

A Sequential Multi-Isotopic Analysis of Norse Cattle Teeth

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(i.e. temperature and rainfall). The ratios of nitrogen and carbon within the dentine will respect trophic level (e.g. from the consumption of milk to that of plant matter) and the presence of marine foods (e.g. seaweed) in the diet. These methodologies can therefore track fluctuations in annual dietary compositions and geographical mobility, providing evidence for transhumance within a landscape and changes in seasonal foddering strategies (Balasse 2003). To achieve an understanding of key points in cattle life histories it is necessary to focus sampling on teeth that developed from before birth and can provide a record that spans at least one annual cycle to catch seasonal variations in management.

Stable isotope analysis of domestic fauna from the Western Isles has used bulk collagen sampling to obtain a single nitrogen and carbon value that represents the dietary protein intake over a number of years (King *et al.* 2017). Analysis of domestic fauna from multiple sites has revealed details of the animal husbandry practices in the Western Isles (e.g. Mulville *et al.* 2009; Jones 2014; Jones and Mulville 2018).

There are limitations in using single samples to represent the isotopic composition of an individual. This method assumes that dietary protein sources remain constant over time, and relies on inter-individual and species comparisons to deduce husbandry practices. The methodology cannot identify dietary changes during a life, thus restricting the interpretation of the fauna's interactions with humans (King *et al.* 2017). To gain a better understanding of husbandry techniques, a comprehension of dietary composition and geographical location of specimens throughout life is necessary (Makarewicz 2017), which can be achieved through the application of incremental isotopic analysis.

Incremental stable isotopic analysis

Incremental stable isotopic analysis is based upon the principle that mammalian dental tissues (enamel and dentine) form sequentially (Lan *et al.* 2014). By taking incremented samples along the axes of growth following the specific eruption pattern of the tooth, stable isotopic ratios specific to chronological points in an individual's early life can be identified (Balasse *et al.* 2001). Most sequential protocols have been performed on molar teeth, as they yield greater volumes of material in their incremented bands. The analysis of molar teeth is also useful in the expansion of an individual's isotopic timeline, as, following eruption patterns, inter-tooth analysis can be performed on succeeding molars from the same individual. As these teeth will often form in succession (rates dependent on species), an extended isotopic chronology can be achieved (Gillis *et al.* 2013). In zooarchaeology this method has mostly been applied to domesticated mammalian fauna, primarily those with hypsodont molars (e.g. cattle). These high crowning teeth mineralise over a long period and provide an elongated isotopic timeline (Brookman and Ambrose 2012, 256).

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Isotopic analysis of teeth can indicate the diet and climate that an individual experienced over the duration of tooth formation. By taking multiple incremented samples from an individual, along a growth axis of dental tissue, it is possible to generate an isotopic biography of the subject by age and season and reconstruct past animal husbandry practices (Balasse *et al.* 2001; 2012; Gron *et al.* 2015; Makarewicz *et al.* 2017, 71).

The stable isotope ratio of oxygen isotopes in enamel can provide information on seasonal variations in climate

Recent studies into ungulate dentition have begun to criticise sequential isotopic work on hypsodont enamel, because it assumes that enamel mineralisation is a lineal process that follows eruption patterns (Kierdorf *et al.* 2013). Enamel may not simply form in sequential bands along the growth axis but be subject to maturation which occurs after initial formation (Passey and Cerling 2002; Zazzo *et al.* 2012).

Alternatively, Suga (1982) suggested that complete enamel formation within ungulate mammals may take longer than once perceived, with mineralisation continuing after a tooth's eruption. They propose that, as mineralisation is a three-layer process – with the initial stage depositing enamel sequentially down the growth axis, and the later phases repeating the process – isotopic signatures are delayed, representing the time of the last phase of enamel deposition, a period likely to be after the time of eruption

The true formation rate of cattle enamel is unknown (Jordana *et al.* 2014). It is thought to be highly variable, with structure and morphology interlinked with dietary behaviour and the environment (Hillson 2005; Famoso *et al.* 2013). Dietary composition and variable water intake have a direct relationship with enamel thickness, and therefore the period of crown formation. Individuals with thinner enamel crowns have shorter periods of mineralisation (Smith *et al.* 2003). Considering the thinness of the enamel crowns sampled in this project, a relatively rapid rate of enamel formation may be concluded, and consequently a shortening of the isotopic timeline. However, external factors such as attrition and burial context may also contribute to enamel thinning (Upex *et al.* 2014).

