Proc Soc Antiq Scot 150 (2021), 385–406
https://doi.org/10.9750/PSAS.150.1321

Reconstructing the childhood diet of individuals buried with the Pictish monastic community at Portmahomack

Jyoti Stuart-Lawson* and Shirley Curtis-Summers†

ABSTRACT

This research aims to reconstruct the childhood diets (aged 9–10 years) of the individuals buried during the active years of the Pictish monastic community (hereafter referred to as PMC) from early medieval (7th–11th century) Portmahomack in north-east Scotland, using ^{13}C and ^{15}N isotopes. Dietary reconstructions were achieved by isotope analysis of $\delta^{13}C$ and $\delta^{15}N$ on the tooth root apex from permanent first molars (M1) of 26 adult male individuals. The results indicate that the individuals in the PMC predominantly consumed terrestrial C_3 resources during childhood, with a rich terrestrial protein diet and some marine resource consumption. Statistically significant differences were observed between childhood and adulthood diets (adult isotope data from Curtis-Summers et al 2014; 2020), suggesting that when these individuals were children, they consumed more marine protein than in later years as adults. This is true for all individuals, whether or not they spent significant time in Portmahomack during their childhoods. This is the most extensive study of the childhood diet of individuals from the PMC and so makes a significant contribution to augmenting information on diet and lifestyles in Pictish Scotland.

INTRODUCTION

SITE BACKGROUND

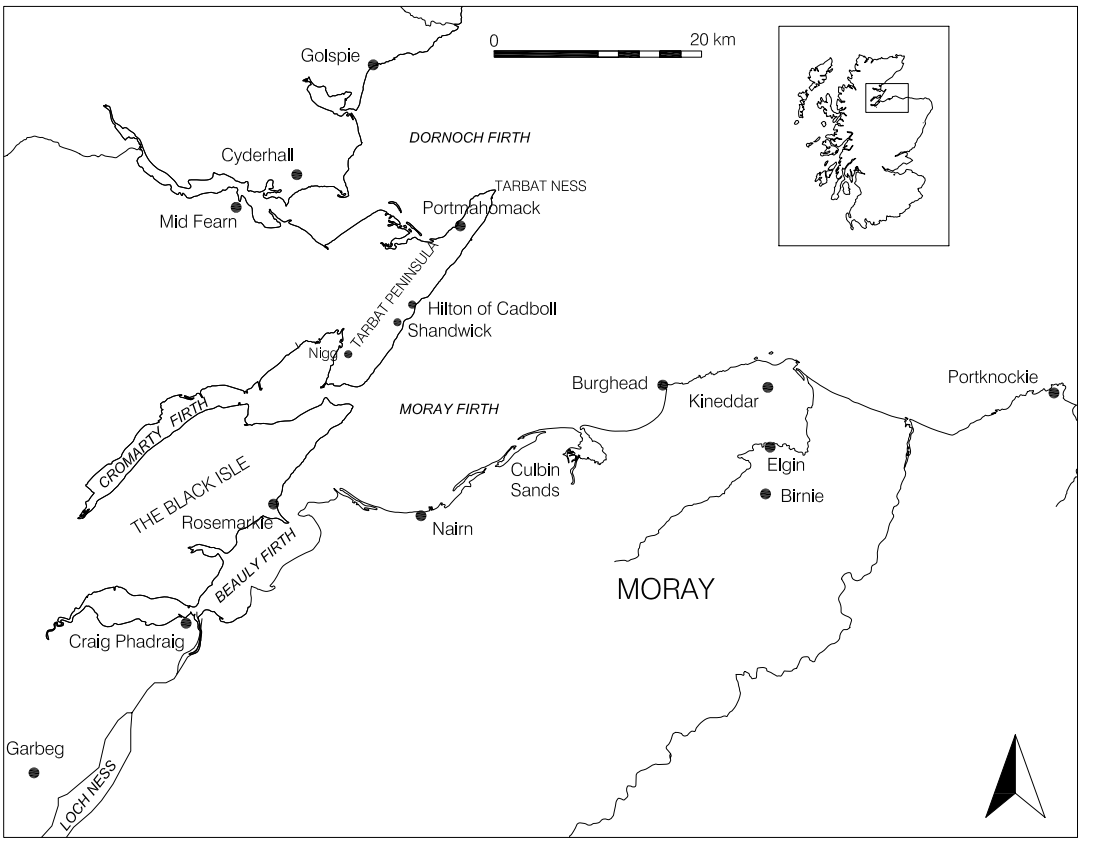
Portmahomack in Easter Ross is the first excavated Pictish monastic site in Scotland. These archaeological excavations provide a unique insight into Pictish monastic life, religious practices, culture and economic activities (Carver 1995; 1997; 1999; 2004; 2006; 2008; 2009; 2016a; 2016b; 2016c; 2019a; 2019b; Carver & Spall 2004; Carver et al 2016).

Portmahomack is situated on the Tarbat Peninsula, north-east Scotland (Illus 1) (Canmore ID: 15664). These shores might have enabled easy landing in the Moray Firth region during the early medieval period and this is possibly why a settlement was formed here. On an elevated position above the village is a church dedicated to St Colman (Carver 2004: 4) and the excavations took place near to the church.

The site was divided into four excavation sectors, and four main occupation phases have been identified (periods 1–4), outlined in Carver (2016a: 44–7) (Illus 2). Period 1 – 5th to 7th centuries (AD 400–680) – was when the site was believed to be a centre for Pictish settlers, possibly of high status. There was evidence of arable farming in sector 1, cist burials and a roundhouse in sector 2, and a combination of plain and long

* Oxford Archaeology South, Janus House, Osney Mead, Oxford, OX2 0ES stuarta.jo@gmail.com

† School of Archaeological and Forensic Sciences, University of Bradford, Bradford, West Yorkshire BD7 1DP s.curtis-summers@bradford.ac.uk

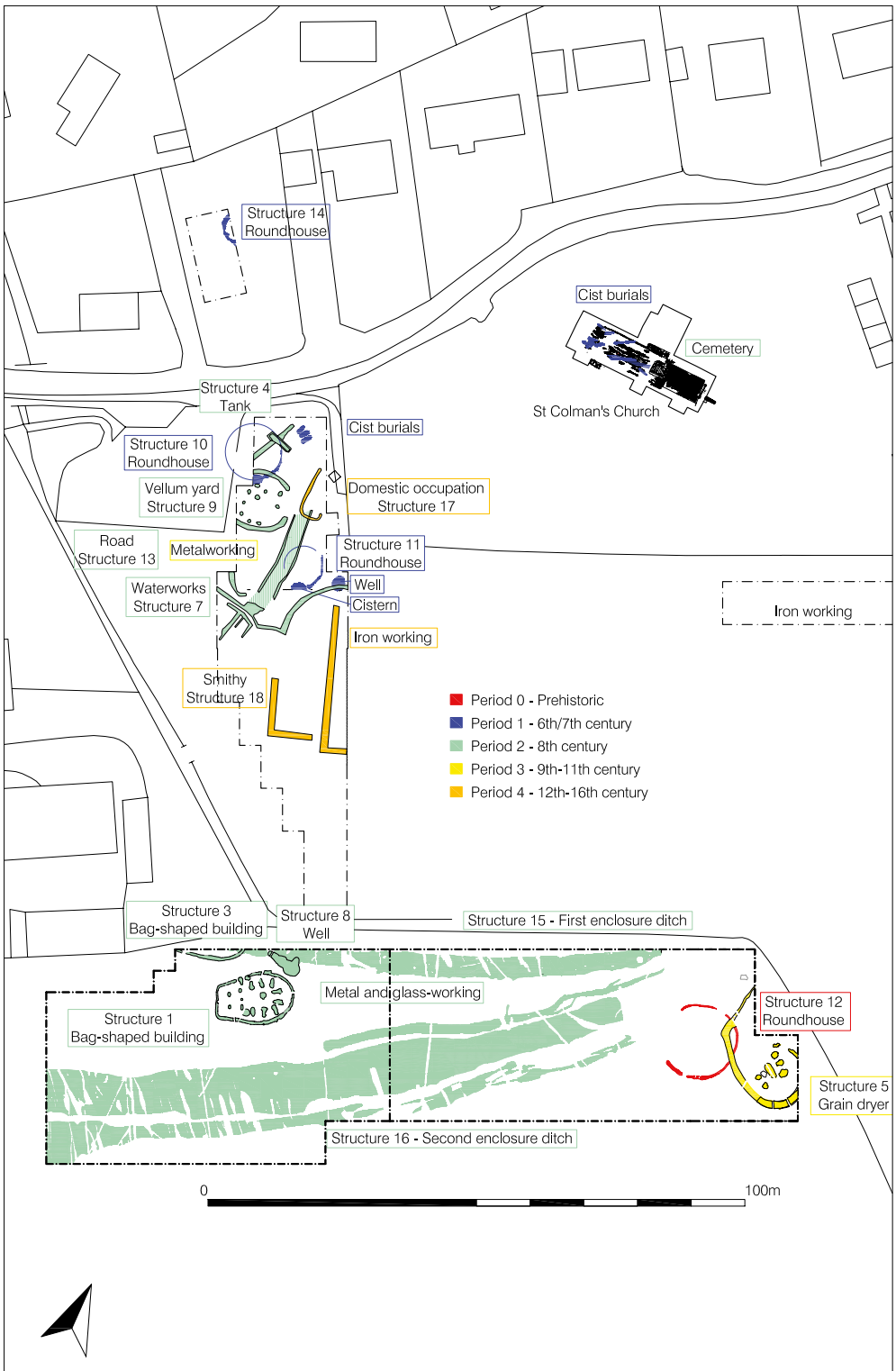


Illus 1 Location of Portmahomack on the Tarbat peninsula. (Carver 2004: 5)

cists in sectors 3 and 4. Period 2 – AD 680–810 – was a monastic phase, with most burials being of males, and finds that suggest monastic activities: vellum making (Carver & Spall 2004: 192–8), a Latin inscribed stone and writing implements. Other finds included two enclosures with a 'bag shaped' building, a pond and bridge, and signs of metalworking and glass working. At the end of period 2, there was evidence of burning at the site and deliberate cut marks to the crania of two individuals, possibly victims of a raid during a Viking invasion. In period 3 – AD 800–1050 – Portmahomack possibly became a trading centre rather than a monastery, with evidence of arable farming (wheat and barley), intensified commercial metalworking and glass working (such as finger-rings and necklaces), and kiln barns where grain was probably being dried (Carver 2016a: 152–4). The site seems to have been abandoned between AD 900 and 1050 but was reoccupied during the 12th–16th centuries (period 4) when it became a parish church community. A new church was built (AD 1200–1400), and evidence was found of coins, pottery and metalworking that suggested more widespread cultural and economic exchanges. This paper will focus on analysis of individuals from periods 2 and 3.

