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RESEARCH ARTICLE

Investigating infant feeding strategies at Roman Bainesse through Bayesian modelling of incremental dentine isotopic data

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Abstract

We present the first study employing Bayesian modelling of isotopic measurements on dentine increments (five human upper first molars) to address Romano-British infant feeding practices at Bainesse (UK). The stable carbon and nitrogen isotope results modelled to 6-month intervals with novel OsteoBioR software revealed some common patterns, with weaning not starting before the age of 6 months and higher animal protein consumption after the age of seven. The latter possibly indicated a 'survival' threshold, evidenced by historical sources and osteological data, hence marking a rise in social status of children. The important role of Bainesse as commercial hub in relation to the fort of Cataractonium does not exclude a priori the possibility that medical treatises and Roman culture were known at the site. However, our results also showed significant intra-individual differences with weaning cessation taking place between 2 and 5 years, suggesting that these were followed only partially and other aspects influenced family decisions on infant feeding practices in Bainesse.

KEYWORDS
Bainesse, Bayesian modelling, breastfeeding and weaning, dentine incremental analysis, infant feeding practices, physiological stress, Roman Britain, stable carbon and nitrogen isotope analysis

1 | INTRODUCTION

Infant feeding practices are the human cultural reflection of a natural physiological need. Newborns consume breast milk as an easily digestible food source of high nutritional quality essential for the support of their immunological system. WHO and UNICEF currently recommend that infants are exclusively breastfed during the first 6 months following birth and indicate breast milk can provide up to a third of an infant's nutritional needs into their second year of life alongside solid foods (World Health Organization, 2013). Exclusive breastfeeding is defined as 'an infant's consumption of human milk with no supplementation of any type' (Gartner et al., 2005), whereas weaning is 'the process by which a baby slowly gets used to eating family or adult foods and relies less and less on breast milk'. (World Health Organization, United Nations Children's Fund, UNICEF, 1988). In practice, cultural and socio-economic factors have much control over the timing and speed at which weaning takes place, which can vary widely across past and present day human populations (Wells, 2006).

Within the Roman Empire, infant feeding practices have been investigated using a variety of methods. The study of material culture, such as fictile baby bottles, provides evidence of the techniques employed by Roman carers to feed their infants, albeit these may be biased by the funerary context in which they are found (Carroll, 2018, pp. 82–85). The critical study of written evidence such as medical works of ancient physicians and of other ancient sources (e.g., work contracts for wet nurses) provides invaluable information on otherwise invisible socio-cultural habits (Centlivres-Challet, 2017). However, we still have to consider that medical works must be contextualised to the audience they were written for, mostly higher strata of Roman society, and that socio-cultural practices suggested by both archaeological and historical evidence may have varied within the Empire (Centlivres-Challet, 2017).

Stable isotope analysis of skeletal remains has been widely applied in Roman contexts to investigate adult and infant diets (Müldner, 2013). Nitrogen and carbon stable isotope analyses of bones and teeth have been employed to estimate breastfeeding and weaning age onsets (Dupras, Schwarcz, & Fairgrieve, 2001; Dupras & Tocheri, 2007; Fuller, Molleson, Harris, Gilmour, & Hedges, 2006; Prowse et al., 2008; Redfern, Gowland, Millard, Powell, & Gröcke, 2018). Group comparisons of isotopic measurements on collagen extracted from bone remains of adult females and non-adults apparently suggest fairly consistent weaning times across the Roman Empire, that is, between 2 and 4 years of age (Prowse, Saunders, Fitzgerald, Bondioli, & Macchiarelli, 2010; Prowse et al., 2008; Redfern et al., 2018). However, these group comparisons constitute an example of the ‘osteological paradox’ because these rely on the study of infants that died prematurely (Beaumont, Montgomery, Buckberry, & Jay, 2015; Wood, Milner, Harpending, & Weiss, 1992). The presence of a potential association between early mortality and weaning practices could thus bias the interpretation of the results (Beaumont et al., 2018). Group comparisons also lack temporal resolution as they are conducted on bones that typically integrate dietary isotopic signals from multiple years of an adult individual due to turnover (Hedges et al., 2007). These group comparisons also do not allow for a direct matching of the diets of individual mothers/carers and their infant(s) (Reynard & Tuross, 2015).

Higher temporal precision in the study of past weaning practices can be achieved by isotopic measurements carried out on dentine extracted from multiple teeth in a single individual, with each tooth having specific formation periods (Dupras & Tocheri, 2007). A subsequent methodological improvement was the ability to perform isotopic measurements on tooth dentine increments offering a chronological resolution equal or better than 1 year (Beaumont, Gledhill, Lee-Thorp, & Montgomery, 2013; Beaumont, Gledhill, & Montgomery, 2014). Nitrogen stable isotopes provide information on protein sources according to their position in a food chain, and their measurements on tooth sections usually provide a clear temporal signal for weaning, because the isotopic values of the carers' milk are higher than those of their own diet (Fogel, Tuross, & Owsley, 1989; Schurr, 1998). As infants consume less breastmilk in favour of solid

