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Changes in molluscan assemblages and sediment type in the outer shelf of the Japan Sea since 13,000 years BP

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Abstract. No previous studies have investigated changes in the offshore molluscan assemblages of the Japan Sea during the last deglacial period. We examined the sedimentary facies and the stratigraphic distribution of molluscs in cored sediments collected at 132 m water depth off Sado Island, Japan. The ages of 13 specimens of molluscan shells were determined by ¹⁴C dating. Moreover, we analyzed the relative abundance of the planktonic foraminifer *Globigerinoides ruber*, which is a proxy of the Tsushima Current. The results show that the cored sediments were deposited from 13,574 ± 121 cal yr BP at a water depth that increased over time from about 50 m to 132 m. Three sedimentary facies are recognized in the cored sediment, in ascending stratigraphic order; coquina sediments, massive silt, and massive fine sand yielding many molluscan shells. The change in substrate was caused mainly by variability in the input of terrigenous deposits at 10,640–9,300 cal yr BP (the transition from coquina to silt) and at 8,860–5,180 cal yr BP (the transition from silt to sand). ¹⁴C data show that the molluscan species *Porterius dalli*, *Cyclocardia ferruginea*, *Tridonta alaskensis* and *Puncturella nobilis* were living in the Japan Sea before the initial inflow of the Tsushima Current at 9,300 cal yr BP. The modern molluscan fauna in the study area, which is dominated by *Limopsis belcheri* and *Crenulilimopsis oblonga*, may have become established by at least 5,180 cal yr BP.

Key words: Japan Sea, last deglacial period, offshore molluscs, planktonic foraminifera

Introduction

The Japan Sea is a semienclosed marginal sea with an area of approximately 1,000,000 km² and average depth of 1,350 m. The sea is connected to the East China Sea through the Tsushima Strait, to the Pacific Ocean via the Tsugaru Strait, and to the Sea of Okhotsk through the Soya and Mamiya straits. These straits are narrow and shallower than 130 m deep. At present, the only oceanic water flowing into the Japan Sea is the warm Tsushima Current, which enters via the Tsushima Strait and makes its way northward along the west coast of Honshu Island (Figure 1). The deep region below the Tsushima Current is occupied by the cold-water Japan Sea Proper Water (JSPW) (Suda, 1932; Moriyasu, 1972). The main thermocline between these two water masses is found at about 150–160 m depth off the Hokuriku and Niigata areas (e.g., Ogata, 1972; Nishimura, 1973, 1974).

Many workers have investigated temporal changes in the fossil assemblage of offshore microorganisms within the Japan Sea since the Last Glacial Maximum (LGM; 25,000–

20,000 yr BP) (e.g., Oba *et al.*, 1991, 1995; Keigwin and Gorbarenko, 1992; Gorbarenko and Southon, 2000; Takei *et al.*, 2002; Ikehara, 2003; Itaki *et al.*, 2004; Domitsu and Oda, 2006, 2008; Yokoyama *et al.*, 2007). From the LGM to 17,500 cal yr BP, the Japan Sea was nearly isolated from the surrounding seas because of the global sea-level drop, and was covered with low-salinity water. From 17,500 to 11,500 cal yr BP, as sea levels rose, the cold Oyashio Current flowed into the Japan Sea through the Tsugaru Strait in the north (Oba *et al.*, 1991). According to Domitsu and Oda (2006), *Globigerinoides ruber* has inhabited the Japan Sea from 9,300 cal yr BP to the present day, indicating that the warm Tsushima Current began to flow into the sea at 9,300 cal yr BP. Modern surface conditions in the southern Japan Sea were established at approximately 6,900 cal BP (Domitsu and Oda, 2008). Such drastic environmental changes may also have caused marked changes in the species compositions of offshore molluscan fauna, although few studies have investigated changes in the fossil assemblage of offshore molluscs within the Japan Sea since the LGM.

