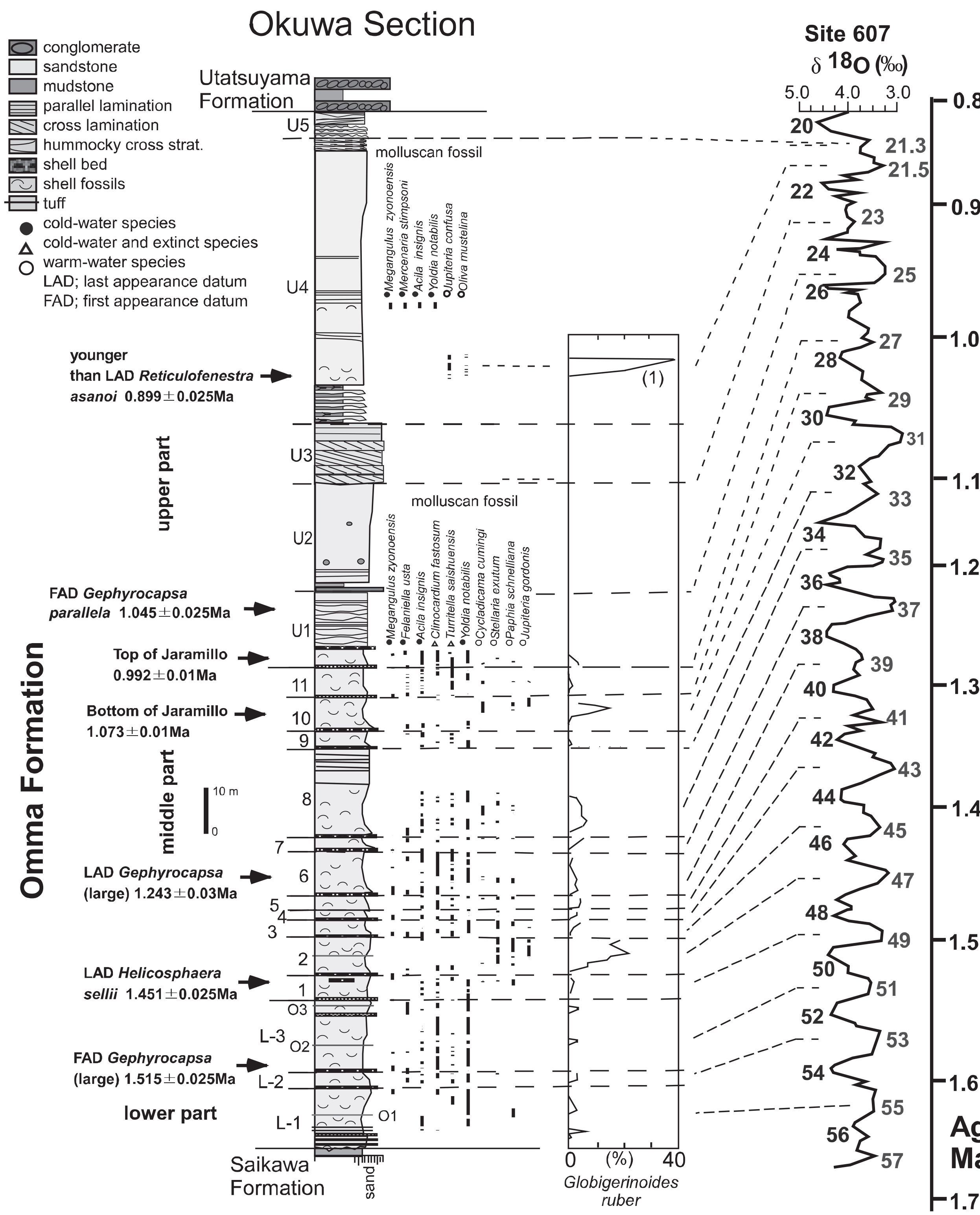
The molluscan fauna changes over time from cold-water, upper-sublittoral species to warm-water, lower-sublittoral species, followed again by cold-water, upper-sublittoral species during the deposition of the depositional sequence. Warm-water species are Indo-Pacific elements that live in the area south of Tsugaru Strait. The cold-water molluscan fauna consists of living and extinct species. Most of living species inhabit in the area north of Tsugaru Strait, while the extinct species are endemic to the Sea of Japan, including *Clinocardium fastosum* and *Turritella saishuensis*. Since fossils records are incomplete, we have not understood the process of extinction of the endemic species.

