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Middle Miocene ostracodes from the Kaigarabashi Formation in Hokkaido, northern Japan: Paleoenvironmental significance

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Abstract. A total of 35 ostracode species belonging to 16 genera are reported for the first time from the Middle Miocene Kaigarabashi Formation in Imagane Town, Hokkaido, northern Japan. Temperate and cryophilic ostracode species are found in the Kaigarabashi Formation. Temperate species comprise *Cornucoquimba moni-wensis*, *Cythere omotenipponica*, *Hermanites posterocostatus*, *Paracytheridea neolongicaudata*, and *Schizocythere kishinouyei*, whereas cryophilic species and genera are composed of *Schizocythere okhotskensis* and *Hemicythere*. The co-occurrence of temperate and cryophilic species and genera suggests that the marine environment was strongly influenced by both warm and cold-water masses. The species diversity and equitability of the fossil ostracode assemblages indicate that the depositional topography was a bay mouth area facing the open sea. Two new species are described: *Callistocythere imaganensis* Mukai and Tanaka sp. nov. and *Aurila hokkaidoensis* Mukai and Tanaka sp. nov.

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Introduction

In the Japanese Islands and surrounding seas, the climate was warmer with an increase in atmospheric greenhouse gases during the Early to Middle Miocene (*ca.* 16.5–13 Ma) worldwide. Average temperatures were about 4°C warmer than today, especially at the peak of the Mid-Miocene Climatic Optimum (MMCO) (*ca.* 16.9–14.7 Ma) and the climate was about 6°C warmer than today. After the MMCO, the climate became colder, and in the Early Pliocene (*ca.* 5 Ma), the climate was almost the same as today (Zachos *et al.*, 2008). With this climate change, six mollusc fossil fauna groups of Akeyo-Kunugidaira fauna (*ca.* 20–16.4 Ma), Asahi fauna (*ca.* 20–15.3 Ma), Yatsuo-Kadonosawa fauna (*ca.* 16.4–15 Ma), Moniwa fauna (*ca.* 15.3–15 Ma), Older Shiobara-Yama fauna (*ca.* 15–11 Ma), and Younger Shiobara-Yama fauna (*ca.* 11–5.3 Ma) have been recognized in Japan during the Miocene (Ogasawara, 1994; Ogasawara *et al.*, 2008) and each fauna corresponds

to the climatic change proposed by Zachos *et al.* (2008).

Ostracodes are small bivalved Crustacea (Oligostraca). Their fossil record dates back to the Early Ordovician (Whatley *et al.*, 1993). Ostracodes are useful for reconstructing paleoenvironments and paleobiogeography because they have no planktonic larval stage during their life and exhibit quite high endemism (Whatley *et al.*, 1993). Japanese Miocene ostracodes assemblages have mainly been reported from the Honshu regions (e.g. the Tohoku region: Ishizaki, 1966; Irizuki, 1994; Irizuki and Matsubara, 1994, 1995; Tanaka, 2009; Hokuriku region: Ishizaki, 1963; Tanaka *et al.*, 2004; Ozawa, 2016; the Kanto region: Irizuki *et al.*, 1998; Tanaka *et al.*, 2012a; Tanaka and Hasegawa, 2013; and the Chubu region: Yajima, 1992; Irizuki *et al.*, 2004) (Figure 1). However, there have been no reports of the Miocene ostracodes from Hokkaido. Here we discovered Miocene ostracode assemblages from the Kaigarabashi Formation, Oshima Peninsula, Hokkaido (Figure 2), for the first time, and

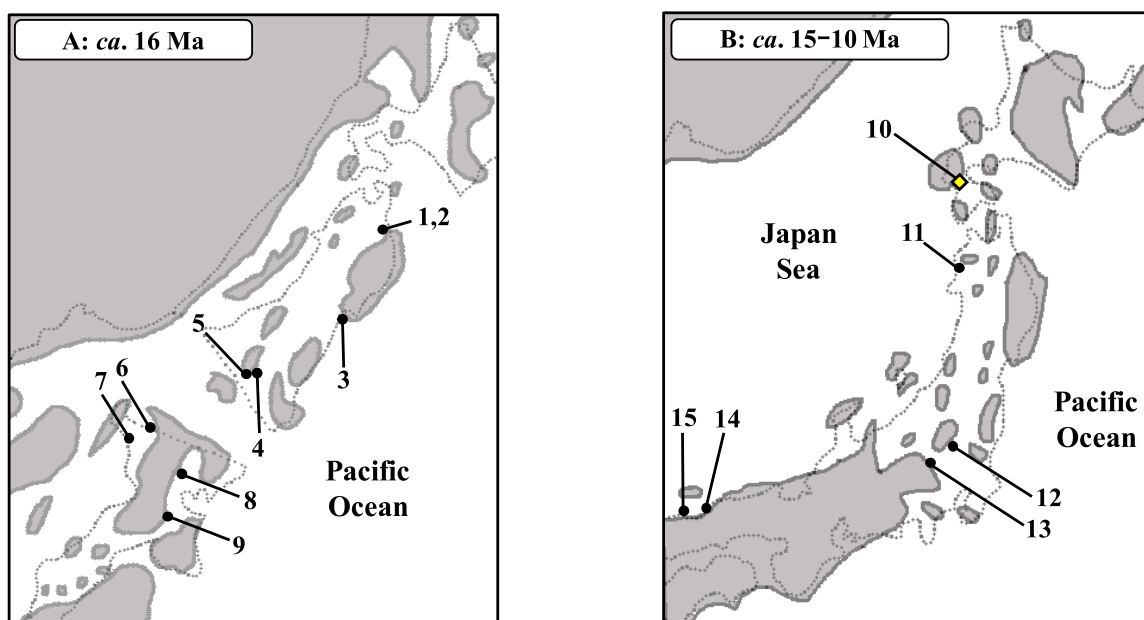


Figure 1. Palaeogeographical map of the Japanese Islands during early Middle Miocene – Late Miocene (*ca.* 16 Ma and 15–10 Ma). **A**, early Middle Miocene (*ca.* 16 Ma); **B**, middle Middle-Late Miocene (*ca.* 15–10 Ma). 1, Kadonosawa Formation (Irizuki and Matsubara, 1994); 2, Suenomatsuyama Formation (Irizuki and Matsubara, 1995); 3, Moniwa and Hatatate formations (Ishizaki, 1966); 4, Midorimachi Formation (Tanaka *et al.*, 2012b); 5, Obata Formation (Tanaka *et al.*, 2013); 6, Yatsuo Group (Ozawa, 2016); 7, Sunagozaka Formation (Ishizaki, 1963 and Tanaka *et al.*, 2004); 8, Akeyo Formation (Yajima, 1992); 9, Iwamura Group (Irizuki *et al.*, 2004); 10, This study; 11, Fujikotogawa Formation (Irizuki, 1994); 12, Kobana Formation (Irizuki *et al.*, 1998); 13, Itahana Formation (Tanaka and Hasegawa, 2013); 14, Fujina and Furue formations (Tanaka *et al.*, 2002, Tanaka and Nomura, 2009); 15, Omori Formation (Tanaka, 2003). These two palaeogeographical maps are based on Chinzei (1991).

discuss the paleoenvironmental setting of this formation using fossil ostracode assemblages. Two new species, *Callistocythere imaganensis* Mukai and Tanaka sp. nov. and *Aurila hokkaidoensis* Mukai and Tanaka sp. nov. are also described.

Geological setting

In the central part of the Oshima Peninsula in Hokkaido (Figure 2), northern Japan, a series of sedimentary facies from the Miocene to Pleistocene periods are widely distributed and have been researched as standard Cenozoic strata in the Oshima Peninsula (Ikeya and Uematsu, 1968; Ishida, 1978, 1981). Stratigraphic and paleontological studies of Neogene deposits were conducted by Nagao and Sasa (1933, 1934), and many researchers have studied this area (e.g. Sawada, 1961, 1962; Hashimoto *et al.*, 1963; Ikeya and Uematsu, 1968; Ishida, 1978, 1981; Nojo *et al.*, 1999). Nagao and Sasa (1933), Hashimoto *et al.* (1963), Ikeya and Uematsu (1968), and Ishida (1981) designated the Kunnui, Yakumo, and Setana formations (Figure 3), in ascending order, which were deposited during the time spanning from the Miocene period to the Pliocene epoch. Subsequently, Nishizuka *et al.* (1989)

and Nojo *et al.* (1994, 1999) reassigned the depositional age of these formations, dating them between the Middle Miocene period to the Middle Pleistocene period based on both biostratigraphy and K–Ar radiometric dating. In the northern part of the Imagane area, molluscan-rich depositional facies have been widely distributed and Nagao and Sasa (1933), Sawada (1961, 1962) called them the Kaigarabashi Sandstone Formation. Hashimoto *et al.* (1963) and Ikeya and Uematsu (1968) placed the formation in part of the Yakumo Formation and named it the Kaigarabashi Sandstone Member. Kanno (1962) referred to the Kaigarabashi Sandstone Formation as “the Meppu Sandstone Formation”. Nishizuka *et al.* (1989) re-examined the lithofacies, biostratigraphy, and distribution of the formation. They concluded that the Kaigarabashi Sandstone Formation should be independently treated as the Kaigarabashi Formation, as the former is situated below the contemporaneous heterotopic facies of the Yakumo Formation. In this study, we follow the definition of the Kaigarabashi Formation put forth by Nishizuka *et al.* (1989) (Figure 3). Based on the molluscan fossils reported by Sawada (1961, 1962), Kanno (1962), and Masuda and Ogasawara (1982) as well as the benthic foraminiferal fossils reported by Hasegawa (1998),

