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Author: Ozawa, Hirokazu

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# Early to middle Miocene ostracods from the Yatsuo Group, central Japan: Significance for the bathyal fauna between Japan Sea and Northwest Pacific Ocean during the back-arc spreading

HIROKAZU OZAWA

Earth Sciences Laboratory, College of Bioresource Sciences, Nihon University, Fujisawa, Kanagawa 252-0880, Japan  
(e-mail: ozawa.hirokazu@nihon-u.ac.jp)

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**Abstract.** This study investigated early to middle Miocene ostracods from the Yatsuo Group (*ca.* 17–15 Ma), located on the Japan Sea coast of central Japan. Ostracods from this area consist of 100 species in 60 genera, with two assemblages defined by Q-mode cluster analysis. The five most abundant genera of each assemblage are *Krithe*, *Propontocypris*?, *Cytherella*, *Argilloecia*, and *Falsobuntonia* in assemblage A, and *Schizocythere*, *Cornucoquimba*, *Callistocythere*, *Neomonoceratina*, and *Paracytheridea* in assemblage B. The depositional environment of each assemblage can be defined as (1) outer-shelf to bathyal areas (assemblage A) and (2) inner-shelf areas (assemblage B). Stratigraphic changes in the faunal composition, with changes in lithofacies, suggest a shallowing-upward phase in this sedimentary basin. These assemblages contain the same species or genera as corresponding Pacific faunas in the early to middle Miocene. The assemblage containing bathyal genera such as *Cytherella* and *Krithe* from Yatsuo at 17–16 Ma is the oldest record from the entire Japan Sea coast, and their fossil records are common to Cenozoic bathyal genera among the Pacific fauna. This fact indicates that these genera could migrate from the Pacific Ocean through the deep-sea passageway to the Japan Sea since at least around 17 Ma during the early Miocene. The shallow-water assemblage of the inner-shelf area around 15.7 Ma has only a small percentage of cold-water genera. The paleo-water temperature in the shallow-sea area around 15.7 Ma in Yatsuo would have been intermediate between warm (subtropical) and cold marine climates around 16 Ma in the Japanese Islands. The ostracod fauna from Yatsuo is significant for the paleogeography and faunal migration of benthos in the Northwest Pacific Ocean during the formation period of the Japan Sea caused by back-arc spreading.

**Key words:** deep-sea passageway, early to middle Miocene, Japan Sea, Northwest Pacific, ostracods, Yatsuo Group

## Introduction

The paleogeography and aquatic environments around the Japanese Islands in the Northwest Pacific region changed greatly during the early to middle Miocene (e.g. Chinzei, 1991; Ogasawara *et al.*, 2008). In the period pre-20 Ma, the Japanese Islands were part of the eastern margin of the Asian Continent, and the Japan Sea still did not exist (Iijima and Tada, 1990; Uemura, 2006; Kano *et al.*, 2007; Tsutsumi, 2014). The Japan Sea began to open as a marginal sea around 20 Ma, caused by back-arc spreading due to pull-apart opening, until 15 Ma (Otofuji *et al.*, 1994; Hoshi and Takahashi, 1999; Hoshi *et al.*,

2006; Baba *et al.*, 2007; Yanai *et al.*, 2010; Sawada *et al.*, 2013). Major geological and tectonic events in this region from the early to middle Miocene led to drastic changes of the aquatic environment from freshwater lakes to shallow seas and deep-sea basins with corresponding changes of benthic faunas (Chinzei, 1991; Tada, 1994; Ogasawara, 1994; Irizuki and Matsubara, 1994; Uemura, 2006).

Benthic ostracods provide good clues to understand the relationship between aquatic environmental fluctuations and faunal changes, because they are sensitive to environmental changes, with high endemism due to no planktic growth stages (Boomer *et al.*, 2003; Ozawa,

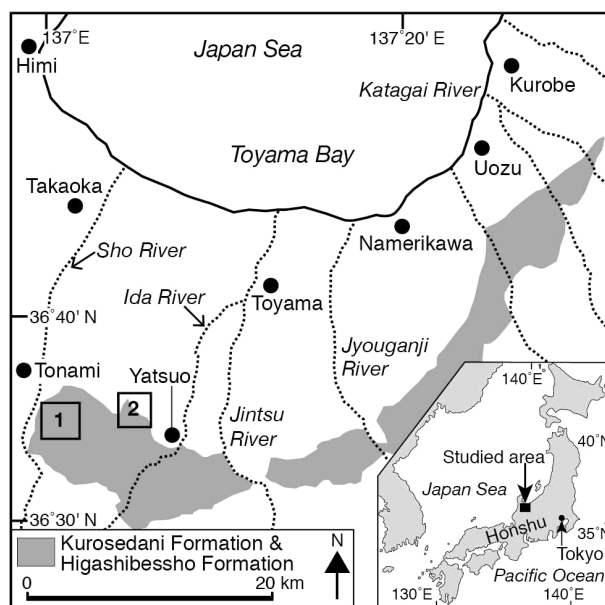
2010, 2013). Several studies have documented the ostracod fauna in shallow-water areas of the inner-shelf region in the Japan Sea for the early to middle Miocene during 20–15 Ma (e.g. Ishizaki, 1963; Yajima, 1988; Tanaka *et al.*, 2004). However, to date, few studies have presented accounts of early to middle Miocene (20–15 Ma) deep-water ostracods from outer-shelf to bathyal areas of the Japan Sea. A preliminary report of Irizuki *et al.* (2006) only touched on this topic. Some studies of shallow- and deep-water ostracods in this sea have been conducted on slightly younger records from the middle to late Miocene (15–7 Ma; Yajima, 1988; Irizuki, 1994; Tanaka *et al.*, 2002; Tanaka, 2003; Tanaka and Nomura, 2009; Matsuura *et al.*, 2013) or shallow-sea assemblages of the early to middle Miocene (17–16 Ma; Ishizaki, 1963; Yajima, 1988; Huh and Paik, 1992; Huh and Whatley, 1997; Tanaka *et al.*, 2004).

The Yatsuo Group comprises the Miocene bathyal stratigraphic unit during 17–16 Ma outcropping in the Japan Sea region. These deposits contain many bathyal calcareous fossils and much chronological data around 16 Ma (Yanagisawa, 1999a; Amano *et al.*, 2004). Kamiya *et al.* (2006) briefly mentioned fossil occurrences of several genera of bathyal ostracods from here, but they did not provide basic details for their specimens such as their geological age, fossil localities or a faunal list with their SEM images. Therefore there are no faunal reports for bathyal ostracods from Yatsuo in detail.

This study investigated ostracods from two formations (Kurosedani and Higashibessho formations) in the Yatsuo Group in order to better understand this important area in the faunal history of the Japan Sea and the Northwest Pacific. Specifically, this study revealed the taxonomic composition and diversity in ostracod faunas, and inferred the nature of the paleo-environment, with representative ostracod faunal lists from this area and their SEM images. The present paper discusses the paleobiogeographical relevance of selected ostracod taxa in bathyal areas, comparing their occurrence with that in other coastal regions of the Japanese Islands during the late Cenozoic. These results allow for inferences regarding the paleogeography of the Japan Sea, an era in which deep-water basins appeared just after the back-arc spreading.

### Geological setting and age

The Kurosedani and Higashibessho formations in the Yatsuo Group, along the Toyama Bay coast of the Japan Sea, are well exposed in the Yatsuo area, southwest of Toyama City, central Japan (Figure 1). Sakamoto and Nozawa (1960) and Hayakawa and Takemura (1987) described their geology in detail. The Kurosedani Forma-



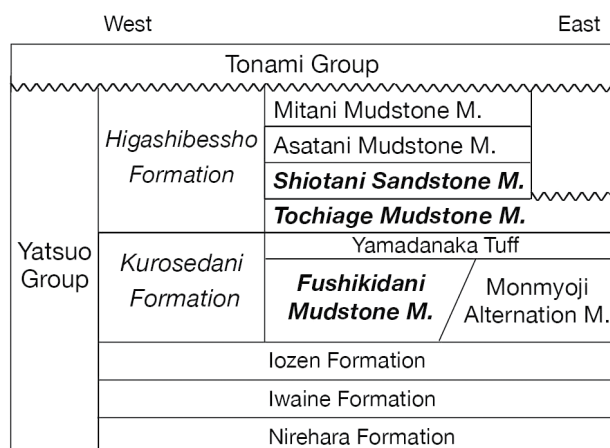
**Figure 1.** Map showing sampling localities for fossil ostracods and distribution of the Kurosedani and Higashibessho formations in the Yatsuo Group, central Japan, showing two studied areas (1 and 2), simplified from Yamada *et al.* (1974) and Kaseno *et al.* (1992). Letters 1 and 2 correspond to use in Figure 4.

tion conformably overlies the Iozen Formation, and is overlain conformably by the Higashibessho Formation (Figure 2). The Higashibessho Formation is unconformably overlain by the Tonami Group.

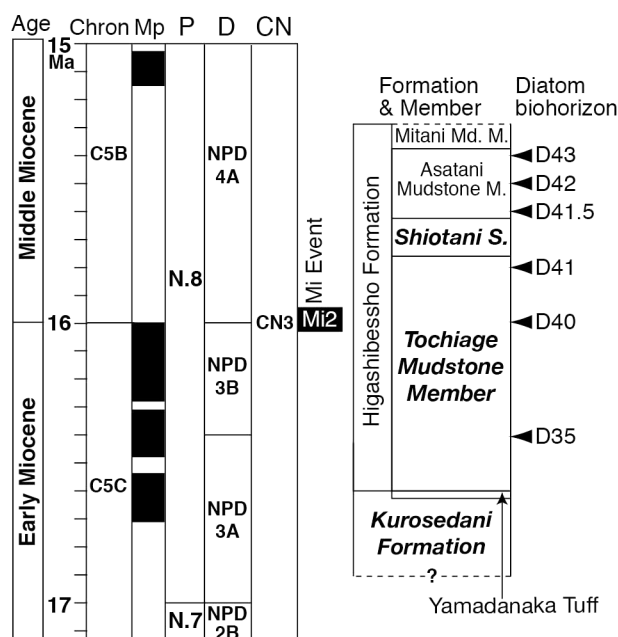
The Kurosedani Formation is composed mainly of mudstone, accompanied by alternations of mudstone–sandstone. This formation consists of five members including the Fushikidani Mudstone Member with the Yamadanaka Tuff (Figure 2). The Higashibessho Formation is composed mainly of mudstone, accompanied by sandstone and alternations of mudstone and sandstone, and consists of four members (Tochiage Mudstone, Shiotani Sandstone, Asatani Mudstone, and Mitani Mudstone members; Figure 2).

The Kurosedani Formation contains early to middle Miocene planktic microfossils (Tanimura, 1979). Previous studies (e.g. Hasegawa and Takahashi, 1992) had placed microfossils from this formation at the lower part of the planktic foraminifer zone N.8 of Blow (1969; Figure 3) and the lower part of the nannofossil CN3 zone of Okada and Bukry (1980). The andesitic lava in the uppermost part of the Iwaine Formation, which is in the lower part of the Yatsuo Group (Figure 2), has a K–Ar age of  $16.4 \pm 0.9$  Ma (Shibata, 1973).

The Higashibessho Formation also contains early to middle Miocene planktic microfossils (Tanimura, 1979;



**Figure 2.** Stratigraphy of the Yatsuo Group in central Japan, after Hayakawa and Takemura (1987), Hasegawa and Takahashi (1992) and Yanagisawa (1999a). Bold-italic letters show the three members examined for ostracods in this study. M: Member.



**Figure 3.** Chronology of the Kurosedani and Higashibessho formations in the Yatsuo Group of central Japan related to biochronology and the geomagnetic polarity time scale, modified from Yanagisawa (1999a). Bold-italic letters show the three members studied for ostracods. Ages from Berggren *et al.* (1995), Lourens *et al.* (2004) and Watanabe and Yanagisawa (2005); P: planktic foraminifer zone (Blow, 1969); D: diatom zone (Akiba, 1986; Yanagisawa and Akiba, 1998), CN: nannofossil zone (Okada and Bukry, 1980), Chron and Mp: geomagnetic polarity (Cande and Kent, 1995); Mi2: Miocene oxygen isotope event 2 (Takahashi, 2004). M, Member; Md, Mudstone; S, Sandstone Member; Mi2, event according to Miller *et al.* (1998) and Takahashi (2004).

