Bringing Home Animals

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Evidence of increasing functional differentiation in pottery use among Late Holocene maritime foragers in northern Japan

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A B S T R A C T

Hamanaka 2 is a multi-phase coastal site in Rebun Island with a ~ 3000-year occupation sequence extending from the final-stage Jōmon and Okhotsk to the Ainu Culture period (1050 BCE-1850 CE). To examine long-term trends in food processing at the site, we collected 66 ceramic sherds across six distinct cultural layers from the Final Jōmon to the Late Okhotsk period for lipid residue analysis. Given the site's beachfront location in an open bay, with ready access to abundant maritime resources, we predicted that the pottery would consistently have been used to process aquatic resources throughout all cultural periods. Though aquatic lipids dominated across the site sequence, the history of pottery use at the site proved more complex. Evidence of plant processing was found in all cultural phases, and from the Epi-Jōmon/Late Final Jōmon transition onwards 30% of the vessels were being used to process mixed dishes that combined both marine and terrestrial resources. By the start of the Okhotsk phase, separate sets of resources were being processed in different pots, suggesting functional differentiation in the use of pottery, and the rise of new kinds of cuisine – including the processing of millet. We tentatively explain these results as a consequence of the growing incorporation of Rebun Island into wider regional trade and interaction networks, which brought new kinds of resources and different social dynamics to Northern Hokkaido in the Late Holocene.

1. Introduction

Rebun Island is strategically located at the juncture of island chains that link diverse cultural spheres, including the Sakhalin Island, the Kuriles, Kamchatka and Hokkaido, and has served as conduits for people, goods and ideas across the maritime Northeastern Asia (Fig. 1). The emergence of the seafaring Okhotsk Cultures expanded on the scale and volume of these interactions, introducing cultigens, domesticated animals and new cultural traditions in Hokkaido between the 6th and 10th centuries CE[1] (Ohyi, 1975; Amano, 2003; Crawford, 2011). Given the island's location and uninterrupted settlement history – overlapping with the Late/Final Jōmon transition, the appearance of the Epi-Jōmon groups and the emergence of the Susuya and the Okhotsk Cultures in the Late Holocene – Rebun may be considered to capture the cultural dynamics of the northern Hokkaido region.

Recently, excavations on the northern coast of Rebun Island at the Funadomari Bay, Hamanaka 2 site, have uncovered a stratified succession of eight cultural layers dating back from the Final Jōmon (~1050–350 BCE) to the Historical Ainu period (~1550–1850 CE) (Hirasawa and Kato, 2019). Over the course of this extended settlement history, the Hamanaka 2 site was occupied by prehistoric communities with a subsistence primarily focused on exploiting the abundant aquatic resources available in the local marine ecosystem (Naito et al., 2010; Miyata et al., 2016). It is unclear, however, to what extent trading and other cultural interactions impacted the local subsistence economy. At the Hamanaka 2 site, archaeobotanical evidence indicates that wild plants were used since the Late Final Jōmon/ Epi-Jōmon periods, whereas barley (*Hordeum vulgare*) was introduced in the Early Okhotsk period (Leipe et al., 2017). Moreover, the Okhotsk – also known for their complex animal mythology – transported adult bears and bear cubs (*Ursus arctos*) to Rebun from the Hokkaido mainland for ceremonial activities, while also practicing small-scale pig (*Sus scrofa inoi*) and dog (*Canis domesticus*) rearing in Rebun Island (Masuda et al., 2001; Watanobe et al., 2001; Hirasawa and Kato, 2019).

In order to understand how these diverse resources were processed and consumed on Rebun Island, we undertook lipid residue analysis of pottery cooking vessels from a total of six cultural phases at the Hamanaka 2 site. Indeed, ceramic containers provide a reliable chrono-

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[1] Dates referring to the Historical Ainu period are historical dates. Dates referring to pre-Ainu periods (e.g. late-stage Jōmon, Okhotsk and Satsumon), unless stated otherwise, are calibrated, calendar radiocarbon dates.

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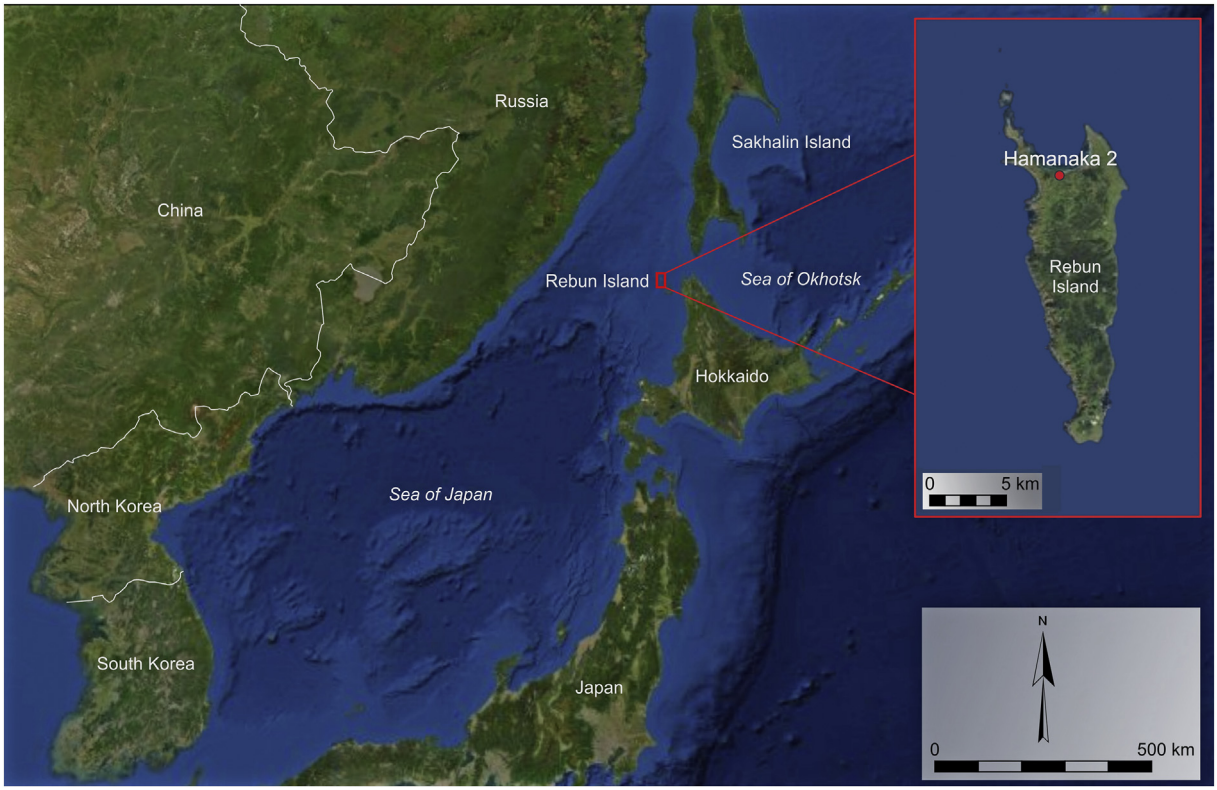

Fig. 1. Map of northeast Asia showing the location of the study site in Rebun Island, Hokkaido (Japan).

cultural context for each occupation layer studied, while the clay matrix's tendency to absorb and preserve organic remains such as lipids for extremely long periods of time (Evershed, 2008; Craig et al., 2013) ensures the biomolecular remains discovered inform of the ancient use of the vessel.

Use of pottery by hunter-gatherers in Northeast Asia has a much deeper history that extends back into the Late Glacial. Previous studies have demonstrated that early pottery in East Asia was first used to process aquatic resources across the Japanese archipelago (Craig et al., 2013) and the lower Amur (Shoda et al., 2020), and that this specialized function persisted into the Holocene (Lucquin et al., 2018), subsequently spreading into other areas, such as the Sakhalin Island (Gibbs et al., 2017) and the Korean peninsula (Shoda et al., 2017). The objective of the present study is therefore to examine whether this pattern of pottery use persisted beyond the Jōmon Culture period and into the Late Holocene in northern Hokkaido. More specifically, we aimed to test whether pottery at the Hamanaka 2 was used exclusively to process aquatic resources, including marine fish and sea mammals, or whether containers were used with products from diverse sources, including plant and terrestrial animal food webs.

2. Research context

2.1. Culture-history

The island of Hokkaido has a distinct cultural trajectory from the rest of the Japanese archipelago, with foraging persisting there as the prevalent subsistence strategy throughout the Jōmon Culture period and into the historic age. In the Late Holocene period, the Final Jōmon (1050–350 BCE) and Epi-Jōmon (350 BCE-350 CE) cultures in general comprise seasonally mobile forager communities with gradually declining demographics and moderate social differentiation (Fig. 2). Especially the Epi-Jōmon communities, however, should be viewed as mixed economies that complement hunting, fishing and gathering with small-scale wild plant use and dog breeding – while also procuring prestigious goods and iron ware through trading. This hybrid subsistence model is further developed following the emergence of the Okhotsk Cultures in the 5th–11th century CE, when the cultural and population dynamics in northern Hokkaido see a drastic change.

Indeed, the Okhotsk Cultures consist of mobile marine hunter and trader communities that derive their cultural and genetic ancestry from the lower Amur, Sakhalin and Hokkaido regions. In Hokkaido, the Okhotsk initially appear in Rebun Island (~5-6th century CE), from where a rapid expansion reaches the northern and eastern coasts of Hokkaido (~7th century CE), and, finally the Kuriles (~8th century CE). While strongly reliant on the marine food web for subsistence, the Okhotsk show a diverse economy where aquatic resources are complemented by cultigens such as barley and domesticated animals such as the pig and dog. The Okhotsk also exhibit a strong cultural identity and notable social differentiation, that were likely maintained through an elaborate animal mythology and the celebration of rituals, such as the Cult of the Bear (Akino, 1999; Utagawa, 1999; Weber et al., 2013). In turn, pottery was used extensively throughout the Okhotsk period in both cooking and burial contexts, with preliminary analyses of bulk stable isotopes in charred surface crusts in Eastern Hokkaido indicating container function to be closely related to the processing of marine aquatic resources (Kunikita, 2016; Kunikita et al., 2017). Moreover, the Okhotsk ceramic ware (Fig. 3) have proven useful in establishing a relative chronology for the culture in northern Hokkaido, where stylistic changes in decoration are found to track larger cultural and demographic trends (Deryugin, 2008; Ono, 2008). These cultural sequences are clearly visible in the material records of well-stratified sites such as Hamanaka 2 and Kafukai 1 in Rebun Island.