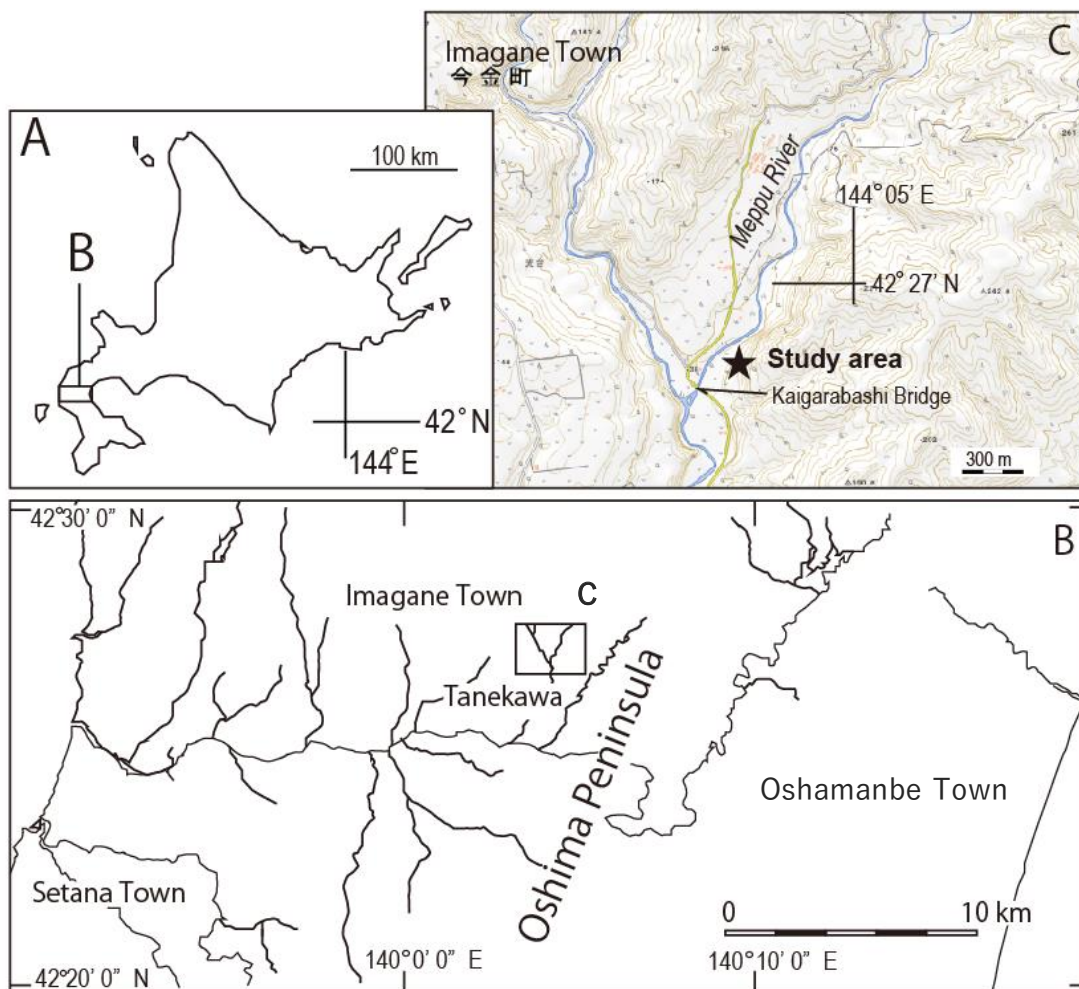


Figure 2. Location of the TM section studied in Imagane Town, Oshima Peninsula, southern Hokkaido. **A**, Map of the Hokkaido, northern Japan; **B**, Detailed map of the Oshima Peninsula, southern Hokkaido; **C**, Map of the study area in Imagane Town, Tanekawa District.

the Kaigarabashi Formation was presumed to have been deposited in the early Middle Miocene. Paleontological studies have reported many molluscs, benthic and planktonic foraminifera, calcareous nannofossils, and diatoms. However, there have been no reports of ostracodes.

The Kaigarabashi Formation is distributed near Kaigarabashi Bridge in the Meppu River watershed, which flows through the Tanekawa area in Imagane Town (Figure 2). This formation is mainly composed of arkosic sandstone created by erosion of the basement rock of granodiorite (Sawada, 1962). The lowermost part of the Kaigarabashi Formation comprises conglomerates. Although the basal boundary is unclear, it is thought that the basement rocks are covered by an unconformity (Sawada, 1961, 1962; Kanno, 1962). In the upper part of the formation, dark grey mudstone and arkose sandstone are alternately layered, and the layer is gradually changed to hard mud-

stone, finally the Kaigarabashi Formation is conformably overlain by the Yakumo Formation (Hasegawa, 1998). Due to the occurrence of characteristic pectinids, such as *Placopecten setanaensis*, *Nanaochlamys notoensis*, and *Patinopecten kagamianus*, the Kaigarabashi Formation can be dated between the Early and the Middle Miocene periods (Sawada, 1961, 1962; Kanno, 1962; Masuda and Ogasawara, 1982). Hasegawa (1998) performed age and paleoenvironmental estimation using benthic foraminiferal assemblages of the Kaigarabashi Formation. The estimation assumed that the depositional time of the Kaigarabashi Formation was from the end of the Mid-Neogene Climate Optimum (MNCO) to the cold period, *ca.* 15–13 Ma (Hasegawa, 1998). It also presumed that the formation was deposited in an area closer to the southern than to the northern limit of the influence of warm mass flowing from the southern sea at that time.

		Nagao and Sasa (1933)	Sawada (1961, 1962)	Kanno (1962)	Hashimoto <i>et al.</i> (1963)	Nishizuka <i>et al.</i> (1989)
Pleistocene						Setana Formation
	Pliocene	U	Niwa alt.	Chinkobe Formation	Setana Formation	Setana Formation
L		Imagane alt.				
		Meppu thick alt.				
		Hakaimappu thin alt.				
Miocene	U	Towarubetsu thick Shell Yurappu thin Shell	Kuromatsunai Formation	Kuromatsunai Formation	Kuromatsunai Formation	Yakumo Formation Kaigarabashi. F.
	M	Kunnui series	Yakumo Formation	KSM Yakumo Formation	Meppu ss. Yakumo Formation	
	L		KSM ~ KRh	Kunnui Formation	Kunnui Formation	
			Kunnui Formation			
Paleo		Basements	Basements	Basements	Basements	Basements

Figure 3. Comparison of the stratigraphic divisions among previous workers (Nagao and Sasa, 1933; Sawada, 1961, 1962; Kanno, 1962; Hashimoto *et al.*, 1963; Nishizuka *et al.*, 1989) treating the Cenozoic sedimentary layers in Oshima Peninsula, southern Hokkaido. Abbreviations are as follows: alt. = alternation; KSM = Kaigarabashi Sandstone Member; KRh = Kayano Rhyolite; Paleo = Paleogene; SS = Sandstone; F = Formation; L = Lower; M = Middle; U = Upper.

Material and methods

The ostracode samples were collected from a small outcrop of the middle part of the Kaigarabashi Formation along the Meppu River watershed, where the observable outcrop is approximately 2.8 m in height. This study calls the investigated area TM (Tanekawa Meppu) section. The lithofacies consist of alternating layers (*ca.* 20–50 cm thick) of greyish to white medium-grained semi-consolidated sandstone and greyish to white fine-grained semi-consolidated sandstone; however, thin pebble layers (10 cm thick) are also sandwiched in some horizons (Figure 4). Parallel lamination was rarely observed, although the disarticulated pectinid bivalves were generally parallel to the lamination.

