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Ostracoda and paleoenvironment of Holocene-raised beach sediment in Skarvsnes, East Antarctica

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Abstract. **Four sediment samples were collected from an outcrop of the Holocene-raised beach in Skarvsnes (Lützow-Holm Bay, East Antarctica) at an elevation of 0–10 m through a geomorphological survey conducted during the 46th Japanese Antarctic Research Expedition (JARE 46). These samples were used for grain size, CNS (carbon, nitrogen, and sulfur) elemental, and ostracod analyses. The ^{14}C dating of an annelid tube collected from the same outcrop was also conducted using an accelerator mass spectrometry. The resultant age was estimated at approximately 5,800 cal. year BP. A total of 16 ostracod species belonging to 10 genera were identified for the first time from all study samples near Lake Suribachi-Ike, Lützow–Holm Bay, East Antarctica. The phytal species were found to be the most dominant, suggesting rich seagrass and/or seaweeds at that time. Autecological methods and modern analog technique of ostracod assemblages were used to estimate the paleoenvironment. The result from the modern analog technique suggested that the paleo-water depth of approximately 30 m at that time is the most probable estimation, implying the glacial-isostatic uplift of approximately 30–40 m (5.1–6.8 mm/year) until sample date.**

Keywords: **East Antarctica, Holocene, ostracod, paleo-water depth, raised beach, Skarvsnes**

Introduction

The Antarctic ice sheet (AIS) is the largest ice sheet on Earth. Recent satellite observations have reported an acceleration of ice mass loss of the AIS (e.g. Williams *et al.*, 2014; Shepherd *et al.*, 2018; Rignot *et al.*, 2019). Thus, its sensitivity to global climate changes has been focused not only from the scientific perspective but also from the social perspective. In order to understand the sensitivity, the geological records of the AIS variability are important. Particularly, the reconstruction of the past AIS volume and the retreat processes of ice sheets along the Antarctic coastal areas since the Last Glacial Maximum (LGM) are expected to lead to the verification of the numerical models of the ice sheet dynamics and the understanding of the interaction between AIS and ocean (e.g. Miura, 2018; Suganuma *et al.*, 2020).

The relative sea level change along the Antarctic coast since the LGM reconstructed by geological records is one of the key factors useful in estimating the past changes in the AIS volume. Because the relative sea level in Antarctica is mainly controlled by the Earth's response to ice mass changes (glacial-isostatic adjustment; GIA) (e.g. Okuno, 2018), the relative sea level reconstruction can be used for the quantitative estimation of the changes in the AIS volume that occurred in the past.

The Syowa Station is located on the Ongul Islands along the Soya coast in Lützow-Holm Bay, East Antarctica (Figure 1). The Quaternary sediments and bedrock are exposed for approximately 120 km along the Soya coast. Several geomorphological and geological studies about the AIS fluctuations in this region during the Quaternary have been conducted (e.g. Yoshikawa and Toya, 1957; Hirakawa and Sawagaki, 1998; Miura *et al.*, 1998; Kawamata *et al.*, 2020a, b). Some of them have focused on the beach sediments containing fossil mollusks (*Laternula elliptica*), which indicate the step beach topography. Miura *et al.* (1998) claimed that this topography was formed by the relative sea level fall due to the crustal uplift caused by the release of the ice sheet load,

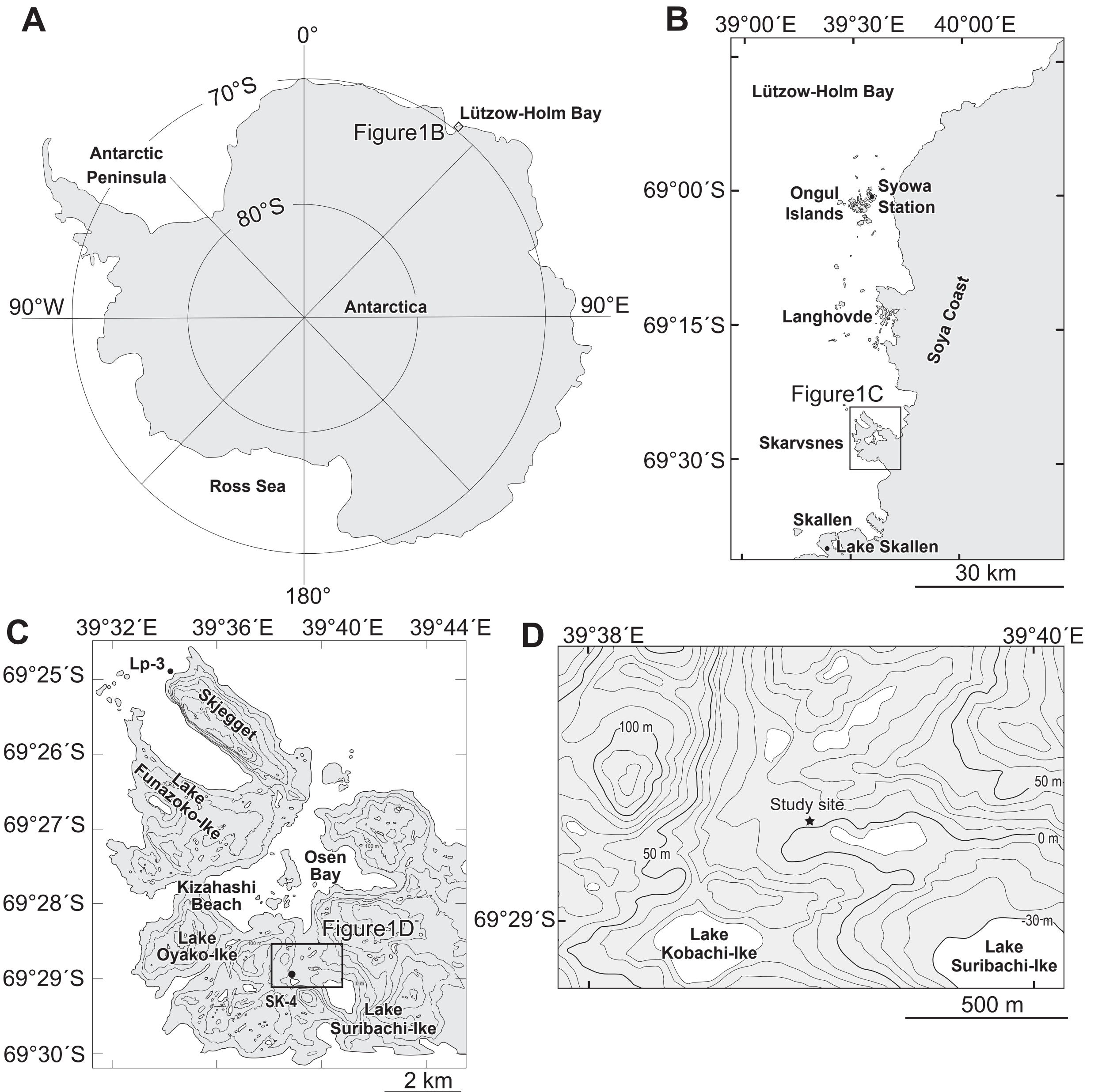


Figure 1. Location maps of the study area. **A, B,** and **C,** index maps of the study area. **D,** location map of the study site. A black star shows the sample site (69°28′49.8″S, 39°38′59.8″E). Each contour interval is 10 m. The base map is published by the Geospatial Information Authority of Japan.

