Cyclic changes in lithofacies and molluscan content in the early Pleistocene Omma Formation,
Central Japan related to the 41,000-year orbital obliquity

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Abstract

Eleven cyclothems based on change in sedimentary facies and molluscan fossil associations are identified in the middle part of the Omma Formation (early Pleistocene), in Kanazawa, Central Japan. The systematic change in the molluscan fossil associations within individual cycles indicates that the oceanic conditions changed in parallel with water depth fluctuations, such that an increase in water depth corresponds to a marine climatic warming. These changes in water depth and oceanic conditions exactly coincides with the oxygen isotope fluctuations reported for deep-sea sediments. The cyclothems identified here in the Omma Formation can be explained best as the result of glacio-eustasy with a period of the 41,000-years, which corresponds to the period of orbital obliquity.

Introduction

The oxygen isotope record in deep-sea cores provides a first approximation of changes in global continental ice volume and hence of the glacio-eustatic sea-level changes during the Pleistocene (e.g., Shackleton and Opdyke, 1976; Shackleton, 1977). Isotopic records available for the whole Pleistocene Epoch show that glacial-interglacial $d^{18}O$ changes between 1.8 and 0.9 Ma were significantly different in frequency and amplitude from those occurring after 0.6 Ma (Williams et al., 1988; Ruddiman et al., 1989).

High-amplitude and low-frequency glacial-interglacial fluctuations with periods of the order of 100,000 years and amplitude of sea-level changes in the order of over 100 m dominate after 0.6 Ma. On the other hand, the oxygen isotope record for the interval between 1.8 and 0.9 Ma is characterized by low-amplitude up to 50 m and high-frequency glacial-interglacial fluctuations with periods of about 41,000 years. Between 0.9 and 0.6 Ma, a transition in climatic states took place and involved a high degree of instability and a complicated mixture of frequencies (Williams et al., 1988).

Records of glacio-eustatic sea-level changes for intervals spanning the last 0.6 m.y. have been established for shallow marine successions including marine terraces (e. g. Chappell and Shackleton, 1986; Tokunashi and Kondo, 1989; Ito, 1992). These records demonstrate the validity of the oxygen isotope record as a proxy for glacio-eustatic sea-level changes. Moreover, a careful comparison between these records and oxygen isotope records generated a better approximation to sea level record than was previously available (Shackleton, 1987). On the other hand, only a few studies with respect to the glacio-eustatic sea-level changes between 1.8 and 0.6 Ma have been carried out on the contemporaneous shallow marine sediment (Beu and Edwards, 1984; Kitamura and Kondo, 1990; Kanazawa, 1990; Kamp and Tumer, 1990; Carter et al., 1991). Therefore, the history of glacio-eustasy prior to 0.6 Ma has not been defined in comparison with that for the last 0.6 m.y.

Early Pleistocene marine sediments widely exposed along the coastal region of the Japanese Islands provide an excellent setting to study the history of glacio-eustatic sea-level changes. The Omma Formation is a well known occurrence of early Pleistocene marine strata in the Sea of Japan and one containing profuse molluscan fossils. Kaseno and Matsuura (1965), Ogasawara (1977) and Matsuura (1985) concluded that the molluscan fossils originated in shallow marine environments ranging from low tide mark to 60 m water depth. The Omma Formation is therefore well suited to the identification of early Pleistocene glacio-eustatic sea-level changes from analysis of temporal changes in both lithology and molluscan fossil associations. In this paper, we document a cyclothem record from the middle part of the Omma Formation, which has a periodicity of 41,000-years.

Stratigraphic framework

The type locality of the Omma Formation (Motiduki, 1930) is located at the bed of the Saikawa River, Kanazawa City, on the Japan Sea coast in Central Japan (Fig. 1). The formation overlies the Middle Miocene Saikawa Formation (Ogasawara, 1977) and is in turn overlain unconformably by the Utatsuyama Formation (Ichihara et al., 1950) (Fig. 2). The marine Saikawa Formation is mainly composed of massive siltstone (Ogasawara, 1977). The Utatsuyama Formation is represented by an alternation of mudstone, coarse-grained sandstone and conglomerate (Nirei, 1969).

