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LATE QUATERNARY EAST ANTARCTIC MELTING EVENT IN THE SÔYA COAST REGION BASED ON STRATIGRAPHY AND OXYGEN ISOTOPIC RATIO OF FOSSIL MOLLUSCS

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Abstract· TAMS ^{14}C ages of *in situ* fossil molluscs (*Laternula elliptica*) from marine beds of raised beaches in the Sôya Coast region, East Antarctica, are divided into two groups late Pleistocene (30–46 ka) in older marine beds and Holocene (3–7 ka) in younger beds The δ^{18}O (PDB) values of 24 fossils in the older marine beds on East Ongul Island and the northern part of Langhovde ranged from about 2 9 to 4 2‰, and those of 27 fossils in the younger beds from about 3 9 to 4 6‰, the variation of the former is wider than that of the latter Relatively lower values of the oxygen isotopic ratio in the Pleistocene fossil compared to the Holocene analogues suggest that relatively more ^{18}O-depleted meltwater was supplied to the sea during the last interstadial than Postglacial age along the northern part of the Sôya Coast Some fluvial sediments associated with the meltwater can often be observed under the Holocene marine beds or over the older marine beds The δ^{18}O values of fossils in the upper part of the older beds are higher than those in the lower part on East Ongul Island On the other hand, the time-series variation of oxygen isotopic ratio during the Holocene shells (since 7 ka) does not show such a tendency These facts lead us to the following conclusions (1) the EAIS had possibly retreated from the northern Sôya Coast prior to the LGM, (2) there was more meltwater along the northern part of Sôya Coast during the last interstadial (30–46 ka) than in the Postglacial age, (3) a relatively strong fluvial process probably caused by the ice melting event might have occurred in the Lutzow-Holm Bay region around 30–46 ka

key words oxygen isotopic ratio, fossil mollusc, East Antarctic Ice Sheet, ice melting event, Late Quaternary

1. Introduction

The melting history of the Antarctic ice-sheet during the Late Quaternary is a significant problem which has a bearing upon global sea-level changes and climatic changes through the formation of bottom and intermediate water Such history can be detected using the oxygen isotopic composition of epipelagic organisms This is because Antarctic ice is depleted by about 30–60‰ in δ^{18}O compared to standard mean ocean water (*e.g.*, LORIUS *et al.*, 1979, 1985, JOHNSEN *et al.*, 1972), and a huge influx of melt water must have a greater effect on epipelagic organism isotopic composition than sea-water temperature variation, especially in the cold Antarctic sea, though the isotopic ratio of organisms is a function of both water temperature and isotopic composition of surrounding water.

In the Sôya Coast region, many molluscan shells have been collected from raised beach deposits, and their radiocarbon ages can be divided into two groups: post glacial and older than 20000 yBP (Fig. 1; MEGURO *et al.*, 1964, YOSHIDA, 1970, 1973, 1983; OMOTO, 1977; FUJIWARA, 1973; MORIWAKI, 1974; NOGAMI, 1977; YOSHIDA and MORIWAKI, 1979; HAYASHI and YOSHIDA, 1994) The occurrence of older fossils is restricted to the Ongul Islands and the northernmost part of Langhovde.

Using the TAMS (Tandetron Accelerator Mass Spectrometry) ^{14}C dating method, IGARASHI *et al.* (1995) showed that (1) shells are clearly classified into two groups: the younger group is 3–8 ka and the older one is 33–42 ka without the $\delta^{13}C$ and reservoir corrections; and that (2) the expansion of the ice sheet margin during the Last Glacial Maximum (LGM) was slight, on the basis of the occurrence and distribution of older fossils.

MAEMOKU *et al.* (1997) and MIURA *et al.* (1999) revealed that beach deposits in the northern part of Langhovde are clearly divided stratigraphically into two marine sediment layers including *in situ* fossil shells of *Laternula elliptica*, and that the TAMS ^{14}C ages of fossil shells of the upper layer ranged from 4 to 5 ka without a reservoir correction, while those from the lower layer ranged from 32 to 46 ka. The marine layers and *in situ* fossil shells were not disturbed by ice sheet loading or scouring. They concluded that (1) two transgressions would have occurred in the last interstadial around 40 ka and Holocene around 5 ka, (2) fluvial process before 5 ka were more active than those at present, and (3) the East Antarctic Ice Sheet (EAIS) had retreated from the northernmost Sôya Coast prior to LGM, and did not re-advance after that. However, there are no studies of the oxygen isotopic composition of molluscs indicating the melting of ice.

In the present paper, on the basis of the difference of isotopic ratios between *in situ* younger and older shell groups and their chrono-stratigraphy and distribution in the Sôya Coast region, we estimate the melting history of Antarctic ice during the Late Quaternary.

2. Stratigraphy of Research Sites and Molluscan Samples

On the northern part of the Sôya Coast facing Lutzow-Holm Bay (Fig. 1), several small raised beaches are distributed on ice-free rocks. Research sites were selected on East Ongul Island, Langhovde and Skarvsnes, where the deposits and micro-relief of raised beaches are especially well developed. Five long and four short trenches were excavated on these beaches, and sections were described in detail, and the more than 70 *in situ* fossil shells of *Laternula elliptica* were sampled from December 1996 to February 1997. Altitude was measured with auto-leveling equipment and a staff, referring to sea-level observed at each site without tidal correction. Then, sixty two samples were measured by TAMS ^{14}C measurement at Lawrence Livermore National Laboratory (California, USA) through Beta Analytic Inc. (Florida, USA). All ^{14}C ages were

