The sequence of local recolonization of warm-water marine molluscan species during a deglacial warming climate phase: a case study from the early Pleistocene of the Sea of Japan

メタデータ	言語: en
	出版者: Elsevier
	公開日: 2008-01-30
	キーワード (Ja):
	キーワード (En):
	作成者: Kitamura, Akihisa, Ubukata, Takao
	メールアドレス:
	所属:
URL	http://hdl.handle.net/10297/521

The sequence of local recolonization of warm-water marine molluscan species during a deglacial warming climate phase: a case study from the Early Pleistocene of the Sea of Japan

Akihisa Kitamura and Takao Ubukata

Institute of Geosciences, Shizuoka University, 836 Oya, Shizuoka 422-8529, Japan.

Fax: +81-54-238-0491, E-mail: seakita@ipc.shizuoka.ac.jp

Abstract

Changes in the fossil assemblage of offshore molluscs within each sixth-order (41-k.y.) depositional sequence of the early Pleistocene Omma Formation document repeated recolonizations of warm-water species into the Sea of Japan. Each recolonization started as soon as the warm Tsushima Current began to flow in the Sea of Japan during a deglaciation and subsequent interglacial period. Here we examined in detail the stratigraphic distribution of six selected significant warm-water species and calculated confidence intervals for their first (local) appearances in a total of ten deglaciations using continuously sampled data. They were subdivided into two groups, based on the chronological order of their first appearance during warming phases. Comparison of geological with biogeographic data reveals that these migration patterns are not always consistent with the modern geographic distributions of the species. These results show that fossil records may anticipate how the assemblage of local species would change in response to climate warming.

Keywords: molluscs; geographic range; climate warming; Sea of Japan; Early Pleistocene

1. Introduction

   Many paleoecological studies in various regions have demonstrated that communities have responded in a Gleasonian manner (Gleason, 1926) to Quaternary climate change (e.g., Overpeck et al., 1992; Roy et al., 1996; Faunmap Working Group, 1996; Jackson and Overpeck, 2000). Based on Gleasonian theory, the manner of the response of each species to environmental change does not accord with an "ecological succession" (Clements, 1916) but depends on its own specific tolerance. Therefore, modeling the responses of communities to environmental changes throughout the Quaternary period requires an understanding of how each species changes its geographic distribution. During the past few decades, a number of studies have described the changes of molluscan faunas in response to the frequent climatic changes during the Quaternary (e.g., Thomsen and Vorren, 1986; Peacock, 1989; Kanazawa, 1990; Kitamura et al., 1994; Kamataki and Kondo, 1997). However, most of these studies have focused on the replacement of the entire fauna, and little attention has been paid to the timing of migration of each species with climatic change, especially with rapid warming. The present study attempts to clarify the precise pattern of migration for significant warm-water molluscan species during a warming climate phase. The chronological order of the first appearance of such species during seven selected deglaciations in the early Pleistocene of the Sea of Japan provides the data for the study. We estimate confidence intervals for the first (local) stratigraphic occurrences of various warm-water species based on the data of Kitamura (1991) and Kitamura et al. (1999, 2000b), and then determined the timing of recolonization of

each species during the seven deglaciations.

2. Geological setting

The planktonic marine $\delta^{18}O$ record of sediment cores from the Oki Ridge demonstrates increase of sea-surface temperature from 8-12 °C at 10 ka to 17-18 °C at 8 ka, showing the beginning of the inflow of the warm Tsushima Current (Oba et al., 1980). The current has come into the Sea of Japan recurrently during each interglacial stage since oxygen isotope stage 59 (Kitamura et al., 2001). The rapid warming (ca. 3.5°C per 1,000 years) caused by the Tsushima Current may have strongly influenced the marine organisms along the west coast of Japanese Islands throughout the past 1.7 Ma.

The early Pleistocene Omma Formation accumulated on the continental shelf of the Sea of Japan (Fig. 1), and contains abundant fossils of benthic molluscs, ostracods and planktonic foraminifers, which are sensitive to environmental changes (e.g., Kaseno and Matsuura, 1965; Ogasawara, 1977; Cronin and Ikeya, 1987; Kitamura and Kondo, 1990; Beu and Kitamura, 1998; Amano and Vermeij, 1998; Kitamura et al., 1999, 2001; Amano and Watanabe, 2001; Ozawa and Kamiya, 2001). The middle part of this formation at the Okuwa type section (Figs. 1 and 2) is composed of eleven sixth-order (41-k.y.) depositional sequences (the sequence 9 is not exposed) that were deposited in inner- to outer-shelf water depths during the oxygen isotope stages 50 to 28 (Fig. 2) (Kitamura et al., 1994, 2000a; Kondo et al., 1998). These sequences include the following elements, in ascending stratigraphic order: (1) a basal sequence boundary that is superposed on the ravinement surface; (2) a transgressive systems tract (TST) (2-5 m thick) consisting of a basal shell bed (0.3m thick) (a condensed onlap shell bed) and overlying fine- to very-fine-grained sandstone; (3) a maximum flooding horizon that has the highest concentration of sand-size carbonate grains; (4) an highstand systems tract (HST) (2-3 m thick) consisting of fine-grained sandstone and sandy siltstone; and (5) an regressive systems tract (RST) (<1.0 m thick) comprised of a coarsening-upward fine-grained sandstone (Kitamura et al., 2000a). Depositional sequences 1, 6 and 11 include complete sets of TST, HST and RST sediments, while other sequences lack RST and even HST sediments because of shoreface erosion at the superjacent sequence boundary (Kitamura et al., 2001).

The transition of the offshore molluscan fauna in the TST of each depositional sequence always begins with prominence of the cold-water *Felaniella* Association. Subsequently, the *Felaniella* Association is replaced by the cold-water *Clinocardium-Turritella* Association because of the change in substrate from well-sorted sand to muddy sand associated with deglacial sea-level rise. Finally, either the warm-water *Stellaria-Paphia* I Association or *Cycladicama* Association dominates over the fauna. This faunal change was caused by inflow of the warm Tsushima Current and the associated rapid warming (Kitamura et al., 1994, 2000b).

