Late Pliocene–early Pleistocene paleoceanographic evolution of the Sea of Japan

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Paleoceanographic evolution of the Sea of Japan during Quaternary

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Abstract

The stratigraphic distribution and abundance of molluscs and planktonic foraminifera within sixth-order (41-k.y.) depositional sequences of the early Pleistocene Omma Formation at Hokuriku Sedimentary Basin provides precious history of the Sea of Japan since 2.5 Ma. The result shows that paleoceanographic history of the sea is divided into three substages. During substage I (2.5-1.71 Ma (stage 60/59)), cold surface water prevailed in the sea which is due to the closure of the southern channel. During substage II (1.71-1.52 Ma (stage 51)), the warm Tsushima Current flowed into the sea at every interglacial highstands. During substage III (1.52-0 Ma), isolation of the Sea of Japan was reinforced by narrowing and/or shallowing of northern channel. These transitions were caused by local tectonics around southern and northern channels, respectively. 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.

Key words: Sea of Japan, Tsushima Current, Pleistocene, Pliocene, planktonic foraminifera, molluscs, depositional sequence

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. The sea is connected to the East China Sea through the Tsushima Strait, to the Pacific Ocean through the Tsugaru Strait, and to the Sea of Okhotsk through the Soya and Mamiya Straits.

These straits are narrow and shallower than 130 m deep (Fig. 1). At present, the only current flowing into the Sea of Japan is the Tsushima Current. The current, a branch of the warm Kuroshio Current, enters the Sea of Japan through Tsushima Strait and makes its way northward along the western coast of Honshu Island (Fig. 1). The current supplies a large quantity of heat and also transports marine organisms into the Sea of Japan. Moreover, the inflow of the Tsushima Current implies that land organisms of Japan were isolated from those of eastern Asia. Therefore, the current likely had a profound influence on the Quaternary paleoenvironment, ecosystems and evolution of organisms within and around the Sea of Japan (e.g., Yasuda, 1982; Oba et al., 1991; Dunber et al., 1992; Tada, 1994; Kitamura et al., 1994, 1997, 2000b; Ishiwatari et al., 1999, Tada et al., 1999).

The history of the Tsushima Current is examined by the stratigraphic distribution of warm-water species living in the water mass influenced by the warm Kuroshio. Warm-water species intruded into the Sea of Japan with the Tsushima Current and were locally exterminated by the succeeding glacial period. Kitamura (1995, 1997) examined the stratigraphic distribution of warm-water molluscan species from the early Pleistocene Omma Formation. The formation is exposed around Kanazawa City on the Sea of Japan coast of central Japan. Its middle and upper parts at its type section (Okuwa section) are composed of sixth-order (41 k.y.) depositional sequences (Figs. 1 & 2) (Kitamura et al., 1994). These sequences deposited in inner to outer shelf and accumulated during oxygen isotope stages 50 to 26 (Fig. 2). The stratigraphic pattern of warm-water species during the last 1.5 Ma is examined based on compiled fossil records from the Omma Formation, and upper Quaternary sediments at ODP Site 797 in the Sea of Japan (Koizumi, 1992). The result suggested that the Tsushima Current inflowed at all interglacial stages from 1 to 49, except for stage 23. However the history of the current before that time was not clear because of lack of study. Recently, Arai et al. (1998) and Takada (2000) analyzed stratigraphy and planktic foraminiferal assemblages from the latest late Pliocene and early Pleistocene before stage 49 in the Hokuriku Sedimentary Basin. Arai et al. (1998) examined planktic foraminiferal assemblages in two sedimentary cycles of the late Pliocene Junicho Formation, Toyama Prefecture. These cyclothems deposited in outer shelf and were caused by glacio-eustatic sea-level changes during the Olduvai Subchron (Arai et al., 1991). They found one individual of planktonic foraminifera warm-water species *Globigerinoides ruber* from each two horizons in the upper portion of the lower cycle. Whereas, Takada (2000) studied planktic foraminiferal assemblages in five sixth-order (41-k.y.) depositional sequences in the early Pleistocene Omma Formation, Toyama Prefecture (Oyabe section) (Fig. 3). These

sequences are numbered successively from 1 to 5. The first appearance datums of *Gephyrocapsa oceanica* and *Gephyrocapsa* (large) are placed at middle portion of Cycle 2 and the base of Cycle 5, respectively (Fig. 3). Warm-water planktonic foraminifer *Gds. ruber* was recognized from Cycles 1, 2 and 3. Using the first appearance datum of *G.* (large) as datum plane, the Omma Formation at Oyabe section can be correlated to the lower part of the formation at Okuwa section. As a result, Hokuriku Sedimentary Basin contains the most complete and undeformed shallow marine late Pliocene-early Pleistocene records in the Sea of Japan. Therefore, fossil faunas in Plio-Pleistocene provide an excellent record of the Sea of Japan, especially the Tsushima Current. In this paper, we examined lithofacies and fossil record of the lower and middle parts of the Omma Formation and discussed precious history of the Tsushima Current based on recent published data as well as the result of our studies.

2. Geological setting of depositional sequences of the Omma Formation

The Omma Formation at Okuwa section has been divided into lower, middle and upper parts based on its litho- and biofacies (Kitamura & Kondo, 1990). Its middle part is composed of eleven sixth-order (41-k.y.) depositional sequences that were deposited in inner to outer shelf depths during oxygen isotope stages 50 to 28 (Figs. 2 & 4) (Kitamura et al., 1994). These sequences are numbered successively from 1 to 11. Three depositional sequences of the middle part can be identified at Yuhidera area, which is 4 km northeast of Okuwa (Figs. 1 & 5). The sequences include the following architectural elements in ascending stratigraphic order: (1) a basal sequence boundary that is superposed on the ravinement surface; (2) a TST (2-5 m thick) consisting of a basal shell bed (0.3 m thick) (a condensed onlap shellbed) and overlying fine- to very-fine-grained sandstone; (3) a maximum flooding horizon that coincides with the horizon that has the maximum concentration of sand-size carbonate grains; (4) an HST (2-3 m thick) consisting of fine-grained sandstone and sandy siltstone; and (5) an RST (< 1 m thick) comprising fine-grained sandstone with a coarsening-upward trend (Kitamura et al., 2000a). They defined the boundary between the HST and RST as the last appearance datum of warm-water planktonic foraminifera. On the basis of recent distribution of molluscan species, the sequence at Yuhidera was deposited in water a few tens of meters deeper than at Okuwa (Kitamura et al., 1997). Thus the preservation of depositional sequences of Yuhidera is better than that of Okuwa. Within depositional sequences in Okuwa, RST and even HST sediments are obliterated by shoreface erosion at the

superjacent sequence boundary (Figs 4 & 5) (Kitamura et al., 2000a; in press).

The 25 m-thick lower part of the Omma Formation consists mainly of bluish-gray fine- to very fine-grained sandstone with abundant well-preserved molluscan fossils. Recently, the lower unconformity and molluscan fossils record of the basal part of the formation were recognized from new outcrops at Okuwa section (Kitamura, 1997) (Fig. 4). Paleobathymetric change is estimated between 0 m and 100 m based on distributional data of living molluscan species (Kitamura, 1991a, 1997). Although two horizons yielding warm-water molluscan fossils were recognized in the lower part, systematic changes of lithofacies and molluscan fossil assemblages in the middle and upper parts of the Omma Formation were not developed in the lower (Kitamura, 1991a).