Methodology

This study performed sequential isotopic analyses on the enamel and dentine of the first and successive second mandibular molars of individual cattle. The analysis of both molars generates an extended isotopic timeline of an individual's early life, with tooth formation initiating *in utero* and then extending through the first 12–13 months of life (enamel), or the first 24–25 months (dentine) (Brown *et al.* 1960; Table 94).

Cattle mandibles were selected from all three phases of Norse occupation at mounds 2 and 2A, Early, Middle and Late Norse. Only mandibles with both the first (M1) and second (M2) molars *in situ* were selected. Loose M1 and M2 molars were rejected given the difficulties

in differentiating between the two teeth and the lack of an extended isotopic timeline when using single teeth (Towers 2013). Complete cattle mandibles are scarce in the faunal assemblage: mostly young individuals are represented and the mandibles have suffered high levels of fragmentation. .

Each mandible was assessed using Grant's (1982) cattle wear stage framework, to provide an estimation of the wear on each tooth and mandible wear stage. Mandibles with molars between the wear stages of A–L were selected for further analysis as these retain sufficient dental tissue for effective sequential analysis. The suitability of the M1 and M2 for sequential enamel and dentine sampling was assessed by examining the outer enamel cap for structural integrity. Those molars showing signs of heavy cracking and crumbling were excluded (Towers 2013).

Following these criteria, five mandibles – representing five individuals – were selected, from different contexts. The mound 2 mandibles (BO02, BO03; both Middle Norse) were both from the right side, confirming that they came from different animals. For mound 2A, two mandibles were sided left (BO01 Late Norse; B005 Early Norse) and one right (BO04 Middle Norse). The contexts from which they came were dated to different phases and no pair was identified. All three Middle Norse mandibles were sexed by aDNA analysis, one being male (BO02) and two female (BO003 and BO04) (McGrory *et al.* 2016).

Sampling was undertaken following the methodologies outlined for enamel by Balasse *et al.* (2012) and for dentine by Balasse *et al.* (2001), with a detailed description of the methods being provided in Griffith (2019). For oxygen isotope analysis, sequential powdered enamel samples were removed along the axis of growth, without damaging the structural integrity of the dentine cusp. To encompass issues of in-life wear, increment diameter was increased along the axis of growth (0.8 mm to 1 mm). This allowed the removal of a viable amount of enamel for mass spectrometry. For dentine the increment size was increased (2 mm +/-0.5 to 4 mm +/-0.5) compared to that of Balasse *et al.* (2001), to consider the potential effects of wear and burial context on collagen yield from the root and exposed dentine (Turner-Walker 2008). A maximum of six increments were selected for analysis, to effectively reveal changes in isotopic ratios over time.

Plotting intra-tooth enamel and dentine isotopic data against relative age necessitates the conversion of distance from the occlusal surface to time. To calculate this, an estimate of the unworn crown height of cattle molars is required, from the enamel root junction (ERJ) to the tip,

Table 94. The chronological development of M1 and M2 mandibular molars in cattle (based upon Brown *et al.* 1960, radiographed eruption data)

Tooth	Crown Formation Begins	Crown Formation Complete	Root Formation Complete
First Molar	<i>In Utero</i>	2/3 Months	13 Months
Second Molar	1 Month	12/13 Months	24/25 Months

as well as the start and finish ages of enamel and dentine formation. The determination of unworn crown height for the analysed individuals from Bornais is restricted since there is an absence of identified unworn M1 and M2 molars within the assemblage. Therefore, this study has estimated unworn crown heights as 45 mm (M1) and 50 mm (M2), through the comparative analysis of previously deduced averages of unworn cattle dentition from other British (pre-industrial) faunal assemblages (Jones 2008 [M1: 43–45 mm, M2: 50–55 mm]; Towers 2013 [M2: 45–50 mm]; Warham 2013 [M2: 50–51 mm]).

The beginning and end of enamel and dentine formation has been estimated from cattle molar eruption patterns published by Brown *et al.* (1960) (Figure 334). One-third of the M1 crown is formed by the time of birth, at an estimated 15 mm from the M1's occlusal surface (Brown *et al.* 1960, 35).

Sequential oxygen isotopic values were normalised to the PDB scale using in-house standards but required conversion to the VSMOW scale in order to compare the data with other published values (Evans *et al.* 2019). This was performed using the published conversion equation of Coplen (1988).

