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Abstract: There is a continuous record of planktonic foraminifers for oxygen isotope stages 50 to 26 (ca. 1.5-1.0 Ma) in the early Pleistocene Omma Formation near Kanazawa City, central Japan, on the Sea of Japan coast. The warm-water species Globigerinoides ruber entered the Sea of Japan with the Tsushima Current during all interglacial periods and went locally extinct in the succeeding glacial periods. This implies that the marine climate of the Sea of Japan varied predominantly with the 41,000-year period of Earth's orbital obliquity. However, the relative abundances of Gds. ruber in marine isotope stages 47, 43 and 31 are significantly higher than those in other interglacial stages. These stages correspond to periods when eccentricity-modulated precession extremes were aligned with obliquity maxima. The Tsushima Current is a branch of the warm Kuroshio Current which is the strong northwestern component of the subtropical North Pacific Ocean gyre. Our data imply that the early Pleistocene climate in the northwestern Pacific was influenced not only by obliquity cycles but also by eccentricity cycles. This study also supports the climate model regarding eccentricity's role in the origin of low-frequency climate changes before the Late Pleistocene ice ages.

Editorial Office March 17, 2006

GLOBAL AND PLANETARY CHANGE

Dear Sir,

I sent the manuscript of a paper entitled "Eccentricity cycles shown by early Pleistocene planktonic foraminifers of the Omma Formation, Sea of Japan" by Katsunori Kimoto and myself. The manuscript consists of 16 pages of text, 4 figures and 1 page of captions of figures. Based on a continuous record of planktonic foraminifers for oxygen isotope stages 50 to 26 in the Omma Formation on the Sea of Japan coast, central Japan, I and colleagues presented that the early Pleistocene marine climate of the Sea of Japan varied predominantly with the 41,000-year period of Earth's orbital obliquity. However, the relative abundances of *Gds. ruber* in marine isotope stages 47, 43 and 31 are significantly higher than those in other interglacial stages. These stages correspond to periods when eccentricity-modulated precession extremes were aligned with obliquity maxima. The Tsushima Current is a branch of the warm Kuroshio Current which is the strong northwestern component of the subtropical North Pacific Ocean gyre. Our data imply that the early Pleistocene climate in the northwestern Pacific was influenced not only by obliquity cycles but also by eccentricity cycles. This study also supports the climate model regarding eccentricity's role in the origin of low-frequency climate changes before the Late Pleistocene ice ages.

We would be grateful if the manuscript could be reviewed and considered for publication in Global and Planetary Change.

Sincerely yours,

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Eccentricity cycles shown by early Pleistocene planktonic foraminifers of the Omma Formation, Sea of Japan

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ABSTRACT

There is a continuous record of planktonic foraminifers for oxygen isotope stages 50 to 26 (ca. 1.5-1.0 Ma) in the early Pleistocene Omma Formation near Kanazawa City, central Japan, on the Sea of Japan coast. The warm-water species *Globigerinoides ruber* entered the Sea of Japan with the Tsushima Current during all interglacial periods and went locally extinct in the succeeding glacial periods. This implies that the marine climate of the Sea of Japan varied predominantly with the 41,000-year period of Earth's orbital obliquity. However, the relative abundances of *Gds. ruber* in marine isotope stages 47, 43 and 31 are significantly higher than those in other interglacial stages. These stages correspond to periods when eccentricity-modulated precession extremes were aligned with obliquity maxima. The Tsushima Current is a branch of the warm Kuroshio Current which is the strong northwestern component of the subtropical North Pacific Ocean gyre. Our data imply that the early Pleistocene climate in the northwestern Pacific was influenced not only by obliquity cycles but also by eccentricity cycles. This study also supports the climate model regarding eccentricity's role in the origin of low-frequency climate changes before the Late Pleistocene ice ages.

Key words; marine climate; Sea of Japan; early Pleistocene; eccentricity

1. Introduction

It is widely known that earth's climate predominantly varied with the 100-kyr period of eccentricity after 0.9-0.8 Ma (Shackleton and Opdyke, 1973). The relatively weak signal of the 100-kyr cycle is even detectable in benthic oxygen isotope records of the early Pleistocene, when Earth's climate predominantly varied with the 41-kyr period of obliquity (Shackleton and Opdyke, 1976; Pisias and Moore, 1981; Ruddiman et al., 1986a, b; Raymo and Nisancioglu, 2003). According to Clemens and Tiedemann (1997), a cross-spectral comparison of Site 659 benthic $\delta^{18}O$ (eastern subtropical Atlantic) and truncated insolation (July 65°N) for 1.2-5.2 Ma shows significant coherence for the 124- and 95-kyr periods. They suggested that the low-frequency oxygen isotope cycles originate through an asymmetrical response mechanism that preferentially introduced variance into the climate system from the warmer portions of the eccentricity-modulated precession cycle. Based on their work, the Earth's climate during the early Pleistocene, especially in interglacial periods, was influenced by the eccentricity-modulated precession cycle.

