

Recent ostracode assemblages from Shushi Bay, Tsushima Island, southwestern Japan and their ecological and zoogeographical characteristics

Toshiaki Irizuki¹, Yuki Fujihara², Hokuto Iwatani³, Shigenori Kawano⁴

Abstract: One hundred and ten ostracode species were identified in 23 surface sediment samples collected from Shushi Bay, Tsushima, Nagasaki Prefecture, Southwest Japan. Four ostracode bioassociations and five biofacies were identified with R-mode and Q-mode cluster analyses. The correlation coefficients between environmental factors and the selected species in each bioassociation revealed the ecological characteristics of the species. This information is useful for reconstructing Holocene environments based on ostracode assemblages. The ostracode assemblages reported here are nearly identical to those found on the Japanese mainland. No ostracode species characterizing the Chinese or Korean ostracode faunas were found in this study.

Key words: Recent, Ostracoda, Shushi Bay, Tsushima Island, Japan

Introduction

The Tsushima Strait, also known as the Korea Strait, is situated between one of the mainland islands of Japan (Kyushu Island) and Korea (Korean Peninsula). It is approximately 200-km wide, and the average water depth is approximately 90 to 100 m (Fig. 1). The Sea of Japan and the East China Sea are connected by this strait. Tsushima Island is located in the central part of the strait and has many small inlets and bays along its ria coast. The Tsushima Strait is thought to be a zoological line of

demarcation for terrestrial animals (e.g., Tokuda, 1969; Sato, 1969). Given that benthic Ostracoda are very small bivalved crustaceans (usually <1 mm, with a calcified carapace) and do not have a planktonic larval life stage, it is likely that this strait is a barrier for the dispersal of ostracodes into shallow seas or is a migration route of Ostracoda (Ishizaki, 1990a, b; Irizuki et al., 2005, 2009; Tanaka, 2008; Tanaka et al., 2019). Many groups have studied ostracodes along and off the coasts of Kyushu Island, the Korean Peninsula, and China (e.g., Cai, 1988; Wang et al., 1988; Zhao and Wang, 1988; Abe and Choe,

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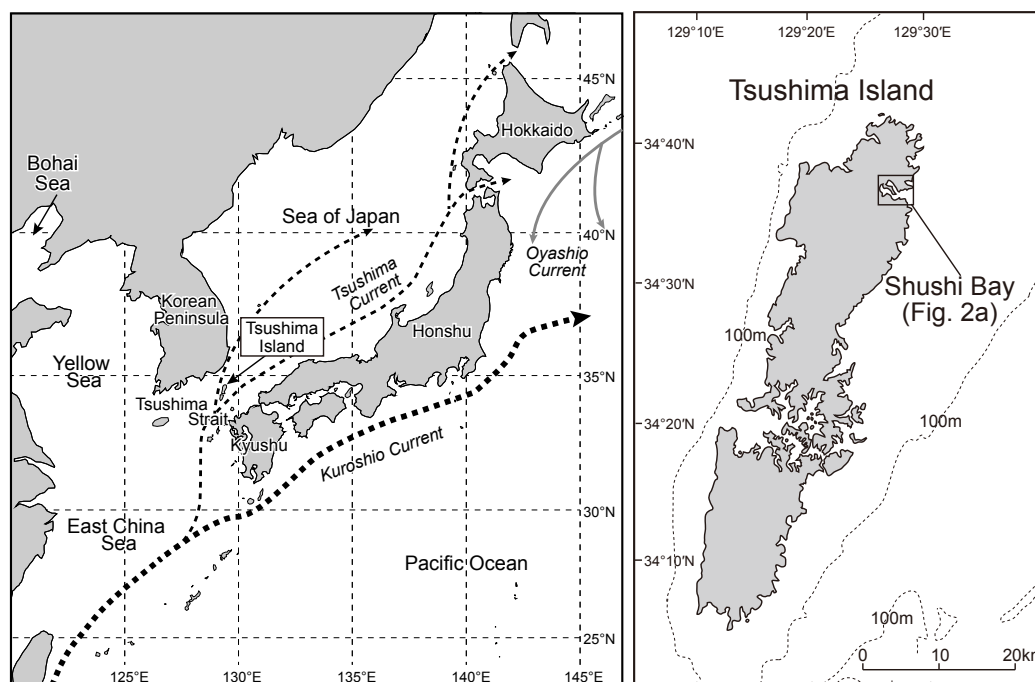


Fig. 1 Locality of the study area.

1988; Iwasaki, 1992; Bodergat et al., 2002; Irizuki et al., 2006; Tanaka, 2008; Tanaka et al., 2019). However, only one study of modern ostracode assemblages from a short sediment core in Asou Bay along the western coast of Tsushima Island has been conducted (Kawano et al., 2013). Thus, here we report modern ostracode assemblages from a bay along the eastern coast of Tsushima Island to define their ecological and zoogeographical characteristics.

Localities and Methods

Tsushima Island is located between Korea and Japan (Fig. 1), and Shushi Bay is located in the northeastern part of the island (Fig. 1). It is a Y-shaped, narrow, elongated bay with the long axis of approximately 4 km (Fig. 2a). The width of the bay at its mouth is approximately 1 km. The water depth increases toward the mouth of the bay, where it is approximately 40 m. Several small rivers and streams flow into the bay; relatively larger rivers are present at Hamakusu, Omasu, and Shushi (Fig. 2a).

A total of 23 surface-sediment samples (SS1 to SS23; Fig. 2a) were collected with an Ekman-Burge grab sampler from a small ship from July 13–15, 2006.

The distance intervals between sample sites were approximately 300 m. The thickness of the oxygenated layer and the color and smell of sediments were recorded. Samples for ostracode analysis were subsequently collected from the uppermost 1 cm of surface sediments using a small spoon. Residual samples were washed on a 2-mm opening sieve on the ship, and materials and macrobenthic animals remaining on the sieve were described. The temperature, salinity, and dissolved oxygen in bottom waters were measured using the Quanta probe (Hydrolab).

Laboratory Procedure

A 10 to 20 g wet sample was weighed and dried in an oven at 70°C for 3 days. It was then weighed and the water content was calculated. The remaining wet samples were weighed, and their dry weights were calculated based on the water content. These wet samples were washed through a 250-mesh sieve (63- μ m opening), dried in an oven at 60°C, and weighed again. The mud content of the samples was calculated. Under a binocular stereomicroscope, ostracode specimens were obtained from the coarser sediment remaining after dry-sieving with a 115-mesh sieve (125- μ m opening). If more than