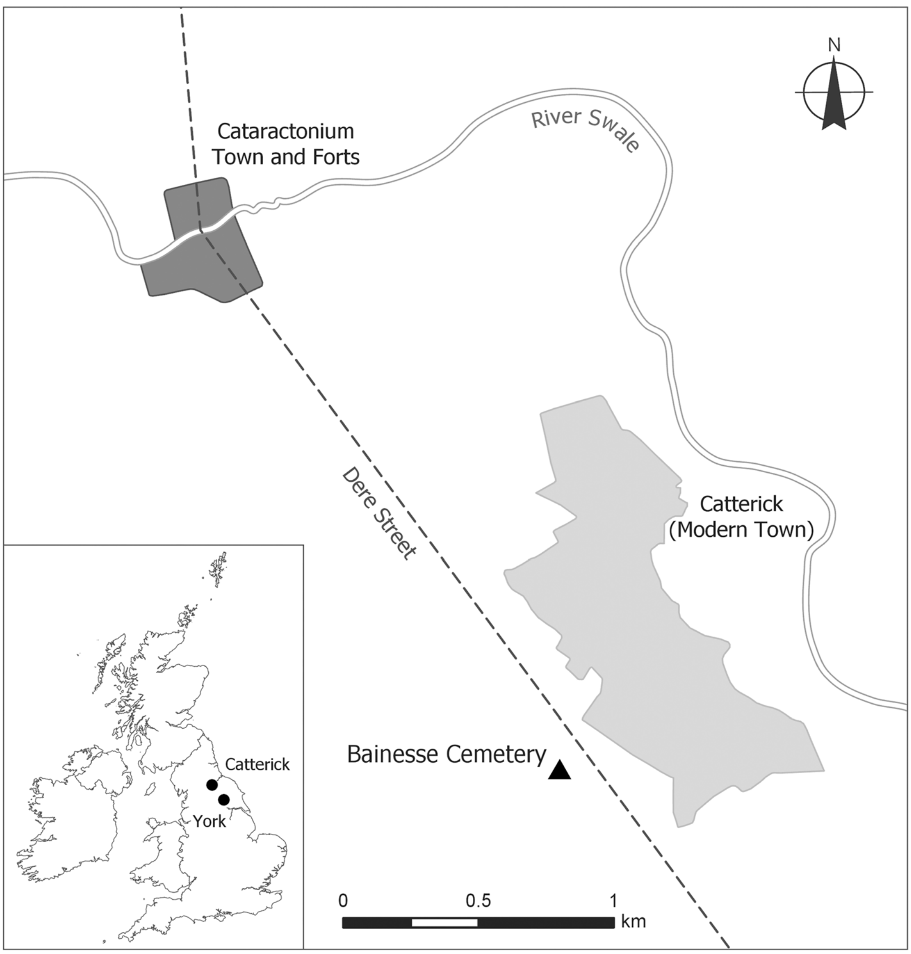


FIGURE 1 Location of Bainesse cemetery. Map by Helen Goodchild, after Chenery et al. (2011); contains OS data © Crown Copyright (and database right) (2020)

foods during the weaning process, their stable isotope nitrogen ratio values decrease. Measurements of carbon stable isotopes on tooth sections are also employed to study weaning although they offer a less clear signal for the onset and completion of weaning (Beaumont et al., 2018; Fuller, Fuller, Harris, & Hedges, 2006). Stable isotope measurements of tooth sections have been widely employed to investigate weaning practices in past populations (e.g., King et al., 2018). However, until now, this method has not been employed to investigate Roman infant feeding practices.

In this paper, we present the first study to investigate Romano-British weaning practices through nitrogen and carbon stable isotope measurements in incrementally sampled dentine. Permanent first molars were sampled from five individuals from Bainesse (UK), aged between 15 and 45 years (Holst, Keefe, Newman, & Löffelmann, 2019). We employed Bayesian modelling to allow for the comparison of isotopic patterns in different individuals using a common temporal scale.

2 | MATERIALS AND METHODS

The settlement at Bainesse (Figure 1), founded during the Flavian period (69–96 CE), was likely a civilian settlement that had potential links with the nearby *Cataractonium* fort (Teasdale, Speed, & Griffith, 2019; Wilson, 2002). The settlement was initially built in timber, but during the second century CE, a new phase of stone buildings may represent a period of economic prosperity; both agricultural and crafting activities are inferred, although Wilson (2002) also proposes the important commercial role Bainesse may have fulfilled for travellers. The location itself of the settlement on both the Swale river and along Dere Street, the main Roman road in Northern Britain, may have promoted Bainesse as an important commercial hub in the area. The settlement was permanently inhabited, unlike the nearby *Cataractonium* fort, and continued to be occupied even after the departure of Roman troops from Britain in 409–410 CE, as implied by the presence of later Anglian burials. However, a period of decline during the third and fourth centuries is still suggested by Wilson (2002).

A cemetery (54.370449°N, −1.635731°W) containing more than 200 burials has been intensively excavated, and the archaeological evidence suggests that it was used from the late first to the late fifth centuries CE (Teasdale et al., 2019). Osteological and palaeopathological analyses (Holst et al., 2019), radiocarbon dating (Moore, Hamilton, & Speed, 2019) and stable carbon and nitrogen isotope analyses (Chenery, Eckardt, & Müldner, 2011; Moore et al., 2019) have previously been carried out on the burial assemblage at Bainesse. Isotopic results of faunal remains as reported by Chenery et al. (2011) suggested a primarily C_3 plant-based human diet with some contribution from ^{15}N-enriched foods such as freshwater fish or pork.

We performed stable carbon and nitrogen isotope analysis on first upper molar sections from five individuals buried at the Bainesse cemetery, radiocarbon dated somewhere between the third and fifth centuries CE (Moore et al., 2019). The sampled individuals consist of one 36–45 year old female (BN213, Cal 230–400 years CE), one 26–35 year old likely female (BN144, Cal 265–410 years CE), one 18–25 year old male (BN15, Cal 255–395 years CE), one male older than 36 years (BN197a, Cal 260–420 years CE) and one 15–16 year old individual whose sex is undetermined (BN124, Cal 315–420 years CE) (Holst et al., 2019; Table 1). Within the cemetery, there were differences in burial practices including burial location. However, it is unclear if these were related to socio-economic aspects or if they were influenced by kinship relationships (Teasdale et al., 2019). In our sampled population, there is an absence of grave goods, little variation in burial practice, but burials were chosen from across different cemetery locations (Teasdale et al., 2019, Grave Catalogue). This dataset is not representative of the whole Bainesse population, although sample selection followed criteria of equal representation in terms of age and sex.

