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Title: Strontium isotope evidence of migration and diet in relation to ritual tooth ablation: A case study from the Inariyama Jomon site, Japan

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Abstract

Ritual tooth ablation was extensively practiced among Jomon (Japanese Neolithic) societies in their final phase (ca. 2800–2500 cal BP). This tradition includes two different tooth ablation patterns, type 4I and type 2C, referring to extraction of the mandibular incisors and canines, respectively. However, the reason for this difference is unclear. Previous carbon and nitrogen stable isotope analysis of human remains from the Inariyama shell mound revealed that type 4I individuals were more dependent on terrestrial resources and type 2C individuals on marine resources. To test this hypothesis, we performed strontium (Sr) isotope ($^{87}Sr/^{86}Sr$) analyses on the same skeletal remains and on modern plants around the site. Because Sr isotope ratios of plants differ according to the local geology and seawater has a consistent Sr isotope ratio, the Sr isotope ratios of tooth enamel can reveal both migration and diet. Comparing Sr isotope ratios in plants and seawater with those of tooth enamel, we identified four possible immigrants. Type 4I locals had significantly higher Sr isotope ratios than type 2C locals. The ratios of the type 4I and type 2C locals were close to those of terrestrial plants and seawater, respectively, suggesting that type 4I locals had incorporated much Sr from terrestrial resources and type 2C locals from marine resources. These results support the hypothesis that ritual tooth ablation reflects dietary differences throughout an individual's life, and they suggest possible occupational differentiation among the Jomon people.

Key words: Human tooth enamel, bone collagen, nitrogen isotope, carbon isotope, social stratification, hunter-gatherers.

1. Introduction

The Jomon culture, which is characterized by cord-marked pottery, lasted from 13 000 to 2300 years BP in the Japanese Archipelago (for details, see Habu, 2004; Harunari, 1986; Imamura, 1996). Generally speaking, the Jomon people were sedentary hunter-gatherers who effectively exploited marine and terrestrial resources. The Late to Final Jomon period (ca. 4000–2300 BP) was a time of climatological cooling, during which the Jomon population size decreased, while the kinds and numbers of ritual artifacts such as ceramic and stone figurines increased (Imamura, 1996).

Jomon society is thought to have been a transegalitarian society, one in which socioeconomic inequalities are associated with rich resources (Hayden, 1995; Takahashi, 2004). Testart (1982) pointed out that socioeconomic inequalities can be associated with a sedentary economy practicing intensive food storage, but not necessarily agriculture. In fact, interfamilial differentiation of occupations or subsistence may have been a fundamental factor leading to the development of stratified societies among the maritime hunter-gatherers of the northern Pacific (Watanabe, 1983). Watanabe (1990) proposed that occupational differentiation had developed in the Jomon society on the basis of an ethnographic comparison with sedentary hunter-gatherers of the northern Pacific Rim, in whom social stratification related to occupational differentiation among males was found. He found evidence for social stratification in the excellent artisanship of Jomon potteries and in the large stone circles that the Jomon people constructed. Jomon dietary differentiation could be an important indicator of social stratification in these sedentary hunter-gatherers of the northern Pacific Rim.

Ritual tooth ablation involving deliberate extraction of frontal teeth has been documented in prehistoric populations in North Africa (Briggs, 1955; Humphrey and Bocaege, 2008), Italy (Robb, 1997), Hawai’i (Pietrusewsky and Douglas, 1993), China (Han and Nakahashi, 1996), Taiwan (Nakahashi, 2008), Thailand (Tayles, 1996), and Japan (Koganei, 1918). Ritual tooth ablation among the Jomon people was characterized by a variety of patterns and was widely practiced during the Late to Final Jomon (e.g., Harunari, 1979, 1986; Watanabe, 1966). Patterns in tooth ablation might provide invaluable information on the social organization of the Jomon people, and several different hypotheses have been proposed regarding the practice. For example, the practice may have been part of a coming-of-age ceremony (Funahashi, 2003; Harunari, 1979; Hasebe, 1919), signified mourning for a deceased family member (Funahashi, 2003; Harunari, 1979), indicated an individual's descent group (Kusaka et al., 2008, 2009), or moiety groups (Tanaka, 1998).

The most influential hypothesis to explain variation in Jomon tooth ablation patterns was formulated by Harunari (1979): On the basis of comparisons of sex and grave patterns of Jomon skeletal remains, he hypothesized that ritual tooth ablation was performed at a coming-of-age ceremony and upon marriage, and that different tooth ablation patterns were used by locals and immigrants to a site. Harunari (1979) noticed that type 4I individuals, with two maxillary canines and four mandibular incisors removed, tended to be buried with personal offerings and hypothesized that these were locals of high prestige. He suggested that type 2C individuals, who lacked all canines, were immigrants married to type 4I individuals. A type 4I pattern can be changed to a type 4I2C pattern by the extraction of two more mandibular canines, but in this study we lumped type 4I2C with type 4I because type 4I2C occurred with low frequency.

Kusaka et al. (2008) performed stable carbon and nitrogen isotope analyses of

Inariyama Jomon skeletal remains and found that different ritual tooth ablation types were associated with dietary differences. Type 4I individuals were more dependent on terrestrial resources (C_3 plants and terrestrial mammals), whereas type 2C individuals were more dependent on marine resources. Their study provided the first evidence for intrapopulational dietary differentiation in Jomon society, supporting the possibility that occupational differentiation, as predicted by Watanabe (1990), also existed.

The purpose of this study was to investigate whether analyses of strontium (Sr) isotope ratios ($^{87}Sr/^{86}Sr$), which can reveal both migration and dietary dependence on marine foods, could be used to detect dietary differentiation among the Inariyama skeletal samples.

2. Strontium isotope analysis

Strontium isotopes have been widely used in archaeological science to reveal diet (Price and Gestsdóttir, 2006) or as tracers of prehistoric residential mobility (e.g., Bentley et al., 2002, 2005, 2007; Ezzo et al., 1997; Haak et al., 2008; Knudson and Price, 2007; Montgomery et al., 2007; Price et al., 2002). Recently, this method has been applied to detect mobility among hunter-gatherers (Haverkort et al., 2008; Kusaka et al., 2009; Tafuri et al., 2006). The rationale is that the Sr isotope composition of animals and plants faithfully reflects the isotope composition of the rocks and soil where they live and grow, because the biologically available Sr derived from rocks and soil is incorporated by biosynthetic processes and passed up food chains without isotope fractionation (Blum et al., 2000). In humans, the Sr isotopic signature in tooth enamel is an excellent archive of Sr from a person's childhood home. Thus, when people migrate between geologically contrasting residential areas, the Sr isotopic signatures in the tooth enamel of immigrants to a region would differ from that in the bones of adult humans as well as from the Sr isotope ratios in soil, plants, and animals of the local region (Bentley, 2006). In addition to detailed $^{87}Sr/^{86}Sr$ measurements of human skeletal remains, extensive mapping of Sr isotopes in plants is necessary to estimate the geographical origin of immigrants (e.g., Evans et al., 2009; Hodell et al., 2004; Kusaka et al., 2009).