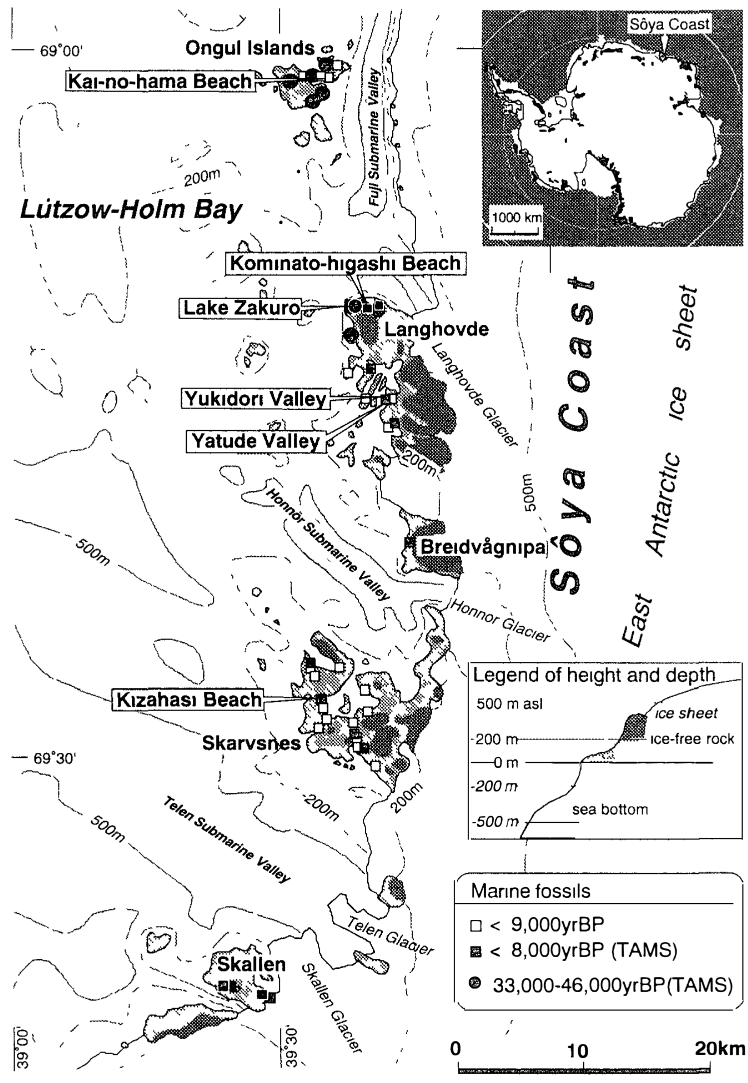

Fig 1 Localities and classified ^{14}C-dates of marine fossils sampled from raised beaches along the northern part of the Sôya Coast Data sources are Appendix 3 in Hayashi *and* Yoshida *(1994),* Igarashi et al *(1995) and this study Contour line of 200 m and 500 m on land are quoted from topographic map on a scale of 1 250000 (Lutzow-Holm Bay) published by the Geographical Survey Institute, Japan Isobaths of 500 m and 200 m are quoted from* Moriwaki *and* Yoshida *(1990)*

reexamined by δ^{13}C correction for the isotopic fractionation effect on ^{14}C/^{13}C ratio. However, we treat ^{14}C ages without a reservoir correction, which involves subtracting about 1300 years for Holocene marine organisms in the Antarctic region (Berkman and Forman, 1996), because the correction for Pleistocene ages is not known at present

2.1. Kai-no-hama Beach on East Ongul Island

The Ongul Islands are located in the northeasternmost part of Lutzow-Holm Bay, 5 km from the margin of the continental ice sheet, separated by the deep Fuji Submarine Valley under Ongul Strait (Fig 1). Raised beaches are found generally below the level of 20 m a.s.l A trench (960206-1, Fig 2) was excavated at altitudes between 2 0 m and

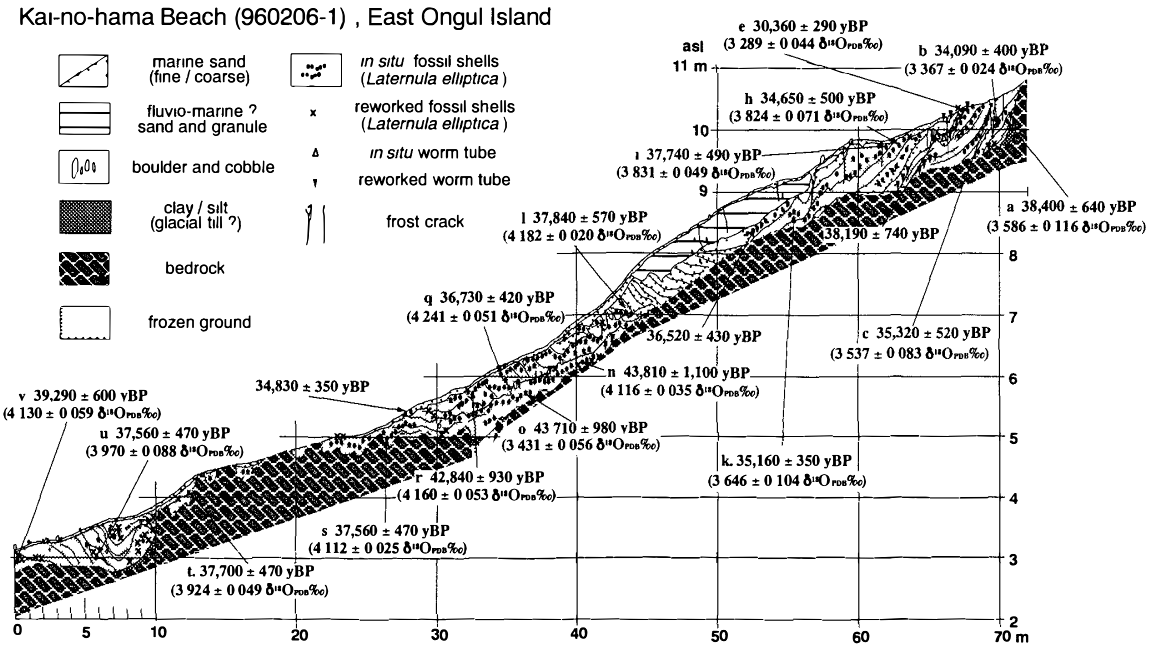

Fig 2 Profile of the trench (960206-1) at Kai-no-hama Beach, East Ongul Island The location is shown in Fig 1. Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratios ($\delta^{18}O_{PDB}$‰) of in situ fossil shells. Lower case letters prior to radiocarbon dating ages correspond to the lower case letters with sample numbers (960206-1) in Table 1.

10.9 m, 73 m in length, 1.0 m in width at Kai-no-hama Beach. This revealed that the beach deposits are clearly divided into several marine layers including *in situ* fossil shells of *Laternula elliptica* and a reworked layer of shell fragments and worm tubes. Most of the sediment layers are mainly composed of well-sorted fine to medium-grained sand with granules. The lower layers show the transgression onlap facies, while the upper layers show the deltaic regression offlap facies. The radiocarbon ages of all fossils in the layers show late Pleistocene ages, ranging from 30360±290 yBP to 43810±1100 yBP. Marine layers and *in situ* fossil shells were not disturbed by ice sheet loading or scouring.

2.2. Kominato-higashi Beach and the saddle between Kominato and Lake Zakuro in the northern part of Langhovde

Langhovde is located 20 to 30 km south of the Ongul Islands, and is bounded on the east by the Langhovde Glacier, which drains continental ice northward (Fig. 1). A deep glacial trough divides this area into two parts, the northern and southern Langhovde areas (YOSHIKAWA and TOYA, 1957).

In the northern part of Langhovde, raised beaches occur around Ko-minato Inlet, about 5 km from the margin of the present ice sheet Kominato-higashi Beach is characterized by several topographic steps with abundant fossil shells in sediments for the present shoreline up to 12 m a.s.l. Two long trenches were excavated at this site: they were named the East trench (E-trench) and the West trench (W-trench) The

E-trench (951227-1) was excavated at altitudes between 4.0 m and 9.6 m. The W-trench (951220-1) was excavated 60 m seaward of the E-trench, with altitudes ranging from 0 8 m to 5.1 m Sketches of the north walls of the E- and W-trenches are shown in Figs. 3 and 4. The detailed stratigraphy of the trenches was described in MAEMOKU