3. Stratigraphic distribution of warm-water molluscs and planktonic foraminifera within depositional sequences in the Omma Formation

The inflow of the Tsushima Current was the principal factor affecting the stratigraphic distribution of warm-water molluscs within depositional sequences of the Omma Formation, although water depth and erosion along an upper sequence boundary also influence the stratigraphic distribution of the warm-water molluscs (Kitamura et al., 2000a). According to Kitamura et al. (1999), the rate of increase in depth of the Tsushima Current at the initiation of flow was 17 m ± 9 m per 1,000 years. This means that the greater the water depth on the continental shelf, the later was the migration of warm-water molluscs. In addition, the maximum depth of the Tsushima Current during the formation of depositional sequence 2 (oxygen isotope stage 47) was estimated to be 100 m (Kitamura et al., 1997). This is because small volume of transport of the current due to the narrow and shallow Tsushima Strait. Thus the stratigraphic distribution of warm-water molluscs constitutes a wedge within an individual depositional sequence prior to any shoreface erosion, which occurs during the subsequent transgression (Kitamura et al., 2000a). In summary, even at times when the Tsushima Current flowed into the Sea of Japan, it is possible for warm-water molluscs to be missing from a given depositional sequence on the continental shelf, because of the thinness of the current and erosion at the superjacent boundary.

On the other hand, planktonic foraminifera are strongly controlled by surface sea water temperature. Moreover they are short-lived and respond rapidly to environmental changes, in comparison

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with adult molluscs that are relatively long-lived and may lag behind changes. But coastal water prevents planktonic foraminifera from living. Furthermore microfossils cannot be examined with the unaided eye in the outcrop. Thus combining planktonic and molluscan fossil analyses necessary to elucidate the detailed history of the Tsushima Current from shallow marine record.

4. Methods of study

The stratigraphic distribution and abundance of molluscan fossil in the Omma Formation at both Okuwa and Yuhidera sections have already been analyzed (Kitamura, 1991a, b, 1997; Kitamura et al., 1994, 1997). In addition, the stratigraphic distribution and abundance of planktonic foraminifera in depositional sequence 2 at both sections have previously been studied (Kitamura et al., 1997; 2000a). In the case of depositional sequence II and III of the upper part of the Omma Formation, calcareous fossils occur partly in the former and do not in the latter. Thus planktonic foraminifera studied here occur in 69 samples taken from intervals other than the above three depositional sequences (Fig. 2). These samples were soaked in hot water for one hour and washed using a sieve with 125-□m-diameter openings. The samples were subsequently split into aliquots containing about 200 specimens. All planktonic foraminiferal specimens were picked and identified. Our definition of warm-water species follows that of Takemoto and Oda (1997). In addition, we re-examined lithofacies of the lower part of the Omma Formation at Okuwa.

5. Result

Planktonic foraminifers were recovered in all except for five of 69 samples. Dominant planktonic foraminiferal species are *Globigerina bulloides, Gna. quinqueloba* and *Neogloboquadrina pachyderma* (Appendix 1). Warm-water taxa are dominated by *Globigerinoides ruber* along with a few individuals of *Gds. sacculifer, Orbulina universa* and *Pulleniatina obliquiloculata. Gds. ruber* seems to be the shallowest dwelling species and stay in surface waters during its life cycle (Fairbanks et al., 1982). In addition, among three species *Gds. ruber, Gds. sacculifer* and *O. universa* which temperature tolerances are known, the lower limit of *Gds. ruber* (19℃) is highest (*Gds. sacculifer* and *O. universa* are 14℃ and 12℃, respectively) (e.g., Hemleben et al., 1989). This means that *Gds. ruber* is most suitable

for index of the warm Tsushima Current.

Within all depositional sequence of the middle part of the Omma Formation, warm *Gds. ruber* occurs from the horizons yielding warm-water molluscs and upper part of TST deposit and HST deposit (Figs. 4 & 5). Planktonic foraminiferal abundance ranges between 0 and 200/g, and changes systematically within depositional sequence in the middle part. Abundance minima are placed at the fine-grained sandstone just above the basal shell bed (its base corresponds sequence boundary), whereas abundance peak horizons commonly are placed at or closely near the maximum flooding horizon which is defined as the horizon of the maximum concentration of sand-size biogenic grains (Figs. 4 & 5). Such stratigraphic pattern of planktonic foraminiferal abundance is common in depositional sequence caused by Quaternary glacio-eustasy in temperate regions (e.g., Armentrout, 1996).

Large numbers of *Globorotalia inflata* occur from samples yielding warm-water species in depositional sequences 2, 3 and 5 at Okuwa and in depositional sequences 2, 3 and 4 at Yuhidera, respectively (Figs. 4 & 5). On the basis of ecostratigraphic datums and biogenic grains, Kitamura (1998) shows that the upper portion of depositional sequence 4 at Okuwa was missing by truncation at an upper sequence boundary. Thus, we think that this missing interval causes the difference between two sections in the stratigraphic distribution of *G. inflata*. In summary, the species appeared at every interglacial stages from stage 47 to 41. Furthermore there is a positive correlation in abundance of between *G. inflata* and *Gds. ruber* at the horizon yielding *G. inflata* (R=0.74, F=28.57, d.f. =1, 23, p<0.01) (Fig. 6). This means that the species immigrated through the Tsushima Strait at interglacial highstand of sea-level with *Gds. ruber*. But this species has not been reported from recent Sea of Japan (Ichikura & Ujiié, 1976; Park & Shin, 1998). It lives beneath the transitional zone formed by the convergence of the warm, high-salinity Kuroshio Current and the cold, low-salinity Subarctic water mass in the western North Pacific (Thompson, 1981; Xu & Oda, 1995) and migrates 200 m water depth during life cycle (Hemleben et al., 1989). Thus, we think that absence of *G. inflata* in the Sea of Japan is caused by not water temperature but shallow depth of the Tsushima Strait (130 m). If this interpretation is correct, *G. inflata* can be used as an indicator of existence of the Tsushima Strait that has water depth more than that of recent.

As a result of re-examination, three cyclothems are identified from the lower part of the Omma Formation and numbered successively from L-1 to L-3 (Figs. 2 & 4). The bases of cyclothems represent

either unconformity or shell beds with erosional base. The sediments in cyclothems L-1 and -3 change

upward from fine-grained sandstone through very fine-grained sandstone or siltstone to fine-grained

sandstone. Whereas cyclothem L-2 lacks the upper fine-grained sandstone unit. There are two horizons

yielding warm-water molluscan species within cyclothem L-1. The lower horizon is 0.2 m thick and

contains many articulated shells of warm-water species *Cycladicama cumingi* (Kitamura, 1997), while

many warm-water species (e.g., *Acila divaricata, Limopsis crenata, Paphia schnelliana*) are found from

2 m-thick upper horizon (Kitamura, 1991) (Fig. 4). Within cyclothem L-3, warm-water molluscan species

Clementia vatheleti and *Olivella spretoides* are recognized from the 25-cm thick horizon at 5 m above the

base (Kitamura, 1991). This study found one individual of warm-water *Onustus exutum* from the

uppermost part of cyclothem L-2.