In any depositional sequence, the sediment of the horizon just below the first appearance of warm-water species is a muddy, fine to very fine-grained sandstone with mud content ranging from 15 to

25%. This type of sediment layer characteristically yields a cold-water *Clinocardium-Turritella* Association consisting of *Clinocardium fastosum*, *Turritella saishuensis saishuensis*, *Acila insignis* and *Yoldia notabilis*, which inhabited the upper sublittoral zone from low-water mark to 50-60 m deep (Kitamura et al., 1994, 2001). In other words, a total of ten immigration events of warm-water molluscs happened under almost the same conditions of sedimentation and water depth. The mollusc assemblages do not contain post-mortem transport of species from other habitats, because many fossil specimens of bivalves are found with their valves articulated. The within-habitat mixing of skeletal elements had been restricted to a surface layer about 10 cm thick throughout deposition of the muddy, fine to very fine-grained sandstone at the transition from glacial to interglacial stages (Kitamura, 1992). Using an average sedimentary rate from the three best-preserved depositional sequences (17.5cm/1000 yrs), persistence of warm-water species at the studied area are time-averaged at an estimated 5,000 to 10,000 years and about 600 years, respectively.

3. Methods

The definition of cold- and warm-water mollusc assemblage of the Omma Formation is based on the modern geographic distribution of living representatives of the species along the continental shelves of Japan. The warm Kuroshio Current veers away from the Japanese Islands at the Boso Peninsula at 35° N latitude (Fig. 1a), which is recognized as a biogeographic discontinuity for marine animals. For this reason, the term "warm-water species", in Japan, has been used to represent the species which lives south of 35° N at present, while "cold-water" usually qualifies the species living north of 35° N.

The 50%, 80% and 95% confidence intervals were calculated for the true first appearance of warm-water species within each depositional sequence, according to Marshall (1997). Since the fossil record is generally incomplete, using the observed range of stratigraphic occurrence of a species may lead us to underestimate the true range of the species. The method of assessing the confidence intervals on stratigraphic ranges, pioneered by Strauss and Sadler (1989) and established by Marshall (1990, 1997), allows an estimation of the stratigraphic range of the species in terms of statistics. When the distribution of a fossil horizon is nonrandom, calculation of the confidence interval on the stratigraphic range of the species requires not only a measure of the number of individuals, but also the fossil recovery potential function. In this case, the method for calculating the confidence interval is applicable only to continuously sampled sections. Consequently, we use the total number of fossils recovered from continuously sampled sections (Kitamura, 1991; Kitamura et al., 1999, 2000b) as a density-distribution function representing the fossil recovery potentiality.

For all *in situ* specimens examined, each individual was taxonomically identified and the number of the individuals within a sample was counted. Each sample consisted of a rectangular sandstone block with the long side being parallel to the strike of the strata, 0.5 m in width and 2.0 m in length on the average. The surfaces of the exposures were so uneven that the thickness of the block ranged from 0.05 to 0.5 cm

depending on the conditions of the section. For disarticulated shells, separated valves were counted and the totals were divided by two to determine the number of individuals. As mentioned above, the mixing of shells was restricted to a surface layer about 10 cm thick throughout deposition of the muddy sand yielding warm-water species. Consequently, the accuracy of the chronological order of immigration of individual is 10 cm in thickness.

In the present study, the following three sequences have been excluded for the following reasons: (1) within depositional sequence 4, no warm-water species occur except for *Stellaria exutum*; (2) in depositional sequence 7, all of the warm-water species excluding *Paphia schnelliana* are found in no more than a single horizon within the sequence; and (3) since depositional sequence 8 has been assigned to two obliquity cycles (Shackleton et al., 1990), the stratigraphic distribution of warm-water species in this sequence is considered to be too complex for the analytical approach.

4. Results

In the present study, we focus on the six species among significant warm-water species in the middle part of the Omma Formation, because their confidence intervals were successfully determined in more than three depositional sequences. All of them are extant species on the shelf around Japan (Kitamura et al., 1994). The 50%, 80% and 95% confidence intervals for them within each depositional sequence are shown in Figures. 3 to 9. Most of the 95% confidence intervals extend across the lower sequence boundary. Within each depositional sequence, molluscan fossils are rare in the horizon represented by the cold-water *Clinocardium-Turritella* Association, compared with the horizon yielding warm-water species. The significant difference of fossil abundance among horizons reflects the difference of the rate of sedimentation between the early and late transgressive phases (Kondo et al., 1998). In the present analysis, low abundances of cold-water species resulted in considerably wide confidence intervals, especially at the 95% level.

In any depositional sequence, the bottom of the 50% confidence interval of *Jupiteria gordonis* is stratigraphically situated above the base of the observed range of *Paphia schnelliana* (except for the sequence 3), *Stellaria exutum*, *Zeuxis castus* and *Cycladicama cumingi* (Figs. 4, 5, 8 and 9). In depositional sequence 10, the bottom of the 80% confidence interval of *J. gordonis* is much higher than that of the observed range of *P. schnelliana* and *C. cumingi* (Fig. 8). In depositional sequence 2, the bottom of the 80% confidence interval of *Crenulilimopsis oblonga* is located above the base of the observed range of *S. exutum* and *Z. castus* (Fig. 8). These results clearly show that, in immigration events during climate warming, *J. gordonis* tended to lag behind *P. schnelliana*, *S. exutum*, *Z. castus* and *C. cumingi*, while *S. exutum* and *Z. castus* heralded the coming of *C. oblonga*.