Towada-type decoration is associated with the Early Okhotsk period (~5-6th century CE) and the earliest signs of the Okhotsk Culture in Hokkaido, while the Kokumon style pottery is attributed to the expansive Middle Okhotsk phase in the 6th and 7th centuries CE. In turn, the Chinsenmon-type decoration is assigned to the peaking Late Okhotsk period (~8th–9th century CE), whereas the Motochi-ware is considered the Final Okhotsk period – and the phase when the culture

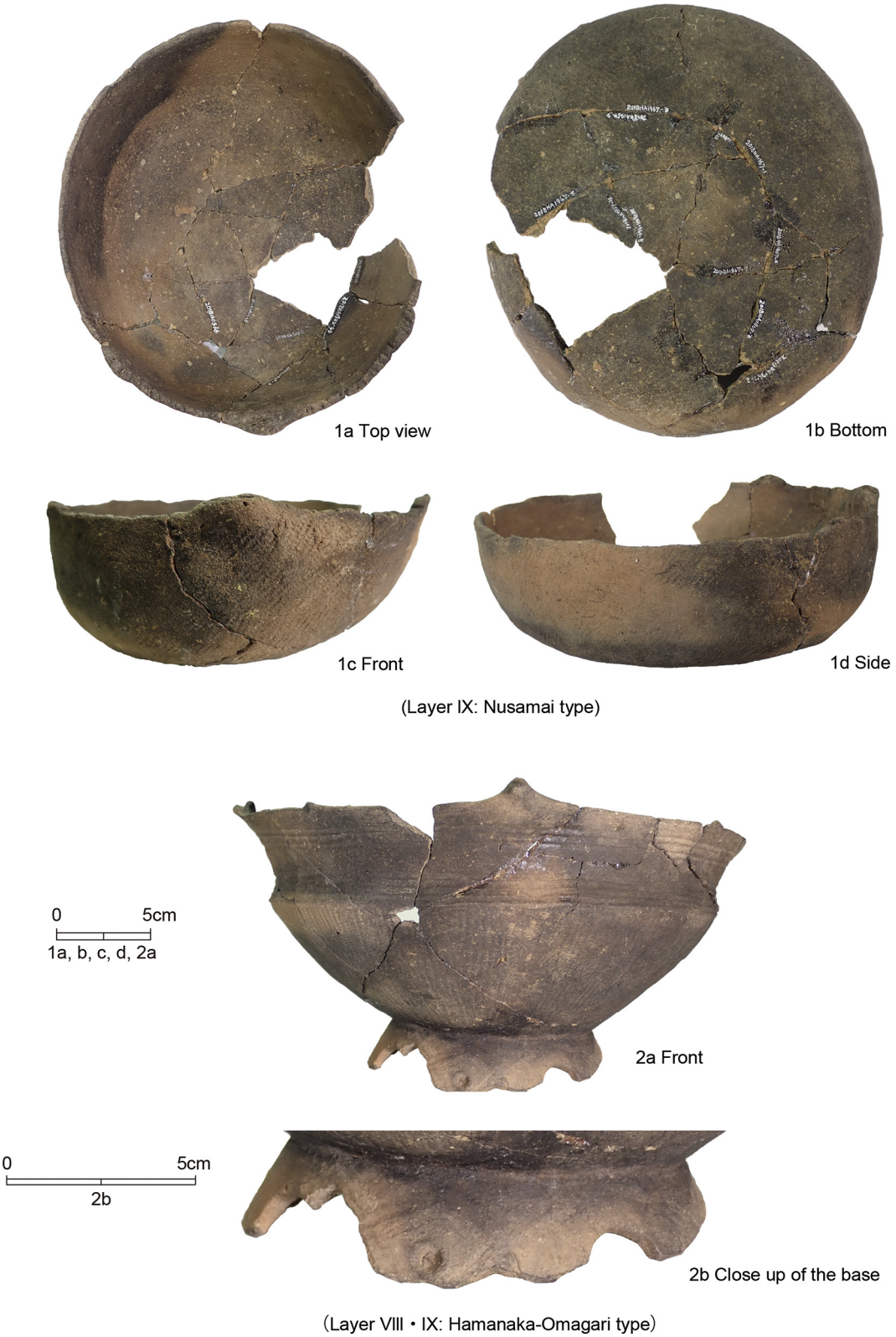

Fig. 2. The most common pottery styles associated with the Final Jōmon (1050–350 BCE) culture contexts in layers IX and VIII at the Hamanaka 2 site (Sakaguchi, 2019).

enters a terminal decline between the 10th and 11th centuries CE (Ono, 2008). In Eastern Hokkaido, where this periodization is not applicable, the end of the Okhotsk is attributed to the culture's amalgamation with the Satsumon Culture and the subsequent formation of the Tobinitai Culture (for instance, see Hudson, 2004). Later, in Eastern Hokkaido the Tobinitai are replaced by the Ainu Cultures – seen as the genetic and cultural descendants of the Okhotsk and Satsumon people (Sato et al., 2009) – in the 13th century (Onishi, 2003; Amano, 2003). In Hokkaido, the Ainu would inhabit various ecological niches and practice a mixed economy (hunting, fishing and gathering, as well as animal husbandry

Fig. 3. Examples of the four most common primary decorative motifs for the Northern Hokkaido Okhotsk Culture pottery, present at the Hamanaka 2 site in layers V, IV, IIIa-e and IIb-c.

and millet and wheat farming) in culturally heterogeneous groups until socially marginalized as a result of the arrival of the Japanese farmers from Honshu in the second half of the 19th century (Watanabe, 1999).

2.2. Study site

Rebun Island is a hilly, wedge-shaped island in the Sea of Japan, located ~50 km west of Cape Nossappu, the northernmost tip of Hokkaido, and ~ 90 km of Sakhalin island to the north. The island has a maximum length and width of 20 km and 6 km, respectively, and a land area of ~80 km^2. Its highest point is Mt. Rebun at 490 m, which is considerably lower than the highest point of Rishiri Island (Mt. Rishiri, 1718 m), a round-shaped island with a conical volcano at its centre, situated ~10 km to the southeast from Rebun Island.

The region is found within the subarctic climate zone. The local climate is primarily controlled by the East Asian Monsoon System and marked by strong seasonal cycles (Igarashi, 2013). The summers tend to be dry and temperate, while the winters are humid and stormy, with the East Asian Winter Monsoon circulation and the Tsushima Warm Current producing heavy snowfall and preventing the formation of sea ice in the Sea of Japan (Nikolaeva and Shcherbakova, 1990). The vegetation on the island is dominated by cool temperate and boreal woody plants and classified within the cool mixed forest biome (COMX) zone (Igarashi, 2013).

Compared to the diverse ecosystems of the much larger Honshu and Hokkaido islands, Rebun Island has a low biodiversity. For instance, no large terrestrial mammals, such as the brown bear (*Ursus arctos*) or deer (*Cervus nippon*), exist there naturally. However, the island provides access to abundant aquatic resources, with offshore fishing concentrated on marine mammal, fish and shellfish species. These resources are complemented by birds, especially seabirds such as albatross (*Aves: Diomedeidae*), that in the past were hunted for their meat at coastal and offshore loci (Eda et al., 2016). Furthermore, salmonid and freshwater fish resources are available in the island's riverine network as well as in Lake Kushu, a nearby inland lake located at Funadomari Bay. Located on the northern coast of Rebun Island, at Funadomari Bay, the Hamanaka site complex consists of shell-midden type deposits on top of a coastal sand dune (Hirasawa and Kato, 2019). The deposits are formed as a result of human activities that accumulate sediment, ecofacts and cultural materials on the site during a span of > 3000 years

(Sakaguchi, 2007). Being a well-stratified site with a long occupation history and on the pathway of migratory routes from in and out of (northern) Japan, the Hamanaka 2 site provides an excellent opportunity to track periodical changes in diet, subsistence and cultural dynamics among the region's communities.

2.3. Subsistence

Located at a beachfront, the site function of Hamanaka 2 evolves throughout its occupation history. After serving as a processing site and a temporary encampment for marine hunter groups in the final-stage Jōmon periods (Final Jōmon and Epi-Jōmon), the site's primary function then shifts to a burial ground in the Towada period, and finally, develops into a shell-midden in the Okhotsk Culture period (Hirasawa and Kato, 2019). That being said, most of the archaeological sites on Rebun Island appear to have been settled with a priority on accessing the resources in the marine ecosystem. To be sure, throughout the sequence of cultural layers at Hamanaka 2, the material assemblages from the final-stage Jōmon periods to the Okhotsk Culture horizons show a recurring pattern with each community relying on the marine food web for subsistence. This is evidenced by bone harpoon heads and other tools typical of maritime communities in the arctic, specialized in fishing and sea mammal hunting.

At Hamanaka 2, among material findings directly related to the local diet are animal bone remains, including abundant fish and sea mammal remains, where species such as the Pacific cod (*Gadus macrocephalus*) and the Pacific herring (*Clupea pallasii*), the Japanese sea lion (*Zalophus californianus japonicus*), the fur seal (*Callorhinus ursinus*), shellfish (ex. Sakhalin surf clam, *Pseudocardian sachalinensis*) and abalone (*Haliotidae*) appear frequently in the material record. This is especially the case with the Okhotsk Culture layers IIIa-IIIe, known as “fish bone layers” due to their high number of fish bones and remains of other aquatic species (Oba and Ohyi, 1981; Hirasawa and Kato, 2019).

In turn, terrestrial animal remains represent up to 5% share of the site's total zooarchaeological record, documented in the Epi-Jōmon/ Late Final Jōmon and Okhotsk contexts. The domesticated species dog and pig, as well as bear individuals that were brought to Rebun from Hokkaido for ceremonial purposes, are recorded most frequently among the land mammal species in the Okhotsk layers. In addition, both wild as well as domesticated plant species appear in the site's botanical record. Whereas evidence of wild plant use is documented across the site's occupation history, from the later Final Jōmon and Epi-Jōmon (VIII-VII) to the Okhotsk Culture periods, barley, the only domesticated species reported at Hamanaka 2 so far, is limited to the Okhotsk layers (Leipe et al., 2017).

3. Materials and methods

3.1. Materials

To reconstruct long-term changes in container function at the Hamanaka 2 site, sherds from a total of 66 ceramic vessels from six distinct cultural layers were collected for molecular and isotopic characterization (Table 1). All samples were selected from the Nakatani locality at Hamanaka 2, excavated between 2011 and 2017, and identified based on decorative and other morphological criteria (Hirasawa and Kato, 2019) (Fig. 4-5). However, the work concerning the identification and classification of Epi-Jōmon-style pottery at the Nakatani location (layers VIII-VII) is yet to be published, and was carried out on a preliminary basis using evidence reported from adjacent archaeological sites (see Hall et al., 2002 and references therein).

The sampled sherds show diversity in inferred container shape and size, with final-stage Jōmon pottery having a round bottom, in contrast with Okhotsk-style pottery that has a flat bottom. The overall estimated rim diameter in the sample set ranged between 90 and 620 mm and wall thickness between 3 and 8 mm. While no notable differences in average wall thickness are found between pottery styles or cultural phases sampled, the Final Jōmon-style containers in layer IX averaged significantly larger rim diameters (346 mm) compared to Kokumon, Chinsenmon and Motochi-style (235 mm) vessels (two-sample Mann-Whitney test, $p < .0001$). Such a difference in container size is likely due to functional differences between the Final Jōmon and Middle, Late and Final Okhotsk vessels.

Table 1
Cultural sequence of the Hamanaka 2 site. Timeline based on pottery typology and calibrated ^{14}C dates at the Hamanaka 2 site, supported by the general chronology for the northern Hokkaido region according to Amano (2003); Ono (2008); Weber et al. (2013); Abe et al. (2016).