PRINCIPLES OF CARBON AND NITROGEN ISOTOPE DIETARY ANALYSIS

The use of stable carbon and nitrogen isotope ratio analysis to reconstruct past diets follows the principle that these elements are incorporated into body tissues such as teeth and bones, from the types of foods consumed during life. These



ILLUS 2 Excavation map. (Carver et al 2016: 289)

isotope ratios can therefore be measured in tissues to provide palaeodietary reconstructions. Stable isotope palaeodietary analysis is a well-established technique (eg DeNiro 1985; 1987; Schwarcz & Schoeninger 1991; Britton 2017). $\delta^{15}N$ values for collagen give an indication of the trophic-level of the food consumed; $\delta^{13}C$ values indicate whether food comes from terrestrial or marine sources, and whether the plants consumed used C_3 or C_4 photosynthetic pathways. Based on Meier-Augenstein's (2010: 28) trophic-level schematic system, every increase in trophic-level leads to an increase in $\delta^{15}N$ values of 2–5‰ (Lee-Thorp 2008: 928). The shift in $\delta^{13}C$ values per trophic-level is generally <1‰ (Schoeninger & DeNiro 1984: 633), although Barnes et al (2007: 356) suggested that up to 2‰ is possible, and the trophic-level shift is lower in herbivores than carnivores (Van Klinken et al 2000: 46–47).

Schwarcz's (2011: 244) carbon and nitrogen food category model shows that marine-based diets have higher values of $\delta^{13}C$ and $\delta^{15}N$ than terrestrial-based diets. Marine mammals' isotopic signatures have higher $\delta^{15}N$ values than marine fish but similar $\delta^{13}C$ values. For freshwater fish, the $\delta^{13}C$ values are low but the $\delta^{15}N$ values are higher (Richards 2020). The usually accepted $\delta^{13}C$ range for a 100% terrestrial diet is -18‰ to -30‰ and the $\delta^{13}C$ values for 100% marine diet start at -12.0‰ (Schwarcz 2011: 244). Lovell et al (1986: 51) found that a standard deviation of 0.3‰ or less for $\delta^{13}C$ indicates a fairly homogeneous diet of the individuals sampled.

$\delta^{13}C$ values can also indicate whether the plants consumed are C_3 or C_4 plants. C_4 plants, such as sugarcane, maize and millet are typically found in warmer climates, such as the tropics. There is no record of C_4 plant use during the early medieval period in Scotland, so C_4 consumption is presumed not to have occurred at Portmahomack at this time (Macgill 1909: 150–8; Müldner et al 2011).

Assuming certain factors that alter bone collagen isotope values can be ruled out, such as evidence of physiological stress, carbon and nitrogen isotope values may reflect adult dietary protein from around the last 20 years of life, compared to around the last 5 years of life for non-adults (Koch et al 1997: 418; Fuller et al 2006: 46; Lee-Thorp 2008: 927). When comparing childhood dentine with faunal bone collagen it is noted that these are two different measurements; faunal bone represents the animals' diet over a long period of time. Bocherens et al (1992) showed the animals' teeth and bone only have similar isotopic ratios if bone skeletal components are continuously developing during the individual's lifetime. Also, if there are different developmental completion rates, then the isotopic values will reflect different time spans (Bocherens et al 1992; Leskovar et al 2019) but these types of results are sufficient for our purposes.

Beaumont & Montgomery (2015: 410) showed that the development of M1 (first molar) commences at birth, with the development of the cusp first, and continues to develop down to the root apex until approximately 10 years of age. Thus, a small section of the root apex allows a snapshot of childhood diet at approximately 9–10 years of age. The root apex used for this study predominantly consists of primary dentine; any secondary dentine found in the root apex is minimal. Therefore, the results would represent the diet at the time of tooth formation. Recently this technique has been used to take several increments of teeth and showed significant changes over short periods of time (eg Beaumont & Montgomery 2016: 2) and the results compared with adult bone (eg Beaumont & Montgomery 2016: 12).

PREVIOUS BIOARCHAEOLOGICAL RESEARCH AT PORTMAHOMACK

Archaeological excavations at Portmahomack revealed remains of a wide variety of animals that could have been eaten, including cattle, pigs, sheep/goats and deer (Carver & Spall 2004: 193; Ashby 2016; Seetah 2016). From the Portmahomack faunal assemblage, abundant cattle remains were found (MNI (minimum number of individuals) = 305); the cattle seem to have been killed when they were older (Seetah 2016). Seetah (2016: D134–D135) suggests the mature cattle were kept predominantly for milk,

cheese and butter production. Some remains of juvenile calves were also found, but Carver & Spall (2004: 189–98) suggested that calf skins could have been used for vellum production. Pig remains were fewer than cattle but isotopic analysis (Curtis-Summers et al 2020: 11) suggests that pigs were eaten, as the adulthood of the same individuals from the PMC's $\delta^{15}N$ values were a trophic-level higher than the cattle and pig $\delta^{15}N$ values. Seetah (2016: D132) recorded marine mammals remains of whales, seals, otters and dolphins, but relatively low numbers of each. However, the period from which the remains date is uncertain.

There was only a small fish assemblage dating from periods 1–3; Holmes (2016a) was able to identify at least three species: char, species of Gadidae (including oceanic cod) and horse mackerel. The isotopic results (Curtis-Summers et al 2020: 5–6) show that the assemblage represents a combination of estuarine and marine fish species. Char live in freshwater, estuarine or marine habitats, whereas horse mackerel and Gadidae occupy marine habitats. By period 4, many more marine fish remains were found, and the higher $\delta^{13}C$ and $\delta^{15}N$ values in human bone collagen suggest a much greater consumption of marine resources by this time (Curtis-Summers et al 2020: 12).

Holmes (2016b) analysed shell middens from period 4 and a small assemblage from periods 1–2, and found that the later assemblage consisted predominantly of whelks (*Buccinum undatum*) and two types of winkles (*Littorina obtusata* or *L fabalis* and *L littorea* (edible)), with smaller numbers of limpets, oysters and cockles. Ash from the burning of *Spirorbis* annelid worms indicated its use in vellum production (Carver & Spall 2004: 195); however, there were no signs of burning of the shellfish, and the whelks were the incorrect species for producing pigments; so individuals from the PMC could have been consuming a small number of shellfish (Holmes 2016b).

In previous research, bone collagen isotope analysis was applied to ribs from 40 individuals to understand the last 20 years of an individual's diet (adulthood diet) (Curtis-Summers et al 2014: 26–7). Results demonstrated that the adulthood diets for periods 2 and 3 individuals had lower $\delta^{15}N$ and $\delta^{13}C$ values compared to period 4. Considering these results, and the scant number of fish bones found from periods 2 and 3, a predominantly C_3 terrestrial-based diet is suggested for the PMC (Curtis-Summers et al 2014: 28). First molar bulk root dentine analysis was performed on five individuals from periods 2 and 3. The dentine from the roots provides an average of the diet between approximately 3.5 and 10 years old, which is the time the roots were forming. The difference (Δ) in $\delta^{13}C$ for the bulk root dentine ranged from 0.1‰ to 0.7‰ above the adult bone collagen and the mean $\Delta\ \delta^{13}C$ was +0.38‰. $\Delta\ \delta^{15}N$ for the bulk root dentine ranged from 0‰ to 1.0‰ and the mean was +0.52‰ (Curtis-Summers et al 2014: 28). This showed that the $\delta^{13}C$ and $\delta^{15}N$ values for these young children were slightly higher than the adult dietary signature of the same individuals, indicating a diet possibly slightly higher in marine resources (Curtis-Summers et al 2014: 27). There was severe occlusal wear on the teeth of a number of Portmahomack adults from the PMC (Curtis-Summers 2015: 464–75; King 2016: D27), suggesting they ate a significant amount of coarse and gritty grain products that needed strong mastication.

Strontium and oxygen isotopic analysis was carried out on the permanent molars and premolar samples of the individuals from the PMC (Walther et al 2016).

Walther et al's (2016) study of Sr/O isotopes showed that many of the PMC did not have local origins. Eleven of the individuals that Walther studied overlapped with our data. Of these, three were definitely local to Portmahomack at the time of the diet analysis, but the rest were likely to have been outside the area during their childhood, from places as widespread as Scandinavia, east Britain and western Scotland. This suggests that the PMC was made up of a majority of individuals who travelled to the area to become part of the community.

RESEARCH QUESTIONS

This research contributes to the corpus of archaeological and bioarchaeological knowledge by providing new isotope evidence regarding the childhood diets of the individuals from the PMC. The new data presented here are compared with previous data on adult diets (Curtis-Summers et al 2014; 2020) in order to investigate possible cultural influences on the diets of children in medieval Portmahomack. The research attempts to answer the following three questions:

1. What does $\delta^{13}C$ and $\delta^{15}N$ isotope analysis of incremental dentine reveal about the childhood (approximately 9–10-year-old) diet of the individuals from the PMC?
2. How does the childhood diet of the individuals from the PMC compare with their adult diets, as found by Curtis-Summers et al (2014) and Curtis-Summers et al (2020)?
3. What does the comparison of childhood and adult diets reveal about cultural practices during periods 2 and 3 at Portmahomack?