In the lower part planktonic foraminiferal abundance range from 0 to 75/g. Abundance peak

horizons within cyclothems L-2 and -3 correspond to the horizon with warm-water molluscs (Fig. 4).

Warm-water planktonic foram *Gds. ruber* is recognized in all horizons yielding warm-water molluscs

(Fig. 4). *G. inflata* is not observed in the lower part of the Omma Formation (Fig. 4).

6. Discussion

As the result of this study, systematic changes in lithofacies and molluscan and planktonic

foraminiferal assemblages of cyclothems L-2 and -3 in the lower part are very similar to those of

depositional sequences in the middle part of the Omma Formation. According to Takayama et al. (1988),

the first appearance datum of *Gephyrocapsa* (large) which coincides with oxygen isotope stage 51

(1515±25 ka; Berger et al., 1994) is placed just above the basal shell bed of cyclothems L-3 (Fig. 2).

Furthermore, the age of cyclothems L-1 and -2 is younger than the first appearance datum of *G. oceanica*

(1664±25 ka; Berger et al., 1994) (Takayama et al., 1988). These mean that the depositional age of

cyclothem L-3 correlates to oxygen isotope stage 51 to 50 and the duration of deposition of the lower two

cyclothems is less than 150,000 yrs. Thus, it is certain that the cyclothem L-3 is a sixth-order (41-k.y.)

depositional sequence. We also interpreted that cyclothem L-2 is same order depositional sequence,

which its upper part (the all most horizon yielding warm-water molluscs) was obliterated by shoreface

erosion at the superjacent sequence boundary (Figs. 2 & 4).

It is noteworthy that cyclothems L-1 has two horizons yielding warm-water molluscs and planktonic foraminiferal species. Since there are not any significant changes in sediment and foraminiferal abundance between two horizons, we think that sedimentary rate was not different during the deposition of between two horizons. If so, duration of warm period of the upper horizon was ten times as much as that of lower horizon. From these, we regard cyclothem L-1 as sixth-order depositional sequence and believe that relatively short warming phase may be caused by millennial scale climatic change during the early Pleistocene (Raymo et al., 1998). If this interpretation is correct, the lowest cyclothems of the lower part are correlated to oxygen isotope stages 56 to 54 (Fig. 2).

As mentioned above, five sixth-order (41-k.y.) depositional sequences are recognized in the early Pleistocene Omma Formation at Oyabe section (Fig. 3). The upper part of cycle 5 consists of brownish fine-grained sandstone and does not yield any calcareous materials such as molluscs and others. Warm-water planktonic foraminifer *Gds. ruber* and *G. inflata* were recognized from Cycles 1, 2 and 3, and Cycles, respectively (Appendix 2) (Fig. 3). The first appearance datums of *G. oceanica* and *G.* (large) are placed at the middle portion of Cycle 2 and the base of Cycle 5, respectively (Fig. 3). Thus, three cyclothems of the lower part of the Omma Formation at Okuwa correlate with Cycle 3 to 5 at Oyabe area (Fig. 3). From this, the absence of warm-water planktonic foraminifera in Cycles 4 and 5 at Oyabe is explained by missing horizons that would have yielded them due to erosion. Our result shows that warm-water organisms appeared at interglacial periods since the first appearance datum of *G. oceanic* (oxygen isotope stage 59).

Many works have dealt with molluscs and planktonic foraminifer of sediment (outer shelf to 911 m) between 1.66 and 2.5 Ma (e.g., Hasegawa, 1979; Morizumi & Ishigaki, 1981; Takayama et al., 1988; Sato et al., 1988; Kheradyar, 1992; Koizumi, 1992; Cronin et al., 1994; Arai et al., 1991, 1997, 1998; Takada, 2000). There are only two records of occurrence of warm-water diatom and planktonic foraminifera. Two individuals of *Gds. ruber* are found from 0.5 m-thick horizon during Olduvai Subchron in the Junicho Formation that have been deposited on the outer shelf (Arai et al., 1998). On the other hand, warm-water diatom was recognized from at least three horizons (Koizumi, 1992). However, there is a serious problem about warm-water diatom as an indicator of the Tsushima Current, because it was identified from the sediment during the later part of stage 2 (Tada et al., 1999). According to

Ishiwatari et al. (1999), the alkenone-based sea-surface temperature measured in sediment cores from the Oki Ridge shows 18°Cat 17.5 ka. This temperature was similar to that of recent (19°C) and might have been caused by a stable stratification of the water column due to input of fresh water. We think that such warming of surface water led proliferation of warm-water diatom that was relict of the previous warm interglacial periods. By contrast, warm-water planktonic foraminifer and molluscs were not reported from sediments during last glacial periods (e.g., Habe & Kosuge, 1970; Emery et al., 1971; Oba et al., 1991). From these, we believe that warm-water planktonic foraminifer and mollusks are better proxies for the Tsushima Current than diatom. In summary, the current flowed episodically before stage 60, and then at every interglacial stage.

There is not significant difference in $\Box^{18}$O values of interglacial stages between before and after stage 59 (Ruddiman et al., 1989; Shackleton et al., 1990; Berger et al., 1994). When oxygen isotope record is regarded as a proxy of glacial eustatic sea level record (e.g., Chappell et al., 1996), there is not a significant difference in sea-level at interglacial stages between both periods. Thus we think that deepening and/or widening of the Tsushima Strait due to local tectonism caused the onset of cyclic inflow of the Tsushima Current. According to Kamata and Kodama (1999), crustal stretching has occurred in the northern Okinawa Trough since 2 Ma. This event was caused by a change in the convergence direction of the Philippine Sea plate. On the basis of timing and nature, we assume that this event led to deepening and/or widening of the Tsushima Strait. The onset of inflow of the Tsushima Current indicates that land organisms of Japan were isolated from those of Asia during at least interglacial sea-level highstands since oxygen isotope stage 59 (*ca.* 1.7Ma). This increase of geographical heterogeneity might have contributed high species diversity of temperate plants in eastern Asia   (Qian & Ricklefs, 2000).

Dunber et al. (1992) presented that increasing tectonic isolation of the Sea of Japan took place at 1.3 Ma based on variation in biogenic opal content of sediment from ODP Site 798 (911 m deep). This age was estimated by using of the last appearance datums of *Helicosphaera sellii* (1.20 Ma) and top of Olduvai event (1.66 Ma). Also Tada (1994) noted that it started oscillating between oxic and anoxic from 2.5 to 1.2 Ma and between highly oxic and euxinic from 1.2 Ma to present of bottom water condition of the Sea of Japan. His estimation (1.2 Ma) is based on the first appearance datums of *G. oceanica* (1.35 Ma) and base of Jaramillo event (0.98 Ma) in ODP Site 797 (2862 m deep). In terms of ages of

stratigraphic datums presented by Berger et al. (1994), the above ages are calculated as 1.52 Ma (1.3 Ma;

Dunber et al., 1992) and 1.42 Ma (1.2 Ma; Tada, 1994), respectively. The difference in ages may be

caused by uncertainty of stratigraphic distribution of datum plains, because many dissolved zones of

calcareous fossils are recognized in Pleistocene sediments from both sites (Kheradyar, 1992; Tada et al.,

1992). This is caused by fluctuation of the CCD related to glacial-eustatic sea-level changes (Oba et al.,

1991; Tada, 1994). The greater the water depth, the larger was the influence of fluctuation of the CCD.