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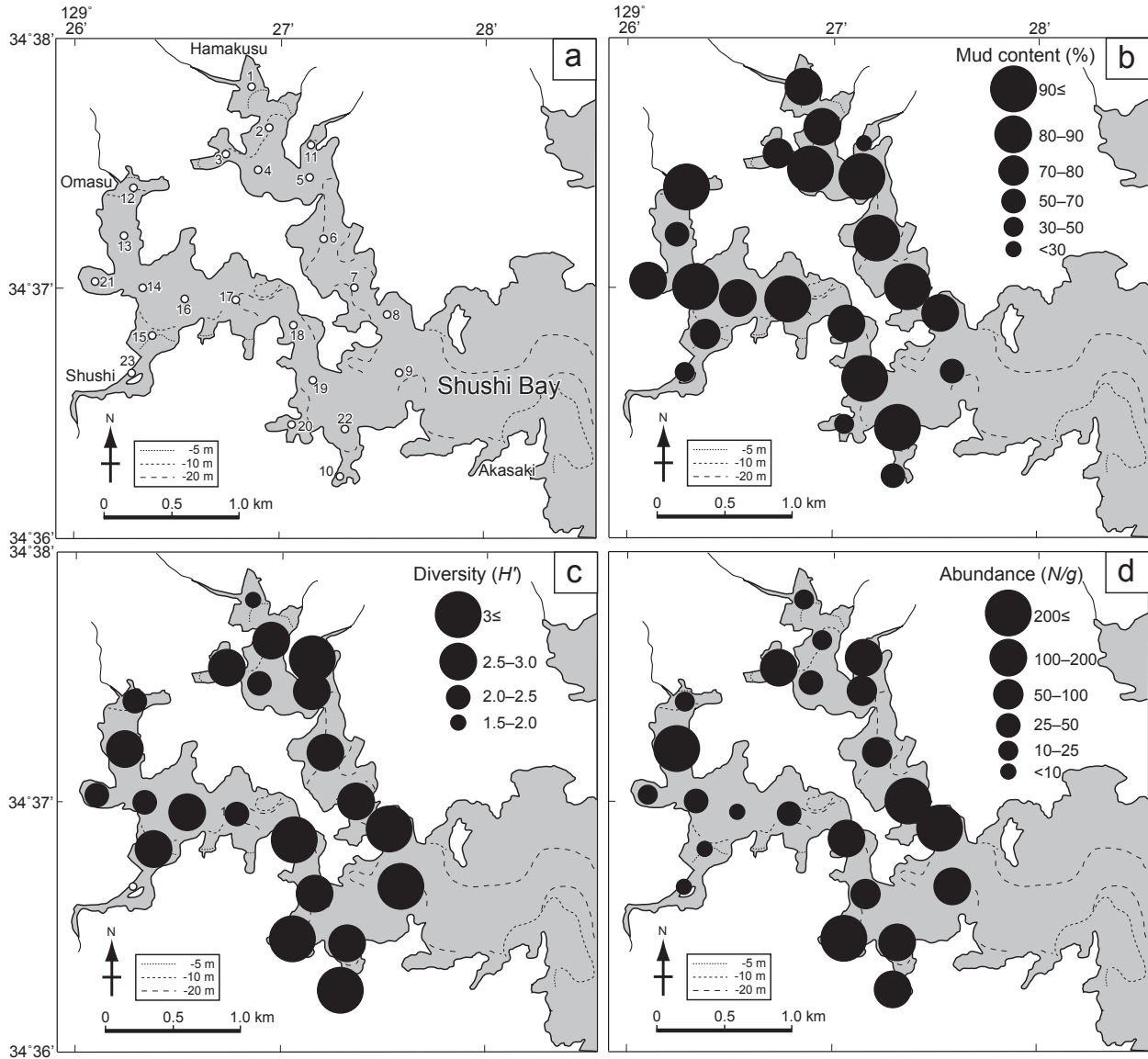


Fig. 2 Maps showing spatial distribution of sample sites (a), mud content (b), diversity (c), and abundance (number of valves/l-g sample) (d).

200 ostracode specimens were found in a sample, a sample splitter was used to divide the sample. Each carapace was counted as two valves. Scanning electron micrographs of selected ostracode specimens were taken using the low-vacuum mode of a JEOL JCM-5000 Neoscope and a JEOL JSM T-220A at the Department of Earth Science, Interdisciplinary Faculty of Science and Engineering, Shimane University.

Results

Environment on the study dates

Water temperature: The temperature of bottom waters ranged from 17.71°C at site SS8 to 21.82°C at site SS23 (Table 1). Although bottom-water temperature depends primarily on weather and measurement time on the investigation days, it was highly negatively correlated with water depth ($r = -0.94$, Table 1).

Salinity: The salinity of bottom waters ranged from 32.42 at site SS23 to 34.30 at sites SS7 and SS8 (Table 1). It was highly positively correlated with water depth ($r =$

Table 1 List of sample and site information. f.s. and m.s in Sediment mean fine sand and medium sand, respectively.

No.	Latitude	Longitude	Date	Time	Water depth (m)	Bottom temp.(°C)	Bottom salinity	Bottom DO(mg/l)	Sediment	Mud content (%)	Thickness of oxic layer (mm)	Macrobenthos, Materials
SS1	34° 37.796'	129° 26.850'	7/13/06	13:35	5.2	21.24	32.75	5.74	mud	84.7	8	granules, plants, annerids, few <i>Theora</i>
SS2	34° 37.644'	129° 26.922'	7/13/06	13:55	12.0	20.92	32.95	6.14	mud	84.9	15	annerids, plants, few shells, <i>Chlamys</i>
SS3	34° 37.536'	129° 26.699'	7/13/06	14:10	10.6	20.99	32.88	6.20	sandy mud	71.4	10	shells (coquina), granule, plants, bryozoans, sea urchins
SS4	34° 37.475'	129° 26.886'	7/13/06	14:23	16.4	20.31	33.28	6.00	mud	98.6	10	few shells, <i>Theora</i> , gastropods
SS5	34° 37.437'	129° 27.136'	7/13/06	14:50	23.0	19.03	33.94	6.37	mud	97.5	10	annerids, <i>Ophiura</i> , plants, sea urchins, few shells
SS6	34° 37.202'	129° 27.210'	7/13/06	15:10	27.4	18.51	34.13	6.56	mud	96.7	15	shells, <i>Theora</i> , <i>Raetellops</i> , plants
SS7	34° 36.992'	129° 27.372'	7/13/06	15:35	31.3	17.83	34.30	6.73	mud	91.8	15	annerids, <i>Theora</i> , <i>Raetellops</i>
SS8	34° 36.901'	129° 27.504'	7/13/06	15:50	28.9	17.71	34.30	6.72	mud	89.4	10+	shells, <i>Mytilus</i> , <i>Raetellops</i> , sea urchins
SS9	34° 36.667'	129° 27.587'	7/13/06	16:08	26.5	18.59	34.06	6.39	muddy m.s.	50.9	10	gravels, shells, <i>Modiolus</i>
SS10	34° 36.229'	129° 27.263'	7/13/06	12:17	15.7	20.59	33.08	6.46	muddy f.s.	51.6	5	granules, shells (coquina), <i>Spondylus</i> , <i>Barbatia</i> , <i>Cardita</i> , <i>Acesta</i>
SS11	34° 37.553'	129° 27.110'	7/13/06	14:40	13.4	20.69	33.08	6.00	m.s.	27.0	20	shells (coquina)
SS12	34° 37.392'	129° 26.261'	7/13/06	9:45	11.0	20.76	33.02	5.96	mud	92.5	10	plants, few shells, <i>Theora</i> , <i>Acesta</i>
SS13	34° 37.196'	129° 26.209'	7/13/06	9:20	11.3	20.72	33.01	6.01	muddy f.-m.s.	56.2	2	gravels, shells (coquina), <i>Chlamys</i> , <i>Dosinia</i> , barnacles
SS14	34° 36.995'	129° 26.331'	7/13/06	9:05	18.7	19.43	33.74	6.06	mud	98.4	5	plants, annerids, <i>Raetellops</i> , <i>Paphia</i>
SS15	34° 36.835'	129° 26.381'	7/13/06	8:55	10.1	20.90	32.88	6.51	mud	79.7	15	<i>Theora</i> , <i>Ophiura</i> , annerids
SS16	34° 36.955'	129° 26.523'	7/13/06	10:30	18.8	19.70	33.69	5.96	mud	88.7	15	plants, shells, sea urchins, few annerids
SS17	34° 36.950'	129° 26.775'	7/13/06	10:50	27.4	19.35	33.81	5.94	mud	97.0	10	annerids, <i>Theora</i> , sea urchins, plants
SS18	34° 36.839'	129° 27.059'	7/13/06	11:07	26.4	19.40	33.74	6.28	sandy mud	84.2	5	granules, shells (coquina), <i>Chlamys</i> , <i>Acesta</i> , <i>Protothaca</i> , <i>Mytilus</i> , <i>Dentalium</i> , oysters, corals, plants, bryozoans, barnacles
SS19	34° 36.620'	129° 27.155'	7/13/06	11:25	29.0	18.99	33.94	6.22	mud	95.6	5-10	annerids, <i>Raetellops</i> , <i>Theora</i> , plants
SS20	34° 36.456'	129° 27.056'	7/13/06	11:55	17.3	20.35	33.28	6.15	muddy m.s.	37.6	10	gravels, shells (coquina), <i>Barbatia</i> , plants
SS21	34° 37.023'	129° 26.083'	7/13/06	10:10	14.4	20.38	33.21	5.60	mud	86.7	2	plants, few shells
SS22	34° 36.428'	129° 27.302'	7/13/06	16:30	26.4	17.88	34.24	6.30	mud	91.5	10-	<i>Raetellops</i> , plants, shells, <i>Ophiura</i> , annerids
SS23	34° 36.654'	129° 26.271'	7/13/06	16:55	2.5	21.82	32.42	6.04	muddy f.s.	37.0	5-10	gravels, plants, few shells