MATERIALS AND METHODOLOGY

Isotopic analysis on root dentine was conducted on 26 human tooth samples (N = 26) from the monastic phase period 2 (P2) and period 3 (P3). All sample preparation and mass spectrometry analysis were carried out at the University of Bradford's isotope facility, following established protocols (Longin 1971; O'Connell & Hedges 1999; Beaumont et al 2013: 284–5). Of the 58 adult skeletons from these periods, 54 were male, two were female and two of unknown sex, with a range of ages from 18 to 60 years approximately (Curtis-Summers et al 2014; 2020). To study childhood diet, dentine from the permanent first molar (M1) was analysed and only adults with M1 present were selected for study to maintain uniformity and accuracy of age-related dietary reconstructions (N = 21 (P2), N = 5 (P3)). For this study, the last 2mm of the root apex was analysed, which represents a childhood age between approximately 9 and 10 years (Beaumont & Montgomery 2015: 410–14). The size of the root canal gets larger as it reaches the pulp chamber. The fact that the root apex was used means that the size of the root canal is very thin (Beaumont et al 2013: 280). To further reduce the effects of tertiary dentine, only the tooth roots without caries and reduced wear were selected, as tertiary dentine develops as an evolutionary response by the pulp chamber against potential infections. Cementum was removed while cleaning all of the tooth root surfaces with an air abrasion drill. The circumpulpal dentine was removed during the 'method 2' process (see below).

Beaumont et al's (2013: 284–5) 'method 2' was applied, involving removal of the surface debris and cementum with an air abrasive or metallic drill. Each tooth root was cut longitudinally along the mid-shaft and transversely, just below the cementum-enamel-junction (CEJ). The samples were demineralised in 0.5M hydrochloric acid (HCl) and refrigerated until the samples had demineralised. Once demineralised, they were rinsed with deionised water in triplicate. The 2mm section of each demineralised root was cut into two 1mm increments using a scalpel and ruler. Each sample was immersed in deionised water, acidified to pH3 with HCl and transferred to a heating block at a temperature of 70°C to dissolve the collagen (gelatinisation) (Beaumont et al 2013: 284–5). The samples were centrifuged for two minutes, before freezing for a minimum of three hours. Once frozen the samples were transferred to a freeze-drier for 24 hours until dry (lyophilisation). The dentine samples, along with in-house and international standards for AIR and V-PDB, were weighed and placed into the auto sampler of a Delta V Advantage with a Flash EA 1112. The international standards are IAEA-600 (caffeine), IAEA-N-1 (ammonium sulphate) and IAEA-CH-3 (cellulose); and the in-house standards used were fish gelatine and BLS (Bovine liver solution).

RESULTS

All $\delta^{13}C$ and $\delta^{15}N$ data for the Portmahomack M1 tooth dentine collagen samples are presented in

TABLE 1
Stable isotope data for collagen extracted from M1 root dentine of individuals from the Portmahomack PMC and comparison of Curtis-Summers et al (2014; 2020) adulthood bone collagen data

Skeleton no.	*Sex (M/F)*[a]	*Age range (years)*[b]	*Burial phase (2/3)*[c]	*Tooth sections (1 or 2)*[d]	*C:N*[e]	*$\delta^{13}C$ ‰ (V-PDB)*	*$\delta^{15}N$ ‰ (AIR)*	*Bone collagen $\delta^{13}C$ ‰ (V-PDB)*[f]	*Bone collagen $\delta^{15}N$ ‰ (AIR)*[g]
38	M	46–59	2	1	3.25	-19.1	13.8	-20.6	12.5
38	M	46–59	2	2	3.24	-19.0	13.3		
40	M	46–59	2	1	3.51	-18.7	14.0	-20.3	12.3
40	M	46–59	2	2	3.51	-18.8	13.6		
42	M	46–59	2	1	3.70	-19.1	14.0	-19.7	12.9
42	M	46–59	2	2	3.60	-19.1	13.7		
44	M	46–59	2	1	3.61	-19.4	13.3	-20.4	12.1
44	M	46–59	2	2	3.51	-19.0	12.8		
47	M	26–35	2	1	3.56	-19.0	13.6	-20.0	12.4
47	M	26–35	2	2	3.53	-18.5	13.6		
53	M	46–59	2	1	3.23	-19.1	12.3	-20.2	11.8
53	M	46–59	2	2	3.25	-19.0	12.3		
54	M	18–25	2	1	3.44	-18.8	13.0	-20.5	12.1
54	M	18–25	2	2	3.45	-18.8	12.8		
122	M	46–59	2	1	3.38	-18.7	14.0	-20.3	13.0
122	M	46–59	2	2	3.28	-18.4	12.6		
126	M	46–59	2	1	3.57	-19.2	12.5	-20.9	10.8
126	M	46–59	2	2	3.49	-19.2	11.9		
127	M?	36–45	2	1	3.53	-19.2	13.7	-20.4	11.8
127	M?	36–45	2	2	3.46	-19.2	13.5		
129	M?	18–25	2	1	3.45	-19.3	12.0	-20.6	11.3
129	M?	18–25	2	2	3.34	-19.1	12.2		
137	M?	36–45	2	1	3.48	-19.1	12.6	-20.5	11.8
137	M?	36–45	2	2	3.48	-19.3	12.0		
144	M	46–59	2	1	3.50	-18.4	15.9	-19.1	14.6
144	M	46–59	2	2	3.56	-18.5	16.0		
151	M	46–59	2	1	3.25	-19.1	13.3	-20.6	12.6
151	M	46–59	2	2	3.26	-19.0	13.3		
152	M	26–35	2	1	3.54	-19.2	13.5	-20.5	11.7
152	M	26–35	2	2	3.50	-19.3	13.7		
153	M	36–45	2	1	3.51	-18.6	14.3	-20.3	12
153	M	36–45	2	2	3.47	-18.7	14.2		

TABLE 1
Continued

Skeleton no.	*Sex (M/F)*[a]	*Age range (years)*[b]	*Burial phase (2/3)*[c]	*Tooth sections (1 or 2)*[d]	*C:N*[e]	*$\delta^{13}C$ ‰ (V-PDB)*	*$\delta^{15}N$ ‰ (AIR)*	*Bone collagen $\delta^{13}C$ ‰ (V-PDB)*[f]	*Bone collagen $\delta^{15}N$ ‰ (AIR)*[g]
154	M	46–59	2	1	3.27	-19.0	13.3	-20–5	11.8
154	M	46–59	2	2	3.23	-19.1	12.9		
158	M	46–59	2	1	3.57	-18.9	14.5	-20.3	12.4
158	M	46–59	2	2	3.54	-18.9	14.1		
164	M	46–59	2	1	3.53	-18.9	14.5	-20.2	12.8
164	M	46–59	2	2	3.49	-19.0	14.2		
176	M	46–59	2	1	3.51	-18.8	14.5	-20.1	12.8
176	M	46–59	2	2	3.56	-19.2	14.7		
189	M	26–35	2	1	3.61	-19.8	12.7	-20.1	11.7
189	M	26–35	2	2	3.52	-19.8	12.8		
111	M	26–35	3	1	3.33	-19.2	13.5	-20.7	12.0
111	M	26–35	3	2	3.28	-19.1	13.1		
136	M	36–45	3	1	3.43	-18.9	13.3	-21.1	11.9
136	M	36–45	3	2	3.43	-18.8	13.4		
145	M	Adult	3	1	3.51	-19.3	12.8	-20.5	12.3
145	M	Adult	3	2	3.51	-19.3	12.9		
147	M	26–35	3	1	3.51	-18.9	12.8	-20.4	11.2
147	M	26–35	3	2	3.50	-18.9	12.9		
156	M	36–45	3	1	3.56	-19.8	13.1	-20.9	12.0
156	M	36–45	3	2	3.47	-19.4	13.0		
					mean	-19.0	13.4	-20.43	12.11
					SD	0.301486	0.86355	0.41817	0.69801

[a, b] Osteological data (age and sex data) (Curtis-Summers 2015: 464–75) and Curtis–Summers et al (2020: 7–8)
[c] Burial phase 2 = AD 680–810; burial phase 3 = AD 800–1050 (Carver et al 2016: 8–9)
[d] Tooth sections 1 = lowest 1mm of tooth root apex; 2 = next 1mm interval of tooth root apex (above section 1)
[e] C:N = %C/%N * 1.1666 (14/12); C:N is the molar ratio with an accepted range of 2.9–3.6
[f, g] Adulthood bone collagen data (Curtis-Summers et al 2014: 27) and Curtis-Summers et al (2020: 12)

Table 1. The C:N ratios for the samples were between 3.2 and 3.6 and so are within the acceptable range for well-preserved collagen (DeNiro 1985: 807). The analytical precision for both carbon and nitrogen is ±0.2‰ (1σ), with $\delta^{13}C$ and $\delta^{15}N$ ratios reported relative to the international standards of Vienna-PDB and AIR, respectively. The results relate to the first two research questions; the third question is addressed in the discussion.

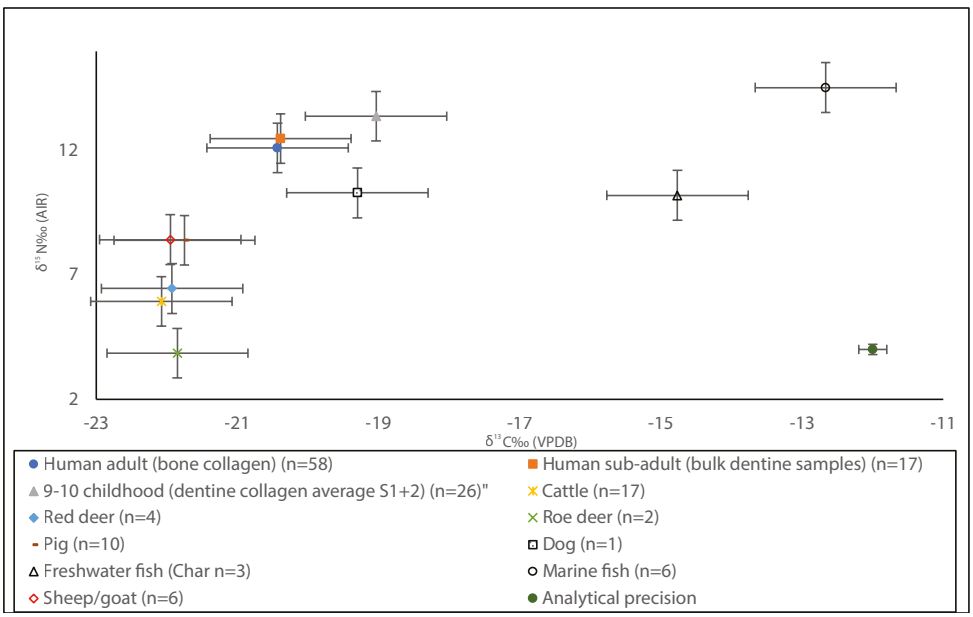
Question 1: What does $\delta^{13}C$ and $\delta^{15}N$ isotope analysis of incremental dentine reveal about childhood diet of the individuals from the PMC at Portmahomack?