Changes in the size of the Laurentide ice sheet caused variations in strength of Pacific subtropical high-pressure off the west coast of North America (COHMAP Members, 1988). The intensification of subtropical high-pressure may have strengthened the subtropical North Pacific Ocean gyre (Sawada and Handa, 1998). Consequently, the northwestern Pacific's early Pleistocene climate might have been influenced by 100-kyr cycles. However, there are few data for cycles in this region, because there are no long deep-sea sediment cores with high-resolution Plio–Pleistocene records, owing to great water depths and poor carbonate preservation. However, there is a continuous record of planktonic foraminifers in the early Pleistocene Omma Formation near Kanazawa City, central Japan, on the Sea of Japan coast. The middle part and the lowest portion of the upper part of the formation are composed of twelve depositional sequences that correlate with marine oxygen isotope stages (MIS) 50 to 26 (ca. 1.5-1.0 Ma) (Kitamura et al., 1994). Percentages of the warm-water planktonic foraminifer *Globigerinoides ruber* change systematically within this depositional sequence, with values increasing upward within the transgressive systems tracts (TST) and ranging from 16 to 22% within the highstand systems tracts (HST) (Kitamura et al., 2001). This species is not found in the regressive systems tracts deposits (Kitamura et al., 2000). Since these depositional sequences are derived from the 41,000-years obliquity cycle (Kitamura et al., 1994), the relative abundance of *Gds. ruber* varied with the 41,000-year period of Earth's orbital obliquity.

The relative abundances of *Gds. ruber* in interglacial stages 47, 43 and 31 are significantly higher than those in other interglacial stages. In order to understand this difference, we examined the relationship between the relative abundance of *Gds. ruber* and the Earth's three orbital components: precession, obliquity and eccentricity. Our results show that there is good alignment among precession, obliquity and eccentricity for the three interglacial stages, which suggests that the early Pleistocene climate in the Northwest Pacific was influenced by eccentricity as well as obliquity.

2. Geological setting

The Omma Formation at its Okuwa type section has been divided into lower, middle and upper parts, based on both litho- and biofacies (Kitamura and Kondo, 1990; Kitamura et al., 1994) (Figs. 1 and 2). Its middle part and the lowest portion of its upper part are composed of twelve sixth-order (41-k.y.) depositional sequences (numbered 1 to 11 in the middle part, in ascending order, and U1 in the upper part) that were deposited in inner- to outer-shelf depths during MIS 50 to 26 (Fig. 2) (Kitamura, 1994; Kitamura et al., 1994;

Kitamura and Kawagoe, 2006). All depositional sequences at the type section, except for 3, 4 and 7, include both TST and HST deposits (Kitamura, 1998). Depositional sequences 3 (MIS 46 to 44), 4 (MIS 44 to 42) and 7 (MIS 38 to 36) consist only of TST deposits, because their HST deposits were truncated by shoreface erosion at the superjacent sequence boundary. Sequences 3 and 4 are present in the Yuhidera area, 4 km northeast of Okuwa, and consist of TST and HST deposits (Kitamura, 1998), evidently because they were deposited in water a few tens of meters deeper than at Okuwa (Kitamura et al., 1997). The Yuhidera area therefore preserves the fossil records of MIS 45 and 43.

Although the last appearance datum of *Helicosphaera sellii* is placed within depositional sequence 1 at the Okuwa section (Fig. 2), this species is found from sequence 2 at Yuhidera (Fig. 3, arrow A). Kitamura et al. (1997) concluded that this discrepancy is explainable by missing horizons at Okuwa that would have yielded *H. sellii*, based on the relative stratigraphic positions of the appearance and disappearance datums of warm-water molluscs in the Okuwa and Yuhidera sections. In summary, there is a complete fossil record of deglaciation, except for MIS 37, in these two outcrop areas of the Omma Formation.

Kitamura (1998) used biostratigraphic and magnetostratigraphic criteria to infer average rates of sedimentation at Okuwa of about 16 cm/ka (Ohmura et al., 1988; Takayama et al., 1988; Sato and Takayama, 1992; Kitamura et al., 1993), with no evidence for deepening or shallowing water. In addition, if oxygen isotope records from deep-sea cores (e.g., Ruddiman et al., 1989; Shackleton et al., 1990; Berger et al., 1994) are regarded as a proxy for the glacio-eustatic sea-level record, no significant changes in average sea level are evidenced in the Omma Formation. This implies that the sedimentation rate matched the subsidence rate, suggesting that there were no great water depths during any of the interglacial sea-level highstands.

