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**Effects of seasonality, forced by orbital-insolation cycles, on offshore molluscs
faunal change during rapid warming in the Sea of Japan**

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Abstract

During oxygen isotope stages 50 to 26, an offshore environment that was unsuitable for both cold- and warm-water mollusks may have temporarily prevailed in the southern Sea of Japan. This inner- to outer-shelf environment existed with a lateral scale of a few kilometers and a vertical scale of a few tens of meters during at least three transitions from oxygen isotope stages 48 to 47, 44 to 43 and 32 to 31. These deglaciation periods coincided with the three highest peak of July solar insolation at 65 ° N (495, 493 and 500 W/m²) between oxygen isotope stages 50 and 26. This implies that anomalously high seasonality induced by orbital-insolation cycles is likely to have played an important role in establishment of nonanalog benthic communities with a very low density and diversity of mollusks in the early Pleistocene Sea of Japan.

Key words: early Pleistocene, marine molluscan communities, Milankovitch cycles, Sea

of Japan

1. Introduction

Many organisms live for much longer than one year, and for them the annual cycle of seasons is a recurrent, predictable event. Typically, such organisms have behavioral and/or physiological mechanisms that allow them to live through the changing seasons (e.g., Bennett, 1990). As a result, the responses of such long-lived organisms to future climate change will be much more complex than those of organisms which have short life spans. Knowledge of past biotic responses to Quaternary climate changes may prove instructive for predicting ecological responses to future climate change (e.g., Overpeck et al., 1992; Faunmap Working Group, 1996; Cronin and Raymo, 1997; Cannariato et al., 1999; Cronin et al., 1999; Jackson and Overpeck, 2000; Davis and Shaw, 2001; Tinner and Lotter, 2001; Lyle et al., 2001). These studies show that communities consisting of species assemblages without modern counterparts tend to be dynamic and are often unstable at times of relatively rapid, large-scale climate and environmental change. While such studies have dealt mainly with terrestrial plant communities from North America and Europe, few studies have addressed the effects of climatic change on shallow-marine communities. Valentine and Jablonski (1993) and

Roy et al. (1995) have shown that Pleistocene marine molluscan assemblages of the Californian region are characterized by thermally anomalous species assemblages, composed of coexisting species that inhabit different climatic regimes today. Because these assemblages generally occur in shell beds that formed at a low sedimentary rate during a sea-level rise, Roy et al. (1996) inferred that the processes of time-averaging had intermixed species of disparate climatic provenance within single shell beds, and thereby produced a nonanalog assemblage.

In contrast, nonanalog benthic-mollusk communities have been recognized in the lower Pleistocene Omma Formation that accumulated during oxygen isotope stages 50 to 26 (Kitamura et al., 2000). These communities briefly prevailed on the continental shelf during warming associated with inflow of the warm Tsushima Current and are characterized by very low diversity and density. Based on the stratigraphic distribution of planktonic foraminifera and the geographic distribution of living mollusks, Kitamura et al. (2000) concluded that these communities represent a marine climate with a higher seasonality (winter temperatures $<6^{\circ}\text{C}$ and summer temperatures $>20^{\circ}\text{C}$) than occurs today. However, these authors based all of their conclusions on analysis of a single local stratigraphic sequence. In order to determine whether a regional or areal environment prevailed, I introduce corroborating data herein from other stratigraphic sections. For the

present study, I studied mollusks from the Omma Formation in Yuhidera area, which is 4 km northeast of Okuwa (Fig. 1).

Moreover I examined the relationship between the fossil patterns and July insolation at 65 ° N to test ideas about the establishment of nonanalogue molluscan communities. Seasonality increased during maxima of northern hemisphere summer insolation, because the climate-system response to 23- and 41-ka cycles represented linear, continuous responses to insolation changes that altered the Earth's radiation budget (Imbrie et al., 1992). Enhanced summer insolation forcing can intensify the subtropical winds which drive the subtropical gyre of the Pacific. This increases the volume of the warm Kuroshio Current, and the Tsushima Current (a branch of the Kuroshio Current). Then the currents may strength seasonality at areas along the Northwest Pacific rim. In fact, high-resolution oxygen isotope values from the fossil coral record show that the seasonal fluctuation of sea-surface temperatures in the Ryukyu Island area were greater during the Last Interglacial stage than those seen in modern coral records from the same reef setting (Suzuki et al., 2001). Since insolation seasonality in the Northern Hemisphere during the Last Interglacial maximum was greater than today (July solar insolation at 65 ° N, 427 W/m² modern vs 486 W/m² Last Interglacial maximum), Suzuki et al. (2001) concluded that the relatively large seasonal