Figure 3). According to Yanagisawa's (1999a) biochronological summary of the Yatsuo Group (Figure 3), microfossils from here correspond to the diatom NPD 3A, 3B, and 4A zones of Akiba (1986), the planktic foraminifer zone N.8 of Blow (1969) and the calcareous nannofossil CN3 zone of Okada and Bukry (1980) with the radiolarian *Calocylletta costata* zone of Motoyama and Maruyama (1998). Yanagisawa (1999a) recognized six diatom biohorizons from D35 (FO *Denticulopsis praelauta*; 16.4 Ma) to D43 (LO *Denticulopsis okunoi*; 15.4 Ma) in the Higashibessho Formation (Figure 3; age from Berggren *et al.*, 1995; Yanagisawa and Akiba, 1998; Watanabe and Yanagisawa, 2005).

Therefore, the Kurosedani and Higashibessho formations likely date to *ca.* 17–15 Ma, corresponding to the early to middle Miocene, based on planktic microfossil records (Figure 3). These formations were deposited during the mid-Neogene climatic optimum *ca.* 17–15 Ma (e.g. Chinzei, 1991) around the isotope event Mi 2 (16.0 Ma; age from Takahashi, 2004) of Miller *et al.* (1998).

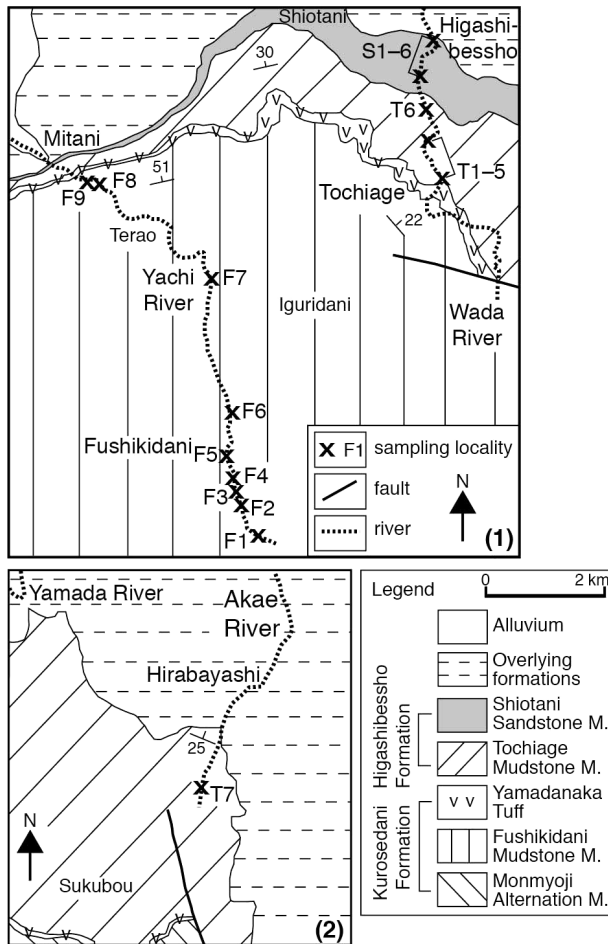
### Materials and methods

Twenty-two rock samples were collected for microfossil analysis from the three members of the Kurosedani and Higashibessho formations (Figures 4, 5). Nine samples (F1–F9) were obtained mainly from the mudstone of the Fushikidani Mudstone Member in the Kurosedani Formation along the Yachi River. Seven samples (T1–T7) were collected mainly from the mudstone of the Tochiage Mudstone Member in the Higashibessho For-

mation along the Wada and Akae rivers (Figure 4). Six samples (S1–S6) were obtained from sandy mudstone layers within alternations of sandy mudstone and fine sandstone of the Shiotani Sandstone Member in the Higashibessho Formation along the Wada River (Figure 5). These samples were collected in the 1970's by Y. Tanimura for his own research (Tanimura, 1979). We cannot observe outcrops for most of these samples at present, because of conservancy work or residential development since the 1980's.

Dried sediment samples in amounts of 80 g were disaggregated using a saturated sodium sulfate solution and naphtha, washed through a 63- $\mu$ m (250-mesh) sieve, and dried at 80°C in an oven. This procedure was repeated until the entire sediment sample had disintegrated. Approximately 200 ostracod individuals were picked from six samples (S1–S6) from fractions between 0.125 and 1.0 mm for each sample split. Other samples yielded





**Figure 4.** Map showing sampling localities for fossil ostracods with distribution of three members in the Yatsuo Group, central Japan, simplified from Sakamoto and Nozawa (1960), Hayakawa and Takemura (1987) and Yanagisawa (1999a). Letters 1 and 2 correspond to use in Figure 1. M: Member.

less than 90 specimens in total, when all specimens that were presented were picked from fractions between 0.125 and 1.0 mm for each sample split. The number of ostracod specimens refers to both valves and carapaces. All the identified adult and juvenile valves (left and right) were counted, and each carapace was counted as one individual. The species diversity was calculated by the Shannon-Wiener function for samples yielding more than 30 specimens.

The author determined fossil ostracod assemblages using Q-mode cluster analysis. In the analysis, Horn's modification of Morishita's overlap index (Morishita, 1959; Horn, 1966) and the unweighed pair-group average (UPGMA) were used as a similarity index and a linkage method, respectively. This study used the free software

package PAleontological Statistics (PAST) provided by Hammer (2014) for the cluster analysis. Samples containing at least 30 specimens were subjected to the cluster analysis. Species represented by less than three individuals in any sample examined were discarded from the present analysis.

All the specimens examined were deposited at the Earth Sciences Laboratory, College of Bioresource Sciences, Nihon University, Fujisawa, Japan. All the sediment samples studied here are stored at the National Museum of Nature and Science, Tsukuba, Japan.

## Results

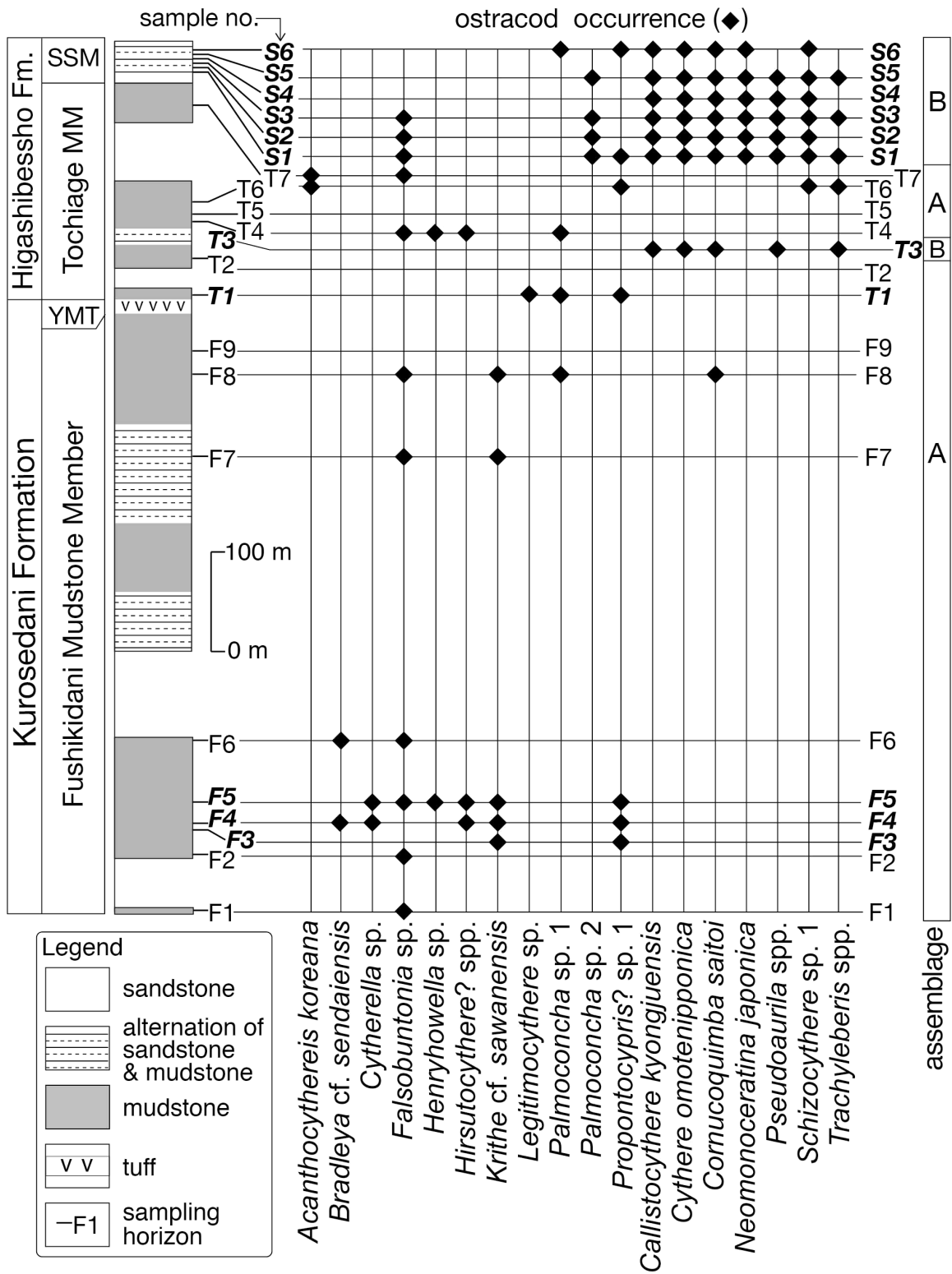
### Occurrence of ostracod

In total, 100 ostracod species in 60 genera were identified from the 22 samples. The Fushikidani and Tochiage mudstone members yielded just under 90 individuals and less than 10 species from each sample (F1–F9 and T1–T7; Table 1), even though ostracod specimens were picked from all fractions, except for the sample F5 yielding 14 species and sample T3 yielding 15 species. The total number of species collected from the Fushikidani Mudstone and Tochiage Mudstone members is 25 and 36, respectively. The species diversity in these samples, calculated by the Shannon-Wiener function, was lower than 1.8, except for sample T3 (2.5; Table 1).

The Shiotani Sandstone Member yielded higher numbers of ostracod taxa (80 species; Table 2) than did the Fushikidani and Tochiage mudstone members. Approximately 20–50 species accounted for approximately 170–300 specimens from each sample of the Shiotani Sandstone Member (S1–S6). The species diversity in these samples, calculated by the Shannon-Wiener function, was approximately 2.4–3.2 (Table 2), which is higher than that for most samples from the Fushikidani and Tochiage mudstone members.

The six samples from the Shiotani Sandstone Member showed an absolute abundance of ostracod fossils (= number of all specimens per 100 g sediment) of approximately 220–740, which is considerably higher than the absolute abundance of approximately 3–110 for the 16 samples from the Fushikidani and Tochiage mudstone members (Tables 1, 2).

The two most abundant species are *Schizocythere* sp. 1 and *Cornucoquimba saitoi* accounting for ca. 30% of the total number of specimens (Table 3). Other species in the genera *Cornucoquimba*, *Neomonoceratina*, *Paracytheridea*, *Callistocythere*, and *Neonesidea* are commonly found from many horizons (Figure 5; Table 2). Species in the above six genera accounted for more than 50% of the total number of individuals (Table 3). These genera currently inhabit shallow-water areas with sandy



**Figure 5.** Columnar sections, frequencies of ostracod species and taxa, ostracod assemblages of the studied area, simplified from Tanimura (1979). YMT, Yamadanaka Tuff; SSM, Shiotani Sandstone Member; MM, Mudstone Member; Fm., Formation. Bold-italic letters show samples used for quantitative analyses. Assemblage names correspond to their use in Figure 6 and Table 4.

**Table 1.** List of fossil ostracods from the Fushikidani and Tochiage mudstone members in the Yatsuo Group. “Irizuki & Yamada, 2004” in this table means Irizuki and Yamada in Irizuki *et al.*, 2004.