5. Discussion and conclusions

As far as the above-mentioned six species are concerned, there is no evidence that ecological factors,

4

such as competition or predation, restrict the geographic distribution of these species. In addition, some of the six species often co-occur with each other and with other species within a single stratigraphic horizon in the Omma Formation (Kitamura, 1991). For these reasons, we believe that neither competition nor predation is a major factor controlling the timing of immigration of each species with climatic change. Comparison of the stratigraphic order of the first appearance of the six species with the modern geographic distribution relies on the assumption that tolerance of these species to environmental change has not significantly change throughout the Quaternary period. Consequently, data on the modern geographic distribution of the six species provide a reliable constraint on modeling the migration of offshore molluscs during a climatic warming phase (Table 1).

The first appearance of *J. gordonis* within a sequence tends to be later than other significant species. Based on the northern limits of geographic distribution and bathymetric ranges at present, *J. gordonis* appears to have a lower tolerance to a low temperature than other species. This fact explains well why its immigration is so late during a warming climate phase. On the other hand, *C. oblonga* lives particularly in deeper water among the six species. Thus, its bathymetric range and/or dispersal capability of larvae may be the reasons for the relatively later immigration of *C. oblonga* during a deglacial warming climate phase.

Because the modern northern limit of distribution of *S. exutum* is more restricted than that of *P. schnelliana, Z. castus, C. cumingi* and *C. oblonga*, its immigration would be expected to follow them. Nevertheless, significant differences are not found in the timing of immigration between *S. exutum* and the latter four species. In the present study, there is no data on the environmental change itself during deglaciations and its influences on the manner of migration of warm-water species. Thus, the reason for the unexpectedly early immigration of *S. exutum* is still uncertain. A possible answer for this question may lie in the high dispersal capability of its larval stage. If so, absence of the significant species except for *S. exutum* in the depositional sequence 4 may imply that the warming during transition from oxygen isotope stages 44 to 43 was so rapid that these warm-water species could not spread their geographic distributions because of their low dispersal capability.

Analyses of fossil shallow marine molluscs of the early Pleistocene Omma Formation demonstrate that the chronological order of immigration of the warm-water species was not always consistent with their modern geographic distributions. This inconsistency may be caused by difference in dispersal capabilities among the species. Therefore detailed information on larval ecology as well as physiological tolerances is necessary to determine how marine molluscs respond to rapid climatic warming. The approach in this study is useful for addressing the issue.

References

Amano, K., Vermeij, G.J., 1998. Taxonomy and evolution of the genus *Ocinebrellus* (Gastropoda: Muricidae) in Japan. Paleont. Res. 2, 199-212.

Amano, K., Watanabe, M., 2001. Taxonomy and distribution of Plio-Pleistocene *Buccinum* (Gastropoda: Buccinidae) in northeast Japan. Paleont. Res. 5, 215-226.

Berger, W.H., Yasuda, M.K., Bickert, T., Wefer, G., Takayama, T., 1994. Quaternary time scale for the Ontong Java Plateau: Milankovitch template for Ocean Drilling Program Site 806. Geology 22, 463-467.

Beu, A., Kitamura, A., 1998. Exposed coasts vs sheltered bays: contrast between New Zealand and Japan in the molluscan record of temperature change in Plio-Pleistocene cyclothems. Sediment. Geol. 122, 129-149.

Clements, F. E., 1916. Plant succession: An analysis of the development of vegetation. Publication 242. Washington, D. C. Carnegie Institution of Washington.

Cronin, T.M., Ikeya, N., 1987. The Omma-Manganji ostracod fauna (Plio-Pleistocene) of Japan and zoogeography of circumpolar species. Jour. Micropalaeontol. 6, 65-88.

Faunmap Working Group, 1996. Spatial response of mammals to late Quaternary environmental fluctuations. Science 272, 1601-1606.

Gleason, H.A., 1926. The individualistic concept of plant association. Torrey Biological Club Bull, 53, 7-26.

Higo, S., Callomon, P., Goto, Y., 1999. Catalogue and bibliography of the marine shell-bearing mollusca of Japan. 749p. Pub. Elle Corporation, Osaka.

Higo, S., Goto, Y., 1993. A systematic list of molluscan shells from the Japanese Is. and the adjacent area. 693p. Pub. Elle Corporation, Osaka.

Ishiyama, S., 1973. Distribution of mollusks and environment off Iwate Prefecture, North Japan. Geol. Survey Jpn, Bull. 24, 519-528 (in Japanese).

Ito, K., 1989. Distribution of molluscan shells in the coastal areas of Chuetsu, Kaetsu and Sado Island, Niigata Prefecture, Japan. Bull. Japan Sea Reg. Fish. Res. Lab. 39, 37-133 (in Japanese with English abstract).

Ito, K., Matano, Y., Yamada, Y., Igarashi, S., 1986. Shell species caught S/S Rokko-Maru off the coast Ishikawa Prefecture. Bulletin Ishikawa Prefectural Fisheries Experimental Station, 4, 1-179 (in Japanese with English abstract).

Jackson, S.T., Overpeck, J.T., 2000. Responses of plant populations and communities to

environmental changes of the late Quaternary. In: Erwin, D.H., Wing, S.L. (Eds), Deep Time: Paleobiology's Perspective. The Paleontological Society, 194-220.

Kamataki, T., Kondo, Y., 1997. 20,000 or 40,000-year depositional sequences caused by glacio-eustatic sea-level fluctuation in the middle Pleistocene Jizodo Formation, Boso Peninsula, central Japan. J. Geol. Soc. Jpn. 103, 747-762 (in Japanese with English abstract).

Kanazawa, K., 1990. Early Pleistocene glacio-eustatic sea-level fluctuations as deduced from periodic changes in cold- and warm-water molluscan associations in the Shimokita Peninsula, Northeast Japan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 79, 263-273.

Kaseno, Y., Matsuura, N., 1965. Pliocene shells from the Omma Formation around Kanazawa City, Japan. Sci. Rep., Kanazawa Univ. 10, 27-62.

