Radiocarbon, Vol 59, Nr 2, 2017, p 423–434 DOI:10.1017/RDC.2016.124
Selected Papers from the 2015 Radiocarbon Conference, Dakar, Senegal, 16–20 November 2015

RADIOCARBON AGE OFFSET BETWEEN SHELL AND PLANT PAIRS IN THE HOLOCENE SEDIMENTS UNDER HAKATA BAY, WESTERN JAPAN

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ABSTRACT. To measure chronological changes in the marine reservoir effect in western Japan, 47 marine shells and 35 terrestrial plants from the same horizons in two cores of Holocene sediments were radiocarbon dated by the KIGAM AMS facility. These cores were obtained from the central and northern parts of Hakata Bay using a Geoslicer device. This drilling tool provided us continuous coverage and many samples. In order to determine the species effects on the marine reservoir effect, both filter feeders and a deposit feeder were selected for study. Based on the analysis of lithology, mollusk assemblage, and ^{14}C dating, two sedimentary units were determined: the upper bay floor sediment and lower estuarine sediment. Reservoir ages of 280 ± 150 yr (n = 17) and 340 ± 140 yr (n = 18) were obtained from the central and northern parts of Hakata Bay during 2000 to 10,000 cal BP, respectively. Based on these results, it is clear that a paleoenvironmental change occurred here as a result of sea-level rise during the deglacial period.

KEYWORDS: reservoir effect, bay sediment, Holocene, AMS radiocarbon dating, Hakata Bay.

INTRODUCTION

Knowledge of the long-term change in the reservoir effect provides indispensable data for calibrating the radiocarbon ages of geological and archaeological samples from marine and brackish environments (Stuiver et al. 1986; Jull et al. 2013; Marine Reservoir Correction Database). Estimating the reservoir effect in East Asia is difficult because it is challenging to obtain known-age marine samples before AD 1955 (Figure 1A, Konishi et al. 1982; Hideshima et al. 2001; Kuzmin et al. 2001, 2007; Southon et al. 2002; Kong and Lee 2005; Shishikura et al. 2007; Yoneda et al. 2007). To address this problem, we measured the ^{14}C ages of marine shell and terrestrial plant pairs from the same horizons from coastal sediments around Korea (Nakanishi et al. 2013, 2015). These results produced reservoir ages (R) of 380 ± 190 yr (n = 48) from Holocene coastal sediments. This study present new ^{14}C results of marine shell and terrestrial plant pairs from two cores from the central and northern parts of Hakata Bay, collected using a Geoslicer device (Shimoyama et al. 2014). This drilling tool is ideal for measuring marine reservoir effects from coastal sediments because it provides continuous coverage and large amounts of sample.

STUDY SITE

Hakata Bay is located on the northern coast of Kyushu Island, in the western part of Japan, in a mid-latitude temperate zone. The coastal water around this lagoon is influenced by the warm Tsushima Current, which originates from the East China Sea and Western Pacific Ocean (Figure 1A). This bay has a 133-km^2 water surface and a maximum water depth of 23 m (Figure 1B). The maximum tidal range is ~2 m. Two sediment cores, HKA2-1 and HIUB1-1, were obtained from the central (33°37′25″N, 130°20′37″E) and northern (33°38′57″N, 130°22′23″E) parts (Shimoyama et al. 2014). Mesozoic metamorphic rocks and Cretaceous granite form the bedrock of this catchment, and no carbonate rocks are found around the bay.

