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Japan Sea ostracod assemblages in surface sediments: their distribution and relationships to water mass properties

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Abstract. The correlation between the depth-areal distribution of the ostracod fauna in surface sediments and water mass properties in the open sea area of the southwestern-northeastern Japan Sea is presented. This is the first report of the temperature and salinity ranges for the ostracod fauna in this sea giving specific values for summer and winter. The fauna on the shelf and continental slope was divided into four assemblage types based on species composition. The depth distribution of these assemblages is stratified and differs between the northern and southern areas. The four assemblages are distributed according to the four different water masses; Tsushima Warm Current Surface Water (TWS), Tsushima Warm Current Core Water (TWC), Japan Sea Intermediate-Proper Water (JSI-P) and Japan Sea Central Water (JSC). Each assemblage is characterized by the following species and temperature-salinity range; (1) TWSA: *Aurila spinifera*, *Schizocythere kishinouyei*, 15–25°C and 33–34.5‰, (2) TWCA: *Bradleya* spp., *Acanthocythereis munechikai*, 7–20°C and 34–34.5‰, (3) JSI-PA: *Krithe sawanensis*, *Acanthocythereis dunelmensis*, 0–10°C and around 34‰, and (4) JSCA: *Laperousecythere robusta*, 5–15°C and around 34‰. The JSCA consists of a part of the species in the cryophilic Omma-Manganji ostracod fauna, which flourished during glacial periods in the Japan Sea. These species inhabit the characteristic and intercalated water mass between the shallowest-warmest current water (TWS) and deepest-coldest water (JSI-P). Their southern distributional areas have decreased since the Pleistocene due to the warm current flowing during interglacial periods. These species live in the restricted water mass environment, changing their depth distributions between the south and north of the Tsugaru Strait. They are interpreted to be the survivors of the cyclic environmental fluctuations in the Japan Sea during the glacial-interglacial periods since the Pleistocene. The results may indicate a water mass temperature of 5–15°C during glacial periods in the shallow-open areas in the Japan Sea.

Key words: Japan Sea, Omma-Manganji ostracod fauna, open sea area, ostracods, water mass properties

Introduction

The Japan Sea is a semiclosed marginal sea, and thus has a characteristic water mass structure as a result of the shallow (< 130 m deep) and narrow straits that connect it to the Pacific Ocean, East China Sea and Okhotsk Sea. The water mass is influenced by warm water from the Tsushima Current at the surface and cold deeper-water masses. The warm Tsushima Current is the only ocean current flowing into the Japan Sea from the south through the Tsushima Strait (Figure 1), and is a branch of the high temperature-salinity Kuroshio Current of the Pacific coast. The Tsushima Current transports a large amount of heat from the south, and flows northwards at the sea surface along the Japanese Islands. A large volume of this warm water flows out to the Pacific Ocean through the Tsugaru Strait, and the rest of the warm current flows to the north, off Hokkaido. Thus, off Hokkaido in the northeastern Japan Sea, there is lower temperature and salinity water than off Honshu. A branch of this warm current flows northwards, and is then cooled drastically in winter. The cold-water mass such as the Japan Sea Proper Water (ca. 0°C) forms in the deep-water areas in the northern Japan Sea (e.g., Gamo and Horibe, 1983; Nishiyama *et al.*, 1990).

The different water-mass environments in the Japan Sea have different species compositions of benthic faunas such as the crustacean one (Nishimura, 1966, 1969; Ikeya and Suzuki, 1992; Yosho and Hayashi, 1994). Therefore, in some areas of this sea, the distribution of the ostracod (Crustacea) fauna is controlled by water-mass properties

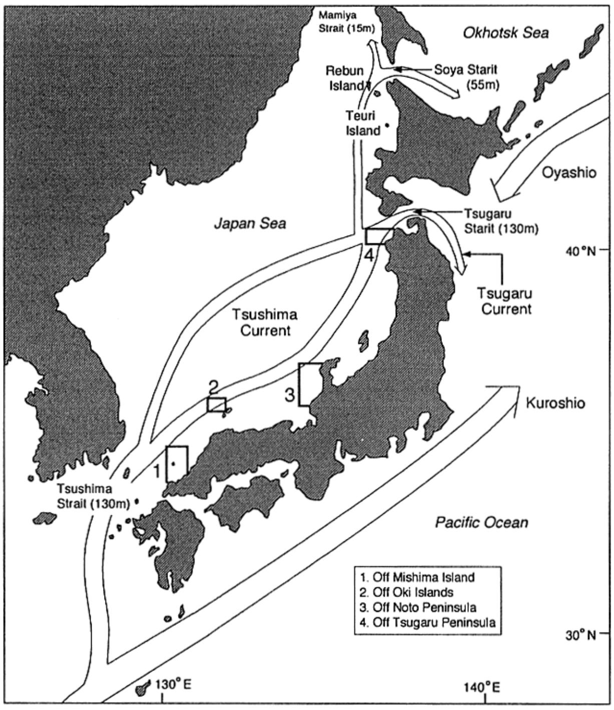

Figure 1. Map of four areas studied, straits connecting Japan Sea and course of main ocean current, showing location of Teuri and Rebun Islands. Modified from Oba *et al.* (1991).

rather than by sediment type or water depth (e.g., Ikeya and Cronin, 1993). Because the warm Tsushima Current flows along the Japanese Islands, it might be expected that each ostracod assemblage would be distributed widely in a geographically longitudinal direction. However, there are publications representing only a part of the coastal areas or for narrow water-depth ranges on the shelf (Okada, 1979; Irizuki, 1989a; Ikeya and Suzuki, 1992; Tsukawaki *et al.*, 1993, 1997, 1998, 1999, 2000; Itoh, 1996; Ozawa *et al.*, 1999) and reports of some species are only intermittent (Ishizaki and Irizuki, 1990; Ishizaki *et al.*, 1993). Thus, there are no detailed reports comparing geographical, water depth and spatial distribution of assemblages in coastal and shelf areas to continental slope areas. Furthermore, in the Japan Sea there are no examples of the relationship between water mass properties based on water temperature-salinity and the distribution of ostracod assemblages.

The ostracod genera of the family Hemicytheridae, *Laperousecythere*, *Johnnealella*, *Baffinicythere*, *Cornucoquimba*, *Daishakacythere*, *Hemicythere* and *Yezocythere*, are common in Pliocene and Pleistocene strata exposed on land in central and northern Japan along the Japan Sea coast (e.g., Hanai and Ikeya, 1991; Irizuki, 1993; Ozawa, 1996). Many species of these genera belong to the cold-water Omma-Manganji ostracod fauna of Cronin and Ikeya (1987), which is one of several Pliocene and Pleistocene faunas from the Japan Sea. The term "Omma-Manganji fauna" was originally applied to the cold-water molluscan assemblages from the Pliocene on the Japanese Islands, named after the areas in central and northeastern Japan (Otuka, 1939; Chinzei, 1978). The term Omma-Manganji ostracod fauna was first offered by Cronin and Ikeya (1987). They illustrated about 50 species and called them circumpolar and cryophilic species, because these ostracods belong to genera inhabiting higher latitudes than the Japan Sea today (Tabuki, 1986).

These genera contain the representative species in the Pleistocene Japan Sea, such as *Laperousecythere robusta*, *Johnnealella nopporensis*, *Baffinicythere robusticostata*, *Cornucoquimba alata*, *Daishakacythere abei*, *Daishakacythere posterocostata*, *Hemicythere orientalis* and *Yezocythere hayashii*. According to Cronin and Ikeya (1987), *Baffinicythere robusticostata* (= *Baffinicythere howei* of Cronin and Ikeya, 1987) belongs to the circumpolar species, and four more species, *Laperousecythere robusta* (= *Patagonacythere robusta* of Cronin and Ikeya, 1987), *Johnnealella nopporensis* (= "*Urocythereis* sp. C"), *Daishakacythere posterocostata* (= "*Urocythereis*" *posterocostata*) and *Yezocythere hayashii* (= "*Urocythereis* sp. A"), are cryophilic. The other three species, *Cornucoquimba alata*, *Daishakacythere abei* and *Hemicythere orientalis*, are not strictly speaking contained in this fauna (Cronin and Ikeya, 1987), but often occur with the above five species from the Pliocene and Pleistocene shallow-marine strata on the Japan Sea side (Tabuki, 1986; Ozawa, 1996; Yamada *et al.*, 2002). Thus, for the sake of convenience the author calls the above eight species "cryophilic hemicytherid species" herein.

The cryophilic hemicytherid species flourished along the Japan Sea coasts from Honshu to Hokkaido during glacial and low-sea-level periods in the shallow and cold-water regions (e.g., Cronin *et al.*, 1994). However, there had been no reports of occurrences for the living specimens with soft parts. Thus, in previous studies, these species were inferred to have been cryophilic species that favored the shallow sea, based on their co-occurrence with molluscan species that flourished in glacial periods when the cold-water areas expanded (Tabuki, 1986; Cronin and Ikeya, 1987; Cronin *et al.*, 1994; Ozawa and Kamiya, 2001; Yamada *et al.*, 2002). As a result of the cyclic appearances of the warm current that flowed during the interglacial periods, linked with the glacio-eustatic sea-level fluctuations (e.g., Kanazawa, 1990; Tada, 1994; Kitamura *et al.*, 1994) since the late Pliocene, it has been generally considered that these cryophilic hemicytherid species became extinct (Ozawa, 2001).

In recent years living specimens of some cryophilic hemicytherid species have been found in restricted areas of the shelf in and around the northeastern Japan Sea (Itoh, 1996; Ozawa, 1998; Ozawa *et al.*, 1999). However, the specific values of the water temperature preferred by the cryophilic hemicytherid species was unknown, that is, the lower and upper limits of temperatures they can survive. Also, the correspondence between the favorable water mass features such as temperature-salinity and the species distributions, and the history of these hemicytherid species since the Pleistocene (for example, the reason for the present restricted distributions in the northern Japan Sea) are still not clarified.