Thus, we think reinforcement of isolation of the Sea of Japan took place around 1.52 Ma (stage 51)

presented by Dunber et al. (1992). Tada (1994) implied that this event (step up of isolation) probably was

related with narrowing and/or shallowing of northern channel. Our result strongly supports this

interpretation, because *Globorotalia inflata* could intrude into the Sea of Japan from oxygen isotope stage

47 to 41 (Figs. 4 & 5).

Tada (1994) concluded that paleoceanographic evolution of the Sea of Japan since 18 Ma was it

divided into five stages. During the youngest Stage 5 (2.5-0 Ma), surface water conditions within the sea

fluctuated between warm and cold, the bottom water oxygenation level fluctuated between hyperoxic and

euxinic. Our results show that Stage 5 is subdivided into three substages. During substage I (2.5-1.71 Ma

(stage 60/59)), cold surface water prevailed in the Sea of Japan which is due to the closure of the southern

channel (Fig. 7). Cold-water organisms lived in the sea, whereas land organisms came and went between

Asia and Japan. This oceanic condition was exactly same as Stage 4 presented by Tada (1994), except for

effect of glacio-eustatic sea level oscillation which started approximately at 2.5 Ma. During substage II

(1.71-1.52 Ma (stage 51)), the Tsushima Current flowed into the sea at the interglacial highstands (Fig.

7). This was caused by opening of the Tsushima Strait due to crustal stretching in the northern Okinawa

Trough. Since the northern channel was wide and/or deep during this substage, the almost all of the

current probably flowed out through the northern channel to the Northwestern Pacific Ocean.

Warm-water organisms intruded into the sea during interglacial periods and were extirpated at the

following glacial period. The opening of the Tsushima Strait produced geographic isolation and provided

more abundant opportunities for diversification of land organisms of Japanese. During substage III

(1.52-0 Ma), the Tsushima Current continuously flowed into the sea at the interglacial highstands, while

narrowing and/or shallowing of northern channel reinforced isolation of the Sea of Japan (Fig. 7). The

decrease of outflow of the Tsushima Current to Pacific probably increased the production of the Japan

Sea Proper Water that ventilated the deeper part of the sea. Consequently, the oxidation level of deep sea at interglacial stages during the substage III was higher than those during the older substages. From the stratigraphic distribution of *G. inflata*, the depth of the Tsushima Strait shoaled after oxygen isotope stage 41 (1.3Ma).

Kawamura (1998) interpreted that the land bridge emerged around 1.2-1.0 Ma from the appearance of elephant species *Mammuthus shigensis* in Japan. Considering incompleteness of fossil record of land mammals, the formation of the land bridge well synchronized with the shoaling of the Tsushima Current inferred from stratigraphic distribution of *G. inflata*. Configuration of land around eastern Asia and Japan during 2.0-1.2 Ma is hotly debated. Kawamura (1998) noted that land bridge did not exist based on elephant fossils, while Koizumi (2000) presented that the land bridge was formed around Plio-Pleistocene boundary based on canine fossils. Our results provide insights into explain this contradiction. The diversifications and extinctions of land organisms of Japanese Islands were strongly influenced by formation and shoaling of the Tsushima Strait at 1.7 and 1.3 Ma, respectively.

Conclusions

High-resolution analyses of lithofacies, molluscan fossils and planktonic foraminifera of the Plio-Pleistocene in Hokuriku Sedimentary Basin split paleoceanographic history of the Sea of Japan since 2.5 Ma (Stage 1 presented by Tada (1994)) into three substages. During substage I (2.5-1.71 Ma (stage 60/59)), cold surface water prevailed in the Sea of Japan which is due to the closure of the southern channel. During substage II (1.71-1.52 Ma (stage 51)), the Tsushima Current flowed into the sea at every interglacial highstand. During substage III (1.52-0 Ma), isolation of the Sea of Japan was reinforced by narrowing and/or shallowing of northern channel. These transitions were due to local tectonics around southern and northern channels and brought geographical heterogeneity of eastern Asia. The episodes caused significant changes in not only paleoenvironment but also geographic distribution and biodiversity of both land and marine organisms within and around Sea of Japan.

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Fig. 1 Map of the Sea of Japan and geologic map of the Omma Formation around Kanazawa City, Central Japan, modified from Imai (1959).

Fig. 2   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 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, I-III: depositional sequence numbers.

Fig. 3 Columnar section of the Omma Formation at Oyabe section, showing stratigraphic distribution of planktonic foraminifera warm-water species *Globigerinoides ruber* and *Globorotalia inflata* and correlation with lower part of the Omma Formation at Okuwa section. Geologic map of the Omma Formation around Oyabe is modified from Sumi et al. (1989).

Fig. 4   Stratigraphic distribution of planktonic foraminifera warm-water species *Globigerinoides ruber*, *Globolotaria inflata* biogenic grains and mud content of the Omma Formation at Okuwa section.

Fig. 5   Stratigraphic distribution of planktonic foraminifera warm-water species *Globigerinoides ruber*, *Globolotaria inflata*, biogenic grains and mud content of the Omma Formation at Yuhidera section.

Fig. 6   Correlation of abundance of *Globolotaria inflata* with abundance of *Globigerinoides ruber* at the horizon yielding *G. inflata*. R=Pearsons's correlation coefficient.

Fig. 7   Paleoceanographic history of the Sea of Japan since 2.5 Ma.

Appendix 1 Planktic foraminifera identified at studied section of early Pleistocene Omma Formation.

