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OSTRACODE EVIDENCE FOR THE PALEOCEANOGRAPHIC CHANGE OF THE MIDDLE PLEISTOCENE JIZODO AND YABU FORMATIONS IN THE BOSO PENINSULA, CENTRAL JAPAN

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Abstract: Extensive study of ostracode assemblages revealed changes of current system and oceanic thermal structure of the Paleo-Tokyo Bay during deposition of the middle Pleistocene Jizodo and Yabu Formations in the Boso Peninsula, central Japan. After reviewing ecological data of extant species around the Japanese Islands, biogeographically and bathymetrically characteristic ostracode species were used to estimate the paleoenvironmental changes of the two formations. Results supported the previous interpretation that each formation was deposited during one glacial-interglacial climatic change. The results also showed that the water was not as cold as previously inferred and the cool-warm change was caused by the alternation of the relatively cooler Tsugaru Warm and Kuroshio Warm Currents, and not of the Oyashio Cold and Kuroshio Warm Currents. The thermal environment at the maximum paleo-depth was found to be different between the two formations---the warmest in the Yabu Formation and unexpectedly cool in the Jizodo Formation. This was probably related to the influx of the Tsushima-Tsugaru Current that was sufficiently energized to advance south, reaching the Boso area and crept under the Kuroshio water only at the maximum depth of the Jizodo Formation. This is the first successful reconstruction of paleoceanic structure for the middle Pleistocene Shimosa Group, in the Boso Peninsula.

Key words: Ostracoda, middle Pleistocene, Jizodo and Yabu Formations, current system, oceanic thermal structure, Paleo-Tokyo Bay.

1. Introduction

In the northern Boso Peninsula on the Pacific side of central Japan, middle Pleistocene shallow marine deposits are widely distributed. They are called the Jizodo and Yabu Formations in the Shimosa Group. Many stratigraphical and paleontological studies, particularly regarding molluscs, have been published since Yokoyama (1922). The two formations are considered to be the deposits of the "Paleo-Tokyo Bay" which is thought to have been broadly opened eastwards and narrowly opened southwards to the Pacific Ocean. Previous works recognized a cyclic lithological change in each formation (Nakagawa, 1960; Sugihara *et al*., 1978; Kikuchi *et al*., 1988; Tokuhashi and Kondo, 1989). The lithofacies changes from non-marine mud to marine sand from the base to the top of both formations. The marine deposit is accompanied by a cold water molluscan assemblage (upper sublittoral) at the beginning, which changes to a warm water (lower sublittoral) assemblage at the middle, and back to a cold water (upper sublittoral) assemblage again in the upper horizon. It has been proposed that the changes of molluscan assemblages have been caused by glacio-eustatic sea-level changes (Aoki and Baba, 1973; Kondo, 1989).

The ostracodes from the two formations were described and used for paleoenvironmental studies (Yajima, 1978, 1982; Moriya, 1982MS). In these previous works, however, the sampling horizons were sporadic, and the detailed discussion on changes of the sedimentary environment on the basis of ostracode faunal analysis, i.e. water depth and relative water temperature, have not been completed. From this point to the present, living ostracode faunas around the Japanese Islands have been extensively studied, e.g. in the Ise and Mikawa Bays (Bodergat and Ikeya, 1988), Toyama Bay (Ishizaki and Irizuki, 1990), Sendai Bay (Ikeya and Itoh, 1991), Otsuchi Bay (Ikeya *et al*., 1992) and off the Shimane Peninsula (Ikeya and Suzuki, 1992). Our knowledge of the geographical and bathymetrical distribution of Japanese ostracodes has been vastly improved. The development of ostracode data as environmental indicators is exemplified best by the recent classical work of Ikeya and Cronin (1993), which proved that the paleo-depth and paleo-temperature could be quantitatively estimated by the ostracode S.C.D. analysis. The work on the late Pliocene Yabuta Formation on the Sea of Japan coast (Cronin *et al*., 1994) represents an applied example of the improved data and procedure for the interpretation of fossil ostracode assemblages.

In the present situation, northeast off the Boso Peninsula, the warm Kuroshio Current meets the cold Oyashio Current. Therefore, in this region, the oceanic thermal structure is complicated. Due to middle Pleistocene climatic changes, the paleoceanic environment of the two formations is expected to have changed with the alternation of ocean currents. Previous works roughly discussed the influence of the warm and cold ocean currents during glacial-interglacial periods (Aoki and Baba, 1973; Kondo, 1989). However, the situation of the currents around the Boso Peninsula becomes more complicated if we take into account the influence of the relatively cool distal Tsugaru Current which might have moved down southwards from the Sea of Japan through the Tsugaru Strait. Thus a detailed discussion on the ocean currents in the Paleo-Tokyo Bay, and certain evidence of the glacio-eustacy, still needs to be undertaken. Under such a situation, extensive study of ostracodes from the two formations would provide answers to these questions.

Materials for this ostracode study were collected consecutively in accordance with the changes of lithofacies and molluscan assemblages. The purpose of this study is 1) review the biogeographical and bathymetrical data of extant ostracode species and synthesize them into a list as a simple and convenient paleoenvironmental standard; 2) trace vertical changes of these indicators in detail within the two formations and reconfirm the glacio-eustacy; 3) estimate the Paleo-Tokyo Bay's oceanic environment, especially water depth and ocean currents; 4) obtain fundamental data for future evolutionary work which will discuss the relationship between heterochrony-originated speciation and environmental changes.

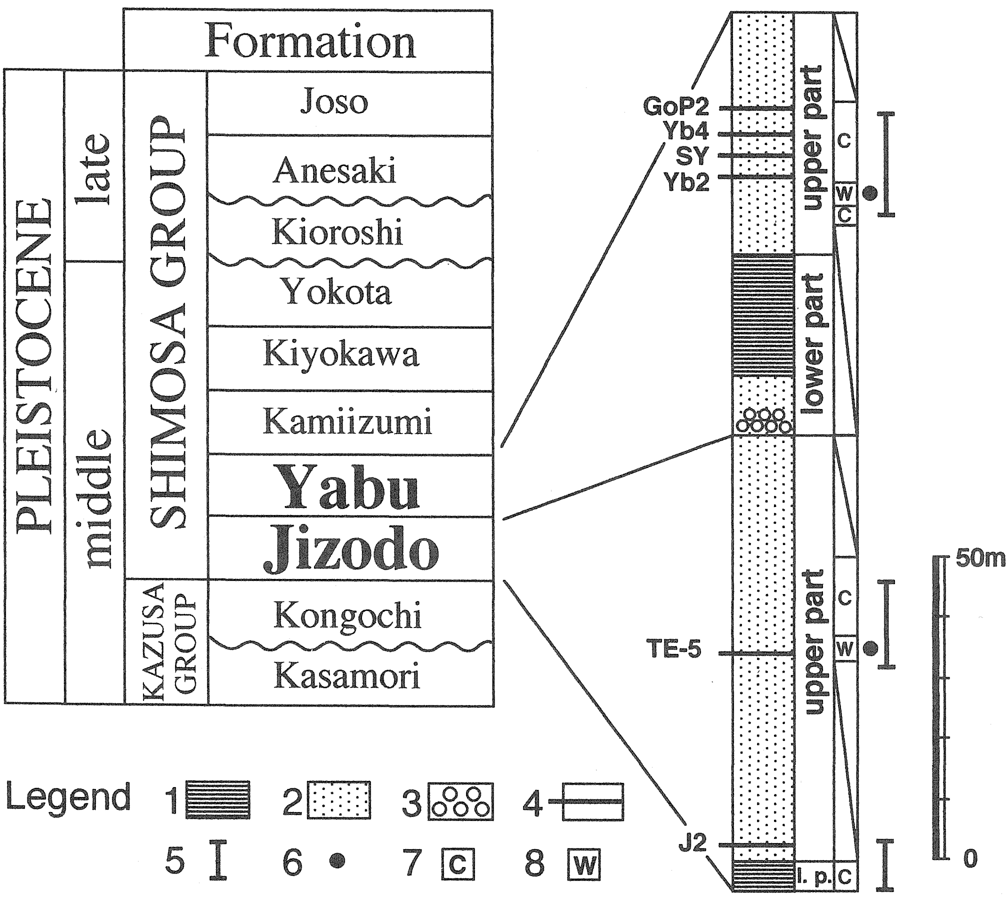

Fig. 1. Stratigraphic sequence of the middle to late Pleistocene starata in the Boso Peninsula, and the simplified columnar section of the Jizodo and Yabu Formations, showing sampling horizons of this study. (modified from Sugihara *et al.*, 1978; Tokuhashi and Endo, 1984; Kondo, 1989). (l. p.: lower part). 1: mud and muddy sand, 2: sand, 3: gravel, 4: tephra, 5: sampling horizon, 6: maximum transgression, 7: dominance of molluscan Oyashio element, 8: dominance of molluscan Kuroshio element.