Results

The detailed results from the intra-tooth enamel carbonate $\delta^{18}\text{O}$, and the dentine collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of both first and second cattle molars are presented in Griffith (2019). A statistical summary of the isotopic results is given for each molar and individual in Table 95. Linear graphical depictions have been utilised to represent how the acquired isotopic values progress over the cattle's early life, with each increment being represented by their mid-point, plotted along the given axis of growth (Figures 335 and 337). Isotopic values acquired from both M1 and M2 have been plotted against Brown *et al.*'s (1960) eruption timelines (Figures 336, 338–339).

$\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values have also been plotted together to reveal potential inter-analysis trends between the two dietary isotopes in each individual (Figure 337). Incremental oxygen results cannot be directly contrasted to the sequential carbon and nitrogen results due to differences in enamel and dentine tissue formation rates (Deutsch *et al.* 1979).

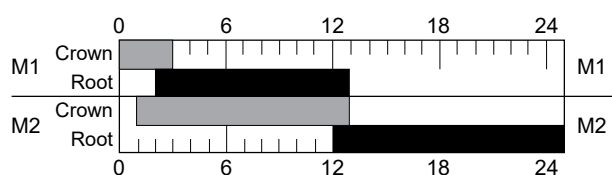


Figure 334. Visual chronology of the crown and root eruption dependant on cattle molar type (Balasse *et al.* 2001)

$\delta^{18}\text{O}$ results

Converted values (analytical error: 0.034‰) of each sampled tooth along the enamel axis of growth are depicted graphically in Figure 335. All values have been plotted for inter-individual comparison along a constructed timeline of enamel growth, from *in utero* to 12–13 months of age (Figure 336).

There is a broad range of observed $\delta^{18}\text{O}$ values, from 21.3‰ to 25.3‰; r^2 : 3.8‰. This range is not biased towards molar types, with M1 increments displaying a value range of 3.3‰ (21.5‰ to 24.8‰), and M2 displaying a value range of 3.0‰ (22.3‰ to 25.3‰). Inter-tooth variances within individuals are seen to reveal substantial fluctuations within isotopic biographies, with the intra-tooth average difference also being substantial.

The inter-tooth sequential patterns of individuals BO02, BO03 and BO04 are sinusoidal, with an average amplitude of variation observed of 2.8‰ (2.3‰ to 3.1‰) (Figure 336). These sequences' sin-curvatures all reach their most enriched peak (24.9‰ to 25.3‰) around the mid-length of the M2s' enamel growth axis, though at slightly varying distances from the occlusal surface (12 mm to 25 mm; <12–13 months). For BO02 and BO03, the most depleted enamel increment (BO02: 22.4‰; BO03: 21.8‰) is observed on the mid-length of the enamel growth axis of the M1, although again at varying distances from the occlusal surface (BO02: 21.35 mm; BO03: 36 mm; postnatal, <2–3 months). Individual BO04 holds its lowest oxygen value at the end of its M2 sequence (BO04: M2.1E: 22.9‰), estimated to be 46 mm from the occlusal surface, although a similar depletion is also observed on the M1 sequence with a minimum of 23.5‰ at an estimated 32 mm from the occlusal surface (Figure 335).