The systematic nature of changes observed in the molluscan fossil associations within individual depositional sequences indicates that the oceanic conditions changed in parallel with fluctuations in water depth, such that increases in water depth corresponded to periods of warming of the marine climate. Thus it is thought that these changes in water depth and oceanic conditions were related to glacioeustasy with a period of the 41,000 years, corresponding to the period of orbital obliquity [14]. Subsequently, co-workers and I have correlated nineteen depositional sequences with oxygen isotope stages 56 to 21.3, based on a combination of sequence stratigraphic and biostratigraphic and magnetostratigraphic data [16]. The data reveal that the Tsushima Current flowed into the Sea of Japan at every interglacial highstand, except for oxygen isotope stages 25, 23, and 21.3, over the period from 1.6 to 0.8 Ma (MIS 56 to 20) (Fig. 2) [16]. The dissolution of shells means that molluscs and planktonic foraminifer cannot be identified for these stages. Contemporaneous fossil records have not been detected around the Sea of Japan.

The relative abundance of warm-water *Globigerinoides ruber* shows cyclic changes that are consistent with those of warm-water molluscs (Fig. 2). The repeated appearance of warm-water molluscs and *G. ruber* shows that they were introduced into the Sea of Japan with the Tsushima Current and locally died out during succeeding glacial periods [9].

PALEOCEANOGRAPHIC CHANGES WITHIN THE SEA OF JAPAN DURING THE PERIOD BETWEEN 3.5 AND 0.8 MA

Plio-Pleistocene marine sediments are well exposed along the Sea of Japan coast along northeastern Japan. Since these strata contain abundant molluscs and planktonic foraminifera, a number of workers have examined the stratigraphic distributions of these organisms. In order to reconstruct the history of the Tsushima Current in the period before and after the interval represented by fossils within the Omma Formation, I and co-worker compiled fossil records according to the following criteria: 1. the identification of many datum planes; and 2. the existence of data for both molluscs and planktonic foraminifers. Several strata meet these criteria, including the late Pliocene Yabuta Formation and the Plio-Pleistocene Junicho Formation (Fig. 3) [16]. To help fill existing gaps in the data, we are currently adding fossil records from the Omma Formation in Toyama Prefecture, Plio-Pleistocene strata in the Jo-



(1) Takayama et al. (1988)

Fig. 2 Columnar section of the Omma Formation at its type section, showing stratigraphic distribution of selected molluscan fossils and the relative abundance of *Globigerinoides ruber*.