Kitamura, A., 1991. The stratigraphic distribution of the molluscan fossil species in the cycle of the middle part of the Omma Formation, Central Honshu, Japan. Sci. Rep. Kanazawa Univ. 36, 31-47.

Kitamura, A., 1992. Time resolution in paleoenvironmental analysis based on mode of occurrence of bivalve fossils - a case study for the middle part of the early Pleistocene Omma Formation, Kanazawa. J. Geol. Soc. Jpn. 98, 1031-1039 (in Japanese with English abstract).

Kitamura, A., 1998. Glaucony and carbonate grains as indicators of the condensed section: Omma Formation, Japan. Sediment. Geol. 122, 151-163.

Kitamura, A., Kondo, Y., 1990. Cyclic change of sediments and molluscan fossil associations caused by glacio-eustatic sea-level changes during the early Pleistocene -a case study of the middle part of the Omma Formation at the type locality. J. Geol. Soc. Jpn. 96, 19-36 (in Japanese with English abstract).

Kitamura, A., Kondo, Y., Sakai, H., Horii, M., 1994. 41,000-year orbital obliquity expressed as cyclic changes in lithofacies and molluscan content, early Pleistocene Omma Formation, central Japan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 112, 345-361.

Kitamura, A., Matsui, H., Oda, M., 1999. Change in the thickness of the warm Tsushima Current at the initiation of its flow into the Sea of Japan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 152, 305-318.

Kitamura, A., Matsui, H., Oda, M., 2000a. Constraints on the timing of systems tract development with respect to sixth-order (41 ka) sea-level changes: an example from the Pleistocene Omma Formation, Sea of Japan. Sediment. Geol. 131, 67-76.

Kitamura, A., Omote, H., Oda, M., 2000b. Molluscan response to early Pleistocene rapid warming in the Sea of Japan. Geology 28, 723-726.

Kitamura, A., Takano, O., Takada, H., Omote, H., 2001. Late Pliocene-early Pleistocene paleoceanographic evolution of the Sea of Japan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 172, 81-98.

Kondo, Y., Abbott, S.T., Kitamura, A., Naish, T., Kamp, P.J.J., Kamataki, T., Saul, G. S., 1998. The relationship between shellbed type and sequence architecture: Examples from Japan and New Zealand. Sediment. Geol. 122, 109-127.

Marshall, C.R., 1990. Confidence intervals on stratigraphic ranges. Paleobiology 16, 1-10.

Marshall, C.R., 1997. Confidence intervals on stratigraphic ranges with nonrandom distributions of fossil horizons. Paleobiology 23, 165-173.

Oba, T., Horibe, Y., Kitazato, H., 1980, Analysis of the paleoenvironment since the last glacial age based on two cores from the Japan Sea. Archeol. Nat. Sci., 13, 31-49. (in Japanese with English abstract).

Ogasawara, K., 1977. Paleontological analysis of Omma Fauna from Toyama-Ishikawa area, Hokuriku Province, Japan. Sci. Rep. Tohoku Univ., 2nd Ser. (Geol.), 47, 43-156.

Okutani, K., Kubodera, T., Kurozumi, T., Saito, H., Sasaki, T., Tsuchida, E., Tsuchiya, K., Hasegawa, K., Hamatani, I., Hayami, I., Hori, S., Matsukuma, A., 2000, Marine mollusks in Japan. 1173p. Tokai University, Tokyo.

Overpeck, J.T., Webb, R.S., Webb, T.III, 1992. Mapping eastern North American vegetation change of the past 18 ka: No-analogs and the future. Geology 20, 1071-1074.

Ozawa, H., Kamiya, T., 2001. Palaeoceanographic records related to glacio-eustatic fluctuations in the Pleistocene Japan Sea coast based on ostracods from the Omma Formation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 170, 27-48.

Peacock, J.D., 1989. Marine molluscs and late Quaternary environmental studies with particular reference to the last-glacial period in Northwest Europe: a review. Quat. Sci. Rev. 8, 179-192.

Roy, K., Valentine, J.W., Jablonski, D., Kidwell, S.M., 1996. Scales of climatic variability and time averaging in Pleistocene biotas: Implications for ecology and evolution. TREE. 11, 458-463.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., Backman, J., 1989. Pleistocene evolution: Northern hemisphere ice sheets and North Atlantic Ocean. Paleoceanog. 4, 353-412.

Shackleton, N.J., Bergeret, A., Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Trans. Royal Soc. Edinburgh Earth Sciences 81, 251-261.

Strauss, D., Sadler, P.M., 1989. Classical confidence intervals and Bayesian probability estimates for ends of local taxon ranges. Mathemat. Geol. 21, 411-427.

Takayama, T., Kato, M., Kudo, T., Sato, T., Kameo, K., 1988. Calcareous microfossil biostratigraphy of the uppermost Cenozoic formations distributed in the coast of the Japan Sea, Part 2: Hokuriku sedimentary basin. Jour. Jpn. Assoc. Petrol. Tech. 53, 9-27 (in Japanese with English abstract).

Takayasu, T., Yunohara, N., 1977. Distribution of recent molluscan shells off Oga Peninsula, Akita Prefecture, Japan. Memorial Volume of Professor Kazuo Huzioka, 385-400 (in Japanese with

English abstract).

Thomsen, E., Vorren, T.O., 1986. Macrofaunal palaeoecology and stratigraphy in late Quaternary shelf sediments off Northern Norway. Palaeogeogr. Palaeoclimatol. Palaeoecol. 56, 105-150.

Tsuchida, E., 1991. Fauna of marine mollusks of the sea around Otsuchi Bay, Iwate Prefecture (2) Neogastropoda. Otsuchi Mar. Res. Cent. Rep. 17, 1-27. (in Japanese with English abstract).