variation in sea-surface temperature might have been driven by enhanced insolation seasonality. The marine climate system during interglacial stages in the Sea of Japan has not change in general since oxygen isotope stage 51 (Kitamura et al., 2001). Moreover, the source of the Tsushima Current is the Kuroshio Current and coastal water of East China Sea. In the Tsushima Current region, a similar phenomenon was probably driven by enhanced insolation seasonality in the Northern Hemisphere during early Pleistocene deglacial periods.

2. Geological setting

Many environmentally sensitive benthic mollusks and ostracods are found in the lower Pleistocene Omma Formation, a deposit which accumulated on the continental shelf in the Sea of Japan (e.g., Cronin and Ikeya, 1987; Kitamura and Kondo, 1990; Kitamura et al., 1994; Amano and Vermeij, 1998; Ozawa and Kamiya, 2001; Kitamura and Ubukata, in press). The Omma Formation at the Okuwa type section has been divided into lower, middle and upper parts, based on its litho- and biofacies (Kitamura et al., 1994). Its middle part and the lowest portion of upper part are composed of twelve sixth-order (41-k.y.) depositional sequences (numbered 1 to 11 in middle part and I in upper part, in ascending order) that were deposited in inner- to

outer-shelf depths during oxygen isotope stages 50 to 26 (Fig. 2) (Kitamura et al., 2001). Depositional sequences 2, 3 and 4 in the middle part of the formation are recognized in the Yuhidera area, which is 4 km northeast of Okuwa (Kitamura et al., 1997; Kitamura, 1998) (Fig. 3). Based on the modern distribution of extant molluscan species, the sequence at Yuhidera is inferred to have been deposited in water a few tens of meters deeper than at Okuwa (Kitamura et al., 1997).

Within each of the 12 depositional sequences, major changes occurred in the offshore molluscan fauna of the continental shelf during the transition from glacial to interglacial stages, owing to rapid warming associated with the inflow of the warm Tsushima Current. Warm-water species (the Kuroshio Fauna) entered the Sea of Japan along with this current, but were locally exterminated during the succeeding glacial period. The sediment just below the appearance horizon of the warm-water species is a muddy, fine to very fine-grained sandstone. This sediment layer contains a cold-water *Clinocardium-Turritella* Association consisting of *Clinocardium fastosum*, *Turritella saishuensis saishuensis*, *Acila insignis* and *Yoldia notabilis*, which dwelled in the upper sublittoral zone from the low-tide mark to 50-60 m (Kitamura et al., 1994). This implies, for all deglaciations, that there was no significant difference in substrate or water depth just before the colonization by warm-water mollusks.

Except for the Cobb Mountain subchron (base of oxygen isotope stage 35; Shackleton et al., 1990), the stratigraphic positions of both the base and top of the Jaramillo subchron and five nannofossil datum planes have been determined in the Omma Formation (Fig. 2) (Takayama et al., 1988; Kitamura et al., 1994). The analysis of molluscan fossils and a high-resolution chronological framework in the Omma Formation provides a rare opportunity to compare the fossil patterns with a radiation curve.

3. Methods

The studied outcrop surface at Yuhidera is vertical to the bedding plane, and there are two modes of occurrence of fossil mollusks in the Omma Formation. The first is within a shell bed at the base of a depositional sequence, and the other consists of *in situ* mollusks in sandstone. Mollusks in the basal shell bed were excluded from this study because they have been reworked from older deposits. In horizons yielding sparse molluscan fossils, all individuals were examined in a "rectangle" about 0.25 m thick on the outcrop surface and 1 m across parallel to bedding plane. For disarticulated shells, two separated valves were counted as one individual (Table 1 in the background dataset 1). In this paper, the definitions of cold- and warm-water species are based on the

geographic distribution of living species along the Pacific coast shelf area of Japan. Since the warm Kuroshio current leaves the Japanese Islands at the Boso Peninsula at 35 ° N latitude, a sharp marine biogeographic boundary is recognized there. Thus, the term "cold-water element" is applied to the fauna living north of 35 ° N, and the term "warm-water element" to that living south of 35 ° N. Species dwelling in both areas are grouped as an "intermediate element". Most of the intermediate element is distributed from 45 ° N to 30 ° N around the Japanese Islands. All extinct species, except for *Pecten (Pecten) byoritsuensis*, are regarded as cold-water species. According to Amano and Ohno (1988), *P. byoritsuensis* is regarded as warm-water species.