FAUNAL $\Delta^{13}C$ AND $\Delta^{15}N$ DATA COMPARISON

The results of the analysis of the 9–10-year-old childhood diet (Table 1) give a mean $\delta^{13}C$ value of -19.0 (±0.30‰), and a mean $\delta^{15}N$ value of 13.4 (±0.86‰). Table 2 and Illus 3 compare the mean of sections 1 and 2 of the 9–10-year-old childhood data to the available local faunal data (Curtis-Summers et al 2020: 5). The omnivores (mainly pigs) might have been consuming human refuse as part of their diet, which raises their $\delta^{15}N$ values (Seetah 2016: D135;

TABLE 2
Differences in stable isotopic values between the 9–10-year-old childhood data (M1 root collagen) and Curtis-Summers et al (2020: 5) bone collagen faunal data

Species	*9–10 dentine average of P2+3 $\delta^{13}C$*	*Faunal $\delta^{13}C$*	*(Δ 9–10 childhood - faunal $\delta^{13}C$)*	*9–10 dentine average of P2+3 $\delta^{15}N$*	*Faunal $\delta^{15}N$*	*(Δ 9–10 childhood - faunal $\delta^{15}N$)*
Cattle	-19.0	-22.1	3.1	13.4	5.9	7.5
Sheep/goat	-19.0	-22.0	2.9	13.4	6.3	5.0
Pig	-19.0	-21.8	2.8	13.4	8.5	5.0
Dog	-19.0	-19.3	0.3	13.4	10.3	3.1
Red deer	-19.0	-21.9	2.9	13.4	6.5	6.9
Roe deer	-19.0	-21.9	2.8	13.4	3.9	9.5
Marine fish	-19.0	-12.7	-6.4	13.4	14.5	-1.1
Char	-19.0	-14.8	-4.3	13.4	10.2	3.2



ILLUS 3 Comparison of isotopic results from Portmahomack. Human data (bone and dentine) and faunal data averages are taken from Curtis-Summers et al (2014: 26–7); 9–10 childhood data (this study). The analytical precision is ±0.2‰ at 1σ.

Curtis-Summers et al 2020: 9). However, $\Delta^{13}C$ and $\Delta^{15}N$ between the 9–10-year-old children and the faunal baseline are more than would be expected from a 1‰ shift per trophic-level for $\delta^{13}C$ and a 2–5‰ shift for $\delta^{15}N$, even allowing for variabilities caused by temperature and food availability demonstrated by Barnes et al (2007: 356). For example, cattle $\Delta^{13}C_{\text{human 9–10 years – cattle}} = 3.1‰$ and $\Delta^{15}N_{\text{human 9–10 years – cattle}} = 7.5‰$. Even for the omnivores, which are a trophic-level higher than the herbivores, $\Delta^{13}C_{\text{human 9–10 years – omnivore}} = 2.8‰$ and $\Delta^{15}N_{\text{human 9–10 years – omnivore}} = 5‰$, suggesting that although the children might be consuming a considerable amount of pork as well as beef and dairy, mutton and plant products, some marine component to the diet must be considered to explain the large differences, which are more noticeable in the childhood data than the adult data of individuals from the PMC (Curtis-Summers et al 2020: 12).

9.0–9.5 AND 9.5–10-YEAR-OLD INCREMENTS COMPARISON

Section 1 of the root dentine reflects diet at age approximately 9.5–10 years, and Section 2 for approximately 9–9.5 years. Section 1 $\delta^{13}C$ values ranged from -19.8‰ to -18.4‰, with a mean of -19.1 (±0.3‰), whereas the $\delta^{15}N$ values ranged from 12.3‰ to 15.9‰, with a mean of 13.5 (±0.8‰). Section 2 $\delta^{13}C$ values range from -19.8‰ to -18.4‰ with a mean of -19.0 (±0.3‰) and $\delta^{15}N$ values range from 12.2‰ to 16.0‰ with a mean of 13.3 (±0.9‰).

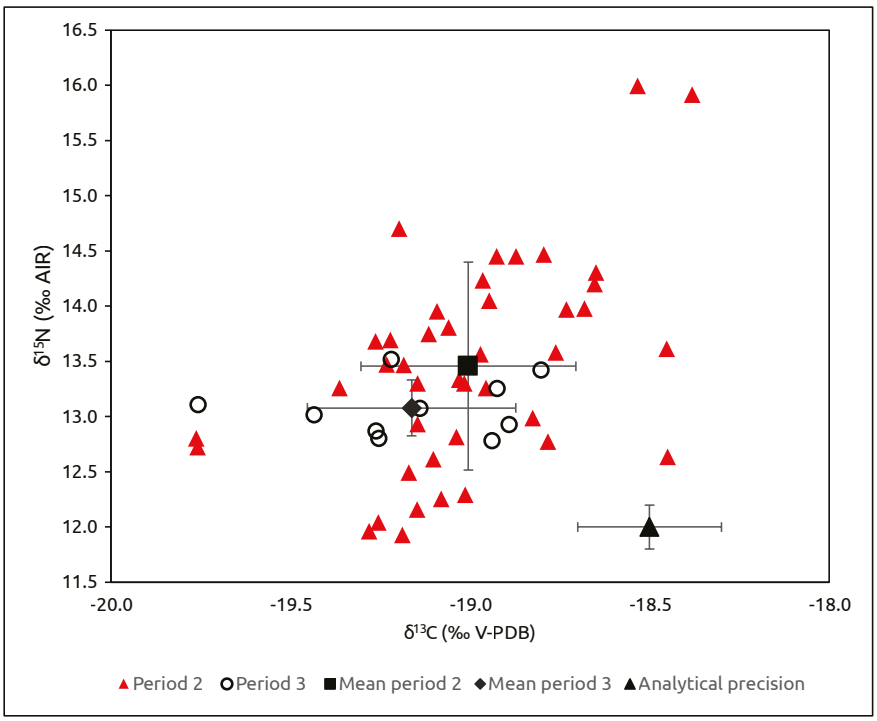
The majority of the individuals showed minimal differences in their sections 1 and 2 $\delta^{13}C$ and $\delta^{15}N$ values, suggesting consistent diets across these childhood ages. The possibility of seasonality being displayed could account for the minimal changes between sections 1 and 2. However, compelling evidence refuting this concept is Walther et al's (2016) data showing that the majority of the individuals were not local to Portmahomack around the age of 9–10 years old (as mentioned previously). One should not assume that seasonality patterns will be the same in different regions. The fact that all of the individuals have similar $\delta^{15}N$ increases between their approximate 9.5–10-year-old and approximate 9–9.5-year-old diets cast doubts about seasonality during the time frame of 9–10 years old (approximately). Therefore, there must be something else affecting the ratios, such as puberty (explored further later on). A two-sample *t*-test was applied and showed there is no significant difference between sections 1 and 2 for either $\delta^{13}C$ or $\delta^{15}N$. Therefore, in subsequent analyses no distinction is made between sections 1 and 2; only the mean values for sections 1 and 2 are used.

PERIOD 2 AND PERIOD 3 COMPARISON

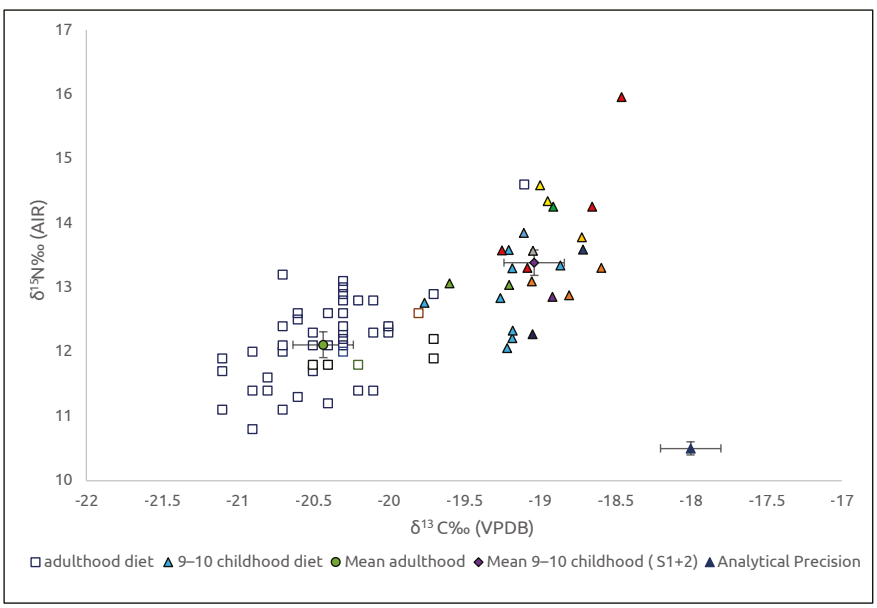
Illus 4 shows comparisons between childhood diets in period 2 (n = 21) and period 3 (n = 5). The mean for period 2 $\delta^{13}C$ is -19.0‰, whereas the mean for period 3 $\delta^{13}C$ is -19.2‰, and the standard deviations (SD) for both periods are identical at ±0.3‰ 2 SD, therefore showing little difference between the two periods and indicating a relatively homogeneous diet. A two-sample *t*-test confirmed there was no significant difference between these carbon values ($p = 0.147$). The results for $\delta^{15}N$ show a significant difference between periods, with the mean for $\delta^{15}N$ being 13.5‰ for period 2, whereas the mean for period 3 was 13.1‰. The standard deviations also demonstrate a much greater spread about the mean for period 2 (SD = 1.0) than for period 3 (SD = 0.3‰). A two-sample *t*-test confirmed a significant difference between these nitrogen values ($p = 0.033$), showing a greater diversity of food resources in period 2. However, the number of individuals analysed (n = 5) from period 3 is small and so might not be representative of the population.

Question 2: How does the childhood diet of the individuals from the PMC compare with their adult diets (as found by Curtis-Summers et al (2014; 2020))?

The distinct difference between childhood diets (this study) and the adult diets (as found by Curtis-Summers et al (2014: 27)) can be seen in Illus 5. The adult data had lower $\delta^{13}C$ and $\delta^{15}N$ values compared to root apex dentine. The mean



Illus 4 Periods 2 and 3 $\delta^{13}C$ and $\delta^{15}N$ values for root apex dentine; analytical precision is ±0.2‰ at 1σ.