overlying formations
Omma Formation
underlying formations

Fig. 1

Fig. 2

Fig. 3

← Horizon yielding warm-water molluscan species *Clementia vatheleti* and *Olivella spretoides*
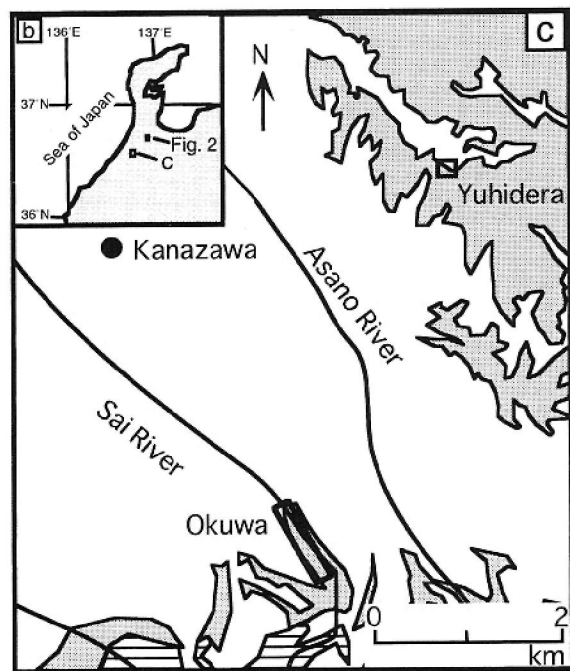