Member name Species name/Sample number	Fushikidani Mudstone Member									Tochiage Mudstone Member							Total
	F1	F2	F3	F4	F5	F6	F7	F8	F9	T1	T2	T3	T4	T5	T6	T7	
<i>Acanthocythereis koreana</i> Huh & Whatley, 1997															3	2	5
<i>Acanthocythereis munechikai</i> Ishizaki, 1981												1					1
<i>Acanthocythereis quadrata</i> Irizuki & Yamada, 2004												4					4
<i>Acanthocythereis</i> cf. <i>tsurugasakensis</i> Tabuki, 1986												2					2
<i>Argilloecia</i> cf. <i>toyamaensis</i> Ishizaki & Irizuki, 1990	2		12	7				1					2		1		25
<i>Australimoosella hanaii</i> Yajima, 1992												1					1
<i>Bradleya</i> cf. <i>sendaiensis</i> Ishizaki, 1966				3		1											4
<i>Callistocythere kyongjuensis</i> Huh & Whatley, 1997												2					2
<i>Callistocythere?</i> sp.													1				1
<i>Cornucoquimba</i> cf. <i>kagitoriensis</i> Ishizaki <i>et al.</i> , 1996										2							2
<i>Cornucoquimba moniwiensis</i> (Ishizaki, 1966)					1												1
<i>Cornucoquimba saitoi</i> (Ishizaki, 1963)								1				1					2
<i>Cornucoquimba</i> sp. 1															1		1
<i>Cythere omotenipponica</i> Hanai, 1959												7					7
<i>Cythere</i> cf. <i>schornikovii</i> Ikeya & Tsukagoshi, 1988												1					1
<i>Cytherella</i> sp.				2	47												49
<i>Cytheropteron uchioi</i> Hanai, 1957					1												1
<i>Cytheropteron</i> cf. <i>sendaiensis</i> Ishizaki, 1966					1									1			2
<i>Cytherura?</i> sp.					2												2
<i>Falsobuntonia</i> sp.	3	1			3	1	4	1					3			3	19
<i>Hemicytherura?</i> sp.									1								1
<i>Henryhowella</i> sp.					1								1				2
<i>Hirsutocythere?</i> <i>nozokiensis</i> (Ishizaki, 1963)				1	3												4
<i>Hirsutocythere?</i> sp.													1				1
<i>Krithe</i> cf. <i>antisawanensis</i> Ishizaki, 1966	3	4				3					1		2				13
<i>Krithe</i> cf. <i>japonica</i> Ishizaki, 1971			7		5												12
<i>Krithe</i> cf. <i>sawanensis</i> Hanai, 1959			57	39	13		2	1		2							114
<i>Legitimocythere</i> sp.										1							1
<i>Loxoconcha pulchra</i> Ishizaki, 1968													1				1
<i>Loxoconcha?</i> sp. 1					1												1
<i>Munseyella</i> sp. 1								1									1
<i>Neonesidea</i> sp.				1	1								2				4
<i>Pacambocythere</i> cf. <i>similis</i> Malz, 1982							1										1
<i>Paijenborchella</i> cf. <i>iocosa</i> Kingma, 1948									1								1
<i>Palmenella limicola</i> (Norman, 1865)											1			1		2	4
<i>Palmoconcha</i> sp. 1								1		1			2				4
<i>Palmoconcha?</i> sp.		1															1
<i>Paracytheridea neolongicaudata</i> Ishizaki, 1966															1		1
<i>Parakrithella?</i> sp.				1													1
<i>Propontocypris?</i> sp. 1			4	10	4					43					1		62
<i>Propontocypris?</i> sp. 2				7	5			1									13
<i>Pseudoaurila ishizakii</i> Irizuki & Yamada, 2004												2					2
<i>Pseudoaurila okumurai</i> (Yajima, 1992)												5					5
<i>Robertsonites reticulatus</i> Irizuki & Yamada, 2004															1		1
<i>Saida?</i> sp.																1	1
<i>Schizocythere</i> sp. 1															1		1
<i>Schizocythere</i> sp. 2																1	1
<i>Sclerochilus?</i> sp.															1		1
<i>Trachyleberis leei</i> Huh & Whatley, 1997												2			1		3
<i>Trachyleberis mizunamiensis</i> Yajima, 1992												2					2
<i>Trachyleberis shukunoharaensis</i> Yajima, 1992												2					2
Number of total individuals	8	6	80	71	88	5	7	7	2	49	2	35	12	2	11	9	394
Number of total species	3	3	4	9	14	3	3	7	2	5	2	15	7	2	9	5	51
Species-diversity index	—	—	0.89	1.48	1.71	—	—	—	—	0.54	—	2.50	—	—	—	—	—
Number of individuals/ 100 g	10.0	7.5	100.0	88.8	110.0	6.3	8.8	8.8	2.5	61.3	2.5	43.8	15.0	2.5	13.8	11.3	—

**Table 2.** List of fossil ostracods from the Shiotani Sandstone Member in the Yatsuo Group. “Irizuki & Yamada, 2004” in this table means Irizuki and Yamada in Irizuki *et al.*, 2004.

Member name Species name/Sample number	Shiotani Sandstone Member						
	S1	S2	S3	S4	S5	S6	Total
<i>Acanthocythereis munechikai</i> Ishizaki, 1981					1		1
<i>Acanthocythereis quadrata</i> Irizuki & Yamada, 2004				1			1
<i>Acanthocythereis</i> cf. <i>tsurugasakensis</i> Tabuki, 1986		1					1
<i>Argilloecia</i> cf. <i>toyamensis</i> Ishizaki & Irizuki, 1990	1	1					2
<i>Bythoceratina?</i> sp.						2	2
<i>Callistocythere kyongjuensis</i> Huh & Whatley, 1997	20	18	6	2	9	9	64
<i>Coquimba</i> cf. <i>ishizakii</i> Yajima, 1987					1	1	2
<i>Cornucoquimba</i> cf. <i>kagitoriensis</i> Ishizaki <i>et al.</i> , 1996	17	11	17	14	2	11	72
<i>Cornucoquimba moniwenensis</i> (Ishizaki, 1966)			9	3	28	12	52
<i>Cornucoquimba saitoi</i> (Ishizaki, 1963)	36	17	50	39	41	42	225
<i>Cornucoquimba</i> sp. 2	1	1					2
<i>Cornucoquimba</i> sp. 3				3			3
<i>Cythere omotenipponica</i> Hanai, 1959	4	8	5	3	9	3	32
<i>Cythere</i> cf. <i>schornikovi</i> Ikeya & Tsukagoshi, 1988	1	3	3	3	1	1	12
<i>Cythere</i> cf. <i>uranipponica</i> Hanai, 1959	3		1		2		6
<i>Cytherella?</i> sp.			1				1
<i>Cytheroma?</i> sp.		1					1
<i>Cytheropteron miurense</i> Hanai, 1957		2		2			4
<i>Cytheropteron</i> cf. <i>sendaiensis</i> Ishizaki, 1966	3	1	3				7
<i>Cytheropteron subuchioi</i> Zhao, 1988	3	1	2		3		9
<i>Cytheropteron uchioi</i> Hanai, 1957					1	1	2
<i>Cytheropteron</i> sp.		5	1		5	7	18
<i>Falsobuntonia</i> sp.	2	1	1				4
<i>Finmarchinella hanaii</i> Okada, 1979	9	16				3	28
<i>Finmarchinella japonica</i> (Ishizaki, 1966)	4	1	1				6
<i>Finmarchinella</i> cf. <i>japonica</i> (Ishizaki, 1966)			1		1		2
<i>Hemicythere emarginata</i> (Sars, 1866)	2		1			3	6
<i>Hemicythere kitanipponica</i> (Tabuki, 1986)		1			1		2
<i>Hemicytherura clathrata</i> Sars, 1866		2					2
<i>Hemicytherura cuneata</i> Hanai, 1957	1						1
<i>Hemicytherura kajiymai</i> Hanai, 1957		1					1
<i>Hermanites posterocostata</i> Ishizaki, 1966	3	3			1	1	8
<i>Kangarina</i> sp.		1			1		2
<i>Kobayashiina hyalinosa</i> Hanai, 1957	1	1					2
<i>Kotoracythere</i> cf. <i>abnorma</i> Ishizaki, 1966	2	2	2	11	4	9	30
<i>Krithe</i> cf. <i>antisawanensis</i> Ishizaki, 1966	3	3					6
<i>Krithe</i> cf. <i>japonica</i> Ishizaki, 1971						1	1
<i>Laperousecythere ishizakii</i> Irizuki & Matsubara, 1995						4	4
<i>Laperousecythere</i> sp.					1		1
<i>Loxconcha nozokiensis</i> Ishizaki, 1963	6	5			1		12

Table 2. Continued.

Member name	Shiotani Sandstone Member						
Species name/Sample number	S1	S2	S3	S4	S5	S6	Total
<i>Loxoconcha pulchra</i> Ishizaki, 1968	3		1				4
<i>Loxoconcha</i> ? sp. 2	1	4			3	7	15
<i>Loxocorniculum kitoraformum</i> Ishizaki, 1966	7	8	1	2	7	6	31
<i>Loxocorniculum</i> sp.	1	1					2
<i>Loxocythere</i> ? sp.						1	1
<i>Metacytheropteron</i> sp.					1	2	3
<i>Munseyella</i> sp. 1		2	2	2	1	8	15
<i>Munseyella</i> sp. 2		2					2
<i>Neomonoceratina</i> cf. <i>hatatensis</i> (Ishizaki, 1966)				2			2
<i>Neomonoceratina ikeyai</i> Irizuki & Yamada, 2004	2		3		2		7
<i>Neomonoceratina japonica</i> (Ishizaki, 1966)	5	9	14	18	9	18	73
<i>Neonesidea</i> sp.	7			5	9	2	23
<i>Paijenborchella</i> cf. <i>hanaii</i> Tabuki, 1986			2		3		5
<i>Palmenella limicola</i> (Norman, 1865)	5	3	6	1	4	4	23
<i>Palmoconcha</i> sp. 1						2	2
<i>Palmoconcha</i> sp. 2	6	5	3		1		15
<i>Paracytheridea neolongicaudata</i> Ishizaki, 1966	17	24	8	7	6	9	71
<i>Paradoxostoma</i> ? sp.	2						2
<i>Pectocythere</i> sp.	2	1				4	7
<i>Perissocytheridea</i> sp.	1						1
<i>Pontocythere</i> cf. <i>miurensis</i> (Hanai, 1959)	4	2	1	1	2	1	11
<i>Propontocypris</i> ? sp. 1	1					1	2
<i>Pseudoaurila ishizakii</i> Irizuki & Yamada, 2004	23	8			10		41
<i>Pseudoaurila okumurai</i> (Yajima, 1992)	3	2	4	1			10
<i>Pseudoaurila</i> ? sp.		1					1
<i>Robertsonites reticulatus</i> Irizuki & Yamada, 2004	11	17	2	2	2	3	37
<i>Schizocythere</i> sp. 1	44	77	59	42	90	79	391
<i>Schizocythere</i> sp. 2		7	2	1	1	4	15
<i>Schizocythere</i> ? sp.		1					1
<i>Sclerochilus</i> ? sp.	1						1
<i>Semicytherura pseudoundata</i> Irizuki & Yamada, 2004	11	18			1	4	34
<i>Semicytherura</i> cf. <i>miurensis</i> (Hanai, 1957)					1		1
<i>Semicytherura</i> cf. <i>hanaii</i> Ishizaki, 1981		1					1
<i>Spinileberis</i> sp.				3			3
<i>Trachyleberis leei</i> Huh & Whatley, 1997	2						2
<i>Trachyleberis mizunamiensis</i> Yajima, 1992			1		5		6
<i>Urocythereis</i> ? <i>gorokuensis</i> Ishizaki, 1966			1				1
<i>Xestoleberis</i> cf. <i>hanaii</i> Ishizaki, 1968	6	6		5	1		18
<i>Xestoleberis</i> cf. <i>setouchiensis</i> Okubo, 1979	7	1					8
<i>Xestoleberis</i> ? sp.						2	2
Number of total individuals	294	307	214	173	272	267	1527
Number of total species	44	47	32	24	39	34	80
Species-diversity index	3.18	3.03	2.49	2.43	2.58	2.70	
Number of individuals/ 100 g	735.0	383.8	267.5	216.3	680.0	333.8	

**Table 3.** Twenty-ranked ostracod species, their numbers of individuals (No.), and their percentages against all individuals from the Yatsuo Group.

Species name	No.	%
<i>Schizocythere</i> sp. 1	392	20.4
<i>Cornucoquimba saitoi</i>	227	11.8
<i>Krithe</i> cf. <i>sawanensis</i>	114	5.9
<i>Cornucoquimba</i> cf. <i>kagitoriensis</i>	74	3.9
<i>Neomonoceratina japonica</i>	73	3.8
<i>Paracytheridea neolongicaudata</i>	72	3.7
<i>Callistocythere kyongjuensis</i>	66	3.4
<i>Propontocypris</i> ? sp. 1	64	3.3
<i>Cornucoquimba moniwiensis</i>	52	2.7
<i>Cytherella</i> sp.	49	2.6
<i>Pseudoaurila ishizakii</i>	43	2.2
<i>Cythere omotenipponica</i>	39	2.0
<i>Robertsonites reticulatus</i>	38	2.0
<i>Semicytherura pseudoundata</i>	34	1.8
<i>Loxocorniculum kitoraformum</i>	31	1.6
<i>Kotoracythere</i> cf. <i>abnorma</i>	30	1.6
<i>Finmarchinella hanaii</i>	28	1.5
<i>Neonesidea</i> sp.	27	1.4
<i>Palmenella limicola</i>	27	1.4
<i>Argilloecia</i> cf. <i>toyamaensis</i>	26	1.4
Total	1506	78.4

and muddy sediments around the Japanese Islands (Frydl, 1982; Ikeya and Itoh, 1991; Kamiya *et al.*, 2001; Ozawa, 2003; Tanaka, 2008; Irizuki *et al.*, 2009).