In the medium to fine-grained sandstone layers in the TM section, disarticulated allochthonous pectinids, namely *Placopecten setanaensis*, *Nanaochlamys notoensis*, and *Patinopecten kagamianus* were parallel to the bedding planes, and most of the shells were preserved in a convex upward position; however articulated pectinid bivalves were also observed. In addition, many bioclasts

such as sea urchin spines, brachiopods, and bryozoans were also contained within the matrix. Sandstone consists of well-sorted quartz, feldspar, and rich biotite. The pebble layers were also well sorted; the matrix consisted of greyish-white fine-grained sandstone, with few fossils, and the pebbles were composed of granodiorite.

In this study, the six ostracode samples were mainly collected from the pectinid-rich horizons; five samples from the fine-grained sandstone (TM0, 1, 2, 3, and 4), and one sample from the medium-grained sandstone (TM5).

All samples were dried in an oven for one week at 35°C. After reacting with approximately 5% hydrogen peroxide, the samples were washed on an upper 1 mm sieve and a lower 125 µm sieve with tap water. After the residue was dried, the ostracods were extracted using a binocular stereomicroscope (Zeiss Stemi 2000-C). Ostracod specimens were counted as one individual each in both the carapace and valve. They were selected for Scanning Electron Microscope (SEM) for imaging and imaged using the Keyence VHX-D500/510 at Kumamoto University. All the specimens are deposited in the Tohoku University Museum.

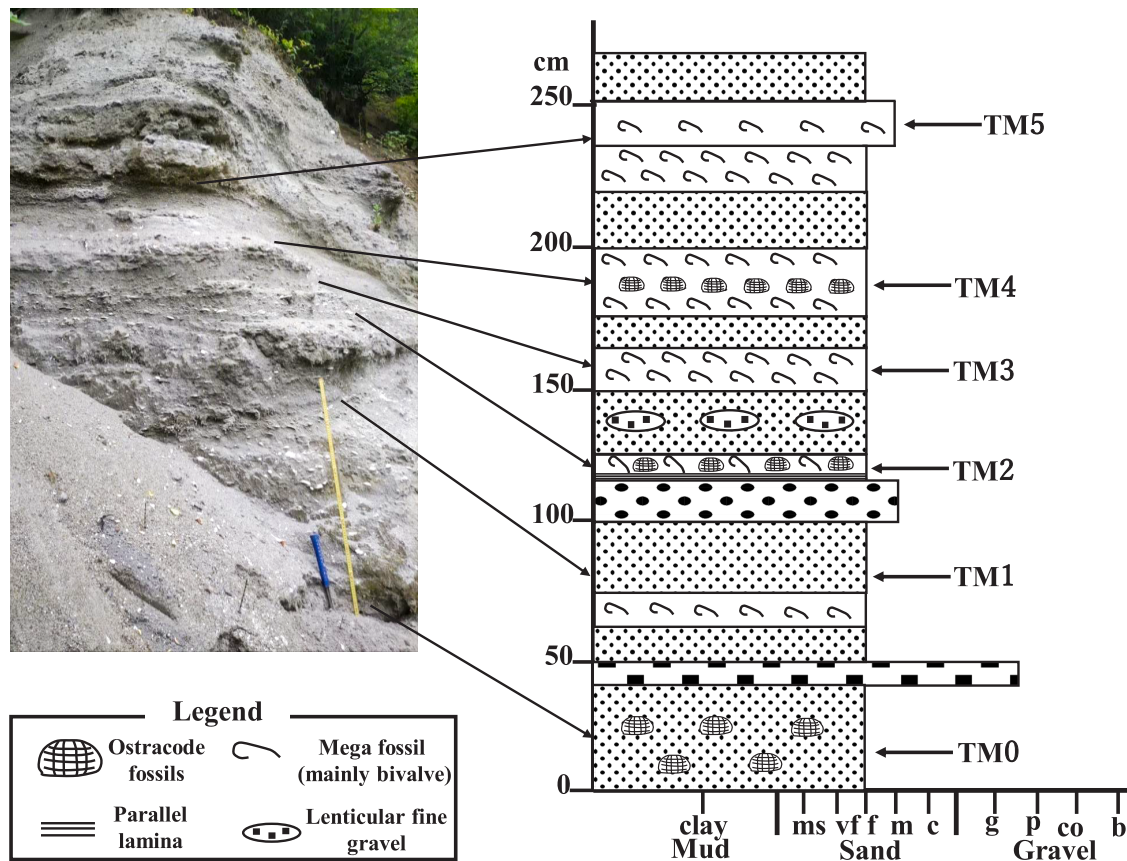


Figure 4. Columnar section of the TM section of the middle part of the Kaigarabashi Formation. Bold italic numbers indicate the ostracode samples in this study. TM0, TM2 and TM4 contained many well-preserved fossil ostracodes. Matrix consists of many sea urchin and bryozoan fragments in sediments; Abbreviations are as follows: ms = muddy sand; vf = very fine; f = fine; m = medium; c = coarse; g = granule; p = pebble; co = cobble; b = boulder.

Results

Fossil ostracode assemblages

Of the six samples collected, 35 species including 16 genera were identified from all samples (TM0–TM5) (Figures 5, 6; Table 1). Among them 75 individuals per 30 g were recovered from the sample TM0, and 52 and 54 individuals were recovered from samples TM2 and TM4 per 30 g of samples (Table 1). The three species, *Hermanites posterocostatus* Ishizaki, 1966 (Figure 5.14), *Paracytheridea neolongicaudata* Ishizaki, 1966 (Figure 6.4, 6.5), and *Schizocythere okhotskensis* Hanai, 1970 (Figure 6.8) were dominant. They were followed by *Schizocythere kishinouyei* (Kajiyama, 1913) (Figure 6.7) and *Schizocythere* sp. (Figure 6.10, 6.11) in the sample TM0. Moreover, *S. okhotskensis*, *Cythere omotenipponica* Hanai, 1959a (Figure 5.11), and *Schizocythere* sp. were found in sample TM2, followed by *C. omotenipponica* and *Callistocythere imaganensis* Mukai and Tanaka sp. nov. (Figure 5.5, 7) in sample TM4.

Species diversity and equitability

The Shannon-Wiener diversity index [H'] was calculated for three ostracode samples (TM0, TM2, TM4). H' was calculated using the following formula (Shannon and Weaver, 1949).

$$H' = -\sum p_i \ln p_i$$

(p_i = production frequency)

The H' value of each sample was 2.42 (TM0), 2.42 (TM2), and 1.96 (TM4), respectively, showing relatively high H' values except for TM4.

The equitability index (E) of the assemblages of three samples was calculated by using the following formula described by Buzas and Gibson (1969):

$$E = e^{H'/S}$$

(S = species number, H' = diversity index)