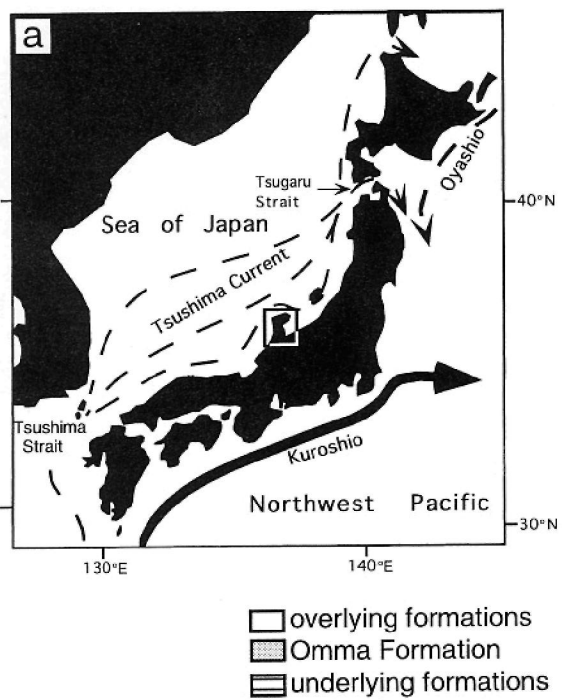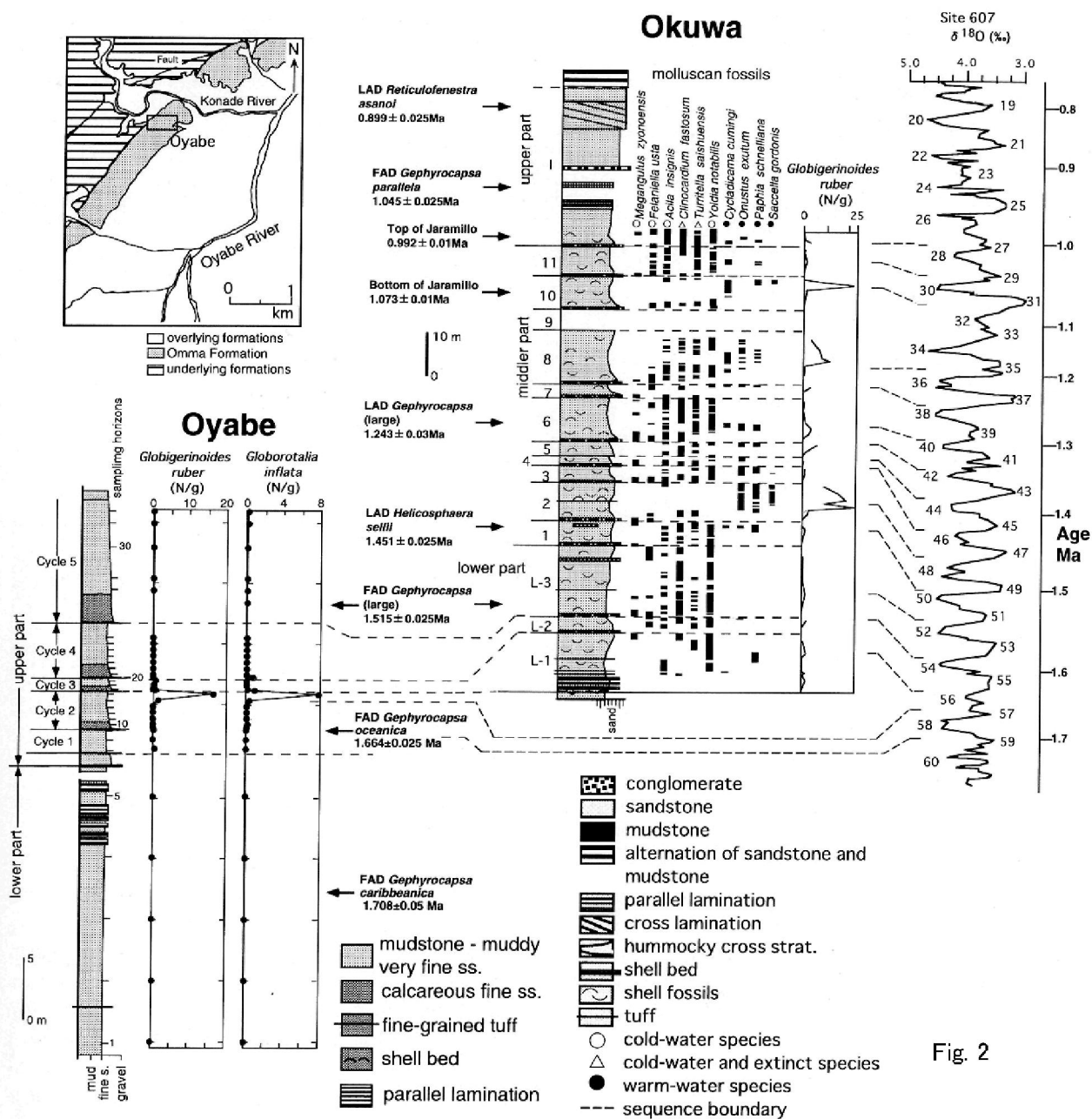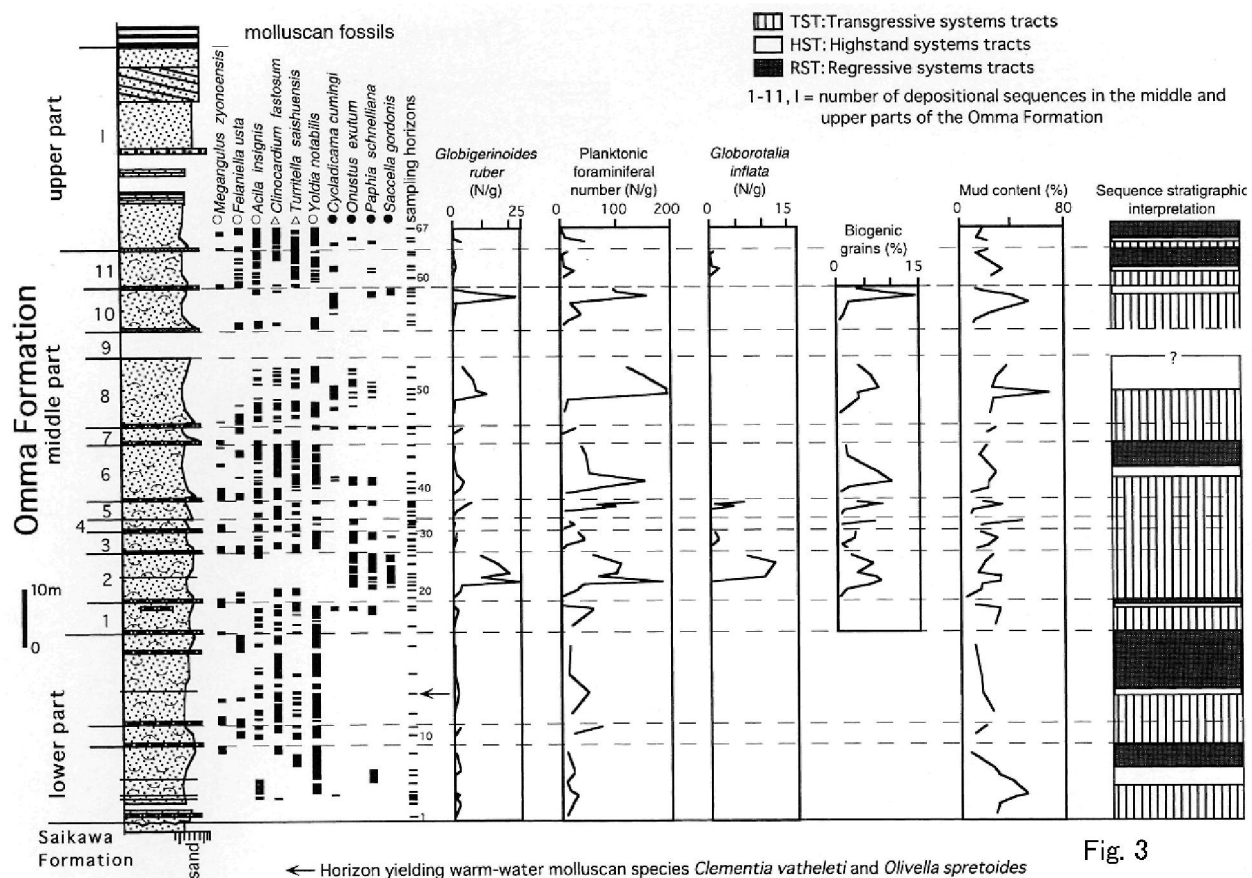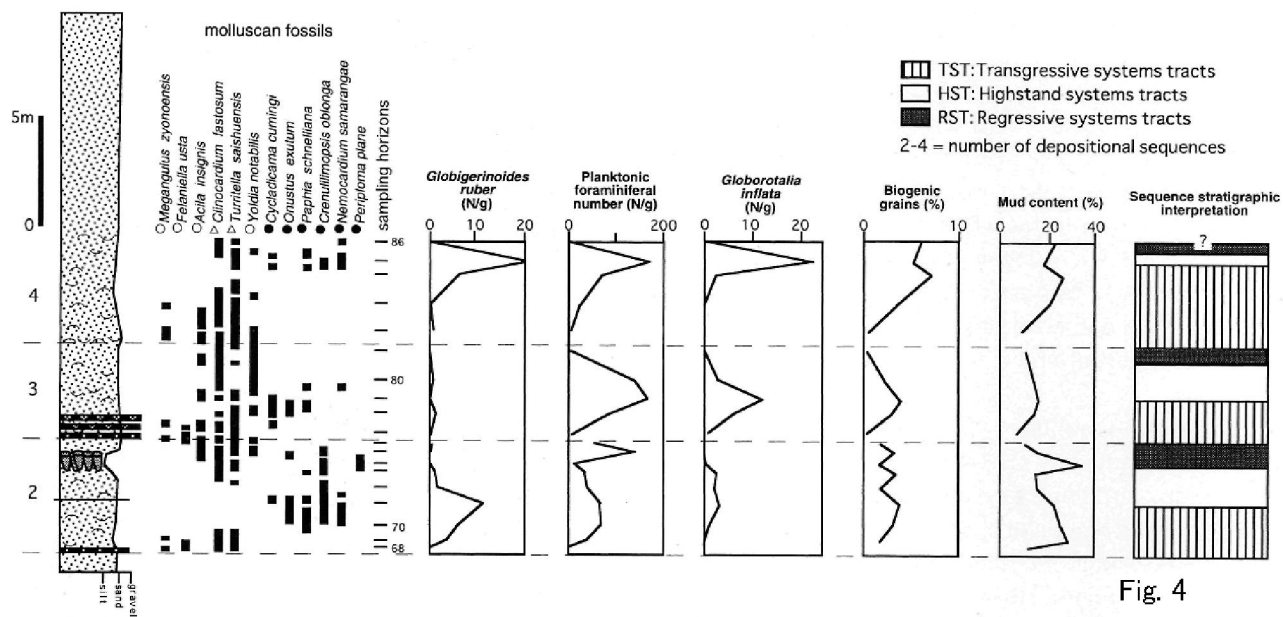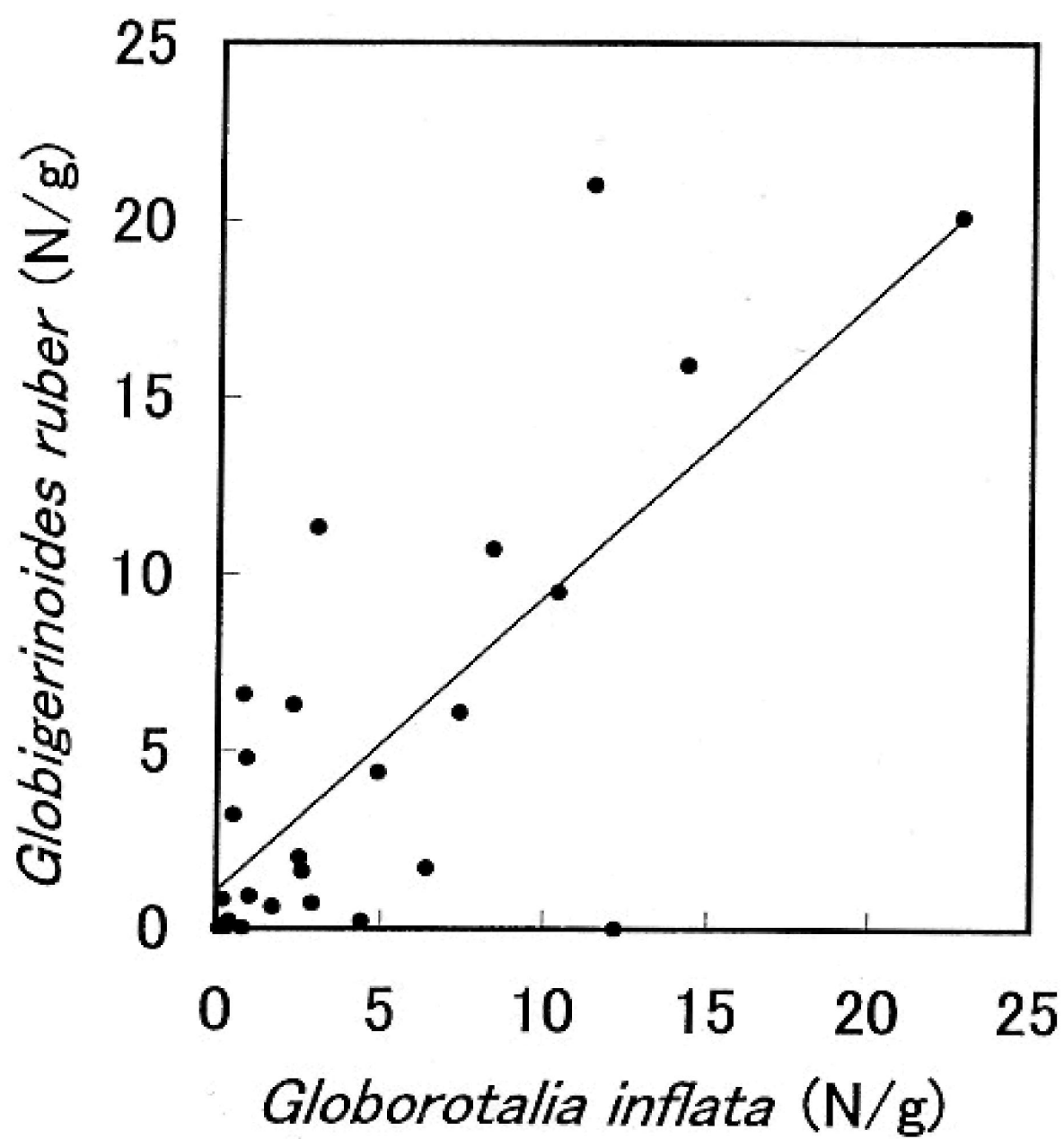
Fig. 4