During the glacial periods in the semi-closed Japan Sea, the water mass and oceanic water circulation differed from conditions at present (e.g., Oba *et al.*, 1991). Further, from the late Pleistocene to Holocene, the glacial-interglacial fluctuations in oceanic environments in the Japan Sea were different from those of other East Asian marginal seas (Ikehara, 1998). An understanding of the water temperature and salinity in the marine areas which the cryophilic hemicytherid species inhabit today may be used to determine the oceanic conditions in the shallow areas of the Japan Sea during glacial periods. In order to do this, we must clarify the present distribution of the cryophilic hemicytherid species and their water mass preferences by investigating a number of areas.

The aims of this study are: 1) clarification of the geographical distributions of ostracod assemblages (i.e., species composition) in surface sediments based on the investigation of the shelf and continental slope in four sea areas from the southwestern to eastern Japan Sea; 2) examination of the detailed water mass properties of the Japan Sea, by comparing the mean values of the water temperature and salinity at the water depths at which ostracod assemblages were collected, in the summer and winter, at six marine localities; 3) clarification of the water temperature and salinity values for the cryophilic hemicytherid species in the present Japan Sea; and 4) determination of the reason for the restricted distribution of the cryophilic hemicytherid species in the post-Pleistocene.

Material and methods

Four sea areas along the southwestern-eastern Japan Sea coast were investigated (Figure 1). In this study, these areas are termed, from south to north, off Mishima Island, Oki Islands, Noto Peninsula and Tsugaru Peninsula. Samples were obtained in September 1995, 1996, 1997 and 1998 during the four cruises KT95-14, 96-17, 97-15 and 98-17 on the R. V. Tansei-maru of the Ocean Research Institute, University of Tokyo. A total of 77 surface sediment samples were collected with an Okean-type grab sampler, from the sea floor on the continental shelf and upper part of the continental slope in the four areas, at approximately 20-1500 m water depths, along one or two survey lines in each area (Figure 2; see Tsukawaki *et al.*, 1997, 1998, 1999, 2000 for the detailed sample data).

The top surface sediments, approximately 5 mm in thickness in an area of about 50×25 cm^2, were examined. Neutralized 10% formalin was added to all the samples immediately after the sampling on the ship during the four cruises. These were then washed through a 63 μm (250 mesh) sieve with water, and oven-dried at 80°C. Up to a total of 200 specimens consisting of both adults and juveniles were picked from fractions between 0.25 and 1.0 mm from each quantitatively divided sample. Some samples yielded fewer than 50 individuals in total even though all the ostracod specimens were picked from the rest of the fractions.

After identification of the ostracod species, the number of individuals was determined by adding the total of single left and right valves (more than one half complete) or a whole carapace. Totals were generally calculated without regarding sex, instar stages or the existence of soft parts. Nineteen samples investigated in this study consisted only of specimens without soft parts. This study deals with the ostracod assemblages, which consist mostly of dead specimens without soft parts, in surface sediments (see Tsukawaki *et al.*, 1997, 1998, 1999, 2000 for the detailed ostracod data). The rate of sedimentation is unknown, but as all the samples were collected from the very surface sediment (ca. 5 mm depth from the bottom), they can be considered to be modern sediments approximately. The term "ostracod assemblage" and "assemblage" as used in this study strictly mean the modern ostracod death assemblage in surface sediments. All material is deposited in the Department of Earth Sciences, Faculty of Science, Kanazawa University, Japan.

In some cases, the Pleistocene ostracod fossils are dominantly contained in the surface sediments mainly on the lower continental shelf (Tsukawaki *et al.*, 1993; Irizuki, 1996), such as the sample G-11 from 176 m water depth off Mishima Island (Tsukawaki *et al.*, 2000). According to Tsukawaki *et al.* (2000), many ostracod specimens in sample G-11 are reworked fossils, based on the species composition of the sample, the poor preservation, the co-existence of typical Plio-Pleistocene foraminifera, and the existence of post-middle Pleistocene strata at the bottom surface and subsurface at and -around this site. Thus, the author excluded the sample G-11 off Mishima from the analysis of the relationship between the ostracod distribution and the present marine environment here.

For the purpose of objectively defining the level of similarity among the assemblages with respect to the ostracod species composition, a cluster analysis using a Pearson correlation coefficient and the furthest neighbour method (SYSTAT version 5.2.1 for Macintosh) was conducted on

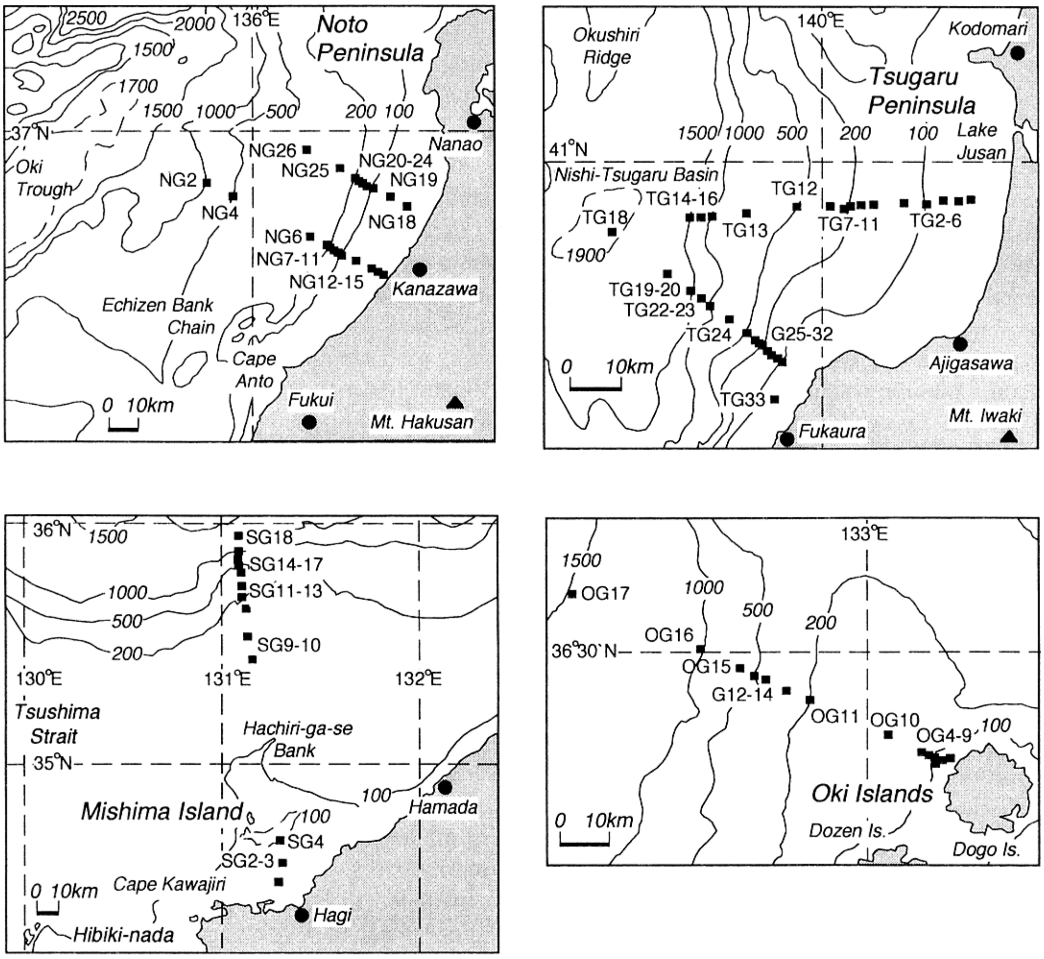

Figure 2. Index map showing sampling localities in four sea areas. A black square shows one sampling site, modified from Tsukawaki *et al.* (1997, 1998, 1999, 2000). Off Tsugaru Peninsula area (upper right), off Noto Peninsula area (upper left), off Oki Islands area (lower right) and off Mishima Island area (lower left).

the basis of similarities between samples.

The mean values of temperature and salinity were used to characterize the physico-chemical environment of the localities, as this was the easiest way to compare regions. The mean water temperature and salinity within a one-degree mesh of latitude and longitude for each depth between 0–300 m (from the Japan Oceanographic Data Center; JODC; http://www.jodc.go.jp/service_j.htm) were utilized. Figure 3 shows the mean values of the temperature and salinity at the surface (0 m) and water depths 10, 20, 30, 50, 75, 100, 125, 150, 200, 250 and 300 m. Some water depths are not the same as the sample collection depths in this study. For example, for a sample taken at 18 m depth, the mean values at the 20 m depth are used. These are the mean values for the 88 years between 1906–1994. The data of temperature and salinity for water depths from which we studied no sediment samples or deeper than 300 m are not examined here.