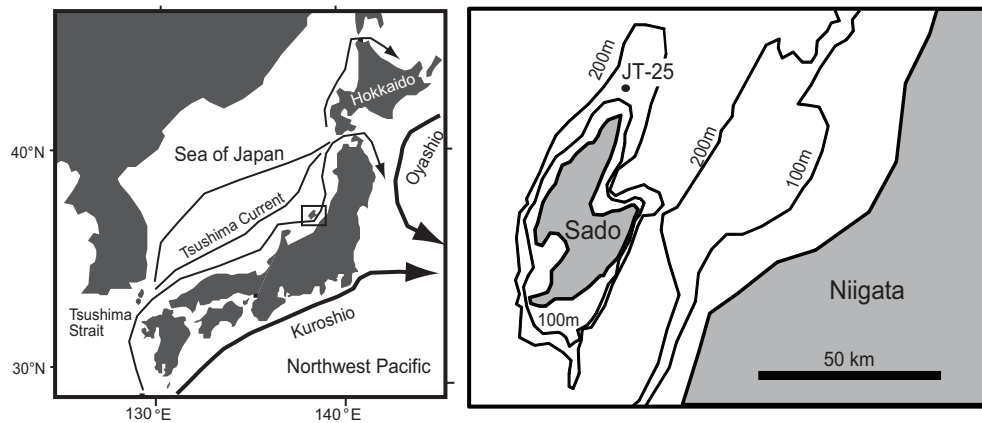


Figure 1. Regional map of the Japan Sea. Location of core JT-25.

Emery *et al.* (1971) and Chiji *et al.* (1981) reported the cold-water molluscs *Mytilus coruscus* ($11,050 \pm 600$ yr BP; Emery *et al.*, 1971), *Macoma calcarea* ($15,740 \pm 400$ yr BP; Emery *et al.*, 1971), *Mercenaria stimpsoni* ($13,130 \pm 280$ yr BP; Chiji *et al.*, 1981) and *Patinopecten yessoensis* ($16,340 \pm 420$ yr BP; Chiji *et al.*, 1981) from the continental shelf within the Japan Sea off southwestern Japan. Other than *M. coruscus*, these species are not found in this area today, but live off western Hokkaido (Okutani, 2000). On the other hand, little is known of the faunal changes in offshore molluscs following the initiation of inflow of the Tsushima Current at 9,300 cal yr BP. To reconstruct temporal changes in the offshore molluscan fauna and sedimentary environment during the last deglacial period, we analyzed sedimentary facies and the stratigraphic distribution of molluscs and planktonic foraminifers in a sediment core recovered from the continental shelf of the Japan Sea.

Study area

A gravity core (JT-25) was collected in 132 m water depth at a site located 7 km north of Sado Island, Japan ($38^{\circ}23.33'N$, $138^{\circ}30.57'E$) during Cruise GH89-2 of the R/V *Hakurei-Marui* of the Geological Survey of Japan in May–July, 1989 (Figure 1). The continental shelf around Sado Island is very narrow (Figure 1). Ito (1989) reported that *Modiolus margaritaceus*, *Crenulilimopsis oblonga*, *Parvamussium intuscostuma*, *Limopsis belcheri*, *Acila divaricata* and *Striodentalium rhabdotum* are the dominant molluscan species around Sado Island at water depths of 100–300 m.

The core tube is 6 cm in diameter. The lowermost sediment in the core is semiconsolidated massive clay (Nakajima *et al.*, 1995). Given that the lowest sea level during the LGM ($25,000$ – $20,000$ yr BP) is estimated to have been -130 to -140 m (Yokoyama *et al.*, 2000, 2001), the study area at this time was located between coastal low-lying land and the

shoreface.

Methods

The sediment core (92 cm thick) was split and described before picking and counting molluscs. Taxonomic identifications of mollusc shells are based on Okutani (2000). For disarticulated shells, separated valves were counted (Table 1). The radiocarbon ages of 13 mollusc shells were determined by Beta Analytic Inc., using accelerator mass spectrometry (Table 2). Calibrated age ranges were calculated using an online radiocarbon calibration program Calib 6.0 program (<http://calib.qub.ac.uk/>). ^{14}C ages are expressed in years before present (years BP), where the present is AD 1950.