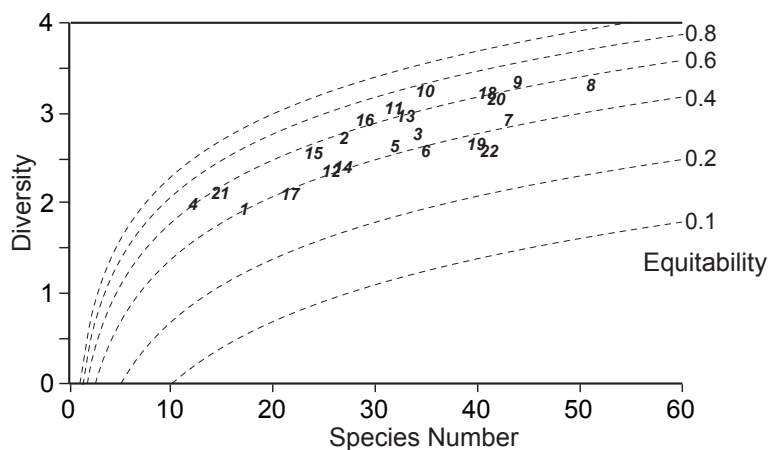


Fig. 3 The relationships among species number, diversity, and equitability in each sample.

0.96) and negatively correlated with water temperature ($r = -0.99$).

Dissolved oxygen: Dissolved oxygen (DO) in bottom waters ranged from 5.60 mg/l at site SS21 to 6.73 mg/l at site SS7 (Table 1). It was highly positively correlated with water depth and salinity ($r = 0.56$ and 0.55 , respectively) and negatively correlated with water temperature ($r = -0.6$). An oxygenated layer was found in all study sites. Its thickness ranged from 2 to 20 mm (Table 1). Thus, the bottom of Shushi Bay was in an oxic condition at the time of our study.

Sediments: Samples collected from the innermost part of several inlets in the bay (SS10, SS11, SS20, and SS23) were composed of muddy fine-to-medium sand with a mud content of 27.0% to 51.6%; the samples contained many shell fragments, except sample SS23 collected from the mouth of the Shushi River, which is the largest river flowing into the bay (Table 1, Fig. 2b). Sample SS9 collected from the bay mouth was also composed of muddy medium sand, with a mud content of 50.9%. Other samples also consisted of muddy sediments. Most samples with a high mud content ($> 90\%$) contained shells of *Raetellops pulchella* and *Theora fragilis* (Table 1), which are representative molluscan species living in oxygen-poor bottoms in enclosed bays.

Ostracode assemblage structure

Several ecological indices were calculated to characterize ostracode compositions for 22 samples containing more than 100 specimens except sample SS23.

Species number (S) and Shannon-Wiener's function (Shannon index, H') were used as ecological indices for species richness and diversity, respectively. The Buzas and Gibson (1969) function was used as an index of equitability (E). Results are shown in Figs. 2c and 3 and Table 2. Species number ranged from 12 in sample SS4 to 51 in sample SS8; the Shannon index ranged from 1.94 in sample SS1 to 3.34 in sample SS9; and equitability ranged from 0.32 in sample SS22 to 0.73 in sample SS10. Abundance (number of valves/g of dry sediment) ranged from 0.3 in sample SS23 to 522 in sample SS13 (Table 2 and Fig. 2d).

Ostracode bioassociation

We identified more than 107 ostracode species in 23 samples (Table 2). Twelve species were represented by total number of specimens more than 100. R-mode cluster analysis of these species was conducted to clarify ostracode bioassociations, which mean ostracode groups consisting of coexisting species. Horn's overlap index (Horn, 1966) was used as a similarity index, and clustering was performed via the unweighted pair group method with arithmetic mean (UPGMA). The PAST program (Paleontological Statistics) was used for analysis; it is a free, easy-to-use data analysis package for paleontological data (Hammer et al. 2001). The analysis revealed four ostracode bioassociations (BC, LN, KA, and NX; Fig. 4).