Oceanic environment along Japan Sea coast

One of the most remarkable oceanographic characteristics of the Japan Sea is the horizontal layering of the water masses (e.g., Miyata, 1958; Moriyasu, 1972). The structure of the water mass is different between the summer and winter. During the winter, the surface waters down to 150 m water depth are mixed by strong seasonal northwest winds. Thus, especially in winter, a thermocline cannot develop, and almost the same temperature and salinity conditions prevail from the sea surface to 150 m depth (Figure 3). On the other hand, because of very weak winds during the summer season, a strong thermocline develops at the sea surface. This thermocline, between warm and cold water, is seen around 150 m depth in the southern Japan

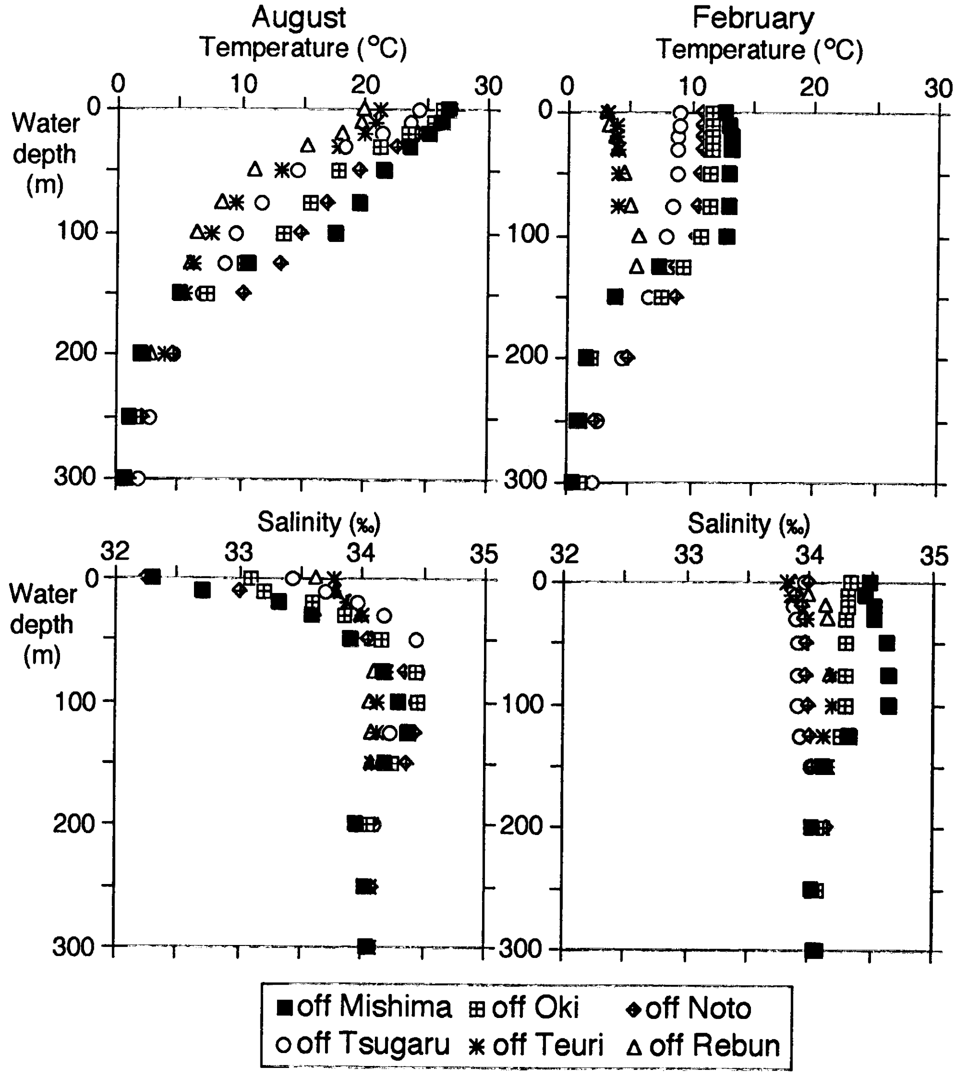

Figure 3. Oceanographic profile of mean temperature and salinity from sea surface to 300 m depth in six areas along Japan Sea coast in August (left two graphs) and February (right two graphs), cited from JODC.

Sea, and at a shallower depth in northeastern areas.

Especially in summer, there is a well developed layer structure of the water mass and the highest salinity sea water is distributed at around 100 m depth (e.g., Miyata, 1958; Naganuma, 1985) (see Figure 3). These water properties are largely divided into two types: the Warm Tsushima Current Water shallower than 150 m and a cold-water mass deeper than 150 m, based on differences of temperature and salinity, although there are some variations in depth differences of the borders in some areas. The warm Tsushima Current water is largely divided into two types, which are called Surface Water, characterized by high temperature (around 20°C in summer conditions) and low salinity (33.0 – 34.0‰), and the Tsushima Warm Current Core Water characterized by the highest salinity (34.5‰) at around 100 m depth, around 15°C in summer. The cold-water mass has relatively lower temperature and salinity (around 34.0‰) than the warm-current water, and is divided into the Japan Sea Central Water (around 10°C), Japan Sea Intermediate Water (2 – 5°C) and Japan Sea Proper Water (less than 2°C) (e.g., Yamamoto and Imai, 1990).

Results

Dominant species and water depth ranges of ostracod assemblages

More than 100 species have been recorded from the four

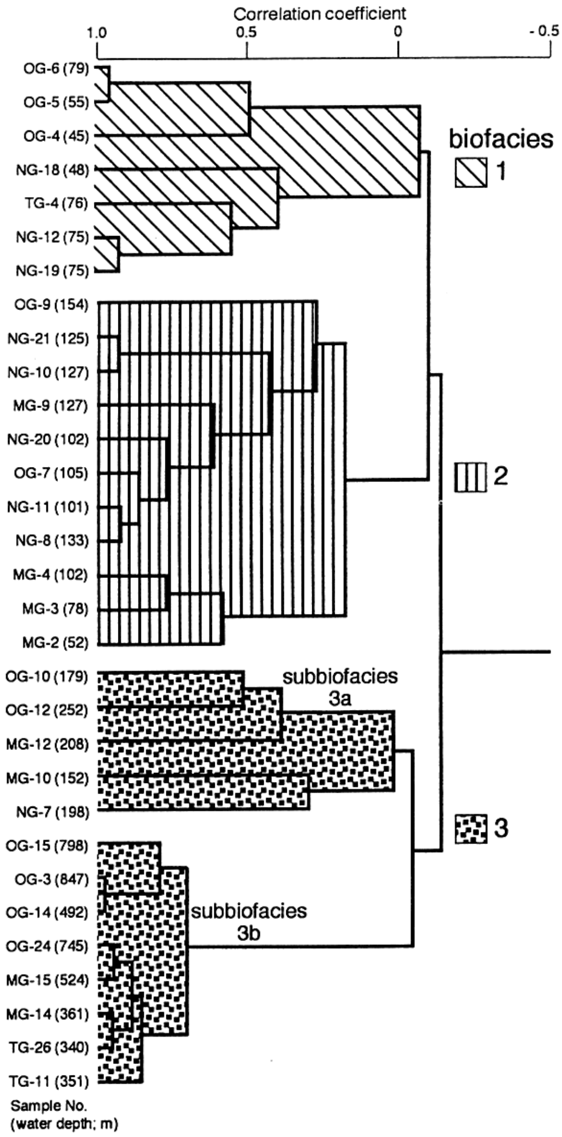

Figure 4. Result of Q-mode cluster analysis for four studied areas, showing clusters of samples representing three major ostracod biofacies. Sample MG means from Mishima Island area, OG from Oki Islands area, NG from Noto Peninsula area and TG from Tsugaru Peninsula area, respectively.

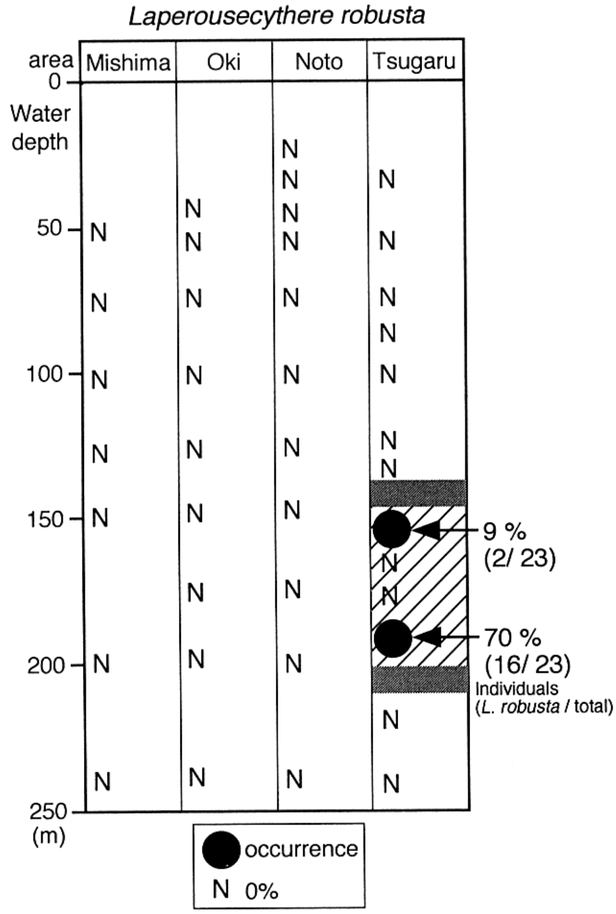

Figure 5. Occurrence and ratio of characteristic ostracod species of biofacies 4 for four studied areas.

areas along the southwestern and eastern Japan Sea coast. The ostracod species from each area are listed in Tsukawaki *et al.* (1997, 1998, 1999, 2000). The 31 samples utilized in this study, each of which is represented by more than 50 individuals, out of a total of 77 samples, were grouped by cluster analysis. Ninety species represented by a minimum of three individuals in any one sample were used in this analysis. The result of Q-mode cluster analysis shows the presence of three biofacies on the basis of 0 level (Figure 4). These biofacies consist of samples which are collected from different water depth ranges. Biofacies 1 is composed of samples from less than 80 m depth in three sea areas: off Oki Islands, Noto Peninsula and Tsugaru Peninsula areas. Biofacies 2 consists of samples from 100–150 m depth in three areas: off Mishima Island, Oki Islands and Noto Peninsula areas. Biofacies 3 is composed of samples from the deepest areas, deeper than 150 m, in all four areas (Figure 4). Two subbiofacies 3a and 3b bounded by a value of 0.1 can be recognized in this biofacies. The ratio of several characteristic species differs between these two subbiofacies. Subbiofacies 3a comprises samples from 150–250 m water depths, and subbiofacies 3b consists of samples from deeper than 350 m.

