Introduction

Many shell-mounds of the Jomon period have been found around Mikawa Bay in Aichi Prefecture (Toizumi, 2000; Iwase, 2008). Many human skeletal remains of the Late–Final Jomon period have been excavated from the Hobi, Ikawazu, and Yoshigo shell-mounds on the Atsumi peninsula, and can be used to reconstruct the subsistence and mortuary practices of the Jomon period. The shell-mounds include archaeological remains of animal bones, lithic tools, and pottery, with little evidence of pit-dwellings.

One burial style of the Final Jomon period consists of a gathering of bones that resembles a square board (banjo-shuseki burial). This is a secondary burial, with the edges of the square formed from long bones of multiple individuals. Some pieces of cranial bone were placed at the corners of the square. The banjo-shuseki burial was named from the burials found in the Yoshigo shell-mounds (Kiyono, 1925). Other mass burials (shuseki in Japanese) discovered are also secondary burials that include multiple semi-articulated and disarticulated individuals arranged in non-square forms. Banjo-shuseki burials were excavated from sites in Aichi Prefecture (Harunari, 1988; Shitara, 1993). Three banjo-shuseki burials and two mass burials have been found at Hobi, and two banjo-shuseki burials and one mass burial have been found at Ikawazu (Ehara et al., 1988; Tahara City Board of Education, 2017). The meaning of secondary burials with multiple individuals is considered to indicate monumental burials formed when several small populations are assembled at a site (Yamada, 1995). The difference in pelvic femur size between single burials and banjo-shuseki burials suggests the possibility that they included individuals of specific social groups, activity roles, or genealogical relationships (Mizushima et al., 2004). Further consideration of the meaning of banjo-shuseki burials requires research with several methods that investigate diet, migration, and age.

One of the prehistoric customs observed in human skeletal remains is ritual tooth ablation. This custom is recorded on most human skeletal remains during the Late–Final Jo-
underground water are similar local signals, and the values of terrestrial animals were estimated in Aichi Prefecture (Kusaka et al., 2009, 2011). The $^{87}$Sr/$^{86}$Sr ratios of modern plants around Mikawa Bay show large variation according to the geology (Figure 1; Kusaka et al., 2009, 2011). The $^{87}$Sr/$^{86}$Sr ratio of seawater and marine animals has a value of 0.70918, in the Jomon period as well as modern period. The ratios of strontium and calcium concentrations are considered indicative of the diet as the ratios decrease according to trophic levels (Schoening, 1979; Sillen and Kavanagh, 1982). This could be caused by the animals’ absorption of strontium relative to calcium in dietary minerals. This process is called ‘biopurification’ (Elías et al., 1982). The two-resource mixing model of Sr/Ca and strontium isotope ratios shows a mixing curve depending on the concentration. However, the reciprocal of the Sr/Ca ratios and isotope ratios shows a linear relationship between the two sources (Bentley, 2006; Kusaka and Shin, 2018). This relationship might support the interpretation of dietary sources and human migration.

The purpose of this study was to identify immigrants of the skeletal population from the Hobi and Ikawazu shell-mounds through strontium isotope analysis. We focused on the isotopic difference between single burials, mass burials, and banjo-shuseki burials. We also evaluated isotopic difference according to tooth ablation types. Our analysis aids the interpretation of these special burial styles during the Jomon period.

Materials and Methods

The Hobi shell-mound has been excavated over 15 times (Tahara City Board of Education, 2017). In the shell-mound, the northern part of the site is named the ‘A’ shell-mound, the eastern part the ‘B’ shell-mound, and the western part the ‘C’ shell mound. The Hobi shell-mound was formed during the last part of the Late Jomon period to the early part of the Yayoi period based on excavated pottery. A total of 155 human skeletal remains have been excavated. Five mass burials, including a banjo-shuseki burial, have been found.

The research team investigating the Hobi shell-mound excavated in the area of the B shell-mound during 2010–2015. The banjo-shuseki burial (Pit burial No. 1) and single burial (Pit burial No. 2) sites were excavated. The details of these excavations are reported in another paper in the same issue of this journal.