Tsuchida, E., Hayashi, I., 1994. Characteristics of lower-sublittoral and bathyal molluscs in the western area of the Sea of Japan. Bull. Japan Sea Natl. Fish. Res. Inst., 44, 81-129. (in Japanese with English abstract).

Tsuchida, E., Kurozumi, T., 1993. Fauna of marine mollusks of the sea around Otsuchi Bay, Iwate Prefecture (4) Bivalvia-1. Otsuchi Mar. Res. Cent. Rep. 19, 1-30. (in Japanese with English abstract).

Tsuchida, E., Kurozumi, T., 1996. Fauna of marine mollusks of the sea around Otsuchi Bay, Iwate Prefecture (6) Bivalvia-3. Otsuchi Mar. Res. Cent. Rep. 21, 1-31. (in Japanese with English abstract).

Valentine, J.W., Jablonski, D., 1993. Fossil communities: Compositional variation at many time scales. In: Ricklefs, R.E., Schluter, D. (Eds), Species diversity in ecological communities: Historical and geographical perspectives. Chicago, University of Chicago Press, 341-349.

Figure captions

Figure 1. The Sea of Japan and surrounding region (a), showing location of Omma Formation (b and c).

Figure 2. Comparison between the stratigraphic distribution of molluscan 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. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 1 of the Omma Formation. The total numbers of molluscan fossils include those of cold-water, extinct cold-water and intermediate species. Transitional association consists of mixture of both cold- and warm-water elements. Horizons represent the level (m) above the top of the basal shell bed. Gray shaded areas indicate observed stratigraphic ranges. Line represents: double line, bottom of the 50% confidence interval; broken line, bottom of the 80% confidence interval; bold line, bottom of the 95% confidence interval. The bottom of the 95% confidence interval of *Cycladicama cumingi* extends across the lower sequence boundary. TST: transgressive systems tract, HST: highstand systems tract, RST: regressive systems tract. (1) cold-water *Megangulus* Association.

Figure 4. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 2 of the Omma Formation. See legend in Fig. 3.

Figure 5. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 3 of the Omma Formation. (1) *Felaniella* Association. See legend in Fig. 3.

Figure 6. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 5 of the Omma Formation. (1) *Clinocardium-Turritella* Association. See legend in Fig. 3.

Figure 7. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 6 of the Omma Formation. (1) *Felaniella* Association, (2) *Clinocardium-Turritella* Association. See legend in Fig. 3.

Figure 8. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 10 of the Omma Formation. (1) an interval barren of molluscs (Kitamura et al., 2000b), (2) *Felaniella* Association. See legend in Fig. 3.

Figure 9. The 50%, 80% and 95% confidence intervals for selected warm-water species within the depositional sequence 11 of the Omma Formation. See legend in Fig. 3.