2. Geological setting

The Jizodo and the Yabu belong to the lowermost formations of the middle to late Pleistocene Shimosa Group (Fig. 1). The Jizodo Formation overlies conformably the Kazusa Group. The Yabu Formation covers the Jizodo Formation conformably, and is overlain with the Kamiizumi Formation of the Shimosa Group conformably. The both formations are lithologically divided into the lower and upper parts respectively (Tokuhashi and Endo, 1984). Although there are local variations, the lower part of the Jizodo Formation is generally about 1−8m thick and consists of non-marine silt, clay and marine muddy sand with densely interbedded cold water molluscan fossils. The upper part is about 50−70m thick and is made up mainly of marine fine to medium sand with warm and cold water molluscan fossils. Widely distributed tephras such as TE-5 (0.39±0.08 F.T. Ma; Suzuki and Sugihara, 1983) are interbedded in this part. The lowerpart of the Yabu Formation is about 1−30m thick and consists of sand gravel and silt with non-marine and cold marine molluscan fossils. The upper part is about 10−35m thick and consists of marine fine to coarse sand with warm and cold water molluscan fossils. Tephras such as SY and GoP2 (0.31±0.05 F.T. Ma; Suzuki and Sugihara, 1983) are embedded (O'hara, 1982; Tokuhashi and Endo, 1984; Kikuchi *et al.*, 1988; Kondo, 1989). Machida *et al.* (1980)

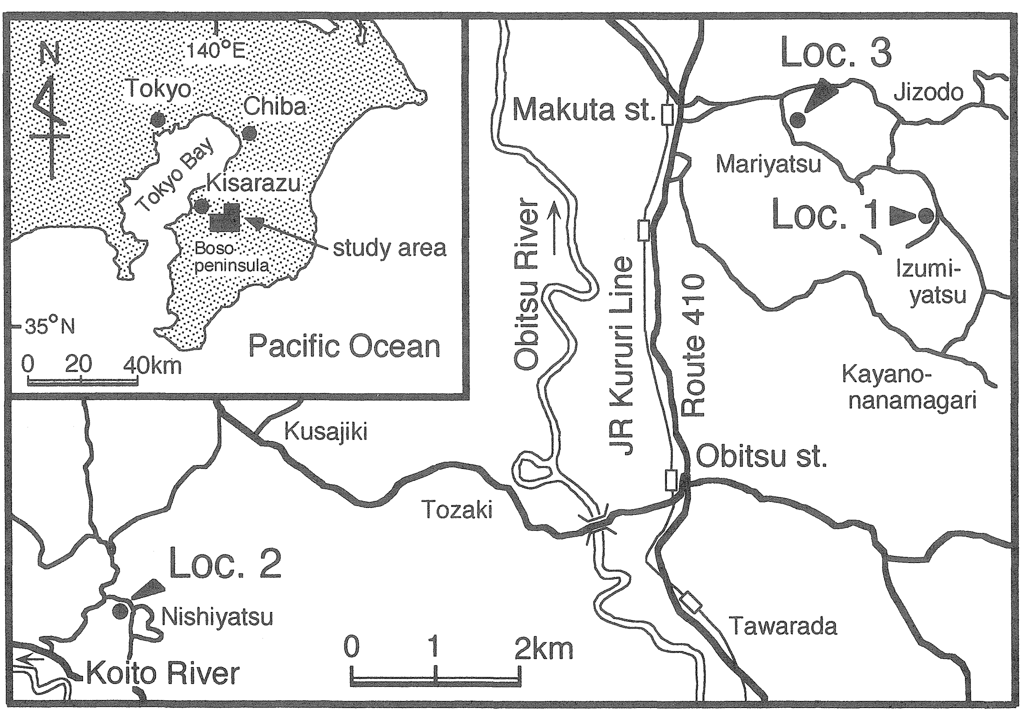

Fig. 2. Index map showing studied localities. Loc. 1: Izumiyatsu, Loc. 2: Nishiyatsu, Loc. 3: Atebi.

stated that the ages of the Jizodo and the Yabu Formations were correlated to the oxygen isotope stages 11 and 9 respectively based on the tephrochronology.

In this study we investigated three large outcrops (Fig. 2). The lower part of the Jizodo Formation is well exposed at Loc. 1 (Izumiyatsu), and the upper part at Loc. 2 (Nishiyatsu). Loc. 1 is about 30m above Loc. 2 stratigraphically (see Fig. 1). The outcrop at Loc. 3 (Atebi) covers both the lower and upper parts of the Yabu Formation. Since the molluscan fossils are poorly preserved in the lower part of the Yabu Formation of this locality, we focused on study on the upper part alone.

A total of 37 sediment samples for the ostracode analysis were collected from the two formations (Figs. 3—5). Samples were collected parallel to the bedding plane to obtain contemporaneous sediments. Burrows filled with overlying sediments were excluded. Each sample was collected within a 10cm interval of the bed.

After being dried in an oven, 320g of consolidated samples and about 400g of unconsolidated samples were washed through a 235 mesh (0.064mm opening) sieve. The dried residues were divided by the quatering method into unit samples which contain about 200 ostracode individuals. The fractions between 0.25mm and 1mm of each sample were picked for all the ostracodes, and the rest of the fractions was stored. The individual number was determined by adding the total of the left and right valves count to the number

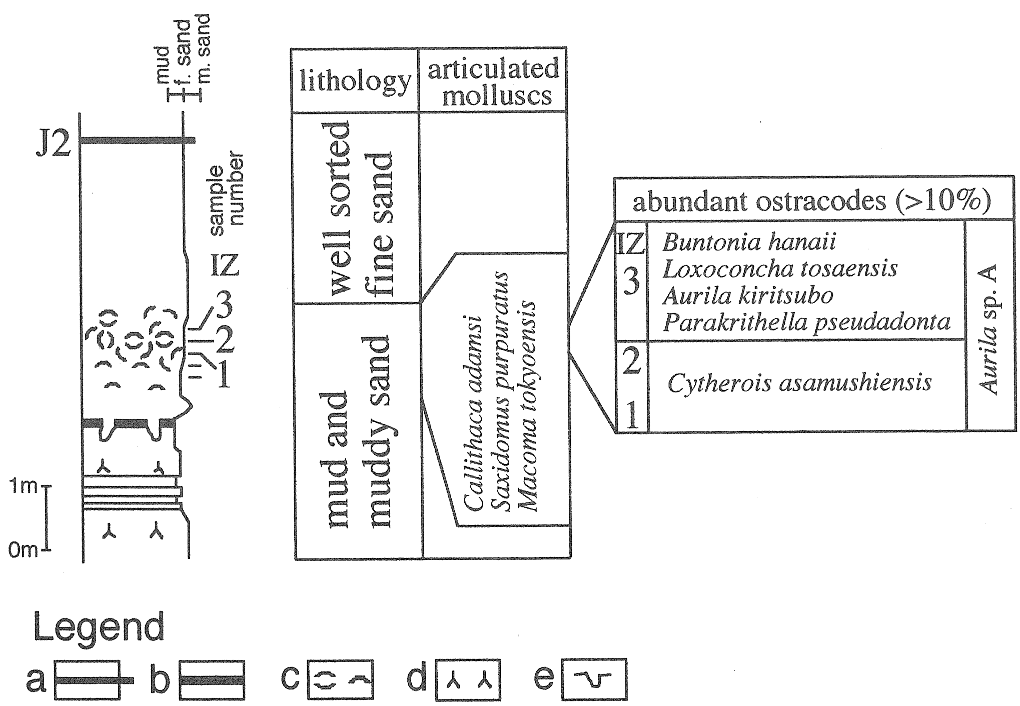

Fig. 3. Columnar section of the lower part of the Jizodo Formation at Loc. 1 (Izumiyatsu), showing sampling levels, lithology, articulated molluscs and abundant ostracodes. a: tephra, b: peat, c: molluscan fossil, d: plant remain, e: burrow.

of carapaces without regard to sex.

3. Brief descriptions of the molluscan and ostracode fossils

Thirty one samples (Figs. 3—5, numbers aside the columns) yielded ostracode speci-

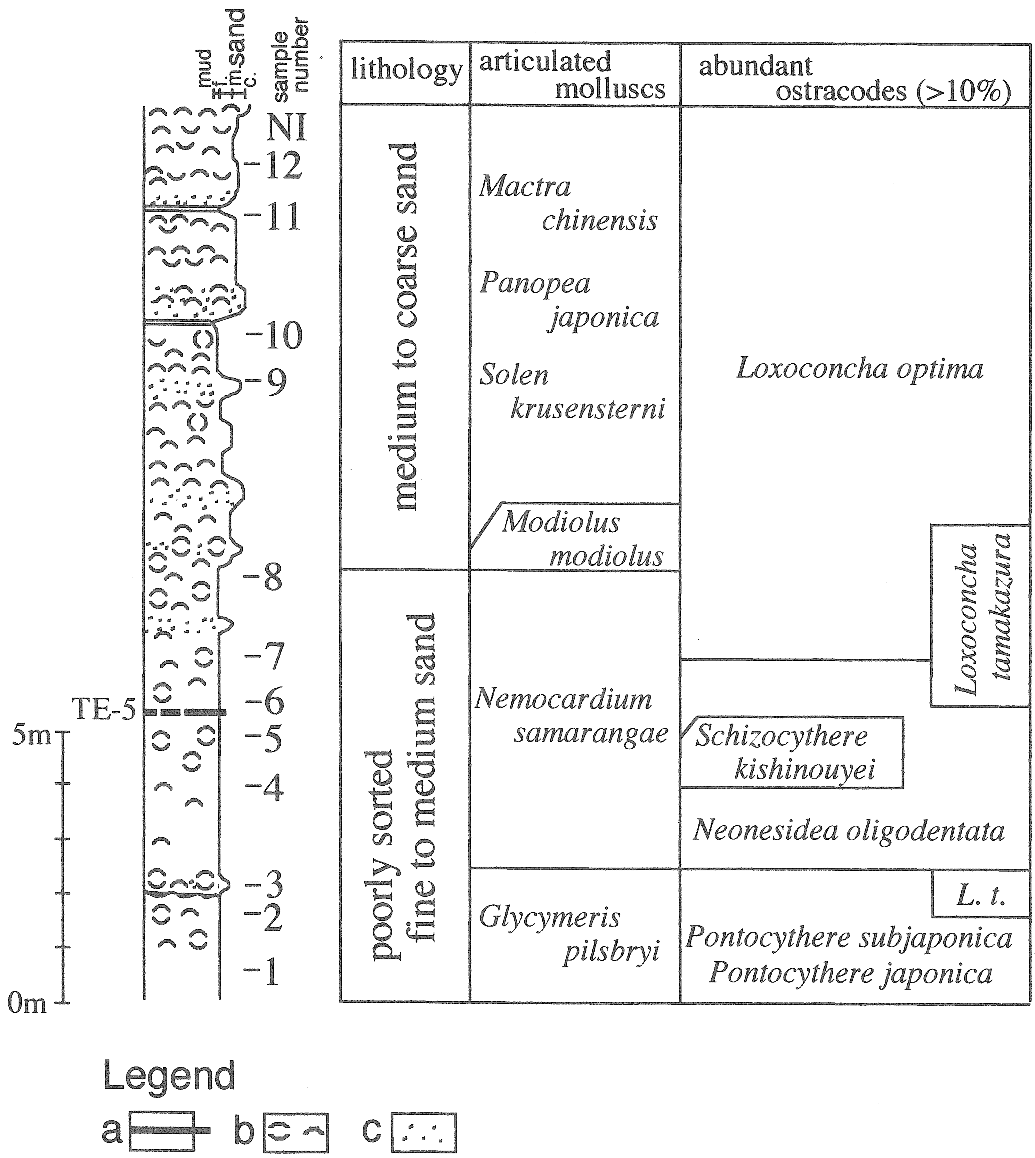

Fig. 4. Columnar section of the upper part of the Jizodo Formation at Loc. 2 (Nishiyatsu), showing sampling levels, lithology, articulated molluscs and abundant ostracodes (*L. t.*: *Loxoconcha tamakazura*). a: tephra, b: molluscan fossil, c: pebble.

mens with a total of 7785, although the ostracodes were rare in the six samples. We identified 136 species among 61 genera. The detailed results of the counting are shown in Table 1.