Species in the genera *Krithe*, *Propontocypris*?, *Cytherella*, *Falsobuntonia*, *Acanthocythereis*, *Robertsonites*, and *Palmenella* are commonly or rarely found from several horizons (Figure 5; Tables 1, 2). These seven genera are found from outer-shelf and bathyal areas with muddy sediments around Japan (Ishizaki and Irizuki, 1990; Ikeya and Suzuki, 1992; Zhou and Ikeya, 1992; Zhou, 1995; Ozawa and Kamiya, 2005; Ozawa and Tsukawaki, 2008; Tanaka *et al.*, 2012a).

There are common or rare occurrences of the genera *Cythere*, *Loxocorniculum*, and *Xestoleberis* along with *Loxoconcha pulchra* from many horizons (Figure 5; Tables 1, 2). These four taxa are all phytal dwellers, living on sea plants, e.g. the seagrass *Zostera* in sandy substrates, and calcareous algae on rocky shores, along the

present-day Japanese coasts (Kamiya, 1988; Tsukagoshi, 1990; Kamiya *et al.*, 2001; Ishii *et al.*, 2005; Sato and Kamiya, 2007; Ozawa and Ishii, 2008, 2014; Ozawa, 2013). The two species of *Pseudoaurila* (*P. ishizakii* and *P. okumurai*) occur also from many horizons (Figure 5; Tables 1, 2). Irizuki *et al.* (2004) stated that these two species probably went extinct during the Miocene, and presumed that they were phytal dwellers on the basis of their carapace shape, which resembles a rugby ball, as a result of adaptation to life on leaves of seagrass or algae (e.g. Kamiya, 1988).

### Ostracod assemblage

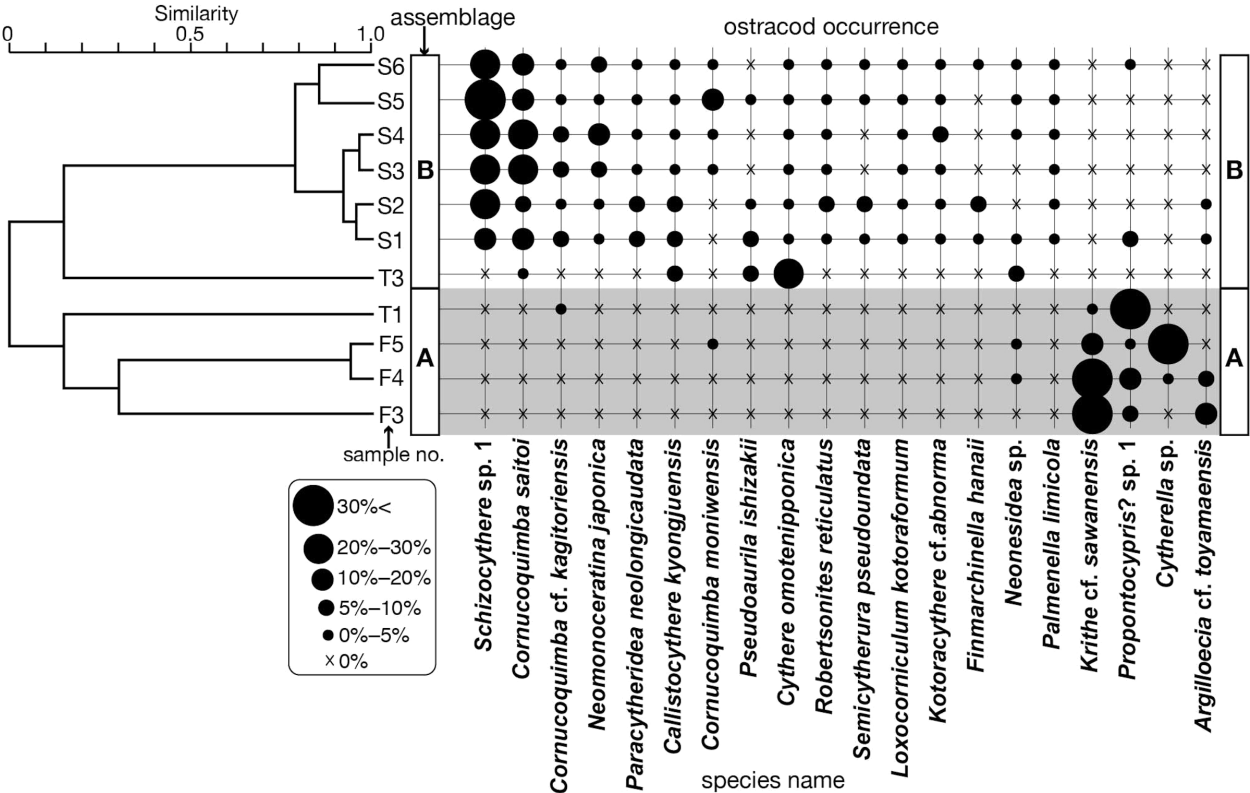
Two fossil assemblages A and B were defined by the Q-mode cluster analysis (Figure 6) using 52 species and 11 samples. Assemblage A (samples F3–F5 and T1), from the Fushikidani and Tochiage mudstone members mainly in mudstone samples, was mainly composed of five genera, i.e., *Krithe*, *Propontocypris*?, *Cytherella*, *Argilloecia*, and *Falsobuntonia* (Figures 5, 6; Table 4). It is enriched by characteristic occurrences of *Bradleya*, *Hirsutocythere*?, *Henryhowella*, *Legitimocythere*, and *Palmoconcha* (Figures 5, 7, 8, Table 4). This study allocated the 11 samples from the Fushikidani and Tochiage mudstone members (samples F1, F2, F6–F9, T2, and T4–T7) that yielded less than 15 specimens and were not examined by cluster analysis to assemblage A on the basis of the species composition, because these samples commonly yielded the above genera (Figure 5).

Most of these characteristics and the genus composition are typical of ostracod assemblages in muddy sediments from outer-shelf to bathyal areas of the present Northwest Pacific and Japan Sea (e.g. Ikeya and Suzuki, 1992; Zhou and Ikeya, 1992; Ikeya and Cronin, 1993; Ozawa, 2003; Ozawa and Kamiya, 2005; Tanaka *et al.*, 2012a). Individuals of these ostracod taxa accounted for approximately 80% of ostracod specimens in the 15 samples of assemblage A, which was characterized by a low number of species and low absolute abundance in muddy sediments, and a species diversity index of approximately 1–2 (Tables 1, 4).

In regard to assemblage A, *Krithe* and *Cytherella* were more dominant in the Fushikidani Mudstone Member than in the Tochiage Mudstone Member, and were accompanied by genera such as *Argilloecia*, *Falsobuntonia*, *Henryhowella*, and *Hirsutocythere*? (Figures 5, 6; Tables 1, 4). In contrast, in the Tochiage Mudstone Member, *Propontocypris*? dominated and was accompanied by *Acanthocythereis* and *Robertsonites* (Figures 5, 6; Tables 1, 4). At present along the Pacific and Japan Sea coasts of Japan, the former genera such as *Krithe* are dominant in relatively bathyal areas at approximately 300–1,000 m water depths, while the latter genera such

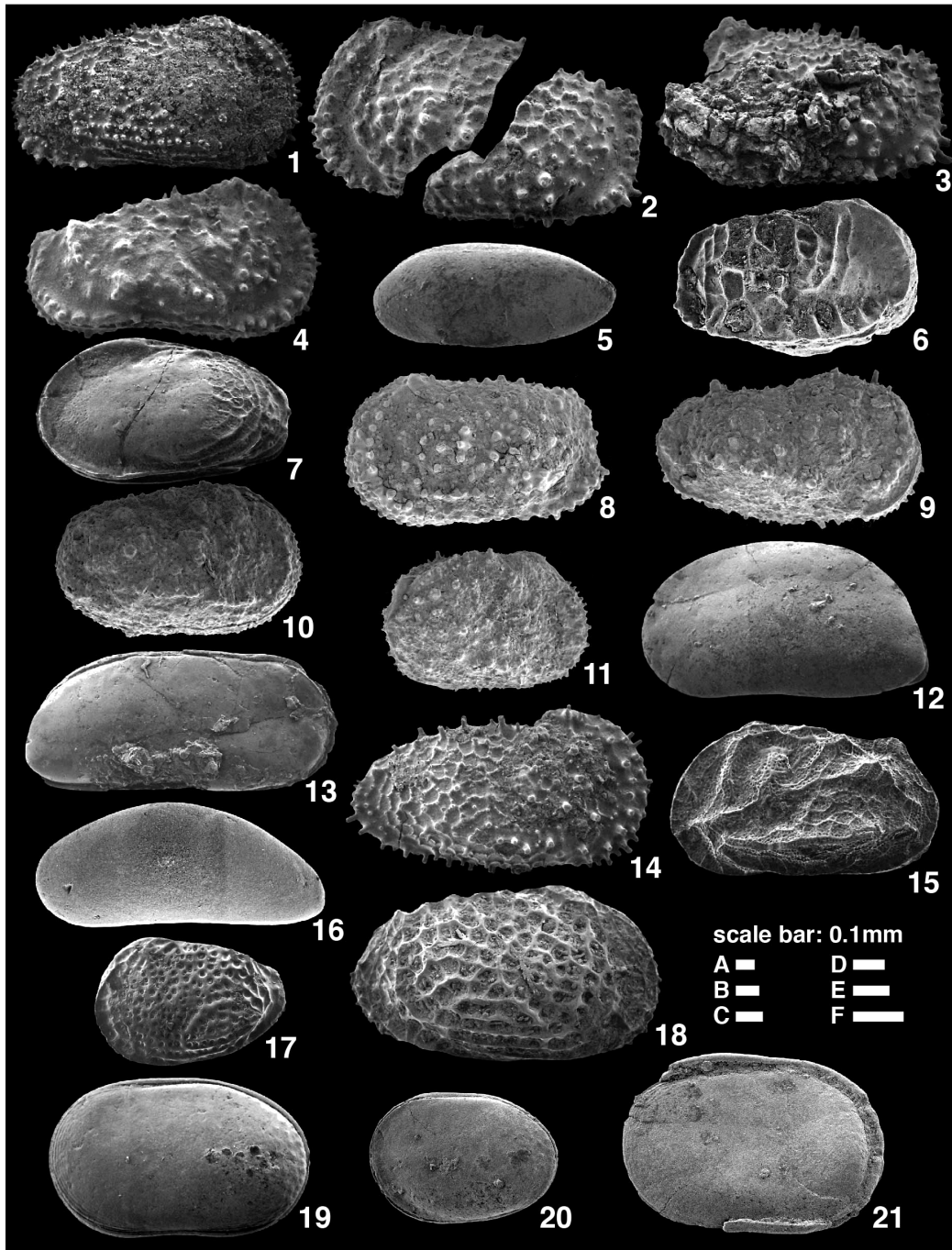
**Table 4.** Summary for two ostracod assemblages (Ass.) from the Yatsuo Group. Diversity index (Diversity) in samples used in cluster analysis, number of species (No. spp.) in all samples, paleoenvironments, and five-ranked ostracod species of each assemblages, with their mean percentages in samples used in cluster analysis of each assemblage (RA) and their maximum percentage in a single sample (RM). Assemblage names correspond to use in Figures 5 and 6.