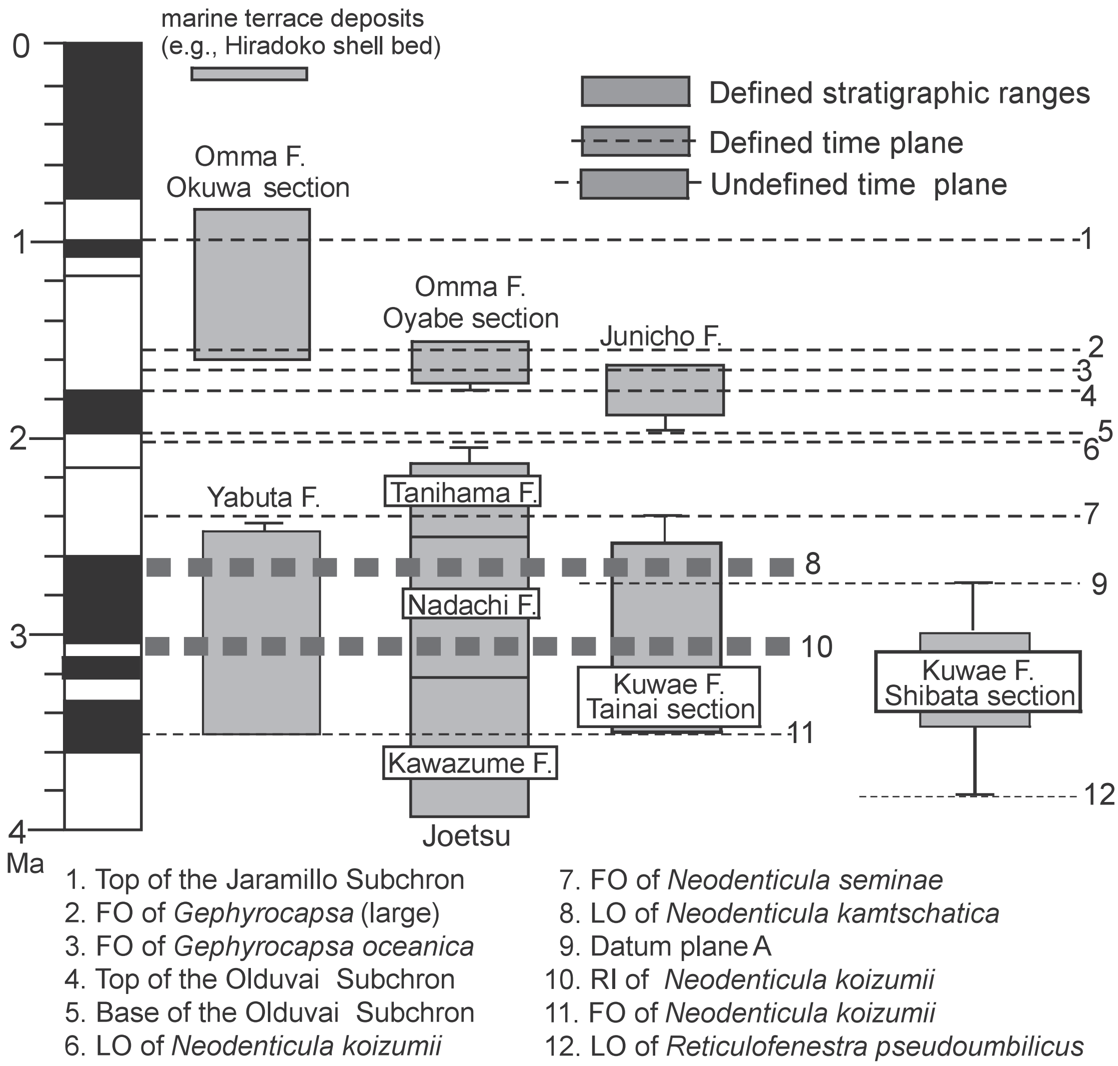


Fig. 3 Correlation of fossil records in the Late Pliocene to Early Pleistocene sediments along the western coast of Honshu Island. Location of fossil records are shown in Fig. 1.

etsu area, and the late Pliocene Kuwae Formation. But we have yet to obtain fossils records over the period from the last occurrence of *Neodenticula koizumi* to the base of the Olduvai Subchron. In addition, marine deposits are not found on land for periods younger than 0.8 Ma, except for marine terrace deposits that formed during the last interglacial period (Fig. 3). Warm-water molluscan fossils are reported from these deposits, indicating that the warm Tsushima Current flowed during oxygen isotope stage 5 [17, 18].

Most of the molluscan species found within the Yabuta, Junicho, and Kuwae Formations are currently living below 150 m water depth within the Sea of Japan [19–22]. Thus, any reconstruction of the inflow of the Tsushima Current depends on the stratigraphic distribution of the warm-water planktonic foraminifer *G. ruber*. The average sampling interval of several thousands to ten thousands years [23–25] is sufficient to detect interglacial to glacial cycles with a period of 41,000 years. However, depositional sequences have not been identified in these formations because of their depth of deposition. In addition, the time intervals between identified datums are in the order of two hundred thousand years (Fig. 3), representing a much lower temporal resolution than that in the Omma Formation.

Fig. 4 shows warm-water fossil records and demonstrates that the history of the warm Tsushima Current in the period between 3.5 and 0.8 Ma can be divided into two intervals. In the interval between 3.5 and 1.71 Ma, the current flowed periodically