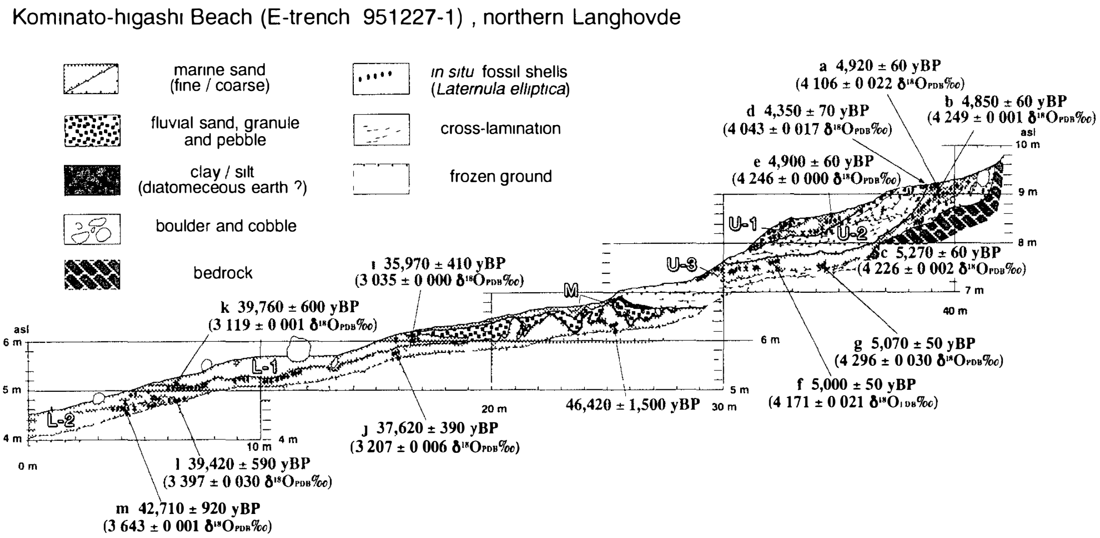

Fig 3 Profile of the East-trench (E) (951227-1) on Kominato-higashi Beach, northern Langhovde The location is shown in Fig 1 Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratios ($\delta^{18}O_{PDB}$‰) of in situ fossil shells Lower case letters prior to radiocarbon dating ages correspond to the lower case letters with sample numbers (951227-1) in Table 1

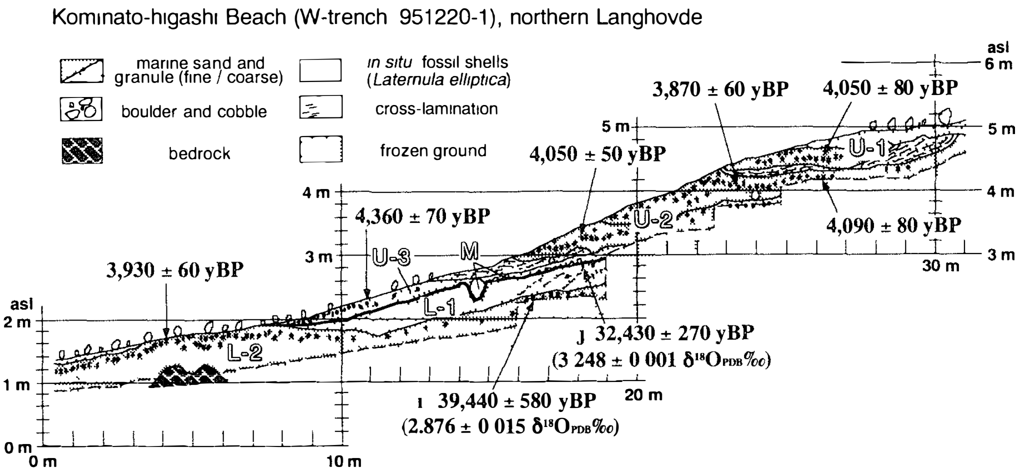

Fig 4 Profile of the West-trench (W) (951220-1) on Kominato-higashi Beach, northern Langhovde The location is shown in Fig 1 Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratio ($\delta^{18}O_{PDB}$‰) of in situ fossil shells Lower case letters prior to radiocarbon dating ages corresponded to the lower case letters with sample numbers (951220-1) in Table 1

et al. (1997) and MIURA *et al.* (1999). The marine deposits are largely divided into two sediment layers (U and L in Figs. 3 and 4), which are separated by a fluvial sand and gravel layer (M in Figs. 3 and 4). The marine sediment layers are composed of well-sorted fine to medium-grained sand with granules or pebble size gravel, and yield abundant fossil shells (*Laternula elliptica*) buried in living positions. Radiocarbon ages of the fossil shells collected from the upper layer ranged from 5270±60 yBP to 4050±80 yBP, and those from the lower layer ranged from 46420±1500 yBP to 32430±270 yBP. The Holocene upper layer is interbedded with deltaic sediments including reworked shell fragments. Both marine layers and *in situ* fossil shells were not disturbed by ice sheet loading or scouring.

Hyper-saline Lake Zakuro (Fig. 1) is about 9 m below the present sea level and surrounded by raised beaches whose maximum altitude is about 12 m a.s.l. to the west of Lake Zakuro. Since the lowest saddle between this lake and Ko-minato Inlet stands at 6 m a.s.l. and is covered with marine deposits including fossil shells, this lake had been part of the sea. A short trench (951223-2) was excavated at the saddle (Fig. 5). It was 1 m in length, 1 m wide and 1 m in depth. The sediment layer was subdivided into four layers which are composed of well-sorted fine- to medium-grained sand with granules and yielded abundant fossil shells composed of *Laternula elliptica* buried in their living positions (*in situ*). All radiocarbon ages of the upper three layers were Holocene (from 3910±40 yBP to 3690±40 yBP), while the lower one was 46120±1000 yBP (951223-2e).

2.3. *The mouths of Yatude and Yukidori Valleys in the southern part of Langhovde*

Raised beaches around the mouths of Yatude and Yukidori Valleys (Fig. 1) are found mostly below the height of 20 m a s l. and fluvioglacial deposits are developed along the lower reaches of the Valleys. The well-marked dissected marine terraces

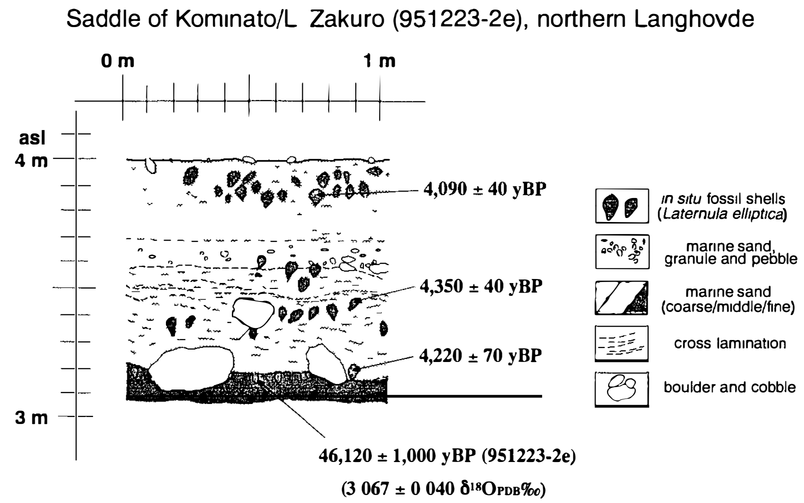

Fig 5 Profile of the trench at the saddle between Kominato and Lake Zakuro (951223-2e), northern Langhovde The location is shown in Fig 1 Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratios ($\delta^{18}O_{PDB}$‰) of in situ fossil shells

reach 18 m a s.l. on the right bank and 11 m a.s l on the left bank at the mouth of the Yatude Valley A schematic profile of Yatude Valley is shown in Fig 6 The lower part of deposits about 5 m in thickness on the right bank terrace is composed of very coarse gravel with boulders larger than 2 m, which have been transported by large quantities of meltwater However, the upper part about 1.5 m thick is mainly composed of well-sorted fine to medium-grained sand with granules, with *in situ* fossils of *Laternula elliptica*, which covered fluvioglacial deposits A small trench was excavated on each terrace. The radiocarbon age of the fossil shell collected from the right bank terrace was 6810±60 yBP (960108-5a), and that from the left bank terrace was 5070± 60 yBP. The radiocarbon age of *in situ* fossils of *Laternula elliptica* on the terrace surface (10.0 m a s l) of Yukidori Valley was 4280±90 yBP (960107-1a).