The samples not used in the cluster analysis (because they contained fewer than 50 individuals) and those having different dominant species from biofacies 1, 2 and 3, are recognized as biofacies 4. The one species *Laperousecythere robusta* occurs characteristically in biofacies 4

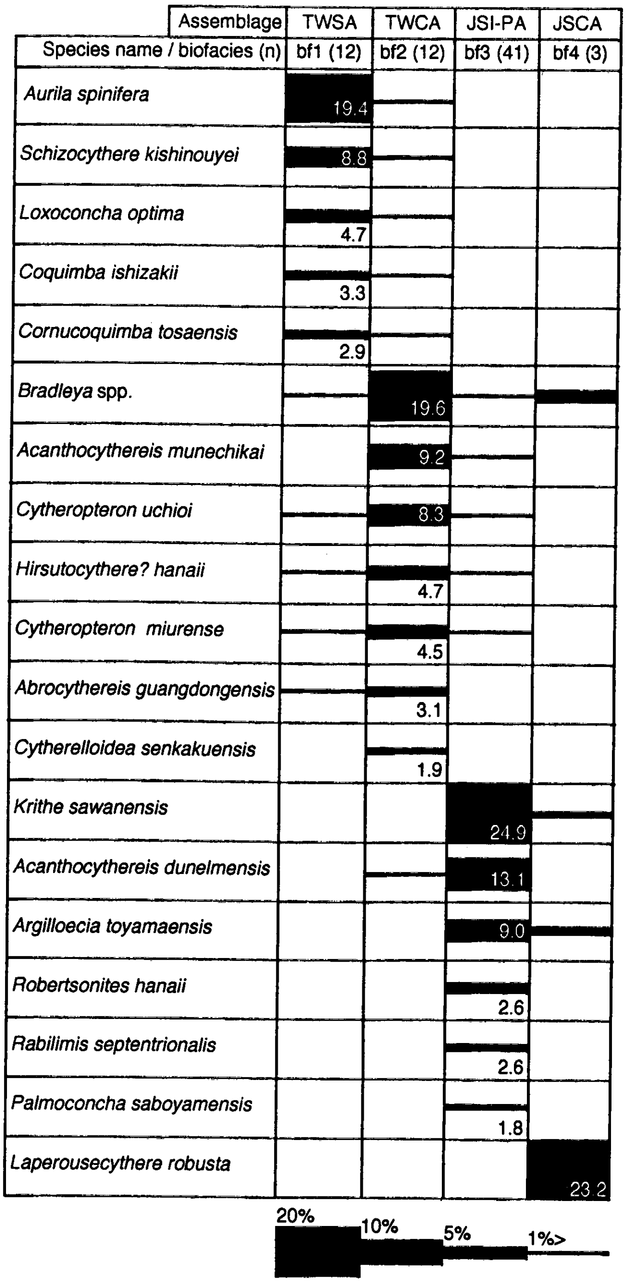

Figure 6. Mean ratio of characteristic ostracod species of four biofacies for four studied areas, with four assemblages names. Abbreviations: TWSA: Tsushima Warm Current Surface Water assemblage (bf1: biofacies 1); TWCA: Tsushima Warm Current Core Water assemblage (bf2: biofacies 2); JSI-PA: Japan Sea Intermediate-Proper Water assemblage (bf3: biofacies 3); JSCA: Japan Sea Central Water assemblage (bf4: biofacies 4). (n) = total number of samples of each assemblage.

(Figure 5). This species occupies 70 % of the sample from 190 m depth off the Tsugaru Peninsula, and five of 16 specimens in this sample have soft parts. The percentages of *L. robusta* are very high in the Tsugaru area (Figure 5). The average percentages of the characteristic species for these four biofacies are represented in Figure 6 (see Tsukawaki *et al.*, 1997, 1998, 1999, 2000 for the distribution of the other species). With the exception of biofacies 4, samples containing fewer than 50 individuals from the four sea areas were sorted to biofacies 1-3 respectively, based on occurrences of characteristic species. SEM photographs of these species are shown in Figure 7.

The characteristic species of biofacies 1 are *Aurila spinifera* (= *Aurila kiritsubo* of Tsukawaki *et al*, 1997, 1998, 1999, 2000), *Schizocythere kishinouyei*, *Loxoconcha optima* and *Coquimba ishizakii*. Biofacies 2 characteristically includes *Bradleya* spp. (*B. nuda*, *B. japonica* and *B.* sp.), *Acanthocythereis munechikai*, *Cytheropteron uchioi* and *Hirsutocythere? hanaii*. These species in biofacies 1 and 2 are distributed on the upper and lower continental shelf, respectively, along the Pacific coast in southeastern Japan, under the warm Kuroshio conditions (Zhou, 1995).

Biofacies 3 is dominated by *Krithe sawanensis* and *Rabilimis septentrionalis*. The former species is predominantly distributed in the lower shelf and continental slope areas of the central to southeastern Japanese Pacific coast (Zhou and Ikeya, 1992; Zhou, 1995). *R. septentrionalis*, *Acanthocythereis dunelmensis*, and the genera *Robertsonites* and *Palmoconcha* are mainly distributed on the continental shelf in high-latitude areas such as the North Pacific and Arctic Ocean (e.g., Tabuki, 1986; Brouwers, 1990, 1993; Ikeya and Cronin, 1993). In the subbiofacies 3a, *R. septentrionalis* and *Robertsonites* spp. are more dominant than 3b, which more dominantly contains *K. sawanensis*, *Argilloecia toyamaensis*, *Palmoconcha saboyamensis* and *Propontocypris uranipponica*. *A. dunelmensis* is dominant in both subbiofacies. These taxa are also included in this biofacies. Biofacies 4 includes *L. robusta*, being characteristic on the shelf along the Okhotsk Sea (Itoh, 1996).

The water depth ranges of distributions for the three assemblages from off the Teuri and Rebun Islands in the northeastern Japan Sea are recognized (two columns on the right in Figure 8). The surface sediment samples from off Teuri Island (-300 m depth; Ozawa *et al.*, 1999) and Rebun Island (-130 m; Itoh, 1996) areas have already been examined. The author considers that the three assemblages in the Rebun and Teuri areas recognized by these two studies are similar to biofacies 1, 4 and 3 (shallow to deep) (Figure 8), on the basis of co-occurring species in the southern four areas, e.g., *L. optima*, *L. robusta*, *K. sawanensis* and *R. septentrionalis*. The subbiofacies are not clearly recognized in the biofacies 3 of the northern two areas, because of the dominance of both *K. sawanensis* and *R. septentrionalis* deeper than ca. 70-100 m (Itoh, 1996; Ozawa *et al.*, 1999). Very low species diversity and low occur-

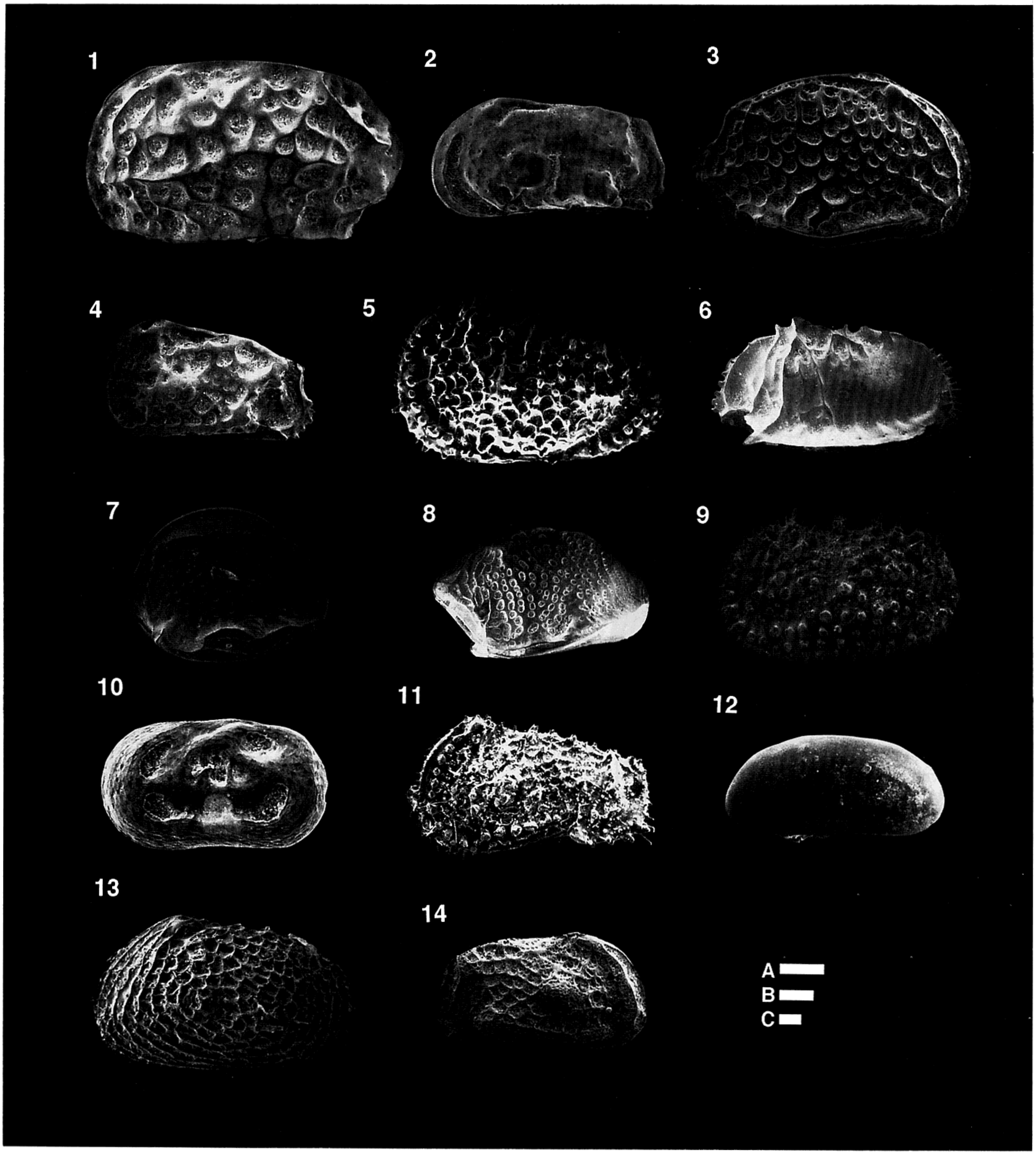

Figure 7. Ostracod species in four assemblages from present Japan Sea. **1**. *Schizocythere kishinouyei* (Kajiyama), LV. **2**. *Coquimba ishizakii* Yajima, LV. **3**. *Aurila spinifera* Schornikov, RV. **4**. *Cornucoquimba tosaensis* (Ishizaki), LV. **5**. *Acanthocythereis munechikai* Ishizaki, LV. **6**. *Bradleya nuda* Benson, RV. **7**. *Cytheropteron uchioi* Hanai, RV. **8**. *Cytheropteron miurense* Hanai, RV. **9**. *Hirsutocythere? hanaii* Ishizaki, LV. **10**. *Cytherelloidea senkakuensis* Nohara, LV. **11**. *Acanthocythereis dunelmensis* (Norman), LV. **12**. *Argilloecia toyamaensis* Ishizaki and Irizuki, RV. **13**. *Rabilimis septentrionalis* (Brady), LV. **14.** *Laperousecythere robusta* (Tabuki), RV. Scale bars: 0.1 mm (A for 1, 8; B for 2–5, 7, 10, 12; C for 6, 9, 11, 13, 14). All specimens excluding one juvenile valve (14) are adult valves. 1–10 from Noto Peninsula area; 11, 12, 14 from Tsugaru Peninsula area; 13 from Teuri Island area. Abbreviations: LV: left valve, RV: right valve.