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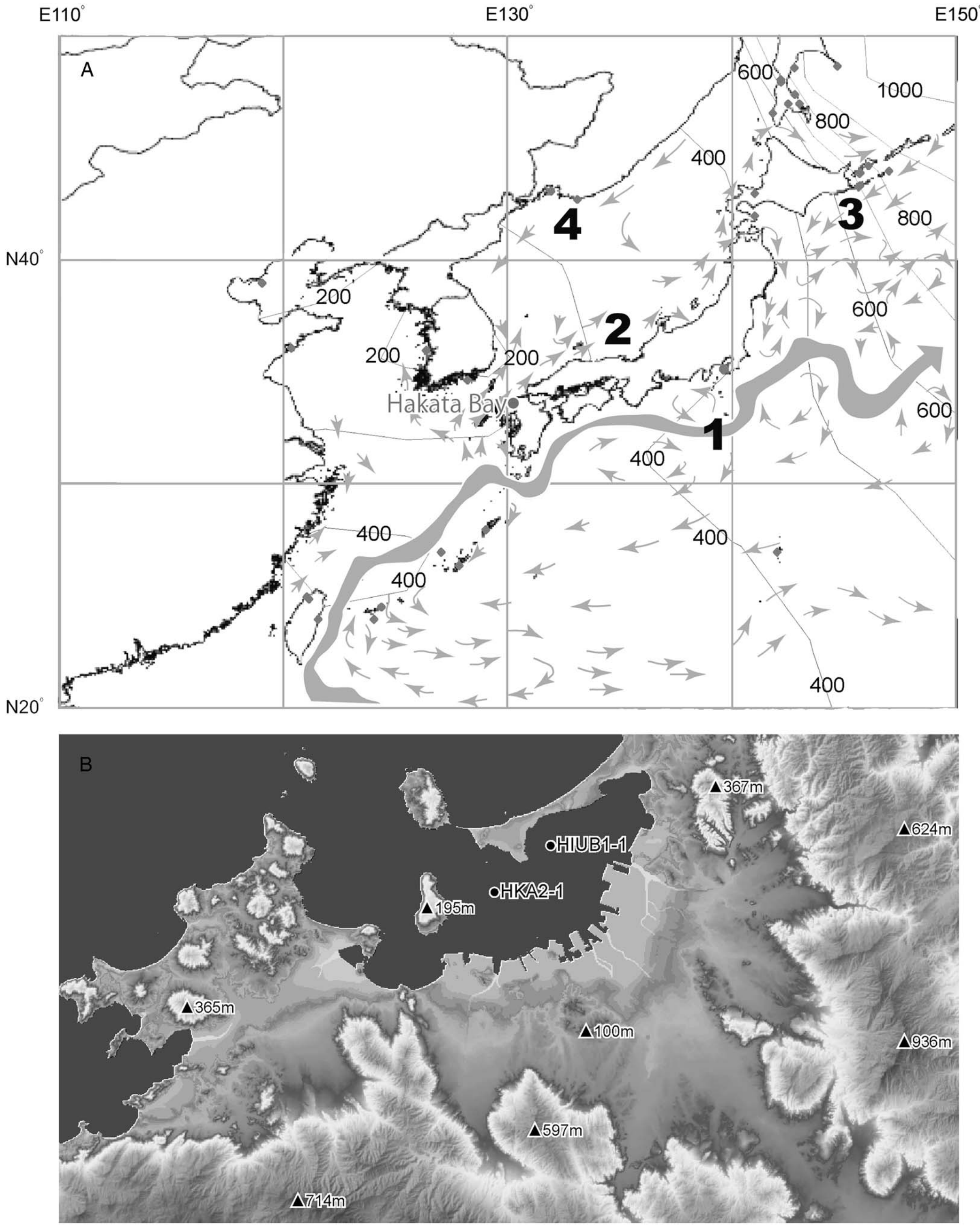

Figure 1 (A) Contour map of modern marine reservoir ages (R) around the study area: 1. Kuroshio Current, 2. Tsushima Current, 3. Oyashio Current, and 4. Liman Current. Modified from Nakanishi et al. (2015). (B) Topographic map around the drilling sites around Hakata Bay. The map was illustrated using Kashmir 3D.

METHODS

Sedimentological Analysis

Two cores were collected: HKA2-1 is 9.5 m long and HIUB1-1 is 11.8 m long. These were drilled from the central and northern parts of Hakata Bay, respectively. We utilized >20-m-long, 30-cm-wide, and 10-cm-thick bores collected using the Geoslicer device (Nakata and Shimazaki 1997; Haraguchi et al. 1998). This drilling tool provided continuous coverage with 11 kg of sediment per 20 cm depth. These samples were washed and sieved with a 2-mm mesh. The weights of the material were measured before and after washing. Plants and shells were picked from the residue and weighed. To better understand the sedimentary environment, we identified mollusk assemblages in the samples using a classification scheme based on Okutani (2000). Plant and carbonate samples in good condition were collected from the core for accelerator mass spectrometry (AMS) ^{14}C dating.