Mud content and the relative abundance of the planktonic foraminifer *G. ruber* were examined in 1-cm-thick samples at 2.5-cm intervals from the middle and upper parts (40–10 cm and 10–0 cm depths, respectively) of the core (but not from the lower part because of time averaging; see below). Each sample was washed through a 63- μm -mesh sieve and dried at 70°C. The dried >63- μm fractions were sieved again through a 125- μm -mesh sieve, and the >125- μm fractions were divided into aliquots for picking. For assemblage analysis, at least 200 specimens (>125 μm) were picked. We then identified and counted *G. ruber* from each sample. The species is most suitable as an index of the Tsushima Current (Kitamura *et al.*, 2001). The utility of this index has been strongly supported by a study of the distribution of planktonic foraminiferal species from surface sediments of the Japan Sea (Domitsu and Oda, 2005).

Results

The sediment core is divided into lower, middle, and upper parts. The lower part (40–92 cm depth) consists of upward-fining coquina sediments (Figure 2) that include many bio-

Table 1. List of molluscan species in cored sediments. A: articulated shells, D: disarticulated shells. Data on the modern bathymetric range and substrate are from Higo *et al.* (1999) and Okutani (2000).

Species	Bathymetric range (m)	Part		Lower					Middle		Upper
		Substrate	Horizon	1	2	3	4	5	6	7	8
<i>Puncturella nobilis</i>	tidal zone-85	rubble				2					
<i>Homalopoma granuliferum</i>	50-300	coarse sand and stones									1
<i>Nuculana (Nuculana) pernula pernuoides</i>	20-400	fine sandy mud				A0/D2		A0/D1			
<i>Nuculana (Thestylea) yokoyamai</i>	50-450	fine sand and mud				A0/D1				A1/D0	
<i>Porterius dalli</i>	subtidal-300	rocks and boulders			A0/D1						
<i>Limopsis belcheri</i>	100-800	sandy mud									A4/D6
<i>Limopsis uwadokoi</i>	10-400	sandy mud					A0/D2				
<i>Crenulilimopsis oblonga</i>	20-200	sand and fine sandy mud				A0/D2		A0/D1	A0/D1		A2/D25
<i>Cyclocardia ferruginea</i>	35-400	sand	A0/D1	A0/D1	A0/D2	A0/D2	A0/D1				
<i>Tridonta alaskensis</i>	50-200	fine sand and sandy mud					A0/D1				
<i>Tridonta sp.</i>						A0/D1	A0/D1	A0/D1			
<i>Keenaea samarangae</i>	50-300	sandy mud									A0/D1
<i>Anisocorbula venusta</i>	tidal zone-200	sand					A0/D1	A0/D1			
<i>Hiatella orientalis</i>	tidal zone-300	root of seaweed or rocks					A0/D2				
<i>Myadora japonica</i>	10-990	fine sand and mud									A0/D1