3. Methods

Sea-surface temperatures are inferred using the transfer function method, as well as from the oxygen isotopes and Mg/Ca ratios of planktonic foraminifers. Thompson (1981) and Takemoto and Oda (1997) presented planktonic foraminiferal transfer functions for the northwest Pacific Ocean off Japan. Unfortunately, these functions cannot be used to infer the early Pleistocene Sea of Japan sea-surface temperature, for the following two reasons: First, the mid-latitude species *Globorotalia inflata* is very rare in the modern southwest Sea of Japan (Park and Shin, 1998; Kuroyanagi and Kawahata, 2004; Domitsu and Oda, 2005), even though it was common there in all interglacial stages from MIS 47 to 41 (1.45-1.30 Ma) (Kitamura et al., 2001). This may be a result of the shallowing of Tsushima Strait after MIS 41 (1.3Ma). Second, ecologically modern *Neogloboquadrina pachyderma* sinistral evolved between 1.1 and 1.0 Ma (Huber et al., 2000; Kucera and Kennett, 2002), therefore, although this species is a major climate indicator, it cannot be used to reconstruct paleoceanography prior to the middle Pleistocene. Since most molluscs shells in the Omma Formation can be easily scored with a knife, they are assumed to have been contaminated by secondary carbonate minerals. In fact, diagenetic calcite from the warm-water bivalve *Glycymeris rotunda*, which has an aragonitic shell, was detected by X-ray diffraction. It is very likely that such diagenetic alteration has also occurred in the planktonic foraminifers, so no geochemical investigation of Omma Formation fossil were pursued.

We incorporated the planktonic foraminiferal records from Kitamura et al. (2001) and Kitamura and Kimoto (2004) into the present study (Fig. 3). Within-habitat mixing of skeletal elements evidently was restricted to a surface layer about 10 cm thick during deposition in the interglacial stages (Kitamura, 1992). Using an average sedimentary rate determined for the middle part of the Omma Formation, time-averaging is estimated at about 600 years. The average sampling interval is approximately 1 m, which corresponds to 6 kyr.

We focused on the maximum relative abundance (MRA) of the warm-water species *Gds. ruber* in each depositional sequence (Table 1). The number of individuals per sample ranges from 126 to 340, with a mean of 251. Warm-water taxa are dominated by *Gds. ruber* (>95 %), along with a few individuals of *Gds. sacculifer*, *Orbulina universa* and *Pulleniatina obliquiloculata* (Kitamura et al., 2001). *Gds. ruber* is the shallowest-dwelling species, remaining in surface waters during its life cycle (Fairbanks et al., 1982). Of the three species for which temperature tolerances are known, the lower limit of *Gds. ruber* (19°C) is highest (*Gds. sacculifer* and *O. universa* are 14°C and 12°C, respectively) (Hemleben et al., 1989). This implies that *Gds. ruber* is the most suitable warm-water indicator for the warm Tsushima Current (Kitamura et al., 2001).

Domitsu and Oda (2005) investigated the relative abundance of *Gds. ruber* in modern surface sediments of the Sea of Japan. The relative abundances of *Gds. ruber* are 0-0.5% and 0.6-4.1% off the Matsumae Peninsula of Hokkaido and off Niigata in central Japan, respectively (Fig. 1), whereas they are 28.2-39.3% and 20.6% off Yamaguchi and Shimane, respectively (Fig. 1). By statistically relating monthly mean sea-surface temperatures (Japan Oceanographic Data Center) to the abundance of *Gds. ruber*, we see significant correlations for December (n=4, r=0.99, p=0.01), March and April (n=4, r=0.96, $p<0.05$) and September (n=4, r=0.95, $p<0.05$). This implies that the relative abundance of *Gds. ruber* is an index for SST in the Sea of Japan. However, this relationship cannot be directly applied to the reconstruction of early Pleistocene SST in the Sea of Japan, because, as noted, the early Pleistocene hydrographic and biotic conditions of this marginal sea differed significantly from modern ones.

In this study we correlate the MRA of *Gds. ruber* with marine climates of the warmest interglacial periods. Analysis of marine molluscan assemblage suggests that the Sea of Japan coast was warmest between 8 ka and 6 ka during the Holocene (Kito et al., 1998). This period is nearly coincident with the timing of the peak of July 65°N insolation at 10 ka. Thus, we infer that the MRA of *Gds. ruber* correspond to the times of the Northern Hemisphere 65° summer insolation maxima for each deglaciation (Fig. 3).