In addition, Sr isotopic analyses can be used to assess the dietary dependence of local individuals on marine resources. Sr isotope ratio of seawater has varied over geologic time (McArthur et al., 2001), but it can be assumed consistent in the last 10000 years. Marine organism incorporates Sr from seawater, and shows the same Sr isotope ratios with seawater. Then, the bones and teeth of individuals who consumed a lot of marine foods are expected to have the same Sr isotope ratio as seawater. In contrast, the Sr isotope ratios of locals who consumed terrestrial resources should reflect those in local plants and animals. These differences might allow us to evaluate dietary dependence on marine or terrestrial resources among local individuals from their skeletal Sr isotope ratios. Although terrestrial plants might have the same $^{87}Sr/^{86}Sr$ ratio as seawater, depending on environmental conditions such as geology and sea-spray impacts, we assumed that an individual whose tooth enamel had a nonmarine Sr isotope signature consumed significant amounts of terrestrial plants and animals.

Using Sr isotope analyses, we first determined which of the skeletal samples belonged to immigrants, and then we used the results from locals to test the hypothesis, based on the stable carbon and nitrogen isotopic analysis results, that the Sr isotope ratios of type 4I locals would be close to those of the local terrestrial resources, and that those of type 2C locals would be close to the seawater Sr isotope ratio.

3. Materials

The Inariyama shell mound is located on the Toyohashi Plain, Aichi Prefecture (Fig. 1). The mound was excavated in 1922 (Kiyono, 1969), when about 60 human skeletons were recovered. Pottery types found at Inariyama indicate that the shell mound accumulated during the Final Jomon period (ca. 3000–2300 BP). The sex of human bone samples was determined from hipbone morphologies (Phenice, 1969) and cranial features (Buikstra and Ubelaker, 1994). Age at death was estimated from the morphologies of the pubic symphysis (Brooks and Suchey, 1990), the auricular surface of the ilium (Lovejoy et al., 1985), cranial sutures (Meindl and Lovejoy, 1985), and dental attrition (Lovejoy, 1985). Age at death of Inariyama human skeletal remains for this study was categorized into the followings: adolescents (12–20 years), young adults (20–35 years), and middle adults (35–50 years; Buikstra and Ubelaker, 1994).

For this study, we used samples from the third molars and ribs of 17 individuals with definite ritual tooth ablation (Table 1). The samples are housed in the Laboratory of Physical Anthropology, Department of Zoology, Graduate School of Science, Kyoto University. Third molar forms during 9–13 years old (mean age) of an individual, but the range varies: cusp formation begins at 7–12 years old, and crown formation completes at 10–17 years old (Hillson, 1996). Tooth enamel matures during several months or a year after the formation (Montgomery and Evans, 2006). We assumed that tooth enamel in the third molar retains Sr acquired from the diet during late childhood to early adolescence and that bone reflects the averaged Sr isotope ratio from about the last 10 years of an individual's lifetime, because the turnover time of bone is about 10 years or more (Stenhouse and Baxter, 1979). This dietary signature in bone, however, would be modified by diagenetic alteration, as discussed later. Carbon and nitrogen stable isotope ratios of these samples were cited from Kusaka et al. (2008, 2010).

We collected plant samples from 36 locations in the vicinity of Mikawa Bay and along the Pacific coast (Table 2). We also examined data of 40 plant samples from this area reported by Kusaka et al. (2009). Thus, we used a total of 76 plant samples to evaluate regional differences in environmental Sr isotope ratios.

4. Methods

4.1. Strontium isotope analysis

Human tooth and bone samples were ultrasonically cleaned in ultrapure water and then dried. A dental drill equipped with a diamond burr and a tungsten carbide burr was used to abrade the tooth enamel and bone samples. After abrading the surfaces to remove soil-derived substances, we collected 5-mg samples of enamel and of compact bone of the ribs.

The strontium isotope analyses, including the pretreatment steps, were performed at the Research Institute for Humanity and Nature. Buffered acetic acid solution (0.1 M, pH = 4.5, 1 ml) was used to eliminate diagenetic contaminants from the enamel and bone samples (Hoppe et al., 2003; Sillen, 1986; Trickett et al., 2003) as follows. First, the samples were agitated for 10 minutes in the acetic acid solution and centrifuged, and then the supernatant was discarded. This procedure was performed twice. Then, the samples were agitated another 10 minutes and centrifuged, and the supernatant was retained for measurement. Each plant sample (0.5 g; ashed in a muffle furnace at 650 °C for 24 hours) was placed in a centrifuge tube with ultrapure water (10 ml) and then left overnight. After centrifugation, the supernatant was used as the sample solution.

All sample solutions were dried in Teflon® vials on a hotplate. Then HNO_3 (14 M) was added, and the vials were left on the hotplate at 200 °C to decompose organic matter. The samples were then dissolved in HCl (2 M), and Sr was separated chromatographically by using a cation exchange resin (DOWEX®, 50 × 8, 200–400 mesh). Strontium isotope ratios were measured on a degassed tungsten filament with a TRITON thermal ionization mass spectrometer (Thermo Fisher Scientific). Sample $^{87}Sr/^{86}Sr$ data was normalized to the standard reference material of the NIST SRM 987 (0.710250; Faure and Mensing, 2005). Internal precision based on ion counting 100 times was ±0.000002–0.000007 (= 1 standard error). External precision determined by repeated measurements (n = 25) of NIST SRM 987 was ±0.000007 (= 1 standard deviation [SD]) with a mean value of 0.710284 throughout all measurements made over 2 months. All $^{87}Sr/^{86}Sr$ data are listed in Tables 1 and 2.

4.2. Statistical analysis

Statistical analysis was performed with JMP software (SAS institute). Dietary differences between type 4I and type 2C locals were assessed by the Wilcoxon test. Statistical significance was evaluated as $P < 0.05$. Differences in the Sr isotope ratios of plants among five study regions, which were categorized to assess regional differences in Sr isotope ratios, were assessed by one-way analysis of variance (ANOVA) and by multiple t-test comparisons.

5. Results

5.1. Geographic $^{87}Sr/^{86}Sr$ distribution of plants

A geologic map of the study area and the geographic $^{87}Sr/^{86}Sr$ distribution of plants are shown in Figure 2A and 2B, respectively. We subdivided the study area into five subareas on the basis of the topography and geology (Table 3; Fig. 2B): the Atsumi Peninsula, the Yumihari Mountains, the Mikawa highlands, the West Mikawa Plain, and the Chita Peninsula. The $^{87}Sr/^{86}Sr$ ratio showed a wide range of variation, with high ratios (up to 0.7142) dominating the northern study area and low ratios (as low as 0.7056) occurring in its eastern part (Table 2). Strontium isotope ratios in plants from the Atsumi and Chita peninsulas had intermediate values.