Fifteen samples of tooth enamel, which include second premolar to third molars, and five rib bone samples from the Hobi banjo-shuseki burial were used for strontium isotope analysis. One tooth enamel and a rib bone sample from a single burial were also used (Table 1).

The Ikawazu shell-mound has been excavated over 10 times since 1903. The site dates from the late part of the Late Jomon to the Final Jomon period (Hisanaga, 1972; Kusaka et al., 2015). In total, 191 human skeletal remains have been found. In 1984, 22 burials and 44 individuals were excavated (Ehara et al., 1988). Tooth metric analysis and other archaeological analyses were conducted on these samples. During the excavation in 2008–2010 and 2013, human skeletal remains of 14 individuals from the last part of the Final Jomon period were identified. The burial postures of these individuals comprised six flex burials, one sitting burial, two extended burials, and other unknown burials (Tahara City Board of Education, 2015). Radiocarbon dates of four human skeletal remains from Ikawazu excavated in 1922 were reported as 2440–3070 cal BP (Kusaka et al., 2011).
In Ikawazu, four tooth enamel samples from single burials, two enamel samples from the *banjo-shuseki* burial (Nos. 1-1, 1-2), three enamel samples from the mass burial (Nos. 6-1, 6-5, 6-8), and seven enamel samples of other kinds of burials were analyzed from the excavation in 1984. Two tooth enamel samples from 2008 and one bone sample from
2013 were also used for the analysis. Five tooth enamel samples and six bone samples were obtained from the materials excavated in 2010. Most tooth enamel samples were taken from the second premolars of the Ikawazu specimens. For strontium isotope analysis, approximately 5 mg of tooth enamel and bone samples were drilled using a dental
drill and tungsten carbide bar. Powdered samples were washed with buffered acetic acid (0.1 mol/L, 30 min). About 2 mg of each sample was digested with nitric acid (3.5 mol/L) for strontium isotope analysis. Strontium was purified from most of the samples using a strontium-specific resin (100–200 mesh; Eichrom Technologies Inc.). Multi-collector inductivity-coupled plasma mass spectrometry (MC-ICP-MS, Neptune; Thermo Fisher Scientific Inc.) was performed at the National Museum of Japanese History. Strontium from three tooth enamel samples of the Hobi banjo-shuseki burial was purified using a cation exchange resin (DOWEX 50WX8, 200–400 mesh: Muromachi Chemicals Inc.), and the strontium isotope ratios of three samples were measured by thermal ionization mass spectrometry (TIMS; Triton, Thermo Fisher Scientific Inc.) at the Research Institute for Humanity and Nature. Because both systems used NIST SRM-987 strontium solution ($^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$; Faure and Mensing, 2005) to standardize strontium isotope ratios of samples, the measured results are comparable between the two systems. The standard error of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios was lower than 0.000010 for MC-ICP-MS and 0.000021 for TIMS.

To measure the Ca/Sr ratios, samples (0.5 mg) washed with buffered acetic acid were used. The samples were dissolved in nitric acid (1 wt%) and diluted approximately 10000 times. The concentrations of calcium and strontium were measured by inductively coupled plasma optical emission spectrometry (iCAP PRO XP; Thermo Fisher Scientific. Inc.) at Tokai University. Diluted calcium standard solution and multi-element standard solution (XSTC-622, SPEX) were used to estimate the calcium and strontium concentrations in the samples.

**Results**

The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel from the Hobi samples were $0.709533 ± 0.000202$ ($N = 16$), and those of bone were $0.709103 ± 0.000142$ ($N = 6$). The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel were significantly higher than those of bones (Wilcoxon test, $\chi^2 = 9.14, P = 0.003$).

The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel from the Ikawazu samples were $0.709479 ± 0.000632$ ($N = 23$), and those of bone were $0.708877 ± 0.000031$ ($N = 7$). The mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel were significantly higher than those of bones (Wilcoxon test, $\chi^2 = 10.01, P = 0.002$).