indicating that they were raised beach sediments. The raised beach sediments are widely detected below an elevation of 20 m around the Soya coast, mainly consisting of Holocene marine deposits (Miura *et al*., 1998). Several studies on the ^{14}C dating of fossil mollusks in raised beach sediments have been conducted in Skarvsnes, at the eastern coast of Lützow-Holm Bay (Figure 1; Hirakawa and Sawagaki, 1998; Miura *et al*., 1998). These studies report that the depositional ages were estimated at 8,800 to 4,500 ^{14}C year BP and that the study area has risen by approximately 20 m since *ca.* 9 ka. Moreover, they reported that annelid tubes (*Serpula narconensis*) existed until approximately 4,500 ^{14}C year BP. However, this species has broad habitat ranges; thus, the detailed paleoenvironment remains unknown.

Ostracoda is a class of meiofaunal crustaceans and has

Figure 2. Overview photograph of the study site near Lake Suribachi-Ike, Skarvsnes.

two tiny calcified valves that are easily fossilized (Horne *et al.*, 2002). It lives in wide water areas from freshwater marsh to deep marine. It is one of the useful indicators (microfossils) to reconstruct paleoenvironments because several species are restricted to a particular environment, and several late Neogene species exist in modern times (Horne *et al.*, 2002; Tsukagoshi, 2017). Two papers have been published on modern benthic ostracods from the surface sediments around the Lützow-Holm Bay district (Hanai, 1961; Yasuhara *et al.*, 2007). However, there are no reports on ostracod assemblages from Holocene-raised beach sediments in this district.

Therefore, the present study aimed at reconstructing the depositional environment of marine sediments, especially at the paleo-water depth, in the raised beach along Lake Suribachi-Ike, Skarvsnes, Lützow-Holm Bay, based on grain size analysis, CNS (carbon, nitrogen, and sulfur) elemental analysis, and ostracod analysis.

Material and methods

Study site

The study site was situated at an outcrop near Lake Suribachi-Ike, Skarvsnes (69°28′49.8″S, 39°38′59.8″E) (Figure 1). The location of the study site was surveyed using a handheld Global Positioning System device (EMPEX Instruments, Inc., Pokenavi 65EX). The elevation of the site was estimated within 0–10 m with reference to a topographic map of the Geospatial Information Authority of Japan.

Yoshida (1983) and Miura *et al.* (1998) indicated that Skarvsnes is the largest ice-free area (approximately 63 km^2) with the highest peak Skjegget at 400 m above the sea level, in the Lützow-Holm Bay region. Skarvsnes protrudes westward into Lützow-Holm Bay from the continental ice sheet and is indented by several coves. The bedrock in this area is composed of garnet-biotite gneiss and porphyroblastic gneiss (Ishikawa *et al*., 1977). Raised beaches are developed in several places around the coves and hypersaline lakes, such as Lake Suribachi-Ike and Lake Funazoko-Ike, which are situated in deep glacial depressions below the present-day sea level (Figure 1C).

The studied outcrop was composed of dark-gray silt containing rich annelid tubes and a few mollusks (Figure 2), and it was excavated approximately 4 cm from the surface to collect samples.

Experimental analyses

A bulk sediment sample was collected from the outcrop. Four samples (Sr4tw01–Sr4tw04, in ascending order) were sliced at an interval of 1 cm from the study site. The samples were subjected to ^{14}C dating and to the analyses of the grain size, CNS elements, and ostracods.

The ^{14}C dating of an annelid tube from the Sr4tw03 sample was conducted using an accelerator mass spectrometer (AMS) method at the laboratory of Beta Analytic Inc. at JGI, Inc., Japan.

For grain size analysis, approximately 0.03 g of dried samples were soaked in 6% hydrogen peroxide for several days to remove the organic matter. After subjecting the samples to ultrasonic cleaning for several seconds, all the samples were analyzed using a laser diffraction particle size analyzer (SALD-3000S) at the Department of Geoscience, Interdisciplinary Faculty of Science and Engineering, Shimane University.

For CNS elemental analysis, approximately 3 g of the dried samples were powdered using an agate mortar and pestle, and approximately 9–11 mg of each powdered sample was placed in a thin Ag film cup and then weighed. Then, 1 M HCL was added several times to a sample in order to remove the carbonate fraction until the reaction ceased, followed by drying for 2 h. The dried samples were subsequently weighted and wrapped in a thin Sn film cup for combustion. The total organic carbon (TOC), total nitrogen (TN), and total sulfur (TS) contents were measured with the CHNS Elemental Analyzer at the Estuary Research Center, Shimane University using the FISON Organic Elemental Analyzer.

For the ostracod analysis, the samples were dried, measured, and then wet-sieved using a 250-mesh (opening: 63 μm) sieve, followed by drying in a 45 deg. oven. Under a binocular stereomicroscope, the ostracod specimens were obtained from the coarser sediment residues after dry sieving through a 115-mesh (opening: 125 μm) sieve. If >200 ostracod specimens were identified in a sample, a sample splitter was used to divide the sample. Each carapace was counted as two valves. Scanning electron micrographs of the uncoated specimens of the most important ostracod species were digitally imaged using the low-vacuum mode of the JEOL JCM-5000 Neoscope at the Department of Geoscience, Interdisciplinary Faculty of Science and Engineering, Shimane University.

Data analysis

The grain size indicators such as mean grain size, median grain size, and sorting index were calculated according to the equations suggested by Folk and Ward (1957).

The TOC/TN (C/N) ratio and TOC/TS (C/S) ratio were calculated to infer the origin of organic matter and paleoenvironment (Berner, 1982; Berner and Raiswell, 1984; Sampei *et al.*, 1997).

The modern analog technique (MAT) of the ostracod assemblages was used for the reconstruction of the paleoenvironment. This method employs a measure of faunal dissimilarity to compare the fossil samples to each reference sample in the modern oceanographic database. The squared chord distance (SCD) was used for a dissimilarity index (Overpeck *et al*., 1985), which was calculated using the following equation (computed as follows):

$$\mathrm{SCD} = \sum(p_{ik}^{1/2} - p_{ij}^{1/2})$$

Where, SCD indicates the dissimilarity coefficient value between the two ostracod samples i and j. p_{ik} and p_{jk} denote the proportion of kth ostracod species in samples i and j, respectively (Ikeya and Cronin, 1993). The SCD values range from 0.0 to 2.0, with 0.0 indicating identical proportions of species within the samples being compared. In this study, the modern thanatocoenosis data by Yasuhara *et al.* (2007) was used for the reference samples. Yasuhara *et al.* (2007) reported modern ostracods from 55 surface sediment samples collected from water depths of 10.4–870 m in Lützow-Holm Bay. A total of 31 samples containing >30 ostracod specimens studied by Yasuhara *et al.* (2007) were subjected to MAT in the present study. Several species of both *Paradoxostoma* and *Xestoleberis* were compiled at the genus level.