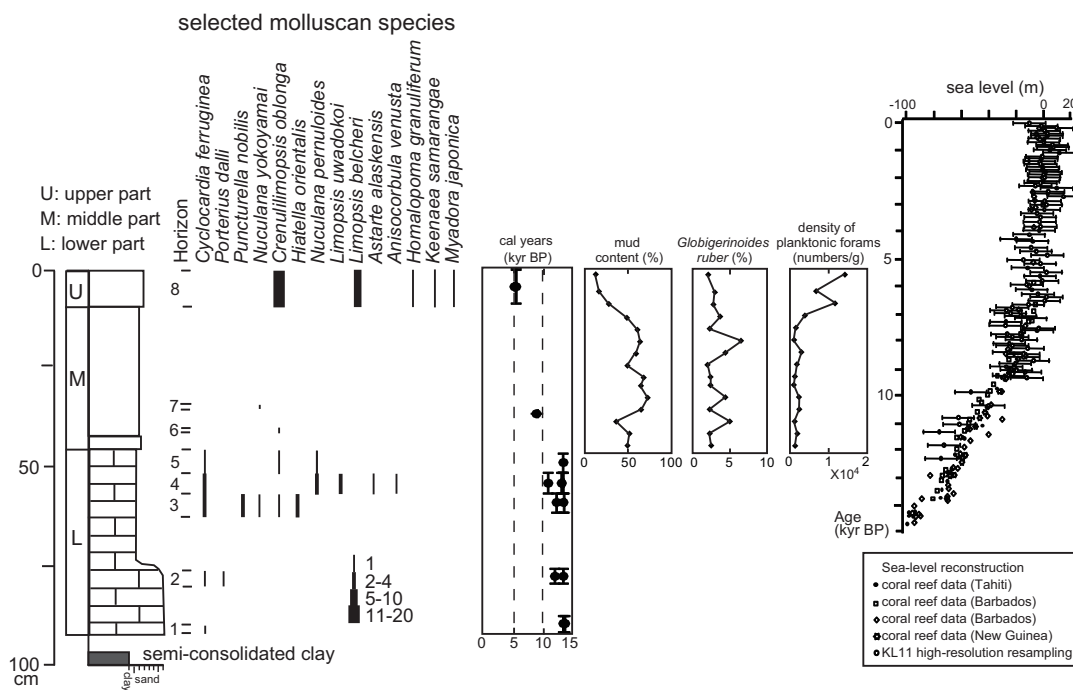


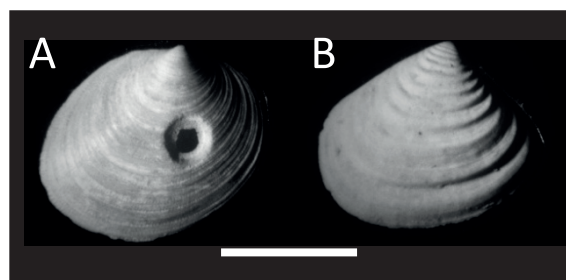
Figure 2. Columnar section of the cored sediment, showing stratigraphic changes in molluscan species, mud content, relative abundance of the planktonic foraminifer *Globigerinoides ruber*, and the number density of planktonic foraminifers, along with depositional rates inferred from the ¹⁴C ages of molluscs and a sea-level reconstruction (Siddall *et al.*, 2003).

clastic fragments such as coralline algae, bryozoans, and molluscs. Eleven molluscan species including *Porterius dalli*, *Cyclocardia ferruginea*, *Tridonta alaskensis* (Figure 3) and *Puncturella nobilis* are identified from the lower part (Hori-

zons 1 to 5); all bivalves are disarticulated and weakly abraded, indicating that the shells may be transported after death for any distance from their original habitats. However, the assemblage shows no evidence of the postmortem

Table 2. Results of ^{14}C dating of molluscs. All samples were analyzed by accelerator mass spectrometry (Beta-Analytic Corporation).

Laboratory number	Species	Preservation	Measured ^{14}C age (BP)	$\delta^{13}\text{C}$ (‰)	Conventional ^{14}C age (BP)	Calibrated age cal BP
Beta-134201	<i>Limopsis belcheri</i>	Articulated shell	4370 ± 70	3.4	4840 ± 70	5147 ± 106
Beta-134202	<i>Limopsis belcheri</i>	Articulated shell	4410 ± 70	3.5	4880 ± 70	5182 ± 104
Beta-134200	<i>Nuculana (Thestyleda) yokoyamai</i>	Articulated shell	7860 ± 40	1.1	8290 ± 40	8862 ± 82
Beta-134199	<i>Cyclocardia ferruginea</i>	Disarticulated shell	11550 ± 80	2.8	12010 ± 80	13399 ± 84
Beta-134198	<i>Limopsis uwadokoi</i>	Disarticulated shell	9310 ± 70	3.4	9780 ± 70	10641 ± 90
Beta-134197	<i>Cyclocardia ferruginea</i>	Disarticulated shell	11100 ± 100	2.7	11560 ± 100	13030 ± 124
Beta-133917	<i>Tridonta alaskensis</i>	Disarticulated shell	11120 ± 40	2.9	11580 ± 40	13101 ± 50
Beta-133916	<i>Puncturella nobilis</i>	Disarticulated shell	10270 ± 40	2.7	10730 ± 40	12128 ± 93
Beta-133915	<i>Cyclocardia ferruginea</i>	Disarticulated shell	11510 ± 40	2.9	11970 ± 40	13392 ± 58
Beta-126557	<i>Cyclocardia ferruginea</i>	Disarticulated shell	10110 ± 90	2.1	10550 ± 90	11789 ± 176
Beta-133914	<i>Porterius dalli</i>	Disarticulated shell	11400 ± 50	2.6	11860 ± 50	13323 ± 57
Beta-133913	Pectinoidea	Fracture	11390 ± 40	2.1	11840 ± 40	13307 ± 54
Beta-126558	<i>Cyclocardia ferruginea</i>	Disarticulated shell	11710 ± 100	0.8	12130 ± 100	13574 ± 121