An estimate of the time-averaging of fossil records is needed when attempting to infer biotic responses to rapid climate change (e.g., Faunmap Working Group, 1996; Roy et al., 1996). Here I analyze the mode of occurrence of the infaunal bivalve *Phacosoma japonicum*, which is common in a horizon with warm-water mollusks within depositional sequence 2 at Yuhidera. The relationship between shell length and the range of burrowing depth of *P. japonicum* is shown by Kondo (1987). Maximum burrowing depth increases with growth and reaches about 15 cm. For individuals less than 3 cm in shell length, burrowing depth is about five times as great as shell length.

4. Results

Since Kitamura et al. (2000) have described the responses of molluscan species to rapid warming for ten stage transitions from the Omma Formation at Okuwa, those from three stage transitions at Yuhidera are presented in this paper.

The appearance of warm-water mollusks occurs in the lower part of the muddy, fine-grained to very fine-grained sandstone within the Omma depositional sequence at Yuhidera as well as Okuwa. Among the total of 28 articulated valves of *Phacosoma japonicum*, 22 individuals are in reworked orientations, aligned parallel to bedding planes (Table 2 in the background dataset 2). Since this species can burrow as deep as 5-15 cm below the sediment-water interface (Kondo, 1987), I think that the mixing of skeletal elements was restricted to a surface layer about 10 cm thick during deposition of the muddy, fine-grained to very fine-grained sandstone. The shallow-burrower *Paphia schnelliana* is found in the horizon yielding *Phacosoma japonicum*, while the shallow-burrower *Clinocardium fastosum* occurs in sediment just below this horizon. Although many individuals of *P. schnelliana* and *C. fastosum* are articulated and well-preserved, they are not in the life position but are mostly aligned parallel to bedding planes (reworked orientation). Since the burrowing depth of these species is less than 10 cm (Kitamura, 1992), its mode of occurrence supports the estimated degree

of mixing.

In depositional sequence 3 (correlated with oxygen isotope stage transition 46 to 45), the faunal change is represented by the appearance together of warm- and cold-water species in a 1.75-m-thick horizon (Fig. 3). This co-occurrence of warm- and cold-water mollusks is not an artifact of post-depositional mixing. In depositional sequence 4 (stage transition 44 to 43), the number of cold-water species and individuals decreases up section, and warm-water species appear 25 cm above the disappearance horizon of cold-water species (Fig. 3). Both cold- and warm-water species co-occur in thin horizons within depositional sequence 2 (stage transition 48 to 47). The horizon in this sequence is only 10 cm thick but contains the cold-water taxon *Turritella saishuensis saishuensis*, and the warm-water taxa *Onustus exutum*, *Paphia schnelliana* and *Zeuxis caelatus*. Based on the degree of mixing of the skeletal elements of *P. japonicum*, it is likely that warm-water species did not co-exist with cold-water species during the warming phases in depositional sequence 2.

The rate of increase in thickness of the Tsushima Current is calculated to be 17 ± 9 m per 1000 years during the initiation of flow (Kitamura et al., 1999). Although the establishment of warm-water mollusks in the Yuhidera area may have occurred slightly later than in the Okuwa area, the lag time is too short to investigate with

time-series analysis. In this study, the establishment of warm-water mollusks in the two areas is regarded as geologically contemporaneous. My result shows that patterns of molluscan faunal change were essentially the same at both Okuwa and Yuhidera (Fig. 3). Thus, an environment that was unsuitable for both cold- and warm-water offshore mollusks may have extended a few km laterally and a few tens of meters vertically on the southern Sea of Japan inner- to outer-shelf during stage transitions 48 to 47 and 44 to 43. Such environmental conditions may also have temporarily prevailed during the warming phase of stage transition 36 to 35 and 32 to 31 (Kitamura et al., 2000).