Results

Radiocarbon age

The conventional AMS ^{14}C age of 6,180 ± 30 year BP from an annelid tube fraction in the Sr4tw03 sample was calibrated by OxCal 4.4 (Bronk Ramsey, 2009; Reimer *et al*., 2013) using a ΔR of 720 years, leading to a total correction of 1120 years, as recommended for the region (Yoshida and Moriwaki, 1979). An error of ±100 years for the reservoir effect (Yoshida and Moriwaki, 1979) was also considered in the calendar age calculation. As a result, the age ranged from 5,598 to 6,086 cal. year BP (95.4%) (Figure 3, Table1), and the median age was 5,831 cal. year BP.

Grain size analysis

The mean grain size and the median grain size ranged from 6.79 to 7.29 φ and 6.91 to 7.29 φ, respectively. The sorting index ranged from 1.74 to 2.19 (Table 2).

CNS elemental analysis

The TOC, TN, and TS contents ranged from 0.85 to 1.30 wt%, 0.16 to 0.24 wt%, and 0.28 to 0.44 wt%, respectively. The C/N and C/S ratios ranged from 5.14 to 5.76 and 2.74 to 3.99, respectively.

Ostracod assemblages

A total of 16 species belonging to 10 genera of ostracods were identified in the four samples. All species were previously reported from the modern surface sediments

Table 1. Radiocarbon date of an annelid tube in the Sr4tw03 sample.

Code number	Conventional radiocarbon age	$\delta^{13}C$ (‰)	1σ calibrated age	2σ calibrated age
Beta-552160	6,180 ± 30 BP	+0.55	5,943 - 5,703 cal BP (68.2%)	6,086 - 5,598 cal BP (95.4%)

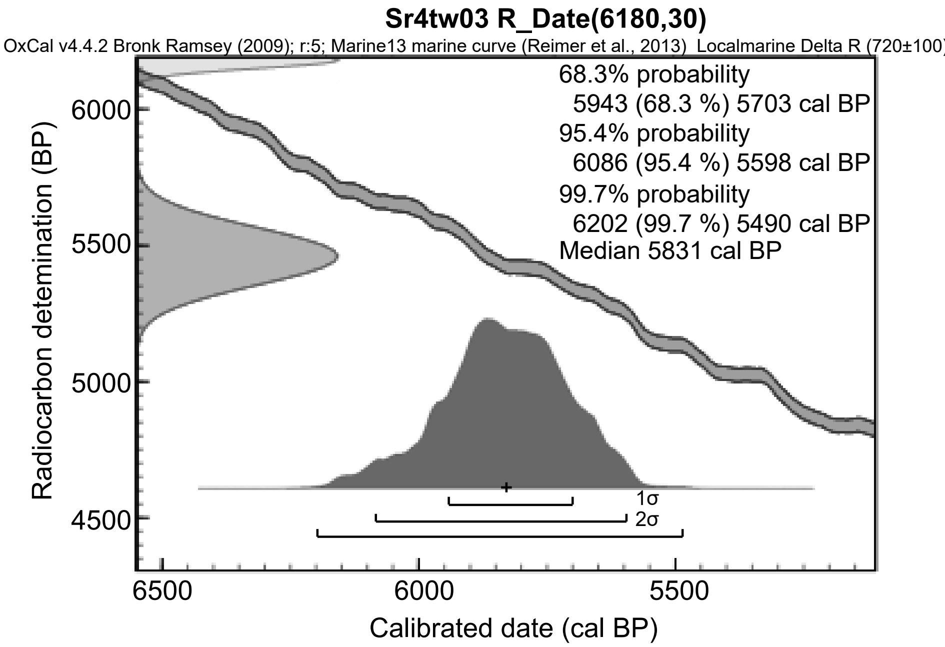


Figure 3. Radiocarbon date of an annelid tube in the Sr4tw03 sample.

Table 2. The results of grain analysis and CNS elemental analysis of the study samples collected near Lake Suribachi-Ike.

Sample	Sr4tw01	Sr4tw02	Sr4tw03	Sr4tw04
Nitrogen (wt%)	0.16	0.19	0.24	0.23
Carbon (wt%)	0.85	1.12	1.22	1.3
Sulphur (wt%)	0.28	0.28	0.44	0.35
C/N	5.39	5.76	5.14	5.54
C/S	3.08	3.99	2.74	3.73
Median grain size (φ)	7.29	6.96	6.91	7.1
Mean grain size (φ)	7.29	6.79	6.96	7.03
Coefficient of sorting	1.8	2.19	1.74	1.88

in Lützow-Holm Bay (Yasuhara *et al.*, 2007). Scanning electron micrographs of the selected ostracod species are presented in Figure 4. The ostracod assemblages from the samples were characterized by *Hemicytherura irregularis* (Müller, 1908), *Semicytherura costellata* (Brady, 1880), *Patagonacythere longiducta* (Skogsberg, 1928), *Paradoxostoma* spp., and *Xestoleberis* spp.

The valve number of ostracods per gram of the sediment sample indicated extremely high values in the samples Sr4tw01 to Sr4tw03, indicating 400–500 valves/g of the sample. However, the Sr4tw04 sample showed the lowest value of 133 valves/g of the sediment (Table 3). The MAT results revealed that the lowest SCD values in each sample ranged from 0.5 to 0.7 between the modern study samples and the reference samples reported by Yasuhara *et al*. (2007). Three samples Sr4tw01 to Sr4tw03 were correlated to the modern site at a water depth of 30.2 m (site Lp3, Yasuhara *et al*., 2007), but the Sr4tw04 sample was correlated to the modern site at a water depth of 91.0 m (site Dk9, Yasuhara *et al*., 2007) (Table 4).

Discussion

Paleoenvironment of the mid-Holocene

The TOC, TN, and TS contents of the sediments are known as useful proxies for the reconstruction of the depositional environment (e.g. Berner, 1982; Sampei *et al*.,