The following describes the articulated molluscan and abundant ostracode species of each locality. The percentages show the ratio against the total ostracode individuals within each sample. We term more than 10% species as "abundant species" in this study.

In the lower part of the Jizodo Formation (Loc. 1), we collected five samples from the poorly sorted muddy fine sand which yielded the articulated molluscan shells e.g. *Callithaca adamsi, Saxidomus purpuratus* and *Macoma tokyoensis* crowdedly. Only the upper three samples, numbered from IZ-1 to IZ-3, yielded ostracodes (Fig. 3). These samples included abundant *Aurila* sp. A and *Cytherois asamushiensis*. The total percentage of the two species decreases upwards from 90% in IZ-1 to 20% in IZ-3. *Buntonia hanaii, Loxoconcha tosaensis, Aurila kiritsubo* and *Parakrithella pseudadonta* were abundant in IZ-3.

In the upper part of the Jizodo Formation (Loc. 2), we obtained eight samples from the lower half horizon, poorly sorted fine to medium sand with articulated shells of molluscs, e.g. *Glycymeris pilsbryi* and *Nemocardium samarangae*, and four samples from the upper half horizon, medium to coarse sand with articulated *Panopea japonica* and *Solen krusensterni* (Fig. 4). One sample (NI-11) was collected from a muddy sand layer about 10cm thick, interbedded in medium to coarse sand. All twelve samples, which are numbered from NI-1 to NI-12, produced ostracodes. The Jizodo Formation of this locality are characterized by being rich in *Neonesidea oligodentata* and *Loxoconcha optima*. The former species is about 15−25% in NI-3−6, and the latter occupies about 20−30% in NI-7−12. The ostracode assemblage defined by abundant species roughly coincide with that of the molluscan assemblage. For example, *Pontocythere japonica, P. subjaponica*−*Glycymeris pilsbryi* appeared concurrently in the lower horizon (NI-1−2). *Neonesidea oligodentata*−*Nemocardium samarangae* were in the middle horizon (NI-3−7), and *Loxoconcha optima*−*Panopea japonica, Solen krusensterni, Mactra chinensis* in the upper horizon (NI-8−12) (Fig. 4).

In the upper part of the Yabu Formation (Loc. 3), sixteen of twenty samples, which are numbered from AT-1 to AT-16, yielded ostracodes (Fig. 5). We obtained seven samples (AT-1, 15, 16 and four other with no ostracode samples) from medium-coarse sand with articulated *Glycymeris yessoensis*. Four samples (AT-2−5) were collected from poorly sorted fine to medium sand with articulated *Glycymeris pilsbryi* densely, and nine samples (AT-6−14) were from well sorted and bioturbated fine sand with articulated *Venercardia ferruginea* and *Panopea japonica*. The Yabu Formation is characterized by the abundance of *Loxoconcha optima, L. tamakazura* and *Schizocythere kishinouyei*. The boundary horizons of ostracode abundant species correspond with molluscan species, that is *Loxoconcha optima*−*Glycymeris yessoensis* at the lowest horizon (AT-1), and the uppermost horizon (AT-15 and 16). *Loxoconcha tamakazura*−*Glycymeris pilsbryi* were found between AT-2−5, and *Schizocythere kishinouyei*−*Panopea japonica, Venercardia fer-*

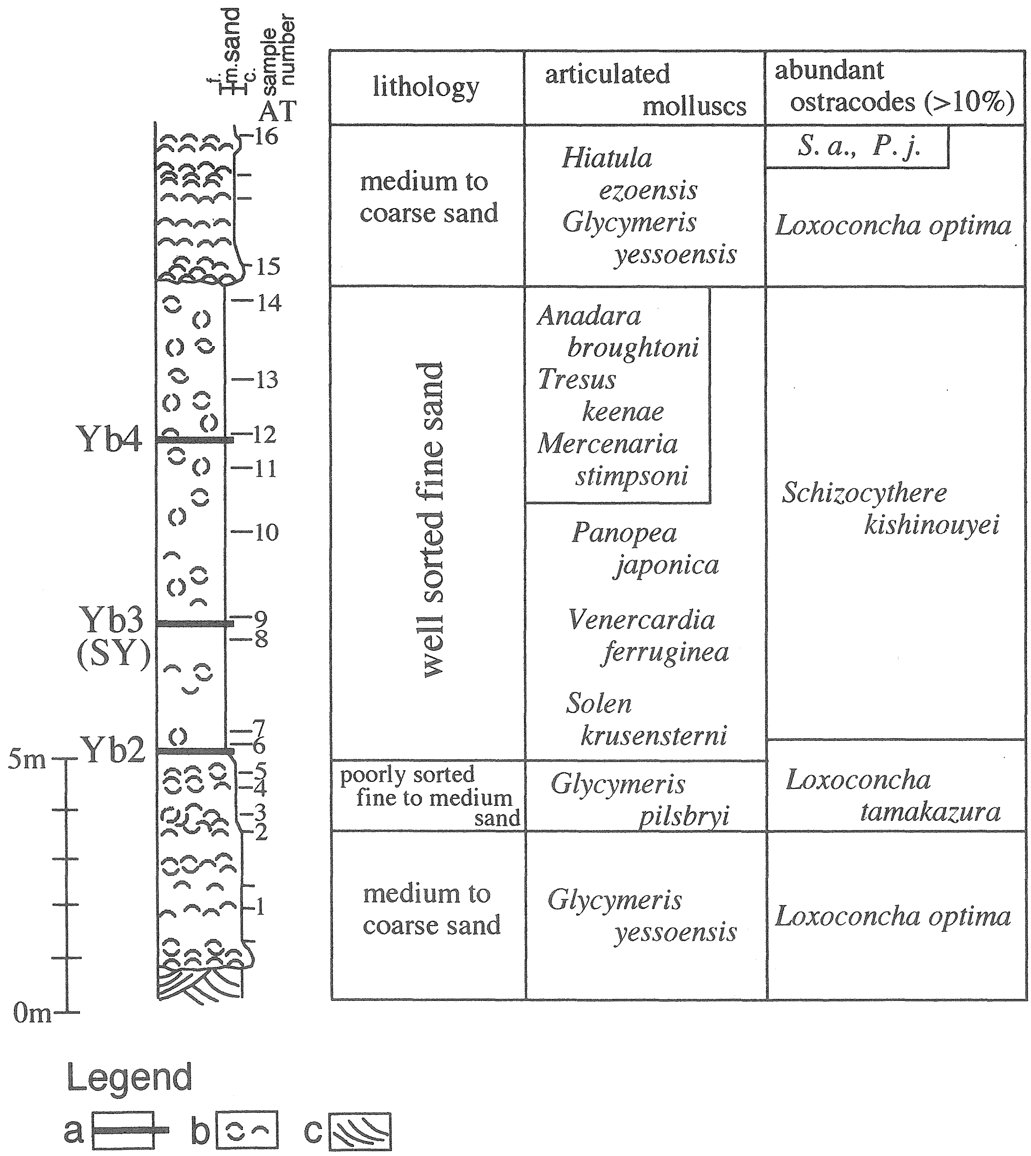

Fig. 5. Columnar section of the upper part of the Yabu Formation at Loc. 3 (Atebi), showing sampling levels, lithology, articulated molluscs and abundant ostracodes (*S. a.*: *Schizocythere asagao*, *P. j.*: *Pontocythere japonica*). a: tephra, b: molluscan fossil, c: cross lamination.

ruginea, *Solen krusensterni* in the middle horizon (AT-6–14).

It is difficult to infer the detailed paleoceanic environment on the basis of ostracode abundant species. For example, *Neonesidea oligodentata* has wide tolerance for bathymetry from the tidal zone to the depth of ca. 150m. Therefore, in this study, we inferred the paleoceanic environment by the environmentally valuable species for water depth, geographical distribution and ocean current indexes based on the review of previous studies and the personal field observation for the extant species data, as described in the following chapter.

4. Analytical methods

We proposed four geographical divisions for the sea around the Japanese Islands which made the paleoceanographic ostracode analyses convenient. The divisions, W, T, M and C (Fig. 6) are primarily based on the current system around the Japanese Islands (Fig. 7) with attention to the sea water temperature. The division W includes the Kuroshio and proximal Tsushima Currents. The M corresponds to the mixing zone of the Tsugaru Current and Kuroshio Current. The T covers the distal Tsushima Current, including the Tsugaru Current, and the division C corresponds to the Oyashio Current. The boundary between W and others are bordered by 11℃ of the surface water temperature in winter.