Phase	Typology	Layer	Chronology
Final Okhotsk	Motochi	IIIa-IIc	950–1150 CE
Late Okhotsk	Chinsenmon	IIIb-d	750–950 CE
Middle Okhotsk	Kokumon	IIIe	550–750 CE
Early Okhotsk	Towada	V-IV	400–550 CE
Sand layer	No findings	VI	
Epi-Jōmon/ Late Final Jōmon	Unclassified Epi-Jōmon-type, Hamanaka-Omagari, Nusamai	VIII-VII	1050 BCE-350 CE
Final Jōmon	Hamanaka-Omagari, Nusamai	IX	1050–350 BCE
Sand layer	No findings	X	

3.2. Methods and sampling

The recovery of the sample material for analysis was carried out for ceramic powder and charred surface crusts with the following steps; 0.5–1 g of ceramic powder material was collected from the clay matrix by using a Dremel 3000 hand drill – a sterilized drill head was used for each individual sample – by drilling a surface area of 1–2 cm^2 on the inner wall of the vessel at ~6–7 mm depth. The outer 1–2 mm was discarded to avoid contamination from soil or handling of the sherd. In the case of food crusts > 15 mg of charred deposit material adhered to the inner wall were extracted with a sterilized scalpel and crushed mechanically. Rim sherds were prioritized due to their better preservation of organic remains (Charters et al., 1993) and visible decorative marks that allowed them to be assigned to their proper chrono-cultural contexts.

In total, 66 ceramic sherd and 24 charred interior surface crust samples were analyzed using a gas-chromatography mass spectrometry (GC–MS). In addition, compound-specific stable carbon isotope analysis of two primary alkanoic acids ($C_{16:0}$ and $C_{18:0}$) was carried out using gas-chromatography combustion isotope ratio mass spectrometry (GC-c-IRMS) (Craig et al., 2013). The lipids in ceramic and charred crust materials were recovered according to a one-step extraction and methylation protocol following a solvent treatment (Papakosta et al., 2015). Moreover, 16 of the 24 charred crust deposits examined with GC–MS had enough remaining sample material for a bulk stable carbon and nitrogen isotopic composition characterization with an elemental analyzer isotopic ratio mass spectrometry (EA-IRMS) (Evershed et al., 1994). An additional eleven inner charred surface deposits with only ~1–2 mg of sample material were selected for bulk stable isotope analysis. They could not be analyzed for lipids with GC–MS due to suboptimal sample sizes. Hence the total number of charred crusts analyzed for bulk stable isotopes was 27. A more detailed description of the analytical procedures is provided in the appendix.

It was anticipated that the pottery residue analysis at Hamanaka 2 would produce results comparable to those previously reported in other northeast Asian contexts (Lucquin et al., 2016; Gibbs et al., 2017; Lucquin et al., 2018):

- High (> 65%) rate of ω-(*o*-alkylphenyl)alkanoic acids (C_{18}–C_{22}), a diagnostic biomarker associated with repeated heating of aquatic

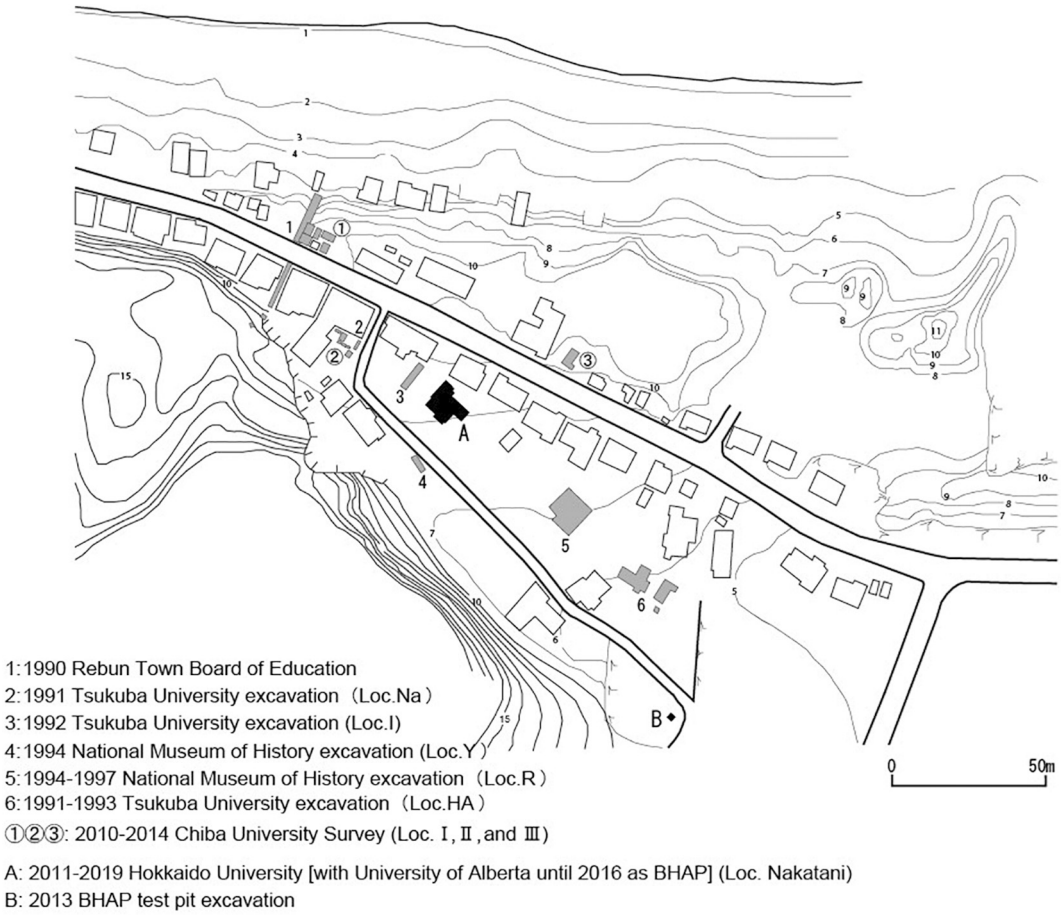

Fig. 4. Location of the Hamanaka 2 site excavation area (A) at the Nakatani locality.

oils at > 270 °C (Hansel et al., 2004).

- The full suite of isoprenoids (phytanic ac., pristanic ac. and 4,8,12-trimethyltridecanoic acid, i.e. TMTD) documented in > 65% samples (Evershed, 2008).
- Absence of diagnostic compounds associated with agriculture and terrestrial food webs such as porcine lipids (Dudd et al., 1999), or plant biomarkers such as phytosterols, long-chain alkanols and miliacin (Heron et al., 2016).
- Compound-specific isotopic values of $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ fatty acids measuring consistently > −26‰, established for the marine food web (Lucquin et al., 2016).
- Bulk stable isotope values > −26‰ for $\delta^{13}C$ and > 8‰ for $\delta^{15}N$, indicating high trophic-level aquatic source in charred surface crust deposits (Craig et al., 2013).

4. Results

4.1. Molecular analyses

A GC–MS-aided separation and quantification of absorbed and surface residues was successful in recovering interpretable lipid concentrations (> 5??g/g^{-1}) from all 66 ceramic vessels examined (n = 66 absorbed, n = 24 surface residues) (Table 2). The measured lipid preservation rate was high across the sample set, with the mean and median yields for acid-extracted absorbed residues being 3267 and 2740??g/g^{-1}, and for surface residues 1683 and 1254??g/g^{-1}, respectively. Both absorbed and charred surface crust samples were available for analysis in 24 vessels. No notable differences could be observed – save for one Final Jōmon-type vessel, which we consider an outlier – between these two sources of lipids. In the description below, we have therefore combined the evidence from absorbed and charred surface residues, with absorbed residues prioritized due to their superior preservation rate.

Saturated fatty acids were dominant across the sample set, with hexadecanoic acid being the most abundant fatty acid in 95% (63/66) of the samples. Diagnostic biomarkers associated with the presence of marine or aquatic products appear frequently across the sample set. ω-(*o*-alkylphenyl)alkanoic acids (APAAs) are compounds formed as a result of heating C_{16}-C_{22} unsaturated fatty acids. While they can also be found in some terrestrial animal and plant resources, a sample with the whole range of C_{18}-C_{22} APAAs is strictly associated with the processing of aquatic oils (Hansel et al., 2004). APAAs with carbon chain-lengths C_{18}-C_{22} were present in 52% (34/66) of the vessels analyzed. Long-chain ketones, formed during protracted heating of aquatic oils at > 270 °C (Evershed, 2008), were recorded in four (6%) samples.

Isoprenoid fatty acids (phytanic ac., pristanic ac. and 4,8,12-trimethyltridecanoic acid, i.e. TMTD) are found in marine and ruminant animal tissues, though especially TMTD is linked to the presence of aquatic oils (Lucquin et al., 2018). In total, all three isoprenoids were documented in 50% (33/66) of the containers sampled. Additionally, the source of phytanic acid – the most prevalent isoprenoid in the dataset with 90% (60/66) rate of occurrence – was examined in seven absorbed lipid extracts by measuring the sample's SRR/RRR diastereomer ratio (Lucquin et al., 2018). The ratio measured above 75,5% in five samples, indicative of a source from an aquatic rather than terrestrial ruminant organism. In the case of two samples, however, the low concentration of lipids did not allow for the phytanic acid composition to be measured accurately.

In turn, branched-chain fatty acids, associated with plants, as well as marine and ruminant animals, were detectable in all 66 vessels

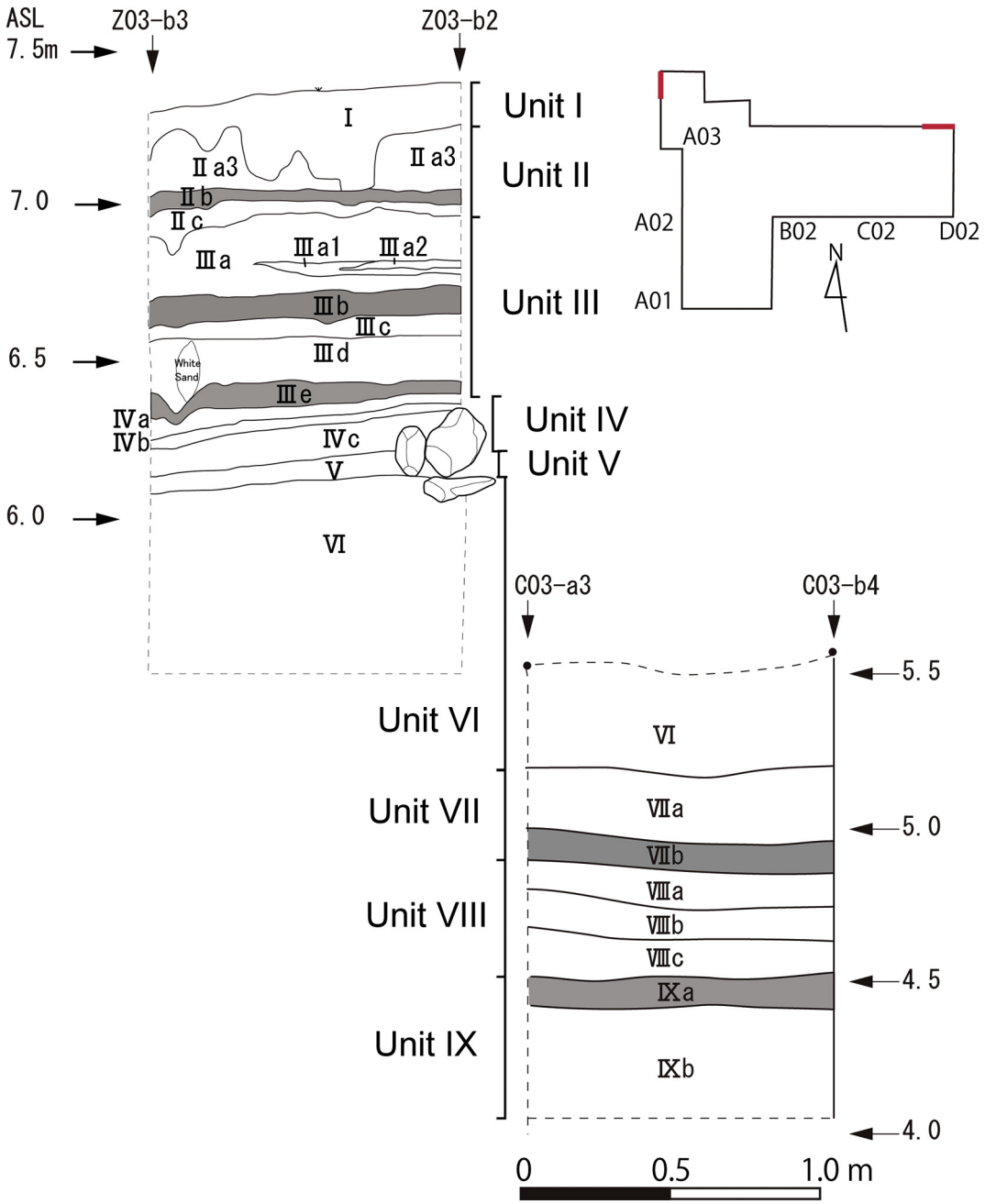

Fig. 5. The study site's stratigraphic sequence (Hirasawa and Kato, 2019). The strata marked with gray color indicate high concentrations of charcoal. Depth expressed in meters ASL, i.e. above sea level.