Teeth, once fully formed, do not undergo further remodelling, and in the case of first molars, the sequential deposition of dentine allows for the reconstruction of dietary histories from birth until approximately the age of 10 (AlQahtani, Hector, & Liversidge, 2010). Different methodologies have been proposed to investigate infant feeding practices by sampling tooth sections (e.g., Beaumont et al., 2013; Eerkens, Berget, & Bartelink, 2011). The Beaumont et al. (2013) sampling methodology, with temporal estimates described in Beaumont and Montgomery (2015), has become a standard for investigating infant feeding practices given the high temporal resolution

TABLE 1 Description of individuals analysed in this study

Individual	Radiocarbon lab code	Sex	Age at death	Uncal 14C (years BP)	Cal 14C (years BP, 2σ)	Palaeopathological stress markers
BN15	SUERC-67722	M	18–25	1734 ± 32	Cal 255–395 CE	Dental enamel hypoplasia; Cribra Orbitalia
BN124	SUERC-67693	UN	15–16	1705 ± 32	Cal 315–420 CE	Dental enamel hypoplasia
BN144	SUERC-67704	?F	26–35	1724 ± 32	Cal 265–410 CE	Absent
BN197a	SUERC-67716	M	36+	1,678 ± 32	Cal 260–420 CE	Dental enamel hypoplasia; Cribra Orbitalia
BN213	SUERC-67732	F	36–45	1758 ± 32	Cal 230–400 CE	Dental enamel hypoplasia

Note. Radiocarbon measurements were reported previously in Moore et al. (2019). Palaeopathological markers of potential stress were reported in Holst et al. (2019).

(~6 months) that it offers. In our study, we employed Method 2 as described in Beaumont et al. (2013).

Collagen was extracted using a modified Longin (1971) method for carbon and stable isotope measurements. The lab work was carried out at the BioArCh laboratories (University of York). Further details on employed lab protocols can be found in Method S1.

We employed the novel Bayesian model OsteoBioR developed within the Pandora and IsoMemo initiatives (https://isomemoapp.com) to model stable isotope measurements on tooth increments. This allowed us to take into account the varying thickness of sampled tooth increments and to estimate the temporal progress of δ^{15}N and δ^{13}C at equal time intervals (6 months) for all individuals. Further details on model description and its implementation can be found in Method S2.

3 | RESULTS

Measurement results of stable isotope analysis on dentine increments are reported in Table S1. To avoid bias related to different intra- and inter-individual temporal scales arising from combined increments (due to low collagen yield) and small variations in the thickness of sampled sections, we employed the Bayesian model OsteoBioR to represent for each individual the variations in isotopic ranges at a common scale (Method S2). Traditional δ^{13}C-δ^{15}N-Age plots are available in Figure S1. The model uncertainty for isotopic ranges is larger than raw measurements because variations in sample thickness and measurement on combined segments are taken into account.

The first increment of the M1 tooth corresponds approximately to the first 6 months of the life of an individual, a period during which the infant is expected to rely only on breastmilk (Beaumont & Montgomery, 2015). The highest δ^{15}N values are expected for the first increment assuming that only the mother breastfed the infant and that she did not change her diet prior to weaning completion. This maximum is typically followed by a temporal decrease which is indicative of a reduction in breastfeeding and an increase in the consumption of solid foods. Physiological stress may also impact isotopic values and thus can complicate dietary interpretation (Beaumont & Montgomery, 2016). In our dataset, only BN144 lacks palaeopathological evidence for undetermined physiological stress during childhood, although this might also be a preservation bias (Holst et al., 2019; Table 1). There are some instances where a rise in δ^{15}N section values is accompanied by a decrease in δ^{13}C (BN124, BN144, and BN213) for which one cannot exclude a possible malnutrition event. However, a clear distinction between nutritional stress and dietary change is problematic. Research on modern individuals has primarily relied on hair keratin allowing for a high temporal resolution. Neuberger, Jopp, Graw, Püschel, and Grupe (2013) and D'Ortenzio, Brickley, Schwarcz, and Prowse (2015) reported isotopic shifts of 1–2‰ for δ^{15}N and ~1‰ for δ^{13}C in extreme cases of starvation and cachexia over short time spans and were related with different physiological stress conditions (e.g., terminal cancer). However, these shifts might also reflect a contribution from a change in diet as exemplified in the case of a pregnant woman by D'Ortenzio et al. (2015). Assuming that isotopic shifts of similar magnitude are expected for tooth dentine, we can probably assign larger isotopic shifts primarily to dietary changes. As for the interpretation of smaller isotopic changes, we are constrained by instrumental uncertainty and uncertainties introduced during sampling although the latter are reflected in the Bayesian modelling results. Furthermore, it is possible that dietary shifts may result in isotopic patterns that could also be associated with malnutrition. An increase in the consumption of freshwater fish results in an increase in human collagen δ^{15}N values and a decrease in δ^{13}C values, an isotopic pattern that could otherwise be associated with metabolic stress (Fuller, Fuller, Harris, & Hedges, 2006).