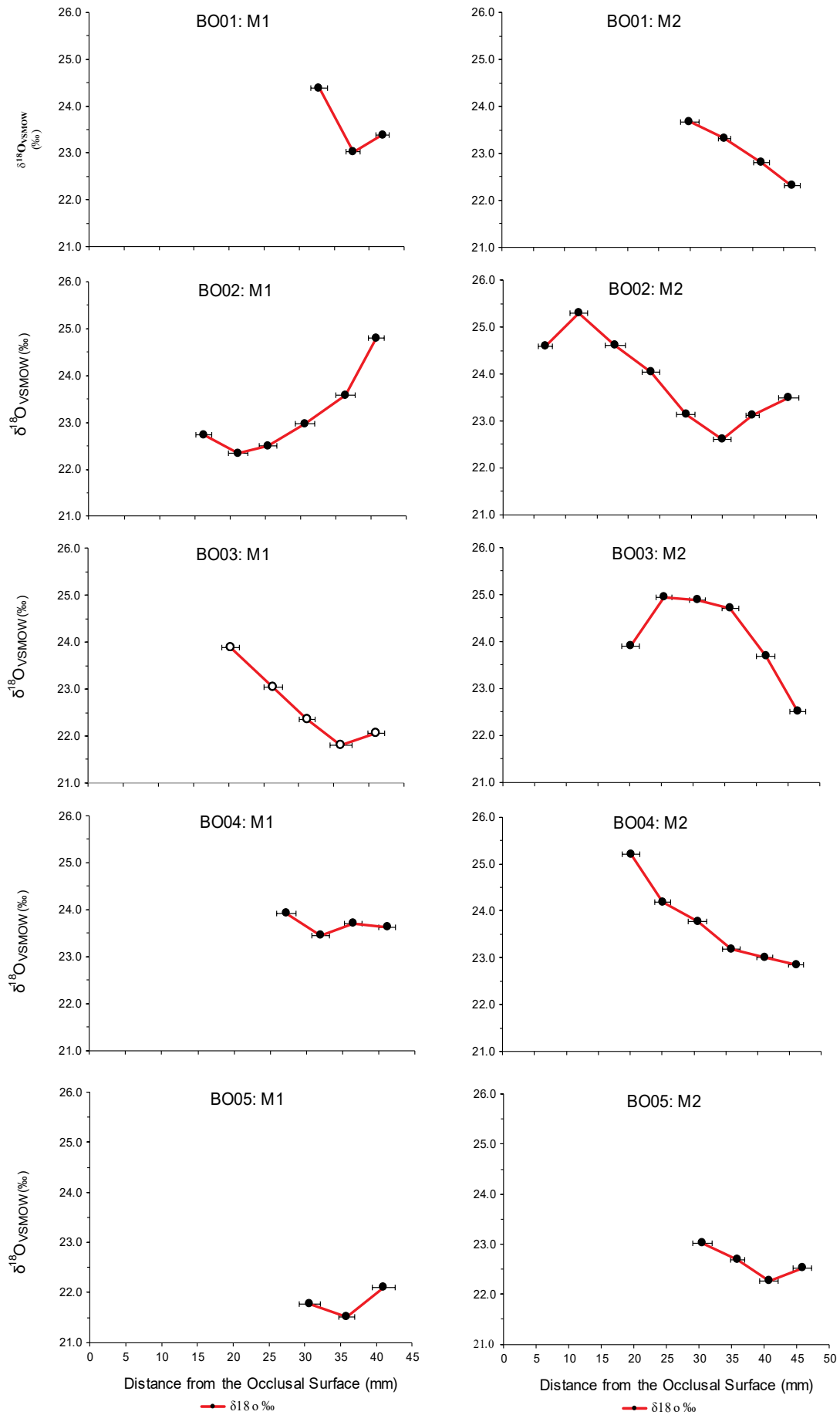
As the successional enamel formation of both molars is reflective of the isotopic biography of the animal's first year of life, the patterned oxygen isotopic variation reflects the seasonality of the oxygen isotopic composition of ingested water (Blyth 2001, 10). The most enriched values are assumed to reflect the summer months, whilst the lowest $\delta^{18}\text{O}$ values are anticipated during the winter months (Sharma *et al.* 2004). This sinusoidal sequence curvature thus reflects the age at which an individual experienced their first summer and winter months.

The sequential oxygen profiles of BO01 and BO05 are significantly limited in interpretation due to the loss of earlier isotopic data along the growth axis caused by in-life wear. As such, it is difficult to discern a sinusoidal pattern within these two individuals, although this projection is likely considering the linear enrichment and depletion trends observed on the short sequences of the M1 and M2 of both individuals (BO01: M2 depletes by 1.4‰ over the growth axis) (Figure 336). However, the gaps in isotopic chronology, and the subsequent inability to discern an accurate sinusoidal patterning, mean that the determination of the age at which these individuals experienced the summer and winter months cannot be ascertained.

Table 95. Summary statistics for $\delta^{18}\text{O}_{\text{YSMOW}}$, $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{15}\text{N}_{\text{AIR}}$ values for each sampled tooth and individual