examined. To further examine the source of branched-chain FAs, the ratio of $C_{17:0\ br}/C_{18:0}$ (where $C_{17:0\ br}$ comprises both iso and anteiso variants, $C_{i17:0}$ and $C_{a17:0}$) was calculated for 15 absorbed lipid samples with $C_{18:0}/C_{16:0}$ ratio > 0.50 and exhibiting measurable chromatogram peaks in $C_{17:0\ br}$ (Dudd et al., 1999). The measured ratio was observed in the range of 0.012–0.094, indicating the presence of terrestrial animal resources in said samples (Hjulström et al., 2008).

Unsaturated fatty acids ($C_{16:1}$–$C_{22:1}$) were detectable in 88% (58/66) of the samples, while short-chain (C_7-C_{12}) dicarboxylic acids were found in 80% (53/66) of the samples. Both compounds are considered characteristic of either aquatic animal fats or plant lipids. That said, cholesterol was recorded in 62% (41/66) of the samples, confirming the presence of animal resources. This was further supported by the presence of C_{42}–C_{52} triacylglycerides (TAGs) – also derived from animal fats (Evershed et al., 1990) – present in 24% (16/66) of the samples.

Evidence of plant lipids were detected frequently across the sample set, with 77% (51/66) of the vessels analyzed containing at least one diagnostic plant biomarker, confirming that plant resources were used throughout the site's occupation history. That said, plant lipids represent a small, < 1%, portion of each samples' total lipid extract (TLE), indicating that plant processing was not the primary function in any of the Hamanaka 2 vessels examined. Long-chain alkanols (C_{22}–C_{32}) were detected in 55% (36/66) of the samples, while dehydroabietic acid (DHA), a terpenoid associated with tree resin, was present in 58% (38/66) of the containers examined. Resin may have been used either as sealant or the compound may also have been introduced to the clay matrix if wood was used as combustible during the firing of the vessel or from smoke during use. In addition, phytosterols (β-sitosterol, stigmasterol) were detected in two (3%) samples. Furthermore, miliacin, a derivative of (broomcorn) millet (Heron et al., 2016) was detected in

Table 2
Sample-by-sample summary of molecular, compound-specific ($\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$) and bulk stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analyses of both absorbed lipid and food crust samples. Abbreviations: DA (dicarboxylic acids), Chol. (cholesterol), DHA (dehydroabietic acid) and LCAL (long-chain alkanols), SRR/RRR (Phytanic acid diastereomer ratio). APAAs (*ω*-(*o*-alkylphenyl)alkanoic acids), LCK (long-chain ketones), Phytanic acid (Phyt.), Pristanic acid (Prist.), and TMTD (4,8,12-trimethyltridecanoic acid) were considered the primary diagnostic biomarkers for aquatic lipids.

Sample code	Phase	Lipid yield μg^{-1}	Aquatic biomarkers	Other diagnostic compounds	Sample type	$\delta^{13}C_{16:0}$ (SD) (‰)	$\delta^{13}C_{18:0}$ (SD) (‰)	$\Delta^{13}C$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Interpretation
2016HA-0734	Final Jōmon	940	$C_{16–22}$ APAA, Phyt.	$C_{8–11}$ DA, Chol., LCAL, DHA	Absorbed	– 22.99 (0.018)	– 22.84 (0.180)	0.15	– 18.20	15.94	Marine
2016HA-0735	Final Jōmon	2970	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., LCAL, DHA	Absorbed, crust	– 22.94 (0.060)	– 22.62 (0.670)	0.32	– 21.59	13.64	Marine
2016HA-0736	Final Jōmon	3550	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–11}$ DA, Chol., LCAL, DHA	Absorbed	– 23.67 (0.410)	– 23.40 (0.030)	0.27	– 21.97	12.80	Aquatic
2016HA-0812	Final Jōmon	2420	$C_{18–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., LCAL, DHA	Absorbed	– 23.37 (0.004)	– 23.34 (0.030)	0.03	– 19.45	13.80	Marine
2016HA-0819	Final Jōmon	4330	Phyt., Prist.	$C_{7–11}$ DA, Chol., LCAL, DHA, $C_{17:0br}/C_{18:0}$ 0.058	Absorbed	– 23.22 (0.103)	– 23.27 (0.004)	– 0.05			Aquatic, Terrestrial animal?
2016HA-0823	Final Jōmon	3050	$C_{16–22}$ APAA, TMTD, LCK, Phyt., Prist.	$C_{7–12}$ DA, LCAL, DHA	Absorbed, crust	– 22.73 (0.037)	– 22.68 (0.020)	0.05	– 21.05	14.71	Marine
2016HA-0902	Final Jōmon	4430	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, DHA	Absorbed, crust	– 23.73 (0.066)	– 24.05 (0.010)	– 0.32			Aquatic
2016HA-0908	Final Jōmon	820	Phyt., Prist.	$C_{8–12}$ DA, LCAL, DHA	Absorbed	– 23.61 (0.033)	– 24.81 (0.074)	– 1.20	– 22.40	13.66	Aquatic
2016HA-1004	Final Jōmon	8150	$C_{16–22}$ APAA, TMTD, LCK, Phyt., Prist.	$C_{7–12}$ DA, LCAL, DHA	Absorbed	– 23.02 (0.532)	– 23.52 (0.139)	– 0.50	– 22.38	15.12	Marine
2016HA-1025	Final Jōmon	1070	$C_{16–22}$ APAA, Phyt.	$C_{7–12}$ DA, LCAL, Chol., DHA	Absorbed, crust	– 23.18 (0.149)	– 23.47 (0.203)	– 0.29	– 20.93	17.11	Marine
2016HA-1050	Final Jōmon	440	Phyt., Prist.	$C_{9–11}$ DA, Chol., DHA	Absorbed	– 23.10 (0.006)	– 23.10 (0.052)	0.00	– 19.93	14.64	Marine
2016HA-1093	Final Jōmon	840	Phyt.	$C_{8–11}$ DA, DHA $C_{17:0br}/C_{18:0}$ 0.034	Absorbed	– 22.86 (0.018)	– 23.00 (0.088)	– 0.14	– 21.92	19.20	Marine, Terrestrial animal?
2017HA-1560	Final Jōmon	2760	$C_{18–22}$ APAA, Phyt., Prist.	$C_{7–12}$ DA	Absorbed, crust	– 24.74 (0.021)	– 24.06 (0.108)	0.67	– 19.70	14.22	Aquatic
2017HA-1555	Final Jōmon	1700	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, DHA	Absorbed, crust	– 23.11 (0.080)	– 22.32 (0.011)	0.78	– 22.71	14.83	Marine
2017HA-0913	Final Jōmon	1750	TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol., DHA	Absorbed, crust	– 22.68 (0.059)	– 21.52 (0.028)	1.15	– 20.45	14.44	Marine
2017HA-0911	Final Jōmon	1560	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, DHA	Absorbed, crust	– 23.52 (0.065)	– 22.45 (0.066)	1.06	– 20.79	13.87	Marine
2016HA-0406	Epi–Jōmon/Late Final Jōmon	3210	Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol., DHA	Absorbed	– 23.98 (0.034)	– 24.15 (0.128)	– 0.17			Aquatic
2016HA-0816	Epi–Jōmon/Late Final Jōmon	6100	Phyt., Prist.	$C_{7–10}$ DA, LCAL, Chol., DHA, $C_{17:0br}/C_{18:0}$ 0.069	Absorbed, crust	– 22.79 (0.129)	– 23.10 (0.030)	– 0.31			Marine, Terrestrial animal?
2016HA-SG0191	Epi–Jōmon/Late Final Jōmon	50	–	DHA, $C_{17:0br}/C_{18:0}$ 0.027	Absorbed, crust	– 24.57 (0.035)	– 22.53 (0.654)	2.04	– 22.87	15.28	Marine, Terrestrial animal?
2016HA-0368	Epi–Jōmon/Late Final Jōmon	2030	Phyt., Prist.	$C_{8–11}$ DA, LCAL, Chol.	Absorbed	– 24.19 (0.426)	– 24.40 (1.200)	– 0.22			Aquatic
2016HA-0586	Epi–Jōmon/Late Final Jōmon	8910	Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol.	Absorbed	– 22.98 (0.451)	– 21.68 (0.041)	1.29			Marine
2016HA-0073	Epi–Jōmon/Late Final Jōmon	710	$C_{16–22}$ APAA, Phyt.	$C_{8–12}$ DA, Chol.	Absorbed	– 25.30 (0.039)	– 24.99 (0.432)	0.30			Aquatic
2016HA-0507	Epi–Jōmon/Late Final Jōmon	5780	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol.	Absorbed	– 25.22 (0.033)	– 24.45 (0.004)	0.76			Aquatic
2017HA-0063	Epi–Jōmon/Late Final Jōmon	70	–	β-sitosterol, Chol., LCAL, DHA, $C_{17:0br}/C_{18:0}$ 0.032	Absorbed	– 28.76 (0.142)	– 28.54 (0.187)	0.21			Porcine, Plant
2017HA-0320	Epi–Jōmon/Late Final Jōmon	9690	$C_{16–22}$ APAA, Phyt.	$C_{7–12}$ DA, LCAL	Absorbed, crust	– 22.95 (0.105)	– 21.54 (0.210)	1.40	– 22.5	17.24	Marine

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Table 2 (*continued*)