The Omma Formation at the type section (Okuwa) attains 210 m thick and has a northeast-southwest strike with 10-20° dip to the northwest. On the basis of the litho- and biofacies, the Omma Formation is divided into lower, middle and upper parts (Kitamura and Kondo, 1990). Eleven cyclic changes in both sedimentary facies and molluscan fossil associations can be recognized in the middle part of the formation (Kitamura and Kondo, 1990). All of the cycles are identified in the formation exposed along the Fushimigawa River at Yamashina (Figs. 1 and 3). These cycles are numbered successively from 1 to 11 (Fig. 2).

The 25 m-thick lower part of the Omma Formation consists of a bluish-gray fine-grained sandstone, except for the basal part which is composed of a silty, very fine-grained sandstone (Fig. 2). The environment during the deposition of nearly all of this part of the succession is inferred to have been shallower than 20-30 m, although cyclic changes of litho- and biofacies as seen in the middle part of the formation are not observed in the lower part (Kitamura, 1991a).

The thickness of the upper part of the Omma Formation is 110 m, and seven sedimentary facies are recognized within it. On the basis of the stack of these facies, the upper part is mainly composed of coastal and shallow-marine deposits and can be regarded as consisting of three depositional cycles related to relative changes of sea level (Fig. 2) (Kitamura in press).

Geologic age

Biostratigraphic and magnetostratigraphic data indicate that the Omma Formation at the type section is Early Pleistocene in age (Hasegawa, 1979; Takayama et al., 1988; Ohmura et al., 1989; Sato and Takayama, 1992). According to Takayama et al. (1988) and Sato and Takayama (1992), five nannofossil biohorizons

are defined in the Omma Formation. The first appearance datum (FAD) of Gephyrocapsa (large) is located at about 10 m above the base of the formation (Fig. 2). The last appearance datum (LAD) of Helicosphaera sellii and Gephyrocapsa (large) are placed in the upper portion of Cycle 1 and the middle portion of Cycle 6, respectively, both in the middle part of the formation. Both the FAD of Gephyrocapsa parallela and LAD of Reticulofenestra asanoi are located at the lower portion of the upper part (Fig. 2).

A magnetostratigraphic study by Ohmura et al. (1989) indicates that this formation is assigned to the Matuyama Reversed Polarity Chron and a normal polarity horizon near the boundary between the middle and upper parts is assigned to the Jaramillo Subchron (Fig. 2). Recently, Kitamura et al. (1993) made a detailed magnetostratigraphic investigation to determine the stratigraphic positions of both the base and top of the Jaramillo Subchron more precisely than the early work of Ohmura et al. (1989). The result shows that the base and top of the Jaramillo Subchron are placed at $3 \text{ m} \pm 15 \text{ cm}$ above the base of the Cycle 10, and $65 \text{ cm} \pm 15 \text{ cm}$ above the top of the Cycle 11, respectively (Fig. 4). The fission-track age of the O2 tuff layer was reported by Ohmura et al. (1989) as $1.4 \pm 0.2 \text{ Ma}$ (Fig. 2).

Methods

To document a detailed change in lithofacies in each cycle, grain-size analyses were conducted on selected samples. This was undertaken by sieving for the sand fraction and by hydrometer measurement for the mud fraction.

The stratigraphic distributions and abundances of molluscan fossils that occur in the middle part of the Omma Formation was determined in detail by the following two methods. For a shell bed, all the molluscan individuals embedded in the bedding surface of 2 m wide and 5-30 cm thick of each bed were identified and counted, and their mode of occurrence observed. In the horizon yielding molluscan fossils sporadically, all the individuals were identified and counted and their mode of occurrence was examined in a rectangular block 1 m long parallel to strike and 0.5 m wide. The surface of the exposures is so uneven, that thickness of the block ranged from 5 to 50 cm. For disarticulated shells, separated valves were counted as one individual.

Sedimentary Cycles

The thickness of individual cycles in the Omma Formation is highly variable ranging from 2 m to 12 m with an average thickness of 7 m. The sediments of cycle were divided into three lithofacies, a basal shell bed, a well-sorted fine-grained sandstone and a muddy fine- to very fine-grained sandstone. In a representative cycle, they are, in ascending order, a basal shell bed, a well-sorted fine-grained sandstone, a muddy fine- to very fine-grained sandstone and a well-sorted fine-grained sandstone (Fig. 5). Variation from this typical cycle, such as omission of a certain unit, is not uncommon.