The equitability indices were relatively high and 0.59

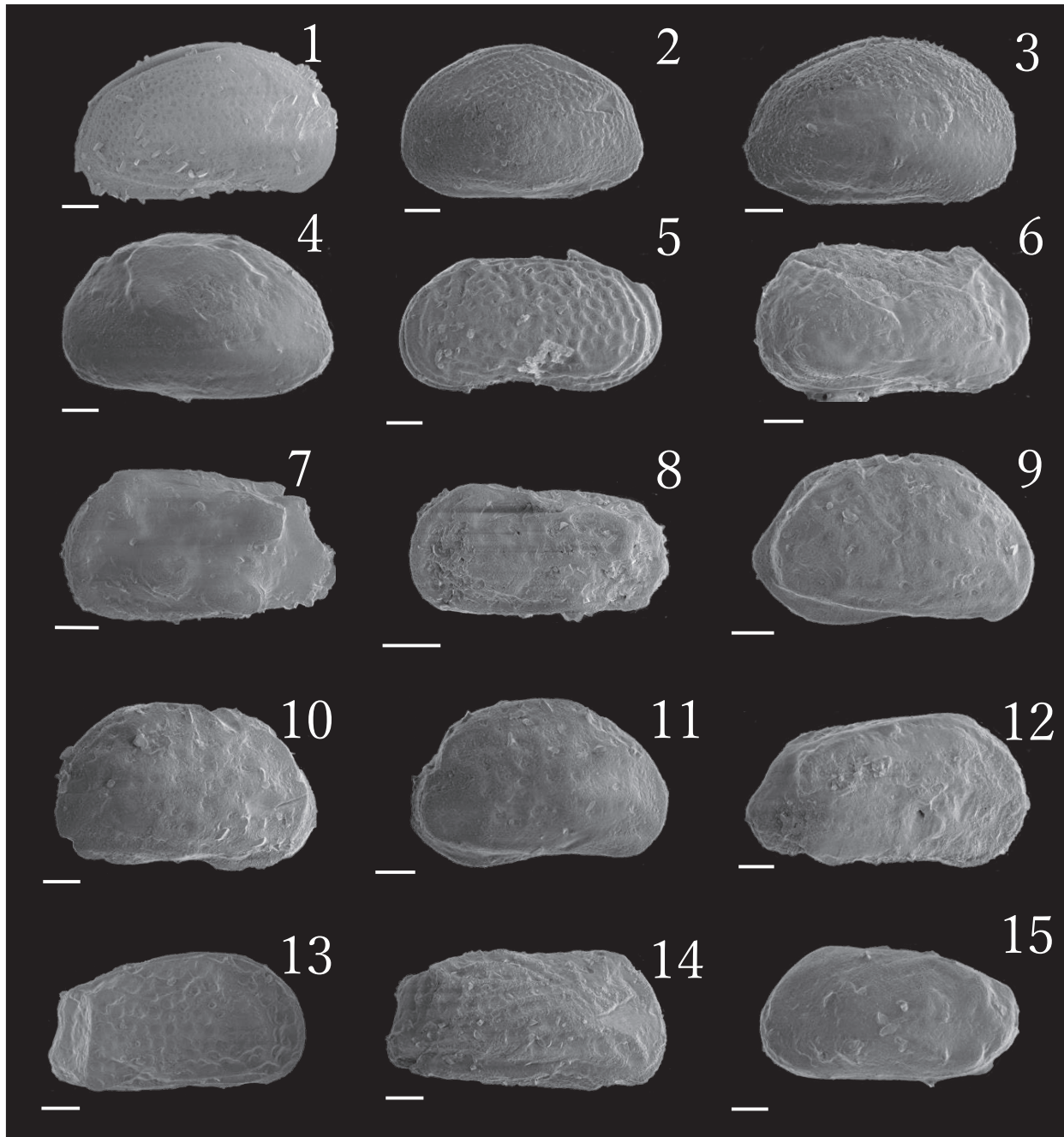


Figure 5. SEM images of fossil ostracodes from the Kaigarabashi Formation. **1**, *Aurila hokkaidoensis* Mukai and Tanaka sp. nov., RV; **2**, *Aurila joushuensis* Tanaka *et al.*, 2012 in Tanaka *et al.*, (2012), LV; **3**, *Aurila togakushiensis* Ozawa in Ozawa *et al.* (2008), RV; **4**, *Aurila* sp., left side of CA; **5**, *Callistocythere imaganensis* Mukai and Tanaka sp. nov., LV; **6**, *Callistocythere* sp., CA left side; **7**, *Cornucoquimba moniwensis* (Ishizaki, 1966), left side view of CA; **8**, *Cornucoquimba* sp., left side view of CA; **9**, *Cythere cronini* Tsukagoshi and Ikeya, 1987, RV; **10**, *C. cf. nopporoensis* Tsukagoshi and Ikeya, 1987, CA left valve; **11**, *C. omotenipponica* Hanai, 1959, RV; **12**, *Finmarchinella* sp., right side view of CA; **13**, *Hemicythere* sp., right side view of CA; **14**, *Hermanites posterocostatus* Ishizaki, 1966, right side view of CA; **15**, *Kotoracythere* sp. A, right side view of CA. Abbreviations: LV = left valve; RV = right valve; CA = carapace. All scale bars are 100 μ m. Specimens of 1, 5, 9–11, 13, 14 from sample TM0; 6–8, 12 from sample TM2; 2–4, 15 from sample TM4.

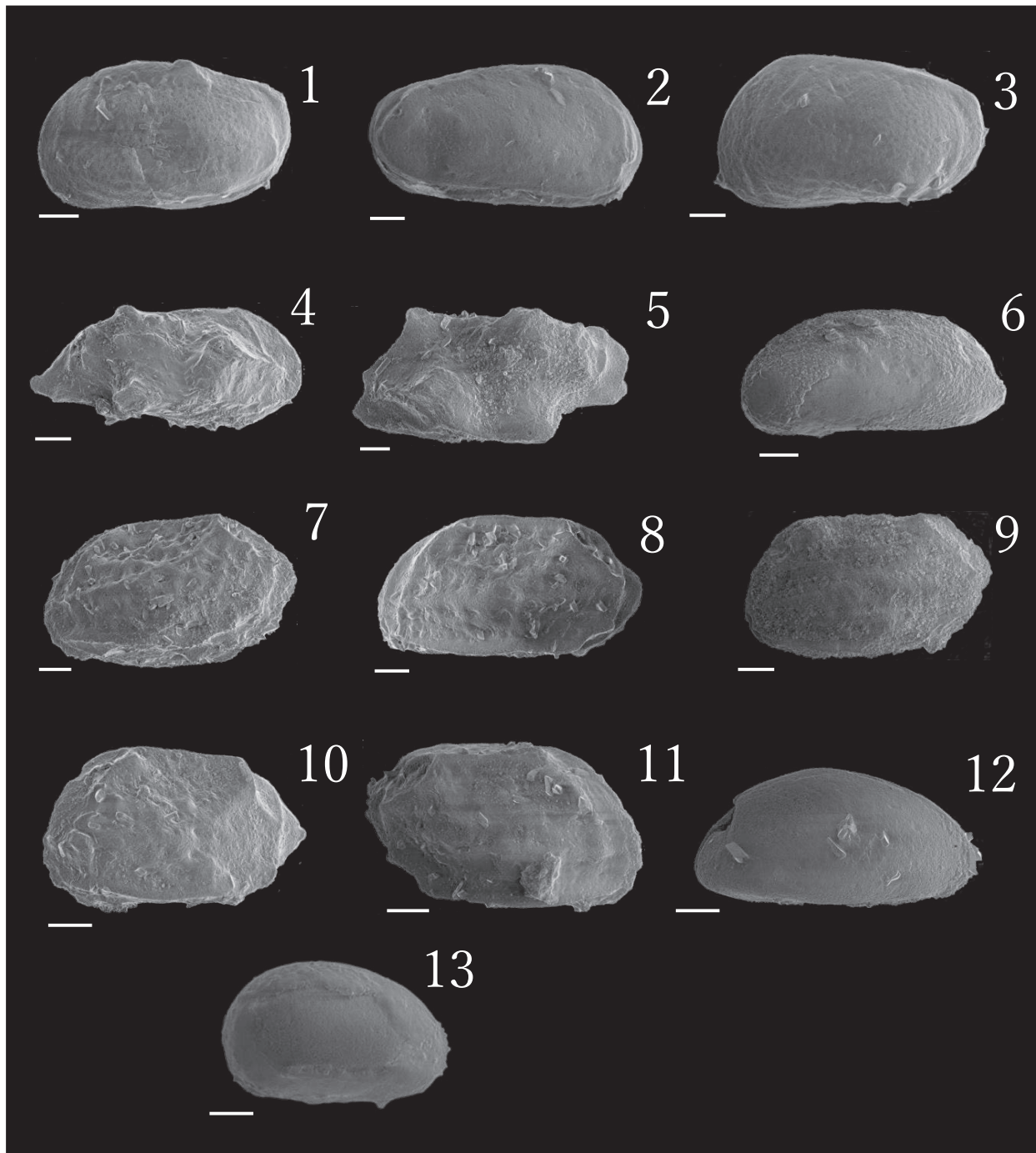


Figure 6. SEM images of fossil ostracodes from the Kaigarabashi Formation. **1**, Loxoconchidae (?) left side view of CA; **2**, *Munseyella* sp. A, right side view of CA; **3**, *Munseyella* sp. B, left side view of CA; **4**, **5**, *Paracytheridea neolongicaudata* (Ishizaki, 1966) (**3**, LV; **4**, RV); **6**, *Pontocythere subjaponica*, left side view of CA; **7**, *Schizocythere kishinouyei* (Kajiyama, 1913), left side view CA; **8**, *S. okhotskensis* Hanai, 1970, left side view CA; **9**, *Schizocythere* aff. *hatatensis* Ishizaki, 1966, LV; **10**, *Schizocythere* sp. A, left side of CA; **11**, *Schizocythere* sp. B, left side view of CA; **12**, *Xestoleberis* cf. *setouchiensis* Okubo, 1979, left side view of CA; **13**, *Xestoleberis* sp., left side view of CA. Abbreviations: LV = left valve; RV = right valve; CA = carapace. All scale bars are 100 μ m. Specimens of **4**, **5**, **7**, **8**, **10**, **11** from sample TM0; **1**, **9** from sample TM2; **2**, **3**, **6**, **12**, **13** from sample TM4.

Table 1. List of fossil ostracode species from the Kaigarabashi Formation.