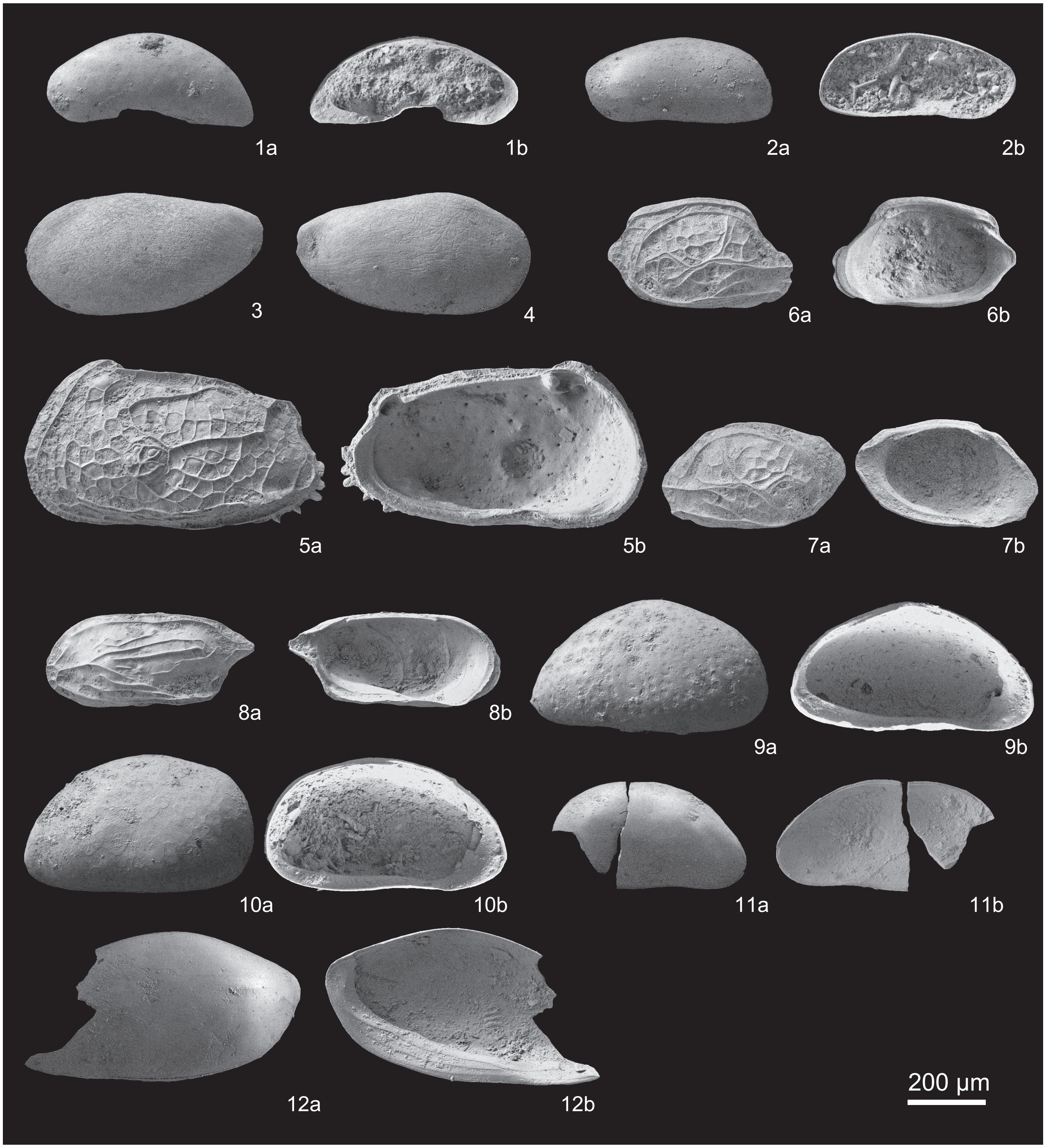


Figure 4. SEM photographs of main ostracod species. **1,** *Macrocyprina* sp., juvenile left valve, sample Sr4tw02, SMU-IC-F0001; a, left lateral view; b, internal view; **2,** *Argilloecia* sp., juvenile left valve, sample Sr4tw04, SMU-1C-F0002; a, left lateral view; b, internal view; **3, 4,** *Nealocythere antarctica* Schornikov, 1982, sample Sr4tw02; 3, left valve, SMU-IC-F0003; 4, right valve, SMU-IC-F0004; **5,** *Patagonacythere longiducta* (Skogsberg, 1928), female left valve, sample Sr4tw04, SMU-IC-F0005; a, left lateral view; b, internal view; **6, 7,** *Hemicytherura irregularis* (Müller, 1908), sample Sr4tw01; 6, adult right valve, SMU-IC-F0006; a, right lateral view; b, internal view; 7, adult left valve, SMU-IC-F0007; a, left lateral view; b, internal view; **8,** *Semicytherura costellata* (Brady, 1880), adult left valve, sample Sr4tw01, SMU-IC-F0008; a, left lateral view; b, internal view; **9,** *Xestoleberis* sp. 1, adult left valve, sample Sr4tw01, SMU-IC-F0009; a, left lateral view; b, internal view; **10,** *Xestoleberis* sp. 2, adult left valve, sample Sr4tw01, SMU-IC-F0010; a, left lateral view; b, internal view; **11,** *Paradoxostoma* sp. 1, broken juvenile right valve, sample Sr4tw02, SMU-IC-F0011; a, right lateral view; b, internal view; **12,** *Paradoxostoma* sp. 2, broken adult left valve, sample Sr4tw01, SMU-IC-F0012; a, left lateral view; b, internal view.

Table 3. Occurrence list of Holocene fossil ostracods from the study samples collected near Lake Suribachi-Ike.

	Sr4tw01	Sr4tw02	Sr4tw03	Sr4tw04
Argilloecia sp.	1		1	2
Cytheropteron abyssorum Brady, 1880				1
Hemicytherura irregularis (Müller, 1908)	21	12	26	7
Nealocythere antarctica Schornikov, 1982	4	10		
Macrocyprina sp.	4	3	4	
Microcythere sp.		1		
Paradoxostoma sp. 1	3	9	1	1
Paradoxostoma sp. 2	4	3	2	1
Paradoxostoma sp. 3	3	2	2	
Paradoxostoma sp. 4	1	3	2	
Paradoxostoma sp. 5	3		2	
Patagonacythere longiducta (Skogsberg, 1928)	10	9	4	28
Semicytherura costellata (Brady, 1880)	24	22	14	10
Xestoleberis sp. 1	67	55	52	14
Xestoleberis sp. 2	9	5	3	3
Xestoleberis sp. 3	1			
Total number of valves	155	134	113	67
Total number of species	14	12	12	9
Sample dry weight (g)	0.37	0.26	0.21	0.5
Individual number of ostracods 1-g sediment sample	420.98	510.23	530.83	133.02