At Bainesse, exclusive breastfeeding appears to cease at 6 months or soon after. Bayesian estimates show that weaning for the Bainesse individuals was completed between [2–2.5] and [4.5–5] years (Figures 2–6). Previous research relying on the comparison of bone and tooth isotopic measurements of infants and mothers from across the Roman Empire placed the completion of weaning between the ages of two and four (e.g., Dupras et al., 2001; Prowse et al., 2008), a range consistent with that proposed for Roman Britain (e.g., Fuller, Molleson, Harris, Gilmour, & Hedges, 2006; Redfern et al., 2018). Nonetheless, this result might be biased by methodological issues related to group comparisons of bone measurements (Reynard & Tuross, 2015). Our results would indicate that this range may be extended even further, perhaps up to the age of five. Given a lack of incremental studies from other Roman sites, we compared our data with published examples from early medieval individuals from Britain (fifth and tenth centuries) (Beaumont et al., 2014, 2018), Greece (fifth to sixth centuries) (Kwok, Garvie-Lok, & Katzenberg, 2018) and continental Europe (fourth to seventh centuries) (Crowder, Montgomery, Gröcke, & Filipek, 2019; Czermak, Schermelleh, & Lee-Thorp, 2018). To make our results directly comparable with previous literature results, we also modelled these at 6-month intervals using the Bayesian model OsteoBioR (see Section 2). For early Anglo-Saxon Britain, a single individual from fifth-century West Heslerton, Yorkshire, completed weaning at [1.5–2] years (after Beaumont et al., 2014). Another six British individuals from late Anglo-Saxon Raunds (tenth century) completed weaning between [2.5–3] and [4–4.5] years (after Beaumont et al., 2018). A study at early Byzantine Nemea (No. = 25) showed that the majority of infants were fully weaned at approximately between [1.5–2] and [2.5–3] years apart from two outliers fully weaned at [1–1.5] and [4–4.5] years (after Kwok et al., 2018). As for populations that settled within the Roman Empire during the Migration Period, we compared our results with those from a Gepid cemetery in Archiud, Romania and an unspecified Germanic population settled in Niedernai, France. At Archiud, four individuals completed their weaning between [2.5–3] and [4–4.5] years (after Crowder et al., 2019). At Niedernai, four individuals completed weaning between [2–2.5] and [3.5–4] years (after Czermak et al., 2018). Thus, most sampled early medieval individuals completed weaning between the ages of two and four, although there were a few with earlier or later dates of weaning completion. In contrast, our Romano-British

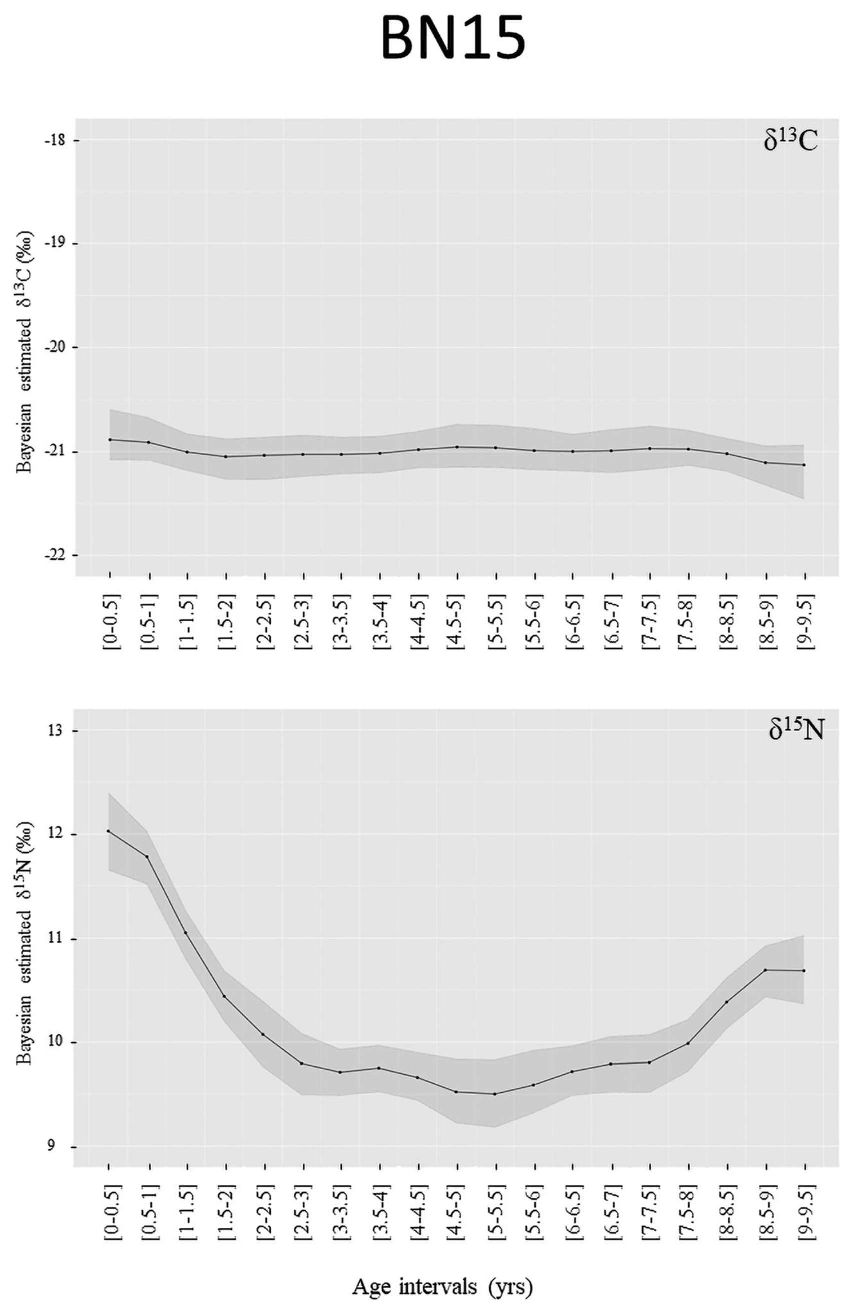


FIGURE 2 Bayesian temporal modelling of M1 incremental dentine δ^{13}C and δ^{15}N for BN15

dataset shows that three out of five individuals were fully weaned after the age of four, that is, BN124 at [4.5–5], BN144 at [4–4.5] and BN213 at [4–4.5]. BN15 and BN197a were fully weaned at [2.5–3] and [2–2.5], respectively.