A long trench (960106-1), interrupted by a basement rock, was also excavated on a raised beach at the mouth of Yatude Valley, as shown in Fig 6. The lower trench was at altitudes between 1.8 m and 3 7 m, and the upper trench was at altitudes between 4 9 m and 5 5 m The deposits are clearly divided into several marine layers including

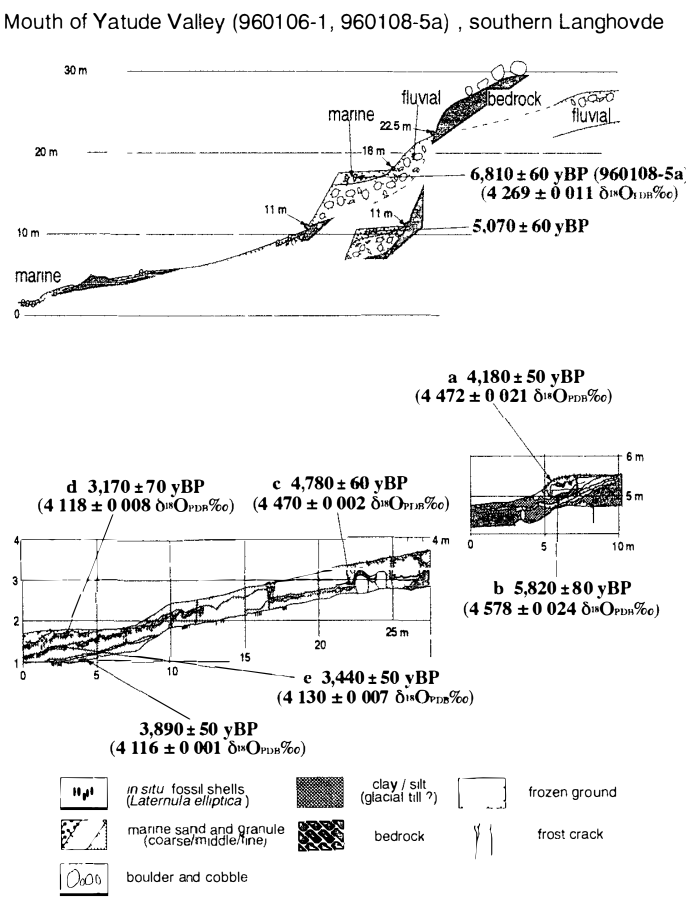

Fig 6 Profile of the terrace (960108-5a) and trench (960106-1) at the mouth of Yatude Valley, southern Langhovde The location is shown in Fig 1 Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratios ($\delta^{18}O_{PDB}$‰) of in situ fossil shells Lower case letters prior to radiocarbon dating ages corresponded to the lower case letters with sample numbers (960106-1) in Table 1

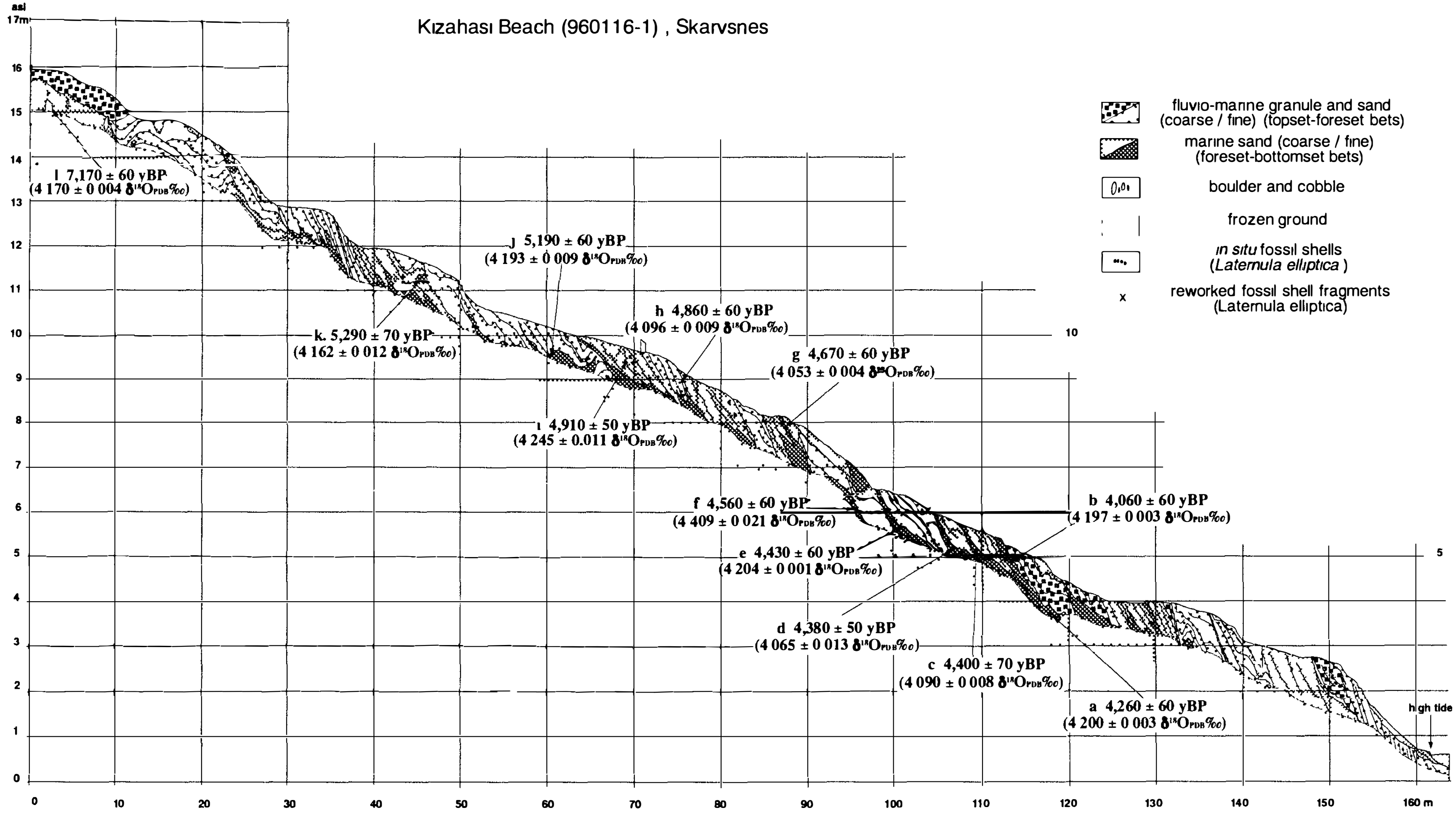

Fig 7 Profile of the trench (960116-1) at Kızahası Beach, Skarvsnes The location is shown in Fig 1 Figures with arrows indicate AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect, and oxygen isotopic ratio ($\delta^{18}O_{PDB}$‰) of in situ fossil shells. Lower case letters prior to radiocarbon dating ages corresponded to the lower case letters with sample numbers (960116-1) in Table 1

in situ fossil shells of *Laternula elliptica* The radiocarbon ages of the fossil shells collected from the upper trench were 5820±80 yBP and 4180±50 yBP, and those from the lower trench ranged from 4780±60 yBP to 3170±70 yBP during the Holocene