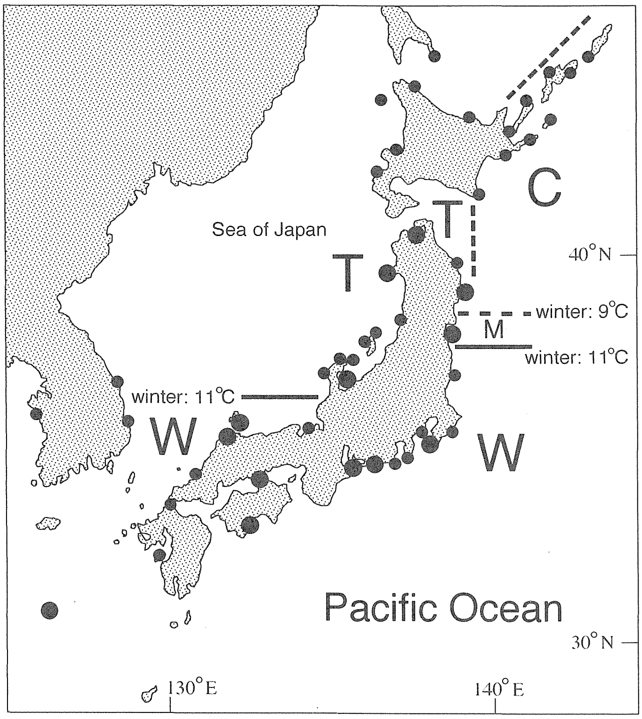

Fig. 6. Four geographical divisions (W, T, M and C) of the oceanic condition around the Japanese Islands mainly based on the distribution of current system and winter sea surfacewater temperature. Solid circles show localities where the extant ostracode faunas were studied. Larger symbols represent the localities with more than 10 samples, and smaller symbols show these less than 10 samples. The data of water temperature was cited from Rikanenpyo (1994).

Geographical distribution of about 100 extant species among 136 species from the two formations were examined and plotted on the map of the Japanese Islands. The literatures used as a data source include; Bodergat and Ikeya (1982), Frydl (1982), Ikeya and Hanai (1982), Ikeya and Itoh (1991), Ikeya and Suzuki (1992), Ikeya and Tsukagoshi (1988), Ikeya *et al.* (1985, 1992), Ishizaki (1968, 1969, 1971, 1981), Ishizaki and Irizuki (1990), Kamiya (1988), Okada (1979), Okubo (1980), Schornikov (1974), Tsukagoshi (1988), and Tsukagoshi and Ikeya (1991).

As a result, we identified nine patterns for the species biogeographical distributions. They are; W, M-W, T-M-W, C-T-M-W, M, T-M, C-T-M, T, C (Fig. 8). Several species which have no recent distributional data, e.g. *Schizocythere asagao, Cytheropteron* aff. *eremitum* and *Palmoconcha* sp., are included in this figure, since they could not be ignored because of their abundance. We determined their positions by considering the ecology of the concurrent species and the congeneric extant species. We defined the species with W and M-W distribution as representing the warm water species (higher than ca. 11℃, see Fig. 9, left column). Equally, the species with distribution of C, T, C-T-M, T-M, and M were combined to represent the cool water species (lower than ca. 11℃). Species with wide distribution such as T-M-W and C-T-M-W were excluded from the warm-cool analyses. " Warm-cool ratio" was calculated for each sample by counting the ratio of individual number of warm water species to the total number of warm and cool water species (Figs. 10－12, second graphs from the right).

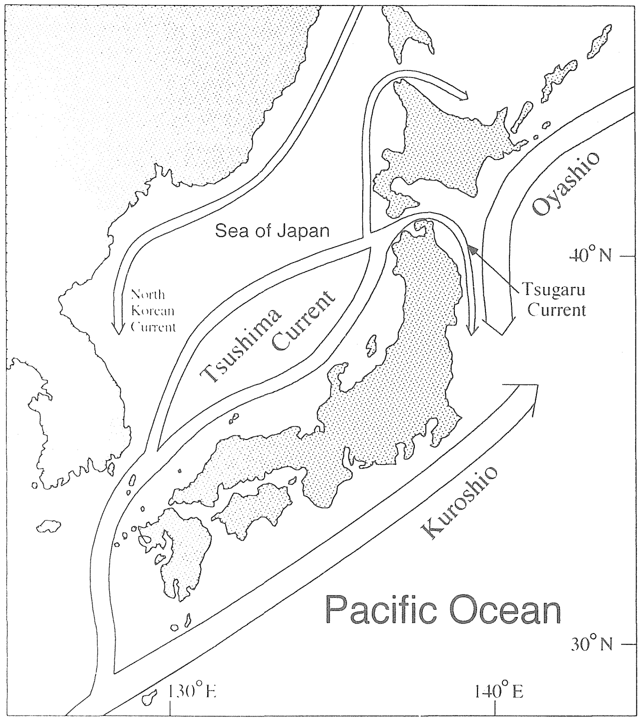

Fig. 7. The present current system around the Japanese Islands.

Our geographical divisions are unique in the point that they are tightly related to the distribution of ocean current rather than mere water temperature. Considering the oceanographical situation off the Boso Peninsula, the ratio of T and T-M may represent the influx of the distal Tsushima Current from the Sea of Japan. In contrast, W represents the case of strong influence of the Kuroshio Current. Influence of each current could be thus illustrated by the ratio of ostracode distribution pattern (Figs. 10－12, right graphs).

We also examined and concluded that 69 out of 136 species were defined as "depth indicating species". They were grouped into four divisions by water depth of the habitats i.e. S1 (tidal zone－30m), S2 (sublittoral zone－50m), D1 (50－100m) and D2 (more than 100-150m) (Fig. 8). Some species that have wide tolerance for the water depth were excluded from Fig. 8.

As a preliminary depth analysis the first five abundant depth indicative species in each sample were used to roughly estimate the paleo-depth (Figs. 10－12, left graphs). This "roughly estimated depth" was determined by the distributional range of the largest total individuals for the five species.

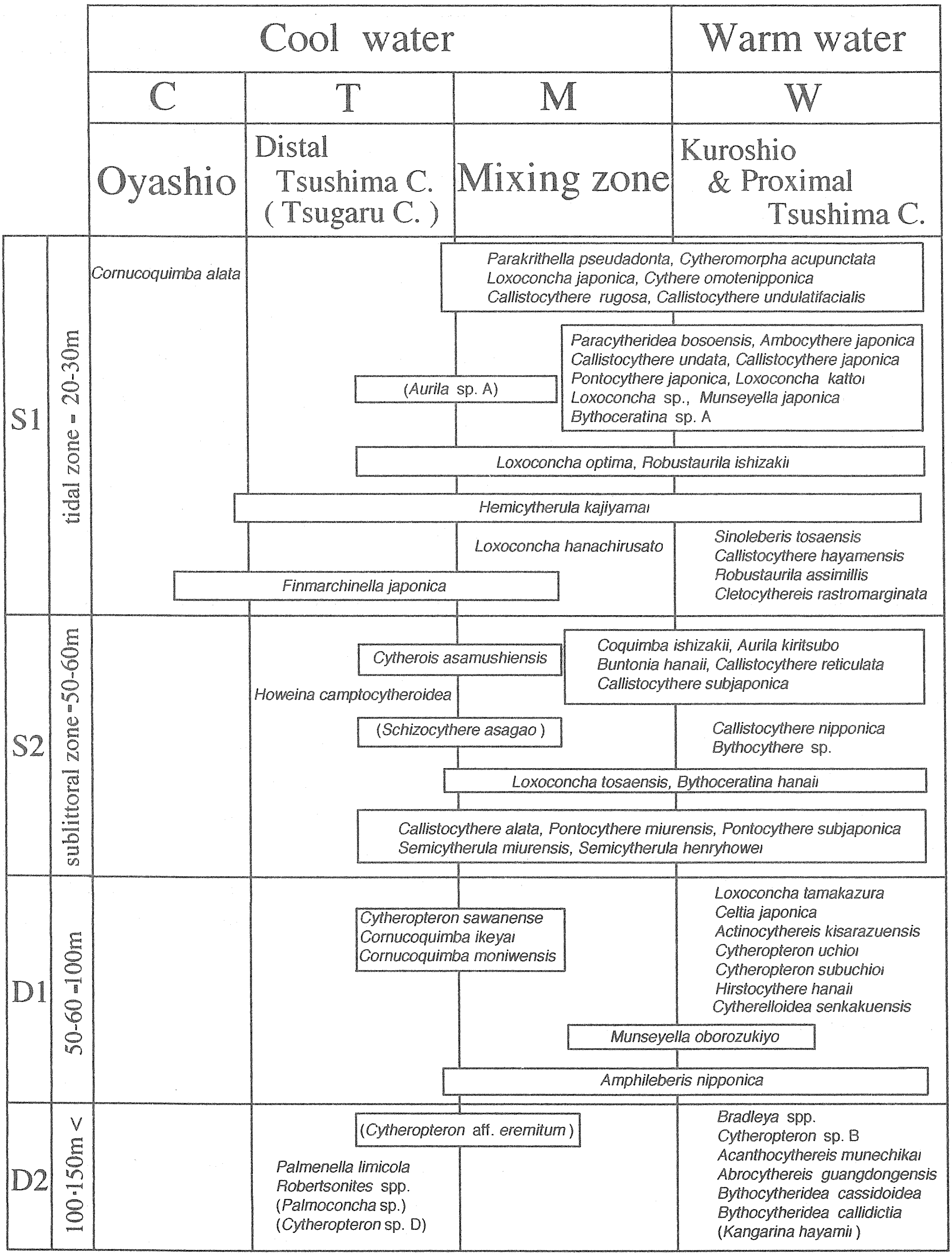

Fig. 8. Distributions of the ostracode species of the Jizodo and Yabu Formations in the geographical and bathymetrical divisions. Species without data of recent distribution are in parentheses.