The isotopic results for post-weaning stages vary among the different individuals (Figure 2). Individual BN197a, in particular, shows temporal oscillations in δ^{15}N values and for the last age interval [9–9.5] also a significant drop in both δ^{13}C and δ^{15}N values. Lower δ^{15}N values are likely to result from a lower intake of animal protein, whereas lower δ^{13}C values could arise from a higher consumption of an unknown fat source with comparatively more negative δ^{13}C values than protein or carbohydrates (Fernandes, 2016). However, it is also possible that this isotopic shift is associated with malnutrition or physiological stress (D'Ortenzio et al. 2015). The remainder of the individuals shows an overall increase in δ^{15}N values with age, as expected during anabolic growth stage, although this occurs at different rates and at different time gaps following the completion of weaning. The increase of δ^{15}N values becomes steeper around the ages of seven or eight for individuals BN15, BN144 and BN213. BN124 also shows an increase in δ^{15}N following weaning but the sample was not preserved beyond the interval [6–6.5] years. The δ^{13}C values for the different individuals are approximately within the range −22‰ to −20‰, which likely indicates dietary intakes from predominantly terrestrial C_3-type protein sources, but some consumption of freshwater fish

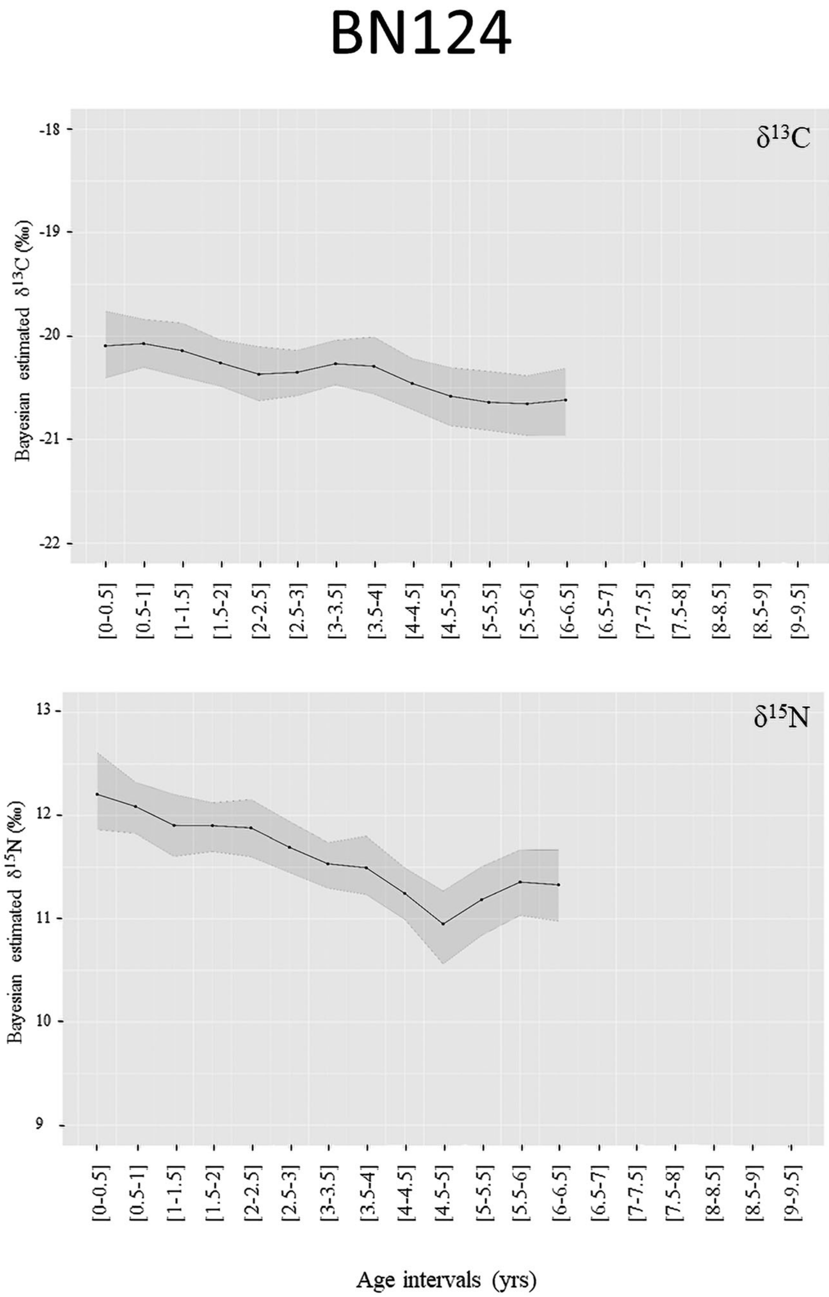


FIGURE 3 Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN124

cannot be excluded, as also hypothesised by previous isotopic analysis undertaken on adults from the site (Chenery et al., 2011; Moore et al., 2019).