The observed $^{87}Sr/^{86}Sr$ variation in plants explicitly correlated with differences in surface geology. It is noteworthy that the observed relationships between $^{87}Sr/^{86}Sr$ ratios and rock type are predictable in light of the empirically known $^{87}Sr/^{86}Sr$ range in the earth's lithosphere (i.e., $^{87}Sr/^{86}Sr > 0.712$ in granitic continental crust and $^{87}Sr/^{86}Sr$ = 0.707–0.709 in minerals of marine origin; e.g., Bentley, 2006). Plants on Atsumi Peninsula, which geologically consists of limestone and chert of the Chichibu Belt, had a $^{87}Sr/^{86}Sr$ ratio (mean ± SD) of 0.70908 ± 0.00030. Those in the Yumihari Mountains, in which the distribution of the limestone and chert of the Chichibu Belt overlaps with metamorphic rocks of the Sambagawa Belt, had a $^{87}Sr/^{86}Sr$ ratio of 0.70862 ± 0.00115. In the Mikawa highlands, consisting of granitic rocks of the Ryoke Belt, the $^{87}Sr/^{86}Sr$ ratio in plants was 0.71114 ± 0.00184, whereas in the West Mikawa Plain, which consists of Pliocene gravel, sand, and clay, the plant $^{87}Sr/^{86}Sr$ ratio was 0.70955 ± 0.00024. Plants in Chita Peninsula, which is composed of Miocene and Pliocene marine sedimentary rock, had a $^{87}Sr/^{86}Sr$ ratio of 0.70922 ± 0.00086.

The mean plant $^{87}Sr/^{86}Sr$ ratios in the five areas differed significantly from one another (one-way analysis of variance, $P < 0.0001$). Student's t-test results (Table 4) showed that the mean $^{87}Sr/^{86}Sr$ ratio of plants in the Mikawa highlands was significantly higher than that of plants of Atsumi Peninsula, the Yumihari Mountains, or Chita Peninsula. The mean $^{87}Sr/^{86}Sr$ ratio of plants in the West Mikawa Plain was not significantly different from the mean ratios in the other areas.

A sea-spray effect was observed in the $^{87}Sr/^{86}Sr$ ratios of coastal areas (Fig. 2B). Even in the northern study area, plants from coastal areas had lower $^{87}Sr/^{86}Sr$ isotope ratios than those from inland areas. The lowest $^{87}Sr/^{86}Sr$ ratios occurred in the inland part of the eastern study area. The Atsumi Peninsula is probably greatly affected by sea spray, causing most of the plant $^{87}Sr/^{86}Sr$ ratios to equilibrate toward that of seawater and exhibit small variation. The dominant contribution of marine-derived strontium from rainwater and sea-spray was also observed in the coastal Hawaiian soil (Whipkey, et al., 2000) and in the British biospheres (Evans et al., 2010).

5.2. Strontium isotope ratios of tooth enamel and bone

The strontium isotope ratio (mean ± 1 SD) in human tooth enamel was 0.70925 ± 0.00081, varying in the range of 0.70658–0.71074 (Table 1, Fig. 3). Human bone had a $^{87}Sr/^{86}Sr$ ratio of 0.70914 ± 0.00010, with a range of 0.70903–0.70939. The standard deviation of the ratio in tooth enamel was larger than that in bone, indicating that the Inariyama population included some immigrants from other areas, provided that diagenetic effects did not alter the biogenic enamel Sr.

Strontium isotopic records in bone hydroxyapatite are generally susceptible to diagenetic alteration because of the relatively porous crystal structure of bone hydroxyapatite (Hoppe et al., 2003; Sillen, 1986; Trickett et al., 2003). Specifically, compact bone from the rib, such as we studied, is apparently more porous than the compact bone of the long bones. Diagenesis would be expected to narrow the primary $^{87}Sr/^{86}Sr$ variation in the bone samples, altering the ratio toward that of the ambient groundwater (Bentley, 2006). Soil water has the same Sr isotope ratio as plants growing in the soil (Nakano et al., 2001). The Sr isotope ratios of plants at the Inariyama site indicate that the sediments there were derived from metamorphic rocks with a high Sr isotope ratio (about 0.7100) from the northern Mikawa highlands as well as from metamorphic rocks and limestone with a lower Sr isotope ratio (0.7086) from the eastern Yumihari Mountains. Another source of Sr is seawater, which has a ratio of 0.70918 (Faure and Mensing, 2005), because in coastal areas $^{87}Sr/^{86}Sr$ ratios can be dominantly determined by that of sea spray or rainwater with a high sea-salt component (Bentley, 2006; Whipkey et al., 2000). A high contribution of Sr from the sea-salt component of precipitation at the Inariyama site is compatible with the findings of Nakano et al. (2006), who reported that a mean $^{87}Sr/^{86}Sr$ ratio (0.7089) in modern precipitation in Japan, measured at five sites, is close to that of seawater. Diagenetic Sr would reflect the mixing of Sr from these two sediment sources and seawater, and diagenesis would thus result in bone $^{87}Sr/^{86}Sr$ ratios of 0.7090–0.7094 in all individuals.

To evaluate the diagenesis of human bone, we compared the $^{87}Sr/^{86}Sr$ values of ribs and enamels of adolescents. Because enamel gives the $^{87}Sr/^{86}Sr$ values of the diet during late childhood and adolescence and the bone gives the averaged value for about the final 10 years of life, we assumed that the rib and enamel of an adolescent would show the same $^{87}Sr/^{86}Sr$ ratios. Among four adolescents, one individual (sample No. 236) showed almost the same $^{87}Sr/^{86}Sr$ ratios in bone and enamel, suggesting that diagenetic alteration was negligible or that the diagenetic solution had the same $^{87}Sr/^{86}Sr$ ratio as the enamel (Fig. 4). Sample No. 228 had a distinctly lower $^{87}Sr/^{86}Sr$ ratio in bone (0.7091) than in enamel (0.7097). Likewise, the remaining two individuals (No. 210 and 253) had lower $^{87}Sr/^{86}Sr$ ratios in bone than in enamel by 0.0001 and 0.0002, respectively. These Sr isotope differences suggest that the diagenetic solution had Sr with lower $^{87}Sr/^{86}Sr$ ratios than the Sr responsible for enamel mineralization.

5.3. Migration and diet in the Inariyama population

To discriminate immigrants from locals, it is necessary to delimit the “local” $^{87}Sr/^{86}Sr$ range. Our previous carbon and nitrogen isotope analyses revealed that the Inariyama people consumed considerable amounts of seafood, although the proportion in the diet differed among individuals (Kusaka et al., 2008, 2010). A large proportion of seafood in the diet causes human bone Sr ratios to equilibrate toward the seawater range of 0.70912–0.70924 (2σ range; Faure and Mensing, 2005). The mean Sr isotope ratio of plants within a radius of 10 km of the Inariyama shell mound was 0.7100 ± 0.0022 (n = 12). Because the foraging area of modern hunter-gatherers is generally within 10 km of their settlement (Binford, 2001), we consider this value to be indicative of the Sr isotope ratios of terrestrial sources used by the local Inariyama population. We assumed that the local, biologically available Sr isotope ratios were 0.7091–0.7100. Most of the observed bone and enamel Sr isotope ratios varied between 0.7091 and 0.7100 (Fig. 3), presumably reflecting the dietary mixing of marine (0.7091) and terrestrial (0.7100) resources in different proportions. The 13 of the 17 individuals whose enamel ratios were within this range were locals.