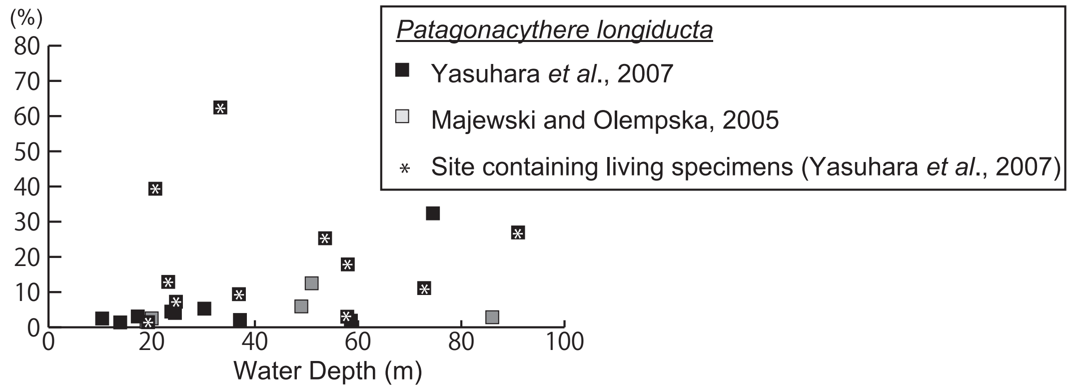
1997; Irizuki and Seto, 2004). TOC content is dependent mainly on the sedimentation rate and the organic matter loads. The C/N ratio is also useful for indicating the origin of organic matter: 6–9 for marine plankton and >15 for higher terrestrial plants. The C/S ratio has some utility for evaluating oxic or anoxic conditions in the brackish and marine environments: approximately 3 for normal marine and approximately 1 for brackish and the enclosed bay (Berner, 1982; Berner and Raiswell, 1984; Sampei *et al.*, 1997). The C/N ratio of all samples ranged from 5 to 6, suggesting that the organic matter originated mainly from the marine plankton. The C/S ratio indicated an approximate value of 3.0. Thus, the depositional environment was considered to be the oxic open marine condition. These observations suggested that the terrigenous organic matter input due to glacial erosion in the hinterland did not largely influence the study site. This data was supported by the ostracod data. Abundant phytal ostracods such as *Paradoxostoma* spp. and *Xestoleberis* spp. in the study samples reflected rich seaweeds and/or seagrasses near the study site at approximately 5,800 cal. year BP, which in turn indicated high water transparency. Based on the MAT results, the paleoenvironment of the present study site was considered to be similar to the modern environment of site Lp3 of Yasuhara *et al*. (2007). The site Lp3 is situated in the outer bay of Skjegget and at the entrance boundary of the oceanic water in Skarvsnes, where the open marine water always entered. Thus, it is suggested that the depositional environment at that time was a silt bottom under the oxic open marine condition with rich seaweeds or seagrasses near the study site. As the modern Osen Bay near the present study site is an enclosed bay with scarce ostracods, the paleoenvironment in the present study site at mid-Holocene was largely different from the modern environment.

Table 4. The squared chord distance (SCD) between the present study samples (Sr4tw01–Sr4tw04) and the modern samples of Yasuhara *et al.* (2007). Numerals in boldface show the least SCD.

Yasuhara *et al*. (2007)		Squared chord distance			
Modern sample site	Water depth (m)	Sr4tw01	Sr4tw02	Sr4tw03	Sr4tw04
To-1	58	1.21	1.2	1.32	1.05
To-3	33.3	1.3	1.32	1.4	0.74
To-8	77.5	2	2	2	1.95
Kuc-6	36.9	1.36	1.34	1.42	1.23
Kuc-11	24.5	1.81	1.79	1.84	1.69
Nuc-10	13	1.25	1.23	1.33	1.27
Nuc-13	14.5	1.21	1.19	1.3	1.23
Fc-5	53.6	0.77	0.81	0.85	0.6
Dk-3	23.8	1.59	1.6	1.62	1.5
Dk-6	17.3	1.87	1.88	1.88	1.72
Dk-9	91	0.73	0.75	0.82	**0.57**
Lp-3	30.2	**0.59**	**0.57**	**0.67**	0.75
Lp-5	72.8	0.92	0.87	1.02	0.86
Lp-7	57.9	1.62	1.62	1.66	1.5
Lp-8	19.3	0.91	0.84	0.98	1.04
Hm-2	37.1	1.12	1.13	1.14	1.2
Hm-6	23.2	0.76	0.69	0.84	0.85
Nk-1	20.7	1.28	1.26	1.39	0.83
Nk-3	75.5	1.77	1.78	1.77	1.83
Sk-4	24.7	1.79	1.79	1.84	1.58
Sk-11	88.7	2	1.96	2	2
Sk-19	174.3	2	1.92	2	2
Sk-21	225.3	1.79	1.72	1.79	1.79
Sk-22	254.6	1.86	1.83	1.86	1.86
Sd-4	54.3	2	2	2	1.96
Rd-2	10.4	1.54	1.5	1.59	1.49
Rd-3	13.9	1.63	1.59	1.67	1.63
Rd-6	58.6	1.93	1.93	1.95	1.77
Rd-9	74.5	1.58	1.59	1.64	1.14
5	495	2	2	2	2
6	620	2	2	2	2

Paleo-water depth and glacial-isostatic uplift at the study site

The paleo-water depth of the study site was estimated based on our results using the following two methods. The first method was based on the autecological information about each ostracod species. The dominant representative phytal genera such as *Hemicytherura*, *Paradoxostoma*, and *Xestoleberis* are inadequate to estimate the paleo-water depth based on their autecological information because their valves are easily transported from their habitats (on seaweeds or seagrasses) to the seafloor after their death. *Semicytherura costellata* lives on the *Corallina* turf in the intertidal pools (Hayward, 1981), which is also not a useful species. Moreover, the autecology of *Nealocythere antarctica* remains uncertain. On the other hand, the species living in or on substrates are good indicators of the paleo-water depth. Figure 5 depicts the water depth range of infaunal species observed in the present study. *Cytheropteron abyssorum* (Brady, 1880) and *Patagonacythere longiducta* are extremely important species to infer the paleo-water depth. *C. abyssorum* lives in the deepest areas in all species observed in this study. Several studies have reported *C. abyssorum* valves from the water depths of 1,910 m and 4,741 m (Brady, 1880; Chapmann, 1919), while others have reported its living specimens abundantly from the water depths of 50–100 m (Majewski and Olempska, 2005; Yasuhara *et al*., 2007). In addition, Yasuhara *et al.* (2007) reported a few dead specimens of *C. abyssorum* at a water depth of 17.3 m. As only one juvenile specimen was detected in the present study, the paleo-water depth was believed to be <*ca.* 50 m. On the other hand, *P. longiducta* occurred commonly in all the samples. Both adult and juvenile valves of this species were contained in each sample. Brouwers (1988) suggested that the adult to juvenile ratio provides an important method of determining whether a fossil assemblage has been transported or is in place. She proposed several standards for the adult to juvenile ratios; 1:8 (the ideal preservation of the living population), 1:3 to 1:5 (realized preservation of a life or near-life assemblage), 1:1 to 4:1 (a death assemblage in high-energy environment), and 1:2 to 1:5 (a death assemblage in low-energy environment). We examined the adult to juvenile ratio of *P. longiducta*. As a result, the number of adult and juvenile valves was 1 and 9 in the Sr4tw01 sample, 1 and 8 in the Sr4tw02 sample, 1 and 3 in the Sr4tw03 sample, and 12 and 15 in the Sr4tw04 sample, resepectively. Thus, the adult to juvenile ratio ranged from 1:1.25 to 1:9. This suggests that *P. longiducta* in this study was preserved around its habitats or in low-energy environment. Living specimens of this species were often reported widely from the shallow-water bottoms at water depths of 19–91 m in the Antarctic and subantarctic seas (e.g. Majewski