We focus on the larger MRA data from the Okuwa and Yuhidera areas for depositional sequences 3 and 4. As noted above, since the fossil record of depositional sequence 7 is unsuitable, we did not examine MIS 37. In depositional sequence 8, the MRA of *Gds. ruber* occurs within the horizon yielding the molluscan *Onustus-Paphia* II Association; this sequence correlates with MIS 35 (Fig. 2), which has been assigned to two obliquity cycles (Shackleton et al., 1990). This assignment is consistent with the observation that the thickness of this sequence is comparable to that of the two sequences above or below it. Since the warm-water molluscan *Onustus-Paphia* II Association lies within the lower portion of the sequence (Fig. 2), we think that the age of the MRA of *Gds. ruber* coincides with July 65°N insolation maxima within the earlier obliquity cycle (Fig. 3). Shells of both micro- and macrofossils in the upper portion of depositional sequence 8 have been dissolved (Fig. 2).

We were unable to obtain planktonic foraminiferal records of the glacial periods in Omma Formation deposits, owing to the lack of suitable sediments due to shoreface erosion, so we were unable to perform spectral analysis to accompany our planktonic foraminiferal data. As an alternative, we examined correlation coefficients between the MRA of *Gds. ruber* and three orbital parameters (eccentricity, obliquity and precession) for the July 65°N insolation maximum in each deglaciation.

4. Results

There is a positive correlation between the MRA of *Gds. ruber* and July 65°N insolation (r=0.81, p<0.01) (Fig. 4a). The correlation between the MRA of *Gds. ruber* and eccentricity is r=0.81, which is statistically significant at the 99% level (Fig. 4b). It is self-evident that there is a significant correlation between the MRA of *Gds. ruber* and precession (r=-0.84, p<0.01) (Fig. 4c), because eccentricity changes modulate the amplitude of the precessional signals. There is no significant correlation between the MRA of *Gds. ruber* and obliquity (p>0.05) (Fig. 4d). There are five peaks of eccentricity cycles between 1.5 and 1.0 Ma (Fig. 3). We did not examine the relationship between the two eccentricity peaks and the MRA of *Gds. ruber*, owing to the lack of planktonic foraminiferal records, form depositional sequence 7 and the upper portion of depositional sequence 8. However, the other three peaks are aligned with obliquity maxima and correspond to the MRA of *Gds. ruber* in MIS 47, 43 and 31, which are significantly larger than in other stages (Fig. 3).

5. Discussion

The warm-water species *Gds. ruber* entered the Sea of Japan with the Tsushima Current. This current is a branch of the warm Kuroshio Current which is the vigorous northwestern component of the subtropical North Pacific Ocean gyre. Based on the alkenone-derived sea-surface temperature record over the past 25 kyr, Sawada and Handa (1998) inferred that the subtropical North Pacific Ocean gyre may have reached a maximum from 8 to 7 ka. As noted above, the marine climate of the Sea of Japan coast was warmest between 8 ka and 6 ka. It is therefore likely that the strength of the gyre resulted in warming of the marine climate of the Sea of Japan.

The subtropical North Pacific Ocean gyre was controlled by variations in the intensity of trade winds associated with subtropical high-pressure off the western coast of North America. COHMAP Members (1988) demonstrated that the subtropical high pressure was displaced to the south and weakened from about 18 to 12 ka, because of the widespread Laurentide ice sheet in North America. It then intensified gradually during melting and reduction of the Laurentide ice sheet, due to increased solar radiation in summer during deglaciation. Boreal summer insolation reached a maximum during the middle Holocene, when subtropical high-pressure must also have peaked. Our data imply that reduction of the Laurentide ice sheet over North America at MIS 47, 43 and 31 was greater than during the other interglacial stages. This conclusion is supported by fact that the $\delta^{18}O$ values of these stages were relatively light from 1.5 to 1.0 Ma at DSDP 607 (Ruddiman et al., 1989), 677 (Shackleton et al., 1990), 806 (Berger et al., 1994) and 1090 (Venz and Hodell, 2002).

Ruddiman (2003) recently suggested that the 100-kyr cycle during the last 0.9 Myr resulted from the eccentricity pacing of forced processes embedded in obliquity and precession cycles. The increased modulation of precession due to eccentricity every 100,000 years produces 23,000-year greenhouse-gases (CO_2 and CH_4) maxima that enhance ablation caused by summer insolation and drive climate deeper into an interglacial state. Moreover, he noted that this process works most effectively when a precession peak is closely aligned with a nearby obliquity maximum. This is consistent with the interpretation that the low-frequency oxygen isotope cycles during early Pleistocene originated through an asymmetrical response mechanism that preferentially introduced variance into the climate system from the warmer portions of the eccentricity-modulated precession cycle of Clemens and Tiedemann (1997). As noted above, MIS 47, 43 and 31 corresponded to periods when eccentricity-modulated precession extremes were aligned with obliquity maxima. Therefore, we believe that the significantly high MRA of *Gds. ruber* in these interglacial stages are signals of a warmer climate linked to 100-kyr cycles. If this interpretation is correct, then eccentricity cycles enhanced the strength of the subtropical North Pacific Ocean gyre through major ice-sheet melting, and consequently influenced the Northwestern Pacific region's early Pleistocene climate.