Bioassociation BC: This bioassociation consisted of four species: *Bicornucythere bisanensis* (Okubo),

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Table 2 (Continued)

<i>Munseyella japonica</i>	1	2	8	12	22	15	17	10	2	19	2	1	4	21	10	34	1	10					
<i>Neonesidea oligodentata</i>		1																					
<i>Neonesidea</i> sp.			1																				
<i>Neopellucistoma?</i> sp.					3													4					
<i>Nipponocythere bicarinata</i>	3	24	35	17	3	1	10	12	2	30	2	12	13	7	5	7	23						
<i>Paracathacythere costarericulata</i>	1							1	1														
<i>Paracypris</i> sp.					1	1																	
<i>Paracytheridea neolongicaudata</i>						1																	
<i>Paracytheroma</i> sp.		1					1																
<i>Paradoxostoma</i> spp.	1	4		2	2	9	29	6	1	1	1	5	13	16	2	2	16						
<i>Parakrithella pseudadonia</i>		1		2	4	2	4	7	2	1	2				5		2						
<i>Pistocythereis bradyformis</i>	5			5				2	2	1													
<i>Pistocythereis bradyi</i>		2	23	18	3			3	3	1	9	4	1	1	3	8							
<i>Platymicrocythere</i> sp.																							
<i>Proponotocypris attenuata</i>					2																		
<i>Proponotocypris japonica</i>				2	1	3	5	4	1			2	2	2	2	4		1					
<i>Proponotocypris</i> sp. 1				1				1															
<i>Proponotocypris</i> sp. 2					2																		
<i>Pseudaurilla japonica</i>	1			4	6	1		1	3	2	22	1	2	2	1	1							
<i>Pseudocythere</i> sp. 1				1																			
<i>Pseudocythere</i> sp. 2						1	1																
<i>Pseudocythere</i> sp. 3													3										
<i>Pseudopsammocythere tokyoensis</i>		1	4	3	3	2	6	2	4	3	2	1	1	3	2	3	2						
<i>Robustaurilla salebrosa</i>	1																						
<i>Sanyuana</i> sp.																							
<i>Schizocythere kishinouyei</i>				1			1																
<i>Sclerochilus mukaishimensis</i>														2	1			1					
<i>Semicytherura kazahana</i>																							
<i>Semicytherura miurensis</i>						3	2																
<i>Semicytherura mukaishimensis</i>						1						3	1	2	2	1	1	2					
<i>Semicytherura sasameyuki</i>																4							
<i>Semicytherura wakamurasaki</i>																							
<i>Semicytherura</i> sp.																							
<i>Spirileberis quadriculeata</i>	7	4	30	5	6	1		9	9	17	3	26	14	1	4	13	1						
<i>Thalassocypris inujimensis</i>	2																						
<i>Thalassocypris?</i> sp.						3																	
<i>Trachyleberis nitsumai</i>	2	1	4				4	13	18		5	18	2	6	2	7							
<i>Trachyleberis aff. verrucifera</i>			2				2	2	1	5													
<i>Trachyleberis</i> sp. 1							7		1	8	1			5		2							
<i>Trachyleberis</i> sp. 2												2	1			2							
<i>Trachyleberis?</i> sp.																							
<i>Xestoleberis hanaii</i>	11	36	1	1	6	5	9	7	6	8	7	5	2	29	21	3	5	13	6	9	2		
<i>Xestoleberis opalescens</i>	2	1				1		1															
<i>Xestoleberis sagamiensis</i>	2	4					1	2	1	1				2	3	25	2						
<i>Xestoleberis setouchiensis</i>	1	1	1				4	5	2					1	1	1	2						
<i>Xestoleberis</i> sp.																							
<i>Xestoleberis?</i> sp.																							
<i>Xiphichilus</i> sp.		1												2	1								
Cyprididae gen. et sp. indet. 1																							
Cyprididae gen. et sp. indet. 2																							
Gen. et sp. indet.																							
Number of valves	142	119	263	203	256	188	176	213	169	189	212	162	186	201	165	152	193	194	240	211	154	248	14
Abundance (N/g)	10.9	10	160	31.3	80.6	88.2	267	296	106	156	189	24	522	37.7	4.23	6.26	25.1	152	90.9	287	24.7	184	0.31
Species Number	17	27	34	12	32	35	43	51	44	35	32	26	33	27	24	29	22	41	40	42	15	41	5
Diversity (H')	1.94	2.71	2.76	2.02	2.66	2.59	2.92	3.3	3.34	3.25	3.06	2.35	2.97	2.4	2.55	2.92	2.09	3.22	2.65	3.14	2.09	2.57	
Equitability	0.41	0.56	0.46	0.63	0.45	0.38	0.43	0.53	0.64	0.73	0.66	0.4	0.59	0.41	0.53	0.64	0.37	0.61	0.35	0.55	0.54	0.32	

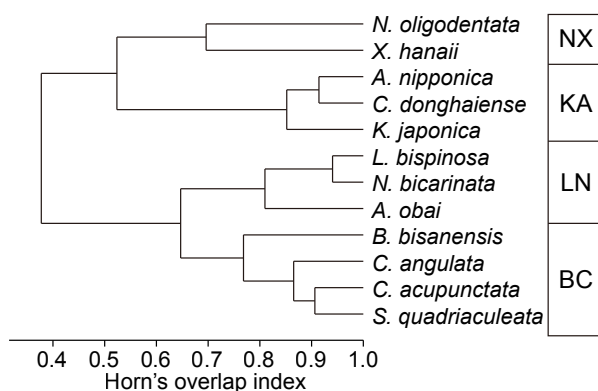


Fig. 4 Dendrogram showing the result of R-mode cluster analysis of main species. BC, LN, KA, and NX mean ostracode bioassociations.

Cytheromorpha acupunctata (Brady), *Spinileberis quadriaculeata* (Brady), and *Callistocythere angulata* Okubo. They were abundant in the innermost part of inlets in Shushi Bay (Fig. 5) and have been observed in the inner to middle part of enclosed Japanese bays (e.g., Okubo, 1979; Ikeya and Shiozaki, 1993; Irizuki et al., 2011).

Bioassociation LN: This bioassociation consisted of three species: *Loxococoncha bispinosa* Kajiyama, *Nipponocythere bicarinata* (Brady), and *Ambtonia obai* (Ishizaki). They were abundant in the inner to middle part of Shushi Bay (Fig. 6) and have been observed in the middle part of enclosed Japanese bays (e.g., Ishizaki, 1968; Yasuhara and Irizuki, 2001; Yasuhara et al., 2007; Irizuki et al., 2008, 2009, 2011, 2015, 2018).

Bioassociation KA: This bioassociation consisted of three species: *Krithe japonica* Ishizaki, *Amphileberis nipponica* (Yajima), and *Cytheropteron donghaiense* (Zhao). They were dominant in deeper parts of Shushi Bay near the bay mouth (Fig. 6) and have been observed in muddy middle to outer bays at water depths of more than 20 m (e.g., Yasuhara and Irizuki, 2001; Yasuhara et al., 2007; Irizuki et al., 2008, 2009, 2011, 2015, 2018).

Bioassociation NX: This bioassociation was composed of two species: *Neonesidea oligodentata* (Kajiyama) and *Xestoleberis hanaii* Ishizaki. They were found in most sites in the bay (Fig. 5) and are phytal species (living on seaweeds and/or sea grasses in shallow coasts and rocky shores) (e.g., Okubo, 1975, 1984; Kamiya, 1988; Irizuki et al., 2008).

Ostracode biofacies

To identify ostracode biofacies, we conducted Q-mode cluster analysis for 22 samples containing greater than 100 specimens and for 59 taxa including more than 3 specimens in either sample. The clustering method was the same as for the R-mode cluster analysis. The analysis revealed five ostracode biofacies (IM, SB, IS, MM, and MS) (Fig. 7).