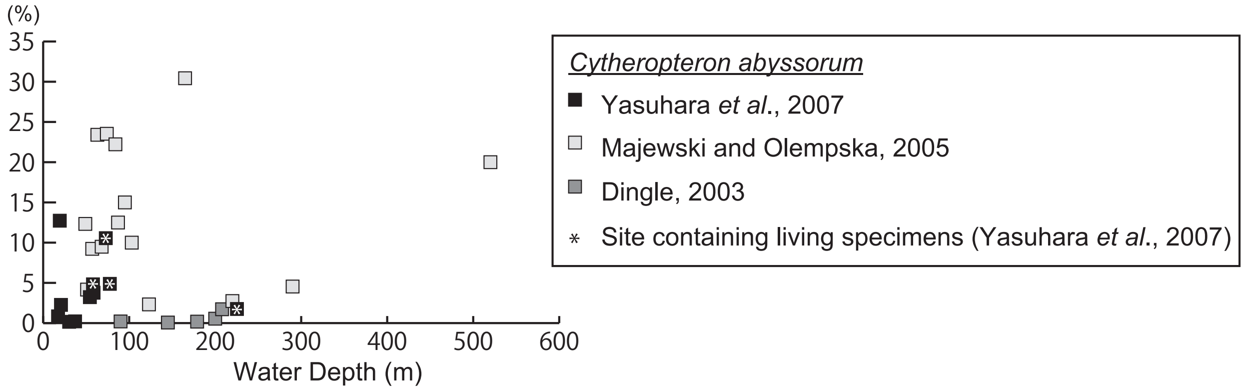


Figure 5. Graphs showing the relationships between water depth and percentages of *Patagonacythere longiducta* and *Cytheropteron abyssorum* based on the three previous papers (Dingle, 2003; Majewski and Olempska, 2005; Yasuhara *et al*., 2007). The sites with no specimens of these species are not shown in the graphs. * shows the sites containing living specimens (Yasuhara *et al*., 2007).

and Olempska, 2005; Yasuhara *et al*., 2007) (Figure 5). Thus, these results suggest that the study site was deposited on the upper sublittoral area.

The second method to estimate the paleo-water depth of the study site was MAT. The results of MAT in this study indicated that the ostracod assemblages from three of the four samples were most similar to those from the modern site at a water depth of 30.2 m (site Lp3, Yasuhara *et al*., 2007; Figure 1C). Only the Sr4tw04 sample was correlated to the modern site at a water depth of 91.0 m (site Dk9, Yasuhara *et al*., 2007), but this sample contained only 67 individuals, suggesting that the reliability of the MAT analysis is lower than the others. In this manner, as three of the four samples indicated the same result, and the paleo-water depth of the study site was estimated to be 30.2 m. This value falls in the range of the paleo-water depth estimation based on the autecological information, which ensures the reliability of the MAT result. Because the study site is now situated within the elevation of 0–10 m, the relative sea level was thought to be situated within the range of 30–40 m at approximately 5,800 cal. year BP.

Hirakawa and Sawagaki (1998) reconstructed the paleoenvironment around Lake Suribachi-Ike based on the ^{14}C ages of marine shells and annelid tubes, and the geomorphological and geological surveys. They estimated the relative sea level at 8,539–8,834 cal. year BP (2σ) (8,440 ± 140 ^{14}C BP by Hirakawa and Sawagaki, 1998) at approximately 26 m and also reported that marine water inundated around Lake Suribachi-Ike until 4,083–3,445 cal. year BP (2σ) (4,530 ± 70 ^{14}C BP by Hirakawa and Sawagaki, 1998), when the sea level had fallen below an elevation of approximately 20 m. Verleyen *et al.* (2017) estimated that the sea level was at least 32.7 m at 5,265–4,653 cal. year BP (2σ) (the median age: 4,913 cal. year BP) based on the ^{14}C age of a marine shell collected from raised beach sediment near the present study site (Loc. SK-4; Figure 1C). These two results seem to be generally concordant with our result. On the other hand, Verleyen *et al.* (2017) also reported that the paleoenvironment in Lake Kobachi-Ike changed from marine to lacustrine conditions at 2,314–2,502 cal. year BP (2σ) based on the analyses of diatom assemblages, the fossil pigments, and magnetic susceptibility of a sediment core from the lake. They assumed that the initiation of the dominance of the brackish-water diatoms, accompanied by the increase in a pigment exclusively produced by cyanobacteria and a decrease in magnetic susceptibility, is an indicator of the isolation of the lake. However, the marine diatoms continued to occur until the top of the core, suggesting that the input of freshwater was not sufficient to change the saline condition instantaneously. Therefore, we assume that Lake Kobachi-Ike possibly became semi-lacustrine at some time before 2,314–2,502 cal. year BP. Takano *et al*. (2012) also studied the paleoenvironment and glacial-isostatic uplift during the Holocene at Lake Skallen at Skallen (Figure 1B) and Lake Oyako-Ike at Skarvsnes (Figure 1C). They reconstructed the transition from marine to freshwater conditions in these lakes based on the analyses of diatom assemblages, biogenic silica, and geochemical data. The ages of the transition were estimated at 2,940 ± 100 cal. year BP for Lake Skallen and 1,060 ± 90 cal. year BP for Lake Oyako-Ike, respectively. They also calculated the mean crustal uplift rate with 3.2 mm/year based on the ages of marine–lacustrine transitions from the two lakes. Based on their model, the elevation of the relative sea level at 6,000 cal. year BP was estimated to be at 15.8 m. However, this relative sea level estimation at approximately 6 ka was based on the linear extrapolation of 25 km spatially separated geological records, which may explain the slightly lower value in comparison to our data.

The relative sea level change at the study area since the LGM can also be estimated by GIA models (Whitehouse *et al*., 2012; Argus *et al*., 2014). The relative sea level in Skarvsnes at approximately 6 ka was estimated at an elevation of approximately 11 m by the W12 model (Whitehouse *et al*., 2012) and 18 m by the ICE-6G model (Argus *et al*., 2014). Thus, these relative sea level estimations are not consistent with our result (within 30–40 m in the present study).

If no eustatic change occurred since approximately 5,800 cal. year BP, the present study suggests that the glacial-isostatic uplift can be estimated to be at 30–40 m, implying that the glacial-isostatic uplift rate ranges from 5.1 to 6.8 mm/year. This estimation is concordant with the average glacial-isostatic uplift rate by the geodetic Very Long Baseline Interferometry (VLBI) observations on 4 sites (Syowa Station, Hobart from Australia, HartRAO from South African Republic, and O'Higgins from Chile) from 1998 to 2006 (4.6 ± 2.2 mm/year), but larger than that based on the GPS (2.3 ± 0.3 mm/year) (Kaminuma, 2008).

Not much modern ostracod data has been obtained to date from <20 m in the water depth around the study site. In particular, no modern ostracod data from <10 m in water depth are available. In addition, the lowest SCD value was 0.57 in the present MAT results, suggesting a limitation in the reliability of the paleo-water depth estimation in this study. Therefore, further modern ostracod observations are warranted to reinforce our findings in the future.