We then assessed dietary dependence on marine or terrestrial food of type 4I and 2C locals by examining their Sr isotope ratios. Tooth enamel of type 4I locals yielded a Sr isotope ratio of 0.7096 ± 0.0003, significantly higher than the tooth enamel ratio of type 2C locals of 0.7092 ± 0.0001 (Wilcoxon-test, $\chi^2 = 6.63$, $P = 0.0100$), suggesting that type 4I locals were dietarily more dependent on terrestrial food and type 2C locals on marine food.

6. Discussion

6.1. Migration and diet

Comparison of Sr isotope ratios of tooth enamel with nitrogen isotope ratios ($\delta^{15}N$) of bone collagen can reveal detailed information on human migration and diet (Fig. 5). The enamel $^{87}Sr/^{86}Sr$ ratio in one type 2C male individual (No. 241, in upper left corner of Fig. 5) exceeded that of terrestrial plants from around the Inariyama site, demonstrating that this male was an immigrant. This inference is supported by his bone collagen having the lowest $\delta^{15}N$ value, indicating heavy dependence on terrestrial resources. The Sr and N isotope signatures suggest that this male came from the northern Mikawa highlands and died less than 10 years after his entry into Inariyama society. In contrast, another type 2C individual (No. 231, in lower right corner of Fig. 5) showed the lowest Sr ratio of 0.7066, different from that expected for a diet obtained around the Inariyama site but consistent with ratios in the Yumihari Mountains (Fig. 2B). This individual might have been an immigrant who had consumed a large amount of terrestrial Sr sources from around the Yumihari Mountains. The $\delta^{15}N$ value of this individual was as high as those of type 2C locals, suggesting that this individual ate the same foods as other type 2C individuals in Inariyama. Both these two type 2C individuals (represented by No. 231 and 241) were apparently immigrants to Inariyama.

Two other individuals (No. 217 and 229) were also likely immigrants because their enamel Sr isotope ratios (0.7090) were lower than that of seawater (Fig. 5). The local range of Sr isotope ratios at the contemporaneous Yoshigo site on the eastern Atsumi Peninsula was 0.7086–0.7092 (Kusaka et al., 2009). Thus, these two individuals might have migrated from the Yoshigo site. However, the possibility that they were locals cannot be excluded because their enamel Sr isotope ratios were as low as the range of the ratio in all bones from Inariyama (Fig. 3), which is an indicator of diagenesis.

We also compared the spatial organization of Inariyama burials with the strontium isotope analysis results (Fig. 6). As noted by Harunari (1979), three main clusters of burials are discernible at the site, and type 4I and 2C individuals tended to be buried in different clusters. The north cluster comprised mainly type 4I individuals, and the middle cluster mainly type 2C individuals. The south cluster included both type 4I and 2C individuals, and could be further divided into a northern type 4I group and a southern type 2C group. All clusters included local individuals. Two possible immigrants (No. 217, 229) were buried in the north cluster, and the two other apparent immigrants (No. 241, 231) were buried in the south cluster. We suggest that immigrants were not buried separately from local individuals at Inariyama.

The hypothesis that type 4I represents locals and type 2C represents immigrants (Harunari, 1979) is not supported because locals included both type 4I and 2C individuals, although the two obvious immigrants both show type 2C tooth ablation. This trend is the same as that shown by strontium isotope analysis results for the Yoshigo population (Kusaka et al., 2009). Not all type 2C individuals were immigrants, but type 2C individuals might have been more likely to include immigrants than type 4I individuals.

Strontium isotopes cannot discriminate local people from immigrants who migrated from geological environments similar to Inariyama or from those who consumed large amounts of seafood even if they had migrated from geological environments different from Inariyama. Despite these limitations, we identified 13 individuals as locals whose enamel had $^{87}Sr/^{86}Sr$ ratios of 0.7091 to 0.7100.

6.2. Dietary differentiation

The strontium isotope analysis revealed that type 4I Sr isotope ratios were significantly higher than type 2C ratios. Type 4I Sr isotope ratios were between those of terrestrial (0.7100) and marine (0.7091) resources, and type 2C ratios were close to those of marine resources. The type 4I Sr isotope ratios were more variable than the type 2C ratios, because of the variation in dietary dependence on marine resources of type 4I locals as well as the variation in the Sr composition of local terrestrial resources. These results support the hypothesis that type 4I locals incorporated much of their Sr from terrestrial resources whereas type 2C locals incorporated much of their Sr from marine resources. Thus, dietary differences can be associated with tooth ablation patterns among the Inariyama.

Categorization by sex showed that local type 4I males had higher enamel Sr isotope ratios than local type 2C males (Fig. 3), which supports dietary differentiation among males. On the other hand, all females in our data were type 4I, so we could not test the hypothesis for females. However, both male and female local individuals with type 4I tooth ablation had higher Sr isotope ratios than type 2C males, indicating that type 4I males and females consumed foods from similar dietary sources.

When we compared Sr isotope ratios of locals with collagen $\delta^{15}N$ values (Fig. 5), type 4I locals whose enamel Sr isotope signal suggested relatively abundant consumption of terrestrial sources in their late childhood to adolescence were also dependent on terrestrial sources as adults, as indicated by relatively low collagen $\delta^{15}N$ values. Type 2C locals, who probably consumed a greater amount of marine food in their childhood, were also dependent on marine food as adults, as indicated by higher collagen $\delta^{15}N$ values. These tendencies suggest that type 4I locals and type 2C locals consumed greater amounts of terrestrial sources and marine sources, respectively, throughout their lifetime. To further confirm whether type 2C locals depended on marine resources, other indexes of stable isotope ratios such as $\delta^{13}C$ values should be applied to tooth enamel in addition to $^{87}Sr/^{86}Sr$ and $\delta^{15}N$ values.

6.3. Ritual tooth ablation and occupational differentiation

Our dietary differentiation hypothesis, which was based on carbon and nitrogen isotope analysis results (Kusaka et al., 2008), was supported by the results of strontium isotope analysis. The carbon and nitrogen isotope analyses revealed a relationship between ritual tooth ablation type and the average dietary profile during about 10 years before an individual's death. The Sr isotope analysis results on third molar enamel allow us to infer the diets during late childhood to adolescence. These methods revealed that ritual tooth ablation types were associated with differential consumption of resources through life; that is, type 4I individuals consumed mainly terrestrial food, and type 2C individuals consumed mainly marine food. If we assume that children and adults shared acquired foods in a family group, we can also infer that different types of tooth ablation represent different family groups.

When we assessed the diet in relation to sex and ritual tooth ablation type, we found that type 4I males and type 2C males consumed different food resources, whereas type 4I males and type 4I females had similar diets. In hunting-gathering subsistence societies, males usually hunt larger game while females gather plants and catch smaller animals (Kelly, 1995). In males, at least, the different ritual tooth ablation patterns might reflect occupational differentiation, between type 4I males who hunted and type 2C males that fished. Meanwhile, type 4I males and females apparently consumed similar food resources as a result of food sharing.