Illus 5 Dentine collagen (this study) and adult bone collagen (Curtis-Summers et al 2014: 27) $\delta^{13}C$ and $\delta^{15}N$ values and mean values; analytical precision is ±0.2 ‰ at 1σ.

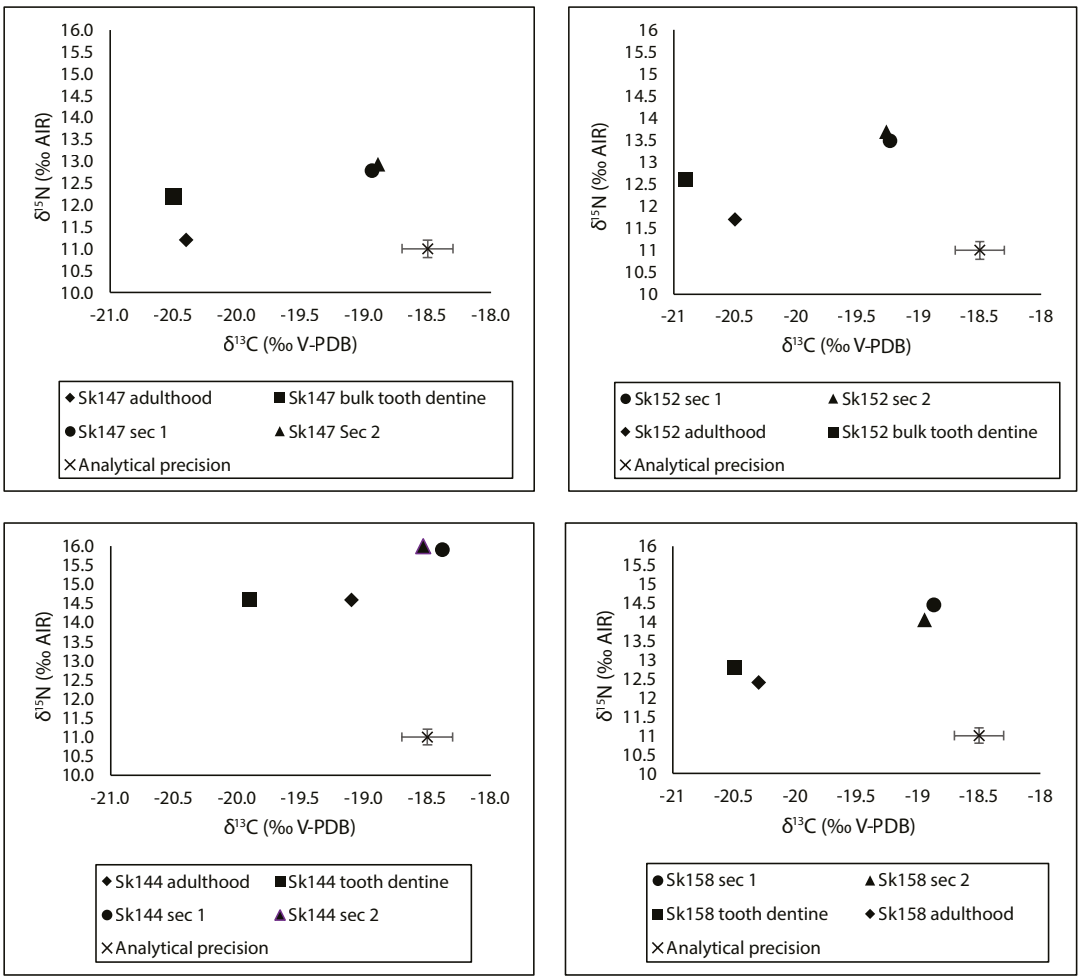
TABLE 3
Differences in stable isotopic values between bone collagen (Curtis-Summers et al 2014: 27) and dentine root apex collagen (this study)

Skeleton no.	*Sex[a]/ Period[b]*	*Tooth section[c]*	*Bone $\delta^{13}C$*	*Dentine $\delta^{13}C$[d]*	*(Δ dentine-bone $\delta^{13}C$)*	*Bone $\delta^{15}N$[e]*	*Dentine $\delta^{15}N$*	*(Δ dentine-bone $\delta^{15}N$)*
144	M/2	1	-19.1	-18.4	0.8	14.6	15.9	1.3
144	M/2	2	-19.1	-18.5	0.6	14.6	16.0	1.4
127	M?/2	1	-20.4	-19.2	1.2	11.8	13.7	1.9
127	M?/2	2	-20.4	-19.2	1.2	11.8	13.5	1.7
152	M/2	1	-20.5	-19.2	1.3	11.7	13.5	1.8
152	M/2	2	-20.5	-19.3	1.2	11.7	13.7	2.0
154	M/2	1	-20.5	-19.0	1.5	11.8	13.7	1.5
154	M/2	2	-20.5	-19.2	1.3	11.8	12.9	1.1
158	M/2	1	-20.3	-18.9	1.5	12.4	14.5	2.1
158	M/2	2	-20.3	-19.0	1.4	12.4	14.1	1.7
151	M/2	1	-20.6	-19.2	1.5	12.6	13.3	0.7
151	M/2	2	-20.6	-19.0	1.6	12.6	13.3	0.7
164	M/2	1	-20.2	-18.9	1.3	12.8	14.5	1.1
164	M/2	2	-20.2	-19.0	1.3	12.8	14.3	1.4
136	M/3	1	-21.1	-18.9	2.2	11.9	13.3	1.4
136	M/3	2	-21.1	-18.8	2.3	11.9	13.4	1.5
147	M/3	1	-20.4	-18.9	1.5	11.2	12.8	1.6
147	M/3	2	-20.4	-18.9	1.5	11.2	12.9	1.7

[a] Osteological data (age and sex data) (Curtis-Summers 2015: 464–75) and Curtis-Summers et al (2020: 7–8)
[b] Burial phase 2 = AD 680–810; burial phase 3 = AD 800–1050 (Carver et al 2016: 8–9)
[c] Tooth sections 1 = lowest 1mm of tooth root apex; 2 = next 1mm interval of tooth root apex (above section 1)
[d, e] $\delta^{13}C$ and $\delta^{15}N$ bone collagen isotopic values (Curtis-Summers et al 2014: 27)

of the adult diet for $\delta^{13}C$ is -20.4‰ whereas for root apex dentine the mean for $\delta^{13}C$ is -19.0‰. For the adult diet the $\delta^{15}N$ mean is 12.1‰, and for root apex dentine $\delta^{15}N$ the mean is 13.4‰. Table 3 illustrates differences between the bone and the root apex dentine from skeletons which were common to both studies. Differences for $\delta^{13}C$ range from 0.6‰ to 2.2‰ and for $\delta^{15}N$ differences range from 0.7‰ to 2.0‰. The two-sample paired *t*-test showed that the differences between the child root apex dentine and adult bone collagen were significant at the 0.001 level ($\delta^{13}C$, $p = 0.000$, $\delta^{15}N$, $p = 0.000$), thus confirming that that there was a significant change in diet between childhood (9–10 years old) and adulthood. Therefore, more marine resources appear to have been consumed by some of the individuals from the PMC for whom dietary data are available during childhood compared to during adulthood.

Four individuals (Skeletons 147, 152, 144 and 158) were also studied by Curtis-Summers et al (2014: 27) (see Illus 6a–d). They obtained an average of the diet between the years of 3.5–10 via bulk dentine analysis, thus enabling comparison between the early childhood diet, 9–10-year-old diet and adult diet. The adult and the overall

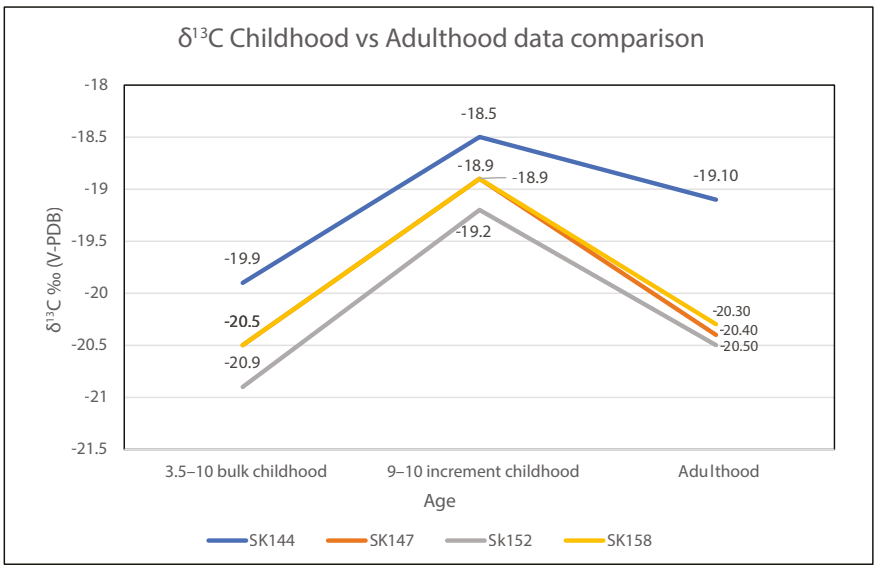


ILLUS 6A–D Adult bone collagen isotope data for the following individuals: a) SK147; b) SK152; c) SK144; and d) SK158 (Curtis-Summers et al 2014: 27), compared to childhood (3.5–10 years old) tooth bulk analysis (Curtis-Summers et al 2014: 27) and sectioned dentine for the same individuals (this study).