Sample code	Phase	Lipid yield μg^{-1}	Aquatic biomarkers	Other diagnostic compounds	Sample type	$\delta^{13}C_{16:0}$ (SD) (‰)	$\delta^{13}C_{18:0}$ (SD) (‰)	$\Delta^{13}C$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Interpretation
2016HA-0856	Towada	6380	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., LCAL, DHA	Absorbed	– 23.88 (0.054)	– 24.20 (0.124)	– 0.32			Aquatic
2016HA-0450	Towada	7870	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA	Absorbed	– 23.21 (0.008)	– 22.57 (0.030)	0.63			Marine
2016HA-SG0133	Towada	160	$C_{18–22}$ APAA, Phyt.	$C_{17:0br}/C_{18:0}$ 0.013, SRR/RRR 77.7%	Absorbed	– 28.19 (0.103)	– 28.48 (0.330)	– 0.30			Aquatic, Terrestrial animal
2016HA-0320	Towada	190	–	LCAL, DHA, $C_{17:0br}/C_{18:0}$ 0.014	Absorbed	– 29.10 (0.066)	– 29.00 (0.021)	0.09			Porcine
2011HA-SG0143	Towada	7910	$C_{16–22}$ APAA, TMTD, LCK, Phyt., Prist.	$C_{7–12}$ DA, Chol.	Absorbed	– 23.66 (0.054)	– 23.02 (0.301)	0.63			Marine
2011HA-1638	Towada	2720	$C_{16–22}$ APAA, Phyt., Prist.	$C_{8–12}$ DA, Chol.	Absorbed, crust	– 23.59 (0.024)	– 22.32 (0.090)	1.26			Marine
2011HA-3374	Towada	2910	$C_{16–22}$ APAA, TMTD, LCK, Phyt., Prist.	$C_{8–12}$ DA	Absorbed	– 22.40 (0.003)	– 22.29 (0.002)	0.10	– 22.59	15.18	Marine
2011HA-3992	Towada	120	Phyt.	β-sitosterol, Stigmasterol, Chol., DHA, $C_{17:0br}/C_{18:0}$ 0.012, SRR/RRR 83.9%	Absorbed	– 28.55 (0.185)	– 28.46 (0.067)	0.08			Porcine, Plant
2017HA-0073	Towada	20	–	DHA, $C_{17:0br}/C_{18:0}$ 0.013	Absorbed	– 26.12 (0.118)	– 26.21 (0.412)	– 0.09			Porcine
2016HA-0878	Kokumon	750	TMTD, Phyt.	Chol.	Absorbed	– 25.14 (0.011)	– 24.86 (0.052)	0.28			Aquatic
2016HA-0881	Kokumon	3080	TMTD, Phyt., Prist.	$C_{8–10}$ DA, Chol., LCAL, DHA	Absorbed, crust	– 23.93 (0.105)	– 24.29 (0.063)	– 0.36	– 21.61	16.50	Aquatic
2016HA-0887	Kokumon	6200	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–10}$ DA, Chol., LCAL, DHA	Absorbed	– 23.69 (0.047)	– 24.06 (0.030)	– 0.37			Aquatic
2016HA-0867	Kokumon	2090	TMTD, Phyt., Prist.	$C_{8–10}$ DA, Chol.	Absorbed	– 24.57 (0.055)	– 25.00 (0.042)	– 0.43			Aquatic
2016HA-0868	Kokumon	3040	TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol.	Absorbed	– 22.78 (0.036)	– 23.04 (0.079)	– 0.26			Marine
2016HA-0875	Kokumon	3730	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL,Chol., DHA	Absorbed, crust	– 22.63 (0.076)	– 22.90 (0.041)	– 0.27	– 23.11	12.22	Marine
2016HA-1001	Kokumon	7830	TMTD, Phyt., Prist.	Miliacin, $C_{7–10}$ DA, LCAL, Chol., $C_{17:0br}/C_{18:0}$ 0.094, SRR/RRR 99.7%	Absorbed, crust	– 22.88 (0.065)	– 23.27 (0.045)	– 0.39			Marine, Terrestrial animal, Millet
2016HA-0861	Kokumon	70	Phyt.	DHA	Absorbed	– 25.58 (0.068)	– 27.18 (0.018)	– 1.60			Porcine, Ruminant?
2016HA-0866	Kokumon	2760	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{8–12}$ DA, LCAL, DHA	Absorbed	– 24.07 (0.052)	– 24.37 (0.001)	– 0.30			Aquatic
2016HA-0773	Kokumon	5650	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol., DHA	Absorbed, crust	– 22.94 (0.238)	– 22.43 (0.082)	0.50			Marine
2011HA-SG0201	Kokumon	330	$C_{16–22}$ APAA, Phyt., Prist.	$C_{17:0br}/C_{18:0}$ 0.028	Absorbed	– 25.02 (0.179)	– 25.46 (0.190)	– 0.45			Aquatic, Terrestrial animal?
2016HA-0752	Chinsenmon	4130	TMTD, Phyt., Prist.	$C_{8–10}$ DA, LCAL, Chol., SRR/RRR 99.7%	Absorbed	– 23.06 (0.021)	– 23.03 (0.195)	0.03			Marine
2016HA-0754	Chinsenmon	770	Phyt., Prist.	LCAL, Chol., $C_{17:0br}/C_{18:0}$ 0.016	Absorbed	– 23.79 (0.103)	– 23.73 (0.021)	0.06			Aquatic, Terrestrial animal?
2016HA-0777	Chinsenmon	7510	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–11}$ DA, LCAL, Chol., DHA	Absorbed, crust	– 22.63 (0.117)	– 23.29 (0.299)	– 0.66			Marine
2016HA-0790	Chinsenmon	340	$C_{16–22}$ APAA, Phyt., Prist.	$C_{11–12}$ DA, LCAL, DHA	Absorbed, crust	– 22.35 (0.002)	– 23.25 (0.209)	– 0.90	– 21.50	15.38	Marine
2016HA-0880	Chinsenmon	70	–	$C_{8–10}$ DA, LCAL, DHA, $C_{17:0br}/C_{18:0}$ 0.026	Absorbed	– 24.21 (0.349)	– 25.93 (0.293)	– 1.72			Aquatic, Terrestrial animal?
2016HA-0851	Chinsenmon	40	–	LCAL, DHA, SRR/RRR 96.8%	Absorbed	– 28.61 (0.027)	– 29.11 (0.001)	– 0.50			Porcine
2016HA-0852	Chinsenmon	3750	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol., DHA	Absorbed, crust	– 23.15 (0.444)	– 23.10 (0.458)	0.05			Marine

(*continued on next page*)

Table 2 (*continued*)

Sample code	Phase	Lipid yield μg^{-1}	Aquatic biomarkers	Other diagnostic compounds	Sample type	$\delta^{13}C_{16:0}$ (SD) (‰)	$\delta^{13}C_{18:0}$ (SD) (‰)	$\Delta^{13}C$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Interpretation
2016HA-0054	Chinsenmon	1780	Phyt., Prist.	$C_{8–11}$ DA, Chol.	Absorbed	– 23.46 (0.023)	– 22.85 (0.093)	0.60			Marine
2016HA-0228	Chinsenmon	6530	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., DHA	Absorbed, crust	– 24.55 (0.069)	– 22.42 (0.000)	2.12	– 22.85	15.17	Marine
2016HA-0346	Chinsenmon	100	Phyt.	$C_{17:0br}/C_{18:0}$ 0.066	Absorbed	– 27.95 (0.223)	– 27.84 (0.095)	0.10			Porcine
2011HA-SG0069	Chinsenmon	350	Phyt.	$C_{8–10}$ DA	Absorbed	– 24.05 (0.035)	– 25.11 (0.269)	– 1.07	– 20.43	15.05	Aquatic
2011HA-SG0081	Chinsenmon	8010	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol.	Absorbed	– 24.30 (0.057)	– 25.79 (0.120)	– 1.50	– 21.27	15.94	Aquatic
2016HA-0121	Motochi	1910	$C_{16–22}$ APAA, Phyt., Prist.	$C_{8–12}$ DA, Chol.	Absorbed	– 23.48 (0.046)	– 22.77 (0.194)	0.70			Marine
2016HA-0378	Motochi	140	Phyt., Prist.	$C_{9–10}$ DA, LCAL, Chol.	Absorbed, crust	– 24.09 (0.332)	– 25.18 (0.251)	– 1.10	– 20.63	15.65	Aquatic
2016HA-0207	Motochi	60	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{8–12}$ DA, DHA, $C_{17:0br}/C_{18:0}$ 0.031	Absorbed, crust	– 23.75 (0.035)	– 25.06 (0.197)	– 1.32	– 23.19	14.88	Aquatic, Terrestrial animal?
2016HA-0784	Motochi	30	Phyt., Prist.	–	Absorbed	– 25.55 (0.051)	– 26.01 (0.013)	– 0.47			Aquatic
2011HA-0349	Motochi	8930	TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol.	Absorbed	– 23.50 (0.025)	– 22.60 (0.074)	0.89			Marine
2011HA-0733	Motochi	6760	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., DHA	Absorbed, crust	– 23.64 (0.011)	– 22.85 (0.250)	0.78	– 22.80	16.58	Marine
2011HA-1366	Motochi	5530	$C_{16–22}$ APAA, TMTD, Phyt., Prist.	$C_{8–12}$ DA, Chol.	Absorbed	– 23.38 (0.007)	– 22.51 (0.008)	0.86	– 22.33	15.89	Marine
2011HA-1483	Motochi	8120	TMTD, Phyt., Prist.	$C_{7–12}$ DA, Chol., DHA	Absorbed, crust	– 22.94 (0.045)	– 22.10 (0.103)	0.83			Marine
2016HA-0130	Motochi	9650	TMTD, Phyt., Prist.	$C_{7–12}$ DA, LCAL, Chol.	Absorbed	– 22.86 (0.007)	– 21.41 (0.160)	1.44			Marine