Systematic paleontology

We briefly discuss the 12 species below, adding the following measurements. L: carapace length (mm), H: carapace height (mm). The specimens illustrated in this study are deposited in Shimane University Museum, Japan.

Class Ostracoda Latreille, 1802
Subclass Podocopa Sars, 1866
Order Podocopida Sars, 1866
Suborder Cypridocopina Jones, 1901
Superfamily Macrocypridoidea Müller, 1912
Family Macrocyprididae Müller, 1912
Genus ***Macrocyprina*** Triebel, 1960
Macrocyprina sp.

Figure 4.1a, b

Materials.—11 specimens.
Measurements.—SMU-IC-F0001 (juvenile left valve; Figure 4.1a, b), L = 0.5294 mm, H = 0.2395 mm.
Remarks.—Specimens in this study were juvenile or broken adult valves. Based on the valve morphology, they are possibly assigned to *Macrocyprina* based on valve outline.
Occurrence.—Sr4tw01, Sr4tw03 in this study.

Superfamily Pontocypridoidea Müller, 1894
Family Pontocyprididae Müller, 1894
Genus ***Argilloecia*** Sars, 1866
Argilloecia sp.

Figure 4.2a, b

Materials.—4 specimens
Measurements.—SMU-IC-F0002 (juvenile left valve; Figure 4.2a, b), L = 0.4810 mm, H = 0.2204 mm.
Remarks.—Four specimens in this study were only juvenile valves. Although the muscle scars could not be recognized, we tentatively assigned them to the genus *Argilloecia* based on valve outline. This species is very similar to *Argilloecia antarctica* Hartmann, 1986 and *Argilloecia* sp. of Whatley *et al.* (1998a), in the general outline shape. *A. antarctica* has a rounder posterior margin than *Argilloecia* sp. of this study. *Argilloecia* sp. of Whatley *et al.* (1998a) has rounder anterior and posterior margins than *Argilloecia* sp. of this study.
Occurrence.—Sr4tw01 and Sr4tw03 in this study.

Suborder Cytherocopina Baird, 1850
Superfamily Cytheroidea Baird 1850

Family Bythocytheridae Sars, 1866
Genus ***Nealocythere*** Schornikov, 1982
Nealocythere antarctica Schornikov, 1982

Figure 4.3, 4.4

Nealocythere antarctica Schornikov, 1982, p. 5–8, figs. 1.1–1.17, figs. 2.1–2.9; Hartmann, 1986, p. 168, 169, p. 203, Abb. 54, p. 204, Abb. 53, 54, p. 220, Tafel V, figs. 2–4; Hartmann, 1989, p. 286, Tafel XIII, figs. 7–9; Hartmann, 1990, p. 208, p. 236, Abb. 64, p. 244, Tafel VI, figs. 52–58; Yasuhara *et al*., 2007, p. 487, pl. 4, fig. 13.

Materials.—14 specimens.

Measurements.—SMU-IC-F0003 (juvenile left valve; Figure 4.3), L = 0.6108, H = 0.3145.

Remarks.—Type specimens (Schornikov, 1982) and specimens in Hartmann (1986, 1989, 1990) have only weak striae extending from anterior to posterior part on the valve surface, whereas specimens in Yasuhara *et al.* (2007) have distinct ones. All specimens in this study were only juvenile valves and the complicated fine striae were found on the valve surface.

Occurrence.—Antarctic Peninsula (Schornikov, 1982; Hartmann, 1986, 1989, 1990); Soya Coast (Yasuhara *et al*., 2007); Sr4tw01 and Sr4tw02 in this study.

Family Hemicytheridae Puri, 1953
Genus ***Patagonacythere*** Hartmann, 1962
Patagonacythere longiducta (Skogsberg, 1928)

Figure 4.5a, b

Cythereis (*Procythereis*) *longiductus* Skogsberg, 1928, p. 145, pl. 1, fig. 8; text-fig. 12

Patagonacythere longiducta antarctica Benson, 1964, p. 30, pl. 2, figs. 7–9; text-figs. 21, 22; Gou and Li, 1985, p. 87, pl. III, figs. 1–2.

Patagonacythere longiducta (Müller, 1908). Hartmann, 1988, p. 162, Tafel I, figs. 3, 4.

Patagonacythere longiducta (Skogsberg). Hartmann, 1987, p.154, Tafel III, figs. 40–42, p.155, Tafel IV, figs. 43–51; Hartmann, 1989, p. 281, Tafel VIII, figs. 1, 2, 3b; Hartmann, 1990, p. 240, Tafel II, figs. 16–18, p. 241, Tafel III, figs. 19–22; Hartmann, 1991, p. 220, Tafel I, figs. 1, 2.

Ambostracon (*Patagonacythere*) *longiductus* (Skogsberg). Whatley *et al*., 1998b, p. 127, pl. 4, figs. 5–7.

Materials.—51 specimens.

Measurements.—SMU-IC-F0005 (female left valve; Figure 4.5a, b), L = 0.7727 mm, H = 0.4352 mm.

Remarks.—The specimens in this study are more similar to *Patagonacythere longiducta antarctica* Benson, 1964 than the type specimen of *Patagonacythere longiducta* (Skogsberg, 1928) in having less robust reticulation and absence of a vertical ridge joining the posterodorsal ridge and posteroventral ridge, but the posterodorsal ridge pattern of the present study specimens is more similar to the type specimen than *P. longiducta antarctica*. Thus, there seem to be several morphological variations in *P. longiducta*. As Brandão and Karanovic (2021) did not accept the use of *Patagonacythere longiducta antarctica*, i.e., synomymised name of *P. longiducta,* we also followed this opinion. This species is also similar to *Australicythere devexa* (Müller, 1908) and *Australicythere polylyca* (Müller, 1908) in the general outline. *P. longiducta* develops distinct ridges parallel to anterior marginal rim but *A. devexa* has some short transverse ridges in anterior part. *A. polylyca* is larger than *P. longiducta* and has a different reticulation pattern.

Occurrence.—Antarctic Peninsula, Scotia Sea (Whatley *et al*., 1998b); Admiralty Bay (Majewski and Olempska, 2005); Bransfield Strait (Hartmann, 1988); Ross Sea (Benson, 1964); South Georgia (Skogsberg, 1928); East Antarctic, Soya Coast (Yasuhara *et al*., 2007); all the samples in this study.

Family Cytheruridae Müller, 1894
Genus ***Hemicytherura*** Elofson, 1941
Hemicytherura irregularis (Müller, 1908)

Figures 4, 6a, b, 7a, b

Cytheropteron irregulare Müller, 1908, p. 109, pl. 18, figs. 2, 3, 8.

Hemicytherura irregularis (Müller). Neale, 1967, p. 22, pl. 2, figs. d, e, g, j; Briggs, 1978, p. 28, figs. 2, 17; Whatley *et al*., 1988, p. 193, pl. 1, figs. 5, 6; Hartmann, 1989, p. 243, Abb. 19–24, p. 282, Tafel IX, figs. 6–9; Hartmann, 1990 p. 242, Tafel IV, figs. 38, 39; Hartmann, 1992, p. 418; Hartmann, 1993, p. 230; Whatley *et al*., 1998b, p. 125, pl. 3, figs. 17, 18; Majewski and Olempska, 2005, p. 29, Fig. 8.6, 8.7.