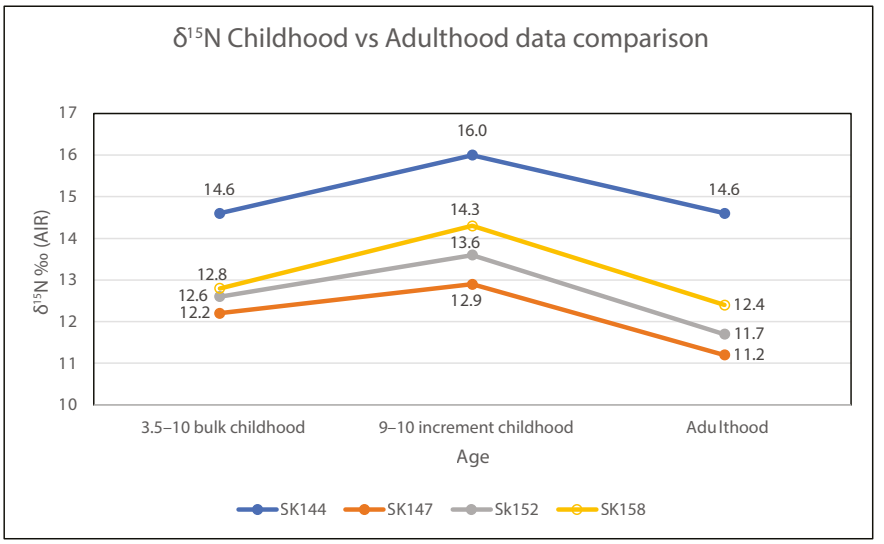
childhood diets (3.5–10 years old) tend to have lower $\delta^{13}C$ and $\delta^{15}N$ when compared with the 9–10-year-old diet. The regularity of these patterns (see Illus 7 and 8 and Tables 4 and 5) may suggest some increase in the marine component of the diet around the ages of 9–10 years compared to earlier childhood and adulthood. No comparison has been made between different ages within adulthood and the 9–10-year-old dentine, as Curtis-Summers et al (2014) found no statistically significant difference between different age groups of adult individuals. It is noticeable that SK144 has higher $\delta^{13}C$ and $\delta^{15}N$ values at all life stages, suggesting that he had a diet richer in marine resources than the other individuals from the PMC throughout his life.

DISCUSSION

What can we say about the childhood diets of the Portmahomack individuals from the PMC?



Illus 7 Comparison of $\delta^{13}C$ isotopic analysis of bulk childhood (3.5–10 years old) and adulthood (Curtis-Summers et al 2014: 27) in relation to the 9–10-year-old childhood of SK144, SK147, SK152 and SK158.



Illus 8 Comparison of $\delta^{15}N$ isotopic analysis of bulk childhood (3.5–10 years old) and adulthood (Curtis-Summers et al 2014: 27) in relation to the 9–10-year-old childhood of SK144, SK147, SK152 and SK158.

TABLE 4
Differences in carbon and nitrogen stable isotopic values between Curtis-Summers et al (2014: 27) 3.5–10 years childhood bulk dentine collagen data and 9–10 years childhood root increment dentine collagen data

Skeleton no.	*Sex*	*Age*	*Period*	*3.5–10 bulk dentine* $\delta^{13}C^{a}$	*9–10 dentine* $\delta^{13}C^{b}$	*(Δ 3.5–10 bulk dentine: 9–10 childhood* $\delta^{13}C)^{c}$	*3.5–10 bulk dentine* $\delta^{15}N^{d}$	*9–10 dentine* $\delta^{15}N^{e}$	*(Δ 3.5–10 bulk dentine: 9–10 childhood* $\delta^{15}N)^{f}$
144	M	46+	2	-19.9	-18.5	1.4	14.6	16.0	1.4
147	M	26–45	3	-20.5	-18.9	1.6	12.2	12.9	0.7
152	M	26–45	3	-20.9	-19.2	1.7	12.6	13.6	1.0
158	M	46+	3	-20.5	-18.9	1.6	12.8	14.3	1.5

[a] $\delta^{13}C$ values for 3.5–10 years childhood bulk dentine (Curtis-Summers et al 2014: 27)
[b] $\delta^{13}C$ values for the 9–10 years childhood diet (this research)
[c] $\delta^{13}C$ differences between 3.5–10 years bulk dentine and 9–10 years childhood increments (this research)
[d] $\delta^{15}N$ values for 3.5–10 years childhood bulk dentine (Curtis-Summers et al 2014: 27)
[e] $\delta^{15}N$ values for the 9–10 years childhood diet (this research)
[f] $\delta^{15}N$ differences between 3.5–10 years bulk dentine and 9–10 years childhood increments (this research)

TABLE 5
Differences in isotopic values between Curtis-Summers et al (2014: 27) bone data (adulthood) and 9–10 years dentine data (childhood – this study)

Skeleton no.	*Sex*	*Age*	*Period*	*9–10 dentine (this research)* $\delta^{13}C^{a}$	*Adulthood* $\delta^{13}C^{b}$	*(Δ childhood/ adulthood* $\delta^{13}C)^{c}$	*3.5–10 dentine (this research)* $\delta^{15}N^{d}$	*Adulthood* $\delta^{15}N^{e}$	*(Δ 3.5–10 childhood/ adulthood* $\delta^{15}N)^{f}$
144	M	46+	2	-18.5	-19.10	-0.6	16.0	14.6	1.4
147	M	26–45	3	-18.9	-20.40	-1.5	12.9	11.2	1.7
152	M	26–45	3	-19.2	-20.50	-1.3	13.6	11.7	1.9
158	M	46+	3	-18.9	-20.30	-1.4	14.3	12.4	1.9

[a] $\delta^{13}C$ values for 9–10 years childhood diet (this research)
[b] $\delta^{13}C$ bone collagen values for adulthood diet (Curtis-Summers et al 2014: 27)
[c] $\delta^{13}C$ differences between 9–10 years childhood dentine and adulthood bone data
[d] $\delta^{15}N$ values for 3.5–10 years childhood bulk dentine (Curtis-Summers et al 2014: 27)
[e] $\delta^{15}N$ bone collagen values for adulthood diet (Curtis-Summers et al 2014: 27)
[f] $\delta^{15}N$ differences between 3.5–10 years childhood dentine and bone collagen for adulthood

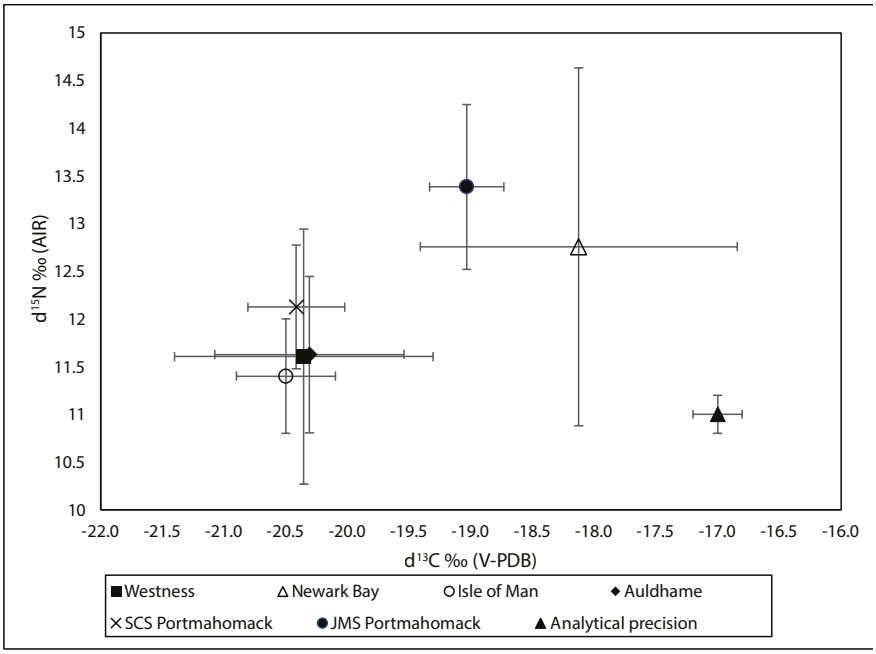
SITE COMPARISONS

The archaeological sites used for comparisons (Illus 9) are those from a similar time period as periods 2 and 3 at Portmahomack (7th–11th centuries) and only skeletons with radiocarbon dates within that period have been used, as some of the sites spanned a greater time period. Westness, on the Orkney island of Rousay, had a Pictish but not monastic colony in the 4th–9th centuries before Viking colonisation (Barrett & Richards 2004: 250) and the skeletons selected are taken from this era. Newark Bay, on Mainland Orkney, was colonised by the Vikings between AD 850 and AD 950, who brought a heavier reliance on fish in the diet, thus explaining the relatively high $\delta^{13}C$ and $\delta^{15}N$ values. Auldhame is a medieval monastic settlement situated on the East Lothian Scottish coast, near Tantallon Castle (Lamb et al 2012: 765).

The overall average 9–10-year-old childhood isotopic values from this study are located intermediately between those at Newark Bay and the other sites for $\delta^{13}C$, but rather higher than for the early medieval group at Newark Bay for $\delta^{15}N$. This implies that the diet was also intermediate, perhaps with a somewhat higher component of marine resources than for sites such as Westness, Auldhame and Isle of Man. In contrast, Portmahomack bone collagen data by Curtis-Summers et al (2014: 36) shows similar diets to those consumed at Westness, Auldhame and Isle of Man.

9–10-YEAR-OLD CHILDHOOD DIET

Curtis-Summers et al (2014: 38; 2020:11) concluded that adults from the PMC from periods 2–3 consumed predominantly C_3 plant resources in the form of bread and pottage and terrestrial



Illus 9 Similar sites comparison: Westness and Newark Bay, Pictish, 7th–11th centuries (Barrett & Richards 2004: 252–6); Auldhame, 7th–11th centuries (Lamb et al 2012: 773–5); Portmahomack, 6th–11th centuries (Curtis-Summers et al 2014: 36); and the Isle of Man (Hemer et al 2017: 432).

proteins, such as lamb, pork, beef and venison, with minimal marine consumption. In contrast, the 9–10-year-old childhood diet had a higher proportion of marine or freshwater resources. From the archaeological remains found at Portmahomack (Seetah 2016) and isotopic analysis (Curtis-Summers et al 2020: 5), the fish resources could be estuarine char or marine cod and horse mackerel. Although few fish remains were found from periods 1–3 compared to period 4, char was the predominant species found in those periods, but was not found in period 4. As char is an anadromous fish, their isotopic ratios will reflect the proportion of the char's life cycle that is spent in either marine or freshwater environments. Also, 63% of the period 1–3 assemblage was burnt compared with 2% for period 4 (Holmes 2016a: D136). This suggests that the fish procurement and processing were different in periods 1–3 from period 4, when fishing occurred on a much larger scale. It is also possible that the place where fish processing was occurring in periods 2 and 3 is still unexcavated (Seetah 2016: D135).