Interfamilial occupational differentiation is a characteristic of Arctic and Subarctic hunter-gatherers (Watanabe, 1983). Ethnographic observations of the Ainu in Hokkaido record both hunting-oriented and fishing-oriented families (or lineages) in a population (Watanabe, 1972, 1983, 1990). A similar occupational differentiation based on family and distinguished by ritual tooth ablation type might also have existed in the Inariyama population. Hunting oriented people, who mainly consumed terrestrial food, shared ritual tooth ablation type 4I, whereas fishing oriented people, who consumed a lot of marine food, shared type 2C. The ritual tooth ablation type may also identify family groups associated with particular occupational task groups, and family group identity may also be expressed in the different burial clusters in the Inariyama cemetery. The Final Jomon period society may thus have been not egalitarian but transegalitarian, containing socioeconomic inequalities. As suggested by Watanabe (1990), interfamilial differentiation by occupation or subsistence may have been an important factor in the development of Jomon society.

The occupational differentiation of the Jomon people rests on the assumption that the Inariyama human skeletal remains are contemporaneous. However, a dietary shift over time might be associated with a change of rituals, such as from heavy consumption of terrestrial resources with type 4I tooth ablation to heavy consumption of marine resources with type 2C tooth ablation. Increased dietary dependence on marine foods through time has been inferred from carbon and nitrogen stable isotope analysis of human bones from southern California (Walker and DeNiro, 1986). This possibility should be investigated through the radiocarbon dating of human skeletal remains.

7. Conclusions

We investigated the possibility of dietary differentiation in the Inariyama Jomon population. Previous carbon and nitrogen isotope analyses suggested that dietary dependence on terrestrial or marine resources was associated with different tooth ablation types. We tested whether this dietary differentiation could be detected by strontium isotope analyses. We distinguished four possible immigrants and 13 locals, with two type 2C individuals more likely to be immigrants. It is possible that some individuals identified as locals migrated from an area with similar geology, but this cannot be shown by Sr isotope ratios of enamel alone. Among locals, type 4I males and females incorporated Sr from terrestrial resources during their late childhood to adolescence, whereas type 2C males incorporated Sr from marine resources. Both the carbon and nitrogen isotope analyses and the Sr isotope results suggested a consistent trend, namely, dietary differences between type 4I and type 2C individuals throughout life. These results support dietary differentiation among Jomon peoples, and by extension, occupational differentiation into hunters and fishers. However, the possibility of a dietary shift associated with cultural change has not been excluded.

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Table 1. Results of strontium isotope analysis of the Inariyama samples

Sample No.	Sex	Age at death	Tooth ablation type	$^{87}Sr/^{86}Sr$ in enamel		Std Err	$^{87}Sr/^{86}Sr$ in bone		Std Err	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Local vs. immigrant
210	Unknown	Adolescent	2C	0.709178	±	0.000007	0.709042	±	0.000004	−17.6	8.8	Local
211	Female	Middle adult	4I	0.709987	±	0.000004	0.709050	±	0.000004	−17.6	9.4	Local
212	Male	Young adult	4I	0.709164	±	0.000003	0.709160	±	0.000004	−17.6	9.9	Local
217	Female	Young adult	4I	0.708960	±	0.000005	0.709086	±	0.000003	−17.0	9.7	Immigrant
218	Male	Young adult	4I	0.709419	±	0.000004	0.709027	±	0.000004	−17.6	10.1	Local
224	Female	Middle adult	4I	0.709682	±	0.000004	0.709082	±	0.000004	−16.2	9.7	Local
228	Female	Adolescent	4I	0.709682	±	0.000004	0.709070	±	0.000003	−18.2	8.5	Local
229	Female	Middle adult	4I	0.708983	±	0.000004	0.709181	±	0.000005	−15.4	9.9	Immigrant
231	Male	Young adult	2C	0.706585	±	0.000003	0.709109	±	0.000004	−15.0	11.2	Immigrant
232	Male	Young adult	2C	0.709172	±	0.000003	0.709111	±	0.000005	−15.1	10.4	Local
233	Male	Middle adult	2C	0.709131	±	0.000004	0.709119	±	0.000005	−14.3	11.3	Local
236	Male	Adolescent	2C	0.709144	±	0.000003	0.709193	±	0.000004	−15.1	11.6	Local
238	Male	Young adult	2C	0.709139	±	0.000004	0.709385	±	0.000004	−14.5	10.4	Local
241	Male	Middle adult	2C	0.710740	±	0.000004	0.709322	±	0.000004	−17.7	7.3	Immigrant
249	Male	Middle adult	4I	0.709541	±	0.000004	0.709107	±	0.000004	−18.0	9.3	Local
251	Male	Young adult	2C	0.709321	±	0.000004	0.709164	±	0.000004	−15.1	10.2	Local
253	Female	Adolescent	4I	0.709394	±	0.000006	0.709236	±	0.000004	−16.8	9.3	Local

Table 2. Results of strontium isotope analysis of plants in the study area

Sample No.	Specific name	Latitude	Longitude	$^{87}Sr/^{86}Sr$		Std Err
AP41	*Myrica rubra*	34.7092	137.3654	0.709637	±	0.000004
AP42	*Quercus glauca*	34.7722	137.3845	0.709299	±	0.000004
AP43	*Cinnamomum camphora*	34.8241	137.3934	0.710236	±	0.000004
AP44	*Cleyera japonica*	34.8054	137.5110	0.709365	±	0.000004
AP45	*Prunus speciosa*	34.8264	137.5741	0.705594	±	0.000003
AP46	*Castanopsis cuspidata*	34.7636	137.5047	0.709931	±	0.000004
AP47	*Symplocos glauca*	34.6888	137.5544	0.709120	±	0.000004
AP48	*Aphananthe aspera*	34.7137	137.7028	0.709248	±	0.000004
AP49	*Castanopsis cuspidata*	34.8049	137.6883	0.708791	±	0.000004
AP50	*Cinnamomum okinawense*	34.8983	137.6501	0.708890	±	0.000004
AP51	*Aucuba japonica*	34.9266	137.6003	0.706549	±	0.000004
AP52	*Aucuba japonica*	34.9629	137.5702	0.709517	±	0.000004
AP53	*Illicium anisatum*	34.9749	137.4753	0.711607	±	0.000004
AP54	*Magnolia praecocissima*	34.9274	137.4307	0.709433	±	0.000003
AP55	*Illicium anisatum*	34.9669	137.4137	0.709093	±	0.000004
AP56	*Castanopsis cuspidata*	34.9238	137.3133	0.713502	±	0.000004
AP57	*Quercus acutissima*	34.8753	137.3285	0.713539	±	0.000004
AP58	*Ilex rotunda*	34.9201	137.1755	0.708634	±	0.000003
AP59	*Quercus variabilis*	34.9752	137.2650	0.709319	±	0.000004
AP60	*Lindera triloba*	35.0151	137.3583	0.713234	±	0.000004
AP61	*Castanopsis cuspidata*	35.0570	137.2357	0.710835	±	0.000004
AP62	*Ligustrum lucidum*	35.0048	137.1765	0.711223	±	0.000004
AP63	*Camellia sasanqua*	34.9275	137.0916	0.709236	±	0.000003
AP64	*Cinnamomum camphora*	34.8304	137.0243	0.709687	±	0.000004
AP65	*Cinnamomum camphora*	34.9311	137.0029	0.709506	±	0.000003
AP66	*Ilex integra*	34.9467	136.9239	0.709722	±	0.000003
AP67	*Prunus mume*	34.8807	136.9023	0.709705	±	0.000004
AP68	*Quercus glauca*	34.7940	136.9171	0.709589	±	0.000004
AP69	*Aphananthe aspera*	34.7018	136.9606	0.708952	±	0.000004
AP70	*Camellia japonica*	34.7296	136.9132	0.707620	±	0.000004
AP71	*Ilex integra*	34.7708	136.8523	0.708846	±	0.000004
AP72	*Ilex rotunda*	34.8221	136.8752	0.708650	±	0.000003
AP73	*Machilus thunbergii*	34.9459	136.8474	0.710686	±	0.000003
AP74	*Cleyera japonica*	34.9770	136.9069	0.709224	±	0.000003
AP75	*Dendropanax trifidus*	34.9790	136.9902	0.709875	±	0.000004
AP76	*Ilex rotunda*	35.0122	137.0412	0.709468	±	0.000004