AMS ^{14}C Dating

To establish a stratigraphically consistent chronology for the HKA2-1 and HIUB1-1 cores and to evaluate the marine reservoir effect during the Holocene epoch, we used AMS to measure the ^{14}C ages of 35 terrestrial macrofossils and 47 marine calcareous samples. Fragile samples such as twigs and thin shells as well as articulated shells of dominant species were selected as much as possible because they were less likely to be reworked. Samples were repeatedly washed with an ultrasonic cleaner and then cleaned chemically using acid-alkali-acid (AAA) or acid treatments to remove secondary contaminants. Samples of ^{14}C-free wood and IAEA C-1 were treated with the same procedure for control measurements. The carbonate samples were milled. The samples, NIST OxII, IAEA C-7, and C-8, were combusted in an elemental analyzer and the CO_2 gases were purified cryogenically in a high-vacuum automatic preparation system (Hong et al. 2010a) and then converted into graphite by reduction on Fe powder with hydrogen gas in a quartz tube. The ^{14}C ages of the samples were measured with the standard samples at the AMS facility at KIGAM (Hong et al. 2010b). We corrected the carbon isotopic fractionations using δ^{13}C measured at the AMS facility. The ^{14}C ages of terrestrial plants were converted into calendar dates using IntCal13 (Reimer et al. 2013) and CALIB 7.1 (Stuiver and Reimer 1993). Marine reservoir (R) values were calculated by subtracting the ^{14}C age of the marine shell sample from the ^{14}C age of the terrestrial plant sample (Stuiver et al. 1986).

RESULTS

Based on the core analysis, we identified two sedimentary units (the upper inner bay sediment and lower estuary sediment as illustrated in Figure 2). Lithofacies, mollusk assemblage, depositional environments, and ages of the units are described below. An age/depth diagram is given in Figure 3. The base of these sediments, below a depth of 9.04 m in the HKA2-1 core, consisted of a semiconsolidated mud bed (Simoyama et al. 2014).

Bay Floor Sediment: 0.00–4.20 m Depth in Core HKA2-1 and 0.00–7.20 m Depth in Core HIUB1-1

Description

This sediment consisted of a homogeneous mud bed containing shells. The proportion of plant fragments increased in the upper portion, whereas that of marine shells, such as *Paphia undulata* (Born, 1778), *Veremolpa micra* (Pilsbry, 1904), *Scapharca kagoshimensis* (Tokunaga, 1906), *Fulvia mutica* (Reeve, 1844), and *Raetellops pulchellus* (Adams and Reeve, 1850), increased in the middle portion (Figure 2). The content of mud and sand is more than 97%. ^{14}C ages were ranged from modern to 7470 BP. A high concentration of volcanic glass, such as bubble wall

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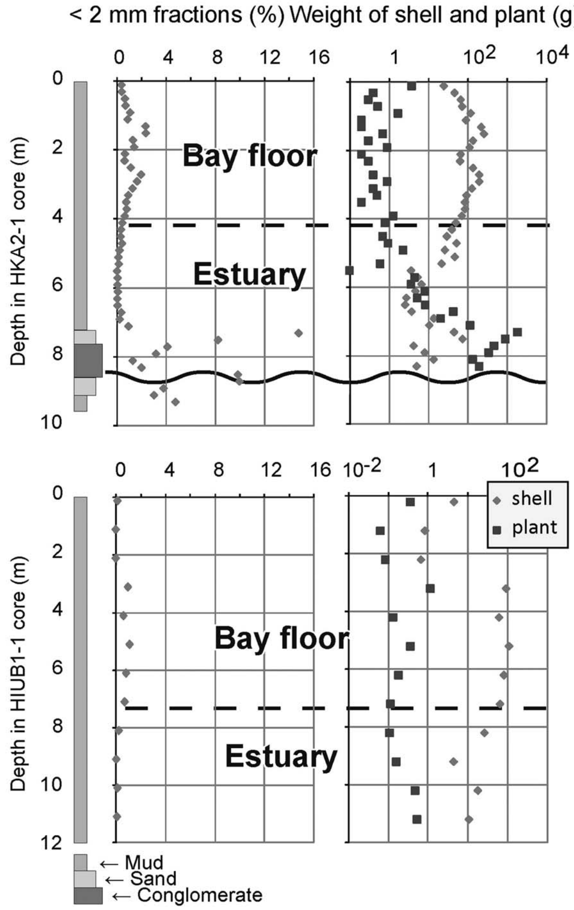