Fig. 5

Substage I 2.5-1.7 Ma
Interglacial stage
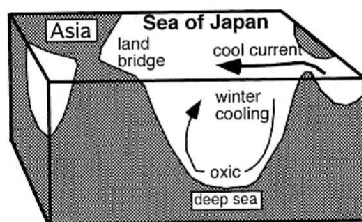
Land organisms migrated
between East Asia and Japan

Substage II 1.7 -1.5 Ma
Interglacial stage

Opening of the Tsushima Strait

Intrusion of warm organisims into the sea,
isolation of land organisms in Japanese Islands

Substage III 1.5-0 Ma
Interglacial stage

Narrowing and/or shallowing of
the northern strait

Reinforce of isolation of the sea

Fig. 6

Appendix 1

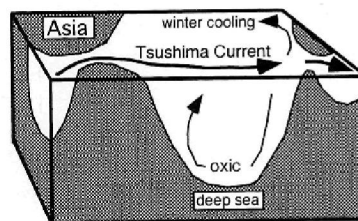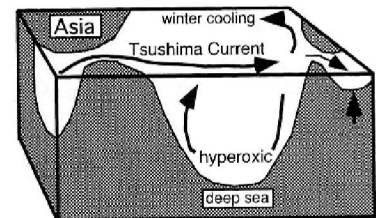| Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19*	20*	21*	22*	23*	24
Locality	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuw
Part	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	lower	middle	middle	middle	middle	middle	middle	middle	middle	midd
Cycle	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	1	1	1	2	2	2	2	2	
mud content (%)	27.1	30.9	41.7	44.0	51.4	37.3	28.6	24.6	7.3	11.7	17.8	23.1	17.4	15.5	10.7	27.3	30.4	12.5	6.0	16.0	16.0	30.0	30.0	14
Globigerina bulloides	2	46	28	22	35	3	15	13	3	29	43	13	78	3	25	95	76	1	0	48	60	66	42	8
Globigerina woodi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Globigerina quinqueloba	0	0	0	0	0	0	0	0	0	1	2	1	2	0	0	18	63	0	0	65	106	61	72	3
Globigerina glutinata	0	0	0	0	0	0	0	0	0	0	1	1	2	0	0	1	1	0	0	5	21	34	14	
Globigerinoides ruber	0	1	0	3	0	0	0	2	0	2	0	0	3	0	2	0	5	0	0	9	14	27	33	8
Globigerinoides sacculifer	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0
Globigerinoides tenellus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Globigerinoides sp.	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
Neogloboquadrina pachyderma	0	5	9	8	8	7	15	17	2	0	4	2	8	0	1	5	59	0	0	0	0	0	0	
Neogloboquadrina pachyderma (s.)	0	5	6	7	6	7	11	14	2	0	1	0	1	0	0	4	34	0	0	0	0	0	0	
Neogloboquadrina pachyderma (d.)	0	0	3	1	2	0	4	3	0	0	3	2	7	0	1	1	25	0	0	0	0	0	0	
Neogloboquadrina dutertrei	0	0	1	0	0	0	1	1	0	0	3	1	2	0	1	2	0	0	0	5	4	4	2	
Neogloboquadrina incompta	0	0	0	0	0	0	2	0	0	0	1	0	3	1	0	0	0	0	0	4	14	4	9	2
Orbulina universa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Globorotalia inflata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	3
Pulleniatina obliquiloculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
others	0	13	23	18	16	9	32	40	1	4	27	3	36	8	33	64	136	0	0	11	10	12	14	2
Total	2	65	61	51	59	20	65	73	6	36	85	21	134	12	62	185	340	1	0	147	229	210	222	26
Number of planktonic foraminifera (N./g)	1	15	19	12.4	9	4	12	12	6	21	75	5	44.7	7	13	19	57.6	0.4	0	31	43.2	186	64	9
Number of *Gds. ruber* (N./g)	0.0	0.2	0.0	0.7	0.0	0.0	0.0	0.3	0.0	1.2	1.8	0.0	1.0	0.0	0.4	0.0	0.8	0.0	0.0	1.9	2.6	23.9	9.5	21
Number of *G. inflata* (N./g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.4	11

Sample number	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Locality	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuw
Part	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	midd
Cycle	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	7	8	8	8	8	8	8	10	
mud content (%)	13.9	25.6	45.6	7.9	8.2	24.2	28.7	19.0	7.5	21.2	21.8	25.4	15.0	19.1	20.7	25.6	23.7	26.5	67.8	25.7	29.0	35.1	12.0	13
Globigerina bulloides	7	97	66	2	7	136	75	123	5	99	127	88	105	95	0	5	12	9	93	65	33	21	7	4
Globigerina woodi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	
Globigerina quinqueloba	2	1	18	0	2	27	26	14	0	15	23	28	12	16	0	0	2	5	13	6	18	8	5	
Globigerina glutinata	0	3	4	0	0	6	9	0	0	18	8	27	2	0	0	0	0	6	0	0	0	0	0	
Globigerinoides ruber	0	4	4	0	0	10	11	10	0	7	7	9	0	1	0	6	1	4	18	10	9	4	0	
Globigerinoides sacculifer	1	0	0	0	0	1	1	2	0	0	2	0	0	0	0	0	0	0	1	1	0	0	0	
Globigerinoides tenellus	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	
Globigerinoides sp.	0	0	1	0	0	1	0	3	0	0	4	0	0	0	0	0	0	0	1	0	1	1	0	
Neogloboquadrina pachyderma	1	16	15	2	1	11	10	26	3	14	24	29	39	27	0	19	11	19	37	34	57	44	1	
Neogloboquadrina pachyderma (s.)	0	8	0	0	1	5	8	14	3	10	15	20	31	13	0	16	9	18	29	26	44	38	1	
Neogloboquadrina pachyderma (d.)	1	8	0	2	0	6	2	12	0	4	9	9	8	14	0	3	2	1	8	8	13	6	0	
Neogloboquadrina dutertrei	0	0	1	0	0	0	4	2	0	1	2	0	0	2	0	4	0	0	7	10	0	2	0	
Neogloboquadrina incompta	0	1	4	0	1	1	1	2	0	0	0	1	0	2	0	0	0	0	2	5	0	0	2	6
Orbulina universa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	
Globorotalia inflata	0	0	0	0	0	11	2	12	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	
Pulleniatina obliquiloculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
others	2	46	78	0	2	79	107	41	2	49	135	97	98	69	0	16	23	35	123	111	99	82	3	
Total	13	168	191	4	13	283	248	235	10	203	333	279	256	212	0	50	49	24	304	244	217	162	22	18
Number of planktonic foraminifera (N./g)	2	15	12	2	2	126	108	144	4	68	152	47	45	36	0	19	1	5	200	195	174	130	4	
Number of *Gds. ruber* (N./g)	0.0	0.4	0.3	0.0	0.0	4.4	4.8	6.1	0.0	2.3	3.2	1.5	0.0	0.2	0.0	2.3	0.0	0.8	11.8	8.0	7.2	3.2	0.0	0
Number of *G. inflata* (N./g)	0.0	0.0	0.0	0.0	0.0	4.9	0.9	7.4	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0