2.4. *Kizahasi Beach in Skarvsnes*

Skarvsnes, the largest ice-free oasis in the Lutzow-Holm Bay region, with an area of 63 km^2 (Fig 1), which projects northwestward from the ice sheet Raised beaches develop in many places along the present shoreline A marked stepped topography is well developed as raised beaches at Kizahasi Beach, where seventeen steps can be distinguished below the level of 18 m a.s l Each step is rather small and low, ranging from 20 to 100 cm in relative height, and extends along the present strandline Comparatively conspicuous steps are recognized at 11–12 m a.s l. A long trench (960116-1) was excavated at Kizahasi Beach (Fig. 7) It was at altitudes between 0 3 m and 17 0 m. The deposits composed of well-sorted fine to medium-grained sand show a series of small deltaic structures. The ends of topset beds of deltaic structures usually correspond to the upper edges of each topographic step Twelve *in situ* fossil shells of *Laternula elliptica* occur in the foreset or the bottomset beds of the deltaic sediments Their radiocarbon ages ranged from 7170±60 yBP to 4260±60 yBP during the Holocene

3. Analytical Procedure of Oxygen Isotopic Ratio and Result

Fifty one smashed bulk samples of the *in situ* fossil *Laternula elliptica* were analyzed for oxygen isotopic components The isotopic measurement followed the procedure by WADA *et al.* (1984) The carbonate tests were reacted in saturated pyrophosphoric acid at 60 00°C, and the resulting CO_2 gas was analyzed with the Delta-S mass spectrometer of Shimane University and the MAT-250 mass spectrometer of Shizuoka University. The value thus obtained was converted into a value against a PDB standard by using NBS 20. The analysis is accurate to within ±0 05‰ The obtained results are shown in Table 1 and Figs. 2 to 7.

The oxygen isotopic ratios and radiocarbon ages of molluscs (Fig 8), and their relevance to stratigraphy, and distribution are summarized as follows.

1) The values of the $\delta^{18}O$ (PDB) for the younger shells ranged from about 3 9 to 4 6‰, on the other hand, the values for the older shells ranged from about 2.9 to 4.2‰.

2) The variation of oxygen isotopic ratios of 30–46 ka shells in Kominato-higashi Beach, the saddle between Kominato and Lake Zakuro and Kai-no-hama Beach are relatively larger than those of Holocene shells (since 7 ka)

3) The time-series variations of oxygen isotopic ratio of Holocene shells (since 7 ka) seem to have no tendency

4) In the last interstadial sediments, the variation of oxygen isotopic ratio of Kai-no-hama Beach is larger than that of the northern part of Langhovde, and the $\delta^{18}O$ (PDB) values of the lower marine layers of Kai-no-hama Beach tend to be relatively higher than those of the upper layers

Table 1 TAM radiocarbon ages and oxygen isotopic ratio of in situ fossil shells (Laternula elliptica) obtained from raised beach in the Sôya Coast region.