Table 3. Summary of Sr isotope ratios in plants of the five study subareas

Area name	*N*	$^{87}Sr/^{86}Sr$	SD
Atsumi Peninsula	17	0.70908	0.00030
Yumihari Mountains	20	0.70862	0.00115
Mikawa highlands	25	0.71114	0.00184
West Mikawa Plain	5	0.70955	0.00024
Chita Peninsula	9	0.70922	0.00086

Table 4. Difference in mean Sr isotope ratios in plants among the five study subareas and Student's *t*-test results (unpaired data with unequal variance)

	Yumihari Mountains	Mikawa highlands	West Mikawa Plain	Chita Peninsula
Atsumi Peninsula	0.00046 $P = 0.2728$	0.00206 $P < 0.0001$*	0.00048 $P = 0.4626$	0.00014 $P = 0.7844$
Yumihari Mountains		0.00252 $P < 0.0001$*	0.00094 $P = 0.1431$	0.00061 $P = 0.2378$
Mikawa highlands			0.00158 $P = 0.0130$	0.00192 $P = 0.0002$*
West Mikawa Plain				0.00033 $P = 0.6393$

*Statistically significant

Figure legends

Fig. 1. Map of the study area showing the location of the Inariyama and Yoshigo shell mounds.

Fig. 2. (A) Geologic map of the study area, modified from the 1:200,000 integrated geologic map (Geological Survey of Japan, AIST, 2005). The circles indicate plant sampling locations with sample numbers. The circles of AP40 and AP2 are the location of the Inariyama and the Yoshigo, respectively. The large circle indicates a 10 km range from the Inariyama. (B) Map of the geographic distribution of Sr isotope ratios in plants in the vicinity of Mikawa Bay. The graphic representation was performed with ArcGIS (ESRI, Inc.) software by using the kriging calculation method.

Fig. 3. Strontium isotope ratios in human tooth enamel and bone from Inariyama. Pairs of $^{87}Sr/^{86}Sr$ ratios, each pair generated from a different individual, are shown distributed along the horizontal axis, and the individuals are further categorized by sex and ritual tooth ablation type. The gray horizontal bar indicates the local $^{87}Sr/^{86}Sr$ range of 0.7091–0.7100.

Fig. 4. Strontium isotope ratios in human tooth enamel and bone from Inariyama categorized by age at death. The gray horizontal bar indicates the local $^{87}Sr/^{86}Sr$ range of 0.7091–0.7100.

Fig. 5. Strontium isotope ratios in human tooth enamel and nitrogen isotope ratios ($\delta^{15}N$) in bone collagen of individuals from Inariyama. Collagen data are from Kusaka et al. (2008). The dark gray horizontal bar indicates the seawater $^{87}Sr/^{86}Sr$ range of 0.7091–0.7092. The light gray horizontal bar indicates the local $^{87}Sr/^{86}Sr$ range of 0.7091–0.7100.

Fig. 6. Plan showing burials at the Inariyama site, modified from Harunari (1979) and Kiyono (1969). Analyzed burials are those of individuals whose bones and teeth were used for isotope analyses. Immigrants are marked with an asterisk and sample number. Large circles delimit arbitrarily defined burial clusters.

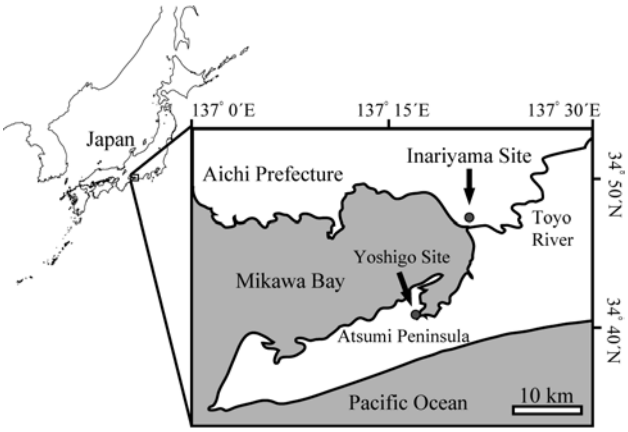

Japan
137° 0′E
137° 15′E
137° 30′E
34° 50′N
34° 40′N
Aichi Prefecture
Inariyama Site
Toyo River
Yoshigo Site
Mikawa Bay
Atsumi Peninsula
Pacific Ocean
10 km

Figure 1.