The Ca/Sr ratios ($\text{Ca}/\text{Sr} \times 10^3$) of tooth enamel from the Hobi samples were $0.99 ± 0.24$ ($N = 14$), and those of bone were $0.34 ± 0.03$ ($N = 5$). The Ca/Sr ratios of tooth enamel were significantly higher than those of bones (Wilcoxon test, $\chi^2 = 10.52, P = 0.001$), and the variation in the Ca/Sr ratios of tooth enamel was larger than that of bones (Bartlett test, $F = 11.72, P < 0.001$).

The Ca/Sr ratios and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were compared to interpret dietary resources and migration (Figure 2). Among the Hobi samples, the Ca/Sr ratios of enamel were not correlated with the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($R^2 = 0.081, P = 0.326$), but the

![Figure 2](image-url)
The 87Sr/86Sr ratios of bone were positively correlated ($R^2 = 0.884$, $P = 0.017$).

The Ca/Sr ratios of tooth enamel from the Ikawazu samples were $1.17 \pm 0.39$ ($N = 21$), and those of bone were $0.41 \pm 0.10$ ($N = 7$). The Ca/Sr ratios of tooth enamel were significantly higher than those of bones (Wilcoxon test, $\chi^2 = 15.22, P < 0.001$), and the variation in the Ca/Sr ratios of tooth enamel was larger than that of bones (Bartlett test, $F = 9.70, P = 0.002$).

Among the Ikawazu samples, the Ca/Sr ratios of enamel were negatively correlated with the $^{87}$Sr/$^{86}$Sr ratios ($R^2 = 0.280, P = 0.014$), but the Ca/Sr ratios of bone were not correlated ($R^2 = 0.388, P = 0.135$).

The $^{87}$Sr/$^{86}$Sr ratios were compared between the burial style groups. Statistical comparison was difficult because of the small sample size: one enamel sample is from a single burial among the Hobi, and two enamel samples were from banjo-shuseki burials among the Ikawazu. Most of the enamel samples from the Hobi banjo-shuseki burial exhibited higher $^{87}$Sr/$^{86}$Sr ratios than one enamel sample from a single Hobi burial. Four enamel samples from Ikawazu banjo-shuseki burial, mass burial, fragmentary burial, and mixed burial tended to show high $^{87}$Sr/$^{86}$Sr ratios (Figure 2). These four individuals were males.

The $^{87}$Sr/$^{86}$Sr ratios were evaluated between the groups of tooth ablation types. Among the Hobi samples, three samples showed type 2C, and there were no type 4I individuals (Table 1). Among the Ikawazu samples, most of type 2C enamel samples exhibited higher $^{87}$Sr/$^{86}$Sr ratios, and one enamel type 4I and two enamels of type 4I2C exhibited lower $^{87}$Sr/$^{86}$Sr ratios (Figure 3). However, most of samples excavated in 1984 showed type 2C. Notably type 2C and type 4I2C enamel samples excavated in 2010 tended to show similar values. One enamel sample of type 4I with tooth filing showed moderate $^{87}$Sr/$^{86}$Sr ratios.

**Discussion**

The strontium isotope analysis of human skeletal remains from the Hobi shell-mound exhibited a range of 0.708903–0.709791, and the mean $^{87}$Sr/$^{86}$Sr ratios of enamel samples were significantly higher than those of the bone samples. The range of the mean $^{87}$Sr/$^{86}$Sr ratios plus or minus two standard deviations (mean ± 2SD) can be used to establish the biologically available strontium for the population (Bentley, 2006). The local range based on the bone samples was 0.708819–0.709387. The $^{87}$Sr/$^{86}$Sr ratios of modern plants have also been used to infer the range of local strontium (Hodell et al., 2004). The mean $^{87}$Sr/$^{86}$Sr ratios of modern plants around 10 km from the site were calculated from previously reported data (Figure 1; Kusaka et al., 2009, 2011). The 2SD range of modern plants was 0.708721–0.709469, which is slightly larger than that of bone samples. The $^{87}$Sr/$^{86}$Sr ratios of only two tooth enamels were included in the ranges of both bone samples and modern plants.