5. Discussion

I compare the fossil patterns with a radiation curve based on both the base and top of the Jaramillo subchron and five nannofossil datum planes, except for depositional sequence 8 that correlates to oxygen isotope stage 35 (Fig. 3). This is because this stage evidently has been assigned to two obliquity cycles (Shackleton et al., 1990). Depositional sequences are correlated to the obliquity signal with a lag of 8 kyr (Imbrie et al., 1984) and then the maximum of Northern Hemisphere July solar insolation at 65 ° N for each deglaciation is regarded as a major change associated with inflow of the warm Tsushima Current. This comparison shows that stage 48/47, 44/43 and 32/31 had

65 ° N insolation values of 495 W/m², 493 W/m² and 500 W/m² per day, respectively. These deglaciation periods coincide with the three highest peaks of insolation for all deglaciations between oxygen isotope stages 50 and 26 (Fig. 3), which were higher than during the Last Interglacial maximum (486 W/m²). In contrast, during all deglacial stages with the insolation of less than 480 W/m² per day, warm-water species migrated into the Sea of Japan and lived alongside cold-water species. The difference in the insolation of deglacial periods situated between two patterns of faunal change is approximately 10% of that between maximum and minimum summer radiation (Fig. 3).

From these data, I believe that higher seasonality forced by insolation changes resulted in an environment that was unsuitable for both cold- and warm-water offshore mollusks in study area. If this interpretation is correct, such nonanalog benthic communities with very low density and diversity of mollusks will not be established again for the next 150,000 yr (Berger, 1978), as long as present global and/or regional climate systems are maintained.

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Figure caption

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

Figure 2. Comparison between the stratigraphic distribution of mollusc species in the Omma Formation at its type section and the oxygen isotope record at DSDP Site 607 (Ruddiman et al., 1989). Biostratigraphic datum horizons are after Takayama et al. (1988); magnetostratigraphic data are 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 the chronology of Berger et al. (1994).

Figure 3. Columnar section of the Omma Formation at Yuhidera, showing stratigraphic distribution of molluscan fossil associations and the oxygen isotope record at DSDP Site 607 (Ruddiman et al., 1989).

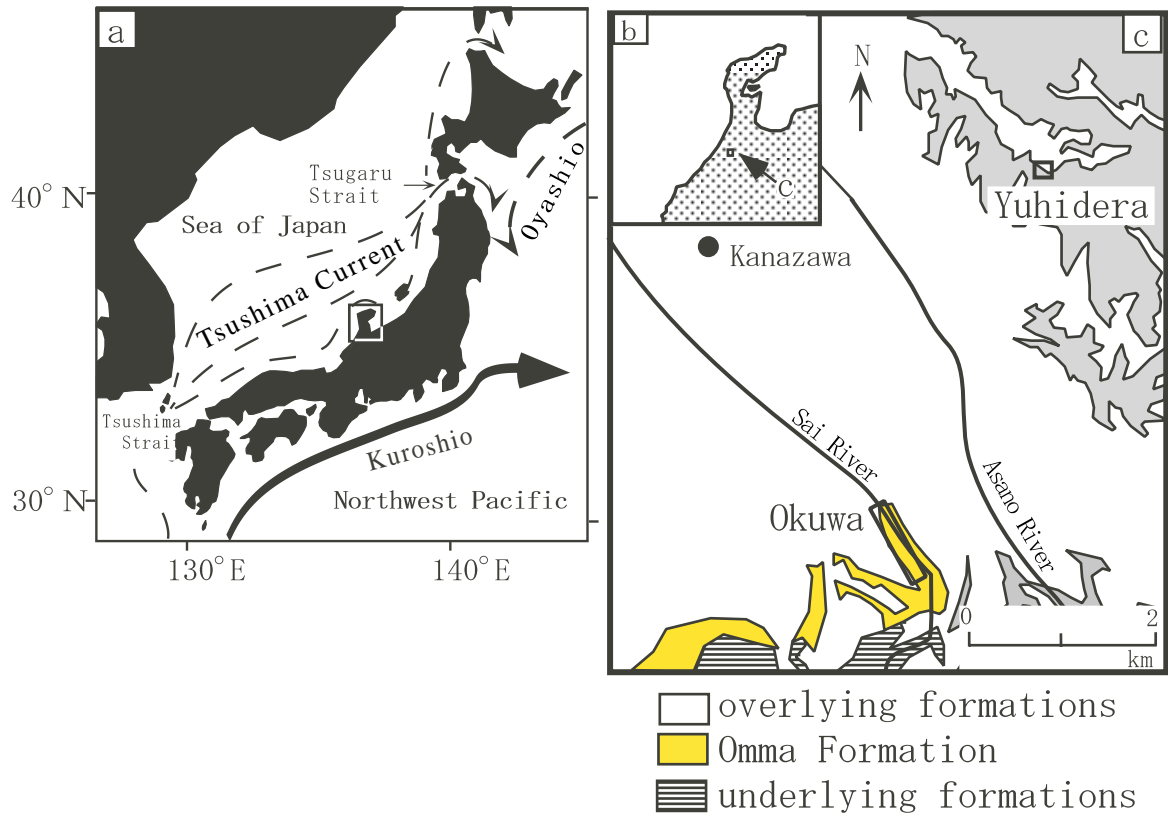
Figure 4. Stratigraphic distribution of mollusks at both Okuwa and Yuhidera in 12 sixth-order (41 k.y.) depositional sequences of the Omma Formation, and the 8-ky lag of orbital obliquity and insolation at 65 ° N in July during the time interval of oxygen isotope stages 50 to 26.