Biofacies IM (inner mud biofacies): This biofacies was composed of eight samples (SS1, SS3, SS4, SS5, SS12, SS14, SS16, and SS21). It was divided into two sub-biofacies. Sub-biofacies IM1 (SS1, SS3, SS12, and SS21), distributed in the innermost part of the bay at water depths of 5.2 m to 14.4 m (Fig. 7), was composed of mud to sandy mud with a mud content of 71.4% to 92.5% (average 83.8%). The dominant species were those from bioassociation BC (*B. bisanensis*, *C. acupunctata*, *S. quadriaculeata*, and *C. angulata*). Species from bioassociation LN (e.g., *L. bispinosa*) were subordinate species. Species diversity and equitability ranged from 1.94 to 2.76 (av. 2.28) and 0.40 to 0.54 (av. 0.45), respectively (Fig. 3, Table 2). Density was low to moderate (11–160, av. 55). Sub-biofacies IM2 (SS4, SS5, SS14, and SS16), distributed in the inner part of the bay at water depths of 16.4 m to 23.0 m, was composed of mud, with a mud content of 88.7% to 98.6% (av. 95.8%). The dominant species were *B. bisanensis* and *K. japonica*. Subordinate species were *L. bispinosa*, *N. bicarinata*, and *A. obai*. All species were members of bioassociation LN. Species diversity and equitability ranged from 2.02 to 2.92 (av. 2.50) and 0.41 to 0.64 (av. 0.53), respectively. Density was low to moderate (6 to 81, av. 39).

Biofacies SB (seaweed beds biofacies): This biofacies was composed of two samples (SS2 and SS15) with mud contents of 79.7% and 84.9% (av. 82.3%); the samples were collected from the inner part of the bay at water depths of 10.1 m and 12.0 m (Fig. 7). *X. hanaii* and *S. quadriaculeata* were the dominant species in this biofacies. *X. hanaii* lives on and around seaweeds and sea grasses (Okubo, 1984; Kamiya, 1988). *S. quadriaculeata* lives in mud to sandy mud in the inner part of enclosed Japanese bays (Ikeya and Shiozaki, 1993). Species diversity and equitability were moderate ($H' = 2.55$ and 2.71 , av. 2.63 ; $E = 0.53$ and 0.56 , av. 0.54) (Fig. 3, Table 2). Density was low (4 and 10, av. 7).

Biofacies IS (inner sand biofacies): This biofacies was

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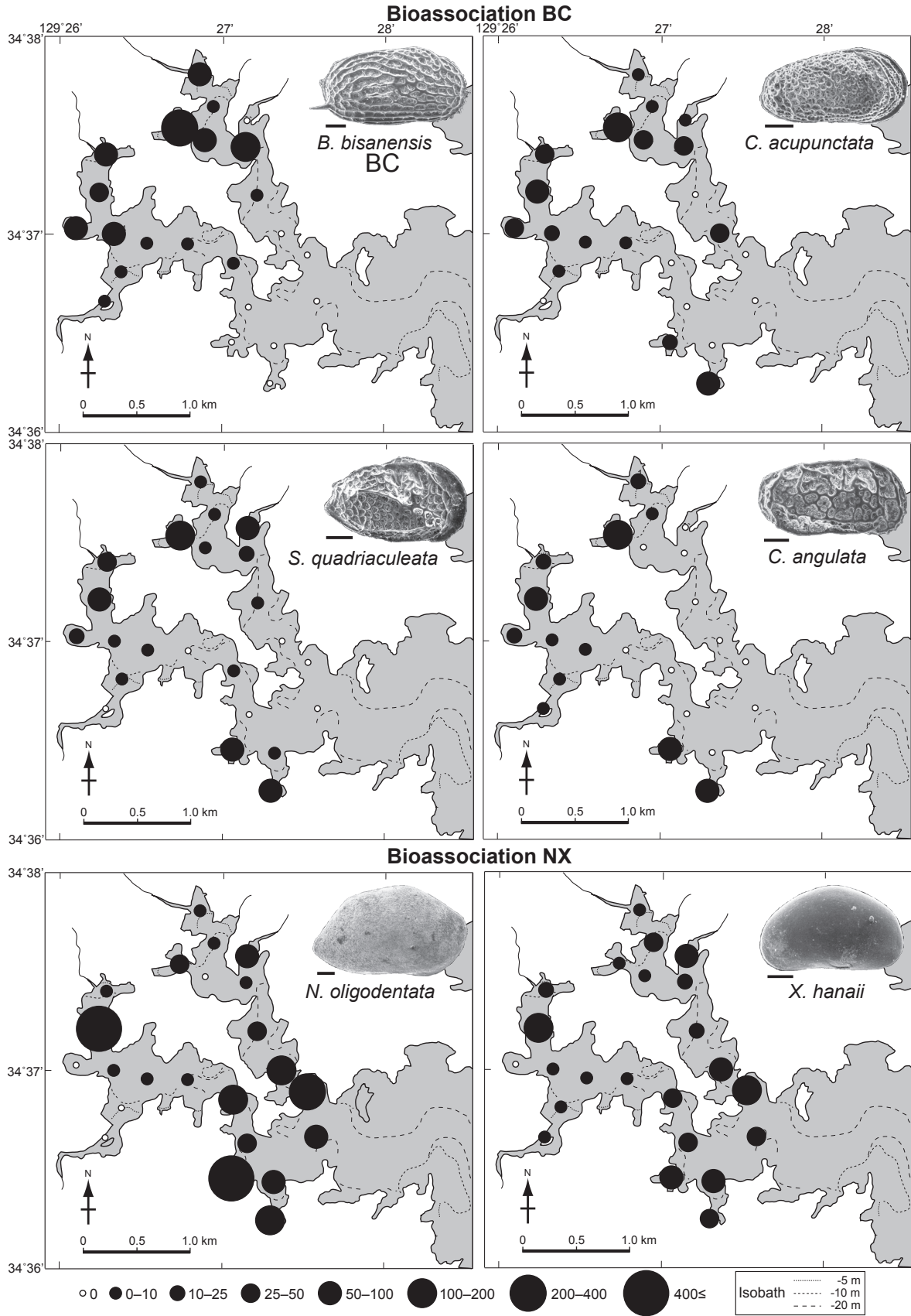


Fig. 5 Spatial distribution of abundance (number of valves/10-g sample) of ostracode species in bioassociations BC and NX. Scale bars = 0.1 mm.