The $^{87}$Sr/$^{86}$Sr ratios of tooth enamel and bone samples originate from the dietary resources. The incorporation of marine resources showed a value of 0.70918 (Faure and Mensing, 2005). In coastal areas, the effects of sea-spray cause significant changes in terrestrial resources (Whipkey et al., 2000). The dietary sources of the Jomon population are composed of a mix of terrestrial and marine resources. The mean $^{87}$Sr/$^{86}$Sr ratios of the bone samples from Hobi were 0.709103. The mean value of dietary sources for Hobi would be approximately 0.7091–0.7092. Therefore, the tooth enamel of a single burial (Pit burial No. 2, HB-99) and one tooth enamel among the banjo-shuseki burial (Pit burial No. 1, B1038) show the signature of locals who grew up in the site. Other enamel samples suggest the possibility that they are not of local origin.

The $^{87}$Sr/$^{86}$Sr ratios of tooth enamel in animal remains can be used to establish the locally available strontium (Price et al., 2002; Bentley et al., 2004). The $^{87}$Sr/$^{86}$Sr ratios of deer enamel samples from Hobi were 0.708318 ± 0.000355 ($N = 8$), and those of wild boar enamel samples were 0.708846 ± 0.000467 ($N = 7$; E. Ishimaru, in preparation). The isotope ratios of the tooth enamel of animals indicate the geological location of their teeth. The Jomon population incorporates the meat of these animals. It is unclear whether the value of meat is the same as that of tooth enamel, but these values would be a good reference for locally available strontium. The mean values of deer and wild boar were lower than those of marine resources. This does not contradict the biologically available strontium based on human bone and terrestrial plant samples.

The $^{87}$Sr/$^{86}$Sr ratios of human skeletal remains from the Ikawazu shell-mound were in the range of 0.708760–0.711452. The mean $^{87}$Sr/$^{86}$Sr ratios (±2SD) of the bones exhibited a narrower range of 0.708815–0.708939. The range of modern plants around Ikawazu was 0.708615–0.709647. The mean value of the modern plants was 0.709131, and the values of dietary resources for Ikawazu were estimated to be approximately 0.7091–0.7092. Two enamel samples from deer had a mean value of 0.70958. This value suggests the possibility that these deer were hunted in a distant place and imported to the site, or that plants with these values were available around nearby sites. Although most of the modern plants on the Atsumi peninsula exhibit lower values than seawater, the highest value was...
0.7096 in the southern coastal area (Figure 1). Based on the ±2SD range of modern plants, the four enamel samples were not in local ranges. A higher value can be observed in four male enamel samples excavated in 1984: one sample among the *banjo-shuseki* burial (No. 1-2; 0.709786), one sample among the mass burial (No. 6-5; 0.710354), one sample from a fragmentary burial (No. 13; 0.710675), and one sample from a mixed burial (No. 15-2; 0.711452). These samples suggest that they might have originated from the outer place of the site or human skeletons were conveyed to the site in the case of secondary burials.

The Ca/Sr ratios of tooth enamel samples were higher than those of bone samples in both the Hobi and Ikawazu shell-mounds. This indicates that the strontium concentration was high in the bone samples. The variation in Ca/Sr ratios was smaller in bone samples than in tooth enamel samples. Bones generally have a porous structure, and diagenetic strontium from sediments and groundwater tends to be adsorbed (Price, 1989). This could be a cause of the difference in the strontium concentration between the tooth enamel and bones. This tendency also explains the narrower range of ⁸⁷Sr/⁸⁶Sr ratios in the bone samples.