Table 1 in the background dataset 1 Molluscan fossils identified from the Omma

Formation in Yuhidera area. Molluscan fossils identified from the Omma

Formation in Yuhidera area.

Table 2 in the background dataset 2 Relationship between the shell orientation of articulated specimens and shell length of *Phacosoma japonicum*.



Kitamura Fig.1

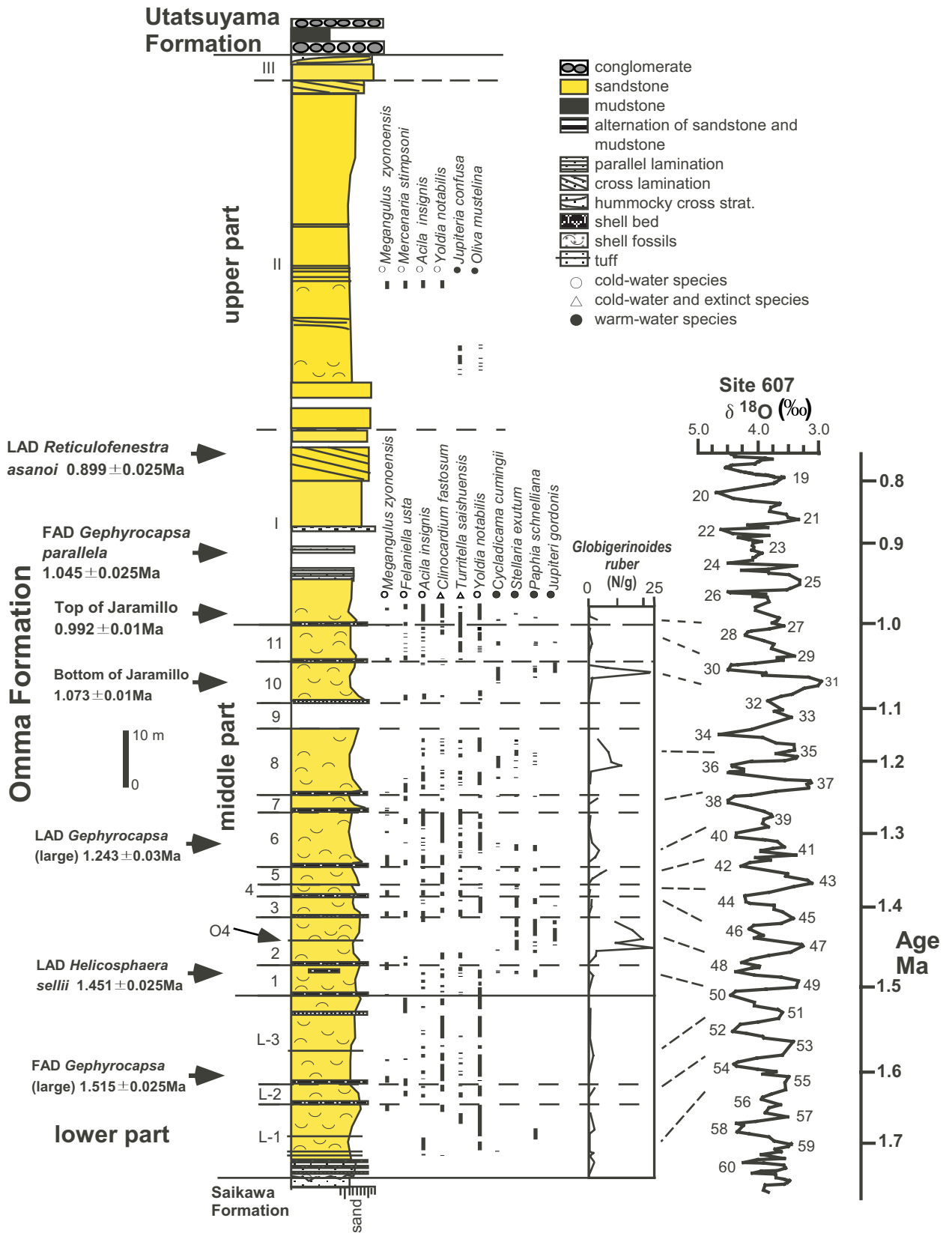


Fig. 2 Kitamura

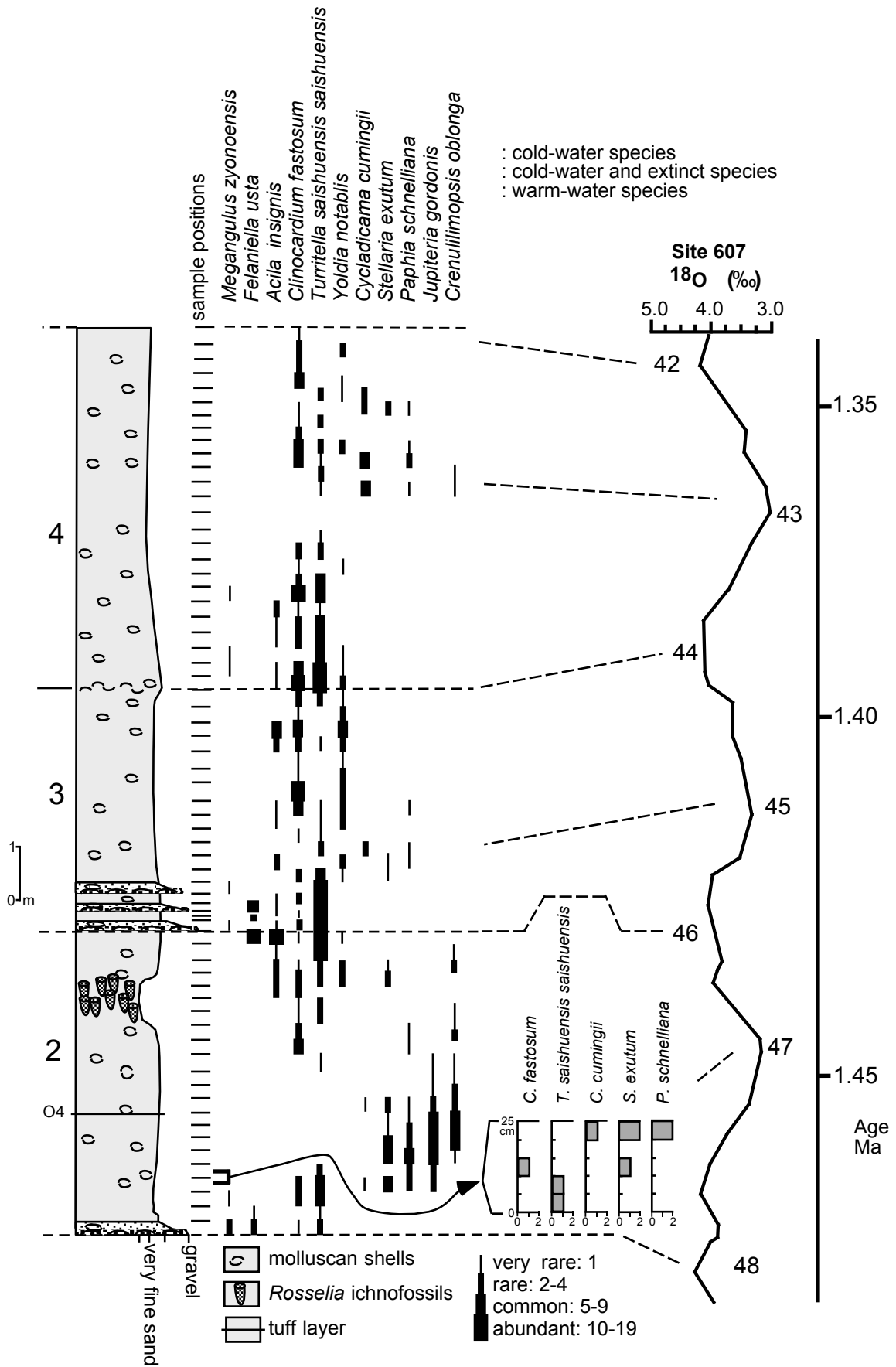
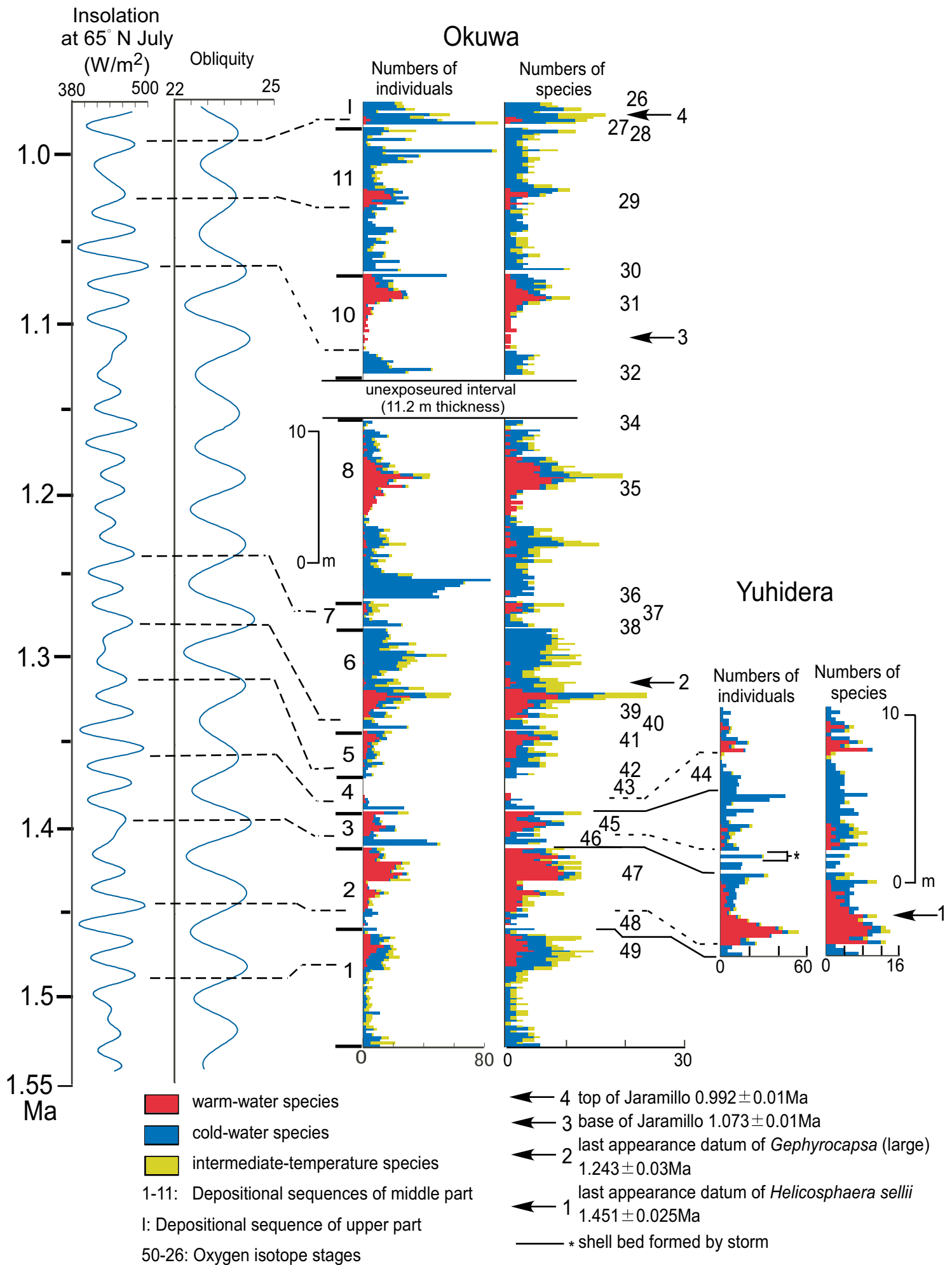


Fig. 3 Kitamura



Kitamura Fig.4