Ass.	Diversity	No. spp.	Paleoenvironment	Five-ranked species	RA (%)	RM (%)
A	0.54–1.71 (mean: 1.12)	2–14 (mean: 5)	outer shelf to bathyal area	<i>Krithe</i> cf. <i>sawanensis</i>	36.3	71.3
				<i>Propontocypris</i> ? sp. 1	27.9	87.8
				<i>Cytherella</i> sp.	14.1	53.4
				<i>Argilloecia</i> cf. <i>toyamaensis</i>	6.2	15.0
				<i>Propontocypris</i> ? sp. 2	3.9	9.9
B	2.49–3.18 (mean: 2.70)	15–47 (mean: 34)	inner shelf area	<i>Schizocythere</i> sp. 1	21.9	33.1
				<i>Cornucoquimba</i> <i>saitoi</i>	13.9	23.4
				<i>Neomonoceratina</i> <i>japonica</i>	4.5	10.4
				<i>Cornucoquimba</i> cf. <i>kagitoriensis</i>	4.3	8.1
				<i>Paracytheridea</i> <i>neolongicaudata</i>	3.9	7.8

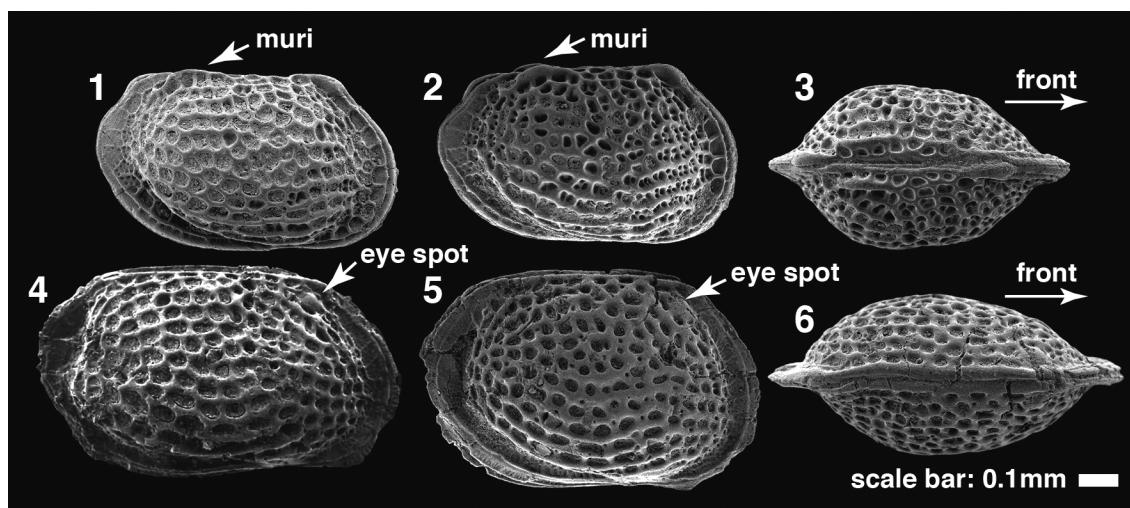


**Figure 6.** Dendrogram showing the result of Q-mode cluster analysis of 11 samples and the relative abundances of the dominant ostracod species in each assemblage. Assemblage names correspond to their use in Figure 5 and Table 4.





**Figure 7.** SEM images of fossil ostracods from the Yatsuo Group. RV: right valve, LV: left valve, CA: carapace. **1**, *Acanthocythereis koreana* Huh and Whatley, 1997, RV; **2**, **3**, *Acanthocythereis quadrata* Irizuki and Yamada in Irizuki *et al.*, 2004; **2**, LV; **3**, LV; **4**, *Acanthocythereis* cf. *tsurugasakensis* Tabuki, 1986, CA right side; **5**, *Argilloecia* cf. *toyamaensis* Ishizaki and Irizuki, 1990, CA left side; **6**, *Bradleya* cf. *sendaiensis* Ishizaki, 1966, CA right side; **7**, *Falsobuntonia* sp., CA left side; **8**, *Hirsutocythere?* *nozokiensis* (Ishizaki, 1963), CA left side; **9**, *Hirsutocythere?* sp., CA right side; **10**, **11**, *Henryhowella* sp.; **10**, CA right side; **11**, CA right side; **12**, *Krithe* cf. *sawanensis* Hanai, 1959, CA left side; **13**, *Krithe* cf. *antisawanensis* Ishizaki, 1966, CA right side; **14**, *Legitimocythere* sp., RV; **15**, *Palmenella limicola* (Norman, 1865), LV; **16**, *Propontocypris?* sp., RV; **17**, **18**, *Robertsonites reticulatus* Irizuki and Yamada in Irizuki *et al.*, 2004; **17**, LV; **18**, RV; **19–21**, *Cytherella* sp.; **19**, CA left side; **20**, CA left side; **21**, CA left side. All specimens are adults, except for **6**, **11**, **17** and **20** which are juveniles. Scale bars 0.1 mm: A for **9**; B for **1**, **8**, **10**, **11**, **16**; C for **4**; D for **2**, **3**, **6**, **7**, **12–14**, **17–21**; E for **5**; F for **15**. Specimens of **1** from sample S1, **14**, **16** from sample T1, and **18** from sample T6.



**Figure 8.** SEM images of fossil ostracods from the Yatsuo Group. CA: carapace. **1–3**, *Palmococoncha* sp. 1; 1, male, CA right side; 2, female, CA right side; 3, female, CA dorsal side; **4–6**, *Palmococoncha* sp. 2; 4, male, CA right side; 5, female, CA right side; 6, female, CA dorsal side. All specimens are adults. Specimens of 1 from sample F8, 2, 3 from sample T4, 4, 6 from sample S1, and 5 from sample S2.

as *Propontocypris* and *Robertsonites* are dominant or common from outer-shelf to bathyal areas at approximately 150–300 m water depths (e.g. Zhou and Ikeya, 1992; Zhou, 1995; Ozawa and Kamiya, 2001, 2005; Ozawa, 2003).

A small number of shallow-sea genera on inner-shelf areas, such as *Schizocythere* and *Cornucoquimba* in the present Japan Sea and Northwest Pacific (e.g. Ikeya and Cronin, 1993; Ozawa, 2003), occurred from the Tochiage Mudstone Member (samples T1 and T5–T7; Table 1). These genera occurred very rarely in the Fushikidani Mudstone Member.

Assemblage B (samples T3 and S1–S6) was dominantly composed of the shallow-sea genera *Schizocythere* and *Cornucoquimba*, accompanied by *Callistocythere*, *Neomonoceratina*, *Pseudoaurila*, *Cythere*, *Paracytheridea*, *Loxocorniculum*, *Neonesidea*, *Pontocythere*, and *Xestoleberis* (Figures 5, 6, 9, 10; Table 4). This assemblage mainly occurred in sandy mudstone layers within alternations of mudstone and sandstone of the Shiotani Sandstone Member (samples S1–S6) and in part of the Tochiage Mudstone Member (sample T3; Figures 5, 6). Most of these dominant genera inhabit inner-shelf areas of the modern Japan Sea and Northwest Pacific (e.g. Ikeya and Cronin, 1993; Zhou, 1995; Kamiya *et al.*, 2001; Ozawa and Kamiya, 2001; Ozawa, 2003, 2010; Tanaka, 2008; Irizuki *et al.*, 2009). Individuals of species in these genera accounted for approximately 80% of ostracod specimens in this assemblage, which was characterized by a high number of species and absolute abun-

dance in sandy sediments, and a species diversity index of approximately 3 (Tables 1, 2, 4). Assemblage B had a much higher number of species and higher ostracod abundance than did assemblage A from the Fushikidani and Tochiage Mudstone members, except for sample T3 (Tables 1, 2, 4).

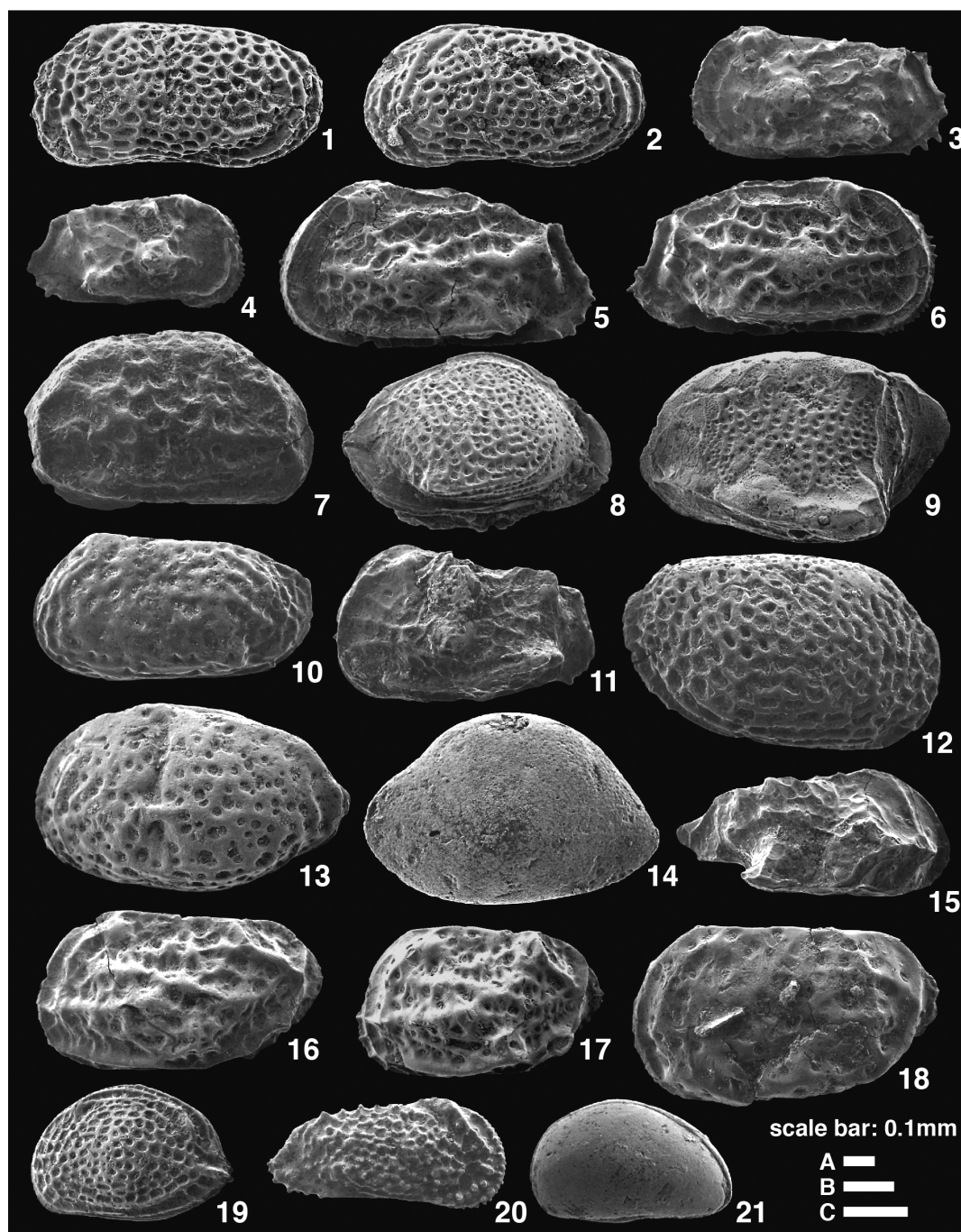
Most species found in assemblage B, e.g. *Callistocythere kyongjuensis*, *Cornucoquimba saitoi*, *Loxococoncha nozokiensis*, *Neonesidea* sp., *Pseudoaurila ishizakii*, *P. okumurai*, *Schizocythere* sp. 1, and *Trachyleberis mizunamiensis* belong to the main species in the ostracod TS (*Trachyleberis mizunamiensis*–*Schizocythere* sp.) association, defined by Irizuki *et al.* (2004) from the Pacific inner shelf (shallower than 30 m) of the Japanese early Miocene fauna.

## Discussion

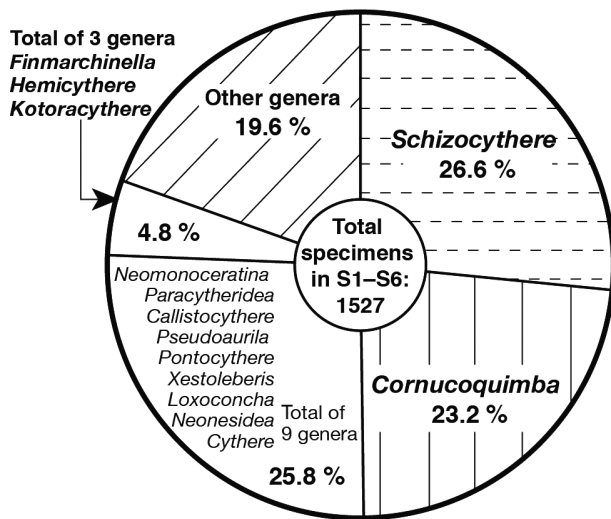
### Water depth of depositional environments

The presence of assemblage A indicates a paleo-environment in outer-shelf to bathyal areas, while assemblage B suggests an inner-shelf paleo-environment. Further detailed examinations of differences of the genus composition in assemblage A between the two mudstone members suggest a shallowing upwards-phase.