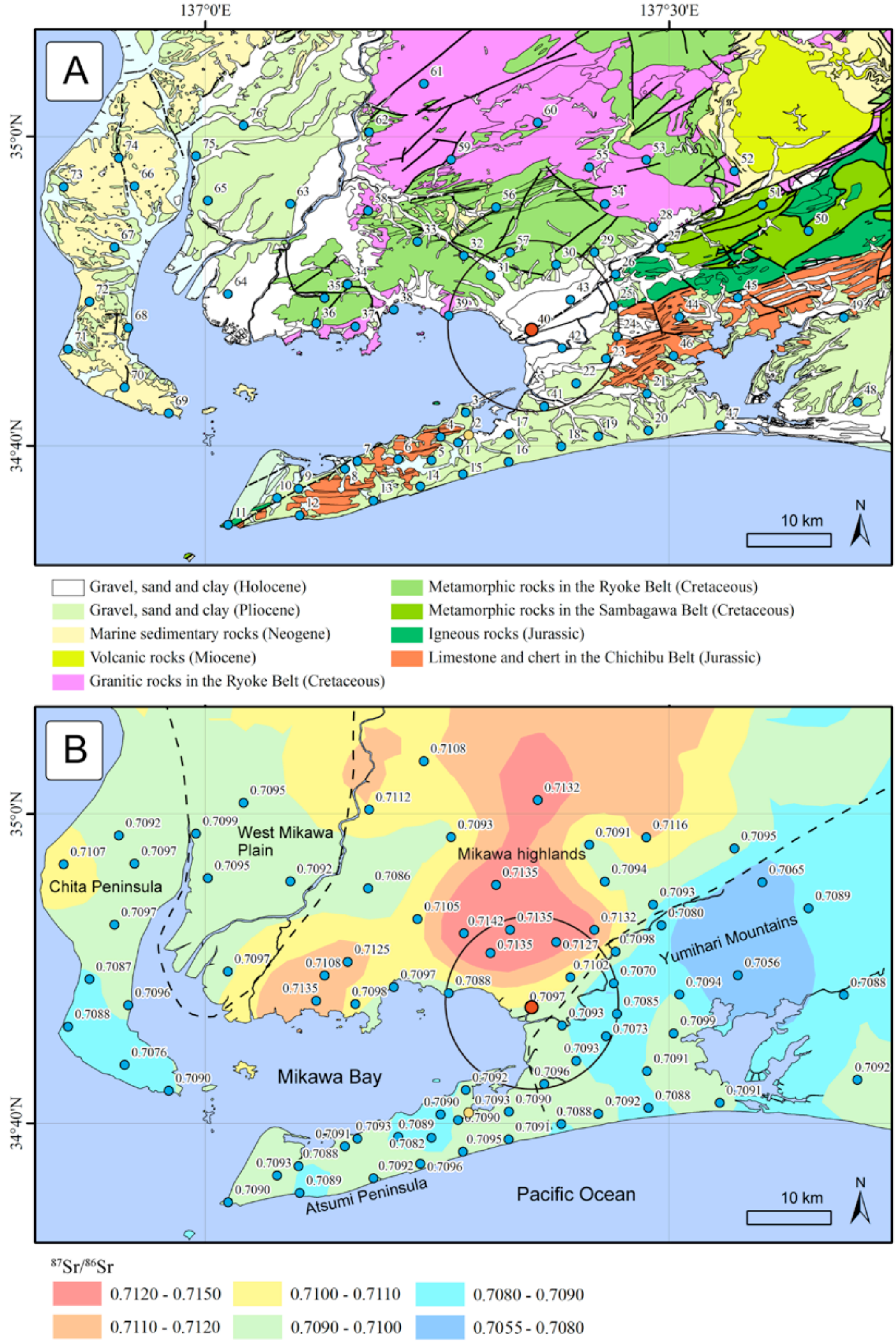

137°0'E
137°30'E
35°0'N
34°40'N
A
10 km
N
Gravel, sand and clay (Holocene)
Gravel, sand and clay (Pliocene)
Marine sedimentary rocks (Neogene)
Volcanic rocks (Miocene)
Granitic rocks in the Ryoke Belt (Cretaceous)
Metamorphic rocks in the Ryoke Belt (Cretaceous)
Metamorphic rocks in the Sambagawa Belt (Cretaceous)
Igneous rocks (Jurassic)
Limestone and chert in the Chichibu Belt (Jurassic)
B
West Mikawa Plain
Chita Peninsula
Mikawa highlands
Yumihari Mountains
Mikawa Bay
Atsumi Peninsula
Pacific Ocean
10 km
N
⁸⁷Sr/⁸⁶Sr
0.7120 - 0.7150
0.7110 - 0.7120
0.7100 - 0.7110
0.7090 - 0.7100
0.7080 - 0.7090
0.7055 - 0.7080

Figure 2.

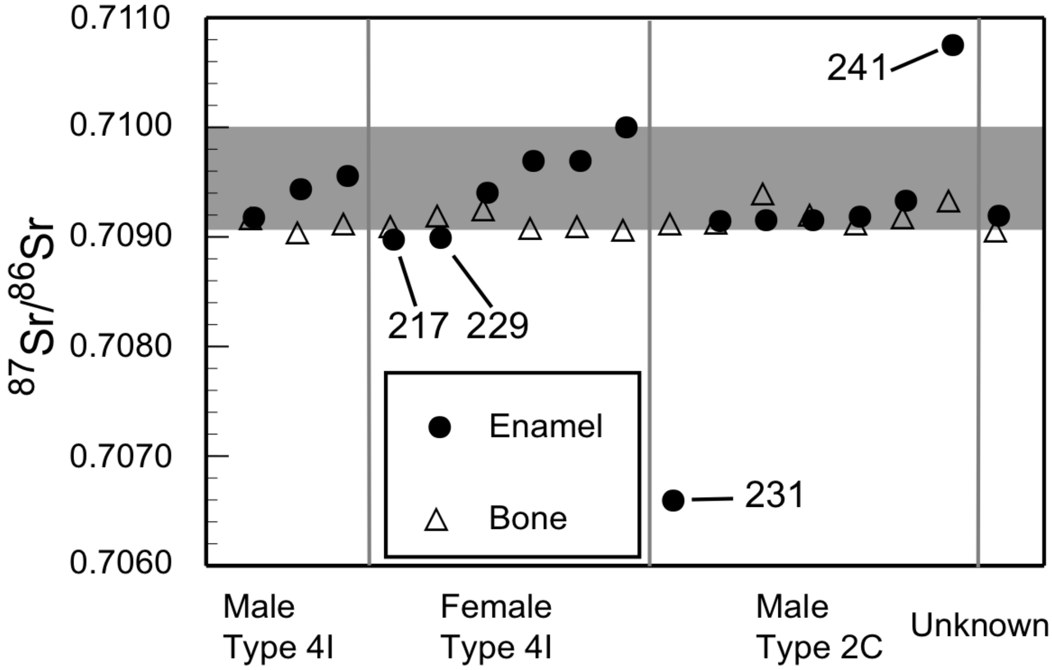
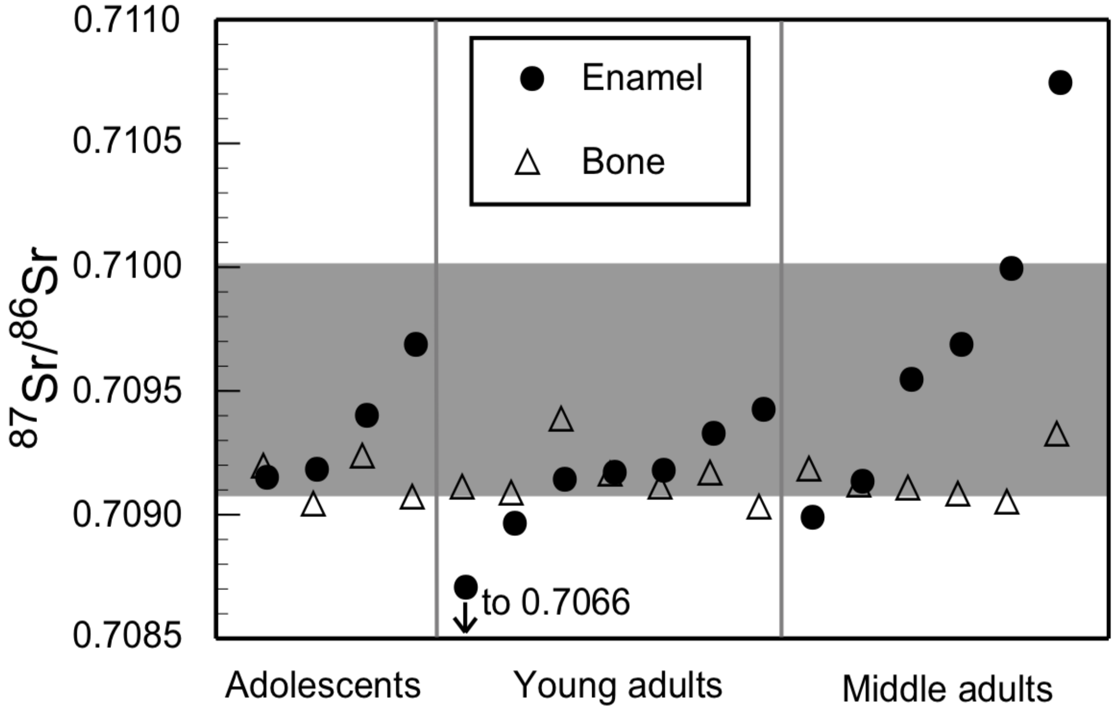