Only a small collection of shellfish was found, dating to periods 2–3. As the shellfish remains were found in the vellum-makers' building, it may be that the shellfish were collected along with seaweed on which the *Spirorbis* shells used to produce lime to clean the skins were found (Carver 2016a: 130–1; Hall & Kenward 2016: D143). A small amount of shellfish could have been consumed as a by-product of this collection.

The use of marine mammals was likely to be opportunistic, as the total MNI (minimum number of individuals) came to approximately 23 (Seetah 2016: D132). Butchery marks were found on whale remains, indicating intensive exploitation of whale meat and blubber (Seetah 2016: D135). Such opportunistic exploitation of whales and seals could explain the small number of individuals with dietary shifts between 9–9.5 (approximately) years old and 9.5–10 (approximately) years old (Illus 1). In present times, whales are beached on the shores near Portmahomack (SPP Reporter 2013). If beaching of whales similarly occurred during the 6th–9th centuries, perhaps these animals were exploited for blubber and for the childhood diet of the individuals from the PMC. Seals resting on the beach can be quite easily harvested. Marshall (2013: 14) mentioned that the monks at Iona also had fish, seals and shellfish available to them. Clarkson (2012: 97) stresses the value of seal meat, skin and blubber for dietary consumption as well as for fuel, lubrication and possibly vellum production.

It is difficult to determine unequivocally from $\delta^{13}C$ analysis of collagen how much of the diet is marine, as collagen only provides a measure of the protein component of the diet. Moreover, the protein level in diet and the wide variation of marine species, and consequently, different isotope values, must be considered, hence an appropriate faunal baseline is an important inclusion to reconstruct past diets. Analysis of $\delta^{13}C$ in carbonate from apatite enables an estimation of the energy proportion in carbohydrate and lipids as well. This enables the marine part of the diet to be more clearly distinguished (Kellner & Schoeninger 2007: 1112; Krueger & Sullivan 1984).

Another confounding factor could be that physiological and/or nutritional stress caused higher $\delta^{15}N$ isotopic values in the 9–10-year-old's diet. This is unlikely, however, for three reasons. Firstly, the *Anglo-Saxon Chronicle* (Giles 1914: 4–155) reported eight episodes of famine between AD 48 and AD 1082 in England, so individuals from the PMC at Portmahomack could have been affected at some point. Both the *Anglo-Saxon Chronicle* and the *Chronicum Scotorum* (Hennessy 1866: 113–319) reported that the famine was greatest in the British Isles between AD 1005 and AD 1044. When cereal crops were scarce people could have relied more than usual on both terrestrial animal and marine resources. If this were the case in Portmahomack, one would expect individuals in period 3 to have higher $\delta^{15}N$ than those from period 2. However, this research shows little dietary change between these periods. Secondly, the age-at-death of the individuals from PMC investigated varied from around 18 to over 45 years old and their radiocarbon dates were different, so the individuals studied would have been unlikely to experience nutritional stress simultaneously at the age of 9–10

years. Thirdly, nutritional and physiological stress are usually manifested by opposing covariance between $\delta^{13}C$ and $\delta^{15}N$, the $\delta^{13}C$ values decreasing as the $\delta^{15}N$ values increase (Beaumont & Montgomery 2016: 13). This pattern is not seen in the four individuals with available data for 3.5–10 years, 9–10 years and adult diet (see Illus 6, 7, 8 and 9).

The most tantalising evidence came from these data and Walther et al's (2016) Sr and O data. The fact that SK144, 147, 152 and 158 all have a similar increase in nitrogen at the age of around 9–10 years, despite the Sr and O results indicating that the majority of them were not resident in Portmahomack at the time, suggests that wider cultural or biological factors were at work. A possible factor for the increase in $\delta^{15}N$ levels could be puberty. SK144, 147, 152 and 158 could be experiencing growth spurts around the age of 10 years, which could explain the increase of marine resources as a form of protein. Taniguchi (2002) highlights that proteins are required for growth and repair, such as producing hormones and repairing tissues during the growth periods. According to Goldman (2018), boys in the modern era tend to start the first phase of puberty (Tanner stage 1) around the age of 10 years and physical changes starts to occur when they reach 11–13 years. However, puberty can start early or later than usually predicted and one ought to question whether the occurrence of puberty development stages would be the same for individuals dating to the early medieval period.

Chronic infections can manifest in an individual during puberty which can delay puberty development in both males and females. However, the visibility of this effect through isotopic means is still an enigma. Lewis et al (2016: 1) believe that chronic infections, such as tuberculosis (TB), colitis, chronic bowel conditions and leprosy, can occur during adolescence due to an individual's susceptibility and potentially delay puberty growth. On reviewing the pathological notes in the skeletal reports (Curtis-Summers (2015) ; King & Curtis-Summers 2016) for SK144, 147, 152 and 158, it appears that none of these four individuals had substantial chronic diseases at the age of 9–10 years and the carbon and nitrogen ratios would therefore not be affected. For instance, SK144 had osteoarthritis on the vertebrae, SN (Synovial joint disease), DJD (degenerative joint disease) and dental diseases. Therefore, the likelihood of chronic diseases affecting the early adolescent stages for the four individuals at Portmahomack is minimal. The individuals whose chronic condition could have affected puberty development are SK38 and 164 (signs of neoplastic disease), and SK54 (some form of pulmonary disease, possibly TB). Only SK176 and 189 displayed signs of nutritional stress via dental enamel hypoplasia. Isotopically there is no correlation between $\delta^{13}C$ and $\delta^{15}N$ among those who experience chronic/nutritional stress in contrast to those who do not show these signs.

Question 3: What does the comparison of childhood and adult diets reveal about cultural practices?

There are indications that some who became part of the Portmahomack PMC may not have arrived in the community before they were 9–10 years old, despite the 9–10-year-old childhood diet being fairly homogeneous (shown by the SD for $\delta^{13}C$ being only 0.3‰). The similarity of the $\delta^{13}C$ and $\delta^{15}N$ values from different age categories of the four individuals (SK144, SK147, SK152 and SK158) shows that they may all have had higher marine consumption between the ages of 9 and 10 years than they did in younger childhood or adulthood (Illus 6a–d). This is all the more remarkable because all four individuals appear to have different origins at the time of dietary analysis (9–10 years old), based on strontium and oxygen isotope evidence (Walther et al 2016): SK144 was local, SK147 probably from western Scotland, SK152 apparently from outside Britain and SK158 perhaps from eastern Britain or Ireland. Furthermore, since both $\delta^{13}C$ and $\delta^{15}N$ values tend to be lower in some contemporary sites compared to Portmahomack, it would be unlikely to find a group of individuals with different origins all having similar high values for $\delta^{13}C$ and $\delta^{15}N$ between the ages of 9 and 10 years. This may hint at some kind of universal late

childhood dependence on marine foods across a range of areas.

Results from this study suggest the diet of one individual (SK144) was significantly more marine based throughout his childhood. This supports previous isotope evidence on bone collagen that identified this individual as consuming a significant amount of marine protein during adulthood compared to the other individuals (Curtis-Summers et al 2020: 11). There are several possible reasons for SK144 having more of a marine diet than the other individuals. Firstly, SK144 could have consumed more marine resources due to his local coastal upbringing. Secondly, if the results do indicate growth spurts (although this must be considered unlikely – see above) it could be possible that SK144 experienced a bigger growth spurt than other individuals. Another reason could be due to the opportunistic consumption of whale, which could potentially increase the $\delta^{15}N$ levels.

CONCLUSION

The childhood diet of those buried during the monastic phase at Portmahomack was rich in meat and, for some, in marine resources compared to their adulthood diets. Most importantly, the richness of the marine diet does not seem to have varied significantly according to where the childhood was spent. It has been shown to be unlikely that these results are due to physiological processes, leaving open the possibility that cultural or social factors may be involved. To answer a number of questions about childhood diet of those buried during the monastic phase at Portmahomack, questions have surfaced that can only be answered with further study. Potential areas for further research include:

1. Incremental dentine analysis on the Pictish and medieval skeletal collection at Portmahomack would enable investigations into the dietary transitions from childhood to adolescence to adulthood, if data from M1, M2 and M3 were combined. Sampling of multiple tooth roots from the same individuals would help to confirm with increased accuracy the values at a particular age. This would provide dietary information from infancy up to the age of 21 years old. This might elucidate at what point the transition to an adult diet occurred. It would also enable a better understanding of whether there were seasonal dietary changes, such as opportunist consumption of marine mammals.
2. It may be beneficial to conduct incremental dentine investigations on childhood and adolescent diets from similar sites across Scotland to see whether the dietary patterns found here are part of a more general transition in diet at different ages in the early medieval period and to further confirm that these results are not linked to some kind of universal physiological or metabolic factor. Dentine apatite analysis enables a clearer picture of whether the resources in the diet are from a marine or a terrestrial source. Further research should include both collagen and apatite analysis from incremental dentine for the childhood diet, and from bone for the adult diet.

ACKNOWLEDGMENTS

Sincere thanks are given to the Tarbat Historic Trust for allowing access to skeletal samples for this research and to the helpful staff at the Tarbat Discovery Centre during sample collection. Thanks also to Ms M Gorton, Dr J Towers and Dr J Beaumont for their assistance with isotope lab procedures and for illuminating discussions about this research.

REFERENCES

Ashby, S 2016 ‘Bone and antler objects’, *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D86–D91. Edinburgh: Society of Antiquaries of Scotland.

Barnes, C, Sweeting, C J, Jennings, S, Barry, J T & Polunin, N V C 2007 ‘Effects of temperature

and ration size on carbon and nitrogen stable isotope trophic fractionation', *Functional Ecology* 21(2): 356–62.

Barrett, J H & Richards, M P 2004 'Identity, gender, religion and economy: new isotope and radiocarbon evidence for marine resource intensification in early historic Orkney, Scotland, UK', *European Journal of Archaeology* 7(3): 249–71.

Beaumont, J & Montgomery, J 2015 'Oral histories: a simple method of assigning chronological age to isotopic values from human dentine collagen', *Annals of Human Biology* 42(4): 407–14.

Beaumont, J & Montgomery, J 2016 'The Great Irish Famine: identifying starvation in the tissues of victims using stable isotope analysis of bone and incremental dentine collagen', *PLOS ONE* 11(8): e0160065. https://doi.org/10.1371/journal.pone.0160065.

Beaumont, J, Gledhill, A, Lee-Thorp, J & Montgomery, J 2013 'Childhood diet: a closer examination of the evidence from dental tissues using stable isotope analysis of incremental human dentine', *Archaeometry* 55(2): 277–95.