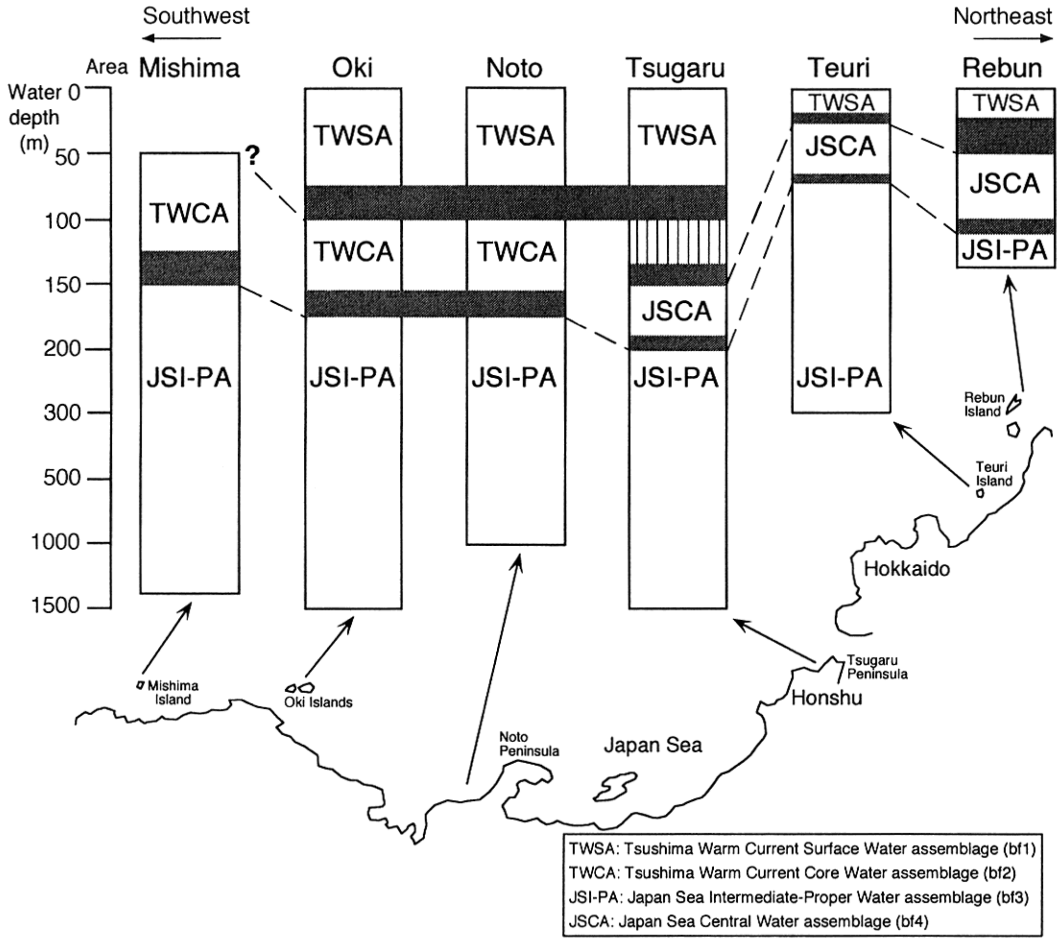

Figure 8. Water depth ranges of distribution of four ostracod assemblages in six sea areas along Japan Sea coast (Rebun: Itoh, 1996; Teuri: Ozawa *et al.*, 1999). Vertical lines at depths ca. 100–150 m off Tsugaru Peninsula area show interval of low occurrence of ostracods.

rence of ostracods were found in the sediments between 100–150 m off the Tsugaru area (Figure 8; Ozawa, 1998; Tsukawaki *et al.*, 1999).

In this study, the Tsushima Warm Current Surface Water assemblage is biofacies 1 (TWSA in Figures 6, 8), Tsushima Warm Current Core Water assemblage is biofacies 2 (TWCA), Japan Sea Intermediate-Proper Water assemblage is biofacies 3 (JSI-PA), and Japan Sea Central Water assemblage is biofacies 4 (JSCA). These assemblages are named after the water mass name in which each assemblage occurs (see Figures 6, 8).

These four assemblages are stratified in each area (Figure 8). The Japan Sea Intermediate-Proper Water assemblage (JSI-PA in Figures 6, 8) is distributed in the deepest parts of all of the six areas, and the Tsushima Warm Current Surface Water assemblage (TWSA) occurs at five locations from the Oki to Rebun areas. The Tsushima Warm Current Core Water assemblage (TWCA) is seen around 100 m depth from the Mishima to Noto areas, and the Japan Sea Central Water assemblage (JSCA) is distributed in the three northern areas from off Tsugaru to Rebun. Assemblages are very similar among the three southern areas from off Mishima to Noto. However, the assemblages between the southern three and northern three areas are different. In the northern areas from off Tsugaru to Rebun, the Tsushima Warm Current Core Water assemblage (TWCA) is not recorded. In the northern two areas the lower depth limit of the Tsushima Warm Current Surface Water assemblage (TWSA) is 50 m shallower than in the southern two areas, off Oki and Noto. Also, the upper depth limit of the assemblages in Japan Sea Central Water (JSCA) and Japan Sea Intermediate-Proper Water (JSI-PA) is approximately 50–100 m shallower than in the area south of the Tsugaru Strait.

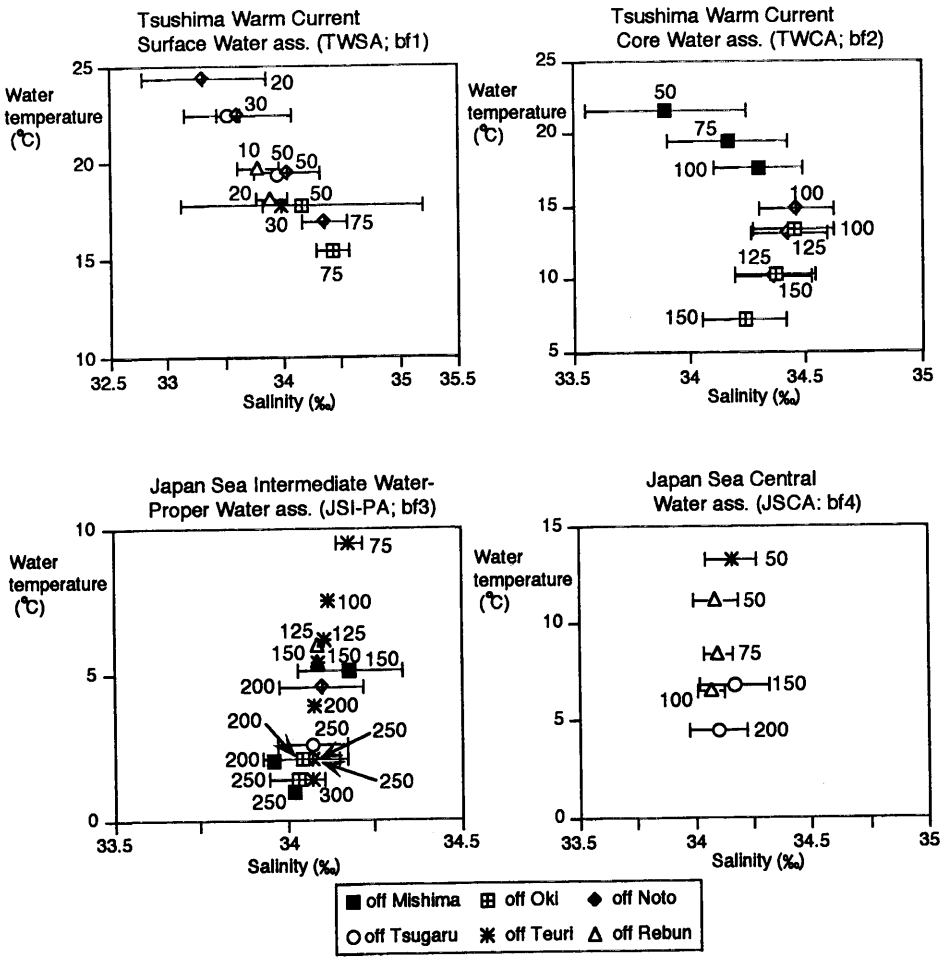

Figure 9. Plots showing water temperature and salinity on T-S diagram for depths for each ostracod assemblage along Japan Sea coast in summer (August). Bars show standard deviation for salinity. Scale of horizontal and vertical axes is different in each graph.

Assemblage distributions and restricting factors

The mean values of water temperature and salinity for the samples from each depth in the six sea areas were examined on a T-S (temperature-salinity) diagram of the sort often used in the oceanographic analysis of water mass properties. At first, the mean values in August were used, because the layering structure of the water masses and thermocline in the shallow sea area in August is better developed than in other months.