	TM0	TM1	TM2	TM3	TM4	TM5	Total
<i>Aurila hokkaidoensis</i> Mukai and Tanaka sp. nov.	2	0	0	0	0	1	3
<i>Aurila joushuensis</i>	0	2	0	0	2	0	4
<i>Aurila togakushiensis</i>	2	0	1	0	2	0	5
<i>Aurila</i> sp.	3	0	4	1	4	0	12
<i>Callistocythere imaganensis</i> Mukai and Tanaka sp. nov.	3	0	1	1	4	0	9
<i>Callistocythere</i> sp.	0	0	1	0	0	1	2
<i>Cornucoquimba moniwiensis</i>	1	0	1	0	0	0	2
<i>Cornucoquimba saitoi</i>	0	0	0	0	1	0	1
<i>Cornucoquimba</i> sp.	1	0	0	0	0	0	1
<i>Cythere cronini</i>	1	0	0	0	1	0	2
<i>Cythere</i> cf. <i>nopporoensis</i>	2	0	0	0	0	0	2
<i>Cythere omotenipponica</i>	3	0	2	0	5	0	10
<i>Cythere</i> sp.	0	1	1	0	0	0	2
<i>Finmarchinella</i> sp.	0	0	1	0	0	0	1
<i>Hemicythere</i> sp.	1	0	1	0	0	0	2
<i>Hermanites posterocostatus</i>	21	1	14	2	15	0	53
<i>Kotoracythere</i> sp. A	0	0	0	0	1	0	1
<i>Kotoracythere</i> sp. B	0	0	0	0	1	0	1
<i>Laperousecythere</i> sp.	0	0	1	0	0	0	1
Loxoconchidae (?)	0	0	0	0	3	0	3
<i>Munseyella</i> sp. A	0	0	0	0	1	0	1
<i>Munseyella</i> sp. B	0	0	0	0	1	0	1
<i>Neomonoceratina</i> aff. <i>tsurugasakensis</i>	0	0	1	0	0	0	1
<i>Neomonoceratina</i> sp.	0	0	0	0	1	0	1
<i>Paracytheridea neolongicaudata</i>	13	2	5	2	6	0	28
<i>Pontocythere subjaponica</i>	0	0	0	0	1	0	1
<i>Schizocythere</i> aff. <i>hatatensis</i>	1	0	1	0	0	0	2
<i>Schizocythere kishinouyei</i>	4	0	1	0	0	0	5
<i>Schizocythere okhotskensis</i>	7	1	5	0	1	1	15
<i>Schizocythere</i> sp. A	2	1	1	0	1	0	5
<i>Schizocythere</i> sp. B	1	0	0	0	0	0	1
<i>Schizocythere</i> sp. C	0	0	1	0	0	0	1
<i>Schizocythere</i> sp. D	7	0	9	0	1	0	17
<i>Xestoleberis</i> cf. <i>setouchiensis</i>	0	0	0	0	1	0	1
<i>Xestoleberis</i> sp.	0	0	0	0	1	0	1
Total	75	8	52	6	54	3	198
species number	18	6	19	4	21	3	35
species diversity	2.42		2.42		1.96		
equitability	0.59		0.58		0.37		

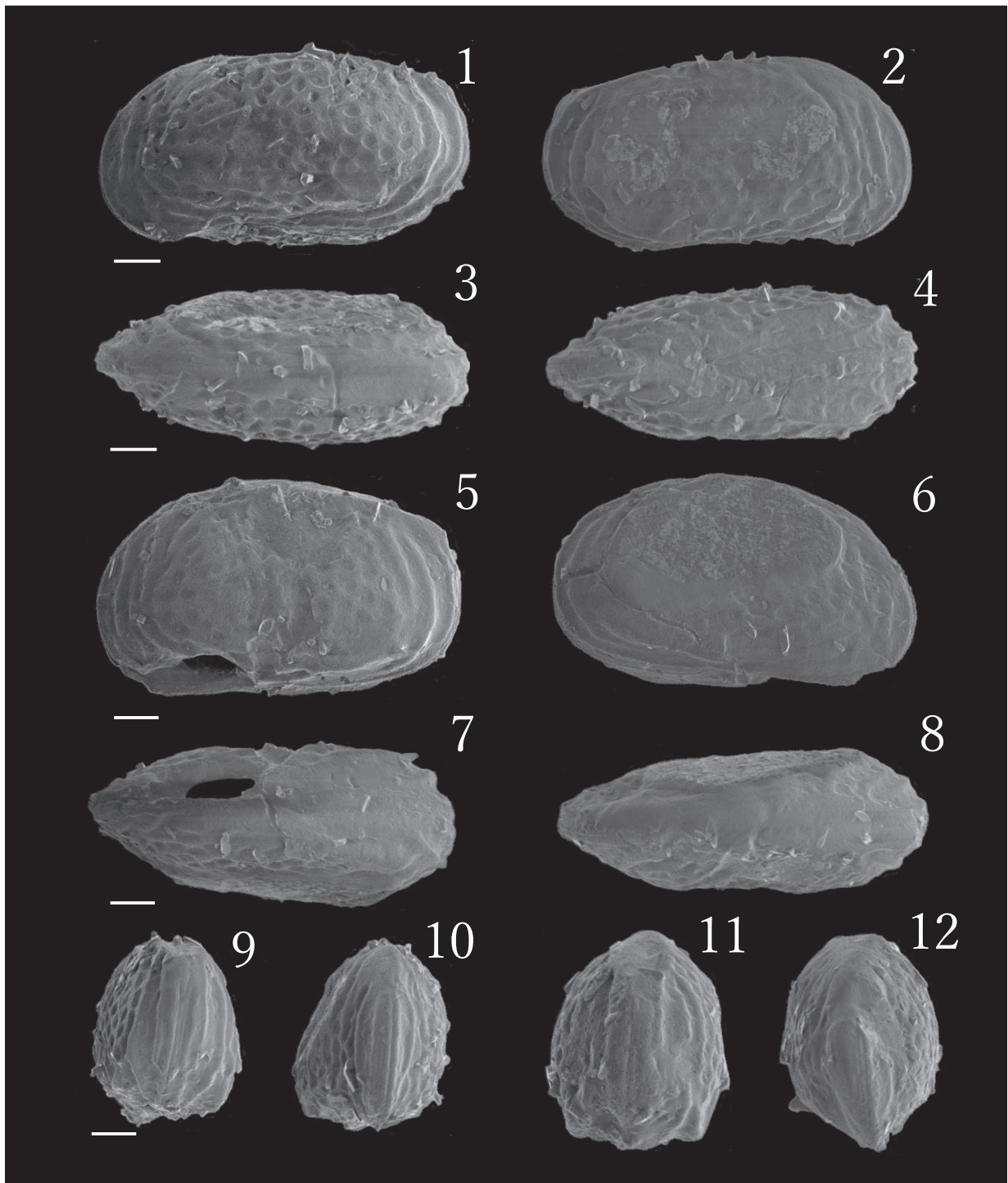


Figure 7. SEM images of *Callistocythere imaganensis* Mukai and Tanaka sp. nov. 1–4, 9–10, holotype, male, sample TM0, (IGPS–112776); 5–8, 11, 12, paratype, female, sample TM4, (IGPS–112777). 1 and 5, RV; 2 and 6, LV; 3 and 7, VS; 4 and 8, DS; 9 and 11, An; and 10 and 12, Ps. Abbreviations: LV = left valve; RV = right valve; DS = Dorsal Side; VS = Ventral Side; An = Anterior; Ps = Posterior. All scale bars are 100 μ m.