The base of the 5 to 30 cm thick basal shell bed rests on an erosional surface. This bed is packed with shells and terrigenous granules intermixed with sand. The bivalves are dominantly disarticulated, oriented parallel to the bedding plane, and occur in contact with each other being shell-supported. A well-sorted (sorting-coefficient of 0.7), fine-grained (2.5 to 3.0 ϕ mean grain size) sandstone, 0.5 to 1 m thick, usually overlies the basal shell bed. The mud content of the sandstone is 5 to 10% (Fig. 5). The sandstone is massive and contains a large number of articulated shells of Felaniella usta. The shells are dominantly oriented parallel to the bedding plane. The middle and upper portions of each cycle are typically composed of a muddy, fine- to very fine-grained sandstone from 0.5 m to 8 m thick. The mean grain size of the sandstone is 2.7 to 3.5 ϕ with the mud content ranging from 15 to 45% (Fig. 5). This sandstone is also massive and contains sporadic molluscan fossils.

Molluscan fossil associations

Biostratinomy

The species preserved in the life position are limited to deep burrowers, such as Panopea japonica, Barnea japonica and Clementia yatheleti, although the middle part of the Omma Formation yields abundant molluscan fossils. Most of the other bivalves are conjoined and well-preserved, but are not in the life position and mostly aligned parallel to bedding planes. This indicates that the shells were not transported far after death for any distance from their original habitats. Thus, the molluscan fossils in the middle part of

the Omma Formation are considered to be indigenous.

Faunal association

Many of molluscan fossils recovered from the Omma Formation are living in the modern shelf around Japan. Thus, the environmental changes that occurred during the deposition of each sedimentary cycle can be inferred from the modern distribution of molluscan species (Figs. 6 and 7). The molluscan fossils in the middle part of the Omma Formation can be grouped into 9 associations based on both stratigraphic distribution and relative abundances of dominant species. The term "association" used here is defined as a suite of recurrent assemblage similar in their specific composition. The characteristic and associated species of each association is shown in Table 1. Figure 8 summarizes the environmental conditions of each of the molluscan associations, such as water depth and water regime, adopted from literature performing to living molluscs. Environmental characteristics of these associations in oceanic conditions (cold-, transitional- and warm-water) and in water depth of habitat are inferred from information available on living species (e.g. geographic distributions by Kuroda and Habe, 1952; Higo, 1973; Oyama, 1973; Matsukuma, 1986 and Matsukuma et al., 1988; Horikoshi, 1989, bathymetry by Oyama, 1952, 1973 and Habe, 1977). The definitions of cold- and warm-water species are based on the geographic distribution of living species along the Pacific coast shelf area. Since the warm Kuroshio Current comes off the Japanese Islands at the Boso Peninsula at 35°N latitude, a sharp boundary of the marine biogeography can be recognized in this area (e.g. Horikoshi, 1962). Thus, the term "cold-water element" is applied to fauna living in the area north of 35°N latitude, and "warm-water element" to those south of 35°N. Species dwelling in both of the areas are grouped as "intermediate element". Four associations are composed mainly of cold-water elements and four associations are dominated by warm-water elements. The remaining association is a mixture of cold- and warm-water elements.

Peronidia Association

The molluscs of this association occur mainly in the basal shell bed. This association is characterized by large and thick bivalves such as Peronidia zyonoensis, Mercenaria stimpsoni and Pseudamiantis

tauyensis and smaller bivalves Glycymeris yessoensis and F. usta. In addition, Acila insignis, Mizuhopecten yessoensis yokoyamae and a gastropod Turritella saishuensis saishuensis are found commonly (Table 1). Many specimens of M. stimpsoni, P. tauyensis and A. insignis are articulated and they usually lie parallel to the bedding plane, whereas P. zyonoensis, G. yessoensis and M. yessoensis yokoyamae usually occur as disarticulated valves. These detached valves do not show preferred azimuthal orientation, and they commonly tend to be oriented convex-up. Encrusted epifauna, such as barnacles and bryozoans, are very rare on the shells, although constituents of this association are not preserved in life position. The mode of preservation of the shells indicates that they were exposed on the sea floor for too short a period after post-mortem reworking to be encrusted by epifauna.

Most species of this association are now living in the area north of 35°N latitude (Fig. 6). The living fauna comparable with this association are found on fine- to coarse-grained sandy bottom substrates shallower than 30 m deep off Kushiro, eastern Hokkaido (Matsui, 1990). Therefore, the association seems to have inhabited the zone between the low tide mark and a depth of 30 m in cold-water (Fig. 8).