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Figure captions

Fig. 1 The Sea of Japan and surrounding region, showing location of the Omma Formation near Kanazawa City, Central Japan, modified from Imai (1959).

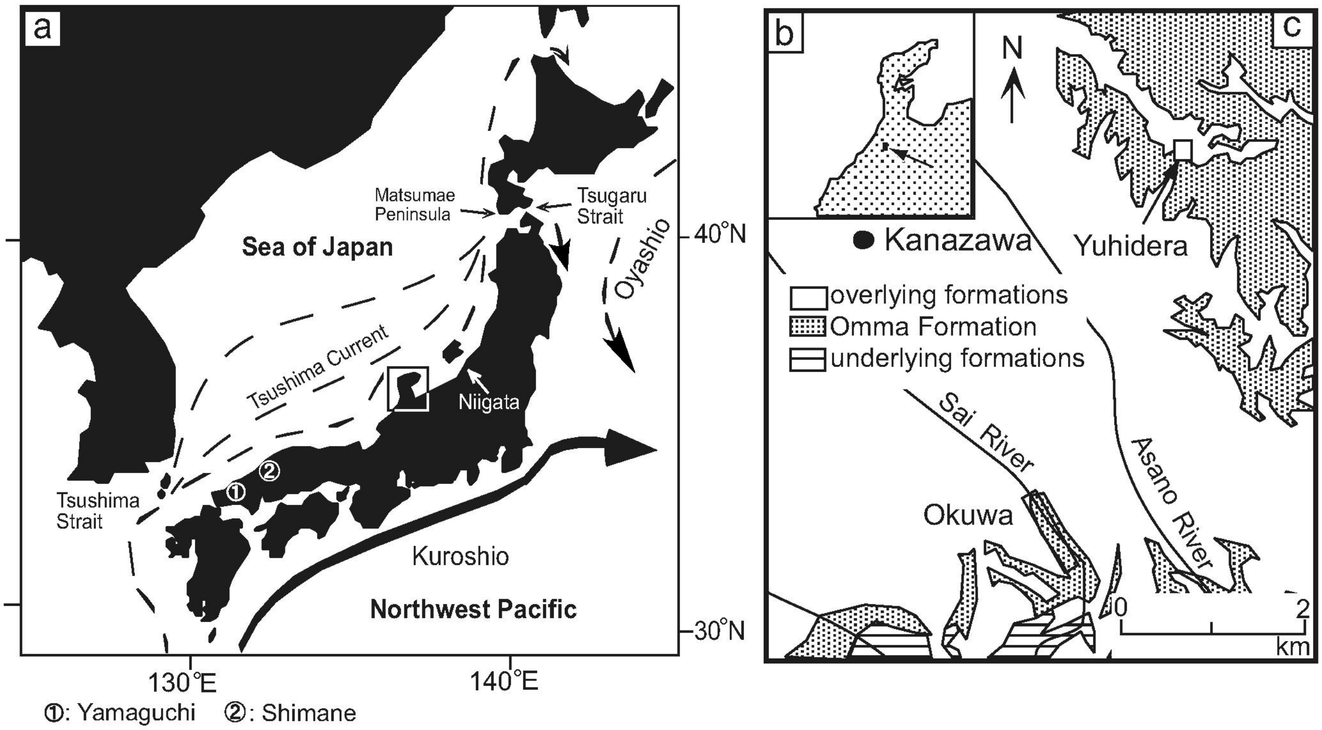
Fig. 2 Columnar section of the Omma Formation at its type section. Biostratigraphic datum horizons are after Takayama et al. (1988) and Sato and Takayama (1992); magnetostratigraphic data from Ohmura et al. (1989) and Kitamura et al. (1994); time scale for the oxygen isotope record at DSDP Site 607 and 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, U1-U5: depositional sequence numbers.

Fig. 3 Stratigraphic distribution of the warm-water planktonic foraminifer species *Globigerinoides ruber* from the Omma Formation in the Okuwa and Yuhidera areas, showing Northern Hemisphere 65° summer insolation, precession, obliquity and eccentricity during the time interval of oxygen isotope stages 50 to 26 (Berger, 1992).

Fig. 4 Relationship between maximum relative abundance of *Globigerinoides ruber* and each orbital parameter of eccentricity, obliquity and precession at July 65°N insolation maxima for each deglaciation period. (a) July 65°N insolation. (b) eccentricity. (c) precession. (d) obliquity.