4 | CONTEXTUALISING ROMAN SOURCES ON CHILDHOOD AND NON-ADULT DATA AT BAINESSE

The most notable ancient Roman authors on topics related to infant feeding practices were Soranus of Ephesus (second century CE), Galen (129 to ca. 200 CE) and Oribasius (ca. 320–403 CE), who spent most of their professional lives in Rome and wrote primarily for Roman aristocracy and Roman provincial elites (see Prowse et al., 2008). The start of weaning practices observed in our study is generally consistent with the advice given by Soranus (*Gyn*., 2.17–48; Temkin, 1956) to Roman parents, who recommended the introduction of semi-solid foods 6 months after infants' birth. The Greek physician Damastes (second century CE) (reported in *Soranus*, *Gyn*., 2.48; Temkin, 1956) recommended prolonging exclusive breastfeeding up to the age of one but only for female infants. The $\delta^{15}N$ values for the female individual BN213 show an increase after 6 months, which could have resulted from a change in the mother's diet, or malnutrition (Neuberger et al., 2013; Reitsema, 2013) or continued breastfeeding by the employment of a wet-nurse (Centlivres-Challet, 2017). For this individual, the peak in $\delta^{15}N$ values was reached at the age of 1 year

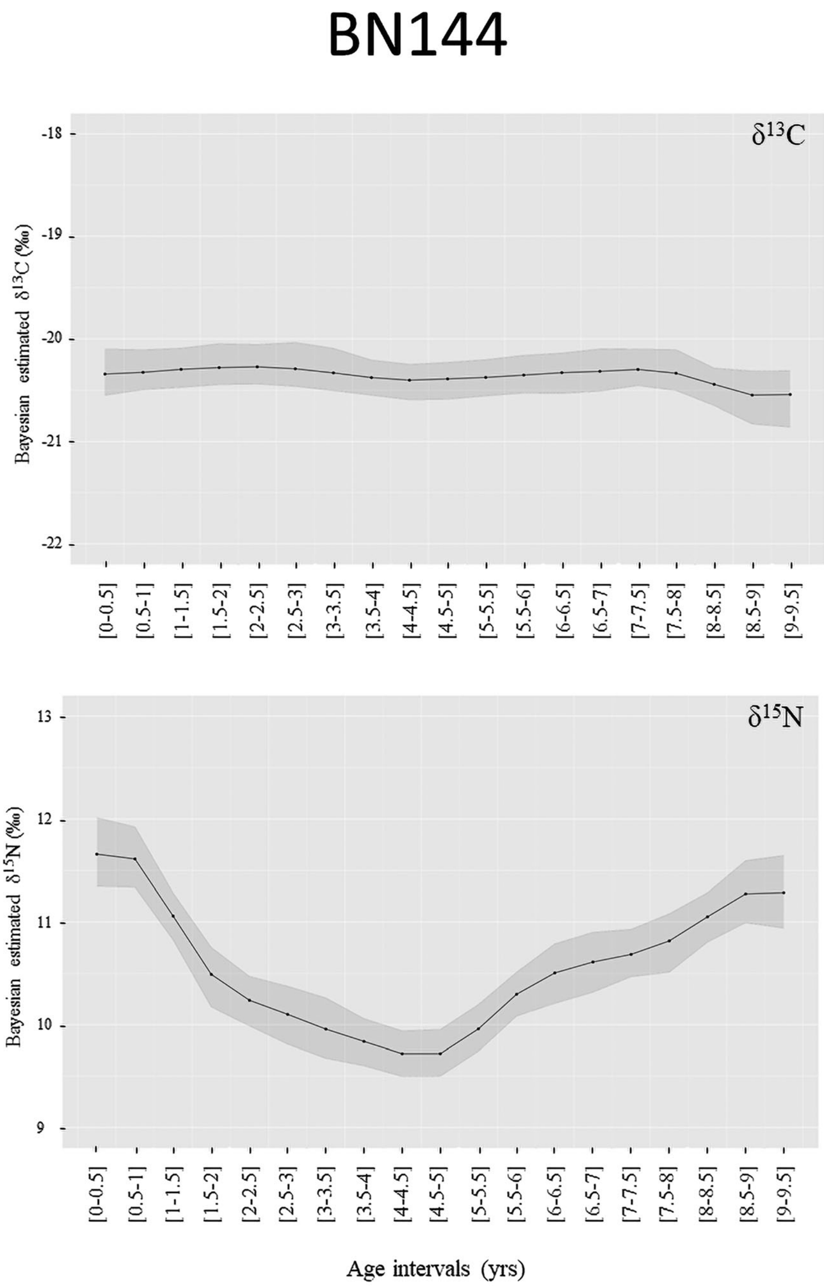


FIGURE 4 Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN144

and few months approximately in accordance with the Damastes' recommendations. A similar pattern is observed in BN144, a probable female individual. As for the completion of the weaning process, Soranus suggested that this should be completed at the age of two. The same recommendation was given by Antyllus (second century CE) (lost work cited in *Orybasius*, *Incert*.; Grant, 1997) and Oribasius (*Incert*.; Grant, 1997). However, Galen (*Hygiene*; Johnston, 2018) recommended that weaning should be completed at the later age of three. To what extent the population at Bainesse would have access to the recommendations made by Roman physicians is unclear. It is possible that they were knowledgeable of the medical treatises, perhaps through the medium of travellers and soldiers headed to *Cataractonium*, but if so, our results suggest that this was followed only partially.