Macoma sector Association

This association is confined to the basal shell bed of Cycle 10. The characteristic species of the association are Macoma sector and A. insignis. They are associated with Yoldia notabilis, Clinocardium fastosum, Panopea japonica and an inarticulate brachiopod Lingula unguis (Table 1). These bivalves, even P. japonica, are not in life position and are embedded parallel to the bedding, showing post-mortem reworking. On the basis that P. japonica can burrow as deep as 40-50 cm below the sediment-water interface (Kondo, 1987), sediment reworking during formation of the shell bed may be attained to a depth greater than 40 cm below the interface. Most bivalves, however, are conjoined and well-preserved. Therefore, they appear to have been buried soon after reworking and to be indigenous.

Both M. sector and P. japonica usually live in the upper sublittoral zone shallower than 30 m deep, and A. insignis and Y. notabilis are cold-water elements (Figs. 6 and 7). Thus, this association is thought to have inhabited the region between the low tide mark and a water depth of 30 m in cold-water environment (Fig. 8). It is also noted that most of the species of this association, particularly M. sector, are characteristic of an open coast environment.

Felaniella Association

The Felaniella association is characterized by the dominance of F. usta and subordinate of A. insignis, besides rare associates of P. zyonoensis and T. saishuensis saishuensis (Table 1). This association occurs in a well-sorted fine-grained sandstone. The species diversity of the association is low, with less than 8 species. The density of F. usta is very high and rarely reaches 160 individuals per m² on a bedding plane.

Judging from the ecological data of F. usta, the paleoenvironmental condition of the association was upper sublittoral zone from tide mark to 50-60 m in depth under cold-water (Fig. 8).

Clinocardium-Turritella Association

This association occurs sporadically in muddy very fine-grained sandstone. The characteristic species of the association are C. fastosum, A. insignis, Y. notabilis and T. saishuensis saishuensis (Table 1). They are associated with Ennucula tenuis, Cryptomya busoensis, Liocyma fluctuosa and Cryptonatica janthostomoides. Many bivalves are conjoined and well-preserved, but are not found in the life position. They are mostly aligned parallel to the bedding plane.

Although both of C. fastosum and T. saishuensis saishuensis are extinct species, this association probably dwelled in the upper sublittoral zone of cold-water environment, according to the data of living related species (Fig. 8).

Barnea Association

This association is almost exclusively composed of B. japonica (soft-bottom pholadid bivalve) preserved in life position. The association is confined to the upper part of the muddy very fine-grained sandstone in Cycle 4. The density of B. japonica ranges from 14 to 60 individuals per m². The species diversity of this association is very low, less than 3 species.

B. japonica is known to be the dominant taxa at water depths shallower than 30 m in the mud bottom of Ariake Bay in Kyusyu currently under the influence of the Kuroshio warm current. Thus, the paleoenvironmental condition of the association appears to be an embayment shallower than 30 m deep in warm-water environment (Fig. 8).

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226 Cycladicama Association

227 This association is characterized by the predominant occurrence of conjoined valves of a thin-shelled
228 and well-inflated bivalve Cycladicama cumingi in association with a few individuals of B. japonica and
229 Paphia schnelliana. C. cumingi are scattered sporadically in the muddy very fine-grained sandstone with a
230 density of about 10 individuals per m² on a bedding plane. The species diversity of the association is low
231 (less than 10 species). Most of the C. cumingi valves are articulated and randomly oriented. All of the
232 conjoined shells of the species have been collapsed by compaction.

233 Based on the modern habitat of C. cumingi and other species around Japan (Figs. 6 and 7), this
234 association is thought to dwell in an upper sublittoral zone under warm-water (Fig. 8).

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236 Tugurium-Paphia I Association

237 The characteristic species of the association are warm-water elements such as Tugurium exutum, P.
238 schnelliana, Nassarius caelatus and Saccella gordonis (Table 1). Besides the warm-water species Limopsis
239 crenata, a cold-water element Y. notabilis is occasionally found. This association occupies the middle part
240 or upper part of the muddy very fine-grained sandstone. The bivalves are conjoined and well-preserved, but
241 are not in the life position. They are dominantly aligned parallel to the bedding plane.

242 Judging from the ecological data of the living species and the absence of the characteristic species of
243 the Tugurium-Paphia II Association which are found in the lower sublittoral zone, the association appears
244 to inhabit from 20-30 to 50-60 m deep in warm-water (Fig. 8).