Common or rare occurrences of phytal-dwelling taxa such as *Cythere* and *Xestoleberis* from assemblage B (samples S1–S6) suggest the existence of beds of calcareous algae on the rocky shore and eelgrass *Zostera* on a sandy substrate around the intertidal zone near the site of



**Figure 9.** SEM images of fossil ostracods from the Yatsuo Group. RV: right valve, LV: left valve, CA: carapace. **1, 2**, *Callistocythere kyongjuensis* Huh and Whatley, 1997; **1**, CA left side; **2**, CA left side; **3**, *Cornucoquimba* cf. *kagitoriensis* Ishizaki *et al.*, 1996, CA left side; **4**, *Cornucoquimba moniwiensis* (Ishizaki, 1966), RV; **5, 6**, *Cornucoquimba saitoi* (Ishizaki, 1963); **5**, LV; **6**, RV; **7**, *Cythere omotenipponica* Hanai, 1959, RV; **8**, *Cytheropteron* cf. *sendaiensis* Ishizaki, 1966, CA right side; **9**, *Cytheropteron* sp., LV; **10**, *Kotoracythere* cf. *abnorma* Ishizaki, 1966, LV; **11**, *Laperousecythere ishizakii* Irizuki and Matsubara, 1995, LV; **12**, *Loxoconcha nozokiensis* Ishizaki, 1963, RV; **13**, *Neomonoceratina japonica* (Ishizaki, 1966), LV; **14**, *Neonesidea* sp., CA left side; **15**, *Paracytheridea neolongicaudata* Ishizaki, 1966, RV; **16, 17**, *Schizocythere* sp. 1; **16**, LV; **17**, LV; **18**, *Schizocythere* sp. 2, LV; **19**, *Pseudoaurila ishizakii* Irizuki and Yamada in Irizuki *et al.*, 2004, CA left side; **20**, *Trachyleberis leeii* Huh and Whatley, 1997, RV; **21**, *Xestoleberis* cf. *hanaii* Ishizaki, 1968, CA right side. Scale bars are 0.1 mm: A for 3, 4, 14, 19–21; B for 1, 2, 5–8, 10, 11, 15–18; C for 9, 12, 13. All specimens are adults, except for 11 and 15 which are juveniles. Specimens of 1, 2 from sample S2, 3, 4, 9, 11, 12 from sample S6, 5, 6, 10, 13, 15–17 from sample S5, 7, 8, 14, 19 from sample S1, 18 from sample S3, 20 from sample T2, and 21 from sample S4.



**Figure 10.** Relative frequency (%) of dominant ostracod genera from the Shiotani Sandstone Member (samples S1–S6; assemblage B).

these samples. The fact that the depositional environment has relatively strong water currents at the site of these samples can explain the high abundance of ostracod fossils and the high occurrence of phytal species which were probably transported from near the intertidal zone to the inner-shelf area, also considering that samples S1–S6 were composed of sandstone, which is evidence for some sorting influence.

Stratigraphic changes in these genera or species composition for the assemblages A and B, with lithofacies from mudstone to alternation of mudstone and sandstone in the study area (Figure 5), suggest a shallowing-upward phase of the paleo-setting for this sedimentary basin. The paleo-environment changed from bathyal to inner-shelf as a whole between *ca.* 17 and 15.7 Ma.

#### Temperature of bathyal water

Numerous paleo-environmental studies, including those based on molluscan analyses, have suggested that a warm tropical–subtropical aquatic environment appeared in shallow- and deep-sea areas of Japan during the mid-Neogene climatic optimum at *ca.* 17–15 Ma, except for the cooling event Mi 2 around 16 Ma (e.g. Chinzei, 1991; Ogasawara, 1994; Amano *et al.*, 2004; Irizuki *et al.*, 2004). The deep-water ostracod genera found in the assemblage A from the Fushikidani and Tochiage mudstone members (*ca.* 17–16 Ma; Figures 3, 5), e.g. *Cytherella*, *Bradleya*, and *Hirsutocythere*? (e.g. Figure 7), are distributed together in the present Kuroshio Warm Current area in the outer-shelf to bathyal

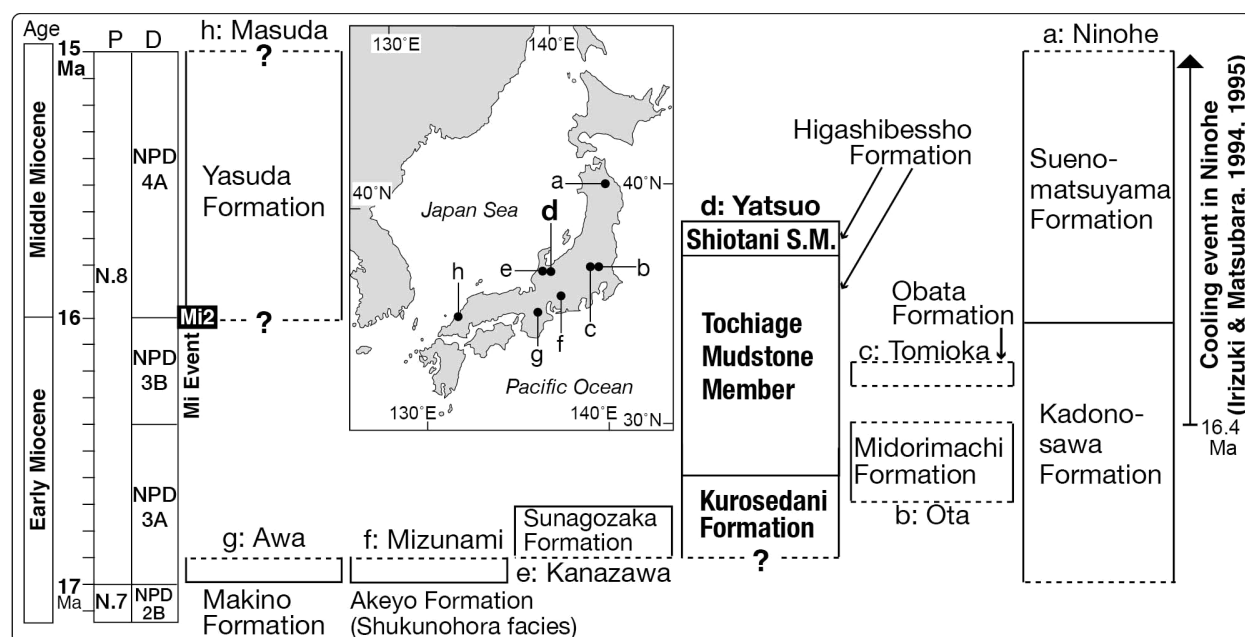
regions off southern Japan on the Pacific and East China Sea coasts (Ishizaki, 1983; Zhou, 1995). Therefore, during the depositional period of the two mudstone members, a relatively warm-water environment of 5–10°C like that created by the present Kuroshio Current (Ikeya and Cronin, 1993) would have been found in the outer-shelf to bathyal areas at Yatsuo.

This condition was different from the relatively cold-water environment prevailing in the outer-shelf to bathyal areas in the present Japan Sea (Japan Sea Intermediate–Proper Water; Ozawa, 2003), less than 2°C (e.g. Ikeya and Cronin, 1993; Ozawa and Kamiya, 2001, 2005). The depositional period of the two mudstone members in Yatsuo, with bathyal ostracods, correlates to the appearance period of warm-water shallow-sea ostracods in the Mizunami, Kanazawa, Tomioka and Ota areas and lower horizons of the Ninohe area (lower part of the Kadonosawa Formation), with numerous subtropical warm-water ostracod and molluscan assemblages characteristic of Japan (Figure 11; e.g. Irizuki and Matsubara, 1994; Amano *et al.*, 2004; Tanaka *et al.*, 2013).

Previous studies have proposed a global cooling period, i.e., the Miocene oxygen isotope event Mi2 around 16.0 Ma (e.g. Miller *et al.*, 1998; age from Takahashi, 2004; Figure 11). In Yatsuo, the Mi2 event correlates to the depositional period of the Tochiage Mudstone Member (Figure 11), but samples from this member contain no cold-water genera such as *Finmarchinella* (Table 1). According to Irizuki *et al.* (2004), the rapid and dominant appearance of shallow-dwelling cold-water ostracods around 16.4 Ma at Ninohe in north-eastern Japan could reflect a cold marine climate influenced by this cooling event. Evidence of this event was not recorded in the ostracod fauna from the Tochiage Mudstone Member at Yatsuo, probably due to the deep-water environment.

#### Paleobiogeography of bathyal fauna between 17–16 Ma

The assemblage A from Yatsuo contains in conjunction with *Cytherella* species of *Henryhowella* and *Legitimocythere* (Figures 5, 6). All these are common bathyal genera that have lived since the Paleogene in many such regions of the Pacific and other oceans (e.g. Cronin and Compton-Goodin, 1987; Cronin *et al.*, 2002; Yamaguchi, 2004; Bergue and Nicoladis, 2012). Modern and Eocene–Pleistocene sediments from the Pacific coasts of Japan and Southeast Asia include these genera as well as *Krithe* (Figures 7, 12–15) (e.g. Hanai *et al.*, 1980; Ishizaki, 1983; Zhou, 1995; Yamaguchi, 2004). However, up to now, considering the entire coastline of the Japan Sea, from the early Miocene to the present there



**Figure 11.** Stratigraphic correlation of the early–middle Miocene (17–15 Ma) strata in Yatsuo and seven areas of Japan referred in the text. **P**, planktic foraminiferal zone of Blow (1969); **D**, diatom zone of Barron and Gladenkov (1995); **Mi2** event according to Miller *et al.* (1998) and Takahashi (2004). Age data; **a**, Irizuki and Matsubara (1994, 1995); **b**, Takahashi and Yanagisawa (2003); **c**, Takahashi and Hayashi (2004); **d**, Yanagisawa (1999a); **e**, Yanagisawa (1999b); **f**, Irizuki *et al.* (2004); **g**, Irizuki (2003); **h**, Irizuki *et al.* (2006, 2014). S. M.: Sandstone Member.

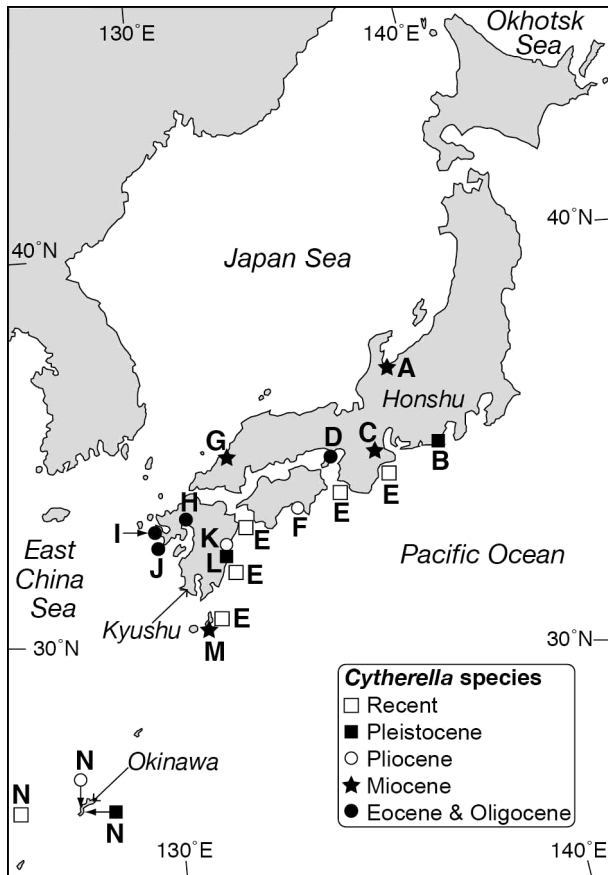
has been just one preliminary report of the genus *Cytherella*, which was found at the coastline's southwestern end in the middle Miocene Yasuda Formation of the Masuda Group (Irizuki *et al.*, 2006; shown as G in Figure 12). Moreover, the geological age of this formation is still vague, because previous studies have presented several different ages, such as the foraminifer Zone N.9 of Blow (1969; Nomura *et al.*, 1993; 14.7–14.2 Ma) and ca. 16–15 Ma (e.g. Irizuki *et al.*, 2014). So the bathyal ostracod assemblage containing the several genera *Cytherella*, *Henryhowella*, and *Legitimocythere* from Yatsuo, which is below D35 (FO *D. praelauta*; 16.4 Ma), is the oldest fossil record from the entire Japan Sea coast.