Region Locality	Samples No	Altitude (m asl)	^{14}C age (yBP) without correction [a]	$\delta^{13}C$ (‰) [b]	^{14}C age (yBP) with $\delta^{13}C$ correction [c]	Code for radiocarbon measurement [d]	$\delta^{18}O_{PDB}$ (‰)	Lab of Univ for $\delta^{18}O$ measurement
East Ongul								
Kai-no-hama Beach	960206-1a	10 2	37,980 ± 640	+0 8	38,400 ± 640	Beta-100322	3 586 ± 0 116	Shizuoka
	960206-1b	10 1	33,670 ± 400	+0 3	34,090 ± 400	Beta-100323	3 367 ± 0 024	Shizuoka
	960206-1c	10 3	34,900 ± 520	+0 3	35,320 ± 520	Beta-100324	3 537 ± 0 083	Shizuoka
	960206-1e	10 1	29,940 ± 290	+0 4	30,360 ± 290	Beta-100325	3 289 ± 0 044	Shizuoka
	960206-1h	9 6	34,210 ± 500	+1 4	34,650 ± 500	Beta-100327	3 824 ± 0 071	Shizuoka
	960206-1i	9 6	37,320 ± 490	+1 4	37,740 ± 490	Beta-100328	3 831 ± 0 049	Shizuoka
	960206-1k	8 6	34,720 ± 350	+1 7	35,160 ± 350	Beta-100330	3 646 ± 0 104	Shizuoka
	960206-1l	6 9	37,400 ± 570	+1 8	37,840 ± 570	Beta-100331	4 182 ± 0 020	Shizuoka
	960206-1n	6 2	43,380 ± 1,100	+1 1	43,810 ± 1,100	Beta-100332	4 166 ± 0 035	Shizuoka
	960206-1o	5 8	43,280 ± 980	+1 0	43,710 ± 980	Beta-100333	3 431 ± 0 056	Shizuoka
	960206-1q	6 0	36,290 ± 420	+1 3	36,730 ± 420	Beta-100334	4 241 ± 0 051	Shizuoka
	960206-1r	6 6	42,400 ± 930	+1 8	42,840 ± 930	Beta-100335	4 160 ± 0 053	Shizuoka
	960206-1s	4 9	37,140 ± 470	+0 2	37,560 ± 470	Beta-100336	4 112 ± 0 025	Shizuoka
	960206-1t	4 4	37,270 ± 470	+1 1	37,700 ± 470	Beta-100337	3 924 ± 0 049	Shizuoka
	960206-1u	3 1	37,120 ± 470	+1 7	37,560 ± 470	Beta-100338	3 970 ± 0 083	Shizuoka
	960206-1v	3 0	38,850 ± 600	+1 6	39,290 ± 600	Beta-100339	4 130 ± 0 059	Shizuoka
Langhovde, North								
Kominato E-trench	951227-1a	10 2	4,480 ± 60	+1 4	4,920 ± 60	Beta-94669	4 106 ± 0 022	Shimane
	951227-1b	10 1	4,440 ± 60	0 0	4,850 ± 60	Beta-94670	4 249 ± 0 001	Shimane
	951227-1c	10 2	4,850 ± 60	+0 8	5,270 ± 60	Beta-94671	4 226 ± 0 002	Shimane
	951227-1d	10 1	3,920 ± 70	+1 1	4,350 ± 70	Beta-94672	4 043 ± 0 017	Shimane
	951227-1e	10 1	4,460 ± 60	+1 7	4,900 ± 60	Beta-94673	4 246 ± 0 000	Shimane
	951227-1f	10 0	4,580 ± 50	+0 7	5,000 ± 50	Beta-94674	4 171 ± 0 021	Shimane
	951227-1g	9 8	4,650 ± 50	+0 7	5,070 ± 50	Beta-109395	4 296 ± 0 030	Shimane
	951227-1i	9 6	35,550 ± 410	+0 1	35,970 ± 410	Beta-94675	3 065 ± 0 000	Shimane
	951227-1j	8 5	37,200 ± 390	+0 3	37,620 ± 390	Beta-109396	3 207 ± 0 006	Shimane
	951227-1k	8 6	39,330 ± 600	+0 9	39,760 ± 600	Beta-94676	3 119 ± 0 001	Shimane
	951227-1l	6 8	39,000 ± 590	+0 5	39,420 ± 590	Beta-109397	3 397 ± 0 030	Shimane
	951227-1m	6 5	42,310 ± 920	+1 0	42,710 ± 920	Beta-94677	3 643 ± 0 001	Shimane
Kominato W-trench	951220-1i	2 2	39,020 ± 580	+0 7	39,440 ± 580	Beta-100345	2 876 ± 0 015	Shizuoka
	951220-1j	2 8	32,010 ± 270	+0 1	32,430 ± 270	Beta-100346	3 248 ± 0 001	Shimane
Kominato/L Zakuro								
	951223-2e	3 2	45,680 ± 1,000	+1 7	46,120 ± 1,000	Beta-94668	3 067 ± 0 040	Shizuoka
Langhovde, South								
Yatude terrace	960108-5a	17 0	6,390 ± 60	+0 2	6,810 ± 60	Beta-94685	4 269 ± 0 011	Shimane
Yatude Valley	960106-1a	5 4	3,750 ± 50	+1 2	4,180 ± 50	Beta-94678	4 472 ± 0 021	Shimane
	960106-1b	5 0	5,390 ± 80	+1 2	5,820 ± 80	Beta-94679	4 578 ± 0 024	Shimane
	960106-1c	2 7	4,360 ± 60	+0 6	4,780 ± 60	Beta-94680	4 470 ± 0 002	Shimane
	960106-1d	1 1	2,750 ± 70	+0 5	3,170 ± 70	Beta-94681	4 118 ± 0 008	Shimane
	960106-1e	1 2	3,020 ± 50	+0 8	3,440 ± 50	Beta-94682	4 130 ± 0 007	Shimane
	960106-1f	1 0	3,460 ± 50	+1 0	3,890 ± 50	Beta-94683	4 116 ± 0 001	Shimane
Yukidori Valley	960107-1a	10 0	3,870 ± 90	+0 7	4,280 ± 90	Beta-109400	3 903 ± 0 001	Shimane
Skarvsnes								
Kizahasi Beach	960116-1a	3 7	3,840 ± 60	+0 4	4,260 ± 60	Beta-94687	4 200 ± 0 003	Shimane
	960116-1b	4 8	3,660 ± 60	-0 4	4,060 ± 60	Beta-94688	4 179 ± 0 003	Shimane
	960116-1c	5 4	3,980 ± 60	+0 6	4,400 ± 70	Beta-94689	4 090 ± 0 003	Shimane
	960116-1d	5 5	3,970 ± 50	-0 1	4,380 ± 50	Beta-94690	4 065 ± 0 013	Shimane
	960116-1e	6 0	4,020 ± 60	-0 1	4,430 ± 60	Beta-94691	4 204 ± 0 001	Shimane
	960116-1f	5 9	4,140 ± 60	+0 1	4,560 ± 60	Beta-94692	4 409 ± 0 021	Shimane
	960116-1g	8 0	4,520 ± 60	+0 4	4,670 ± 60	Beta-94693	4 053 ± 0 004	Shimane
	960116-1h	8 7	4,440 ± 60	+0 5	4,860 ± 60	Beta-94694	4 096 ± 0 009	Shimane
	960116-1i	9 8	4,520 ± 50	-1 2	4,910 ± 50	Beta-94695	4 245 ± 0 011	Shimane
	960116-1j	9 8	4,790 ± 60	-0 5	5,190 ± 60	Beta-94696	4 193 ± 0 009	Shimane
	960116-1k	12 3	4,880 ± 70	-0 2	5,290 ± 70	Beta-94697	4 162 ± 0 012	Shimane
	960116-1l	16 0	6,750 ± 60	+0 4	7,170 ± 60	Beta-94698	4 170 ± 0 004	Shimane

[a] Conventional laboratory-reported ^{14}C ages ± 1σ, based on the Libby half-life of 5,568 years, with reference to 1950

[b] $\delta^{13}C=[\{(^{13}C/^{12}C)_{sample}-(^{13}C/^{12}C)_{PDB}\}/(^{13}C/^{12}C)_{PDB}]\times 1000$, where $(^{13}C/^{12}C)_{PDB}$ = 0 0112372

[c] Calculated from Conventional laboratory-reported ^{14}C ages and $\delta^{13}C$ value

[d] Lawrence Livermore National Laboratory (California, USA)