245

246 Tugurium-Paphia II Association

247 The constituents of this association are similar to those of Tugurium-Paphia I Association but include
248 Glycymeris rotunda, L. crenata, Nemocardium samarangae, Acila divaricata and a scaphopoda Dentalium
249 weinkauffi (Table 1). Specific diversity of this association is higher than that of the Tugurium-Paphia I
250 Association. The association is found at the upper part of the muddy very fine-grained sandstone. Many of
251 the bivalves are conjoined, excellently preserved but oriented horizontal to the bedding plane.

252 The Tugurium-Paphia II Association is analogous to the living lower sublittoral fauna of sandy

substrata in Sagami Bay (Oyama, 1952). This fauna consists of S. gordonis, A. divaricata, G. rotunda, N. caelatus and others. Therefore, this association appears to have inhabited between 50-60 and 100-120 m depth in warm-water (Fig. 8).

Transitional Association

This association is characterized by a mixture of representative species of the Clinocardium-Turritella Association (e.g., C. fastosum, E. tenuis and Y. notabilis) and those of the Tugurium-Paphia I Association such as T. exutum, P. schnelliana and N. caelatus. The shells of cold- and warm-water elements are articulated and well-preserved. No remarkable difference in mode of preservation is recognized between these elements. This suggests that the mixing of the two elements can hardly be attributed to transportation from two different environments or post-mortem processes, but that they coexisted in this area contemporaneously. This association probably lived from 20-30 to 50-60 m deep and a transitional environment between cold- and warm-waters (Fig. 8).

Discussion

The cyclic change in the molluscan fossil associations and the related water depth and oceanic conditions changes are discussed chiefly with respect to Cycle 10 (Fig. 9), which is a particularly good example. The thickness of this cycle is 7.5 m. Molluscan fossils in this cycle can be grouped into 5 associations. The Macoma sector association is found in the basal shell bed (Fig. 9). The Felaniella association occurs in the well-sorted sandstone in both the lower and uppermost parts of the cycle. In the muddy sandstone, molluscan associations change, in ascending order from the Clinocardium-Turritella association, to the Cycladicama association, to the Tugurium-Paphia II association and to the Clinocardium-Turritella association (Fig. 9).

The vertical distribution of molluscan fossils shows that the environment changed from cold-water, upper sublittoral zone (low tide mark to 50-60 m deep) through to the warm-water, lower sublittoral zone (50-60 m to 100-120 m deep), followed again by cold-water, upper sublittoral zone (Fig. 9). This means that the oceanic conditions changed in parallel with the water depth fluctuations. That is, an increase of

water depth corresponds to a marine climatic warming (Fig. 9). The maximum amplitude of the water depth fluctuation corresponds to 50 m, based on the molluscan fossil associations (Fig. 9). Data about the stratigraphic distribution of the molluscan fossil species within each cycle have been reported by Kitamura and Kondo (1990) and Kitamura (1991b).

The alternating occurrence of cold- and warm- or transitional associations can be observed in all the cycles of the middle part of the Omma Formation (Fig. 10). The change of the molluscan fossil associations in Cycles 1, 2, 3 and 8 illustrates clearly that the water depth had changed during the deposition of each cycle as seen in Cycle 10 (Fig. 10). On the other hand, the change of water depths could not be detected from molluscan fossil associations alone in the other cycles (Cycles 4, 5, 6, 7, 9 and 11). However, the pattern of the vertical change in both molluscan fossil associations and lithofacies in these cycles is very similar to that of Cycles 1, 2, 3, 8 and 10. Therefore, we imply that changes of sea-level also took place during the deposition of these cycles but the amplitude was less, probably less than 20-30 m, as determined from the molluscan fossil associations. For these cycles, it is interpreted that the horizon of yielding the warm- or transitional association shows the highest stand of sea-level, as illustrated in Fig. 10.

The bases of the shell beds are erosional in most cycles. There is, however, no evidences of subaerial exposure in the sediment. The erosional bases are located at the bottom of the deepening-upward sequence in each cycle (Figs. 9 and 10). Therefore, the erosional bases have probably been formed by shoreface erosion during an early phase of transgression. We regard the erosional base of the basal shell bed as the lowest stand of sea-level (Fig. 10).