Warm water species		Cool water species
Cytherelloidea senkakuensis	*Actinocythereis kisarazuensis*	(*Eucythere* sp.)
(*Sinocytheridea* sp.)	*Sinoleberis tosaensis*	*Munseyella hatatatensis*
Pontocythere japonica	*Hirstocythere* ? *hanaii*	(*Schizocythere asagao*)
Eucythere yugao	*Cletocythereis rastromarginata*	*Palmenella limicola*
Munseyella japonica	*Abrocythereis guangdongensis*	*Hemicythere* sp. A
M. oborozukiyo	*Celtia japonica*	*H.* sp. B
Callistocythere hayamensis	*Buntonia hanaii*	*H.* sp. C
C. japonica	*Ambocythere japonica*	(*Aurila* sp. A)
C. nipponica	*Bythoceratina callidictya*	*Finmarchinella japonica*
C. reticulata	*B. cassidoidea*	*Cornucoquimba alata*
C. subjaponica	*B. orientaris*	*C. ikeyai*
C. undata	*B.* sp. A	*C. moniwensis*
Hanaiborchella triangularis	*Bythocythere* sp.	(*Yezocythere* sp.)
(*Neomonoceratina microreticulata*)	*Cytheropteron subuchioi*	*Robertsonites* aff. *reticuliforma*
Aurila kiritsubo	*C. uchioi*	*Howeina camptocytheroidea*
Pseudoaurila japonica	*C.* aff. *abnormis*	*Cytheropteron sawanense*
Robustaurila assimilis	*C.* sp. B	(*C.* aff. *eremitum*)
Bradleya japonica	(*Kangarina hayamii*)	(*C.* sp. D)
B. nuda	*Paracytheridea bosoensis*	*Loxoconcha hanachirusato*
(*B.* sp.)	*P. dialata*	(*Palmoconcha* sp.)
Coquimba ishizakii	*Loxoconcha tamakazura*	*Cytherois asamushiensis*
(*Trachyleberis sogwipoense*)	*L. kattoi*	
Acanthocythereis munechikai	*L.* sp.	

Fig. 9. List of the warm and cool water species from the Jizodo and Yabu Formations. Species without present data are in parenthesis.

Then, all the depth indicators were taken into consideration on the second depth analysis. The changes in percentages of S1, S2, D1 and D2 species in each sample are shown (Figs. 10—12, third graphs from the right), and their vertical quantitative changes help us to estimate the gradual change of the paleo-depth. With "roughly estimated depth" and "ratio of depth indicators", the paleo-depth and its change were well estimated. The maximum paleo-depth is estimated by both the "roughly estimated depth" and "ratio of depth indicators".

5. Paleoceanographic results

Water depth

Fig. 10 shows the data of paleo-water depth of the lower part of the Jizodo Formation. The roughly estimated depth is tidal zone—30m in the bottom horizon and the upper two horizons are sublittoral zone—50m. On the percentages, S1 species (*Aurila* sp. A; species in parenthesis are main species) decrease upwards and S2 (*Cytherois asamushiensis*) increase upwards with slight increase of D1 species (*Cornucoquimba moniwensis*). Consequently, the water depth in this part deepened upwards.

The paleo-water depth change of the upper part of the Jizodo Formation is shown in Fig. 11. Roughly estimated depth is tidal zone—30m first (NI-1—2), then abruptly increased. Between NI-3 and NI-6, the estimated depth is constant at 50−100m, and above them suddenly decreases. The ratios of S1 (*Loxoconcha optima* and *Pontocythere japonica*)

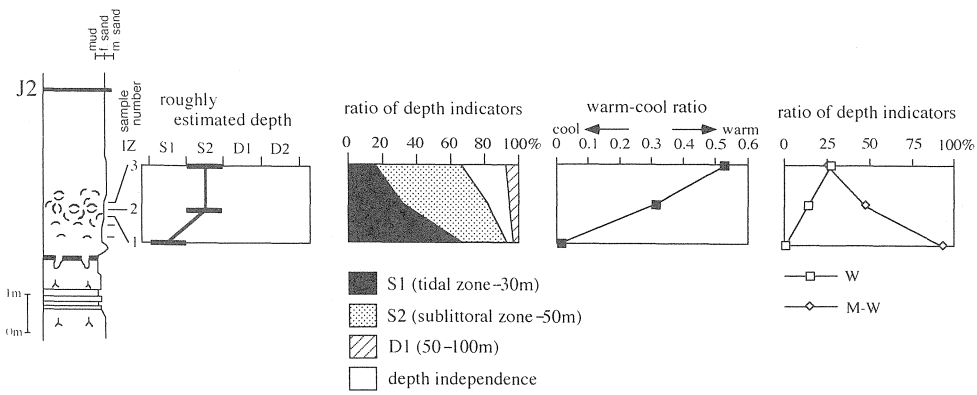

Fig. 10. Roughly estimated depth, ratio of depth indicators, warm-cool ratio, and the ratio of current indicators of the lower part of the Jizodo Formation at Loc.1 (Izumiyatsu). Depth independence shows species with wide bathymetrical range. Legend is equal to that in Fig. 2.

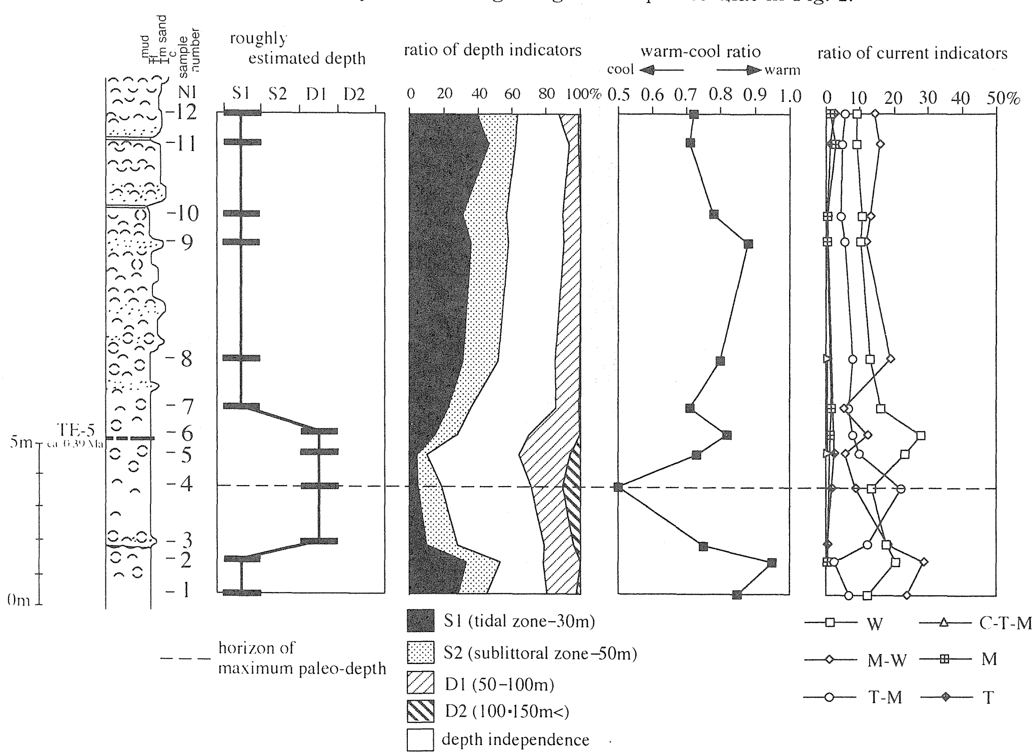

Fig. 11. Roughly estimated depth, ratio of depth indicators, warm-cool ratio, and the ratio of current indicators of the upper part of the Jizodo Formation at Loc.2 (Nishiyatsu). Legend is equal to that in Fig. 3.

and S2 (*Pontocythere subjaponica*) decrease from the base to the middle horizons. At the middle horizon, D1 (*Cytheropteron uchioi* and *Loxoconcha tamakazura*) occupies about 30% (NI-5–6). The percentage of D2 (*Cytheropteron* aff. *eremitum*, *Abrocythereis* cf. *guangdongensis* and *Palmoconcha* sp.) is at a maximum in NI-4 and it is approximately 10%. This horizon seems to correspond to be the maximum depth of the Jizodo Formation and its depth is estimated about 100m, considering the abundance of D1 and D2 species. It is also possible to propose that the maximum depth horizon is NI-5 because of the minimum percentages of S1 and S2. Above the middle horizon, S1 (*L. optima*) and S2 (*Callistocythere alata* and *P. subjaponica*) increase upwards and form a maximum of about 60% in the uppermost horizon. Between the NI-7 and NI-12 horizons, the roughly estimated depth is stable, but the relative increase of S1 species indicates that the water depth tended

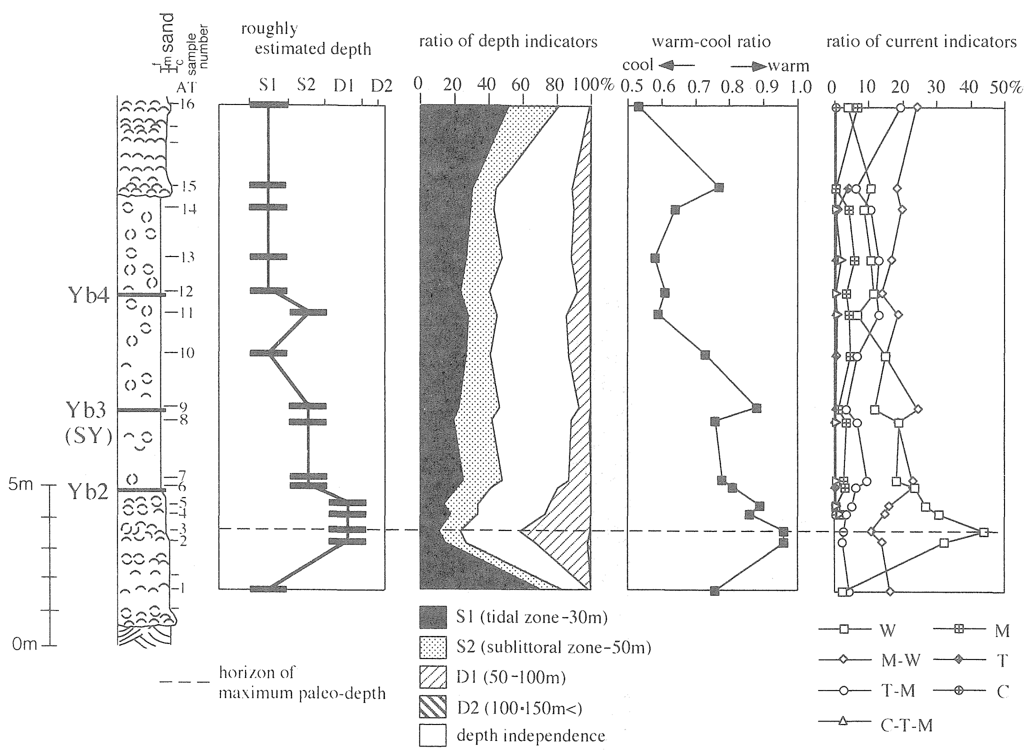

Fig. 12. Roughly estimated depth, ratio of depth indicators, warm-cool ratio, and the ratio of current indicators of the upper part of the Yabu Formation at Loc. 3 (Atebi). Legend is equal to that in Fig. 4.

to be shallowing upwards.