It is possible that local and family traditions influenced the adoption of certain weaning practices, but the variability that we observed may also be indicative of socio-economic aspects. Written evidence (e.g., Diocletian's *Edictum de pretiis rerum venalium*; Graser, 1940) points to the greater economic value that animal foods had in comparison to plant foods and thus it is expected that they were less accessible to individuals belonging to lower socio-economic classes, which possibly included infants. Concerning the latter, many ancient Graeco-Roman physicians and philosophers identified the age of seven as the end of early childhood (*infantia*) (Laes, 2011: 77–100). Gaius' (ca. 110–170 CE) *Institutes*, collected in Justinian's *Institutes* (sixth century CE), regulated that a child under the age of seven was *non multum a furioso distant, quia huius aetatis pupilli nullum intellectum habent* ('not very different from a mentally disabled person, since

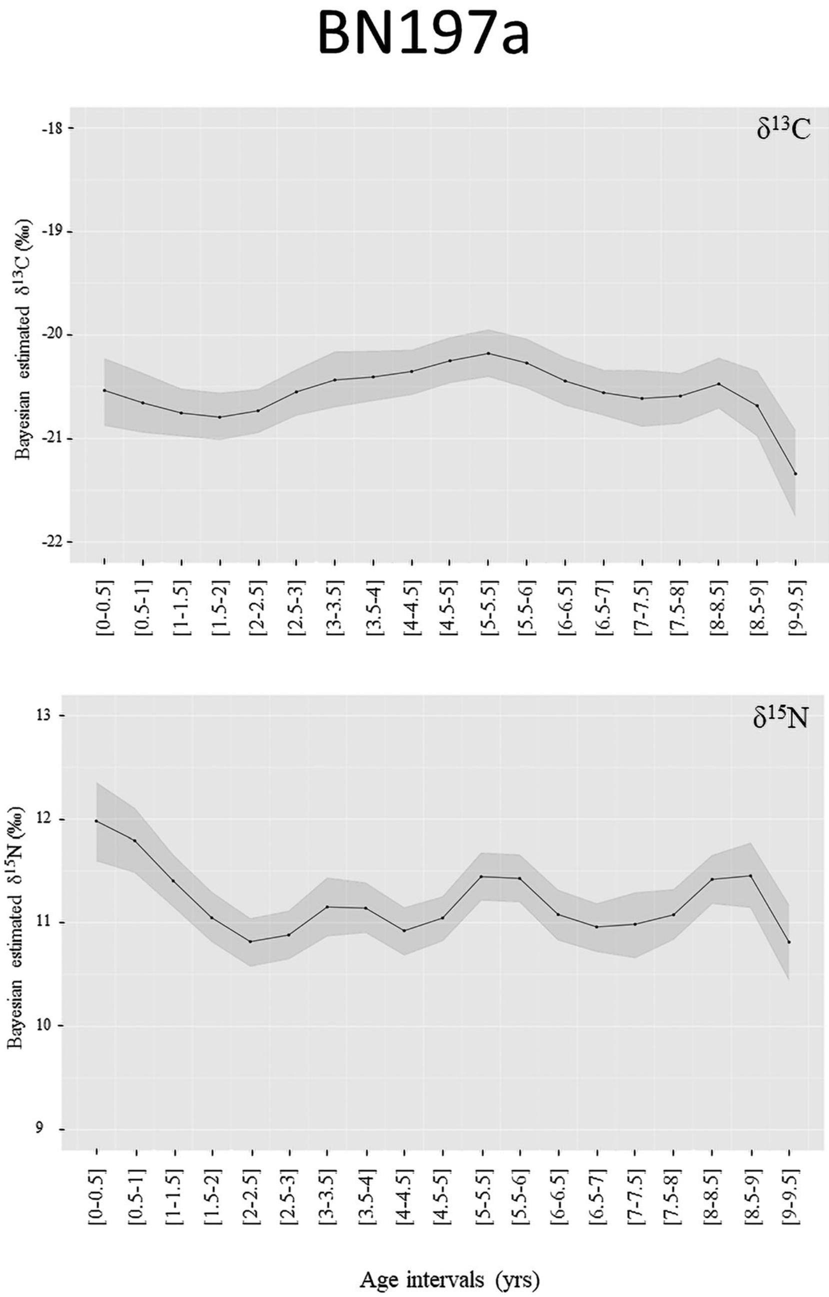
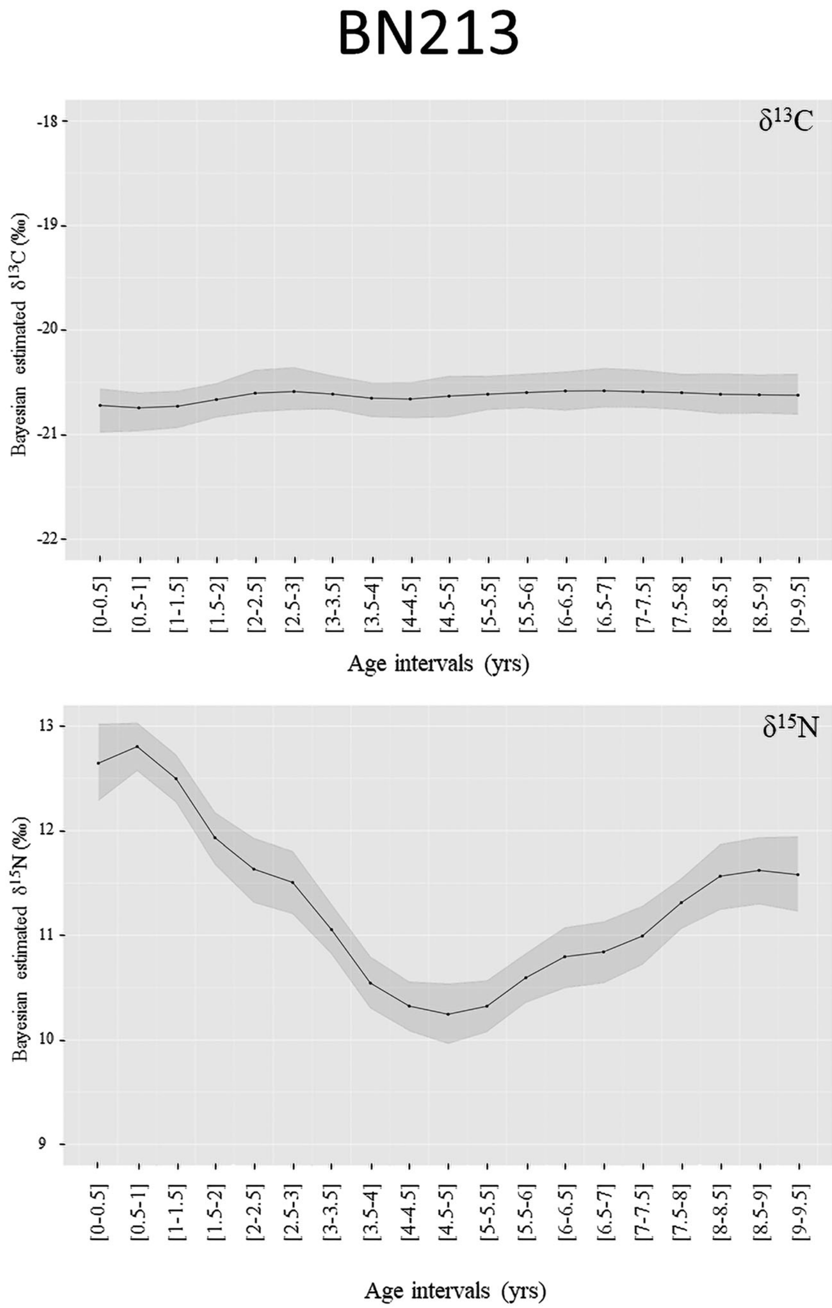