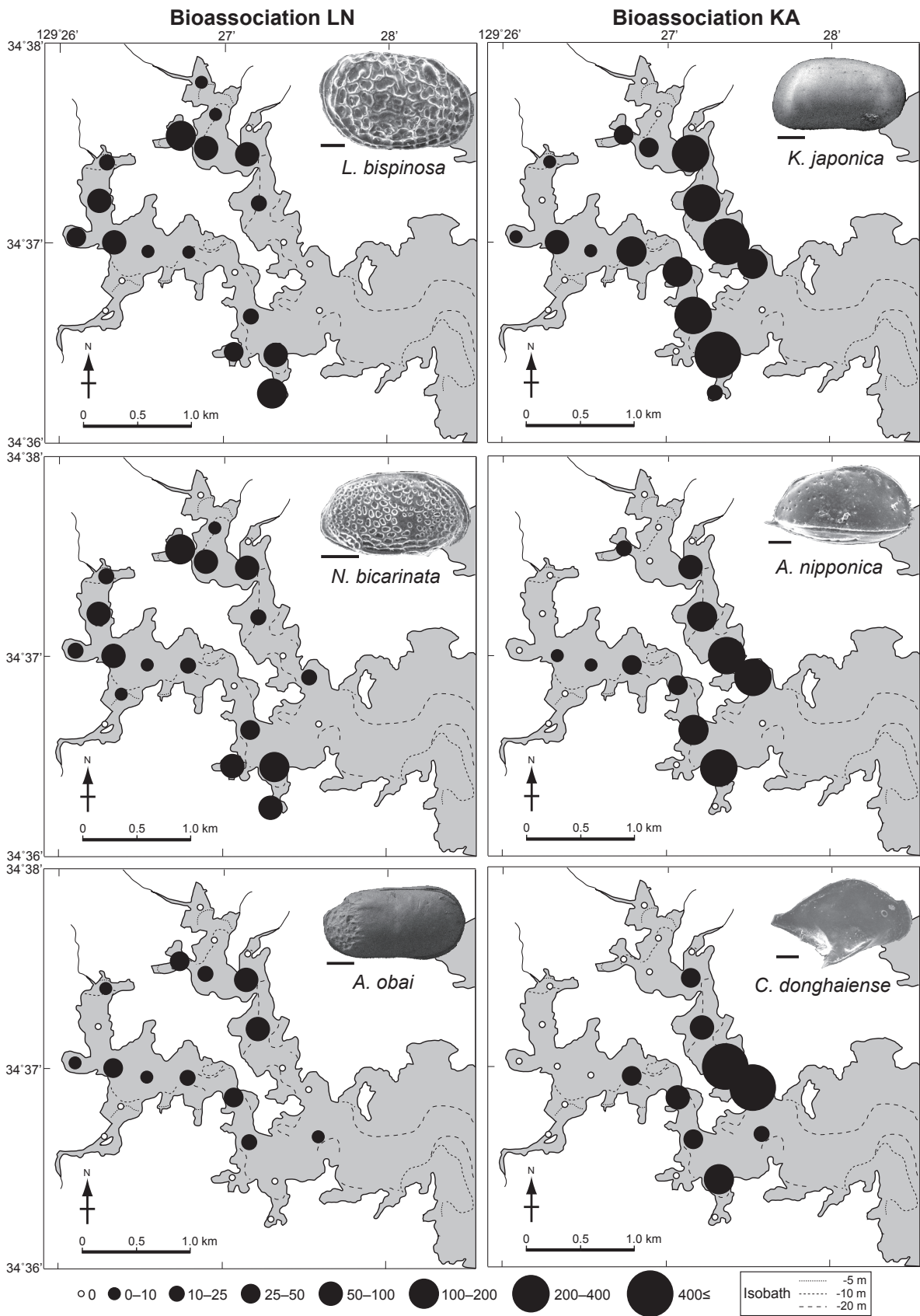


Fig. 6 Spatial distribution of abundance (number of valves/10-g sample) of ostracode species in bioassociations LN and KA. Scale bars = 0.1 mm.

Recent ostracode assemblages from Shushi Bay, Tsushima Island, southwestern Japan and their ecological and zoogeographical characteristics

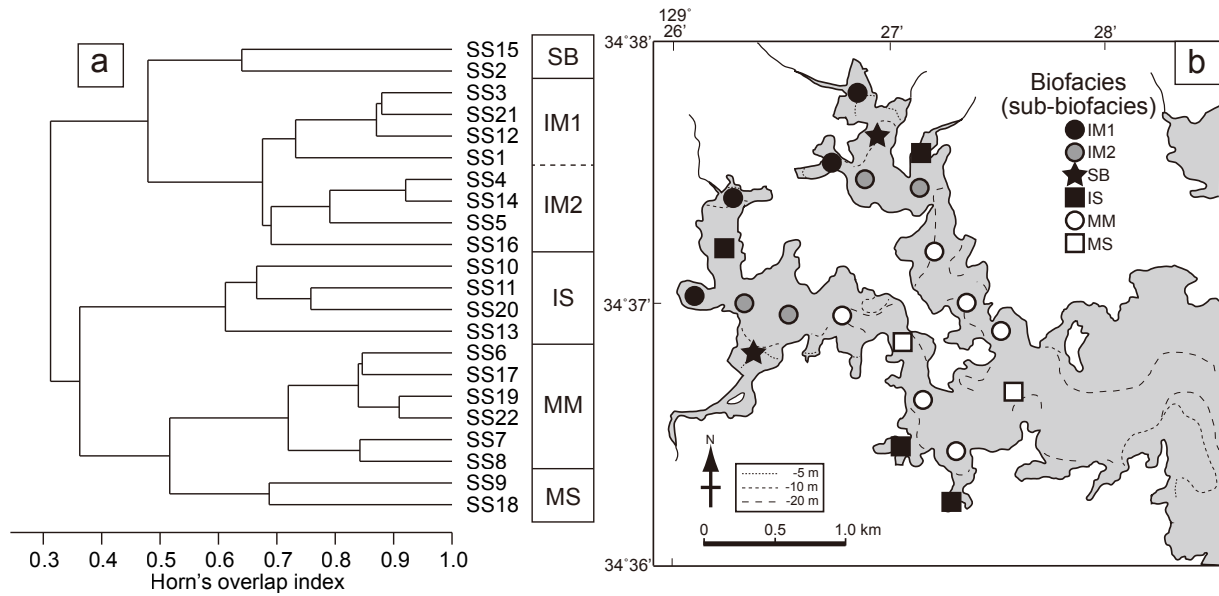


Fig. 7 Dendrogram showing the result of Q-mode cluster analysis (a) and spatial distribution of ostracode biofacies and sub-biofacies (b) (IM1, IM2, SB, IS, MM, and MS).

composed of four samples (SS10, SS11, SS13, and SS20) with a mud content of 27.0% to 56.2% (av. 43.1%); the samples were collected from the inner part of small inlets in the bay at water depths of 11.3 m to 17.3 m (Fig. 7). *N. oligodentata*, *Aurila* spp., and *Loxoconcha* spp. were dominant in this biofacies. They live on and around seaweeds around rocky tidal shores, sea grass beds, and sandy bottoms under the influences of open waters (e.g., Okubo, 1975; Kamiya, 1988). Species diversity and equitability were high ($H' = 2.97\text{--}3.25$, av. 3.10; $E = 0.5\text{--}0.73$, av. 0.63) (Fig. 3, Table 2). Density was highest compared to the other biofacies (156–522, av. 325).