Table 1. Water temperature conditions in the northern limits of the six selected warm-water species.
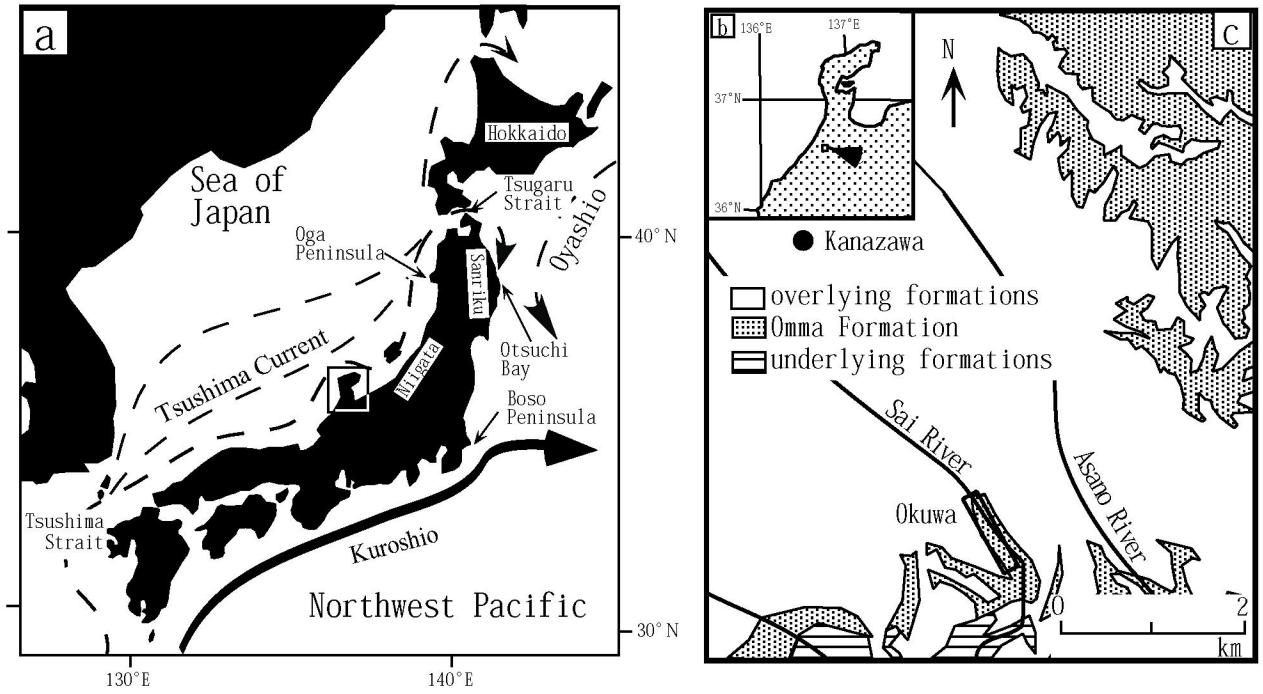
Fig. 1 Kitamura & Ubukata
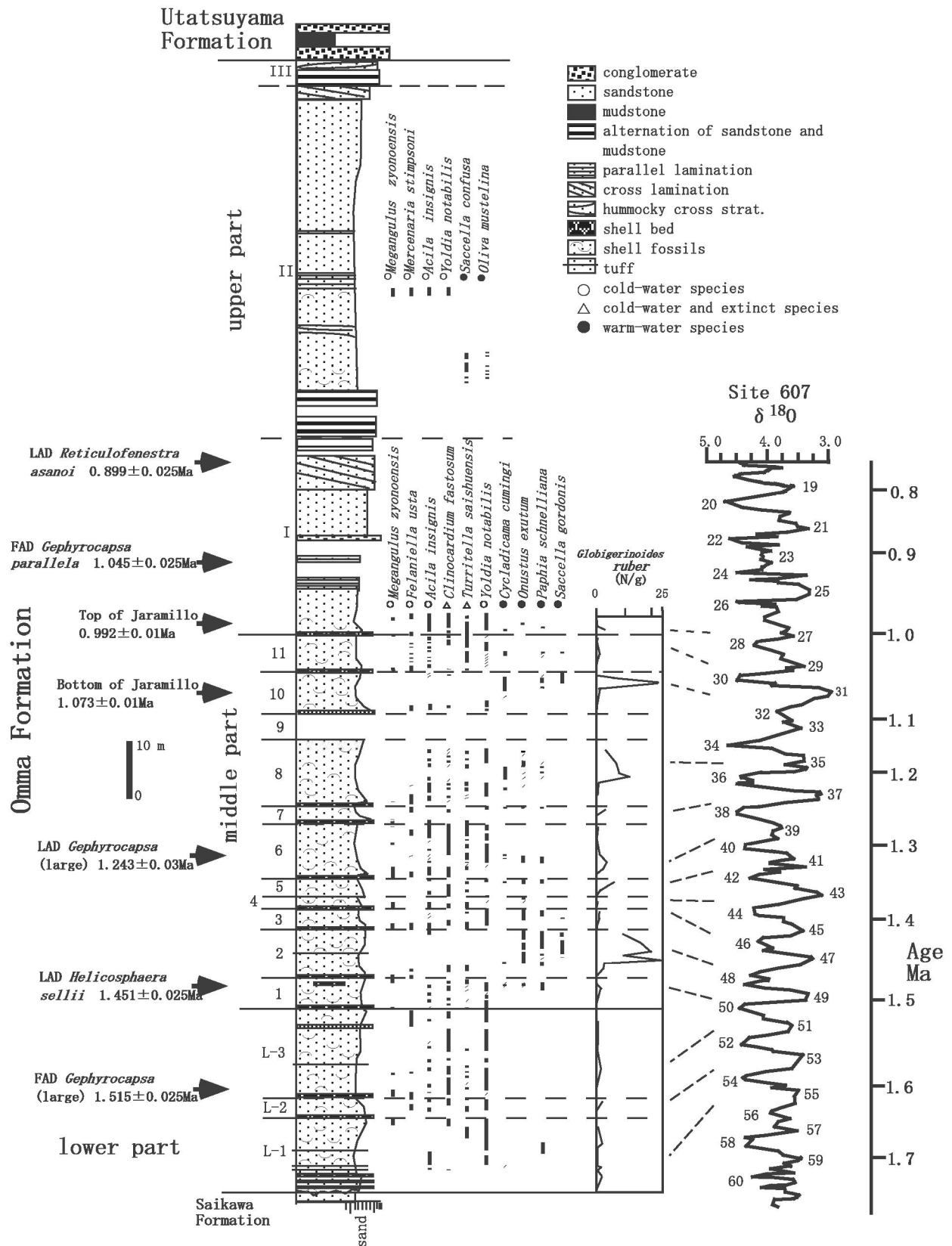
Fig. 2 Kitamura & Ubukata

Horizons	molluscan association	Paphia schne-lliana	Stellaria exutum	Zeuxis castus	Cycladicama cumingi	Jupiteria gordonis	Crenuli-limopsis oblonga	Total numbers of molluscan fossils	sequence stratigraphic interpretation
7.3-7.55	warm-water *Stellaria-Paphia* II Association	1	0	0	0	1	1	13	HST
7.05-7.3		0	2	0	0	0	1	12	
6.8-7.05		1	3	0	0	2	2	13	
6.55-6.8		1	3	0	0	2	0	14	
6.3-6.55		1	2	0	0	1	3	11	
5.9-6.3		2	3	0	0	1	5	31	
5.5-5.9		1	2	0	0	0	8	24	
5.25-5.5		1	0	0	0	1	8	24	
5.0-5.25		3	3	0	0	1	2	18	
4.75-5.0		1	1	0	0	4	1	30	
4.5-4.75		1	6	0	0	1	3	24	
4.25-4.5	warm-water *Stellaria-Paphia* I Association	2	4	0	0	2	0 ↓50	20	
4.0-4.25		0	0	0	0	1	0 ↓80	3	
3.75-4.0		0	1	0	0	1	0	3	TST
3.5-3.75		0	1	0	0	2	0	2	
3.25-3.5		2	1	0	0	2	0	7	
3.0-3.25		2	3	0	0	1	0	10	
2.75-3.0		0	4	0	0	3	0	16	
2.5-2.75		1	1	0	0	3	0	11	
2.25-2.5		0	1	0	0	0	0	4	
2.0-2.25		2	1	0	0	0	0	6	
1.75-2.0		2	1	0	0	1	0	6	
1.55-1.75		1	1	1	1	0	0	6	
1.4-1.55		0	1	3	1	0 ↓50	0 ↓95	5	
1.25-1.4		1	0	1	0	0	0	2	
1.05-1.25	*Clinocardium-Turritella* Association	0	0	0 ↓50	0	0	0	5	
0.75-1.05		0	0 ↓50	0	0 ↓50	0	0	6	
0.5-0.75		0	0	0	0	0 ↓80	0	1	
0.25-0.5		0 ↓50	0	0	0	0	0	2	
0.0-0.25		0	0	0 ↓80	0	0	0	3	