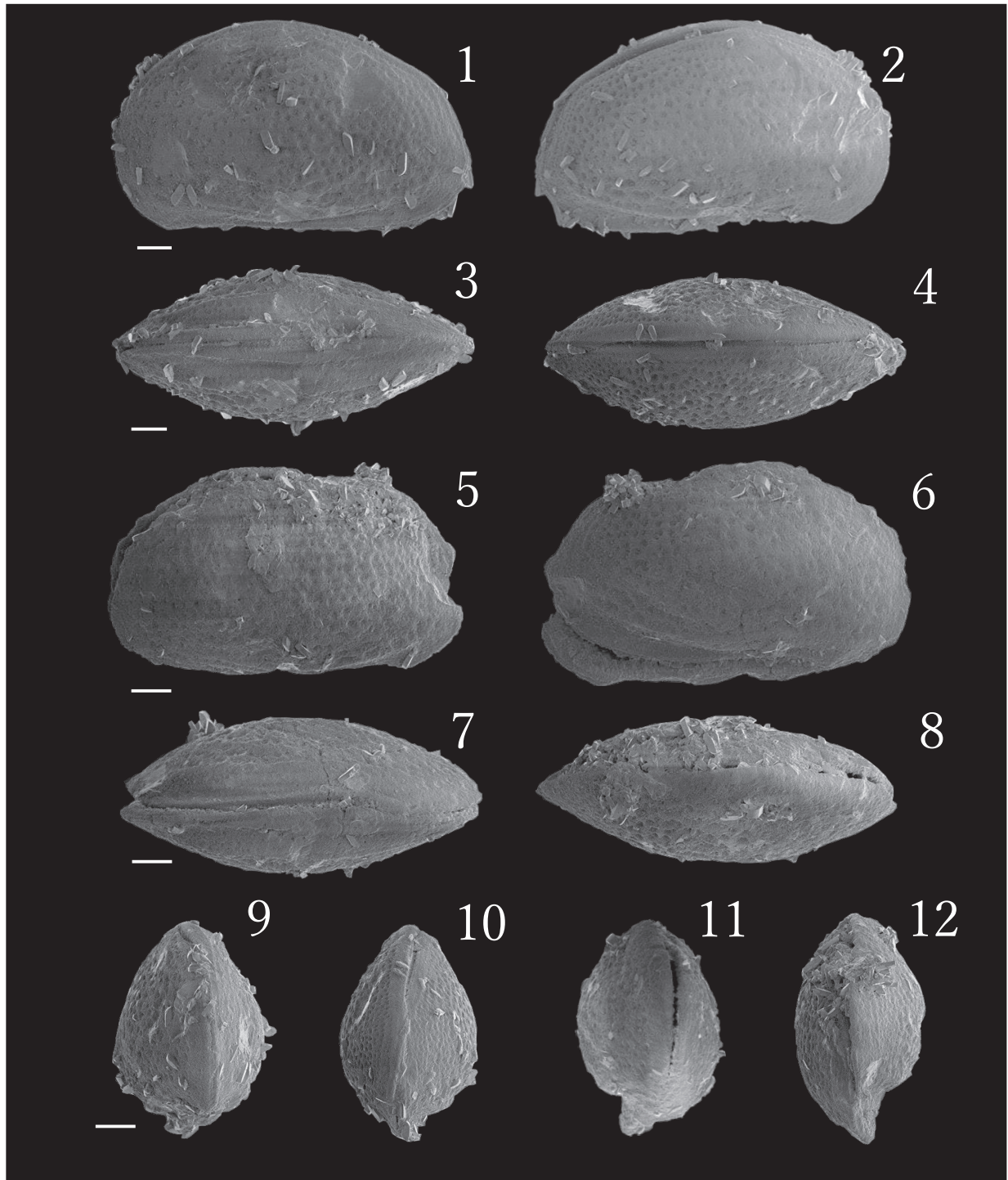


Figure 8. SEM images of *Aurila hokkaidoensis* Mukai and Tanaka sp. nov. 1–4, 9–10, holotype, male, sample TM0 (IGPS–112778); 5–8, 11, 12, paratype, female, sample TM0, (IGPS–112779). 1 and 5, RV; 2 and 6, LV; 3 and 7, VS; 4 and 8, DS; 9 and 11, An; and 10 and 12, Ps. Abbreviations: LV = left valve; RV = right valve; DS = Dorsal Side; VS = Ventral Side; An = Anterior; Ps = Posterior. All scale bars are 100 µm.

(TM0), 0.58 (TM2), and 0.37 (TM4), respectively.

In this study, we used Sendai Bay's ostracode data from Ikeya and Itoh (1991). Ikeya and Itoh (1991) did not list the number of individuals of each species. However, the locality of occurrences of each species is listed (p. 108–127 in Ikeya and Itoh, 1991). They also listed the values of species diversity in each location (p. 103 in Ikeya and Itoh, 1991) in the following form $x \leq H' < y$ where x and y are the values of species diversity H' . In this study, we used the number of species of each location and the average value of H' between x and y .

Discussion

Characteristic species and paleo-water temperature

The species diversity and equitability of the ostracode assemblages from the Kaigarabashi Formation, tended to be high values (*ca.* 2.4) except for TM4 among the three samples. The assemblages from the Kaigarabashi Formation, contained not only the cryophilic species of Hazel (1970), Valentine (1976), Cronin and Ikeya (1987), Ikeya and Cronin (1993), Cronin *et al.* (1994), Irizuki and Matsubara (1995), Ozawa *et al.* (2004), and Irizuki *et al.* (2005), (*i.e.*, *Schizocythere okhotskensis* and a genus *Hemicythere*), but also included the temperate species of Irizuki and Matsubara (1995) (*i.e.*, *Hermanites posterocostatus*, *Paracytheridea neolongicaudata*, *Cythere omotenipponica*, *Schizocythere kishinouyei*, and *Cornucoquimba moniwiensis*) (Table 2).

These results suggest that ostracode assemblages from the Kaigarabashi Formation lived in shallow waters facing the open ocean, and were significantly affected by both cold and warm water masses. Extant cryophilic species are found in the North Atlantic, North America, the Sea of Okhotsk, and the northern Sea of Japan (Hazel, 1970; Valentine, 1976; Ozawa, 2003). *Schizocythere okhotskensis* has been reported from the Sea of Okhotsk at water depths of 8–9 m (Hanai, 1970). Yoneda (1985) mentioned that the warm Soya Current flows into the Sea of Okhotsk and although the effects of the warm current can be seen shallower than 10 m depth, the temperature deeper than 10 m remains between 0 and 2°C throughout a year. On the basis of the distribution of the modern cryophilic species, it is suggested that cold water with a temperature of 0 to 2°C may have flowed into the sea where the Kaigarabashi Formation was deposited.

The temperate species, *Cythere omotenipponica*, *Cornucoquimba moniwiensis*, *Paracytheridea neolongicaudata*, and *Schizocythere kishinouyei* were also found in the Kaigarabashi Formation. Among them, *C. omotenipponica* has been characteristically distributed on the Pacific Ocean side of Japan, which is greatly affected by the Kuroshio Current (*e.g.* Tsukagoshi and Ikeya,

Table 2. Cryophilic and temperate ostracode species from the Kaigarabashi Formation. (Based on Cronin and Ikeya, 1987; Irizuki and Matsubara, 1995; Ozawa *et al.*, 2004; Irizuki *et al.*, 2005).

Cryophilic species and genus
<i>Schizocythere okhotskensis</i> Hanai, 1970
<i>Hemicythere</i>
Temperate species
<i>Cornucoquimba moniwiensis</i> (Ishizaki, 1966)
<i>Cythere omotenipponica</i> Hanai, 1959
<i>Hermanites posterocostatus</i> Ishizaki, 1966
<i>Paracytheridea neolongicaudata</i> (Ishizaki, 1966)
<i>Schizocythere kishinouyei</i> (Kajiyama, 1913)

1987); indeed, this species occurred in the Kaigarabashi Formation. According to Yajima (1992) and Irizuki *et al.* (2004), *C. moniwiensis* has been reported from the Lower Miocene strata in Japan and occurred abundantly during the MNCO. The above authors thought that *C. moniwiensis* adapted to cold climates during global cooling, or that some populations of *C. moniwiensis* were left near the northern limit of its habitat and then adapted to the recent sea area in the mid-temperate to cool temperate under the marine climate. *P. neolongicaudata* was reported by Ishizaki (1966) from the Middle Miocene Moniwa and Hatatate formations in northeastern Japan, together with *C. moniwiensis*. Moreover, Ikeya and Itoh, (1991) and Tanaka *et al.* (2012a) reported that *C. omotenipponica* and *C. moniwiensis* are found in water shallower than 50 m depth, where the temperature is 5–10°C in winter and up to 25°C in summer. Ozawa (2003), and Ozawa and Kamiya (2005) designated *S. kishinouyei* as the TWSA (Tsushima Warm Current Surface Water Assemblage) species. Due to the influence of the Tsushima Current throughout the year, the water temperature remains at between 15 and 25°C in summer, and between 10 and 15°C in winter. The existence of the temperate species suggests that warm water standing at around 10–25°C flowed into the area during the deposition of the Kaigarabashi Formation.

To sum up, the co-occurrences of the cryophilic and the temperate species suggest that the cold water column at 0–2°C in winter and the warm water column at 10–25°C in summer, existed during the deposition of the Kaigarabashi Formation. Hasegawa (1998) examined fossil benthic foraminifera from the Kaigarabashi Formation and estimated that a warm water mass flowed into cold-water masses in this region. Our results support the estimation of Hasegawa (1998). According to the previ-

ous molluscan studies, the Kaigarabashi Formation was deposited under warm water conditions (Masuda and Ogasawara, 1982). The temperature implications from ostracode assemblages tend to be cooler than from molluscan assemblages. Most molluscan fossils were disarticulated and were preserved in a convex upward position suggesting that they were transported from shallower and warmer original habitats.

Circumpolar ostracode species were not found in the Kaigarabashi Formation. The cryophilic species and the temperate species from the Kaigarabashi Formation were similar to those from the Middle Miocene Suenomatsuyama Formation, which were deposited under cool and temperate shallow water based on ostracode assemblages (Irizuki and Matsubara, 1995). *Cythere omotenipponica* and *Paracytheridea neolongicaudata* which indicate shallow water, were found from the Kaigarabashi Formation. Similarly, the Suenomatsuyama Formation also contained two species, indicating a shallow water environment (Irizuki and Matsubara, 1995), suggesting that the two formations were under similar environments.