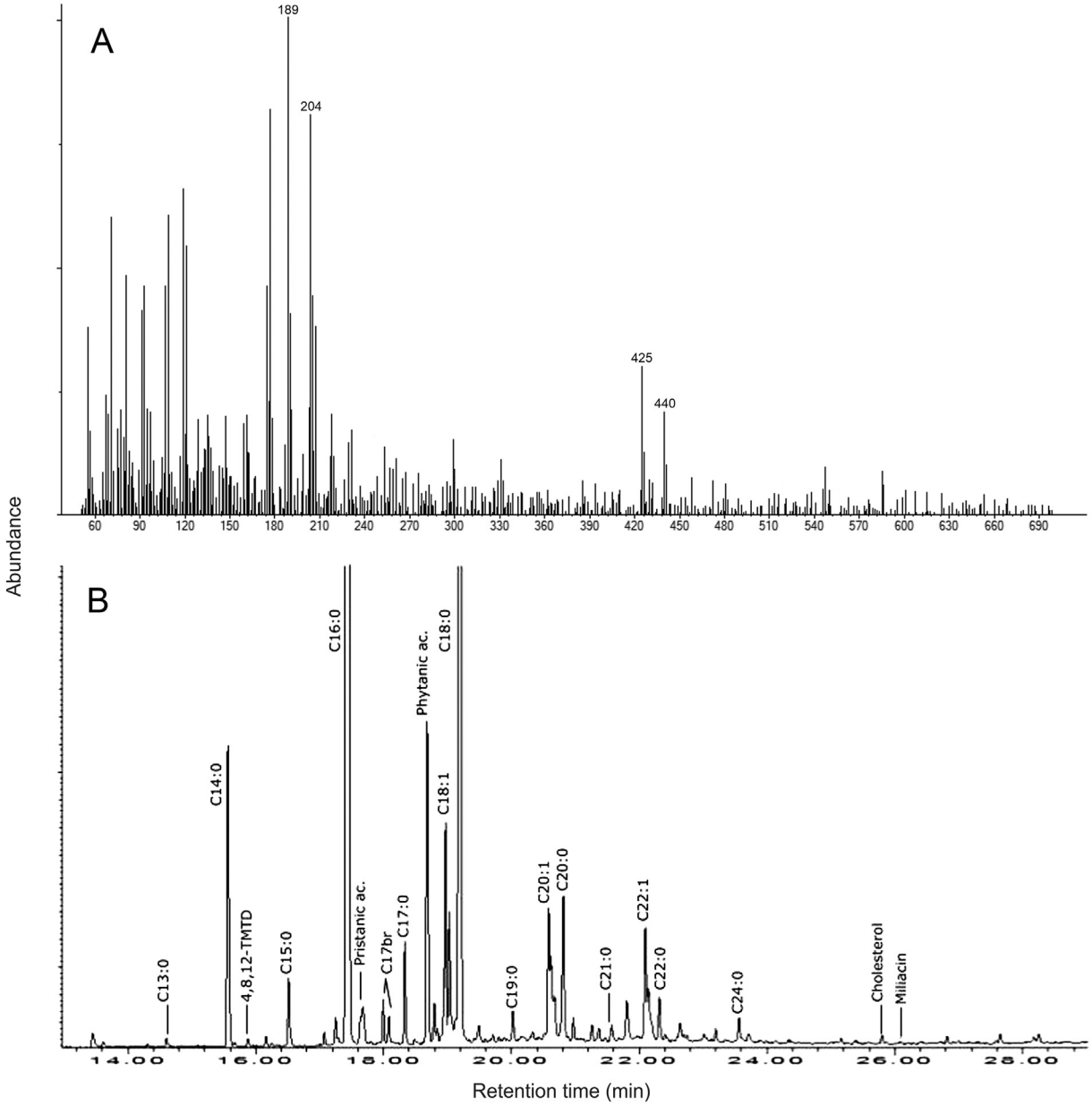

Fig. 6. A: Mass spectrum of miliacin at 26.819 min from a Kokumon-type vessel (2016HA-1001) recovered together with two dog crania in layer IIIa (Heron et al., 2016). B: Partial chromatogram of a solvent extract of the same sample.

one absorbed lipid sample (Fig. 6). The sample in question was recovered from a Kokumon-type vessel, deposited next to two dog crania in layer IIIa.

4.2. Bulk stable isotope analyses

To further characterize container function, charred interior surface crust residues from 27 vessels were examined for bulk stable isotope composition with elemental analyzer isotopic ratio mass spectrometry (EA-IRMS). All samples measured between 11 and 20‰ in $\delta^{15}N$ – a range associated with aquatic food webs – whereas the carbon isotope ($\delta^{13}C$) values ranging between −18‰ and −23.5‰ are indicative of the presence of marine products (Fig. 7). In addition, C/N values ranging approximately between 5 and 10 (Fig. 8) also point to the presence of marine-derived residues in these samples (Yoshida et al., 2013). This is consistent with both molecular and compound-specific stable isotope data – pointing to significant aquatic contributions for all 27 vessels with interior charred crust. It may also indicate that containers with dominant aquatic lipid profiles were used differently than those with either terrestrial or mixed food web sources.

4.3. Compound-specific stable isotope analyses

GC-c-IRMS-supported compound-specific $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ analyses distinguished both aquatic and terrestrial carbon sources in the 66 containers examined (Fig. 9-10). In addition, a nonparametric two-sample Kolmogorov-Smirnov inference test showed a significant ($P \leq .05$) enrichment in $\delta^{13}C_{16:0}$ in the Final Jōmon phase compared to the Epi-Jomon/Late Final Jomon, Towada, Kokumon and Chinsenmon periods. In total, 88% (58/66) of the samples yielded $\delta^{13}C$ values between −25.55 and −22.35‰ in $\delta^{13}C_{16:0}$, and between −26.00 and −21.40‰ in $\delta^{13}C_{18:0}$, which are ranges established for lipids in high trophic-level piscivore sea mammal and fish resources. Aquatic biomarkers were frequently recorded in these vessels: C_{18}–C_{22} APAAs were detectable in 33/58 (57%), and full range of isoprenoids were found in 33/58 (57%) samples (in total, 23 samples, i.e. 40%, contained

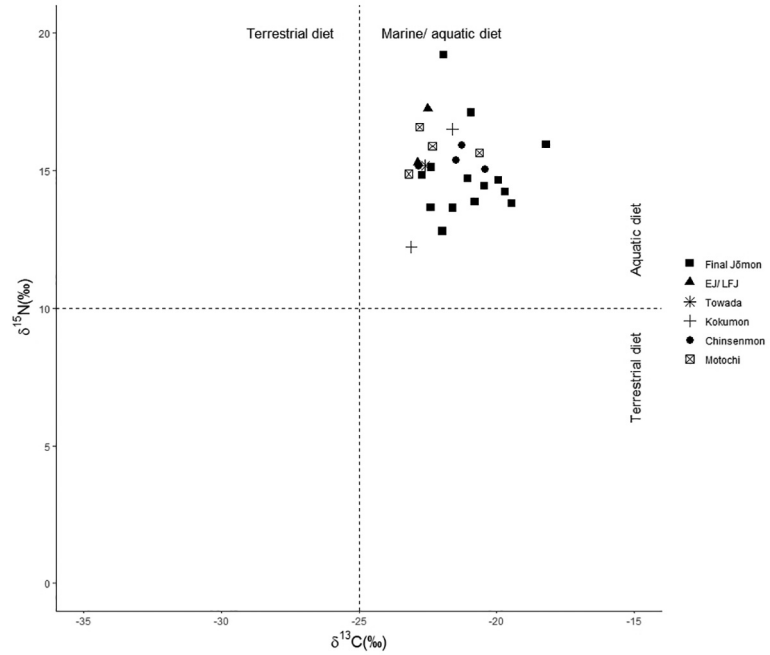

Fig. 7. Bulk stable isotope definitions for $n = 27$ interior surface crusts (EJ/ LFJ – Epi-Jōmon/ Late Final Jōmon).

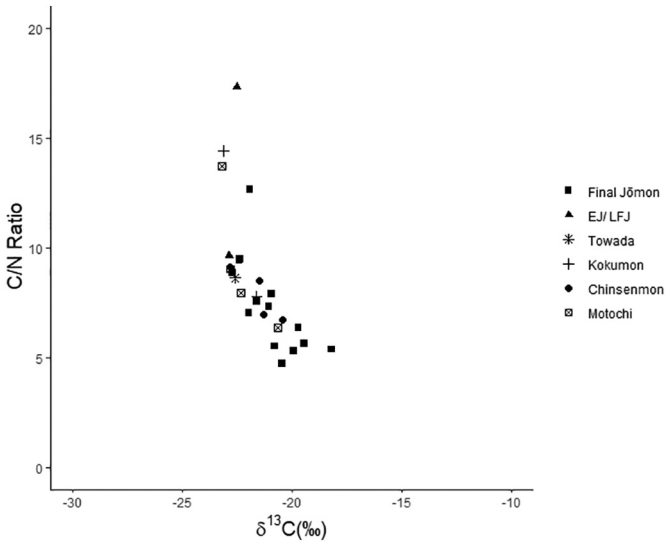

Fig. 8. C/N atomic ratios of bulk stable isotope definitions.

both biomarker categories). In turn, a total of 25 samples within this subgroup had $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values falling within the ranges expected for anadromous fish that partly overlaps with the ranges modeled for the marine food web. The similar molecular configurations between organisms from these two food webs, however, impedes, by and large, distinguishing them in pottery residue analysis. Alternatively, similar isotopic values would result if high-trophic level aquatic and $\delta^{13}C$-depleted terrestrial or freshwater resources were mixed in the same pot. That being said, freshwater contribution could not be modeled in these samples due to the unknown carbon profile of Lake Kushu – an inland lake potentially exposed to seawater – and the absence of modern or ancient reference samples from this food web.

Conversely, eight samples measured $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values between −25.6 and −29.1‰, and −26.2 and −29.0‰, respectively, a range primarily associated with a terrestrial non-ruminant animal food web. These samples are scarce in aquatic biomarkers, as only one sample contained C_{18}–C_{22} APAAs, and the full range of isoprenoids were not found in any sample. We therefore view these samples to have primarily derived lipids from porcine resources, though in the case of at least one sample with APAAs a mixture with aquatic resources is likely.

5. Discussion

The present study is focused on understanding how resource use and container function evolved over 2000 years at the Hamanaka 2 coastal site. For this purpose, we examined organic residues in pottery across six cultural phases from ca. 1050 BCE-1150 CE. Given the prior evidence concerning the subsistence of these cultures, as well as the site's location at an island with access to abundant maritime resources, a persistent focus to the marine food web was predicted. To be sure, molecular and isotopic evidence were anticipated to show high rates of aquatic biomarkers, high-trophic level carbon and nitrogen isotope values, and an absence of diagnostic compounds associated with plant and terrestrial animal food webs.

While these results confirm a persistent focus to the aquatic food web across the site sequence, however, ~25% of the containers examined were instead used to process either terrestrial animal products or mixed dishes of terrestrial animal, plant and aquatic foods (Table 3). Subsequently, three patterns in container function were distinguished: vessels were either used to primarily process i) marine aquatic and anadromous resources (74% of the containers analyzed), ii) mixed dishes of aquatic and terrestrial foods (15%), or iii) terrestrial non-ruminant animal resources (11%).

The processing of high-trophic level marine resources such as sea mammal and fish dominated in the Final Jōmon period – where a larger vessel size compared to more recent periods suggests distinct container functions. Final Jōmon pottery may therefore have been primarily used to extract blubber, as was initially suggested in Miyata et al. (2009). In turn, our evidence indicates that in the ensuing Epi-Jōmon/Late Final Jōmon phase, the local community developed – in parallel with the ancient northeast Asian hunter-gatherer tradition of using pottery to process local aquatic resources – a new strategy where containers start to be utilized to process combined resources from multiple food webs.