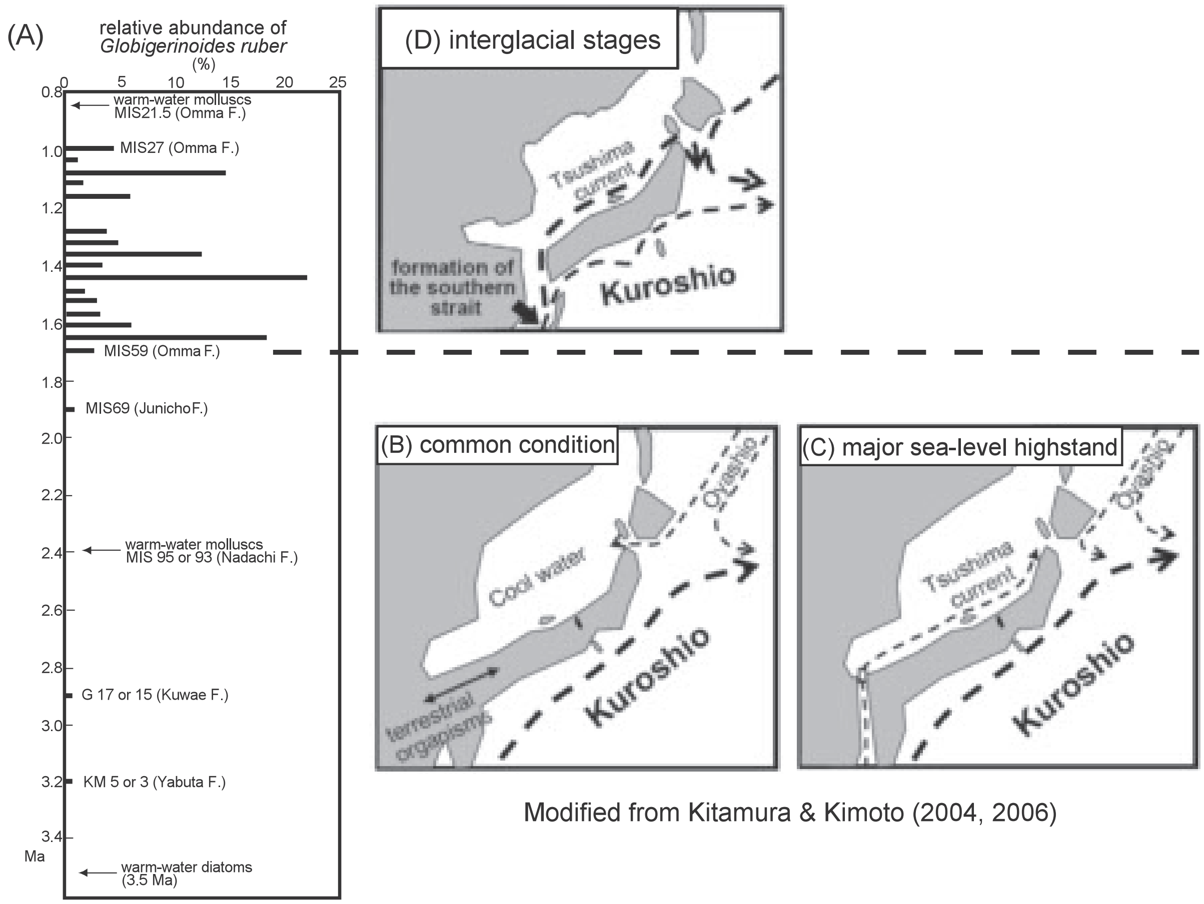


Fig. 4 (A) Stratigraphic distribution of maximum relative abundance of *Globigerinoides ruber* at each interglacial stage. Reconstruction of the southern strait between the Sea of Japan and East China Sea at common condition during 3.5–1.7 Ma (B), major sea-level highstand during 3.5–1.7 Ma (C) and interglacial stages during 1.7–0.8 Ma (D).

into the Sea of Japan at 3.2, 2.9, 2.4, and 1.9 Ma. Comparing these ages with $\delta^{18}O$ stratigraphy, the three older events may correlate with KM5 or 3, G17 or 15 and isotope stages 95 or 93, and isotope stage 69, respectively. During the second interval, between 1.71 and 0.8 Ma, the Tsushima Current flowed into the Sea of Japan at every interglacial highstand, except for MIS 25, 23, and 21.3.

During the Pliocene, between about 4 and 2.7 Ma, many regions of the northern hemisphere experienced a warm climate, including Japan [26–28]. In addition, sea levels during the interglacial periods between 3.3 and 2.5 Ma were up to 50 m higher than the present-day level [29]. Thus, a drastic change in the frequency of inflow of the Tsushima Current occurred with the formation of the southern strait (Fig. 4). This event was caused by crustal stretching in the northern Okinawa Trough associated with a change in the convergence direction of the Philippine Sea plate [9].

CONCLUSIONS

On the basis of the fossil record preserved in marine deposits found in and around the Sea of Japan, the marine environment over the period from 3.5 to 0.8 Ma can be divided into two stages. Before the formation of the southern strait, the sea was only connected to external waters via the northern strait, except for periodic inflows of the Tsushima Current. The sea was cold and relatively stable. Since the formation of the southern strait at 1.7 million years, the environment of the Sea of Japan and organisms within the sea have been strongly influenced by glacial to interglacial cycles and the condition of the southern strait.

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