Figure 2 Sedimentological information for the HKA2-1 and HIUB1-1 cores: sediment columns, interpretation of sedimentary environments, <2-mm fractions, and weight of plants and shells.

and brown color glass, from the Kikai-Akahoya tephra (K-Ah; Machida 2002) was recognized at a depth of 3.2 m in the HKA2-1 core (Shimoyama et al. 2014).

Interpretation

The fine particles of mud and inner bay shells that include *Paphia undulata*, *Scapharca kagoshimensis*, and *Fulvia mutica* suggest that this sediment was deposited in an inner bay benthic environment. This is consistent with the location of the drilling site. The increase in the number of plant fragment up the sections reflects an increased fluvial influence as a result of delta progradation.

Estuary Sediment: 4.20–9.04 m Depth in Core HKA2-1 and 7.20–11.80 m depth in core HIUB1-1

Description

This sediment consisted of mud, sand, and gravel beds with shells. The proportion of plant fragments decreased in the upper portion, whereas that of marine shells, such as *Paphia undulata* and *Veremolpa micra*, increased (Figure 2). The content of intertidal shells, such as

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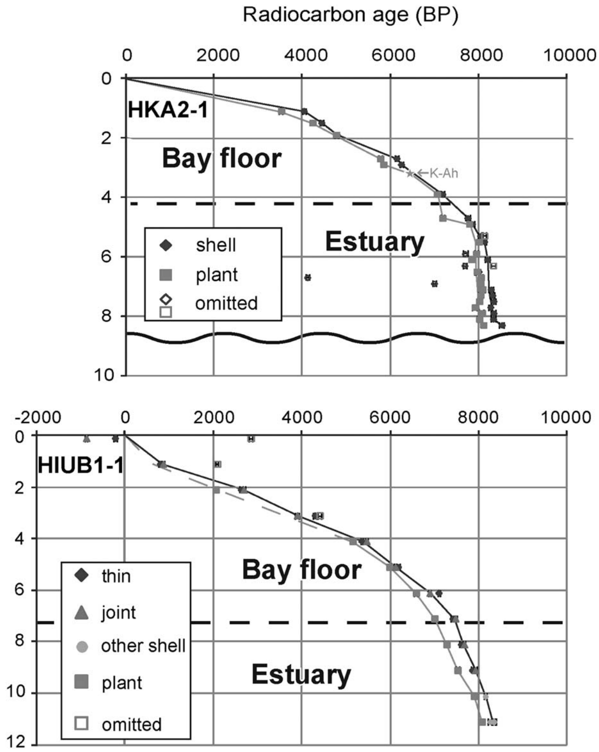

Figure 3 Radiocarbon ages of the HKA2-1 and HIUB1-1 cores. Six pieces of plant age data and five pieces of shell age data were ignored when the accumulation curves were interpreted because they were not consistent with the stratigraphy. K-Ah represents the Kikai-Akahoya tephra.

Sinonovacula constricta, *Batillaria cumingii*, and *Crassostrea gigas*, increased in the lower portion. Burrows such as *Thalassinoides* were observed around a depth of 5–7 m in the HKA2-1 core. ^{14}C ages ranged from 4110 to 8530 BP.