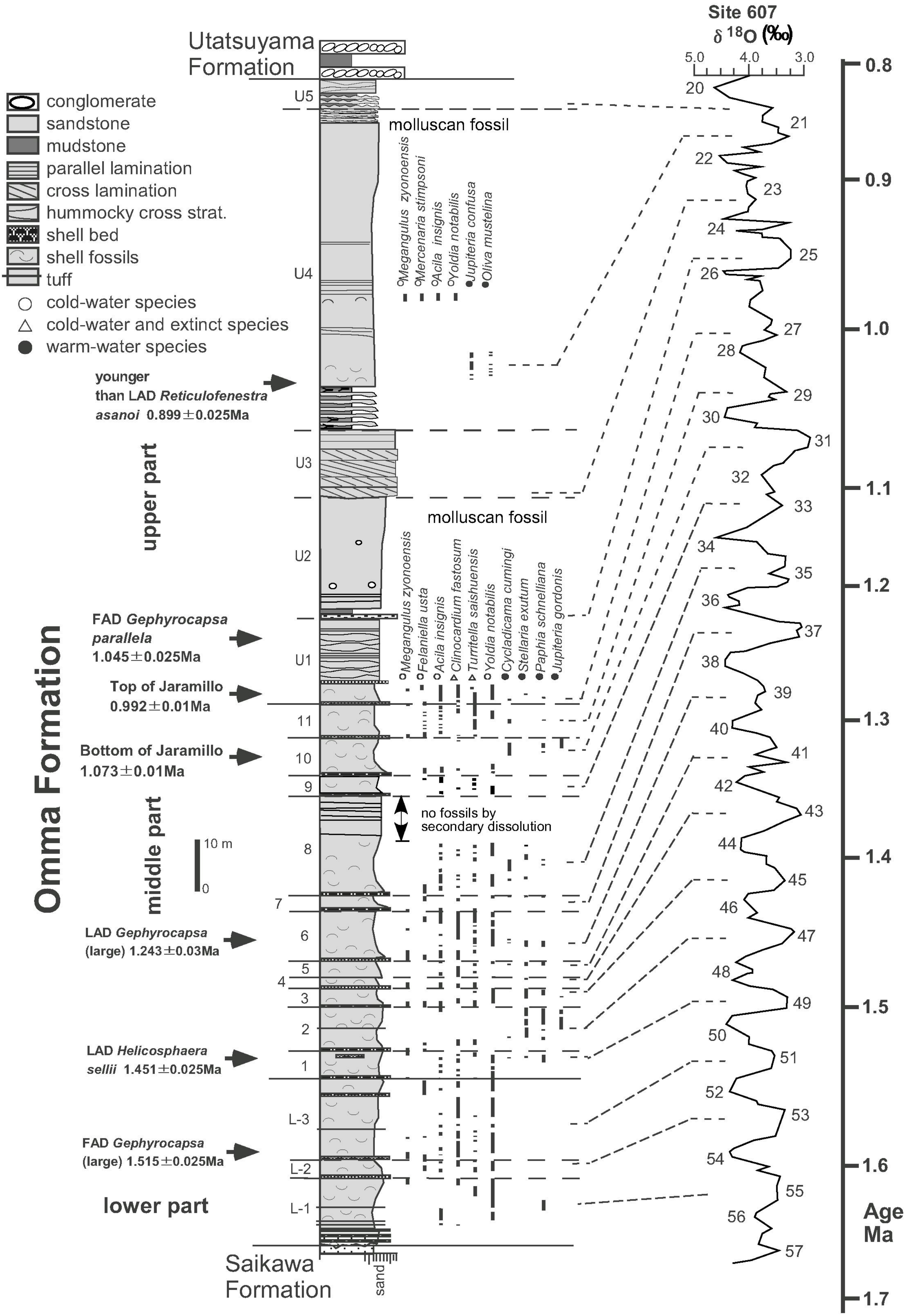
Table 1 Planktonic foraminifera identified at the horizon having the maximum relative abundance (MRA) of the warm-water species *Gds. ruber* in each depositional sequence.