Figure 9 represents the mean temperature and salinity for the water depths of distribution of the four assemblages from the six study areas. The standard deviation is shown only for salinity, because the standard deviation of temperature is very small, approximately 1°C in many cases.

Characteristic values of the water temperature and salinity of the depths of the four assemblages are as follows. In the Tsushima Warm Current Surface Water assemblage (TWSA; biofacies 1) water temperature is 15–25°C (Figure 9, upper left graph), which is the highest among the four assemblages. The salinity range for the TWSA is 33.0–34.5 ‰, and is the widest among the four depth assemblages. In the depth range of the Tsushima Warm Current Core Water assemblage (TWCA; biofacies 2), the water temperature is 7–20°C and the salinity is 34.0–34.5‰ (Figure 9, upper right graph), although the salinity is slightly lower at 50 m depth off the Mishima area. This salinity is the highest among the environments of the four assemblages. The water temperature in the depths of the Japan Sea Intermediate-Proper Water assemblage (JSI-PA; biofacies 3) is less than 7°C, exclusive of one datum (Figure 9, lower left graph), even though the temperatures are relatively high for 75–150 m water depths off Rebun and Teuri. This temperature range is the lowest among the four assemblages. The salinity for the JSI-PA is around 34.0‰. The

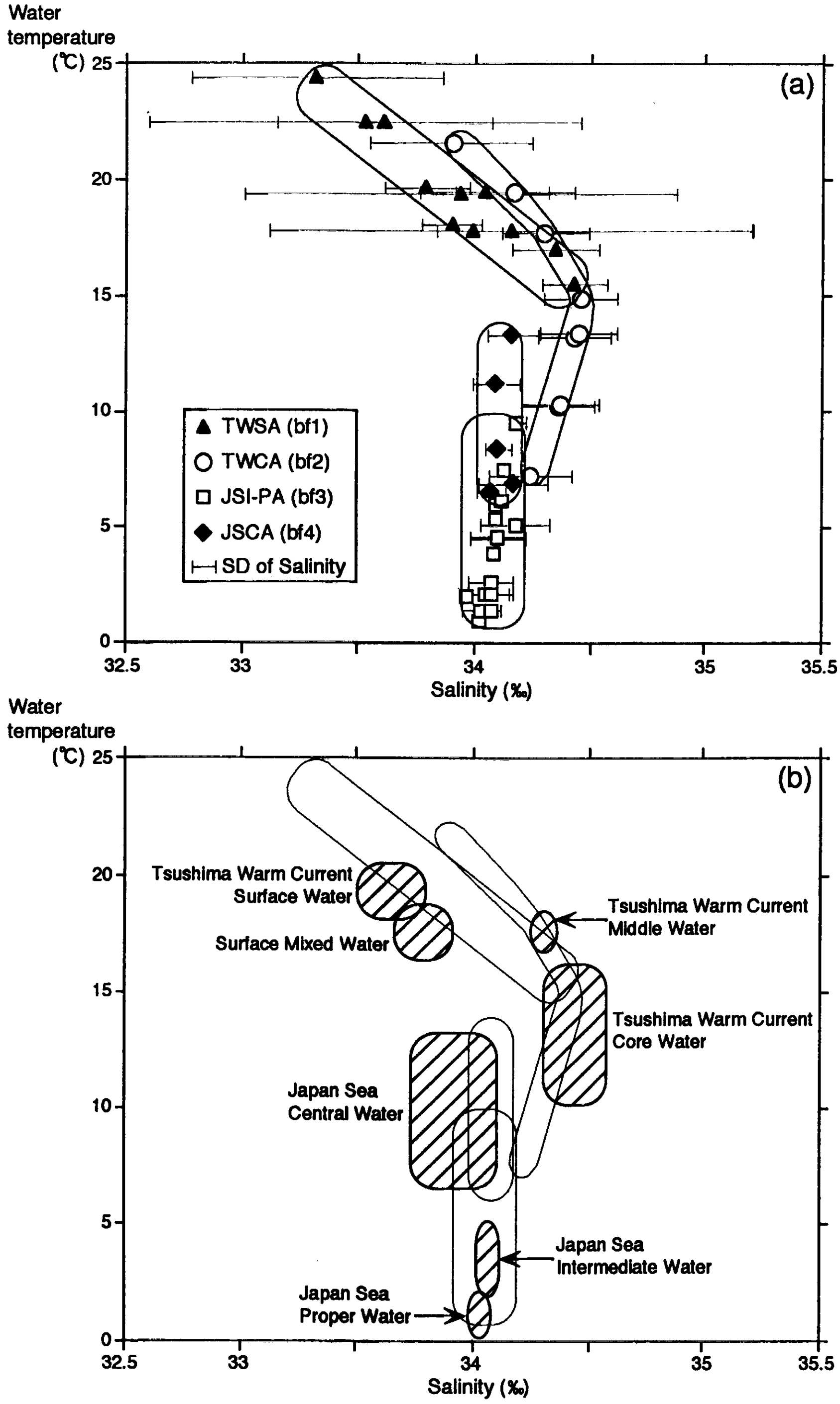

Figure 10. (**a**) Plots showing water temperature and salinity on T-S diagram for four ostracod assemblages from six areas in summer (August). (**b**) Divisions of water mass in Japan Sea from Yamamoto and Imai (1990). See captions for assemblage names in Figure 6.

temperature at the depths of the Japan Sea Central Water assemblage (JSCA; biofacies 4) is 5–15°C (Figure 9, lower right graph), the range of which are intermediate between the depths of the JSI-PA and TWCA. These values for the JSCA show a similar tendency between the south and north of the Tsugaru Strait, although there is approximately 100 m water depth difference between them (150–200 m off Tsugaru and 30–100 m off Teuri and Rebun). The salinity of JSCA is almost the same as that of the JSI-PA.

All the values of the water temperature and salinity for the four assemblages in the six study areas are represented in the graph in Figure 10a. The plotted fields of water temperature and salinity for the four assemblages are generally divided into four areas as highlighted by the four ovals on the graph of Figure 10a, though the margins of the four overlap to some extent.

The comparison between the four ovals in the graph of Figure 10a and the water mass division for the Japan Sea of Yamamoto and Imai (1990) is shown in the diagram in Figure 10b. Because their study divided the water masses of the Japan Sea in great detail, these divisions and the water-mass names are adopted here. They classified the water mass in the Japan Sea into three layers according to depth, that is, the surface, central and deep-water layers along the Japanese Islands. At the surface water layer, shallower than 50 m water depth, the Tsushima Warm Current Surface Water and Surface Mixed Water (more than 15°C and 33–34‰) are distributed along the coasts of Honshu and Hokkaido. In the central water layer, there are two types of water masses. Off Honshu, the Tsushima Warm Current Core Water and Tsushima Warm Current Middle Water (ca. 10–20°C and around 34.5‰) exist around 100 m water depth. These water masses are correlated with the main part and flowing axis of the Tsushima Current. Off Hokkaido Island, the Japan Sea Central Water (ca. 5–15°C and around 34‰) is distributed at water depths between 50 and 100 m, under the warm current surface water. The Japan Sea Intermediate Water and Japan Sea Proper Water (less than 5°C and around 34‰) exist in the water layer, deeper than 100–200 m along the Japanese Islands. Four fields in Figure 10a are correlated with several of their water masses (Figure 10b) as follows: 1) a part of the field of the Tsushima Warm Current Surface Water assemblage (for TWSA in Figure 10) is correlated with the Tsushima Warm Current Surface Water and Surface Mixed Water; 2) the Tsushima Warm Current Core Water assemblage (for TWCA in Figure 10) is correlated with the Tsushima Warm Current Core Water and a part of the plot corresponds to the Tsushima Warm Current Middle Water, characterized by the highest salinity water; 3) the Japan Sea Intermediate-Proper Water assemblage (JSI-PA in Figure 10) shallower than 300 m is correlated with the Japan Sea Intermediate Water and the lowest temperature and relatively lower salinity of the Japan Sea Proper Water; 4) the Japan Sea Central Water assemblage (JSCA in Figure 10) is correlated with the cold Japan Sea Central Water, middle temperatures of the Tsushima Current water and the Japan Sea Intermediate Water. Distribution patterns of the four assemblages recognized in the T-S diagram are correlated with different water mass environments and their different physico-chemical properties (Figure 10b).

This study deals with the ostracod assemblages, which consist mostly of dead specimens without soft parts (ca. 95% in total), in surface sediments. Then, this study essentially discusses the relationship between the water temperature-salinity properties and the distribution of the modern death assemblages. Strictly speaking, in the surface sediments, the sites where dead ostracod specimens occur may be different from those of living animals, as a result of postmortem transportation of empty carapaces (e.g., Irizuki *et al.*, 1999). However, in the case of the Japan Sea ostracods, the distribution of the four ostracod assemblages and the temperature-salinity characteristics of the four water masses are clearly correlated as shown in Figure 10. Therefore, this study considers that the dead shells of ostracods stay within the same water mass environments as in life on a scale of the shelf and slope areas of the Japan Sea, even if these shells are actually transported after death to some degree.

T-S conditions of modern cryophilic hemicytherid species

The Japan Sea Central Water assemblage (JSCA) in this study consists mainly of the cryophilic hemicytherid species such as *Laperousecythere robusta* and *Johnnealella nopporensis*, and the living specimens with soft parts of some species were found (Itoh, 1996; Ozawa *et al.*, 1999; Tsukawaki *et al.*, 1999).

In order to clarify the lower limit of the water temperature for the habitats of the cryophilic hemicytherid species in the Japan Sea Central Water assemblage (JSCA), water mass properties of the Japan Sea during winter are examined. In winter conditions, the water temperatures and salinities are very similar among the different water depths and different areas in the top 150 m (Figure 3). The data plotted on Figure 11 have a smaller range of variation in winter than in summer, and differ considerably in magnitude.