Interpretation

The combination of marine mollusks, such as *P. undulata* and *V. micra*, brackish-water species such as *S. constricta* and *C. gigas*, and terrestrial plant fragments, indicates that this sediment was formed from both marine and terrestrial sources. The changing of the mollusk assemblage and the abundance of plants imply that the influence of seawater increased with time. This would have been induced by the rising sea level in the early Holocene; thus, this sediment is interpreted to be formed in a transgressive estuary environment. The base of gravel bed in HKA2-1 would be the initial transgressive surface (Nummedal et al. 1993).

DISCUSSION

Accumulation Curves of the HKA2-1 Core

Based on 46 ^{14}C ages from the HKA2-1 core, two accumulation curves were constructed according to the ages of the plants and shells, which were interpreted by a scattering pattern in an age/depth diagram and by stratigraphic interpretation (Figure 3). Twigs and shells of dominant species such as *P. undulata*, *S. constricta*, and *C. gigas* were selected as terrestrial and marine age samples, respectively. These curves were consistent with the eruptive age of 7165–7303 cal BP of K-Ah (Smith et al. 2013) and the concentration depth of the volcanic glasses (Figure 3). The age/depth diagram indicated that some samples had to be excluded in the interpretation of accumulation curves and marine reservoir effects. Five shells of *P. undulata* from a depth of 5.8–7.0 m instead of 6.0–6.2 m were 280–4170 yr younger than the corresponding accumulation curve interpreted from other ages of carbonate samples. These ages were omitted when the accumulation curves were interpreted because they were not consistent with the stratigraphy. They were interpreted as contaminated samples, possibly related to burrowing organisms such as shrimp, *Callianassa* spp. (Ichihara et al. 1996). These organisms frequently fortify the walls of their burrows using bivalves or the fragments. We also identified two plant samples from depths of 5.2–5.4 and 6.2–6.4 m that were 200–300 yr older than our accumulation curve interpreted from other ages from terrestrial samples. We determined that these samples were reworked because no problems were found in the sample treatment and measurement procedures. These offsets were significantly less than similar offsets of 120–880 yr reported from plant samples in Holocene coastal sediments around the Yeongsan River in southwestern Korea (Nakanishi et al. 2013). No relatively old age offsets were found for the shell samples when compared with the accumulation curve. These reliable accumulation curves suggest that the sediments in Hakata Bay were suitable for estimating the marine ^{14}C reservoir effect from the ^{14}C ages of shell and plant pairs.

Accumulation Curves of the HIUB1-1 Core

Two accumulation curves were also constructed according to the 36 ^{14}C ages of the plants and shells in the HIUB1-1 core (Figure 3). Twigs and shells of dominant species, such as *Veremolpa micra*, *Raetellops pulchellus*, *Batillaria cumingii*, *C. gigas*, and one unclassified shell fragment, were selected as terrestrial and marine age samples, respectively. Three twigs from a depth of

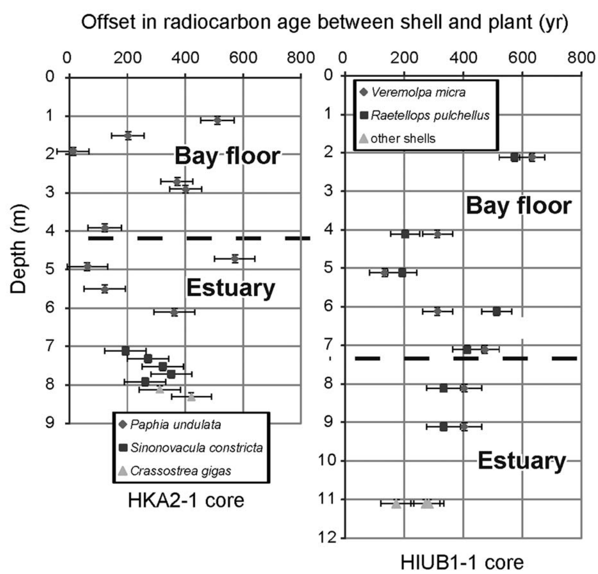

Figure 4 Offset in ^{14}C age between shells and plants from the Holocene sediment under Hakata Bay.

Table 1 Radiocarbon ages of the HKA2-1 core from Hakata Bay that were used for measuring marine reservoir ages.