FIGURE 5 Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN197a

during this age, children do not possess any intellectual faculty') (*Inst*. 3.19.10; Moyle, 1911), remarking how an *infans* (or *pupillus*) could not be considered an autonomous person. This age transition seems to have been part of a cultural concept commonly recognised by Graeco-Roman authors, likely to be grounded on changing biological features (such as the transitional replacement of deciduous teeth and physical growth) and philosophical beliefs (Eyben, 1972; Laes, 2011, pp. 77–100).

The idea of a common cultural knowledge in the Roman world has been heavily criticised, especially when it comes to Britain (e.g., Barrett, 1997; Freeman, 1997). However, what is here inferred is not the vision of a deterministic homogeneous Roman culture, where one could imply the existence of common patterns in Rome as well as in Northern Britain for the only reason of being 'Roman' ('Romanisation'; see Pinto, 2017), but rather an observation on the mechanisms that may have led to this similarity suggested by our results. Beyond the possibility that culture was spread with goods in the commercial hub of Bainesse due to its relationship with *Cataractonium*, a concurring socio-demographic explanation may also be possible. Graeco-Roman authors imbued symbolism to an individual's every seventh year of life, which was considered an *annus climactericus* ('critical year') of transition on both biological and social levels (Eyben, 1972). Although we are aware of the risks of the 'osteological paradox' and bias related to funerary commemoration, a high degree of mortality during early childhood is attested in the Roman world (Carroll, 2011; Rawson, 2003). In Bainesse, Holst et al. (2019)

FIGURE 6 Bayesian temporal modelling of M1 incremental dentine $\delta^{13}C$ and $\delta^{15}N$ for BN213



observed that 69% of non-adult buried individuals were aged between 1 and 6 years, with a peak between 3 and 5 years. Hence, it is possible that to the eyes of Roman society, even in Bainesse, the age of seven may have marked a perceived 'survival' threshold and thus a step on the social scale.

Isotopic studies have also shown that Roman male individuals reaching the status of *PaterFamilias* during adulthood increased their intake of animal protein (Martyn et al., 2018). Also, Prowse et al. (2008, 2010) found that children in Roman Italy likely had a lower social status that was reflected by a lower quality of their diet. Thus, a hypothesis that emerges from our study is that an improvement in children's diet, perhaps with the addition of higher trophic level protein such as freshwater fish, was only made once these passed the socio-cultural step at 7 years. This 'survival' threshold in Bainesse might also help to find an explanation for the prolonged weaning process we observed in surviving individuals from our dataset. Families possibly may have spent more time and care in the process of weaning as a logical solution attempting to protect the child from morbidity and malnutrition. In conclusion, our results would concur with the cultural idea that a certain age may have led to an elevation of Roman children's status and, perhaps, also the access to foods of a higher economic value.

5 | CONCLUSIONS

This study presented the first use of isotopic measurements on tooth increments to reconstruct Roman infant feeding practices for five individuals from the Romano-British settlement at Bainesse. Bayesian modelling was employed to make diachronic results directly comparable among the different individuals and to generate temporal isotopic estimates with an uncertainty reflecting the tooth section sampling process. This revealed significant differences in weaning and post-weaning practices. Nonetheless, all individuals were fed exclusively on breastmilk at least until 6 months of age. Following the introduction of semi-solid food into infants' diet, each individual completed weaning at different ages, between 2 and 5 years. The variability in our data suggests that local socio-economic aspects may have had an impact on weaning practices at Bainesse, although some degree of observed consistency with ancient medical recommendations leads us not to a priori exclude that these were known. Post-weaning isotopic values show an increase in the consumption of animal protein following weaning completion. This becomes particularly accentuated around the age of seven for most individuals, when Roman children potentially rose from their *infantia* status.

Future tooth incremental studies on other Roman populations are necessary to characterise in more detail the variability in infant feeding practices across regions and time periods. It would be of particular interest to investigate how infant feeding practices at the heart of the Roman Empire contrasted with those in Roman provinces. At Bainesse, we suggest that future bioarchaeological analysis could focus on the relationship between the site and the nearby fort of *Cataractonium*.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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