Compared with the typical water mass divisions in the winter Japan Sea of Nishimura (1969) (Figure 11), the two assemblages of the warm Tsushima Current are distributed in the Upper water system, where the temperature is warmer than 7°C, except for the surface area shallower than 30 m off Hokkaido (4°C). The two assemblages in the lower-temperature water masses are seen in the Lower water system, which is less than 7°C (Figure 11). The distribution of each assemblage is controlled mainly by the two types of water masses in winter as shown in Figure 11. As a result, the assemblages in the Tsushima Warm Current Surface Water (TWSA; biofacies 1) and Tsushima Warm Current Core Water (TWCA; biofacies 2) are distributed in water temperatures of about 10°C in winter. In summer, a strong thermocline develops, and these two assemblages are distributed in different water masses. In many sea

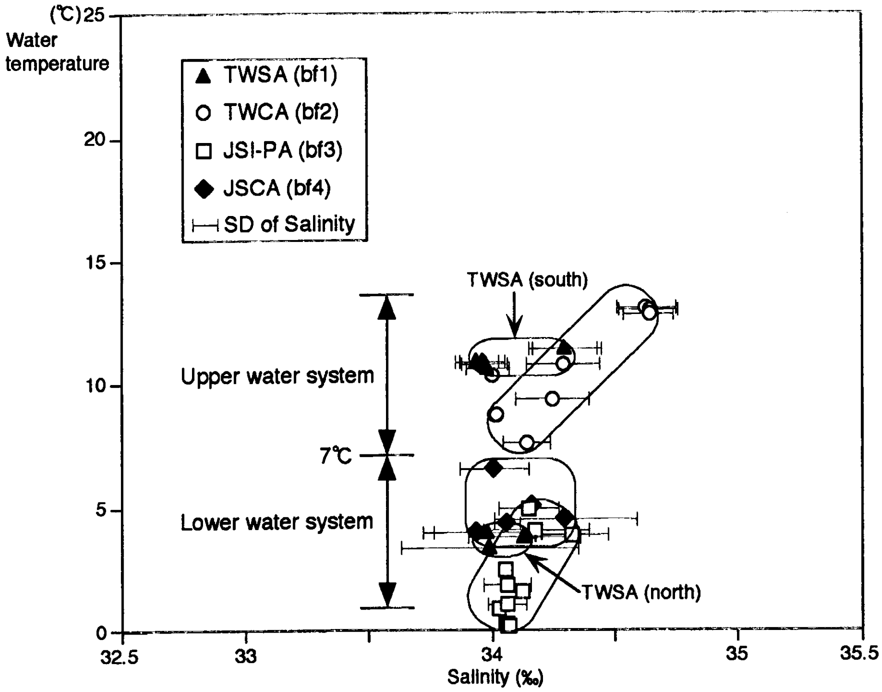

Figure 11. Plots showing water temperature and salinity on T-S diagram for four ostracod assemblages from six areas in winter (February), and division of water masses in Japan Sea, cited from Nishimura (1969). See captions for assemblage names in Figure 6.

areas, the Japan Sea Intermediate-Proper Water assemblage (JSI-PA) in the cold-water mass under the warm Tsushima Current water favours a relatively stable environment with a temperature around 5°C, with smaller seasonal differences.

The water temperatures for the Japan Sea Central Water assemblage (JSCA), containing the cryophilic hemicytherid species, are around 10°C in summer and around 5°C in winter. These values are higher than those of the Japan Sea Intermediate-Proper Water assemblage (JSI-PA) in summer and lower than those of the Tsushima Warm Current Core Water assemblage (TWCA) in winter.

Discussion

T-S conditions for cryophilic hemicytherid species

By examining the water temperature and salinity ranges of the ostracod assemblages in summer, the distributions of the four assemblages can be correlated with different water masses (Figure 10b). The winter range of temperature and salinity for each ostracod assemblage in the Japan Sea is reported here for the first time. The ranges of water temperature for the four assemblages are useful for studying the palaeoceanographical history of the Japan Sea. For example, fluctuations in flowing of the warm current and the presence of shallow-cold-water environments can be recognized, using the data of Plio-Pleistocene ostracod assemblages.

Among the temperature-salinity data of the four assemblages, the water temperatures of the Japan Sea Central Water assemblage, containing the cryophilic hemicytherids (around 10°C in summer and around 5°C in winter), are especially important (JSCA in Figures 10, 11). These values are the same as the palaeo-temperature of the water mass in shallow-sea areas in the Plio-Pleistocene during glacial periods. Thus the dominant occurrences of the cryophilic hemicytherids in the modern Japan Sea and also in fossil assemblages from the Plio-Pleistocene of the Japan Sea, indicate the existence of a water mass showing these unique temperature-salinity characteristics in the past. This winter temperature is very similar to the coldest Japan Sea Intermediate-Proper Water (0 - 5°C through the year; Figures 10, 11) area in this sea. However, the summer temperature of the Japan Sea Central Water assemblage is higher than that of the Japan Sea Intermediate-Proper Water and more similar to that of the Tsushima Warm Current Core Water (10 - 15°C in summer; Figure 10). This unique temperature change between summer and winter can be used to clarify the unknown water mass and oceanic conditions in the shallow areas of the Japan Sea during glacial periods.

The pioneering work by Cronin *et al.* (1994) presented the first estimation of the bottom water temperature of the shallow open sea of the Japan Sea (at an estimated 20–40 m water depth) in glacial intervals during the late Pliocene, 2.7–2.3 Ma. This analysis was based on the ostracod assemblages from the Yabuta Formation, central Japan, which yield many cryophilic hemicytherids such as *Yezocythere* and *Johnnealella*. They recognized the eight glacial events during 2.7–2.3 Ma, and the estimated temperature values for the glacial periods were 15–17°C in summer and 4–7°C in winter, on the basis of results from the modern analog technique (MAT) of comparing fossil and modern assemblages. Modern winter water temperatures for the area of distribution of the cryophilic hemicytherid species in this study are uniform at around 5°C. However, glacial Pliocene summer temperatures estimated by Cronin *et al.* (1994) are at about 5–7°C higher than modern temperatures of around 10°C.

Cronin *et al.* (1994) estimated the Pliocene water temperature using the squared chord distance (SCD) coefficient measure with the ostracod faunal database from modern coretop samples from around the Japanese Islands (Ikeya and Cronin, 1993). However, the data of Cronin *et al.* (1994) for the modern open sea on the continental shelf in the northeastern Japan Sea, where many cryophilic hemicytherid species occur, contained few samples from sites. They used approximately 200 samples from the brackish inner bay and open sea areas on the shelf in the warm current environment, mainly from southwestern Japan, where there are few occurrences of the cryophilic hemicytherid species. Furthermore, they analyzed an ostracod data set consisting of only genus-level identifications for many taxa. SCD values range between 0 and 1, with low SCD values (< 0.25) reflecting very similar ostracod assemblages (Ikeya and Cronin, 1993). The best SCD value between fossil samples from the late Pliocene Yabuta Formation deposited in glacial intervals and modern samples was relatively high, the average being 0.64 (range 0.54–0.74; Cronin *et al.*, 1994). These results mean that their estimated temperature of Yabuta was based on rather dissimilar modern faunas, using data from around the present Japanese Islands and with few cryophilic hemicytherid species. Thus, temperatures should be re-calculated for the bottom water temperature of the Yabuta Formation deposited during the Pliocene glacial periods, using new data from this study, Itoh (1996) and Ozawa *et al.* (1999) from the open sea areas in northeastern Japan Sea. In re-calculating, the new estimated temperature will be lower than the value of Cronin *et al.* (1994), especially in summer.

The salinity in the areas of present distribution of the cryophilic hemicytherid species in the Japan Sea is 34‰ in summer and winter in this study (Figures 10, 11). This salinity value can become a key to infer the oceanic environments in the shallow Japan Sea during the glacial intervals in the Pliocene and Pleistocene, during which the cryophilic hemicytherid species flourished. However, it is unlikely that the salinity condition in the glacial intervals was the same as the present one of around 34‰. That is because the volume of flow of the high salinity (warm current) water during the lower sea-level periods was much smaller than the present Japan Sea due to the low sea-level and shallow depths of the southern straits. Therefore, it is considered that the modern salinity of 34‰ is the maximum value for the cryophilic hemicytherid species, because higher saline water is equivalent to the typical warm Tsushima Current water. The palaeo-salinity during the glacial periods is expected to have been lower than the present salinity. Thus, this present salinity is probably not directly equivalent to the palaeo-salinity of the water mass during the glacial periods, when the volume of flow of the high-salinity-warm water was lower than the present. These salinity values and ranges are points in dispute and further investigations are required. The research and summary for the lowest limit of the salinity for the modern cryophilic hemicytherid species in the low saline water area, such as the innermost bay areas in the northern Japan, will be needed to solve this problem.

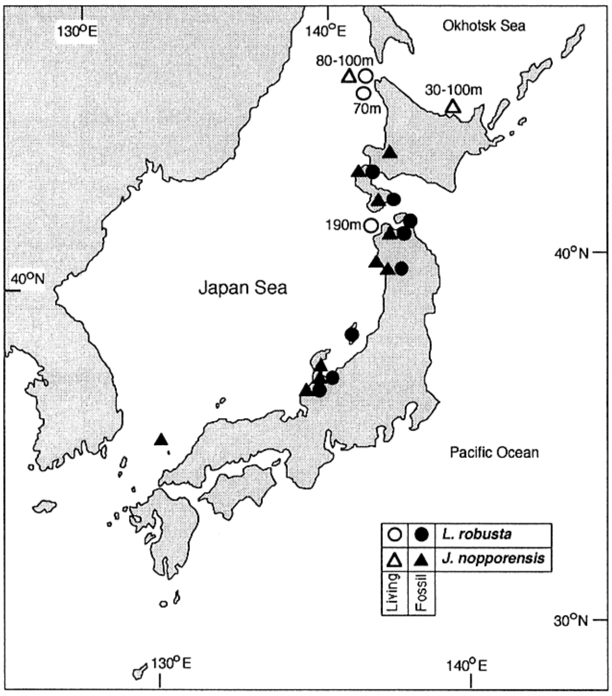

Figure 12. Geographical distribution of Pliocene-Pleistocene fossil and living records of *Laperousecythere robusta* and *Johnnealella nopporensis* around Japan Sea, with water depth of living specimens, compiled from data from previous studies (see text).