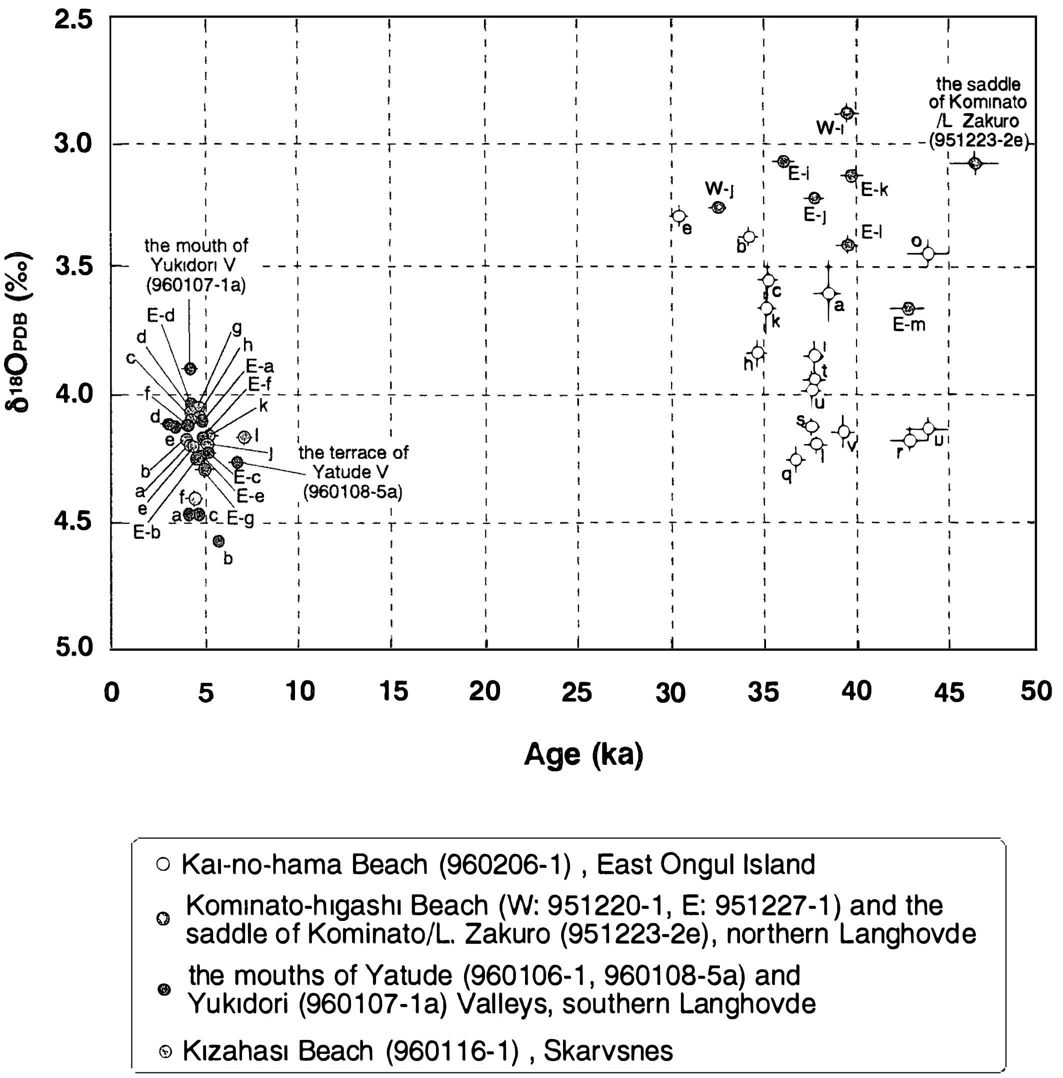

Fig 8 Oxygen isotopic ratio ($\delta^{18}O_{PDB}$‰) of in situ fossil shells obtained from raised beach deposits in the Sôya Coast region, plotted against AMS radiocarbon dating ages (^{14}C yBP) calibrated by $\delta^{13}C$ corrections but not corrected for the reservoir effect Each letter corresponds to the sample numbers in the trenches

4. Discussion

4 1 The cause of difference of oxygen isotopic ratio between the Holocene and 30–46 ka

Laternula elliptica is a predominantly shallow-water species which lived in depths from 1 to 500 m, but mostly less than 100 m and probably commonest shallower than 20 m (DELL, 1990, AHN, 1994) The oxygen isotopic ratio of a mollusc is generally a function of both surface sea-water temperature and isotopic composition of the surrounding surface water. Although we cannot easily determine which factor is more important, the melt water from the Antarctic ice with very low $\delta^{18}O$ values would have affected the isotopic ratio more than sea-water temperature. As shown in Fig 8, the difference of oxygen isotopic ratio between the Holocene and 30–46 ka is about 0 5–1 5 degree ‰. If we estimate the surface water temperature difference by a transfer function (*e.g.*, EPSTEIN *et al.,* 1953), sea-water temperature during 30–46 ka was relatively 2–6°C higher than in the Holocene. This estimation cannot be accepted, since the sea-water temperature of the Antarctic Ocean in high-latitude has probably remained cold throughout the Late Quaternary period. Therefore, we can consider that the difference in oxygen isotopic ratio between the Holocene and 30–46 ka was mostly caused by the ^{18}O-depleted meltwater from the Antarctic ice.

4.2. The relation between the fluvial sediments and the oxygen isotopic ratio

Although we can find sediments related to fluvial processes in the ice-free area in the Sôya Coast region, the ages and the origin of these sediments cannot be determined exactly yet.

At Kai-no-hama Beach on East Ongul Island, part of the upper layers shows a deltaic fluvial facies including coarse sand and granules with lamination and reworked shell fragments as shown in Fig. 2. The formation age is after 36 ka based on the ^{14}C dating ages.

At Kominato-higashi Beach in the northern part of Langhovde, a fluvial sediment layer is intercalated by the two marine sediment layers (Figs. 3 and 4). The fluvial sediments appear to have been deposited under a stronger fluvial process than present meltwater activity, because the present meltwater does not transport boulder gravels in the area (MAEMOKU *et al,* 1997; MIURA *et al.,* 1999). The age of the fluvial deposits can be estimated to be between 5 ka and 36 ka on the basis of ^{14}C ages of fossils in marine sediments as shown in Figs. 3 and 4.

Furthermore, at the mouth of Yatude Valley in the southern part of Langhovde, although the age of the fluvial deposit underlying the marine terrace deposit (Fig. 6) on the right bank is unknown, it certainly occurred before 6.8 ka based on the radiocarbon age (960108-5a). The level of this terrace surface (18 m a.s.l.) must be associated with the Postglacial highest sea level. If these fluvial deposits were also formed during the Holocene transgression (about 7 ka), the oxygen isotopic ratio in the mouth of Yatude Valley would have been affected by the low δ^{18}O fluvioglacial meltwater. However, as shown in Fig. 8, the variation of oxygen isotopic ratio is small, and the values are similar to those for Holocene shells in northern Langhovde and Kizahasi Beach of Skarvsnes. This fact suggests that the fluvial deposits were formed prior to about 7 ka.

Considering the low context of oxygen isotopic ratio in the upper marine bed of the Kai-no-hama Beach and in the older marine bed of Kominato-higashi Beach, this fluvial process was probably due to ice melting from EAIS around 30–46 ka. The production of much meltwater may have continued until after the interstadial transgression, so it eroded the older marine sediment and deposited several coarse sand and large gravels in the northern Sôya Coast region.

4.3. Late Quaternary East Antarctic ice melting event around the Lützow-Holm Bay region

The extremely fragile shells of *Laternula elliptica* dated in the last interstadial and the Holocene remaining in *in situ* form indicate that they have never been disturbed by ice sheet loading or scouring since that time. This fact indicates that the EAIS had retreated from the northern part of Langhovde, probably the northern Sôya Coast, prior to the LGM (IGARASHI *et al.*, 1995). Furthermore, the relatively lower oxygen isotopic ratio and the occurrence of fluvial sediments around 30–46 ka suggest that a huge quantity of ice melting may have occurred around the interstadial transgression.

The variation of oxygen isotopic ratio of 30–46 ka shells on Kai-no-hama Beach is larger than that in the northern part of Langhovde. In addition, on Kai-no-hama Beach, the oxygen isotopic values in the lower part of the marine layers, which show the onlap facies, are lower than those of the upper layers, which show the offlap facies This difference might be interpreted to be caused by the difference of the distance from the ice sheet margin between the Ongul Islands and the northern part of Langhovde Namely, in the northern part of Langhovde close to the ice-sheet margin, the ice meltwater might have immediately affected the surface water, in the Ongul Islands separated from ice-sheet margin by the Fuji Valley deeper than 500 m, the effect of ^{18}O-depleted meltwater on the shallow sea-water surronding the Ongul Islands might have been weak in the early half of the interstadial transgression In contrast, since a significant oxygen isotopic change has not been found during the Holocene in the study area, a huge ice melting event affecting on the surface water did not occur during the Postglacial age after 7 ka.