This study also found two *Palmoconcha* species from Yatsuo (Figures 5, 8; Tables 1, 2), constituting the oldest fossil record of this genus from the entire Japan Sea coast. Yamaguchi and Kamiya (2007) divided *Palmoconcha* species from the North Pacific (latitude 20°–60°N) into two groups by the carapace morphology. One is the *P. parapontica* group, characterized by distinct postero-dorsal muri with no prominent eye spots. The other is the *P. laevimarginata* group, which have no postero-dorsal muri and a distinct eye spots. The former group is distributed only in the Northwest Pacific around Japan from the Oligocene to the present, being endemic to this area,

and the latter group is found on the Northwest and Northeast Pacific coasts (Yamaguchi and Kamiya, 2007). Zhou (1995) reported common occurrences of this genus from outer-shelf to bathyal areas around present-day Japan.

The author considers that *Palmoconcha* sp. 1 from Yatsuo belongs to the *P. parapontica* group, and *Palmoconcha* sp. 2 from the same locale belongs to the *P. laevimarginata* group, based on the existence or absence of the postero-dorsal muri and eye spot (Figure 8). The occurrence of *Palmoconcha* sp. 2 from Yatsuo is the oldest and sole record of the *P. laevimarginata* group from the entire Japan Sea, and that of *Palmoconcha* sp. 1 is the oldest record of this genus from the Japan Sea.

The genus *Falsobuntonia* also has been reported only from the Northwest Pacific (latitude 20°–60°N), and is known as one of the endemic genera in this region from the Oligocene to the present (Yamaguchi and Kamiya, 2007). Previous studies (Ikeya and Suzuki, 1992; Zhou, 1995; Ozawa *et al.*, 2004) reported common occurrences of this genus from outer-shelf to bathyal areas around present-day Japan. *Bradleya*, *Krithe*, and *Pacambocythere* are also bathyal genera, and are commonly reported from outer-shelf to bathyal areas around present-day Japan (e.g. Ikeya and Suzuki, 1992; Zhou and Ikeya, 1992;



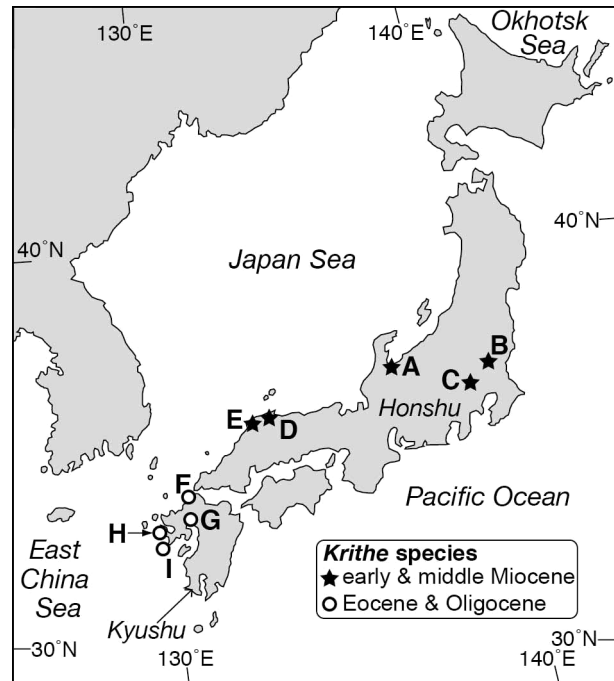
**Figure 12.** Geographical and geological occurrences of the genus *Cytherella* in and around the Japanese Islands from the Eocene to Recent. A, This study; B, Nakao *et al.* (2001); C, Irizuki (2003); D, Yamaguchi *et al.* (2005); E, Zhou (1995); F, Ishizaki (1983); G, Irizuki *et al.* (2006); H, Yamaguchi *et al.* (2006); I, Yamaguchi (2004); J, Yamaguchi (2006); K, Iwatani and Irizuki (2008); L, Iwatani *et al.* (2011); M, Yamaguchi *et al.* (2012); N, Nohara (1987).

Ozawa, 2003).

The occurrence of the last-named three genera from Yatsuo is their oldest record from the entire Japan Sea. These ostracod genera from Yatsuo are significant for the origin, evolution and extinction of the bathyal benthos during the Cenozoic in and around the Japan Sea.

#### Faunal interchange and deep-sea passageway

A Miocene fossil assemblage around 17 Ma containing *Cytherella* and *Pacambocythere* was reported also from the Pacific side of Japan in the Makino Formation of the Awa area, Mie Prefecture (Irizuki, 2003; Figures 11, 12, 14). Therefore, occurrences of outer-shelf and bathyal ostracods in the Yatsuo Group strongly indicate faunal interchange between Northwest Pacific and Japan Sea

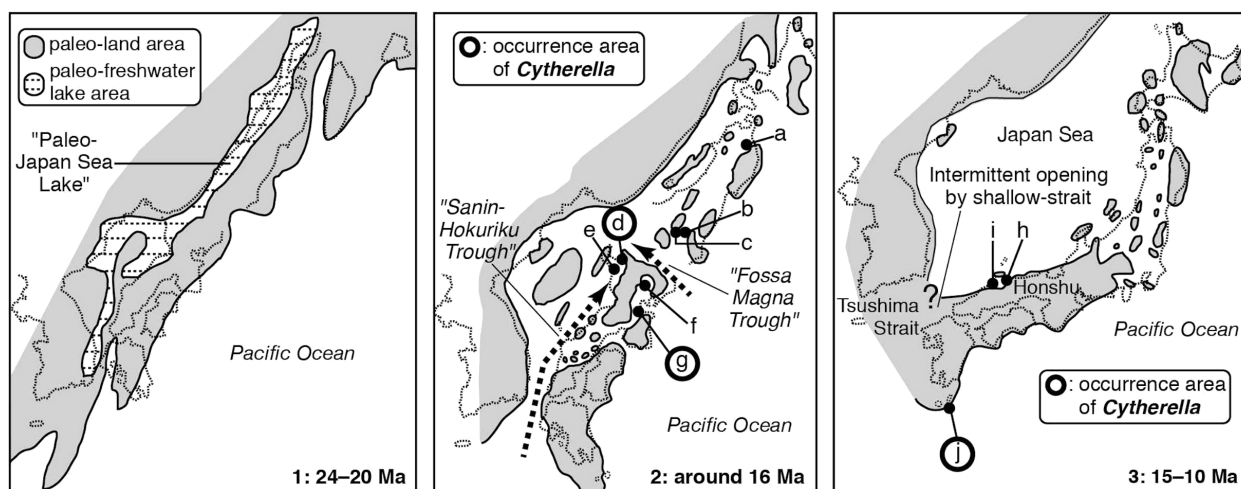


**Figure 13.** Geographical and geological occurrences of the genus *Krithe* in and around the Japanese Islands from the Eocene to middle Miocene. A, This study; B, Irizuki *et al.* (1998); C, Tanaka and Hasegawa (2013); D, Tanaka *et al.* (2002); E, Tanaka (2003), Tanaka and Nomura (2009); F, Yamaguchi and Kamiya (2007); G, Yamaguchi *et al.* (2006); H, Yamaguchi (2004); I, Yamaguchi (2006). Fossil occurrence of *Krithe* from the Miocene Yasuda Formation, southwestern Japan Sea coast (Irizuki *et al.*, 2006; the same locality shown as G in Figure 12) is not presented here, because of its vague age.

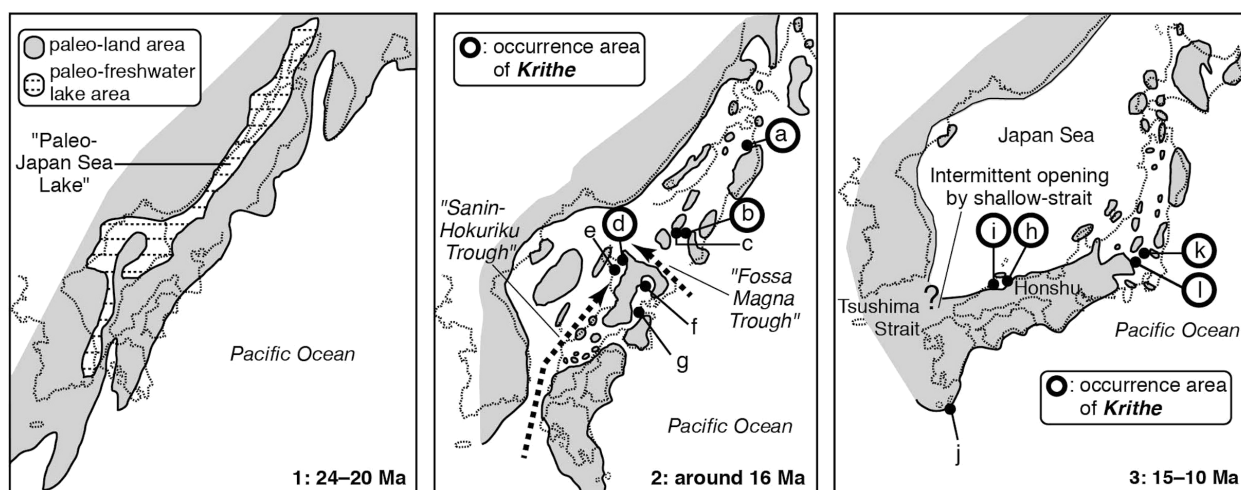
faunas and the existence of a deep-sea passageway, connected to both areas around 17–16 Ma.

Amano *et al.* (2004) have also suggested the existence of Miocene deep-sea passageways connecting to the Pacific, based on molluscan analysis from Yatsuo. They represented occurrences of deep-sea molluscan fossils containing taxa of outer shelf and bathyal areas, from a horizon that is *ca.* 75 m lower than the Yamadanaka Tuff, correlated to the uppermost part of the Kurosedani Formation. The depositional periods of the Yamadanaka Tuff and the sampling horizon of Amano *et al.* (2004) are approximately 16.6 Ma and 16.8 Ma, respectively, based on the diatom biohorizons of Yanagisawa (1999a) as dated by Watanabe and Yanagisawa (2005) (Figure 3), if the rate of sediment accumulation of the Kurosedani Formation is the same as that of the lower horizons of the overlying Higashibessho Formation, i.e., *ca.* 3.3 cm/1,000 years between two diatom biohorizons D35 and D40.

A precise age for the beginning of the formation of the



**Figure 14.** Maps for the Japanese Islands of three Cenozoic periods showing with occurrences of the genus *Cytherella*. 1, early Miocene; 2, early to middle Miocene; 3, middle to late Miocene. Map 1 is simplified from Uemura (2006), and maps 2 and 3 are simplified from Chinzei (1991). Names of paleo-troughs are from Iijima and Tada (1990). Arrows with dotted lines in map 2 indicate the inferred invasion routes of bathyal ostracods from the Pacific to the Japan Sea. Area names in map 2; a, Ninohe; b, Ota; c, Tomioka; d, Yatsuo; e, Kanazawa; f, Mizunami; g, Awa. Area names in map 3; h, Matsue; i, Izumo; j, Tanegashima. Occurrence data of the genus *Cytherella* in maps 2 and 3; d, this study; g, Irizuki (2003); j, Yamaguchi *et al.* (2012). Occurrence data of *Cytherella* from the Miocene Yasuda Formation, southwestern Japan Sea coast (Irizuki *et al.*, 2006; shown as G in Figure 12) is not presented here, because of its vague age.