Fig. 12 shows the paleoenvironmental change of the Yabu Formation. S1 (*L. optima*) is dominant and forms about 70% in AT-1. Together with the roughly estimated paleo-depth, the horizon should have been in tidal zone–30m condition. However, in AT-3, which is just 2m above AT-1 horizon, D1 (*L. tamakazura, Celtia japonica* and *Cythero-pteron subuchioi*) increases and forms more than 40%. This data suggests the horizon should be in the deepest condition for the Yabu Formation and is about 50−100m. Between AT-6 and AT-15, S1 (*L. optima, Pontocythere japonica* and *Callistocythere japonica*) and S2 (*Pontocythere subjaponica* and *Aurila kiritsubo*) are common. At the uppermost AT-16, ratios of S1 species (*L. optima, P. japonica* and *Cythere omotenipponica*) and S2 (*P. subjaponica*) become the largest with the exception of AT-1 and form about 50% and 30% respectively. It is likely it was deposited again in the tidal zone to 30m depth interval. The inferred paleo-depth showed that the maximum depth of the Yabu Formation (50−100m) is shallower than that of the Jizodo Formation (c.a. 100m) between the studied areas.

Warm-cool water environment and currents setting

In the lower part of the Jizodo Formation, the number of warm water species is nine and that of cool water species is five among a total of 28 species, however, there is no Oyashio species (Fig. 13). All the cool water species from this horizon live in the distal area of the warm currents. Warm-cool ratio increases from 0.01 to 0.54 upwards (Fig. 10). This increase indicates that the influence of the Kuroshio Current strengthened during the transgression.

In the upper part of the Jizodo Formation, the 35 warm water species and 14 cool water species were found out of 110 species in total. No Oyashio species were contained (Fig. 13). The warm-cool ratio is generally higher than that of the lower part, and more than 0.7 except NI-4, with a maximum of 0.95 in NI-2 (Fig. 11). These results suggest that the Kuroshio and Tsugaru Currents flowed into the Paleo-Tokyo Bay in this period and that the cold Oyashio Current did not reach the studied area. The warm-cool ratio is high in NI-2 and NI-6 because of abundance of *Aurila kiritsubo, Loxoconcha tamakazura* and *Cytheropteron subuchioi*. The minimum ratio in NI-4 depends on the large individuals of cool water species such as *Cytheropteron sawanense, Cornucoquimba moniwensis, Palmoconcha* sp. and *Cytheropteron* aff. *eremitum*. *Palmoconcha* sp. is a species of the division T, i.e. distal Tsushima Current (Tsugaru Current) in a broad division, but the extant species has been found only from

		Warm	Cool (Oyashio)	Total
Yabu Fm.	middle to upper part	38	15 (1)	115
Jizodo Formation	middle to upper part	35	14 (0)	110
	lower part	9	5 (0)	28

Fig. 13. Number of species from the Jizodo and Yabu Formations. Warm: warm water species, Cool: cool water species, Oyashio: Oyashio species, Total: number of the total species from each part of the two formations.

the Sea of Japan side so far, and can be called a specific species in the Sea of Japan. This species was almost exclusively found in NI-4 and NI-5 in theJizodo Formation. These results indicate that the bottom water temperature was coolest at the very middle (NI-4), but was very warm just below (NI-2 to NI-3) and above (NI-5 to NI-6) the coolest horizon. As presented before, the horizon of NI-4 is thought to represent the maximum paleo-depth (ca.100m). Therefore, in the Jizodo Formation, the water temperature is thought to be very low in the maximum depth period. Aside from the very middle, the general trend of the change is that the temperature was high around the middle horizon and gradually decreased upwards.

In the upper part of the Yabu Formation, 38 warm water species are found out of 115 species in total and it occupies about one-third of all, likewise the upper part of the Jizodo Formation. The 15 cool water species including one Oyashio species occured in this part (Fig. 13). The warm-cool ratio is generally high, more than 0.5, with a maximum of 0.96 in AT-2 and AT-3. This is caused by the abundance of warm water species such as *Loxoconcha tamakazura, Aurila kiritsubo, Celtia japonica* and *Cytheropteron subuchioi*. The minimum is 0.53 in AT-16, and this is caused by the abundance of cool water T species of *Loxoconcha hanachirusato* and *Schizocythere asagao* (Fig. 12). This suggests that the warm Kuroshio Current flowed into the Paleo-Tokyo Bay during the deposition of the upper part of the Yabu Formation and that the cold Oyashio Current did not reach, similar to the case of the Jizodo Formation. As noted above, the horizon of AT-3 is inferred to be in the maximum paleo-depth. Therefore in the Yabu Formation, the bottom water temperature was the highest in the maximum depth period and gradually dropped upwards and downwards stratigraphically.

6. Conclusive Discussions

Ostracode paleoenvironmental indicators

On the basis of the available data on the distribution of extant ostracodes around the Japanese Islands, we proposed nine biogeographical distribution patterns for about 100 extant species out of 136 fossil species from the middle Pleistocene Jizodo and Yabu Formations. In addition we proposed four bathymetrical divisions. Using these patterns and divisions, we are easily and simply able to reconstruct the water depth, warm-cool water environment and the influence of ocean currents, i.e. the Kuroshio, Oyashio and Tsugaru Currents. The present work showed that the analysis of the current system was effectively applied to the paleoenvironment of areas around the Boso Peninsula. Considering the ease and simplicity of the procedure, and given the fruitful results, the set of indicators will be useful for future paleoenvironmental studies.

Contents of the "cool water species"

The alternation of the warm-cold water environment of the Jizodo and Yabu Formations has been previously discussed concerning the alternation of the warm and cold currents (the Kuroshio and Oyashio Currents) on the basis of molluscan and foraminifer fossils (Uchio, 1961; Suzuki and Aoki, 1962; Aoki *et al.*, 1962; Aoki and Baba, 1973; O'hara, 1982; Kondo, 1989). However, it is essential to consider the effect of three ocean currents, the Kuroshio, the Oyashio and the Tsugaru for the study around the Boso Peninsula. The Tsugaru Current flows southwards along the Pacific coast of northeastern Japan through the Tsugaru Strait at present. This current water mixes with the Kuroshio and Oyashio Currents water off the "Sanriku" coast of the northeastern Japan (see Fig. 7).

In contrast to the ostracode species in the Kuroshio and the Oyashio Currents, the Tsugaru Current that originates from the Tsushima Current appears to have its own specific ostracode species, "the cool element of the Sea of Japan" (see Fig. 8). The substance of "cool water species" in the studied area was shown not to be the Oyashio Current species but the Tsugaru and distal Tsushima Currents species.

Oceanic environments

The general pattern of the environmental change was similar between the Yabu and Jizodo Formations except for the maximum water depth period. This pattern shows a gradual increase of water depth and temperature toward the middle horizon from both the uppermost and the lowermost horizons. In the Yabu Formation, many individuals of D1 (50−100m) warm water species comprised the sample of the maximum paleo-depth horizon (AT-3). The horizon was characterized by the strongest influence of the Kuroshio Current within the formation.

For the Jizodo Formation, the samples just above and below the maximum paleo-depth horizon (NI-4), i.e. NI-3, NI-5 and NI-6, are composed of the similar species component of the maximum paleo-depth horizon of the Yabu Formation (AT-3). The resemblance suggests a similar environment between the two formations at these horizons and a similar enviromental change that becomes warmer and deeper toward the middle horizon. These results clearly support the previous interpretation that each formation was deposited during one glacial-interglacial climatic change.

An interesting point is that the horizon of the maximum paleo-depth (about 100m) of the Jizodo Formation contains the distal Tsushima and Tsugaru Current species of D1 and D2 as well as the Kuroshio species of D1, and this brought the unexpectedly "cool" environment of the horizon in the analysis.

Generally, cold heavy water creeps under the warm light water as the Oyashio Current water crawls under the Kuroshio Current water off the Boso Peninsula at present. The difference of the ostracode assemblages at the maximum depth horizon between the two formations can be explained well by the oceanic thermal structure as follows; in the maximum depth period of the Jizodo Formation, the cool Tsugaru Current water (ca. several degree cooler than the Kuroshio water) possibly crept under the warm Kuroshio Current water and affected the bottom water environment of the Paleo-Tokyo Bay. On the other hand, in the case of the Yabu Formation, the Tsugaru Current water did not creep under the Kuroshio water.

On a global scale, it is thought that the warm current intensifies during the warm climate period. The warmer it is the more the amount of melting ice sheet in Arctic increases and it accelerates the deep sea ocean circulation, which finally causes the intensification of the Kuroshio Current around the Japanese Islands. When the climate became warmer in the middle Pleistocene, the Kuroshio Current, Tsushima Current and Tsugaru Current which is a branch of the Tsushima Current would have intensified. If we assume that the climate was warmest in the period of the maximum paleo-depth, we are able to propose the following scenario that caused the differences between the two formations. In case of the period of the Jizodo Formation, both streams of the Kuroshio and Tsushima Currents were sufficiently intensified. As a result, the intensified Tsugaru Current finally reached the Paleo-Tokyo Bay only in the period of maximum depth and crept under the warm Kuroshio Current. The sea-level rise in the period of the Yabu Formation was not enough high to push the Tsugaru Current to reach the Paleo-Tokyo Bay. This assumption is consistent with the data that the maximum paleo-depth was deeper for the Jizodo Formation (about 100m) than the Yabu Formation (50—100m) and that the environment just above and below the horizon of the maximum depth of the Jizodo Formation is similar to the environment of the maximum depth period of the Yabu Formation in depth (50—100m) and temperature (strongest influence of the Kuroshio Current).