In the Epi-Jōmon/Late Final Jōmon phase pottery appears to have been sporadically used to process both terrestrial animal and plant resources. However, the new pattern is more evident in the Okhotsk

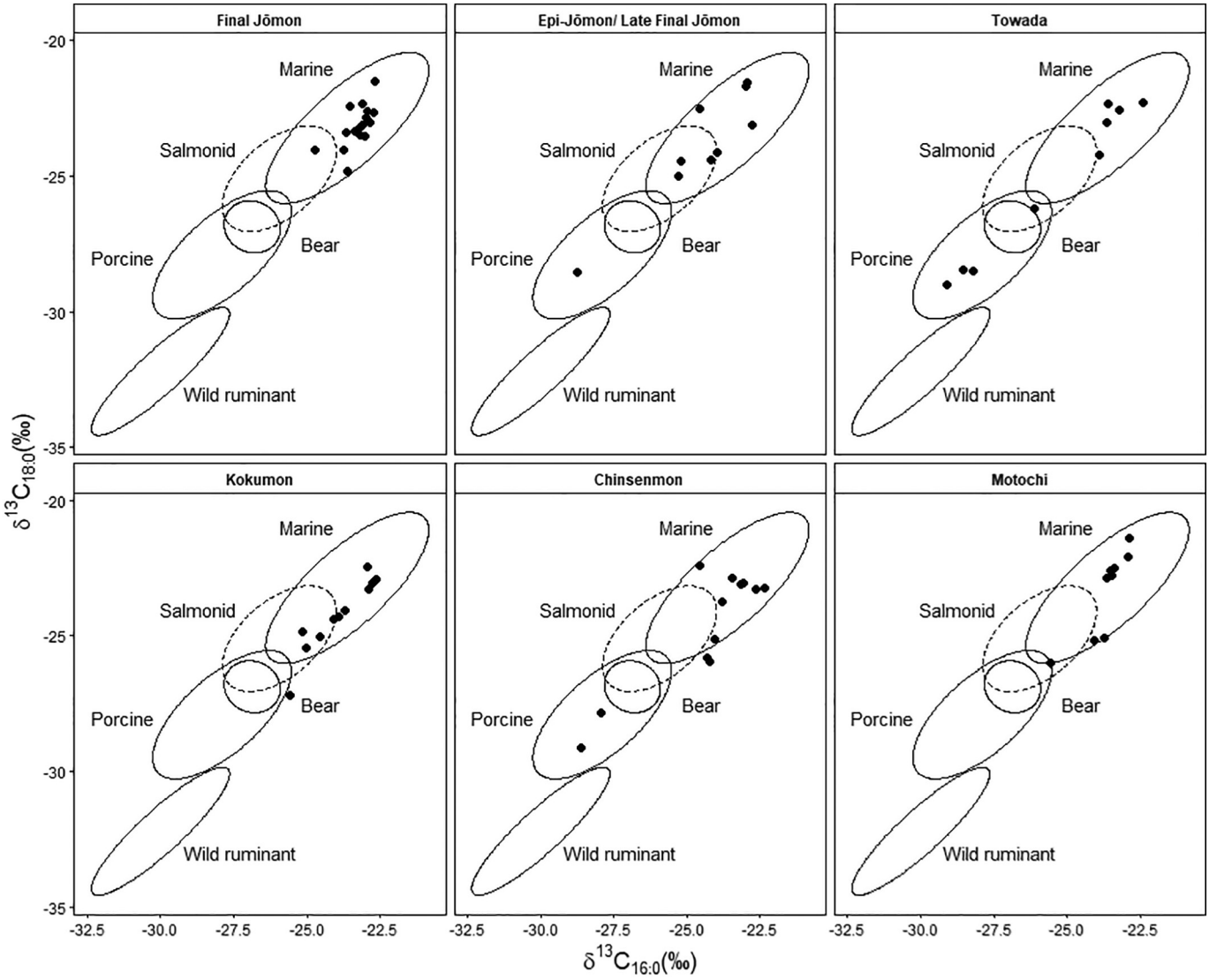

Fig. 9. Measured $\delta^{13}C$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids from absorbed lipid residues at the Hamanaka 2 site ($n = 66$), compared against reference ranges (1-σ confidence interval) from modern tissue and archaeological bone collagen (Naito et al., 2010; Fernandes et al., 2015; Lucquin et al., 2016).

Culture phase in the 1st millennium CE, where aquatic and terrestrial resources are at times processed in separate containers altogether. We view this as a conceptual and conscious distinction between different food resources and conclude that pottery use and resource management strategies at Hamanaka 2 were more complex than initially hypothesized.

Indeed, the Early Okhotsk Towada-style pottery appears to have been used to process marine aquatic and non-ruminant terrestrial resources in separate pots, whereas containers with Kokumon-type decoration in the Middle Okhotsk period were inferred to have been primarily used for cooking mixed dishes of aquatic, terrestrial animal and plant foods. In turn, Chinsenmon-style pottery in the Late Okhotsk phase shows a similar dual-function pattern as documented in the Early Okhotsk phase. However, Motochi-type pottery in the Final Okhotsk period is characterized by a focus on the processing of marine resources, with little evidence of terrestrial animal or plant use. This is supported by the material record at Hamanaka 2, where the layers associated with the Final Okhotsk phase – a period corresponding to the decline and subsequent disappearance of the Okhotsk Culture in Hokkaido – are the most abundant in marine fish remains.

Moreover, based on biomarker and isotopic evidence, while also considering the terrestrial animal species documented in the site's zooarchaeological record, at least pig/wild boar (*Sus scrofa inoi*), and also bear (*Ursus arctos*) and dog (*Canis domesticus*) meat may have been processed in pottery – albeit often mixed with aquatic products. Distinguishing lipids associated with dog from aquatic residues, however, is particularly challenging at Rebun as the Okhotsk are known to have fed these animals with marine fish – and thus dogs are likely to hold a trophic position similar to those of mammalian marine piscivores (Tsutaya et al., 2014).

In turn, freshwater fish contribution could not be accurately estimated in the vessels analyzed due to the unknown carbon profile of Lake Kushu and the Rebun riverine network. Based on available baseline data from mainland Japan, only one (Towada-style) container satisfying the molecular criteria for the presence of aquatic lipids showed a potential contribution from the freshwater food web (Lucquin et al., 2016). Admittedly, a mixture of marine or anadromous and terrestrial animal lipids would likely yield a similar signal. However, the absence of freshwater samples is consistent with the site's material record, where no evidence of freshwater fish remains have been documented to date. That said, future work on modern samples from Lake Kushu should be conducted to further test whether freshwater fish was occasionally mixed in the same pots with marine foods.

Evidence of plant use were present in all of the sampled six cultural

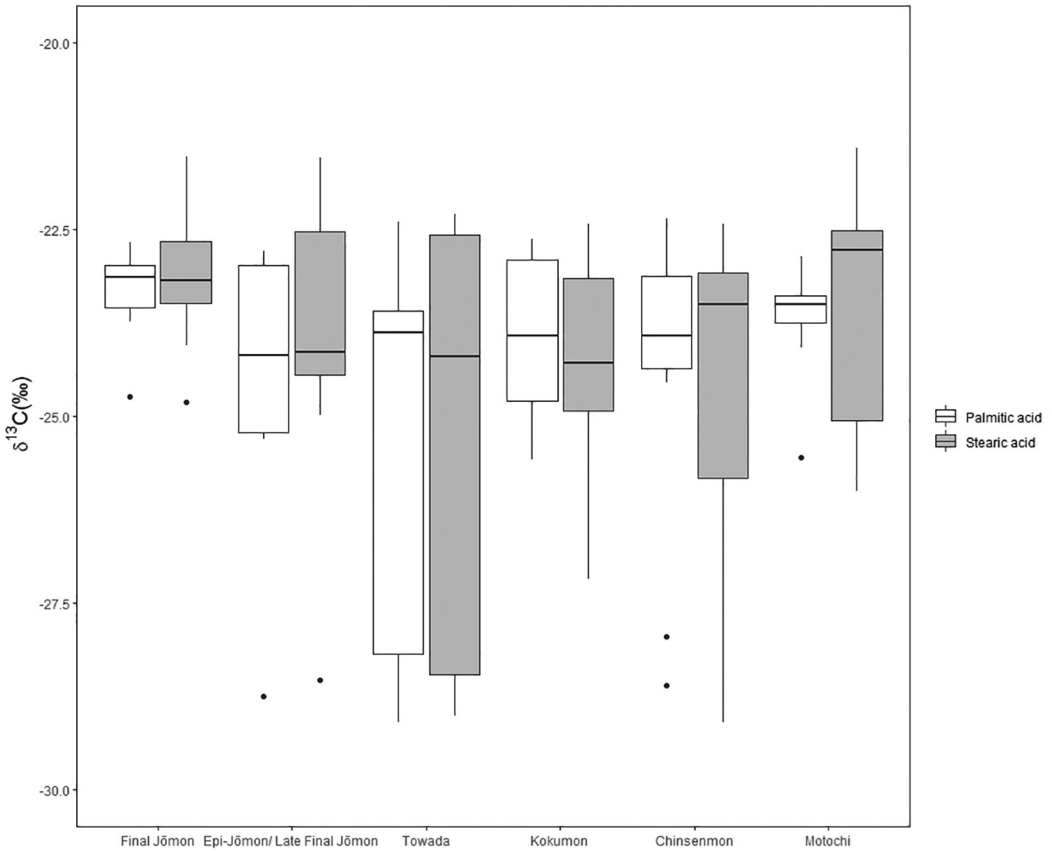

Fig. 10. Compound-specific $\delta^{13}C_{16:0}$ (white) and $\delta^{13}C_{18:0}$ (gray) definitions summarized and visualized for each occupation phase studied using a box plot chart. The interquartile range is indicated by the length of the box, and the median is indicated by the vertical line that intersects it. Outliers are shown as dots and the full spread of the distribution – when the outliers are excluded – is represented by the box and its whiskers on both sides.

layers and in over 75% of the containers analyzed. Plant lipids were consistently found at trace levels, however, meaning that plant processing was not the primary function of pottery at Hamanaka 2. In turn, diagnostic plant biomarkers such as long-chain alkanols and dehydroabietic acid (DHA) were detectable in containers reserved for both aquatic and terrestrial food resources – with DHA likely derived from resin and used on the surface of the pot as sealant. Indeed, the use of sealants should explain the presence of plant lipids – DHA and long-chain alkanols – in 15 of the 16 pots examined from Final Jōmon contexts, where no macrofossil evidence supporting wild plant use was found. That being said, the discovery of miliacin in one Kokumon-style container is the first evidence of millet (*Panicum miliaceum*) – a cultigen possibly acquired through trading – in this region, suggesting that cultigens were at least sporadically processed in ceramic containers in the Okhotsk Culture period.

Lipid residue analyses of Late Pleistocene and Early Holocene pottery in Japan have found the container function among hunter-gatherer groups to be driven by resource availability within the local ecosystems, with pottery uptake characterized as gradual and tied to the processing of local aquatic products (Craig et al., 2013; Lucquin et al., 2018). However, the adoption of the observed dual-function in pottery use at Hamanaka 2 coincides with a cultural transformation in northern Hokkaido at ~1050 BCE, where mobile final-stage Jōmon economies are being replaced by groups with more permanent settlements, larger exchange networks and incipient animal rearing. That said, it has been postulated that the communities in Rebun were trading marine

Table 3
General subsistence compared with the inferred container function for each cultural period examined at the study site (Nishimoto, 2000; Leipe et al., 2018; Hirasawa and Kato, 2019).

Culture	General subsistence	Inferred container function
Final Jōmon	Hunting-fishing-gathering, sea mammal hunting	Processing of high-trophic level marine fish and sea mammal resources, tree resin likely used as sealant
Epi-Jōmon/ Late Final Jōmon	Hunting-fishing-gathering, wild plant use, dog breeding for food	Processing of aquatic resources, sometimes mixed with resources from terrestrial animal and plant food webs
Towada (Early Okhotsk)	Hunting-fishing-gathering, dog breeding for food, wild plant & incipient domestic plant use	Two separate container functions: 1) processing of marine products, and 2) terrestrial animal and plant processing
Kokumon (Middle Okhotsk)	Hunting-fishing-gathering, regular domesticated and wild plant use, ritual bear husbandry, dog and pig domestication	Mixed use of resources from multiple food webs, dominated by aquatic food webs. Use of terrestrial animal resources and plants, including millet
Chinsenmon (Late Okhotsk)	Hunting-fishing-gathering, regular domesticated and wild plant use, ritual bear husbandry, dog and pig domestication	Two distinguishable container functions: 1) processing of marine aquatic products and 2) terrestrial animal meat resources. Some evidence of plant use found in both categories
Motochi (Final Okhotsk)	Marine hunting and fishing, limited domesticated and wild plant use, ritual bear husbandry, dog and pig domestication	Processing of marine or aquatic products. Limited evidence of terrestrial animal or plant processing

products, perhaps sea mammal furs and blubber, in exchange for obsidian, iron tools, domesticate plant seeds and other commodities, as part of a cultural interaction network in the northeastern Pacific region (Oba and Ohyi, 1981; Abe et al., 2016; Lynch et al., 2018).