**Figure 15.** Maps for the Japanese Islands of three Cenozoic periods showing with occurrences of the genus *Krithe*. 1, early Miocene; 2, early to middle Miocene; 3, middle to late Miocene. Map 1 is simplified from Uemura (2006), and maps 2 and 3 are simplified from Chinzei (1991). Names of paleo-troughs are from Iijima and Tada (1990). Arrows with dotted lines in map 2 indicate the inferred invasion routes of bathyal ostracods from the Pacific to the Japan Sea. Area names a–j in maps 2 and 3 correspond to their use in Figure 14, area names in map 3 are k, Tanagura; l, Karasuyama. Occurrence data of the genus *Krithe* in maps 2 and 3; a, Irizuki and Matsubara (1994, 1995); b, Tanaka *et al.* (2013); d, this study; h, Tanaka *et al.* (2002); i, Tanaka (2003), Tanaka and Nomura (2009); k, Irizuki *et al.* (1998); l, Tanaka and Hasegawa (2013). Occurrence data of *Krithe* from the Miocene Yasuda Formation, southwestern Japan Sea coast (Irizuki *et al.*, 2006; shown as G in Figure 12) is not presented here, because of its vague age.

deep-sea basin in the Japan Sea and the time during which deep-sea passageways existed to the Pacific are still vague, because the starting age of the deposition for

the Kurosedani Formation is unclear. However, *Cytherella* is found from the sample F3 in the Kurosedani Formation, and this sample is from *ca.* 500 m lower than the



Yamadanaka Tuff (Tanimura, 1979; Figure 5). If the sedimentation rate of the Kurosedani Formation (Fushikidani Mudstone Member) is equal to that of the lower horizons of the Tochiage Mudstone Member (*ca.* 3.3 cm/1,000 years; Yanagisawa, 1999a), the age of the horizon F4 is estimated to be much older than 17 Ma, i.e., *ca.* 18.2 Ma. Considering the age of lava from the uppermost part of the underlying Iwaine Formation (Figure 2;  $16.4 \pm 0.9$  Ma; Shibata, 1973), this estimated age (*ca.* 18.2 Ma) for the horizon F4 would be much older than this lava age. So the time when these tectonic and faunal-migration events would have started has to be at least around 17.0 Ma, which is slightly older than the age estimated from the molluscan study of Amano *et al.* (2004). Thus, the deep-water basin of the Japan Sea at central Japan had been formed by *ca.* 17 Ma at least, considering these facts. These bathyal ostracods would have passed through the “Paleo-Sanin-Hokuriku Trough” or “Paleo-Fossa Magna Trough”, named by Iijima and Tada (1990), connected to the Pacific around 16 Ma (Figures 14, 15).

The modern shallow-depth limit of several bathyal genera, such as *Krithe*, *Legitimocythere*, and *Henryhowella*, was reported on the basis of researches for grab and core-top samples to be under 1,000 m in the Northwest and Southwest Pacific (e.g. Zhou, 1995; Ayress *et al.*, 1997). Based on these data, the paleo-water-depth of this deep-water passageway might have been shallower than 1,000 m at least.

### Water temperature of shallow water

According to previous studies for many regions shown in Figure 11, shallow-sea ostracod species dominated during 17.0–16.2 Ma, e.g. *Pseudoaurila ishizakii*, *Cornucoquimba saitoi*, and *Schizocythere* sp. 1 (e.g. Yajima, 1992; Irizuki and Matsubara, 1994; Irizuki, 2003; Tanaka *et al.*, 2004, 2012b, 2013). These were warm-subtropical species during the Miocene (Irizuki, 2003; Goto *et al.*, 2013). Among these shallow-sea ostracods, species of *Schizocythere* and *Cornucoquimba* are dominant also in the Shiotani Sandstone Member (15.7 Ma) of Yatsuo with small percentages of species of *Trachyleberis* and *Loxoconcha* (Figures 5, 6, 10, 11). Three shallow cold-water genera, *Finmarchinella*, *Hemicythere* and *Kotoraocythere*, defined by Irizuki and Matsubara (1994, 1995), also occurred in this sandstone (Figure 10; Table 2). However, these three taxa were not found in assemblages from Mizunami–Kanazawa (17.0–16.7 Ma), Tomioka–Ota (16.7–16.2 Ma) or the lower horizons of Ninohe (17.0–16.4 Ma) during 17.0–16.2 Ma (Yajima, 1992; Irizuki and Matsubara, 1994; Tanaka *et al.*, 2004, 2012b, 2013). These genera were dominant in the upper horizons of Ninohe during 16.4–15.0 Ma (in the NPD3B and 4A zones) in the upper part of the Kadonosawa and

Suenomatsuyama formations (Irizuki and Matsubara, 1994, 1995; Figure 11). Thus, dominant occurrences of these cold-water genera indicate a cooling event in the shallow-marine environment of the Ninohe area (since 16.4 Ma; Irizuki and Matsubara, 1994, 1995).

However, deposits of the Shiotani Sandstone Member in Yatsuo around 15.7 Ma have quite small ratios of the three genera *Finmarchinella*, *Hemicythere*, and *Kotoraocythere* (*ca.* 5% of the total number of specimens of samples S1–6; *ca.* 2–7% in each sample; Figures 6, 10). These numbers were much lower than at Ninohe since 16.4 Ma (e.g. Clusters D and E of Irizuki and Matsubara, 1994). There the ratio in total specimens of their two clusters (consisting of 42 samples) at Ninohe around 16.0 Ma was more than 20%, and the maximum ratio of one sample was *ca.* 70% (Irizuki and Matsubara, 1994). For these horizons, it is inferred that the paleo-environment of Ninohe since 16.4 Ma was under cold-marine climate condition (Irizuki and Matsubara, 1994, 1995; Figure 11).

The shallow-sea water temperature during the period of deposition of the Shiotani Sandstone Member (15.7 Ma) in Yatsuo differed from both the warm subtropical condition during 17.0–16.2 Ma in Mizunami–Kanazawa, Tomioka–Ota and Ninohe (17.0–16.4 Ma) and the cold condition since 16.4 Ma at Ninohe. The shallow-sea water temperature of Yatsuo at 15.7 Ma suggest an intermediate environment between those of the warm-subtropical and cold conditions around 16 Ma for Japan. The cause of the difference in the faunal composition of shallow-water environments between Yatsuo and other areas in this cooling period, e.g. differences in latitudes or geographical settings, is not clear. We have to examine more examples of ostracod faunas around 16 Ma from many areas in Japan and its adjacent areas.

### Conclusions

- (1) Twenty-two samples from the lower to middle Miocene Yatsuo Group in central Japan on the Japan Sea coast contained 100 species of ostracods in 60 genera.
- (2) Q-mode cluster analysis distinguished two assemblages. The depositional environment of each assemblage can be inferred as (a) the outer-shelf to bathyal area and (b) the inner-shelf area. Both assemblages contain the same species or genera as respective Pacific faunas in the early to middle Miocene during 17–16 Ma. Stratigraphic changes in the taxonomic composition and lithofacies suggest a shallowing-upward phase in this sedimentary basin, from bathyal to inner-shelf depths.
- (3) This study represents the oldest record of the bathyal

benthonic ostracod fauna (17–16 Ma) from the entire Japan Sea coast. This ostracod fauna is significant for its origin, evolution, and extinction during the Cenozoic in the Japan Sea and its adjacent areas. The assemblage includes bathyal genera, e.g. *Krithe*, *Propontocypris*?, *Cytherella*, *Argilloecia*, and *Falsobuntonia*, that are common to Pacific faunas and those of the Japan Sea coast. This result indicates that these ostracods migrated from the Pacific coast through a deep-sea passageway to the Japan Sea since the early Miocene at least *ca.* 17 Ma.

- (4) The shallow-water assemblage of the inner-shelf area around 15.7 Ma has just small percentages of cold-water genera. This result suggests that the paleo-water temperature at the shallow sea around 15.7 Ma in this region was in an intermediate condition between warm (subtropical) and cold marine climates found around 16 Ma in the Japanese Islands.

#### Taxonomic notes

The author briefly describes the morphology of six species below, using the following measurements in the text: *L*: carapace length (mm), *H*: carapace height (mm). This study follows the classification of ostracod orders in Horne *et al.* (2002).

Subclass Podocopa Sars, 1866  
Order Platycopida Sars, 1866  
Superfamily Cytherelloidea Sars, 1866  
Family Cytherellidae Sars, 1866  
Genus *Cytherella* Jones, 1849

#### *Cytherella* sp.

Figures 7.19–7.21

**Remarks.**—Specimens from Yatsuo are similar to *Cytherella japonica* Ishizaki, 1983, described from Late Pliocene sediments of Shikoku, southwestern Japan in the Northwest Pacific realm, having faint subparallel costae along the anterior margin and granular elements in the posterior margin, with similar carapace length and height. However, they differ in having large and distinct granular elements in the posterior margin with a straight outline of the dorsal and ventral margins. This genus is one of the representative bathyal genera that have been found from the Paleogene to the present in many bathyal regions of the Pacific (Figures 12, 14) and along oceanic coasts elsewhere (e.g. Cronin *et al.*, 2002; Bergue and Nicoladis, 2012). Specimens of Figure 7.19 and 7.21 are adult male and female, and a specimen of Figure 7.20 is juvenile.

Order Podocopida Sars, 1866  
Superfamily Cytheroidea Baird, 1850  
Family Cytheridae Baird, 1850  
Subfamily Schizocytherinae Mandelstam, 1960  
Genus *Schizocythere* Triebel, 1950

#### *Schizocythere* sp. 1

Figures 9.16, 9.17

**Remarks.**—The present species is similar to *Schizocythere okhotskensis* Hanai, 1970 ( $L = 0.79\text{--}0.89$ ,  $H = 0.47\text{--}0.53$  in types; Hanai, 1970) from modern surface sediments obtained east of Soya Cape, Hokkaido, northern Japan on the southwest coast of the Okhotsk Sea. However, it is distinguished from *S. okhotskensis* in having weaker ridges in the anterior marginal, mid-central, postero-dorsal and postero-ventral areas, a different pattern of ridges in the posterior half, and a smaller carapace even in the adult stage ( $L = 0.60$ ,  $H = 0.32$ ; based on Figure 9.16). This species is different from *Schizocythere kishinouyei* (Kajiyama, 1913) from modern surface sediments of the Miura Peninsula, central Japan in the Northwest Pacific realm, in having weaker ridges in the mid-central, ventral marginal and dorsal marginal areas, and different distributional patterns of ridges and reticulations in the postero-ventral and postero-dorsal areas.

#### *Schizocythere* sp. 2

Figure 9.18

**Remarks.**—This species is similar to *Schizocythere ikeyai* Tsukagoshi and Briggs, 1998 described from modern surface sediments of Akkeshi Bay, Pacific coast of Hokkaido, northern Japan. However, the present species differs from *S. ikeyai* in having much weaker ridges in the mid-central, antero-dorsal, and postero-dorsal areas, a different distributional patterns of ridges and reticulations in the mid-central and postero-ventral areas, and a different outline of the anterior and posterior ends of the carapace. This species is different from *Schizocythere* sp. 1 of this study in having less developed reticulations and ridges on the entire carapace, a different distributional patterns of ridges in the posterior half, and a different outline at the posterior end.

Family Trachyleberididae Sylvester-Bradley, 1948  
Genus *Falsobuntonia* Malz, 1982

#### *Falsobuntonia* sp.

Figure 7.7

**Remarks.**—Specimens from Yatsuo are similar to *Falsobuntonia hayamii* (Tabuki, 1986), from Pleistocene

sediments of the Tsugaru Peninsula, on the Japan Sea coast of northeastern Japan, in general outline, but they differ in having well developed reticulation and ridges in the posterior area with a larger valve size ( $L = 0.76$ ). This genus is endemic to the Northwest Pacific coastal regions from the Oligocene to the present (Yamaguchi and Kamiya, 2007).

Family Loxoconchidae Sars, 1925  
Genus *Palmoconcha* Swain and Gilby, 1974

*Palmoconcha* sp. 1

Figures 8.1–8.3

**Remarks.**—Specimens from Yatsuo are very similar to *Palmoconcha parapontica* (Zhou, 1995) from modern surface sediments off southwestern Japan in the Northwest Pacific realm, but they slightly differ by the wide area of the secondary reticulation on the carapace surface. The author considers that this species belongs to the *Palmoconcha parapontica* group defined by Yamaguchi and Kamiya (2007), from the existence of distinct postero-dorsal muri and lack of distinct eye spots. This group is one of two morphological groups of this genus around the Pacific coastal region, and is endemic around Japan from the Oligocene to the present (Yamaguchi and Kamiya, 2007). Specimen of Figure 8.1 is an adult male, and specimens of Figure 8.2 and 8.3 are adult females.

*Palmoconcha* sp. 2

Figures 8.4–8.6

**Remarks.**—Specimens from Yatsuo are very similar to *Palmoconcha propontica* (Hu, 1983) described from Plio-Pleistocene deposits of southern Taiwan in the Northwest Pacific realm, but they slightly differ by the fine reticulation in the anterior area and angular posterior margin. The author considers that this species belongs to the *Palmoconcha laevimarginata* group of Yamaguchi and Kamiya (2007), based on the absence of distinct postero-dorsal muri and existence of eye spots. This group is found in the Northwest and Northeast Pacific margins, and is present in Japan from the Eocene to the present (Yamaguchi and Kamiya, 2007). Specimen of Figure 8.4 is an adult male, specimens of Figure 8.5 and 8.6 are adult females.

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