Specimen	Tooth	$\delta^{18}\text{O}_{\text{YSMOW}}$						$\delta^{13}\text{C}_{\text{VPDB}}$						$\delta^{15}\text{N}_{\text{AIR}}$					
		Mean (%)	St. dev. (%)	Min. (%)	Max. (%)	Range (%)	Median (%)	Mean (%)	St. dev. (%)	Min. (%)	Max. (%)	Range (%)	Median (%)	Mean (%)	St. dev. (%)	Min. (%)	Max. (%)	Range (%)	Median (%)
BO01	M1	23.6	0.71	23.0	24.4	1.4	23.4	-21.7	0.22	-22.0	-21.4	0.6	-21.7	6.3	0.37	5.7	6.6	0.9	6.5
	M2	23.0	0.60	22.3	23.7	1.4	23.1	-21.8	0.23	-22.0	-21.5	0.5	-21.7	6.4	0.30	5.9	6.7	0.8	6.5
	Ind.	23.3	0.66	22.3	24.4	2.1	23.3	-21.8	0.33	-22.0	-21.4	0.6	-21.7	6.3	0.33	5.7	6.7	1.0	6.5
BO02	M1	23.2	0.91	22.4	24.8	2.4	22.9	-21.5	0.15	-21.7	-21.3	0.4	-21.5	6.3	1.03	4.2	7.0	2.8	6.7
	M2	23.9	0.92	22.6	25.3	2.7	23.8	-21.4	0.08	-21.5	-21.3	0.2	-21.5	5.8	1.20	4.4	7.3	3.0	5.8
	Ind.	23.6	0.95	22.4	21.8	2.9	23.3	-21.5	0.11	-21.7	-21.3	0.4	-21.5	6.0	1.10	4.2	7.3	3.1	6.5
BO03	M1	22.6	0.84	21.8	23.9	2.1	22.4	-22.4	0.28	-22.7	-22.2	0.5	-22.4	6.0	0.37	5.5	6.4	0.9	6.0
	M2	24.1	0.94	22.5	24.9	2.4	24.3	-22.4	0.25	-22.7	-22.1	0.7	-22.4	5.6	0.17	5.4	5.9	0.4	5.6
	Ind.	23.4	1.15	21.8	24.9	3.1	23.7	-22.4	0.25	-22.7	-22.1	0.7	-22.4	5.6	0.32	5.4	6.4	1.0	5.6
BO04	M1	23.7	0.19	23.5	23.9	0.5	23.7	-22.1	0.14	-22.3	-22.0	0.3	-22.1	5.8	0.86	4.8	6.8	2.1	5.8
	M2	23.7	0.89	22.9	25.2	2.3	23.5	-21.9	0.17	-22.2	-21.7	0.5	-21.9	4.9	0.17	4.7	5.1	0.5	4.9
	Ind.	23.7	0.67	22.9	25.2	2.3	23.7	-22.0	0.73	-22.2	-21.7	0.5	-22.0	5.3	0.73	4.8	6.8	2.1	5.3
BO05	M1	21.8	0.29	21.5	22.1	0.6	21.8	-21.5	0.18	-21.8	-21.3	0.5	-21.4	4.9	0.17	4.7	5.1	0.4	4.8
	M2	22.6	0.32	22.3	23.0	0.8	22.6	-21.5	0.05	-22.0	-21.2	0.8	-21.4	4.9	0.05	4.8	4.9	0.1	4.9
	Ind.	22.3	0.53	21.5	23.0	1.5	22.3	-21.4	0.12	-22.0	-21.2	0.8	-21.4	4.9	0.12	4.7	5.1	0.4	4.9
Overall	M1	23.0	0.91	21.5	24.8	3.3	23.0	-21.8	0.41	-22.7	-21.3	1.4	-21.7	5.4	0.81	4.2	7.0	2.8	6.0
	M2	23.7	0.92	22.3	25.3	3.0	23.4	-21.8	0.40	-22.7	-21.2	1.5	-21.7	5.5	0.81	4.4	7.3	3.0	5.4
	Ind.	23.3	0.95	21.5	25.3	3.8	23.2	-21.8	0.40	-22.7	-21.2	1.5	-21.7	5.7	0.82	4.3	7.3	3.1	5.6

Figure 335. (opposite page) Measured enamel $\delta^{18}\text{O}$ values for each first and second molar from the five cattle specimens. Samples are positioned on each tooth crown by distance from the estimated unworn occlusal surface (unworn crown height estimated M1 45 mm, M2 50 mm). Increments are represented by their mid-point. Parameter bars represent total increment diameter across growth axis. Analytical error: 0.034%