	Depth				δ^{13}C		Conventional ^{14}C age		Sample code
Core	Top (m)	Bottom (m)	Material	Remarks	‰	±	BP	±	KGM-Otg-
HKA 2-1	1.0	1.2	Twig		–25.4	1.5	3520	40	150689
			Paphia undulata		2.3	2.6	4030	40	150732
	1.4	1.6	Twig		–22.2	1.7	4230	40	150690
			Paphia undulata		3.4	2.0	4430	40	150733
	1.8	2.0	Twig		–25.5	2.1	4770	40	150691
			Paphia undulata		2.0	2.5	4780	40	150734
	2.6	2.8	Twig		–26.9	1.0	5770	40	150692
			Paphia undulata		3.3	2.5	6140	40	150735
	2.8	3.0	Twig		–25.7	3.4	5840	40	150693
			Paphia undulata		–0.3	2.3	6240	40	150736
	3.8	4.0	Twig		–26.0	1.7	7060	40	150694
			Paphia undulata		5.3	2.4	7180	40	150737
	4.8	5.0	Twig		–26.1	0.5	7790	50	150696
			Paphia undulata		3.0	1.1	7850	50	150739
	5.4	5.6	Twig		–27.5	1.6	8010	50	150698
			Paphia undulata		1.3	1.8	8130	50	150741
	6.0	6.2	Twig		–26.1	0.8	7840	50	150700
			Paphia undulata?		–0.9	0.7	8200	50	150743
	7.0	7.2	Twig		–32.3	2.5	8090	50	150705
			Sinonovacula constricta		–8.0	1.5	8280	50	150748
	7.2	7.4	Twig		–32.7	9.0	8040	50	150706
			Sinonovacula constricta		–4.7	0.9	8310	50	150749
	7.4	7.6	Twig		–32.3	7.1	8020	50	150707
			Sinonovacula constricta		–7.6	1.0	8340	50	150750
	7.6	7.8	Twig		–32.5	6.0	7920	50	150708
			Sinonovacula constricta		–5.8	0.5	8270	50	150751
	7.8	8.0	Twig		–26.7	4.0	8080	50	150709
			Sinonovacula constricta		–8.3	1.4	8340	50	150752
	8.0	8.2	Twig		–33.1	5.1	8020	50	150710
			Crassostrea gigas		–5.9	1.4	8330	50	150753
	8.2	8.4	Twig		–26.8	4.1	8110	50	150711
			Crassostrea gigas		–3.1	1.3	8530	50	150754

Table 2 Radiocarbon ages of the HIUB1-1 core from Hakata Bay that were used for measuring marine reservoir ages.

Depth				$\delta^{13}C$		Conventional ^{14}C age		Sample code
Top (m)	Bottom (m)	Material	Remarks	‰	±	BP	±	KGM-Otg-
2.0	2.2	Plant		−30.4	2.9	2050	30	150714
		Veremolpa micra	Jointed	0.8	1.5	2680	30	150759
		Raetellops pulchellus	Thin	−0.6	1.9	2620	40	150760
4.0	4.2	Twig		−31.0	1.2	5150	40	150716
		Veremolpa micra	Jointed	−0.6	1.1	5460	30	150763
		Raetellops pulchellus	Thin	−3.1	1.2	5350	30	150764
5.0	5.2	Twig		−30.7	1.6	5980	40	150717
		Veremolpa micra	Jointed	−0.8	1.2	6110	30	150765
		Raetellops pulchellus	Thin	−2.6	1.0	6170	30	150766
6.0	6.2	Twig		−30.4	1.6	6580	40	150718
		Veremolpa micra	Jointed	−1.4	1.1	6890	30	150767
		Raetellops pulchellus	Thin	−2.1	0.4	7090	30	150768
7.0	7.2	Twig		−30.2	2.2	7000	40	150719
		Veremolpa micra	Jointed	−2.7	1.0	7470	30	150769
		Raetellops pulchellus	Thin	−0.3	1.2	7410	30	150770
8.0	8.2	Twig		−35.0	4.0	7270	50	150720
		Veremolpa micra	Jointed	0.3	0.9	7670	30	150771
		Raetellops pulchellus	Thin	−2.1	0.4	7600	30	150772
9.0	9.2	Twig		−28.2	1.1	7520	50	150721
		Veremolpa micra	Jointed	−0.4	1.1	7920	30	150773
		Raetellops pulchellus	Thin	−1.1	1.3	7850	30	150774
10.0	10.2	Twig		−29.7	3.0	7890	50	150722
		Unclassfied shell	Thin	0.1	0.7	8140	30	150775
11.0	11.2	Twig		−24.5	1.2	8070	40	150723
		Sinonovacula constricta		−2.2	1.0	8340	30	150776
		Crassostrea gigas		−4.0	1.1	8240	30	150777
		Batillaria cumingii		−4.4	0.6	8350	30	150778