Materials.—66 specimens.

Measurements.—SMU-IC-F0006 (adult right valve; Figure 4.6a, b), L = 0.4727 mm, H = 0.2809 mm.

Remarks.—The specimens in this study are the same as the type speciments (Müller, 1908) in valve shape and ornamentation. This species is similar to *Hemicytherura splendifera* (Whatley *et al*., 1988) and *H. anomala* (Müller, 1908) in the general outline and size of the carapace. However, it differs from these species with having a different ornamentation pattern on the valve surface. *H. irregularis* has weaker or delicate ornamentation than *H. splendifera. H. anomala* is characterized by a straight ridge extending from anterior to posterior parts but *H. irregularis* has a sinuate ridge extending from anterior to posterior parts.

Occurrence.—Antarctic Peninsula, Scotia Sea (Hartmann, 1989, 1990, 1992, 1993; Whatley *et al*., 1998b); Admiralty Bay (Majewski and Olempska, 2005); East Antarctic, Soya Coast (Yasuhara *et al*., 2007), all the samples in this study.

Genus ***Semicytherura*** Wagner, 1957
Species ***Semicytherura costellata*** (Brady, 1880)

Figure 4.8a, b

Cytherura costellata Brady, 1880, p. 134, pl. 32, fig. 7a–d; text-fig. 10; Chapmann, 1916, p. 51, pl. 6, fig. 7.
Semicytherura costellata (Brady). Briggs, 1978, p. 28, fig. 2.21; Gou and Li, 1985, p. 83, pl. IV, figs. 9, 10; Hartmann, 1992, p. 418; Dingle, 2003, p. 139, pl. 3, fig. 4; Majewski and Olempska, 2005, p. 29, Fig. 8.2.
Semicytherura cf. *costellata* (Brady). Hartmann, 1989, p. 242, Abb. 15–18, p. 282, Tafel V, fig. 5; Hartmann, 1990, p. 242, Tafel IV, 36, 37; Hartmann, 1993, p. 230; Dingle, 2000, p. 490, Fig. 5.G; Yasuhara *et al*., 2007, p. 492.
Semicytherura aff. *costellata* (Brady). Benson, 1964, p. 17, pl. 2, figs. 3, 5, 6.

Materials.—70 specimens.

Measurements.—SMU-IC-F0008 (adult left valve; Figure 4.8a, b), L = 0.3771 mm, H = 0.2432 mm.

Remarks.—The specimens in this study are the same as the type specimens (Brady, 1880) in valve shape and ornamentation. This species is close to *Semicytherura notalis* (Müller, 1908) in general outline and ornamentation but differs from the latter in having a slightly different ornamentation pattern and more concave outline in the posteroventral part. The species is similar to *Semicytherura clavata* (Brady, 1880), and *Semicytherura closteria* (Whatley *et al*., 1988) in ornamentation but differs from these species in having more prominent ridges on the valve surface and a different outline in the posterior margin.

Occurrence.—Admiralty Bay (Majewski and Olempska, 2005); Marion Island (Dingle, 2003); Ross Sea (Benson, 1964; Briggs, 1978); Victoria Land Basin (Dingle, 2000); South Indian Ocean (Brady, 1880); East Antarctic, Soya Coast (Yasuhara *et al*., 2007); all the samples in this study.

Family Xestoleberididae Sars, 1928
Genus ***Xestoleberis*** Sars, 1866
Xestoleberis sp. 1

Figure 4.9a, b

Materials.—188 specimens.

Measurements.—SMU-IC-F0009 (adult left valve; Figure 4.9a, b), L = 0.6114 mm, H = 0.3500 mm.

Remarks.—This species is similar to *Xestoleberis* sp. 4 of Yasuhara *et al*., 2007 but differs from the latter in having larger pores. *Xestolebeirs* sp. 1 is similar to *X. meridionalis* (Müller, 1908) in general outline and in having large pores on the valve surface but the outline of *X. meridionalis* is more elongate than that of *Xestoleberis* sp. 1.

Occurrence.—All the samples in this study.

Xestoleberis sp. 2

Figure 4.10a, b

Materials.—20 specimens.

Measurements.—SMU-IC-F0010 (adult left valve; Figure 4.10a, b), L = 0.5876 mm, H = 0.3555 mm.

Remarks.—This species differs from *Xestoleberis* sp. 1 in having a more inflated posterior valve shape. The species is similar to *Xestoleberis umbonata* (Whatley *et al*., 1998a) but differs from the latter species in having a more elongate carapace.

Occurrence.—All the samples in this study.

Family Paradoxostomatidae Brady and Norman, 1889
Genus ***Paradoxostoma*** Fischer, 1855
Paradoxostoma sp. 1

Figure 4.11a, b

Material.—14 specimens.

Measurements.—SMU-IC-F0011 (broken juvenile right valve; Figure 4.11a, b), L = 0.4983 mm, H = 0.2752 mm.

Remarks.—This species is very similar to *Paradoxostoma antarcticum* (Müller, 1908) but the latter is more slender in valve shape, and its dorsal margin is triangle in shape.

Occurrence.—All the samples in this study.

Paradoxostoma sp. 2

Figure 4.12a, b

Materials.—7 specimens.

Measurements.—SMU-IC-F0012 (broken adult left valve; Figure 4.12a, b), L = 0.7077 mm, H = 0.3849 mm.

Remarks.—This species is similar to the species belonging to *Sclerochilus* in valve shape but the former has four adductor muscle scars in the inner part of valves. This species is similar to *Paradoxostoma kerguelense* (Müller, 1908) in general outline but the latter species has many pores on the valve surface and several striae on the slightly depressed anteroventral part.

Occurrence.—Sr4tw01 and Sr4tw03 in this study.

Conclusions

1. A total of 16 ostracod species belonging to 10 genera were reported for the first time in 4 samples from the raised beach along Lake Suribachi-Ike, Lützow-Holm Bay, East Antarctica.
2. The autecological method and MAT of the ostracod assemblages indicated that the paleoenvironment at approximately 5,800 cal. year BP was a silt bottom under oxic open marine condition with rich seaweeds

or seagrasses and estimated a water depth of approximately 30 m based on the MAT results.

3. The estimated paleo-water depth implies that the study area glacial-isostatically uplifted 30–40 m since approximately 5,800 cal. year BP. Although the relative sea level estimated in this study cannot be fully explained with reference to the current GIA models, it is concordant with the ^{14}C ages of the marine shells collected from raised beach sediments near the present study site.

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Author contributions

S. S. conceived the original idea and contributed all aspects of the research. T. I. contributed the ostracod taxonomy. K. S. performed the sampling, and the CNS analysis. Y. S. enhanced the discussion of the Antarctic environment. All authors contributed to the writing of the paper.