**Figure 3.** A. *Limopsis belcheri*. B. *Tridonta alaskensis*. Scale bar, 1 cm.

transport of species from other habitats, such as the intertidal zone. All the molluscs are found in the present-day surface sediments of the study area (Ito, 1985, 1989). Consequently, we consider that the molluscan fossils in the lower part of the core are indigenous. The ^{14}C ages of 10 molluscan samples from the lower part range from $13,574 \pm 121$ to $10,641 \pm 90$ cal yr BP (Figure 2, Table 2). A reverse age relationship found in many samples reveals significant time averaging of the fossils due to either bioturbation or re sedimentation.

The middle part (10–40 cm depth) consists of massive silt that contains a disarticulated shell of *C. oblonga* and an articulated shell of *Nuculana (Thestyleda) yokoyamai* (Horizons 6 and 7) that yield a ^{14}C age of $8,862 \pm 82$ cal yr BP (Figure 2, Table 2).

The upper part (0–10 cm depth) is characterized by fine sand that contains many molluscan shells, including *C. oblonga* and *L. belcheri* (Horizon 8) (Figures 2, 3). The ^{14}C ages of two specimens of well preserved and articulated shell valves of *L. belcheri* fall within a narrow range from $5,147 \pm$

106 to $5,182 \pm 104$ cal yr BP (Table 2), possibly indicating winnowing of the surface sediment due to penetration of the core. Because most of the bivalves of the middle and upper parts are well preserved, these fossils are considered to be indigenous.

Globigerinoides ruber occurs in all samples from the middle and upper parts (Figure 2). Planktonic foraminifera are more numerous in the upper part than in the middle part (Figure 2).

Discussion and conclusion

Temporal changes in sedimentary environment

The ^{14}C ages of shell samples indicate that the cored sediments were deposited from $13,574 \pm 121$ cal yr BP. Based on the sea-level curve proposed by Siddall *et al.* (2003) (Figure 2), water depth during deposition of the cored sediment increased over time from about 50 m to 132 m (the present depth). The upward-fining trend in the coquina sediments can be explained by a reduction in hydrodynamic energy associated with sea-level rise.

The change in sedimentary facies from coquina sediments (lower part of the core) to massive silt (middle part) indicates an increase in the input of fine terrigenous sediment. The change in sedimentary facies from the middle to upper parts is characterized by a decrease in the mud content and an increase in the relative abundance of molluscs and planktonic foraminifera (Figure 2), suggesting a reduction in the supply of terrigenous muddy particles to the study area during deposition of the upper part.

The youngest ^{14}C age obtained for shell samples in the lower part of the core is $10,641 \pm 90$ cal yr BP. The sediments of the middle part contain *G. ruber*, which has inhab-

ited the Japan Sea since 9,300 cal yr BP (Domitsu and Oda, 2006) (Figure 2). Consequently, the age of the boundary between the lower and middle parts is estimated to be between $10,641 \pm 90$ and 9,300 cal yr BP. The age of the boundary between the middle and upper parts is between $8,862 \pm 82$ and $5,182 \pm 104$ cal yr BP, based on the ^{14}C ages of shell samples.