Biofacies MM (middle mud biofacies): This biofacies was composed of six samples (SS6–SS8, SS17, SS19, and SS22) with a mud content of 89.4% to 97.0% (av. 93.7%); the samples were collected from the middle to outer part of the bay at water depths of 26.4 m to 31.3 m (Fig. 7). *K. japonica*, *A. nipponica*, and *C. donghaiense* were dominant in this biofacies. They were members of bioassociation KA. Phytal species such as *N. oligodentata* and *X. hanaii*, which were members of bioassociation NX, were also present. Species diversity was moderate to high ($H' = 2.09\text{--}3.30$, av. 2.69), and equitability was low to moderate ($E = 0.32\text{--}0.53$, av. 0.40) (Fig. 3, Table 2). Density was moderate to high (25–296, av. 158).

Biofacies MS (middle sandy mud biofacies): This biofacies consisted of two samples (SS9 and SS18) with a mud content of 50.9% and 84.2% (av. 67.6%). The samples were collected from the middle to outer part of the bay at water depths of 26.4 m and 26.5 m (Fig. 7). *N. oligodentata*, *Loxoconcha* spp., *Aurila spinifera*, and *Cytheropteron* spp. were common in this biofacies. Species diversity and equitability were highest ($H' = 3.22$ and 3.34, av. 3.28; $E = 0.61$ and 0.64, av. 0.63) (Fig. 3, Table 2). Density was high (106 and 152, av. 129).

Discussion

Relationships between ostracodes and environmental factors

Because ostracode specimens in this study were mostly empty valves with minor amounts of carapace and few appendages and because the sedimentation rate at each study site was uncertain, they were not components of census assemblages. However, the correlation coefficients between environmental factors measured in this study (water depth, salinity, dissolved oxygen, and mud content) and the percentages and density of species in each ostracode bioassociation are discussed here (Table 3). Species in bioassociation BC showed a negative correlation with salinity, dissolved oxygen, and water

Table 3 List of the correlation matrix.

Percentage	mud content	diversity	salinity	DO	water depth	bioassociation
<i>Bicornucythere bisanensis</i>	0.30	-0.72	-0.48	-0.63	-0.59	BC
<i>Cytheromorpha acupunctata</i>	0.22	-0.52	-0.58	-0.47	-0.62	BC
<i>Spinileberis quadriaculeata</i>	-0.06	-0.23	-0.66	-0.25	-0.69	BC
<i>Callistocythere angulata</i>	-0.01	-0.35	-0.69	-0.37	-0.74	BC
<i>Loxococoncha bispinosa</i>	0.31	-0.46	-0.18	-0.42	-0.24	LN
<i>Nipponocythere bicarinata</i>	0.41	-0.48	-0.03	-0.30	-0.10	LN
<i>Ambtonia obai</i>	0.49	-0.32	0.24	-0.16	0.15	LN
<i>Krithe japonica</i>	0.57	-0.30	0.65	0.18	0.68	KA
<i>Amphileberis nipponica</i>	0.48	-0.02	0.79	0.47	0.78	KA
<i>Cytheropteron donghaiense</i>	0.38	0.10	0.73	0.54	0.77	KA
<i>Neonesidea oligodentata</i>	-0.58	0.72	0.16	0.35	0.25	NX
<i>Xestoleberis hanaii</i>	0.05	0.04	-0.29	0.04	-0.30	NX

Abundance	mud content	diversity	salinity	DO	water depth	bioassociation
<i>Bicornucythere bisanensis</i>	0.13	-0.29	-0.34	-0.25	-0.39	BC
<i>Cytheromorpha acupunctata</i>	-0.19	0.02	-0.46	-0.09	-0.43	BC
<i>Spinileberis quadriaculeata</i>	-0.55	0.24	-0.51	-0.11	-0.46	BC
<i>Callistocythere angulata</i>	-0.51	0.25	-0.52	-0.09	-0.46	BC
<i>Loxococoncha bispinosa</i>	-0.14	0.01	-0.28	-0.04	-0.28	LN
<i>Nipponocythere bicarinata</i>	-0.06	0.00	-0.01	0.05	-0.05	LN
<i>Ambtonia obai</i>	0.35	-0.12	0.22	0.14	0.19	LN
<i>Krithe japonica</i>	0.41	-0.01	0.71	0.47	0.68	KA
<i>Amphileberis nipponica</i>	0.33	0.21	0.73	0.62	0.66	KA
<i>Cytheropteron donghaiense</i>	0.24	0.30	0.62	0.64	0.60	KA
<i>Neonesidea oligodentata</i>	-0.52	0.58	0.04	0.22	0.08	NX
<i>Xestoleberis hanaii</i>	-0.45	0.65	0.24	0.40	0.25	NX

depth, suggesting that they live in the enclosed inner part of the bay. On the other hand, species in bioassociation KA showed a positive correlation with all environmental factors, suggesting that they live in deeper mud bottoms of the bay under some influences of oxic open waters. In particular, the relationship between water depth and percentage of these species (Fig. 8) indicated that species in bioassociation BC were dominant in the bay at water depths of less than 20 m. In contrast, species in bioassociation KA were dominant at water depths greater than 20 m. Moreover, *B. bisanensis* in bioassociation BC was the most dominant species in sandy mud to mud bottoms at water depths less than 20 m; *K. japonica* and *C. donghaiense* in bioassociation KA were the most dominant species in mud bottoms at water depths of 20–30 m and at greater than 25 m, respectively. Thus, they are useful as an indicator of water depth. Species in bioassociation LN did not show any high correlations with environmental factors, but the majority of them were found in mud bottoms at water depths of 15–20 m; this was a transition zone from the dominance of bioassociation BC to that of bioassociation KA. Thus,

the optimal zones of bioassociations BC, LN, and KA differed. Irizuki et al. (2011, 2015, 2018) discussed the relationships between anthropogenic pollution and embayment species. In particular, *B. bisanensis* and *K. japonica* showed clear relationships between TOC content and their abundance; the former showed positive correlation with TOC content, the latter a negative correlation. Thus, the optimal zone is also related to the amounts and sources of organic matter, which are bases for ostracodes.

Species in bioassociation NX did not show any significant correlations with environmental factors. However, *N. oligodentata* was more abundant in coarser sediment than *X. hanaii* (Fig. 8). Both species live on or around seaweed and sea grass beds in an intertidal zone (e.g., Kamiya, 1988); thus, their valves are easily transported from their habitats after their death. *X. hanaii* is relatively small in size (adult size: 0.6–0.7 mm long), while *N. oligodentata* is larger (adult size: 1.0–1.2 mm long). Thus, we inferred that small juvenile specimens of *X. hanaii* had been transported easily by low-energy currents, and they were therefore more abundant than