Appendix 1

Sample number	61	62	63	64	65	66	67	68**	69**	70**	71**	72**	73**	74**	75**	76**	77	78	79	80	81	82	83
Locality	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Okuwa	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera	Yuhidera
Part	middle	middle	middle	middle	upper	upper	upper	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle	middle
Cycle	11	11	11	11	l	l	l	2	2	2	2	2	2	2	2	2	3	3	3	3	3	4	4
mud content (%)	32.9	28.8	14.3	21.4	23.5	15.0	18.3	12.0	28.0	24.0	23.0	16.0	15.0	34.0	16.0	11.0	7.0	14.0	16.0	14.0	11.0	9.0	21.2
Globigerina bulloides	9	0	0	1	10	24	1	0	73	69	65	68	79	140	149	200	55	72	41	78	7	15	62
Globigerina woodi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerina quinqueloba	5	2	1	0	5	17	1	0	58	77	53	120	126	71	77	41	6	5	9	7	0	1	2
Globigerina glutinata	3	0	0	0	0	1	0	0	0	24	0	2	2	1	1	0	2	1	7	0	0	2	2
Globigerinoides ruber	1	1	0	0	5	8	0	0	32	24	61	13	16	0	0	2	0	4	0	1	0	3	0
Globigerinoides sacculifer	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinoides tenellus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerinoides sp.	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neogloboquadrina pachyderma	14	4	1	2	10	19	2	0	0	0	1	0	0	0	0	0	5	62	17	25	0	6	6
Neogloboquadrina pachyderma (s.)	9	3	1	2	7	10	0	0	0	0	0	0	3	10	2	2	2	45	4	10	0	3	2
Neogloboquadrina pachyderma (d.)	5	1	0	0	3	9	2	0	0	1	1	0	4	5	22	5	3	17	13	15	0	3	4
Neogloboquadrina dutertrei	1	1	0	1	3	1	0	0	0	48	0	8	38	72	284	32	0	1	0	0	0	2	0
Neogloboquadrina incompta	0	0	1	1	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Orbulina universa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globorotalia inflata	22	2	0	1	0	0	0	0	3	16	16	26	1	0	0	2	15	10	4	0	0	0	0
Pulleniatina obliquiloculata	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
others	71	12	1	4	64	113	3	0	131	18	114	32	46	18	66	19	29	49	50	67	1	21	38
Total	126	22	4	10	118	198	7	0	294	263	312	260	333	303	577	294	75	209	134	182	8	51	110
Number of planktonic foraminifera (N./g)	25	4	3	8	49	8.8	1	0	39	72	58	40	33	17	140	60.7	10	90	164	132	2	10	27
Number of *Gds. ruber* (N./g)	0.2	0.2	0.0	0.0	2.1	0.4	0.0	0.0	4.2	6.6	11.3	2.0	1.6	0.0	0.0	0.4	0.0	1.7	0.0	0.7	0.0	0.6	0.0
Number of *G. inflata* (N./g)	4.4	0.4	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.8	3.0	2.5	2.6	0.1	0.0	0.0	0.3	6.4	12.2	2.9	0.0	0.0	0.0

Planktic foraminifera identified at studied section of early Pleistocene Omma Formation at the Oyabe section.

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Part	Lower	Lower	Lower	Lower	Lower	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper
Cycle						1	1	1	2	2	2	2	2	2	2	3
G. bulloides	38	12	49	91	73	107	60	78	225	72	38	25	96	90	79	80
G. quinqueloba	24	26	10	8	4	12	12	17	34	18	8	15	26	29	45	29
G. cf. quinqueloba	0	0	0	8	0	7	2	7	8	0	5	3	11	5	5	3
N. pachyderma	7	4	1	1	0	4	0	7	50	26	18	22	18	22	42	36
N. incompta	20	19	22	19	14	13	9	36	30	23	16	13	21	46	34	13
N. dutertrei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
N kagaensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
G. ruber	0	0	0	0	0	2	0	1	0	0	0	0	0	5	59	9
G. inflata	0	0	0	0	0	0	1	0	0	1	0	0	0	1	28	11
G. uvula	1	0	0	1	2	1	1	0	1	3	2	1	5	5	4	2
sp. indet.	0	0	0	0	0	0	0	0	2	1	4	2	1	0	4	2
Total	90	61	82	120	93	146	84	146	350	144	91	81	178	203	306	185
Number of planktonic foraminifera (N/g)	10.5	40.4	48.5	10.8	8.8	41.5	71.1	40.9	26.1	9.0	24.6	16.5	86.5	56.3	85.9	13.7
Number of G. ruber (N/g)	0	0	0	0	0	0.6	0	0.3	0	0	0	0	0	1.4	16.6306	0.7
Number of G. inflata (N/g)	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.3	7.9	0.8

Sample number	17	18	19[a]	20	21	22	23	24	25	26	27	28	29	30	31	32
Part	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper	Upper
Cycle	3	3	3	4	4	4	4	4	4	4	5	5	5	5	5	5
G. bulloides	51	36	100	119	116	100	132	128	107	143	52	74	70	80	33	54
G. quinqueloba	11	4	38	14	21	15	32	71	42	92	10	37	24	14	16	10
G. cf. quinqueloba	5	7	5	2	5	2	5	2	6	1	4	10	5	0	0	0
N. pachyderma	12	10	15	23	18	22	23	54	35	22	26	32	20	3	4	8
N. incompta	16	12	33	41	61	38	46	33	33	62	8	59	37	20	30	35
N. dutertrei	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
N. kagaensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G. ruber	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
G. inflata	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
G. uvula	1	2	1	1	1	1	4	7	0	1	1	5	2	0	1	2
sp. indet.	0	0	0	0	0	1	0	0	0	1	0	0	11	0	0	6
Total	97	72	193	202	222	179	242	295	223	322	102	217	169	117	85	116
Number of planktonic foraminifera (N/g)	13.2	19.4	157.3	135.5	363.7	412.9	203.9	247.6	244.7	1030.4	37.1	98.5	150.2	15.6	11.3	7.7
Number of G. ruber (N/g)	0	0.3	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of G. inflata (N/g)	0.1	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0.1	0.1

Appendix B