Post-Pleistocene changes of geographical distribution of two cryophilic hemicytherid species

The distribution of the two representative cryophilic hemicytherid species *Johnnealella nopporensis* and *Laperousecythere robusta* is shown in Figure 12, based on Pliocene and Pleistocene fossil records and living specimens (compiled from Ishizaki and Matoba, 1985; Tabuki, 1986; Cronin and Ikeya, 1987; Hanai and Yamaguchi, 1987; Irizuki, 1989b; Hanai and Ikeya, 1991; Cronin *et al.*, 1994; Ozawa, 1996; Itoh, 1996; Kamiya *et al.*, 1996; Ozawa *et al.*, 1999; Tsukawaki *et al.*, 2000; Ozawa, 2000).

Figure 12 suggests that these two species were also distributed in the southern Japan Sea during the glacial periods in the Pliocene and Pleistocene (since ca. 3 Ma at latest; Cronin *et al.*, 1994). These ostracods flourished over wider areas than the present. Fossil records indicate that in the Pleistocene *J. nopporensis* was distributed to the north of Tsushima Strait in the southwestern Japan Sea and *L. robusta* in the Noto Peninsula, central Japan. However, both species presently inhabit a restricted area in and around the northeastern Japan Sea (Figure 12). In the Holocene since ca. 8 ka at the latest, a warm water current has flowed regularly to the Japan Sea (e.g., Oba *et al.*, 1991; Matsushima, 1998) from the southern straits. This changed the oceanic environment in the southern shallow-sea areas to warmer conditions than in the previous glacial period, especially in winter, becoming similar to the present temperature of around 10°C. Thus, an existing suitable water mass environment for the two species, at around 10 °C in summer and around 5°C in winter in the shallow-sea areas in the southwestern Japan Sea off Honshu Island, disappeared. Their areas of distribution became drastically narrower than during periods of lower sea-level. As a result, the centre of their area of distribution moved from the southern Japan Sea to its present position in the northeastern Japan Sea off Hokkaido. The reduction of the geographical distribution for the two species is also seen in other cryophilic hemicytherid species, such as *Daishakacythere abei* and *Yezocythere hayashii*, which live mainly off Hokkaido in the Japan Sea (Ozawa *et al.*, 1999).

For *L. robusta*, the upper and lower depth limits of 150–190 m off the Tsugaru area and the range of 70–100 m depth off Teuri and Rebun islands (depths of JSCA in Figures 8) are different (Figure 12). The depth difference between south and north of the Tsugaru Strait is as great as about 100 m. *L. robusta* effectively changes its depth of distribution by more than 100 m in order to live both south (190 m) and north (70–100 m) of the Tsugaru Strait (Figure 12), being correlated to the water mass conditions suitable for that species. Thus *L. robusta* has unusual ecological features as a shallow-water species.

The geographical range of distribution and water depth suitable for *L. robusta* changed drastically and the areas of distribution became restricted, cyclically many times, due to the temporary flowing of the warm current water from the south, related to the Pleistocene glacio-eustatic sea-level changes (e.g., Kanazawa, 1990; Tada, 1994; Kitamura *et al.*, 1994; Takata, 2000; Ozawa and Kamiya, 2001). However, this species probably managed to survive the environmental fluctuations by means of its ecological tolerance, and has survived until the present in the Japan Sea. The hemicytherid ostracods in the Omma-Manganji ostracod fauna contain many extinct species (Cronin and Ikeya, 1987; Ozawa, 2001; Ozawa and Kamiya, 2001). Thus, ecological features of *L. robusta* are very significant for discussing the adaptation strategy of late Cenozoic ostracods against cyclic environmental fluctuations during the glacial-interglacial periods since the Pleistocene in the Japan Sea.

Winter T condition for TWSA in northern areas

In the water depth of distribution of the Tsushima Warm Current Surface Water assemblage (TWSA), the water temperature in winter is different between the southern three areas (11°C; Upper water system) and northern two areas (4°C; Lower water system), although salinity is restricted to around 34‰ in all areas (Figures 3, 11). North of the Tsugaru Strait in the Teuri and Rebun areas, the winter temperature of the TWSA is lower, because of a smaller volume of warm current water than south of the strait, and almost the same temperatures for the Japan Sea Central Water assemblage (JSCA). Summer temperature for TWSA is similar between north and south of the strait, around 20°C (Figures 9, 11).

The TWSA in the two northern areas consists of species such as *Bythoceratina hanaii*, *Cythere golikovi* and *Loxoconcha optima* (Itoh, 1996; Ozawa *et al.*, 1999). These species, which are members of the TWSA in the southern Japan Sea, dominantly inhabit the northern areas. For example, in the Rebun area, the first two species together make up as much as approximately 50% of the ostracod fauna (Mr. Hiromitsu Itoh, pers. com.). South of the strait, the percentage of occurrence of these two species (less than 7%) is much smaller than that north of it.

Therefore, probably species of TWSA in northern areas could breed in the three seasons under relatively high temperature conditions i.e., except for winter, and tolerate the low water temperature condition, appearing restrictedly in winter. In the northern two areas, several species in TWSA such as *Coquimba ishizakii* and *Loxoconcha viva* (Ozawa *et al.*, 1999) occur rarely. These species are distributed mainly in the southern areas. This fact suggests that species having tolerance for the seasonal cold-water condition are dominant in the northern shallow-sea area, instead of those species which are dominant in TWSA in the southern areas but are unsuited to wintertime-low-

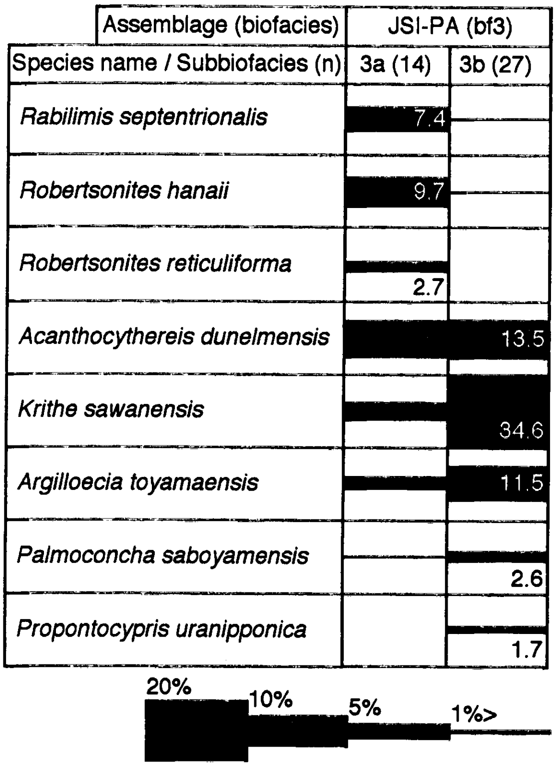

Figure 13. Mean ratio of characteristic ostracod species of two subbiofacies for southern four areas in biofacies 3. See captions of Figure 6 for abbreviations.

temperature conditions in the northern areas.

Subdivision for JSI-PA

Biofacies 3 (JSI-PA) in the four areas south of Tsugaru Strait is divided into two subbiofacies, 3a (150–250 m water depths) and 3b (350–1500 m) (Figure 4), due to the reflection of different ratios of dominant and characteristic species (Figure 13). In the Japan Sea, the temperature and salinity conditions at water depths deeper than 300–400 m are very stable through a year, and are 0–1°C and 34‰ respectively (e.g., Ishizaki and Irizuki, 1990). At around 200 m, the temperature and salinity are relatively stable, and are 2–5°C and 34‰ through the year. Therefore, south of Tsugaru Strait, the subbiofacies 3b deeper than 350 m may be correlated with the Japan Sea Proper Water (0–2°C), and the subbiofacies 3a around 200 m with the Japan Sea Intermediate Water (2–5°C).

However, north of Tsugaru Strait, the subbiofacies within biofacies 3 are not clearly recognized in the water depth range of 100–300 m, judging from the raw data of species occurrences in Itoh (1996) and Ozawa *et al.* (1999). This result is probably caused by the short-range of water depth investigated for biofacies 3 in the northern two areas. Therefore, more detailed correlations between subbiofacies and water masses at the deepest region of the Japan Sea will be a subject for future study. Further investigations for the distribution of species deeper than 300 m water depths are needed, especially in the northern Japan Sea.

Rare occurrences off Tsugaru Peninsula area

From the top layer of sediments at depths of 90–140 m off the Tsugaru Peninsula area, the ostracod occurrences both of carapaces and living specimens are very rare (Figure 8), although the sediment type is fine-grained such as sandy mud or muddy sand with about 40–70% mud content (Tsukawaki *et al.*, 1999).

The ostracod density (= number of individuals per 1 g or 100 cc) of this depth range off Tsugaru is very low, 1/100–1/8000 in comparison with the similar depths of other areas in the Japan Sea (Irizuki, 1989a; Ikeya and Suzuki, 1992). Off the Tsugaru Peninsula area lies the branching area of the warm Tsushima Current before it flows out to the Pacific through the Tsugaru Strait. Thus, by occasional migration of the flow direction of the warm water current along the coast, it is possible that the water temperature and salinity in this area are more susceptible to change than in other areas of the Japan Sea. This environmental character probably prevents the assemblages from living here. A study of the benthic foraminiferal fauna in surface sediments at depths between 40–2700 m off the Tsugaru Peninsula area (Matoba and Honma, 1986) revealed a sudden decrease in specimen density around 100–150 m depth. Furthermore, the ratio of calcareous foraminifera against the total of calcareous and agglutinating foraminifera is lower at this depth range than other depths. Consequently, it is highly possible that some factors that prevent the growth of species with calcareous carapaces exist around this depth range. More investigations of environmental parameters are needed, in particular dissolved oxygen and pH, in order to solve this problem.

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