Figure 1



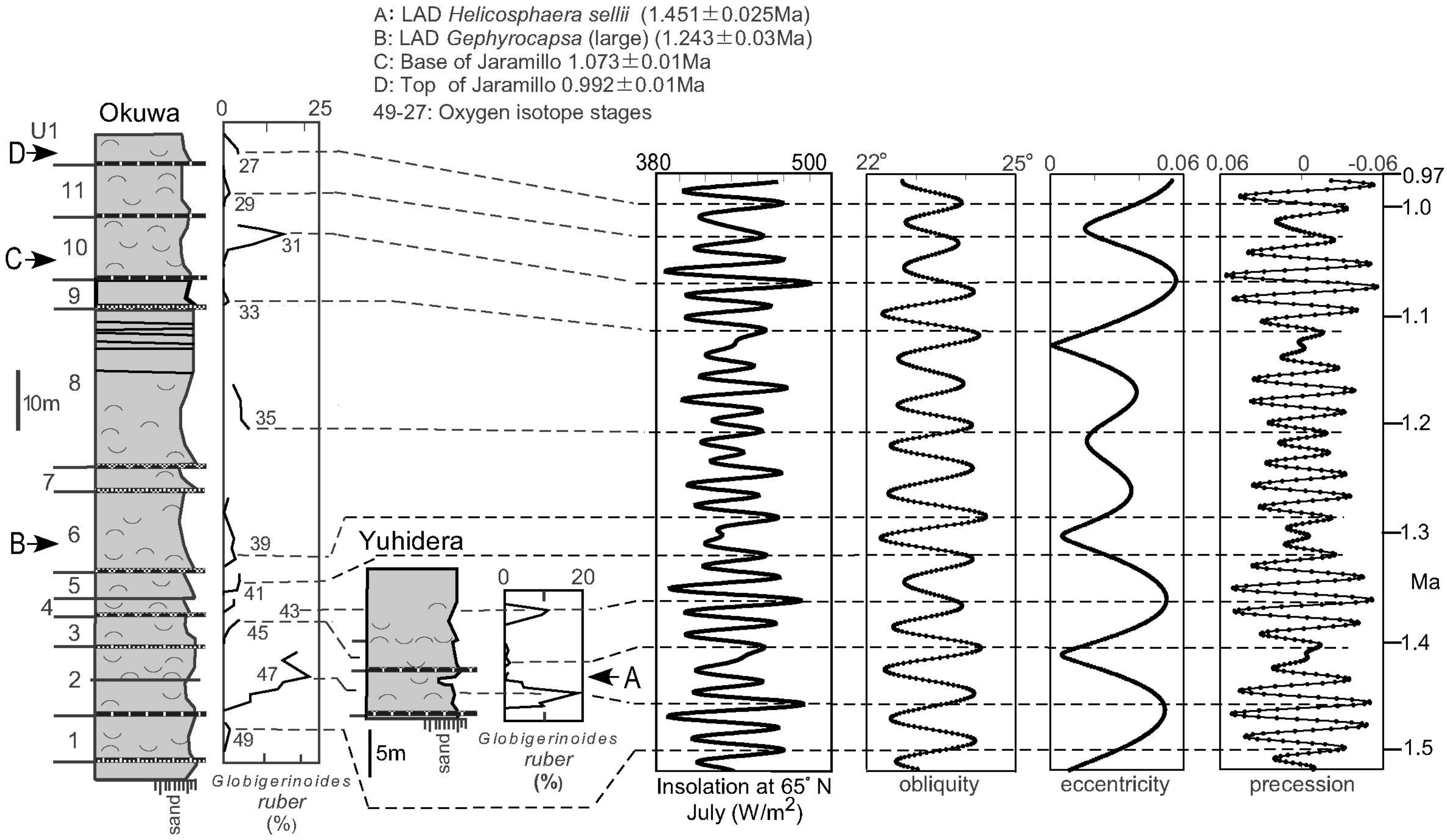
Kitamura and Kimoto Fig. 1

Figure 2



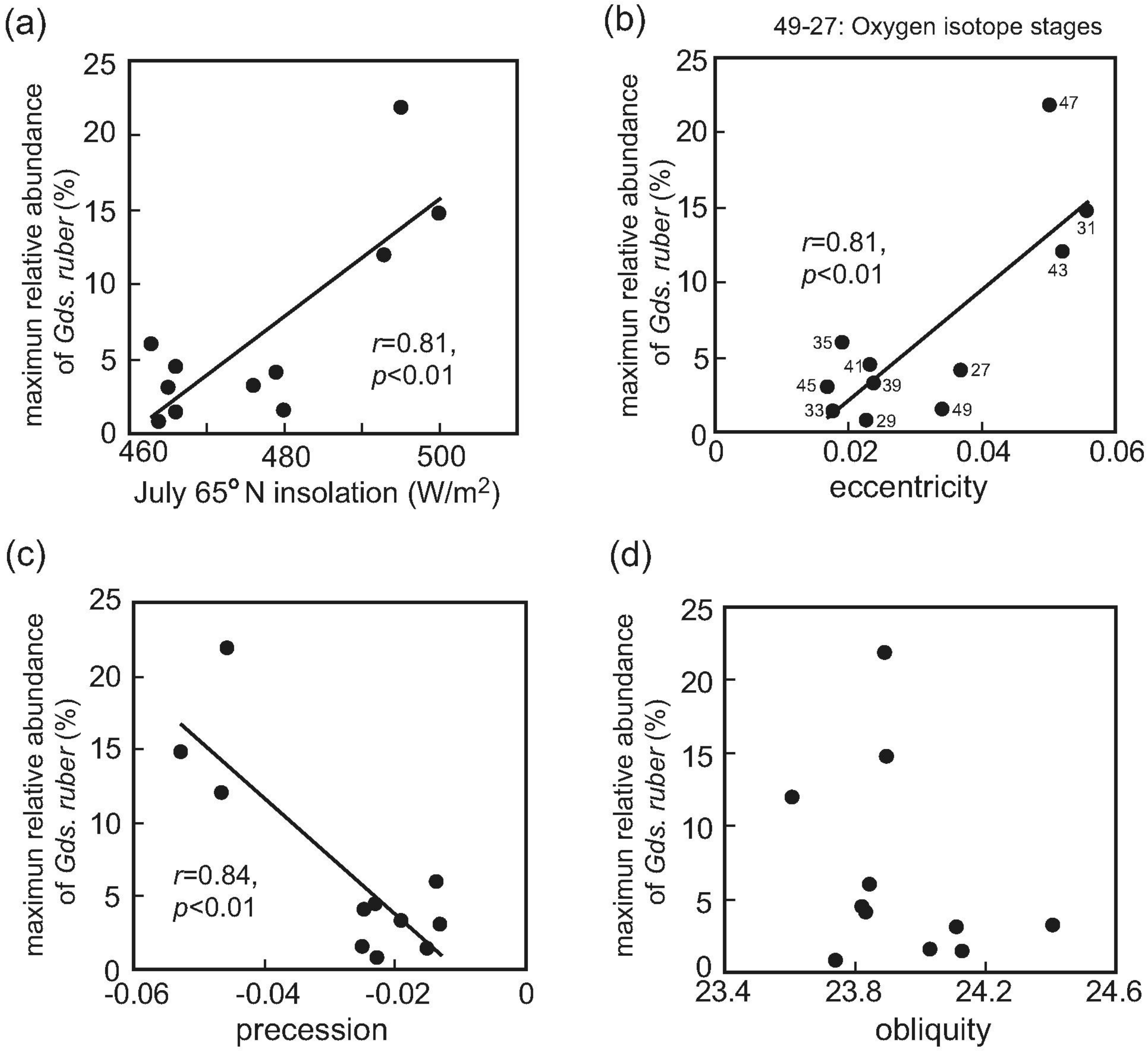
Kitamura and Kimoto Fig. 2

Figure 3



Kitamura and Kimoto Fig. 3

Figure 4



Kitamura and Kimoto Fig. 4

Table 1

Locality	Okuwa											Yuhidera		
Part	middle											middle		
Cycle	1	2	3	4	5	6	8	9	10	11	11	2	3	4
Marine isotope stage	49	47	45	43	41	39	35	33	31	29	27	47	45	43
Globigerina bulloides	76	83	133	97	75	99	93	35	52	9	24	65	72	88
Globigerina woodi	0	0	0	0	0	0	0	0	34	0	0	0	0	0
Globigerina quinqueloba	63	37	11	1	26	15	13	59	27	5	17	53	5	19
Globigerina glutinata	1	4	1	3	9	18	6	0	8	3	1	0	1	3
Globigerinoides ruber	5	57	8	4	11	7	18	3	45	1	8	61	4	38
Globigerinoides sacculifer	0	0	0	0	1	0	1	0	1	0	1	0	0	1
Globigerinoides tenellus	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Globigerinoides sp.	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Neogloboquadrina pachyderma (s.)	34	0	13	8	8	10	29	27	8	9	10	0	45	7
Neogloboquadrina pachyderma (d.)	25	0	11	8	2	4	8	5	1	5	9	1	17	16
Neogloboquadrina dutertrei	0	6	4	0	4	1	7	9	8	1	1	0	1	3
Neogloboquadrina incompta	0	22	2	1	1	0	2	55	94	0	14	0	0	0
Orbulina universa	0	0	0	0	0	0	3	0	0	0	0	0	0	0
Globorotalia inflata	0	31	9	0	2	0	0	0	0	22	0	16	15	43
Pulleniatina obliquiloculata	0	0	0	0	0	0	0	0	0	0	0	2	0	0
others	136	21	73	46	107	49	123	18	27	71	113	115	49	99
Total	340	261	265	168	248	203	304	211	305	126	198	313	209	317
Relative abundance of *Gds. ruber* (%)	1.5	21.8	3.0	2.4	4.4	3.4	5.9	1.4	14.8	0.8	4.0	19.5	1.9	12.0