↓ 80, 95   ↓ 80, 95   ↓ 95   ↓ 80, 95   ↓ 95

Kitamura, Ubukata Fig. 4

Horizons	molluscan association	*Paphia schne-lliana*	*Stellaria exutum*	*Zeuxis castus*	*Jupiteria gordonis*	Total numbers of molluscan fossils	sequence stratigraphic interpretation
3.4-3.9	*Stellaria -Paphia* I Association	4	6	0	0	30	TST
3.0-3.4		3	2	0	0	8	
2.8-3.0		2	5	0	0	12	
2.6-2.8		3	1	1	1	13	
2.3-2.6		1	2	1	1	12	
1.9-2.3		1	5	6	0	21	
1.5-1.9		0 $\downarrow_{50}$	5	4	0 $\downarrow_{50}$	22	
1.25-1.5	*Clinocardium - Turritella* Association	0 $\downarrow_{80}$	5	0	0	7	
1.0-1.25		0	4	0	0	10	
0.9-1.0		0	0	0 $\downarrow_{50}$	0	7	
0.5-0.9		0 $\downarrow_{95}$	0 $\downarrow_{50}$	0 $\downarrow_{80}$	0	42	
0.0-0.5	(1)	0	0 $\downarrow_{80,\,95}$	0 $\downarrow_{95}$	0 $\downarrow_{80}$	51	

$\downarrow_{95}$

Kitamura, Ubukata Fig. 5

Horizons	molluscan association	*Paphia schnelliana*	*Stellaria exutum*	*Zeuxis castus*	*Cycladi-cama cumingi*	*Crenuli-limopsis oblonga*	Total numbers of molluscan fossils	sequence stratigraphic interpretation
3.75-3.85	(1)	0	1	0	0	2	19	
3.65-3.75	*Stellaria -Paphia* I Association	0	2	4	1	2	15	
3.55-3.65		1	1	1	1	4	16	
3.45-3.55		0	5	1	0	2	12	
3.35-3.45		0	1	1	0	1	10	
3.25-3.35		0	1	4	0	0	7	
3.15-3.25		1	2	0	0 ↓$_{50}$	0	8	TST
3.05-3.15	*Clinocardium - Turritella* Association	0	1	0		2	11	
2.9-3.05		0	1	1	0	0	11	
2.75-2.9		0	1	0	0	0 ↓$_{50}$	9	
2.6-2.75		0	0	0 ↓$_{50}$	0	0	6	
2.1-2.6		0 ↓$_{50}$	0 ↓$_{50}$	0	0	0 ↓$_{80}$	14	
1.6-2.1		0	0 ↓$_{80}$	0 ↓$_{80}$	0	0	9	
1.1-1.6		0	0	0	0	0	3	
0.7-1.1		0	0	0	0	0	2	
0.3-0.7		0	0	0	0	0	7	
0.0-0.3		0	0	0	0	0	2	
		↓$_{80, 95}$	↓$_{95}$	↓$_{95}$	↓$_{80, 95}$	↓$_{95}$		

Kitamura, Ubukata Fig. 6

Horizons	molluscan association	*Paphia schne-lliana*	*Stellaria exutum*	*Zeuxis castus*	*Cycladi-cama cumingi*	*Crenuli-limopsis oblonga*	Total numbers of molluscan fossils	sequence stratigraphic interpretation
7.9-8.3	*Clinocardium - Turritella* Association	0	0	0	0	0	16	RST
7.8-7.9		0	0	0	0	0	16	
7.7-7.8		0	0	0	0	0	18	
7.6-7.7		0	0	0	0	0	18	
7.5-7.6		0	0	0	0	0	16	
7.3-7.5		0	0	0	0	0	35	
7.1-7.3		0	0	0	0	0	23	
6.8-7.1		0	0	0	0	0	18	
6.5-6.8		0	0	0	0	0	34	
6.2-6.5		0	0	0	0	0	55	
6.0-6.2		0	0	0	0	0	34	
5.8-6.0		0	0	0	0	0	36	
5.6-5.8		0	0	0	0	0	31	
5.4-5.6		0	0	0	0	0	29	
5.2-5.4		0	0	0	0	0	26	
5.0-5.2		0	0	0	0	0	16	
4.8-5.0		0	0	0	0	0	14	
4.6-4.8		0	0	0	0	0	9	
4.3-4.6		0	0	0	0	0	23	
4.0-4.3		0	0	0	0	1	25	
3.7-4.0		0	0	0	0	1	17	
3.4-3.7		0	0	0	0	0	40	
3.1-3.4		0	0	0	0	6	27	
2.9-3.1	*Stellaria - Paphia* I Association	1	2	1	0	5	58	HST
2.7-2.9		9	5	5	2	4	57	
2.5-2.7		1	3	2	0	2	31	
2.3-2.5		2	3	2	0	3	27	
2.1-2.3		2	3	2	1	1	15	
1.9-2.1		2	6	0	0	2	24	TST
1.7-1.9		2	2	0	0	1	7	
1.5-1.7		2	2	0	0	0	16	
1.3-1.5		1	2	1	0	0	19	
1.1-1.3		0	0	0	0	0 ↓50	7	
0.9-1.1	(2)	0	0	0	0	0	8	
0.5-0.9		0 ↓50	0 ↓50	0	0	0 ↓80	10	
0.0-0.5	(1)	0 ↓80	0 ↓80	0 ↓50	0	0	30	
		↓95	↓95	↓80,95	↓50,80,95	↓95		