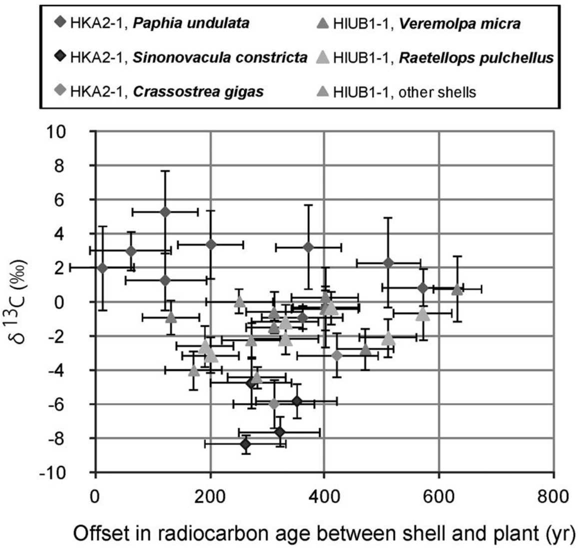

Figure 5 Relation between reservoir age and δ^{13}C values under Hakata Bay.

0.0–3.2 m were 110–2840 yr older than the accumulation curve interpreted from other ages of terrestrial samples. However, the offset in mollusks from the same depth might be associated with differences in feeding types. Thus, no shell ages were omitted from consideration.

Reservoir Effects in the HKA2-1 Core

Seventeen offsets in age between plants and shells of filter feeders, *P. undulata*, *S. constricta*, and *C. gigas*, induced by reservoir effects were interpreted from the same horizons of the HKA2-1 core during 3800–9000 cal BP (Figure 4, Table 1). The reservoir ages (R) were calculated to range from 10 ± 60 to 570 ± 70 yr, and they appeared to change with age and depositional environment (Figure 4). The total average R value was 280 ± 150 yr, the R for the bay floor sediment was 270 ± 190 yr ($n = 6$), and the R determined in estuary sediments was 290 ± 140 yr ($n = 11$). The larger standard deviation of the bay floor sediment might be associated with a much lower (factor of 7 to 8) accumulation rate than that of the estuary (4.0 mm/yr). This relation was also recognized in the HIUB1-1 core. The R values of filter feeders, *P. undulata*, *S. constricta*, and *C. gigas*, were 270 ± 200 yr ($n = 10$), 280 ± 60 yr ($n = 5$), and 370 ± 80 yr ($n = 2$). This relationship of R implies that marine shells such as *P. undulata* have larger valuation than the intertidal shells such as *S. constricta* and *C. gigas*. The larger δ^{13}C values of these mollusks had larger valuation of R values than the smaller ones (Figure 5). The δ^{13}C end-members presumably reflect brine and brackish water. The large R variation of *P. undulata* would be associated with the variegated environment in the central part of Hakata Bay. Similar variability was reported in the Kilen region, with a mean water depth of 2.9 m and 3.34-km^2 water surface, and a former inlet of the Limfjord in Denmark, based on the relation between the marine reservoir ages and multi-isotopic values (Philippsen et al. 2013).