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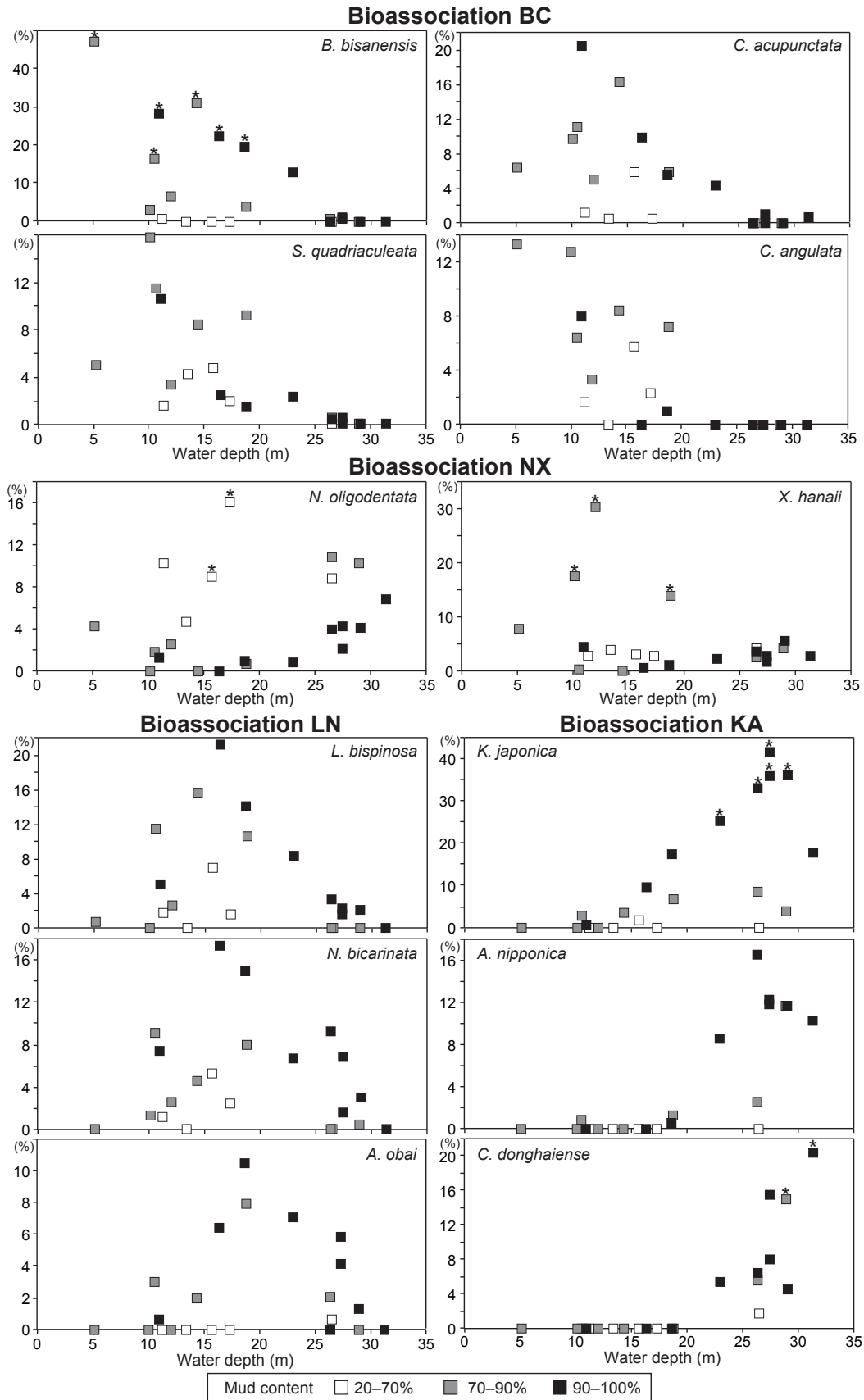


Fig. 8 Panels showing the relationships between water depth and percentages of main species.
* shows most dominant species in each sample.

N. oligodentata in fine sediments.

Ostracode biofacies are primarily related to substrate and water depth. Water depth also reflects a difference in several environmental factors, such as salinity, organic matter content, water temperature, and dissolved oxygen. The boundary between biofacies IM and MM, both of which consisted of sediments with high mud content (> 90%), was situated at a water depth of 20–25 m; this is because the optimal zone of each dominant species, *B. bisanensis* in biofacies IM and *K. japonica* in biofacies MM, was situated at a water depth of 20 m in the bay mentioned above. The fact that biofacies SB contained the intertidal phytal species (bioassociation NX) *X. hanaii* indicates that seaweed and sea grass beds, or rocky shores with seaweeds, are developed in shallower areas near sites SS2 and SS15. Biofacies IS and MS, both of which consisted of coarser sediments, contained mostly high diversity (> 3.0) and high equitability (> 0.6) assemblages composed of species from several different habitats. Biofacies IS was situated in sandy coasts, where wave action dominated other areas, suggesting that ostracodes are always influenced by the sorting and winnowing effects of waves. Whereas, biofacies MS was situated in deeper bay channels, suggesting that shallower sandy and phytal specimens were transported and mixed there.

Comparisons with recent Ostracoda in other enclosed bays in Japan

Ostracode assemblages in Shushi Bay were basically identical to those in enclosed bays of the Kyushu and Honshu Islands (e.g., Ishizaki, 1968; Irizuki et al., 2006, 2009). Only one species belonging to *Bicornucythere*, *B. bisanensis*, was found in the present study; this species is abundantly distributed in inner to middle enclosed bays at water depths of 5–10 m (Ikeya and Shiozaki, 1993) from northern Japan (e.g., Ishizaki, 1971) to southwestern Japan (e.g., Iwasaki, 1992). Along the eastern coasts of the Eurasian continent in eastern Asia, several morphotypes of *Bicornucythere* have been reported (Abe, 1988; Abe and Choe, 1988; Iwasaki, 1992; Yasuhara and Irizuki, 2001; Irizuki et al., 2018). Two of them live in relatively low salinity (*B. sp. M* equivalent to *Keijella bisanensis* form M of Abe, 1988) or wide tidal flat areas (*B. sp. P* equivalent to *Keijella bisanensis* form P of Abe, 1988) in the Honshu and Kyushu Islands (e.g.,

Iwasaki, 1992; The Association for the Environmental Conservation of the Seto Inland Sea, 2009; Tanaka et al., 2019 in press). Wide areas of low-salinity estuaries and tidal flats were not developed along Shushi Bay; thus, samples could not be collected from those areas in this study. Other representative species living along the turbid and tidal flats in Chinese and Korean coasts (e.g., Zhao and Wang, 1988; Zhao and Whatley, 1988), *Sinocytheridea impressa* and *Neomonoceratina* spp., where the tidal range is significant and many rivers flow, were also not found in Shushi Bay. However, this is attributed to the fact that a similar environment is not developed in Shushi Bay now because the Tsushima Island is surrounded by relatively deep seas. Wide tidal flats and turbid conditions might have been developed along Shushi Bay during the low sea-level glacial periods and species in Chinese and Korean coasts might have migrated through the Tsushima Strait. However, these species are thought not to have been able to live in Shushi Bay due to the subsequent transgression.

Conclusions

1. At least 110 ostracode species were identified in 23 surface sediment samples collected from Shushi Bay, Tsushima, Nagasaki Prefecture, Southwest Japan.
2. Four ostracode bioassociations and five biofacies were revealed on the basis of R-mode and Q-mode cluster analyses, respectively.
3. The correlation between environmental factors measured in this study and ostracode bioassociations clarified ecological characteristics of main ostracode species. This information is useful to reconstruct Holocene environments based on ostracode assemblages.
4. Ostracode assemblages were basically similar to those from the Japanese mainland. No continental ostracode elements were found in this study.

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