Paleobathymetry

According to Irizuki and Matsubara (1994), the species diversity and equitability indices of ostracode assemblages are affected by water depth and substrates. For example, the values of species diversity and equitability are low in the mud bottom of the inner bay and sub-bathyal zone, but tend to be high in coastal areas and shallow seas with a depth of approximately 100 m. In this study, we compare the Kaigarabashi Formation with conditions similar to the sedimentary environment. In particular, we compare the Middle Miocene to Pleistocene ostracode assemblage data from eastern Japan and the present bay, which are influenced by both warm- and cold-water masses such as Irizuki and Matsubara (1995).

To compare the Kaigarabashi Formation and its similar depositional environments, we selected six Recent seas and bays (Fig. 9A, B) and 10 geological localities (Fig. 9C, D), and further its diversity and equitability indices were calculated from the following localities:

The Lower Miocene Kadonosawa Formation (Irizuki and Matsubara, 1994), the Yatsuo Group (Ozawa, 2016), the Middle Miocene Suenomatsuyama Formation (Irizuki and Matsubara, 1995), the Upper Miocene Tsunaki Formation (Ishizaki *et al.*, 1996), the Upper Miocene Fujikotogawa Formation (Irizuki, 1994) and Kubota Formation (Yamaguchi and Hayashi, 2001), the Pliocene Sasaoka Formation (Irizuki, 1989), the middle Pleistocene Jizodo and Yabu Formation (paleo Tokyo Bay) (Irizuki *et al.*, 2011) the Pleistocene Noma Formation (Irizuki and Hosoyama, 2000), the Upper Pleistocene Sagami Group (Shimosueyoshi) (Irizuki *et al.*, 2009),

the Holocene Numa Formation (Tateyama Bay) (Frydl, 1982), Modern Aomori Bay (Ishizaki, 1971), the East China Sea (Ishizaki, 1981), the Sendai Bay (Ikeya and Itoh, 1991), and the Osaka Bay (Yasuhara and Irizuki, 2001) (Figure 9). The diversity and equitability indices of the fossil assemblages from the Middle Miocene Kaigarabashi Formation tend to show similarities to those of the shallow sections of Recent Aomori Bay, Sendai Bay (b, d2 in Figure 9B), the Middle Miocene Suenomatsuyama Formation (II in Figure 9C), upper part of the Upper Miocene Kubota Formation (KF in Figure 9D), and lower part of the Pleistocene Noma Formation (NO in Figure 9D). All comparable locations and formations were possibly in shallow water with a depth of less than 100 m and were strongly affected by water masses from the open sea. Among these comparable locations and formations, the depositional paleotopography of the Miocene Kaigarabashi Formation was very similar to that of the Recent mouth of Sendai Bay (Ikeya and Itoh, 1991), which has a depth of 50–100 m and is strongly affected by open seawater. *Schizocythere*, *Cythere*, *Cornucoquimba*, and *Paracytheridea* inhabit the Northwest Pacific along the coast of Japan (e.g. Ozawa, 2016). Ishizaki, (1966), Hanai (1959a), and Yajima (1992) suggested that *Cythere omotenipponica*, *Cornucoquimba moniwenensis*, and *Paracytheridea neolongicaudata* are distributed in shallow waters facing open sea, thus supporting the sedimentary environment inferred from species diversity and equitability indices. These descriptions support our paleobathymetric estimation.

Conclusions

1: A total of 35 species including undescribed species of ostracodes were discovered from the Middle Miocene Kaigarabashi Formation. This study is the first report of Miocene ostracodes from Hokkaido, northern Japan.

2: Cryophilic species and temperate species were recognized in the ostracode assemblages from the Kaigarabashi Formation, thus suggesting that the depositional environment was strongly affected by both cold-water masses and warm-water masses.

3: The species diversity index and the equitability index were calculated for the ostracode assemblages from the Kaigarabashi Formation, and showed relatively high values similar to those of the recent mouth of Sendai Bay (water depth of 50–100 m).

4: Two new species, *Callistocythere imaganensis* Mukai and Tanaka sp. nov. and *Aurila hokkaidoensis* Mukai and Tanaka sp. nov., were described.