Reservoir Effects in the HIUB1-1 Core

The 18 age differences calculated from the shell samples and plant samples of sediments in the HIUB1-1 core were 130 ± 50 to 630 ± 40 yr (Figure 4, Table 2). The total average R value from

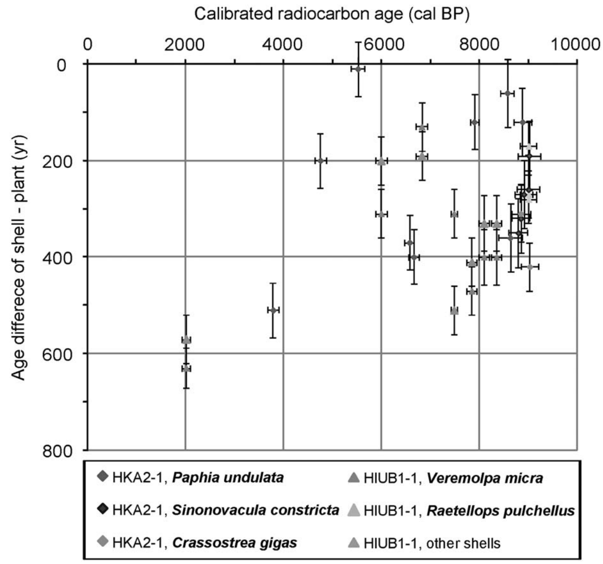

Figure 6 Reservoir ages during the Holocene of Hakata Bay.

all the pairs was 340 ± 140 yr (n = 18), the one bay floor sediment samples yielded an R value of 370 ±170 yr (n = 10), and the estuary sediment average R value was 300 ± 80 yr (n = 8). The differences at the depth of 7.0–11.2 m increased gradually with younger age (Figure 4). This trend was not clear in the HKA-1 core (Figure 4); however, some of them were also plotted on the similar position in the age/R value diagram (Figure 6). The same trend was observed in the transgressive sediments in the southern and western coasts of the Korean Peninsula (Nakanishi et al. 2013, 2015). The trend was interpreted to be affected by an increasing influence of seawater, induced by rising sea level in the early Holocene. The timing of these trends was approximately 9000–8000 cal BP in Hakata Bay and 8000–7000 cal BP in Korea. This age offset would be associated with the difference of sea-level change, induced by the hydro-isostasy (Yokoyama et al. 1996) and the accumulation pattern of coastal sediments (Hori and Saito 2007).

The R values in the HIUB1-1 core were identified by ages of *Veremolpa micra*, a filter feeder (380 ± 160 yr; n = 7); *Raetellops pulchellus*, a deposit feeder (360 ± 140 yr; n = 7); and other shell ages (240 ± 50 yr; n = 4). Significant differences of R values between filter feeders and deposit feeders from the same horizon were not recognized in Hakata Bay. This result would be provided by the sample selection of an articulated shell, *Veremolpa micra*, and a fragile shell, *Raetellops pulchellus*. The diversity of the δ^{13}C values of mollusks from the HIUB1-1 core was smaller than observed in the HKA2-1 core (Figure 5). It is likely associated with the relatively stable environment of the northern part of Hakata Bay, far from a river mouth, instead of the central part of the bay.

CONCLUSION

Reservoir ages were determined at two sites in Hakata Bay, and 35 values gave an average R value of 310 ± 150 ^{14}C yr within 60 ± 140 to 800 ± 150 ^{14}C yr since 9000 cal BP. These results were similar to previously determined values from the Korean Peninsula (380 ± 190 yr; n = 48). The difference was consistent with the local marine reservoir correction values from the southern and western regions of Japan (Nakamura et al. 2016). These R values are associated with the warm Tsushima Current. Research on the region along the cold Liman Current or the

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warm Kuroshio Current is important to understand the temporal and spatial changes of marine reservoir effect during the Holocene.

ACKNOWLEDGMENTS

The authors would like to thank Keiji Yamasaki, Takuya Yamauchi, Takumi Sakaguchi, and Michiko Imura for their help in sieving at Fukuoka University. We thank Dr A J Timothy Jull (Editor in Chief), Dr George Burr (Associate Editor), and reviewers for constructive reviews and valuable comments about the submitted manuscript. This study was supported by Japan Geographic Data Center and Research Project of KIGAM(GP2017-019), which was funded by the National Research Council of Science & Technology of Korea.

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