The stratigraphic distribution of the molluscan fossil associations and changes in both water depth and oceanic conditions of Cycles 9 and 10 at Yamashina are shown in Fig. 11. The pattern of changes in both lithofacies and molluscan fossil associations in each cycle is similar to those of the correlative cycle in Okuwa. We infer therefore that the depositional environments including water depth and water mass type, are similar in both areas. Therefore, the changes in both water depth and oceanic conditions inferred from the Cycle 9 of Yamashina can be integrated into the chart illustrated in Figs. 10 and 13.

The middle part of the Omma Formation is dated as Early Pleistocene when there are known to have been major fluctuations in sea-level caused by glacio-eustasy (e.g., Shackleton and Opdyke, 1976; Beu and Edwards, 1984; Shackleton et al., 1990; Carter et al., 1991). The maximum amplitude of the sea-level

fluctuations inferred from the molluscan fossil associations is nearly equal to that of the glacio-eustatic sea-level fluctuations estimated by Beu and Edwards (1984). Glacio-eustasy can therefore be attributed as the origin of the cyclic changes in both sediments and molluscs in the middle part of the Omma Formation. In order to test the validity of this interpretation, we tried to correlate the changes of water depth and oceanic conditions of the Omma Formation inferred from molluscan fossils as well as lithofacies with the global oxygen isotope record.

We focus on the interval between the bottom and top of the Jaramillo Subchron which are the most reliably dated levels in the Omma Formation. The stratigraphic positions of these magnetic reversal boundaries are converted to the stratigraphic positions of molluscan fossil associations. The bottom and top of the Jaramillo Subchron are located at the lower part of the horizon yielding the warm-water Cycladicama association in Cycle 10, and the horizon yielding the transitional association in the lowermost part of the sedimentary cycle of the upper part of the Omma Formation (Kitamura, in press), respectively (Fig. 12). That is, the bottom and top of the Jaramillo Subchron can be correlated to the early interglacial period, and to the next but one interglacial period, respectively.

Figure 12 shows a correlation for the Jaramillo Subchron between the $\delta^{18}\text{O}$ record of North Atlantic DSDP site 607 (Ruddiman et al., 1989) and the inferred changes in water depth and oceanic conditions in the Omma Formation (Kitamura and Kondo, 1990; Kitamura et al. 1993). There is close agreement between these records. This leads to two conclusions. First, the cyclic changes in sedimentary facies and molluscan fossil associations in the middle part of the Omma Formation can be explained best as the result of glacio-eustasy showing with a cycles 41,000-year periodicity of orbital obliquity; spectral analysis of the $\delta^{18}\text{O}$ data for site 607 has shown that cycles with a period of 41,000-year dominate the record during the Matuyama Chron (Ruddiman et al., 1989). Second, this agreement also confirms simple interpretation of the benthic oxygen isotope record as a first approximation of sea level record during Early Pleistocene.

The oxygen isotope stratigraphy for East Equatorial Pacific ODP site 677 reported by Shackleton et al. (1990) shows that the top and bottom of the Jaramillo Subchron are placed at mid Stages 27 and 31, respectively. Therefore, the depositional age of Cycle 10 and 11 can be correlated with the oxygen isotope stages from 32 to 28 (Fig. 12).

Finally, we proposed the tentative correlation between all sedimentary cycles in the middle part of the

Omma Formation and the oxygen isotope stratigraphy devised by Ruddiman et al. (1989), using three nannofossil biohorizons and one tephra fission-track age (Fig. 13). In this paper we proceed on the simplest assumption, that all sedimentary cycles of the Omma Formation are derived from the 41,000-years obliquity cycle and there is no significant hiatus in the formation. The stratigraphic positions and pattern of water depth changes in the middle part of the Omma Formation clearly correlate with the fluctuations in the oxygen isotope curve. However, we urge caution that the precision of this correlation is not so high as that of correlation during the Jaramillo Subchron, because biostratigraphic datums and fission-track age are not relatively accurate compared to the magnetic reversal boundaries. The uncertainty of correlation can be reduced, if a new record extended into the Olduvai Subchron could be obtained from the Omma Formation.

Conclusions

- (1) Eleven separate and repetitive cyclic changes in both sedimentary facies and molluscan fossil associations are identified in the middle part of the early Pleistocene Omma Formation, in Central Japan.
- (2) The changes of the molluscan fossil associations within an individual cycle indicate that the oceanic conditions changed in parallel with the water depth fluctuations. The maximum amplitude of the water depth fluctuation is probably estimated to be 50 m.
- (3) A close correlation exists between changes of water depth and oceanic conditions derived from the Omma Formation and the deep-sea oxygen isotope record for the Jaramillo Subchron. This good agreement strongly suggests that the cyclothems in the middle part of the formation can be explained best as the result of glacio-eustasy with a period of 41,000-years, which corresponds to the period of orbital obliquity.