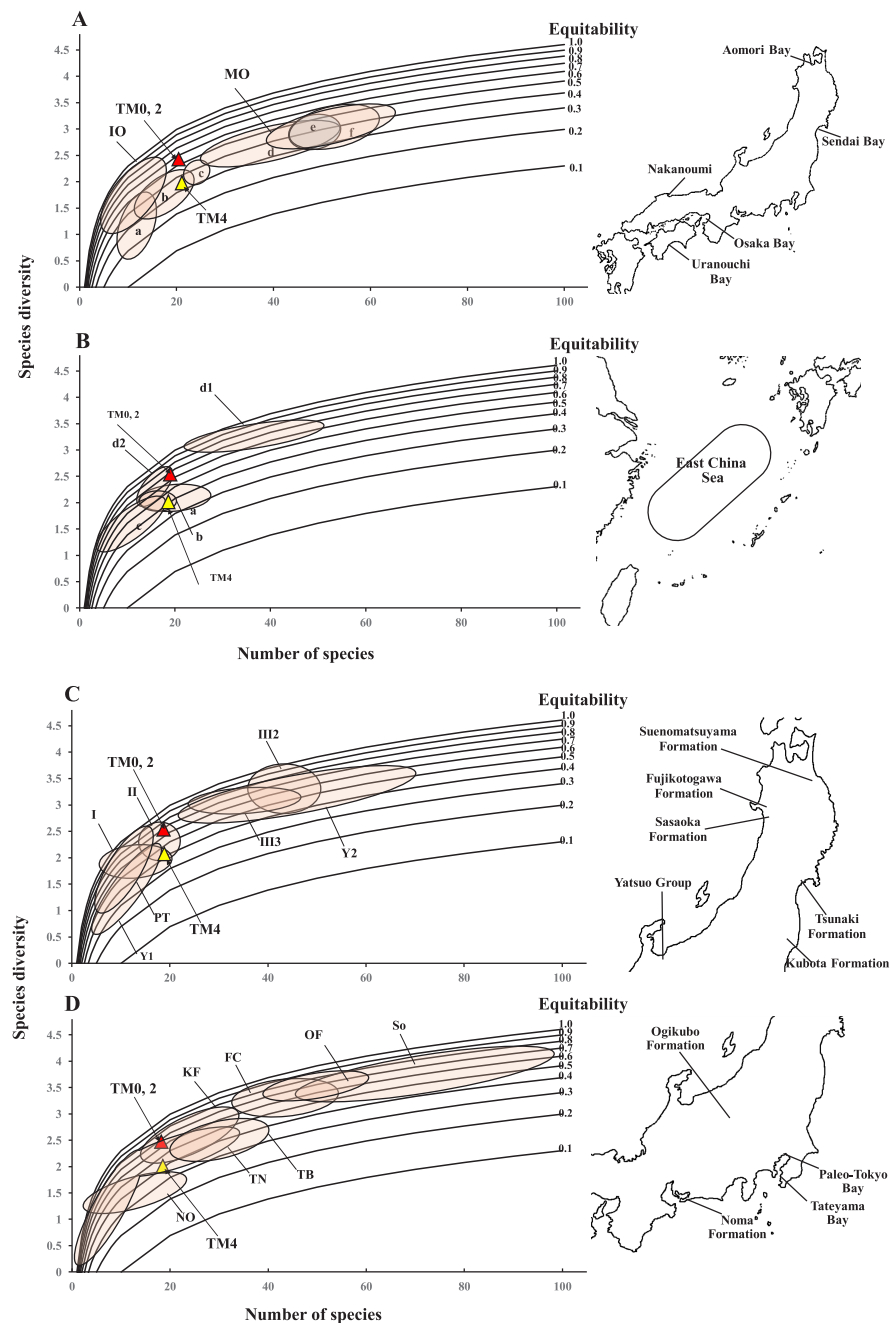


Figure 9. Diagram showing the positions of the recent and Neogene ostracode fossils in relation to species diversity, equitability and number of species. Large ellipses show sample groups constructed by the data of the following previous studies. **A**, Large ellipses show sample groups of recent ostracodes by Irizuki (1989), a; Nakanoumi Estuary (Ishizaki, 1969), b; Inner section of Uranouchi Bay (Ishizaki, 1968), c; Deeper section in Aomori Bay (Ishizaki, 1971), d; Outer section of Uranouchi Bay (Ishizaki, 1968), e; Shallow section in Aomori Bay (Ishizaki, 1971), f; East China Sea (Ishizaki, 1981), IO; Inner section of Osaka Bay and MO; Mouth of Osaka Bay ($n = 22$; Yasuhara and Irizuki, 2001). **B**, Large ellipses show sample groups of recent ostracodes in Sendai Bay ($n = 45$; Ikeya and Itoh, 1991), a; Inner bay, Estuary (0–40 m), b; Outer bay (deeper than 50 m), c; Central inner bay (10–50 m), d1; Estuary (0–10 m), d2; Outer bay (50–100 m). The ellipse in the map shows the areas of investigation conducted in previous studies. **C**, Large ellipses show sample groups of Miocene ostracodes, I, II, III2, and III3 in Suenomatsuyama Formation ($n = 15$; Irizuki and Matsubara, 1995), Y1 and Y2 in Yatsuo Group ($n = 18$; Ozawa, 2016), and PT; Paleo-Tokyo Bay (middle Pleistocene) ($n = 21$; Irizuki *et al.*, 2011). **D**, Large ellipses show samples groups of Miocene–Pleistocene ostracodes, TB; Tateyama Bay (Holocene and recent) ($n = 15$; Frydl, 1982), NO; Noma Formation (Pleistocene) ($n = 6$; Irizuki and Hosoyama, 2000), So; Sasaoka Formation (Late Pliocene) ($n = 13$; Irizuki, 1989), OF; Ogikubo Formation (Pliocene) ($n = 5$; Ozawa *et al.*, 2008), TN; Tsunaki Formation (late Miocene) ($n = 13$; Ishizaki *et al.*, 1996), FC; Fujikotogawa Formation (Late Miocene) ($n = 5$; Irizuki, 1994), KF; Kubota Formation (Late Miocene) ($n = 16$; Yamaguchi and Hayashi, 2001).

Systematic paleontology

Order Podocopida Müller, 1894

Superfamily Cytheroidea Baird, 1850

Family Leptocytheridae Hanai, 1957

Genus *Callistocythere* Ruggieri, 1953

Type species *Callistocythere littoralis* (Müller, 1894)

Callistocythere imaganensis Mukai and Tanaka sp. nov.

Figures 5.5, 7.1–12

Zoobank lsid: urn:lsid:zoobank.org:act:2B3CB06E-5C62-4695-A86B-216203A4C23F

Etymology.—From the town name of the type locality.

Types Holotype, male carapace, IGPS-112776 from the sample TM0 (L = 665.7 µm, H = 321.5 µm). Paratype, female carapace IGPS-112777 from the sample TM4 (L = 662.2 µm, H = 379.9 µm).

Type locality.—Sample TM0 of the Kaigarabashi Formation (Middle Miocene) at Meppu River, Imagane Town, Hokkaido northern Japan (42° 26' 52.93"N, 140° 04' 18.60"E)

Diagnosis.—Carapace subrectangular in lateral view. Coarse reticulations surround stout muri. Dorsal margin straight, ventral margin concave at one-third from the anterior end. Three strong carinal ridges, beginning in the dorsal area at two-thirds of the anterior end and, running parallel along the posterior margin.

Description.—Valve subrectangular in lateral view. Longest at mid-height from the venter, and highest at mid-length from the anterior end. Anterior margin evenly rounded anteroventrally, and mid length of dorsal margin gently sloping toward the posterior; posterior margin broadly rounded ventrally, ventral margin sinuate and concave at one-third from the anterior end. Coarse reticulation surrounded stout muri at middle to posterior areas. Two prominent carinal ridges at the anterior area; an outer short ridge obliquely running from three-fourths height from the venter, and an inner ridge extending below the eye tubercle, running parallel to anterior margin bifurcating at mid-height from the venter, running parallel to the ventral margin, and ending at one-third from the anterior end. Three prominent carinal ridges starting at dorsal margin of two-thirds from anterior end: most posterior ridge, long and starting at dorsal margin running parallel to posterior margin, terminating at one-third from anterior end; a short middle ridge starting from dorsal margin, running parallel to posterior margin, and ending at mid-height from venter; innermost ridge extremely short and ending at two-thirds height from venter. In the anterior view, outline elliptical, widest at one-fourth of the distance from the venter. In the ventral and dorsal views, carapace rice-shaped, widest at mid-length from anterior

end; sexual dimorphism prominent: in lateral view, carapace outline, male more slender than female; in anterior and posterior view, female wider than male.

Remarks.—*Callistocythere imaganensis* Mukai and Tanaka sp. nov. resembles *Callistocythere kyongjuensis* Huh and Whatley, (1997) reported from the Miocene deposit of the Pohang Basin, South Korea, but differs from the latter in having two anterior carinal ridges, three posterior ridges running from the posterodorsal margin, an extremely short innermost posterior ridge, and a concave ventral margin at one-third of the anterior end. The new species resembles *Callistocythere kyokoae* Tanaka of Tanaka and Hasegawa (2013) from the Upper Miocene Itahana Formation, Gunma Prefecture, central Japan, in its lateral outline; however, the new species is distinguished from *C. kyokoae* by its three posterior carinal ridges, coarser reticulation surrounded by stout muri, and a larger size of the valve. This new species is similar to *Callistocythere seojeongriensis* Huh and Whatley (1997) reported from the Miocene sediment of the Yeonil Group of the Pohang Basin, South Korea, but it differs from the latter in having two prominent carinal ridges at the anterior area, an extremely short innermost ridge of the posterior area, and rounded reticulation along the dorsal margin.

Family Hemicysteridae Puri, 1953

Genus *Aurila* Pokorný, 1955

Type species *Aurila convexa* (Baird, 1850)

Aurila hokkaidoensis Mukai and Tanaka sp. nov.

Figures 5.1, 8.1–12

Zoobank lsid: urn:lsid:zoobank.org:act:8834B96F-A643-45C3-AEFE-6A07526B508E

Etymology.—The prefectural name of the type locality.

Type. Holotype, female carapace, IGPS-112778 from the TM0 (L = 668.4 µm, H = 391.1 µm). Paratype, male carapace, IGPS-112779 from the TM0 (L = 672.4 µm, H = 366.5 µm).

Type locality.—Sample TM0 of the Kaigarabashi Formation (Middle Miocene) at Meppu River, Imagane Town, Hokkaido northern Japan (42° 26' 52.93"N, 140° 04' 18.60"E)

Diagnosis.—Carapaces sub-rhomboidal in the lateral view. Flat surface development in anteroventral and posteroventral areas. Several rows of fossae and/or fine pits running from anterior to posterior along the longitudinal direction. In the ventral view, a pair of carinas runs parallel from anterior to posterior.

Description.—Valves are asymmetrical and sub-rhomboidal in lateral view. Maximum height at one-third of anterior end. Anterior margin evenly rounded antero-

ventrally; dorsal margin widely arched; dorsal half of posterior margin straight; ventral half of posterior margin broadly arched, ventral margin concave at one-fourth from anterior end. Prominent caudal processes left valve overlapped with the right valve along the dorsal margin. Flat surface development in anteroventral and posteroventral areas. Fine round pits are developed in the central area. Shallow rounded fossae at ventral arranged along ventral margin. Several rows of fossae and/or fine pits run anterior to posterior along the longitudinal direction. The eye tubercles inconspicuous. In the dorsal and ventral views, carapace fusiform, widest at mid-length. In the ventral view, part of the carina runs parallel from the anterior to the posterior. In the anterior and posterior views, ellipsoidal outline, widest at mid height from venter. Prominent sexual dimorphism: in the lateral view, male carapace outline longer than female but female wider than male.

Remarks.—*Aurila hokkaidoensis* Mukai and Tanaka sp. nov. resembles *Aurila togakushiensis* Ozawa *et al.* (2008) from the Lower Pliocene Ogikubo Formation, Nagano Prefecture, central Japan in its lateral outline; however, it differs from the latter in having flat surface developing in anteroventral area, several rows of fossae, or fine pits running from anterior to posterior along the longitudinal direction, and a prominent caudal process with different carapace length and height. *Aurila hokkaidoensis* Mukai and Tanaka sp. nov. is similar to *Aurila shigaramiensis* Ozawa in Ozawa *et al.* (2008) from the Lower Pliocene Ogikubo Formation, central Japan, in carapace outline, however, the new species is distinguished from *A. shigaramiensis* by its different proportions of shell length and width, flat surface at anteroventral and posteroventral areas, several rows of fossae and/or fine pits running from the anterior to the posterior along the longitudinal direction with the small size of carapace. This new species has broader dorsal margins along the right and ventral margins. This new species is also similar in the carapace outline to *Aurila joushuensis* Tanaka, 2012 in Tanaka *et al.* (2012b) from the Upper Miocene Itahana Formation, Gunma Prefecture, central Japan. However, *A. hokkaidoensis* sp. nov. has a straight dorsal half of its posterior margin, an indistinct eye tubercle, and a pair of carinas in the ventral view.

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Author contributions

K. M. carried out fieldwork, collected ostracods and wrote the manuscript. G. T. checked the draft and taxonomy, and two authors contributed to the writing of the paper.