0.7110
0.7100
0.7090
0.7080
0.7070
0.7060
87Sr/86Sr
241
217
229
231
Enamel
Bone
Male
Type 4I
Female
Type 4I
Male
Type 2C
Unknown

Figure 3.



0.7110
0.7105
0.7100
0.7095
0.7090
0.7085
87Sr/86Sr
Enamel
Bone
to 0.7066
Adolescents
Young adults
Middle adults

Figure 4.

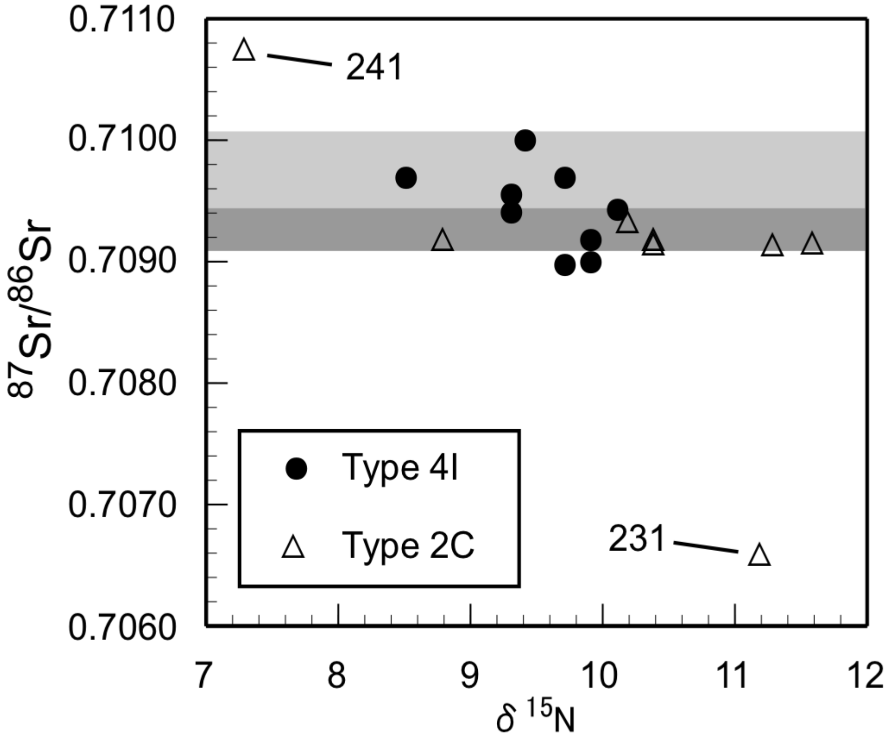

0.7110
0.7100
0.7090
0.7080
0.7070
0.7060
87Sr/86Sr
241
231
Type 4I
Type 2C
7
8
9
10
11
12
δ 15N

Figure 5.

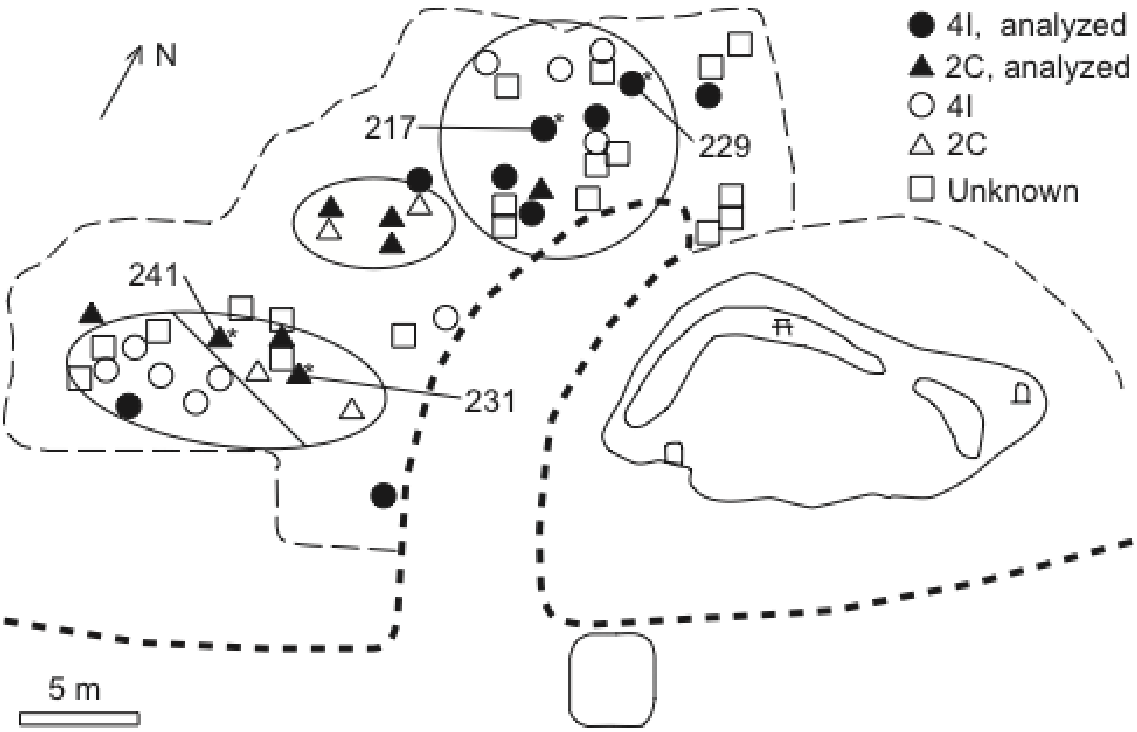


Figure 6.