Another possible hypothesis to explain the difference depends on "topography". In this case, the Tsugaru Current could have reached the Paleo-Tokyo Bay in both the period of the middle horizons of the Yabu and Jizodo Formations. The difference in oceanic thermal structure might be related to the different distance from coasts as we see it in the transverse section off the present Boso Peninsula. It is possible that the sudden cooling at the maximum depth of the Jizodo Formation was caused by the lateral movement of the Tsugaru Current coastward as sea-level increased. However, since there is not enough data available to consider the paleoenvironment in three-dimensions, it is difficult to specify the reason.

In the above discussion, we explained the cool-deep water environment of the Jizodo Formation by the invasion of the intensified Tsugaru Current toward south or the lateral movement of the already-exsiting Tsugaru Current. The hypothesis of the invasion of the intensified Tsugaru Current was well supported in that much of the cool-deep environment was represented by the T-M, and T species (see Fig. 11, right graph). This is different from the cool-shallow water environments of the two formations. The cool-shallow environments were mainly represented by the M and T-M species (e.g. see Fig. 12, right graph). This cool-shallow environment, accompanied by common M-W species, must be derived from the general cooling of the Tsugaru Current and the Kuroshio Current water in the mixing zone during the global climatic cooling. Even though the oceanic situation was not completely specified, it is newly proved that the cool environments appeared twice, in shallow and the deepest conditions, in the Jizodo Formation. This is different from the pattern previously observed in deposits during a glacial-interglacial sea-level change. The previously observed pattern was illustrated by the single cool-warm change in the Yabu Formation and in the early Pleistocene Omma Formation on the Sea of Japan coast (Kitamura and Kondo, 1990). The double cooling in one glacial-interglacial change is thought to have recorded the vertical water mass structure during the middle Pleistocene (Isotope stage 11), and is first described for the Shimosa Group in the Boso Peninsula.

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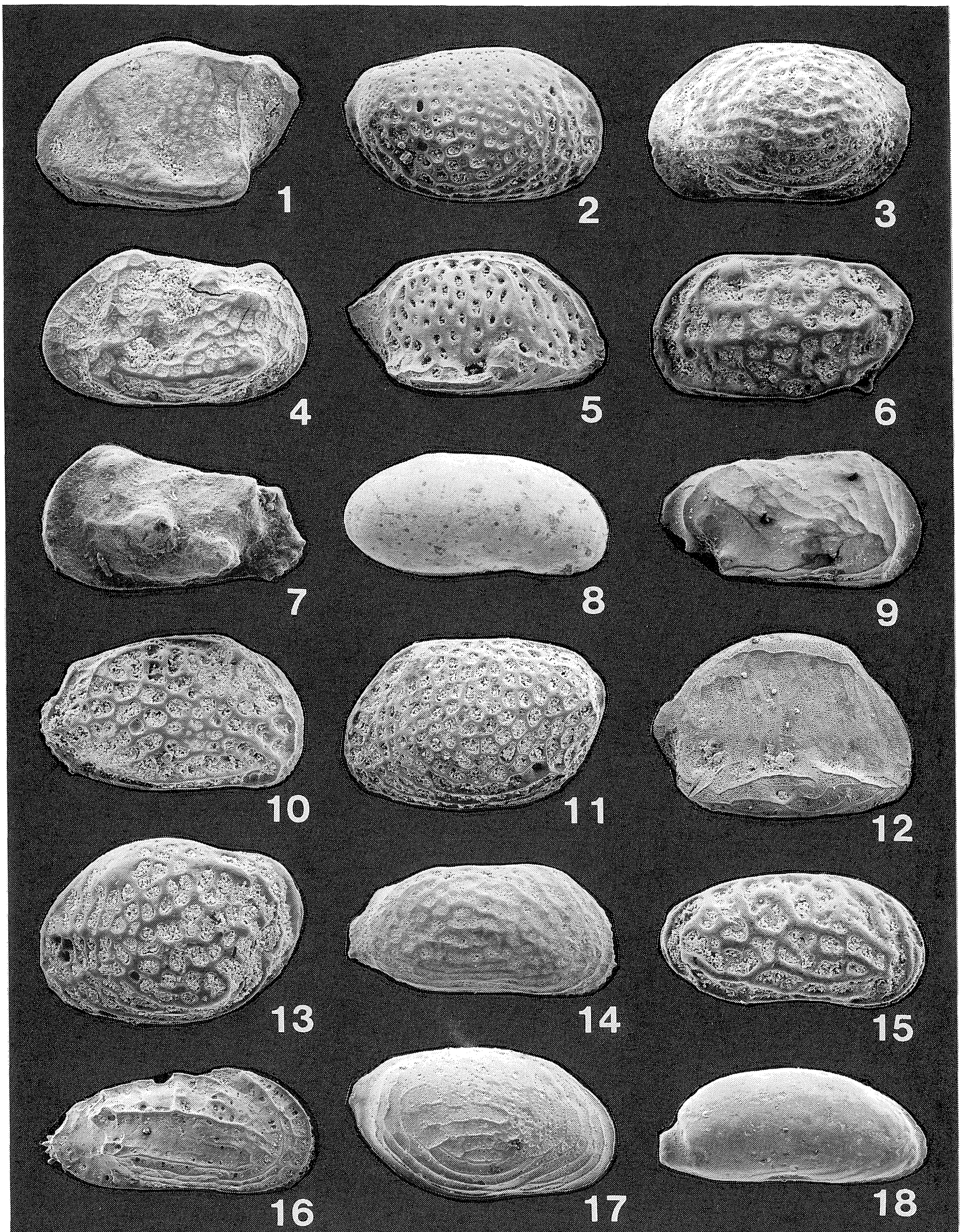

Plate 1. Ostracode species from the Jizodo and the Yabu Formations. 1, *Cytheropteron sawanense* Hanai, LV, ×81; 2, *Loxoconcha hanachirusato* Yajima, RV, ×88; 3, *Palmoconcha* sp., LV, ×73; 4, *Palmenella limicola* (Norman), LV, ×65; 5, *Cytheropteron* aff. *eremitum* Hanai, RV, ×62; 6, *Schizocythere asagao* Yajima, LV, ×64; 7, *Cornucoquimba moniwensis* (Ishizaki), LV, ×62; 8, *Cytherois asamushiensis* Ishizaki, LV, ×42; 9, *Paracytheridea bosoensis* Yajima, RV, ×73; 10, *Aurila kiritsubo* Yajima, RV, ×52; 11, *Loxoconcha tamakazura* Yajima, LV, ×65; 12, *Cytheropteron subuchioi* Zhao, RV, ×62; 13, *Loxoconcha kattoi* Ishizaki, LV, ×84; 14, *Celtia japonica* Ishizaki, RV, ×46; 15, *Callistocythere japonica* Hanai, RV, ×64; 16, *Sinoleberis tosaensis* (Ishizaki), RV, ×60; 17, *Loxoconcha optima* Ishizaki, RV, ×58; 18, *Pontocythere subjaponica* (Hanai), RV, ×60.

Table 1-1. Individual number of the ostracode species from the Jizodo and Yabu Formations.

	Jizodo Formation										
Species name/ Sample number	IZ 1	2	3	NI 1	2	3	4	5	6	7	8
1 Cytherelloidea senkakuensis Nohara								1			
2 Neonesidea oligodentata (Kajiyama)				2	7	26	61	56	24	23	10
3 Propontocypris spp.			1		1	2	2	1		1	
4 Pontocypris spp.											
5 Neocytherideis aoi Yajima											
6 Pontocythere japonica (Hanai)				23	44	7	3	2	3		8
7 P. miurensis (Hanai)		2		1	5			2	1	4	3
8 P. subjaponica (Hanai)	1	1	1	18	34	5	3			3	9
9 Krithe spp.				2	4					1	1
10 Parakrithella pseudadonta (Hanai)		10	21	1			1				
11 Sinocytheridea sp.											
12 Eucythere yugao Yajima					2				2		
13 E. sp.							1				
14 Munseyella hatatatensis Ishizaki											
15 M. japonica (Hanai)											
16 M. oborozukiyo Yajima				1	2						
17 M. sp.											
18 Callistocythere alata Hanai					1						10
19 C. hayamensis Hanai				1							
20 C. japonica Hanai				4	19	4		1		1	9
21 C. nipponica Hanai		1		1							
22 C. reticulata Hanai					1	1	1				
23 C. rugosa Hanai						1	1				
24 C. subjaponica Hanai						3	3		1		
25 C. undata Hanai								1			1
26 C. undulatifacialis Hanai											
27 C. sp.											
28 Cythere omotenipponica Hanai		1						1	1	1	2
29 C. sp.							1		1		
30 Schizocythere asagao Yajima			1	2	5	11	16	4	3	9	14
31 S. kishinouyei (Kajiyama)			1	14	15	8	35	29	13	17	19
32 S. sp.								1			
33 Hanaiborchella miurensis (Hanai)					1					1	1
34 H. trianguralis Hanai			1	4	9		6	6	5	5	6
35 Neomonoceratina microreticulata Kingma											
36 Palmenella limicola (Norman)											
37 Hemicythere sp. A		1									
38 H. sp. B											
39 Yezocythere sp.											
40 Aurila hataii Ishizaki				4	3	3					
41 A. kiritsubo Yajima	1	13	23	5	9	11	13	5	11	4	12
42 A. munechikai Ishizaki											
43 A. sp. A	107	26	20								
44 A. sp. B						6	10	4	2	7	2
45 A. sp. C	6	4	10	26	6	6	2	4	1		1
46 A. sp. D								2		5	2
47 A. sp. E											
48 A. sp. F											
49 A. sp. G											
50 A. sp. H							1				3

Table 1-2.