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Captions

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

Fig. 2. Columnar section of the Omma Formation at the type section (Okuwa), showing biostratigraphic datum horizon (Takayama et al., 1988; Sato and Takayama, 1992) and paleomagnetic data (Ohmura et al., 1989; Kitamura et al., 1993). The age of the LAD *Helicosphaera sellii* is after Gartner (1990). The ages of magnetic polarity change are those proposed by Mankinen and Cox (1988). *A zircon fission-track age of the O2 tuff was given by Ohmura et al. (1989). 1-11: number of sedimentary cycles in the middle part. I, II and III: number of sedimentary cycles in the upper part of the Omma Formation (Kitamura, in press).

Fig. 3. Columnar sections of the middle part of the Omma Formation at the type section and Yamashina.

Fig. 4. Stratigraphic positions of both the base and top of the Jaramillo Subchron in the Omma Formation. Each solid circle shows average direction of remanence after alter field demagnetization of 15-20mT. About three specimens were measured for each horizon. Lithologic units A: Basal shell bed, B: Well-sorted fine-grained sandstone, C: Muddy very fine-grained sandstone, SB: Storm-generated bed. Small alphabets show molluscan fossil associations and are the same as those in Table 1. *Data from Ohmura et al. (1989).

Fig. 5. Stratigraphic changes in lithofacies, mean grain size, mud content and sorting in sedimentary cycle 10. See legend in Fig. 2. The mean grain size expressed with ϕ -scale and sorting coefficient of each sample are calculated with the formulae proposed by Folk and Ward (1957). Mud content is expressed in weight percentage of the particles less than 63 μ m in diameter.

Fig. 6. Geographic distribution of characteristic species of the molluscan fossil associations in the present-day west Pacific. The species are main constituent species in each molluscan fossil associations of the middle part of the Omma Formation. Data based on Kuroda and Habe (1952), Higo (1973), Oyama (1973), Matsukuma (1986) and Matsukuma et al. (1988).

Fig. 7. Bathymetrical range of characteristic species of the molluscan fossil associations, after Oyama (1952, 1973) and Habe (1977).

500 Fig. 8. Relationship between the associations and environmental conditions in terms of water depth,
 501 water regime and sediment.

502 Fig. 9. Stratigraphy of Cycle 10, showing the distribution of molluscan fossil associations, the inferred
 503 changes in oceanic conditions and water depth. Sample numbers, very rare: 1; 2-4; common: 5-9,
 504 abundant: 10-19, very abundant: >19. Small alphabets show molluscan fossil associations and are the
 505 same as those in Table 1. Large alphabets show lithologic units and are the same as those in Fig. 4.

506 Fig. 10. Stratigraphic distribution of the molluscan fossil associations and the inferred changes in water
 507 depth and oceanic conditions during the deposition of the middle part of the Omma Formation. For
 508 the explanation of sediments, see the legend of Fig. 2. Small alphabets a-i show molluscan fossil
 509 associations and are the same as those in Table 1.

510 Fig. 11 Stratigraphic distribution of the molluscan fossil associations of the Cycles 9 and 10 of the
 511 middle part of the Omma Formation at Yamashina. See the legend and caption of Fig. 9.

512 Fig. 12. Correlation for the Jaramillo Subchron between the oxygen isotope record of DSDP607
 513 (Ruddiman et al., 1989) and the inferred changes in water depth and oceanic conditions in the
 514 Omma Formation. See caption of Fig. 4 and legend in Fig. 10.

515 Fig. 13. Tentative correlation between the changes in water depth and oceanic conditions inferred from
 516 molluscan fossil associations of the Omma Formation and oxygen isotope record of DSDP607
 517 (Ruddiman et al., 1989). Data of the lower part of the formation after Kitamura (1991). See legend
 518 in Fig. 12.

519 Table 1. Molluscan fossil associations and their main constituent species in the middle part of the
 520 Omma Formation.