Bocherens, H, Fizet, M & Mariotti, A 1992 'Is collagen from teeth or bones equivalent for isotopic (^{13}C, ^{15}N) diet investigations?', The Paleontological Society Special Publications, vol 6: *Fifth North American Paleontological Convention Abstracts and Program*: 30.

Britton, K 2017 'A stable relationship: isotopes and bioarchaeology are in it for the long haul', *Antiquity* 91(358): 853–64.

Carver, M 1995 *Bulletin of the Tarbat Discovery Programme No. 1.* https://www.york.ac.uk/archaeology/staff/sites/tarbat/bulletins/bulletin1/contents.html. Accessed 18 August 2018.

Carver, M 1997 *Bulletin of the Tarbat Discovery Programme No. 3.* https://www.york.ac.uk/archaeology/staff/sites/tarbat/bulletins/bulletin3/contents.html. Accessed 18 August 2018.

Carver, M 1999 *Surviving in Symbols: A Visit to the Pictish Nation*. Edinburgh: Canongate.

Carver, M 2004 'An Iona of the east: the early-medieval monastery at Portmahomack, Tarbat Ness', *Medieval Archaeology* 48(1): 1–30.

Carver, M 2006 'A Columban monastery in Pictland', *Current Archaeology* 205: 20–9.

Carver, M 2008 *Post-Pictish Problems: The Moray Firthlands in the 9th–11th Centuries*. York: Field Archaeology Specialists Ltd, Groam House Museum.

Carver, M 2009 'Early Scottish monasteries and prehistory: a preliminary dialogue', *The Scottish Historical Review* 88(226): 332–51.

Carver, M 2016a *Portmahomack: Monastery of the Picts*, 2nd edition. Edinburgh: Edinburgh University Press.

Carver, M 2016b *The Story of Saint Colman's Church: Portmahomack, Easter Ross*. Aberdeen: University of Aberdeen.

Carver, M 2016c 'Ideological transitions in Pictland', *in* Flechner, R & Ní Mhonaigh, M (eds) *The Introduction of Christianity into the Early Medieval Insular World*, 305–20. Turnhout: Brepols.

Carver, M 2019a *Formative Britain: An Archaeology of Britain*, *Fifth to Eleventh Century AD.* London: Routledge.

Carver, M 2019b 'Political transition at Portmahomack: the European context', *in* Blackwell, A E (ed) *Scotland in Early Medieval Europe*, 103–16. Leiden: Sidestone Press.

Carver, M & Spall, C 2004 'Excavating a parchmenerie: archaeological correlates of making parchment at the Pictish monastery at Portmahomack, Easter Ross', *Proc Soc Antiq Scot* 134: 183–200.

Carver, M O H, Garner-Lahire, J & Spall, C A 2016 *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*. Edinburgh: Society of Antiquaries of Scotland.

Clarkson, T 2012 *Columba*. Edinburgh: Birlinn.

Curtis-Summers, S 2015 'Reconstructing Christian Lifeways: A Bioarchaeological Study of Medieval Inhabitants from Portmahomack, Scotland and Norton Priory, England', unpublished PhD thesis, University of Liverpool.

Curtis-Summers, S, Montgomery, J & Carver, M 2014 'Stable isotope evidence for dietary contrast between Pictish and medieval populations at Portmahomack, Scotland', *Medieval Archaeology* 58(1): 21–43.

Curtis-Summers, S, Pearson, J A & Lamb, A L 2020 'From Picts to Parish: stable isotope evidence of dietary change at medieval Portmahomack, Scotland', *Journal of Archaeological Science Reports* 31: 1–21.

DeNiro, M J 1985 'Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction', *Nature* 317(6040): 806–9.

DeNiro, M J 1987 'Stable isotopy and archaeology', *American Scientist* 75: 182–91.

Fuller, B T, Molleson, T I, Harris, D A, Gilmour, L T & Hedges, R E 2006 'Isotopic evidence for breastfeeding and possible adult dietary differences from Late/Sub-Roman Britain', *American Journal of Physical Anthropology* 129 (1): 45–54.

Giles, J A 1914 *The Anglo-Saxon Chronicle*. London: G Bell and Sons.

Goldman, R 2018 *The Stages of Puberty: Development in Girls and Boys*. https://www.healthline.com/health/parenting/stages-of-puberty. Accessed 4 May 2021.

Hall, A & Kenward, H 2016 'Summary report on plant and insect remains', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D142–D146. Edinburgh: Society of Antiquaries of Scotland.

Hemer, K A, Lamb, A L, Chenery, C A & Evans, J A 2017 'A multi-isotope investigation of diet and subsistence amongst island and mainland populations from early medieval western Britain', *Journal of Physical Anthropology* 162(3): 423–40.

Hennessy, W M (ed) 1866 *Chronicum Scotorum: A Chronicle of Irish Affairs from the Earliest Times to A.D. 1135*. London: Longman, Green, Reader and Dyer. Also Available at https://archive.org/details/chronicumscotoru00macfuoft. Accessed 15 November 2020.

Holmes, M 2016a 'Fish bones', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D136–D139. Edinburgh: Society of Antiquaries of Scotland.

Holmes, M 2016b 'Shellfish', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D140–D141. Edinburgh: Society of Antiquaries of Scotland.

Kellner, C M & Schoeninger, M J 2007 'A simple carbon isotope model for reconstructing prehistoric human diet', *American Journal of Physical Anthropology* 133(4): 1112–27.

King, S 2016 'Summary report on the Tarbat populations', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D27–D30. Edinburgh: Society of Antiquaries of Scotland.

King, S & Curtis-Summers, S 2016 'Inventory of burial data', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D20–D26. Edinburgh: Society of Antiquaries of Scotland.

Koch, P L, Tuross, N & Fogel, M L 1997 'The effects of sample treatment and digenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite', *Journal of Archaeological Science* 24(5): 417–29.

Krueger, H W & Sullivan, C H 1984 'Models for carbon isotope fractionation between diet and bone', *in* Turnlund, J R & Johnson, P E (eds) *Stable Isotopes in Nutrition*, 205–20. Washington DC: American Chemical Society Symposium Series.

Lamb, A L, Melikian, M, Ives, R & Evans, J 2012 'Multi-isotope analysis of the population of the lost medieval village of Auldhame, East Lothian, Scotland', *Journal of Analytical Atomic Spectrometry* 27(5): 765–77.

Lee-Thorp, J A 2008 'On isotopes and old bones', *Archaeometry* 50(6): 925–50.

Leskovar, T, Beaumont, J, Lisić, N & McGalliard, S 2019 'Auditory ossicles: a potential biomarker for maternal and infant health *in utero*', *Annals of Human Biology* 46(5): 367–77.

Lewis, M E, Shapland, F & Watts, R 2016 'The influence of chronic conditions and the environment on pubertal development. An example from medieval England', *International Journal of Paleopathology* 12: 1–10.

Longin, R 1971 'New methods of collagen extraction for radiocarbon dating', *Nature* 230: 241–2.

Lovell, N C, Nelson, D E & Schwarcz, H P 1986 'Carbon isotope ratios in paleodiet: lack of sex or age effect' *Archaeometry* 28: 51–55.

Macgill, W 1909 *Old Ross-shire and Scotland, as Seen in the Tian and Balnagown Documents*. Inverness: The Northern Countries Newspaper and Printing and Pub Co. Also available at https://archive.org/details/oldrossshirescot00macguoft/page/158/mode/2up. Accessed 9 August 2020.

Marshall, R K 2013 *Columba's Iona: A New History*. Ross-shire: Sandstone Press.

Meier-Augenstein, W 2010 *Stable Isotope Forensics: An Introduction to the Forensic Application of Stable Isotope Analysis.* Chichester: John Wiley and Sons.

Müldner, G, Chenery, C & Eckardt, H 2011 'The "Headless Romans": multi-isotope investigations of an unusual burial ground from Roman Britain', *Journal of Archaeological Science* 38(2): 280–90.

O'Connell, T C & Hedges, R E M 1999 'Isotopic comparison of hair and bone: archaeological analyses', *Journal of Archaeological Science* 26 (6): 661–5.

Richards, M 2020 'Isotope analysis for diet studies', *in* Richards, M & Britton, K (eds) *Archaeological Science: An Introduction*, 125–44. Cambridge: Cambridge University Press.

Schoeninger, M J & DeNiro, M J 1984 'Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals', *Geochimica et Cosmochimica Acta* 48: 625–539.

Schwarcz, H P 2011 'Archaeological and anthropological applications of isotopic and elemental geochemistry', *in* Harmon, R S & Parker, A (eds) *Frontiers in Geochemistry: A Contribution of Geochemistry to the Study of the Earth*, 238–54. New York: Blackwell Publishing/John Wiley and Sons.

Schwarcz, H P & Schoeninger, M J 1991 'Stable isotope analyses in human nutritional ecology', *Yearbook of Physical Anthropology* 34: 283–321.

Seetah, K 2016 'Summary report on animal bones', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D131–D135. Edinburgh: Society of Antiquaries of Scotland.

SPP Reporter 2013 'Whales rescued after Portmahomack beaching drama', *Ross-shire Journal; Incorporating North Star News*. https://www.ross-shirejournal.co.uk/news/whales-rescued-after-portmahomack-beaching-drama-108715/. Accessed 10 November 2020.

Taniguchi, N 2002 'Amino acids and proteins', *in* Baynes, J & Dominiczak, M H (eds) *Medical Biochemistry*, 5–20. Amsterdam: Elsevier Science.

Van Klinken, G J, Richards, M P & Hedges, R E M 2000 'An overview of causes for stable isotopic variations in past European human populations: environmental, ecophysiological, and cultural effects', *in* Ambrose, S H & Katzenberg, M A (eds) *Biogeochemical Approaches to Paleodietary Analysis*, 39–63. New York: Kulwer Academic/Plenum Publishers.

Walther, L, Montgomery, J & Evans, J 2016 'Combined strontium and oxygen isotope data at Portmahomack', *in* Carver, M O H, Garner-Lahire, J & Spall, C A (eds) *Portmahomack on Tarbat Ness: Changing Ideologies in North-East Scotland, Sixth to Sixteenth Century AD*, D34–D40. Edinburgh: Society of Antiquaries of Scotland.