Jizodo Formation				Yabu Formation															
NI 9	10	11	12	AT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
									1										
18	16	13	9	3	12	5	24	14	11	8	22	15	7	4	19	14	11	10	
1		1			5		1				4	3	1		1	1			
							2												
											1	1							
13		7	3	12	7	5	5	2	9	7	5	12	4	5	6	13	8	2	18
5	6	3	6			2	1	3	1	1	2	6	3	1		1			1
15	25	4	19		3	9	7	9	15	5	10	11	7	9	6	8	4	2	6
												1		2	1				
									1										
				1	1														
			1																
						1			1										
														1					
								1											
1										1									
		1																	
20	15	5	15	3	2	1	5	3	1				2			3	1	1	
	14	6	15	1	1	4	11	8	24	8	11	8	6	7	8	11	14	3	3
1	1		1															4	
		2					1		1						1				
		1		1		1	5	4	2				1	2		1	1	1	2
																		1	
9												3		3			2	1	
1	3									1		1							
1	2	6	2		1	2	1	4	1		1	1	1	1	5	5	1	2	7
																		1	
13	9	6	11	6	2	3	10	8	23	15	21	5	6	11	25	36	13	8	33
5	12	15	24	2	5	4	18	22	54	22	50	29	22	30	65	69	40	29	7
2	1	2	2			1			1	1	1	1		2	2	1			
1	1		1		1	2	2	9	6	3	3	3	10	6	7	4	4	3	1
								1					1						
			2													1	1		
				1															
																1			
				1															
1	4	3	2		1	1	1	2	11		7	3	4	1	2	1		2	
6	8	8	6	7	15	7	14	10	30	24	38	25	4	8	8	9	4	1	4
	1											2			1				2
4	4	1	3	4	18	4	11	2	4	5	12	7		2	6	6	4		14
					1	1	1						3		1				
4		2						2			1				3				
		1																	
																2	4		
1																			
			2	1	2		4											8	

Table 1-3.

Species name/ Sample number	Jizodo Formation										
	IZ 1	2	3	NI 1	2	3	4	5	6	7	8
51 Pseudoaurila japonica (Ishizaki)											
52 Robustaurila assimilis (Kajiyama)			1		2		1				
53 R. ishizakii (Okubo)		1	1	1				1			1
54 Finmarchinella japonica (Ishizaki)								1			1
55 Caudites? posterocostatus (Ishizaki)						1	2				
56 Bradleya japonica Benson								1			
57 B. nuda Benson							2				
58 B. sp.							1				
59 Cornucoquimba alata Tabuki											
60 C. ikeyai (Yajima)					1	1			2		2
61 C. moniwensis (Ishizaki)	5	1	10	12			8	3	2	1	
62 C. tosaensis (Ishizaki)		5			3	13	4	2	1	5	1
63 Coquimba ishizakii Yajima				2	3				1	2	2
64 Trachyleberis niitsumai (Ishizaki)		7	4	6	6	5	1	5	3	3	10
65 T. scabrocuneata (Brady)									4		2
66 T. sogwipoense Lee				5	2	2					
67 Sinoleberis tosaensis (Ishizaki)		2		3	2				1		1
68 Acanthocythereis munechikai Ishizaki				3							
69 A. sp. A					2						
70 A. sp. B											
71 A. sp. C											
72 A. sp. D											
73 Actinocythereis kisarazuensis Yajima						2	2	2			
74 A. sp.				1					1		1
75 Abrocythereis guangdongensis Gou								6	1	1	1
76 Cletocythereis rastromarginata (Brady)											
77 Hirstocythere? hanaii Ishizaki								1			
78 Rocaleberis? sp.											1
79 Pistocythereis bradyformis (Ishizaki)										1	
80 Amphileberis nipponica (Yajima)				2	4	1					
81 Ambtonia obai (Ishizaki)			2								
82 Buntonia hanaii Yajima	1	9	27	7	3			1	1		1
83 Ambocythere japonica Ishizaki				1							
84 Robertsonites aff. reticuliforma (Ishizaki)								1			
85 Australimoosella tomokoae (Ishizaki)					1			1	1		5
86 Celtia japonica Ishizaki				2	12	2		1	1		1
87 Bythoceratina callidictia Zhao										5	
88 B. cassidoidea Zhao								1		1	
89 B. hanaii Ishizaki									2	3	1
90 B. orientaris (Brady)											
91 B. sp. A											
92 B. sp. B					1						
93 B. sp. C											
94 B. sp. D											
95 Bythocythere sp.					1					2	1
96 Pseudocythere spp.									1		
97 Hemicytherura cuneata Hanai	1				2		1	1		2	1
98 H. kajiyamai Hanai				1							
99 H. sp.										1	
100 Howeina camptocytheroidea Hanai					1	1					

Table 1-4.

Jizodo Formation				Yabu Formation															
NI 9	10	11	12	AT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
							1	2											
		7			1		1		1										
2	3		1	3	3	3	1		1						4	3	1	4	1
							4	1		1	2			2	2	7	1		
		1	1																
					3													1	
						1	1					1				1			
															1				
							1												1
2			1						1		2				1	2		1	
		1	1			1			1		3		1	6	5	6	3		
14	2	6	2	1		1	1	3					1		1	2		1	
3		4	4					1	6		3	8	3		1	2		6	5
2	6	3	4	1	1	33	18	13	28	4	29	6	8	5	9	6	7		2
1	1		1		4		2												
2			1		3	2		1			1	1	1						
4	2	5		2		3	4	4	14	7	15	10	9		3	3	2	1	6
	1				1	2			1		3				1	2		1	
1																			
				1															
												1			3				
					1														
		2				3							1		2				
					1											1			
															1		1		
	1																1	1	
		1		1			1		1			1							
1	1		3	1							2							1	
	2	3				2					1	1			1	3		1	
	1																		
			1								1								
9	7	8	8	2	2	1	1	2		5	3		2	2	3	1	6	7	
3	1		2		3	11	7	1	9	4	6		3	2	1	5	3		
						1	2	1	2	5	6	1					3		
	1							1	1	1	2	2							
4	2	3	1			1	3		1	1	18	4	4		4	4	2	1	
						1										2			
												2			1				
	2		1		2			1					1		1			1	
			1					1								2			
																1			
		1	1			1	3		2	4	9	5	3	1	7	10	2	1	1
		1						1			3	1							
	1	3			1	1	1	1	2	5	15	5	6	4	3	6	4		1
														2	1				
	1	1	4									1					1	7	

Table 1-5.

	Jizodo Formation										
Species name/ Sample number	IZ 1	2	3	NI 1	2	3	4	5	6	7	8
101 Semicytherura henryhowei Hanai & Ikeya											
102 S. miurensis (Hanai)				1							
103 Cytheropteron miurense Hanai					1				2	2	2
104 C. sawanense Hanai				1	1	1	18	15	6	3	4
105 C. subuchioi Zhao				7	12		3	4	9	4	1
106 C. uchioi Hanai						1	13	20	10	5	3
107 C. aff. eremitum Hanai						7	18				
108 C. sp. A											
109 C. sp. B				2							
110 C. sp. C											
111 C. sp. D											
112 C. sp. E										2	
113 Kangarina hayamii Yajima							5	1			
114 Paracytheridea bosoensis Yajima				4	9	2		1	2	3	9
115 P. dialata Gou & Hung											
116 P. sp.							2		1		
117 Loxoconcha hanachirusato Yajima					1				2	3	
118 L. japonica Ishizaki							1				
119 L. kattoi Ishizaki				1	2	1	3	1	1		5
120 L. optima Ishizaki				18	29	4	2	4	13	36	45
121 L. tamakazura Yajima		8	4	9	37	24	9	19	18	13	24
122 L. tosaensis Ishizaki	1	9	25		2		1		1	1	
123 L. viva Ishizaki				1			1				2
124 L. sp.				4		1					
125 Palmoconcha sp.							4	4			
126 Cytheromorpha acupunctata (Brady)	1	6	6						1		
127 Xestoreberis hanaii Ishizaki				1						1	
128 X. sagamiensis Kajiyama		2	10	6	4		4	1	2	4	6
129 X. suetsumuhana Yajima									1		1
130 X. spp.		1		3	5	1	2			1	
131 Paradoxostoma spp.					3		2	1	2	2	1
132 Cytherois asamushiensis Ishizaki	39	46	16								
133 C. sp.											
134 Cytheroma? sp.				1							
135 Paracytheroma spp.				2							
136 Argilloecia? spp.						1	1				
Miscellaneous				1	1					4	
Total	163	156	185	217	321	165	271	219	161	193	249

Table 1-6.

Jizodo Formation				Yabu Formation															
NI 9	10	11	12	AT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
																1			
								1		2	1	3		1	1	1		1	
1							3		9	3	7	4	5		5	2	2	2	
	2	3	2		2	2		2		4	4	5	7	8	6	4	6	2	1
	2	4	2			11	1		8	6	10	4	4	3	7	7	3		
1	1		1		2		2	2							1			3	
		1	1							1									
									2										
							1												
		1							1					1					
															1				
1	5	3	7		1	3	2	1	11	4	7	6	4	8	12	13	10	11	6
					4	3	1									1			
1												3							
1	1	6	3				5	1	13	6	16	3	10	8	11	22	9	1	12
6	3	4	4		1	1	3	4	9	3	12	7	6	1	4	7	3	1	4
56	65	61	76	74	11	3	8		10	15	15	20	12	18	14	15	8	23	32
18	20	4	20	1	46	65	67	45	58	15	25	11	11	8	6	17	4	12	1
							1												
1							1												
		1					2	1	2	2	7		3	4	2	2	1	1	
		1											1			1			
1		4	1			2	3	1	3	1	2	11	3	1	4	6	4	2	
	1		1		3	2	6	5	6	7	10	4	1	4	7	7	6		1
			1			1		1		3	6	8	7	4	1	3	2		
5	1	2			2	2	2		5	1	12	7	5	2	2	4	1	3	3
1		2	1		2					1			1				1		1
					2						1								
									1				1		1			1	
											2								
1	1	1	1	1	2		3		1	3	1	1		1					
264	259	235	283	131	181	216	287	202	407	215	451	284	206	191	308	369	210	177	176