□ overlying formations
 ▨ underlying formations

▨ Omma Formation

Fig. 1

Fig. 2

Fig. 4

Fig. 5

Legend
○ cold-water species

○ intermediate species

● warm-water species

Fig. 6

species	bathymetric range (m)			
	low tide mark	20-30	50-60	100-120
<i>Peronidia zyonoensis</i>				
<i>Glycymeris yessoensis</i>				
<i>Mercenaria stimpsoni</i>				
<i>Felaniella usta</i>				
<i>Acila insignis</i>				200m
<i>Macoma sector</i>				
<i>Macoma tokyoensis</i>				
<i>Panopea japonica</i>				
<i>Yoldia notabilis</i>				200m
<i>Cryptomya busoensis</i>				
<i>Cryptonatica janthostomoides</i>				
<i>Liocyma fluctuosa</i>				140m
<i>Ennucula tenuis</i>				250m
<i>Barnea japonica</i>				
<i>Cycladicama cumingi</i>				
<i>Paphia schnelliana</i>				
<i>Tugurium exutum</i>				
<i>Nassarius caelatus</i>				200m
<i>Acila divaricata</i>				500m
<i>Saccella gordonis</i>				300m
<i>Saccella sematensis</i>				450m
<i>Limopsis crenata</i>				1000m
<i>Glycymeris rotunda</i>				300m
<i>Nemocardium samarangae</i>				300m

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 13

Association	Characteristic species	Associated species
a. <i>Peronidia</i> Assoc.	<i>Peronidia zyoensis</i> , <i>Glycymeris yessoensis</i> <i>Mercenaria stimpsoni</i> , <i>Pseudamiantis tauyensis</i>	<i>Felaniella usta</i> , <i>Acila insignis</i> <i>Turritella saishuensis saishuensis</i> <i>Mizuhopecten yessoensis yokoyamae</i>
b. <i>Macoma sector</i> Association	<i>Macoma sector</i> , <i>Acila insignis</i>	<i>Felaniella usta</i> , <i>Clinocardium fastosum</i> <i>Panopea japonica</i>
c. <i>Felaniella</i> Assoc.	<i>Felaniella usta</i> , <i>Acila insignis</i>	<i>Peronidia zyoensis</i> , <i>Clinocardium fastosum</i> <i>Turritella saishuensis saishuensis</i>
d. <i>Clinocardium</i> — <i>Turritella</i> Assoc.	<i>Clinocardium fastosum</i> , <i>Yoldia notabilis</i> <i>Turritella saishuensis saishuensis</i> <i>Acila insignis</i> , <i>Cryptomya busoensis</i> <i>Cryptonatica janthostomoides</i>	<i>Liocyma fluctuosa</i> , <i>Ennucula tenuis</i> <i>Mizuhopecten tokyoensis hokurikuensis</i> <i>Cyclocardia ferruginea</i> , <i>Lucinoma annulata</i> <i>Macoma tokyoensis</i> , <i>Antiplanes contraria</i> <i>Ophiostermella ogurana</i> , <i>Suavodrililla declivis</i>
e. Transitional Association	<i>Yoldia notabilis</i> , <i>Paphia schnelliana</i> <i>Ennucula tenuis</i> , <i>Clinocardium fastosum</i>	<i>Acila insignis</i> , <i>Cryptomya busoensis</i> <i>Turritella saishuensis saishuensis</i> <i>Cryptonatica janthostomoides</i> <i>Tugurium exutum</i> , <i>Nassarius caelatus</i>
f. <i>Barnea</i> Assoc.	<i>Barnea japonica</i>	<i>Tugurium exutum</i>
g. <i>Cycladicama</i> Association	<i>Cycladicama cumingi</i>	<i>Tugurium exutum</i> , <i>Paphia schnelliana</i> <i>Barnea japonica</i>
h. <i>Tugurium</i> — <i>Paphia</i> I Assoc.	<i>Tugurium exutum</i> , <i>Paphia schnelliana</i> <i>Nassarius caelatus</i> , <i>Yoldia notabilis</i>	<i>Saccella gordonis</i> , <i>Limopsis crenata</i>
i. <i>Tugurium</i> — <i>Paphia</i> II Assoc.	<i>Tugurium exutum</i> , <i>Paphia schnelliana</i> <i>Saccella gordonis</i> , <i>Limopsis crenata</i>	<i>Dentalium weinkauffi</i> , <i>Acila divaricata</i> <i>Glycymeris rotunda</i> , <i>Saccella semataensis</i> <i>Nemocardium samarangae</i>

Table 1 Kitamura et al