The Ca/Sr ratios of body tissues are affected by those of dietary resources, resulting in a possible relationship between the Ca/Sr ratios, ⁸⁷Sr/⁸⁶Sr ratios, and dietary resources. Among the Hobi enamel samples, the Ca/Sr ratios varied without a connection with the ⁸⁷Sr/⁸⁶Sr ratios (Figure 2). This indicates that the Hobi population would have incorporated several resources with variable strontium concentrations and ⁸⁷Sr/⁸⁶Sr ratios. The positive correlation in the Hobi bone samples indicates the two sources of strontium: one is seawater with a low concentration of strontium and ⁸⁷Sr/⁸⁶Sr ratios of 0.70918, and the other is diagenetic strontium in soil and underground water with a high concentration of strontium and low ⁸⁷Sr/⁸⁶Sr ratios.

Meanwhile, the Ca/Sr ratios were negatively correlated with the ⁸⁷Sr/⁸⁶Sr ratios among the Ikawazu specimens. The high Ca/Sr ratios with low ⁸⁷Sr/⁸⁶Sr ratios suggest the incorporation of terrestrial meat with low strontium concentrations and high trophic level fish. Individuals who showed 0.7093–0.7098 tended to have lower Ca/Sr ratios. They might have incorporated terrestrial plants with high strontium concentrations. If they incorporated marine resources, they would have digested terrestrial plants and meat that were higher than the ⁸⁷Sr/⁸⁶Sr ratios of 0.7098. These two end-members would have caused the negative correlation between the Ca/Sr and the ⁸⁷Sr/⁸⁶Sr ratios in the enamel of Ikawazu specimens. The three individuals with values higher than 0.7103 exhibited lower Ca/Sr ratios. The very high ⁸⁷Sr/⁸⁶Sr ratios indicate that they are not of local origin.

The *banjo-shuseki* burials of Hobi and Ikawazu included samples that show higher ⁸⁷Sr/⁸⁶Sr ratios than those of single burials. This finding means that the ⁸⁷Sr/⁸⁶Sr ratios of food obtained during childhood of individuals in the *banjo-shuseki* burials were different from those of individuals in single burials. The difference in the ⁸⁷Sr/⁸⁶Sr ratios indicates the possibility that the places of resource procurement were different between them, even when living in the same local place. Another possibility is that the individuals in the *banjo-shuseki* burials lived in another location during childhood and immigrated into the settlement during adulthood. If they had died in another place, skeletonized remains could have been transported to the cemetery when the *banjo-shuseki* burials were created. The coastal area of the west Mikawa area, which is located north of Mikawa Bay, had the custom of *banjo-shuseki* burials. Since the ⁸⁷Sr/⁸⁶Sr ratios in that area are high, west Mikawa is one of the candidates for the origin of individuals with high ⁸⁷Sr/⁸⁶Sr ratios. Secondary burials with multiple individuals might be the result of a mortuary practice of grouping several small populations (Yamada, 1995). The pilasteric femur from the *banjo-shuseki* burials in Hobi suggests some differences in activity roles or genealogical relationships (Mizushima et al., 2004). The high ⁸⁷Sr/⁸⁶Sr ratios in the *banjo-shuseki* burials also indicate some peculiar characteristics in Jomon society.

The difference in the ⁸⁷Sr/⁸⁶Sr ratios between the types of tooth ablation is a difficult question based on the results of this study. The individual in a single burial in Hobi (Pit burial No. 2, HB-99) has type 2C, and this individual shows a value likely to be local. The two type 2C samples from the *banjo-shuseki* burial (Pit burial No. 1, B221, B136) present high values, similar to those of immigrants. These results suggest that type 2C individuals in Hobi include both locals and immigrants. Most of the individuals in the 1984 excavation at Ikawazu exhibit type 2C tooth ablation (Figure 3). Exceptionally, the type 4I individual with tooth filing (No. 19) gives a value of 0.709063, which indicates a local individual. Both type 4I2C individuals (Nos. 3 and 4-2) and type 2C individuals (Nos. 1 and 5) from the 2010 excavation exhibit values in the local ranges. These results do not indicate any difference in origin between the type 2C and 4I groups in Hobi and Ikawazu.

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### Competing financial interests

The authors declare no competing financial interests.

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