Kitamura, Ubukata Fig. 7

Horizons	molluscan association	*Paphia schnelliana*	*Cycladicama cumingi*	*Jupiteria gordonis*	Total numbers of molluscan fossils	sequence stratigraphic interpretation
7.0-7.2	(2)	0	0	5	55	HST
6.8-7.0	*Clinocardium - Turritella* Association	0	0	7	13	
6.6-6.8		1	0	6	20	
6.4-6.6		0	0	9	20	
6.2-6.4		0	0	7	20	
6.0-6.2		2	0	13	23	
5.8-6.0		2	0	18	28	
5.6-5.8		1	3	18	29	
5.4-5.6		0	4	15	30	
5.2-5.4	warm-water *Cycladicama* Association	1	10	3	20	
5.0-5.2		0	6	1	11	
4.8-5.0		0	1	0	3	
4.6-4.8		0	5	0	7	
4.4-4.6		0	4	0 ↓50	6	
4.2-4.4		0	6	0	7	
4.0-4.2		0	2	0	3	
3.8-4.0		0	3	0 ↓80	3	
3.6-3.8		0	2	0	2	TST
3.4-3.6		0	3	0	3	
3.2-3.4		0	1	0	1	
3.0-3.2		1	3	0	4	
2.8-3.0		0	0	0	0	
2.6-2.8		0	0	0	1	
2.4-2.6		0	3	0	3	
2.2-2.4		0	1	0	1	
2.0-2.2	(1)	0	0	0	0	
1.8-2.0		0	0	0	2	
1.6-1.8		0	0	0	0	
1.4-1.6	*Clinocardium - Turritella* Association	0	0	0	4	
1.2-1.4		0	0 ↓50	0	10	
1.0-1.2		0	0 ↓80	0	13	
0.8-1.0		0	0 ↓95	0	20	
0.6-0.8		0 ↓50	0	0 ↓95	17	
0.4-0.6	*Felaniella* Association	0	0	0	19	
0.2-0.4		0 ↓80	0	0	46	
0.0-0.2		0	0	0	30	

↓95

Kitamura, Ubukata Fig. 8

Horizons	molluscan association	*Paphia schnelliana*	*Cycladicama cumingi*	*Jupiteria gordonis*	Total numbers of molluscan fossils	sequence stratigraphic interpretation
7.38-7.68		0	0	0	17	
6.98-7.38		0	0	0	35	
6.58-6.98		0	0	0	13	
6.18-6.58		0	0	0	6	
5.78-6.18		0	0	0	32	
5.68-5.78		0	0	0	3	
5.58-5.68		0	0	0	5	
5.48-5.58		0	0	0	15	
5.28-5.48		0	0	0	88	
5.13-5.28		0	0	0	15	
5.03-5.13	*Clinocardium-Turritella* Association	0	0	0	38	RST
4.93-5.03		0	0	0	27	
4.63-4.93		0	0	0	33	
4.53-4.63		0	0	0	16	
4.43-4.53		0	0	0	9	
4.33-4.43		0	0	0	7	
4.23-4.33		0	0	0	13	
4.13-4.23		0	0	0	9	
4.03-4.13		0	0	0	11	
3.93-4.03		0	0	0	9	
3.83-3.93		0	0	0	13	
3.68-3.83		0	0	0	15	
3.58-3.68		0	3	0	23	
3.43-3.58		1	11	1	26	HST
3.33-3.43	*Cycladicama* Association	1	15	1	21	
3.18-3.33		0	19	0	30	
3.08-3.18		0	6	0 ↓ 50	22	
2.98-3.08		2	10	0	28	
2.88-2.98		0	4	0	9	
2.78-2.88		1	0	0	16	
2.68-2.78		0	0	0	7	
2.58-2.68		0	0 ↓ 50	0	9	
2.48-2.58		0	0	0	8	
2.38-2.48		0	0	0	3	
2.28-2.38		0	0 ↓ 80	0	6	
2.13-2.28		0 ↓ 50	0	0	8	
2.05-2.13	*Clinocardium-Turritella* Association	0	0	0	20	TST
1.9-2.05		0	0	0	22	
1.6-1.9		0 ↓ 80	0 ↓ 95	0 ↓ 80	16	
1.53-1.60		0	0	0	3	
1.45-1.53		0	0	0	12	
1.35-1.45		0	0	0	17	
1.3-1.35		0	0	0	8	
1.1-1.3		0	0	0	7	
1.05-1.1		0	0	0	6	
0.9-1.05		0	0	0	15	
0.8-0.9		0	0	0	15	
0.4-0.8		0	0	0	6	
0.3-0.4		0	0	0	24	
0.2-0.3		0	0	0	8	
0.1-0.2		0	0	0	8	
0.0-0.1		0	0	0	25	

↓ 95 (under *Paphia schnelliana*)   ↓ 95 (under *Jupiteria gordonis*)

Kitamura, Ubukata Fig. 9

species	common habitat depth	northern limit	bathymetrical range in northern limit	minimum and maximum bottom water temperatures in northern limit	References
Zeuxis castus	10-200 m	Otsuchi Bay at the northern Sanriku coast	20-70 m	6°C and 16-20°C at 20-70 m deep	Tsuchida (1991)
Cycladicama cumingi	10-50 m	northern Sanriku coast	10-200 m	6°C and 16-20°C at 20-70 m deep	Ishiyama (1973)
Paphia schnelliana	10-100 m	Otsuchi Bay at the northern Sanriku coast	90 m	6°C and 16-20°C at 20-70 m deep	Tsuchida and Kurozumi (1996)
Crenulilimopsis oblonga	50-200 m	Otsuchi Bay at the northern Sanriku coast	50-150 m	6°C and 16-20°C at 20-70 m deep	Tsuchida and Kurozumi (1993)
Stellaria exutum	20-350 m	off the Oga peninsula	20-40 m	9°C and 20-23°C at 30 m deep	Higo and Goto (1993), Higo et al. (1999)
Jupiteria gordonis	20-200 m	off northern Niigata area	20-100 m	9-10°C and 15°C at 100 m deep	Takayasu and Yuzuhara (1977), Ito et al. (1986), Ito (1990), Tsuchida and Hayashi (1994)

Kitamura, Ubukata Table 1