Based on the sea-level curve proposed by Siddall *et al.* (2003) (Figure 2) and the depositional ages of the three parts of the core, water depth during deposition of the lower, middle, and upper parts is estimated to have been 50 m to 90–100 m, 90–100 m to the present depth (132 m), and the present depth, respectively. These findings indicate that the input of fine terrigenous deposits increased from 10,640 to 9,300 cal yr BP, when sea level rose rapidly, but decreased from 8,860 to 5,180 cal yr BP, when sea level was relatively stable or slowly rising. It is well known that the input of terrigenous deposits to offshore areas shows a decrease during times of relatively rapid sea-level rise. Thus, the changes in the supply of terrigenous sediment to the study area cannot be explained by sea-level change.

Nakajima and Itaki (2007) examined the temporal variability of the coarse fraction percentage, and the thickness and frequency of turbidite beds for the past 70 ka along the Toyama Deep-Sea Channel, located 50 km west of the present study area. The results show that turbidite deposition increased during the period from 18 to 8 ka, reflecting an increase in the input of terrigenous sediments from the Honshu mainland associated with enhanced precipitation resulting from intensification of the summer monsoon. In addition, the authors reported a period of intense turbidite deposition in the Toyama Deep-Sea Channel at ca. 10 ka. The authors concluded that enhanced vegetation and restabilized mountain slopes resulted in reduced sediment input to the channel system since 8 ka.

As noted above, in the present study area, the input of fine terrigenous deposits increased at 10,640 to 9,300 cal yr BP and decreased at 8,860 to 5,180 cal yr BP. These trends are consistent with those reported for the Toyama Deep-Sea Channel system, indicating that changes in the supply of terrigenous deposits in the present study area were also caused by varying sediment input associated with changing conditions in the sediment source areas. If this interpretation is correct, the temporal changes in sedimentation within the study area would have occurred over the entire outer shelf of the Japan Sea off Central Japan.

Temporal changes in molluscan fauna

It is widely accepted that the main factors that limit the distribution of offshore molluscs are substrate, water depth and water temperature. The three sedimentary facies recognized in the present study contain markedly different species compositions (Figure 2, Table 1), indicating that the changes in

substrate had a strong influence on temporal changes in the molluscan fauna. As noted above, the changes in substrate were caused by the varying input of fine terrigenous deposits associated with changing conditions in the sediment source areas. These findings imply a possibility that the molluscan faunal change recorded in the study area occurred over the entire outer shelf of the Japan Sea off Central Japan.

As noted above, water depth during deposition of the lower, middle, and upper parts of the core was 50 m to 90–100 m, 90–100 m to the present depth (132 m), and the present depth, respectively. Based on the recent distribution of molluscs (Table 1), all of the species contained in the core sediments, except for *L. belcheri*, can live at the range of water depths encountered in the study area since 13,000 cal yr BP (50–132 m depth). The bathymetric range of *L. belcheri* is 100 to 800 m, meaning that even if the species had lived in the Japan Sea before 10,640 cal yr BP, the water depth during deposition of the lower part would have been too shallow for this species.

The initiation of inflow of the Tsushima Current at 9,300 cal yr BP caused warming of the bottom water temperature and resulted in the establishment of the modern molluscan fauna. The ^{14}C ages of shell samples show that *P. dalli*, *C. ferruginea*, *T. alaskensis* and *P. nobilis* lived in the Japan Sea before 9,300 cal yr BP, prior to the inflow of the Tsushima Current. Our results also show that the modern molluscan fauna, which is dominated by *L. belcheri* and *C. oblonga*, was established by at least 5,180 cal year BP, at least within the study area. The water depth during deposition of the middle part of the core is similar to that during deposition of the upper part. The stratigraphic distribution of *G. ruber* indicates that the Tsushima Current flowed into the study area during deposition of the middle and upper parts. Consequently, we believe that there was no significant difference in bottom water temperature between these periods. Based on the recent distribution of molluscs, the substrate during deposition of the middle part of the core was not unsuitable for all four of the bivalve species found in the upper part (Table 1). Therefore, it is possible that the development of the modern molluscan fauna was caused by a concentration of shells associated with a marked reduction in terrigenous sediment supply rather than by colonization of the study area.

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