We consider this process crucial in explaining the observed diversification in pottery use in the Epi-Jōmon/Late Final Jōmon and Okhotsk periods. Indeed, the adoption of new technologies and resources resulting from increased cultural interactions in northeast Asia occurred at a scale that transformed the lifeways and social dynamics of the local forager groups in northern Hokkaido. The emergence of the Okhotsk Culture further expanded on the exchange network and availability of exotic resources, resulting in a population increase in the region (Amano, 2003; Ono, 2008; Abe et al., 2016). Subsequently, at the Kafukai 1 site in Rebun Island, stone tool-making tradition was virtually lost among the Middle and Late Okhotsk households in ~100 years after large volumes of metal objects became available through trading (Oba and Ohyi, 1981). It would therefore be logical to assume that cuisine would undergo a similar change, as reflected in the change in pottery use, following the introduction of cultigens and domesticated animal species.

Under these circumstances, the changing social dynamics and availability of exotic and prestigious foods may have created a need for reciprocal feasting – a concept ethnographically documented among the Historical Ainu communities in Hokkaido. Located at a beachfront in a migratory pathway, the Hamanaka shell-midden site in Rebun is an ideal candidate for serving as one of the loci for such festivities. With ritual animals such as bears transported alive to Rebun, and subsequently sacrificed and consumed in situ, it is conceivable that pottery was used to serve these exotic resources during banquets. In addition, since households associated with the Okhotsk Culture are documented in the vicinity of the site, the shell midden contexts corresponding to the Early and Middle Okhotsk phases may therefore result from both household refuse and feasting. Provided that container function at household contexts was limited to traditional, locally available aquatic foods – as suggested by the reported human bone collagen diet reconstructions (Naito et al., 2010; Tsutaya et al., 2014) – the observed dual-function in pottery use at Hamanaka 2 would stem from these two socially different activities.

6. Conclusions

In this paper we predicted that pottery use at the Hamanaka 2 site would retain a specialized focus on processing aquatic resources, a pattern of pottery use that was first established back in the Late Glacial and Early to Middle Holocene periods of Northeast Asia. In fact, our results did not meet these exptectations, and we identified a broadening in container function over time. This points to the emergence of new culinary traditions that made use of diverse food groups, which were either being cooked together as mixed dishes, or processed separately in different vessels. This change appears to coincide with the emergence of the Okhotsk Culture. It presents an interesting example of how cuisine and food processing traditions among marine hunter-gatherer economies, while participating in long-range exchange networks, can be disrupted by the introduction of new technologies and exotic resources, including domesticated animals and cultigens – triggering new kinds of social dynamics, such as feasting events and the celebration of animal sending rites. However, more work is required to confirm whether diversification in the use of clay cooking pots and related food-processing activities extends beyond Rebun Island. In addition, further methodological work is also needed for further advancing our understanding of what kind of role plants had in the use of pottery, while also assessing the contribution of freshwater sources through analysis of modern reference samples from Lake Kushu and the Rebun riverine network.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ara.2020.100194.

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Appendix

Methods

Sampling

Recovery of the sample material for analysis was carried out for ceramic powder and charred surface crust with the following steps; 0.5-1 g of ceramic powder material was collected from the clay matrix by using a Dremel 3000 hand drill – the drill head was changed and sterilized with each individual sample – by drilling a surface area of 1-2 cm^2 on the inner wall of the vessel at ~6-7 mm depth. The outer 1-2 mm was discarded to avoid contamination from soil or handling of the sherd. In the case of food crusts, >15 mg of charred deposit material adhered to the inner wall were extracted with a sterilized scalpel and crushed mechanically. The sample material was then transferred quantitatively to clean tubes. The glassware were washed with dichloromethane (CH_2Cl_2) and left to dry in fume cupboards.

Solvent extraction and acid-catalyzed extraction and methylation

The absorbed pottery residues and surface crusts were studied for lipid residues using a gas-chromatography mass spectrometry (GC-MS) according to the extraction protocol in (Papakosta et al., 2015). Compound-specific stable carbon isotope characteristics were examined using a gas-chromatography combustion isotope ratio mass spectrometry (GC-c-IRMS). Surface crust deposits were also analyzed for a bulk stable carbon and nitrogen isotopic composition with an elemental analyzer isotopic ratio mass spectrometry (EA-IRMS) as in (Craig et al., 2013). The general purpose of the solvent extraction was to wash the samples from contaminants prior to the acid extraction step, as in (Papakosta et al., 2015). Therefore, the results of the acid extraction are prioritized in the interpretative part of the study. Once in the tube the sample was first washed with three rounds of solvent extraction; 1.000 μl of dichloromethane (CH_2Cl_2) and 500 μl methanol (CH_3OH) was added, the sample was shaken vigorously and run in an ultrasonicator for 2×15 min with a 15 min pause in between to avoid overheating. The sample was then centrifuged for 30 min at 3000 rpm, after which the clear phase containing the lipids was recovered with a pipette and transferred to a clean tube. This process is repeated twice more, however, without ultrasonication since the yield of the samples was found to be very high. The obtained phase was evaporated with a stream of nitrogen gas and prepared for a GC-MS analysis by derivatizing the total lipid extract (TLE) in 100 μl of

bis(trimethylsilyl)trifluoroacetamide (BSTFA) and chlorotrimethylsilane (TMCS, 10%). The suspension was heated at 70 °C for 20 min, evaporated again with nitrogen gas and, finally, diluted in *n*-hexane. Following the solvent phase the initial sample material was then extracted and transesterified with acidified methanol by adding 200 μl of concentrated sulphuric acid (H_2SO_4) as catalyst in 1.000 μl CH_3OH. Following a heating of 4 h at 70 °C 1.000 μl *n*-hexane is added, the sample is shaken vigorously and centrifuged in 3000 rpm for 5 min. Once the fatty acid methyl esters are recovered in the top phase, the process is repeated twice more and the combined suspension is evaporated with nitrogen gas. Finally, the TLE is silylated as previously described and *n*-hexane is used as dilution ahead of the GC-MS analysis.

GC-MS analysis

Separation and identification of the components was carried out using a HP 6890 gas chromatograph fitted with a SGE BPX5 fused-silica capillary column (30m x 220 μm x 0.25 μm), coupled to a HP 5973 mass selective quadrupole detector. All derivatized extracts were injected in pulsed splitless mode (pulse pressure 17.6 psi, 325 °C). The column oven temperature was programmed to start with 50 °C for first 2 min, after which temperature would rise by 10 °C each minute and reach 360 °C and kept at this temperature for the remaining 15 min. Carrier gas used was helium, with a constant flow set at 2.0 ml/min. The ion source is maintained at 230 °C, with ionization and fragmentation achieved through 70 eV electron impact. The mass filter is configured to scan between m/z 50 and 700, at a rate of 2.29 scans/second. The data were processed using the MSD Chemstation™ software. Quality of the preparatory and analytical work was controlled by analyzing several samples in duplicate. All duplicate GC-MS analyses returned the same result – with small, expected stochastic variability ignored - than the initial analyses.

SRR/RRR diastereomer ratio

SRR/RRR diastereomer ratios were screened using a polar HP-FFAP (polyethylenglycol-TPA) capillary column (50 m x 320 μm x 0.52 μm), with oven started with 2 min isothermal at 90 °C, followed by a temperature increase of 25 °C per min to 120 °C, followed by 8 °C increase per min to 220 °C, then 4 °C increase per min to 240 °C, a temperature that was held for five min. Temperatures in interface, ion source and mass filter were unchanged, aside from the instrument being run in SIM-mode (Selected Ion Monitoring) – scanning the characteristic ion fragments

for phytanic acid methyl ester m/z 101 and 326, and the m/z 74 for methylated fatty acids in general.

Compound-specific stable isotope analysis of $C_{16:0}$ and $C_{18:0}$ FAMEs

After the methylation the samples containing meaningful quantities (i.e. peak size exceeding the background noise level by >200 %) of targeted compounds palmitic and stearic acids ($C_{16:0}$ and $C_{18:0}$ fatty acid methyl esters, i.e. FAMEs) with a >2 $\mu g/\mu l^{-1}$ concentration qualified for a compound-specific $\boldsymbol{\delta}^{13}C$ analysis using gas-chromatography combustion isotope ratio mass spectrometry. The less volatile Toluene substituted *n*-hexane as the medium solvent. The analyses were carried out using a Trace GC supplied with a DB-5 capillary column (60 m x 0.32 mm x 0.25 μm) and paired with a Thermo Delta V mass spectrometer. Sample volumes of 1 µl were injected through a programmable temperature vaporisation (PTV) injector operated in solvent splitless mode. The injection pressure was 70 kPa and the initial temperature was set at 40 °C. The splitless time was set to 1 min; solvent vent temperature was 100 °C and vent flow 100 ml/min. Evaporation pressure was set at 140 kPa, evaporation temperature was 40 °C, evaporation rate 10 °C/sec and evaporation time 0.16 min. Transfer pressure was 210 kPa, transfer temperature 300 °C and transfer rate 12 °C/sec. The cleaning temperature was 320 °C, cleaning rate 14.5 °C/sec, cleaning time 20 min and cleaning flow 100 ml/min. The GC oven was temperature programmed with an initial isothermal of 2 min at 120 °C, followed by an increase of 20 °C/ min to 200 °C, followed by another temperature ramp of 5 °C/min to 315 °C and a final temperature hold of 7 min. The analysed FAMEs were converted to CO_2 via an IsoLink reactor system, where pulses of reference CO_2 gas were injected using a ConFlo IV unit. All samples were automatically injected, where each sample was analyzed twice and the mean of both analyses was used as the value to represent the isotopic composition of the sample. Instrument precision across the compound-specific isotope analyses is reflected by a mean difference of 0.14‰ on repeated measurements. In addition, a standard FAME sample with known isotopic composition was used to monitor the accuracy and performance of the instrument, which, over the course of the analyses, remained at ±0.4‰.

Bulk stable isotope analysis of foodcrusts

Homogenized charred interior surface deposits (>1.5 mg) were analysed by elemental analysis IRMS for $\boldsymbol{\delta}^{13}C$ and $\boldsymbol{\delta}^{15}N$ characterization. $\boldsymbol{\delta}^{13}C$ or $\boldsymbol{\delta}^{15}N$ values are expressed as $[(R_{sample}/R_{standard}^{-1})]$ x 1.000, where R = $^{13}C/^{12}C$ or $^{15}N/^{14}N$. The standard for $\boldsymbol{\delta}^{13}C$ is Vienna

PeeDee Belemnite (V-PDB) and the standard for $\boldsymbol{\delta}^{15}N$ is air N_2. All 27 foodcrust samples analyzed exceeded the quality criterion of >1‰ N. Instrument precision on repeated measurements was ±0.23‰ and accuracy, based on measurements of two standard (modern reindeer and seal) collagen samples was ±0.24‰.