LINSLEY (1996) considered that there was less continental ice during isotope stage 3 (23000 to 58000 years ago) than in the SPECMAP record (IMBRIE *et al.*, 1984), using the Sula Sea oxygen-isotope record. We also propose that considerable melting of the EAIS during 30–46 ka, more than in the Holocene should be taken into account at least in this region

5. Conclusions

The Sôya Coast in the Lutzow-Holm Bay region is located in the margin of the Antarctic ice sheet, where ^{18}O-depleted water from melting ice in deglacial events affected organisms living in shallow-water. The relative difference in the oxygen isotopic composition of the *in situ* fossil *Laternula elliptica* between the Holocene high stand sea-level period and the last interstadial, and their stratigraphy, and the distribution of the raised beach deposits, have revealed the Late Quaternary Antarctic melting history to be as follows: (1) The EAIS had possibly retreated from the northern Sôya Coast prior to the last interstadial, and it did not re-advance over the last interstadial marine sediments even during the LGM. The EAIS probably had advanced before the last interstadial stage, (2) The relatively lower δ^{18}O values of the shells during 30–46 ka, lower than those of 3–7 ka, suggest that there was more meltwater on the northern part of Sôya Coast during the last interstadial than in the Postglacial age. (3) The fluvial process caused by ice sheet melting would have been more active around 30–46 ka than in the Holocene (after 7 ka).

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References

AHN, I.-Y. (1994): Ecology of the Antarctic bivalve *Laternula elliptica* (King and Broderip) in Collins Harbor, King George Island: Benthic environment and an adaptive strategy. Mem. Natl Inst. Polar Res., Spec. Issue, **50**, 1–10.

BERKMAN, P.A. and FORMAN, S.L. (1996): Pre-bomb radiocarbon and reservoir correction for calcareous marine species in the Southern Ocean. Geophys. Res. Lett., **23**, 363–366.

DELL, R.K. (1990): Antarctic Mollusca-with special reference to the fauna of the Ross Sea. R. Soc. N.Z., Bull., **27**, 331 p.

EPSTEIN, S., BUCHSBAUM, R., LOWENSTAM, H.A. and UREY, H.C. (1953): Revised carbonate-water isotopic temperature scale. Bull. Geol. Soc. Am., **64**, 1315–1326.

FUJIWARA, K. (1973): The landforms of the Mizukumi Zawa near Syowa Station, East Antarctica. Nankyoku Shiryô (Antarct. Rec.), **46**, 44–66 (in Japanese with English abstract).

HAYASHI, M. and YOSHIDA, Y. (1994): Holocene raised beaches in the Lutzow-Holm Bay region, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **50**, 49–84.

IGARASHI, A., HARADA, N. and MORIWAKI, K. (1995): Marine fossils of 30–40 ka in raised beach deposits, and late Pleistocene glacial history around Lutzow-Holm Bay, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **8**, 219–229.

IMBRIE, J., HAYS, J.D., MARTINSON, D.G., MCINTYRE, A., MCINTYRE, A., MIX, A.C., MORLEY, J.J., PISIAS, N.G., PRELL, W. and SCHAKLETON, N.J. (1984): The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record. Milankovitch and Climate, Part I, ed. by A. BERGER *et al.* Hingham, D. Reidel, 269–305.

JOHNSEN, S.J., DANSGAARD, W., CLAUSEN, H.B. and LANGWAY, C.C., Jr. (1972): Oxygen isotopes profiles through the Antarctic and Greenland ice sheets. Nature, **235**, 429–434.

LINSLEY, B.K. (1996): Oxygen-isotope record of sea level and climate variations in the Sula Sea over the past 150,000 years. Nature, **380**, 234–237.

LORIUS, C., MERLIVAT, L., JOUZEL, J. and POURCHET, M. (1979): A 30,000-year isotope climatic record from Antarctic ice. Nature, **280**, 644–648.

LORIUS, C., JOUZEL, J., RITZ, C., MERLIVAT, L., BARKOV, N.I., KOROTKEVICH, Y.S. and KOTLYAKOV, V.M. (1985): A 150,000-year climatic record from Antarctic ice. Nature, **316**, 591–596.

MAEMOKU, H., MIURA, H., SAIGUSA, S. and MORIWAKI, K. (1997): Stratigraphy of the late Quaternary raised beach deposits in the northern part of Langhovde, Lutzow-Holm Bay, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **10**, 178–186.

MEGURO, H., YOSHIDA, Y., UCHIO, T., KIGOSHI, K. and SUGAWARA, K. (1964): Quaternary marine sediments and their geological dates with reference to the geomorphology of Kronprins Olav Kyst. Antarctic Geology, ed. by R.J. ADIE. Amsterdam, North-Holland, 73–80.

MIURA, H., MORIWAKI, K., MAEMOKU, H. and HIRAKAWA, K. (1999): Fluctuations of the East Antarctic ice sheet margin since the last glaciation from the stratigraphy of raised beach deposits along the Sôya Coast. Ann. Glaciol., **27** (in press).

MORIWAKI, K. (1974): Radiocarbon datings of fossil shells on raised beaches on the east coast of Lutzow-Holm Bay, East Antarctica. Nankyoku Shiryô (Antarct. Rec.), **48**, 82–90 (in Japanese with English abstract).

MORIWAKI, K. and YOSHIDA, Y. (1990): Bathymetric chart of Lutzow-Holmbukta, Antarctica. Special Map Series of National Institute of Polar Research, Sheet 4. Tokyo, Natl Inst. Polar Res.

NOGAMI, M. (1977): On the raised beaches along the Prince Olav Coast, East Antarctica. Nihon Dai-Yon-Ki Gakkai Yôshishû, **6**, 10 (in Japanese).

OMOTO, K (1977) Geomorphic development of the Sôya Coast, East Antarctica—Chronological interpretation of raised beaches based on levelings and radiocarbon datings Sci Rep Tohoku Univ, 7th Ser, **28**, 101–116

WADA, H, FUJII, N and NIITSUMA, N (1984) Analytical method of stable isotope for ultra-small amounts of carbon dioxide with MAT 250 mass-spectrometer Geosci Rep Shizuoka Univ, **10**, 103–112

YOSHIDA, Y (1970) Raised beaches and saline lakes on the Prince Olav Coast, East Antarctica Gendai no Chirigaku Tokyo, Kokon Shoin, 93–118 (in Japanese)

YOSHIDA, Y (1973) Geomorphology of the ice-free areas and fluctuation of the ice sheet Nankyoku, ed by K KUSUNOKI *et al* Tokyo, Kyoritsu Shuppan, 237–281 (in Japanese)

YOSHIDA, Y (1983) Physiography of the Prince Olav and Prince Harald Coasts, East Antarctica Mem Natl Inst Polar Res, Ser C (Earth Sci), **13**, 83 p

YOSHIDA, Y and MORIWAKI, K (1979) Some consideration on elevated coastal features and their dates around Syowa Station, Antarctica Mem Natl Inst Polar Res, Spec Issue, **13**, 220–226

YOSHIKAWA, T and TOYA, H (1957) Report on geomorphological results of the Japanese Antarctic Research Expedition, 1956–57 Nankyoku Shiryô (Antarct Rec), **1**, 1–13

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