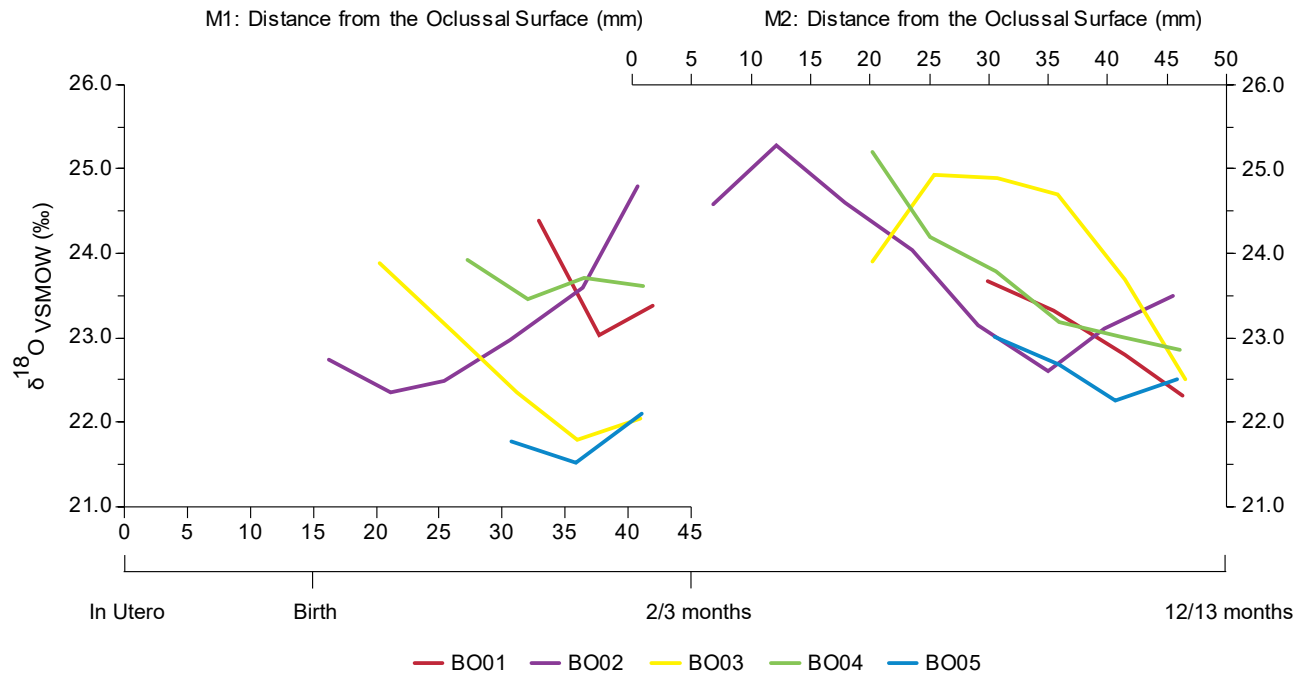


Figure 336. Combined $\delta^{18}\text{O}$ profiles for the all first and second cattle molars measured against the estimated tooth eruption timeline. Analytical error: 0.034‰

The examination of mean $\delta^{18}\text{O}$ values reveal the close clustering of BO01, BO02, BO03 and BO04's isotopic profiles (23.3‰ to 23.7‰). This suggests that the enamel of all these individuals formed under similar environmental conditions. The exception to this trend is individual BO05, the only individual dating to the Early Norse period, which holds a comparatively depleted average value ($22.3\text{‰} \pm 0.53$). Although this could suggest differing environmental conditions experienced during enamel formation, the shorter sequence obtained for BO05 may have generated a profile bias towards the depleted curvature of the theorised sinusoidal pattern.

$\delta^{13}\text{C}$ results

The sequential $\delta^{13}\text{C}$ results (analytical error: 0.090‰) for each analysed molar are presented in composite biplots with their given increments' $\delta^{15}\text{N}$ value (Figures 337). Figure 338 presents the carbon values of all individuals across the sequenced dentine growth axis of their M1 and M2 molars, against an estimated timeline of growth.

The observed range of carbon values across individuals reveals a relatively uniform absolute range of -22.7‰ to -21.2‰ : $r^2 = 1.5\%$. M1 molar values present a further compact range of 1.4‰ (-22.7‰ to -21.3‰), with the absolute range of all carbon results being dictated by those observed on the M2s. In review of the individual carbon isotopic biographies, most of the cattle present minimal evidence for carbon ratio variation over the first 24–25 months of life, with all individuals possessing r^2 values of $<1\%$ (average 0.7‰, range from 0.4‰ to 0.8‰) across

both succeeding molars. The average $\delta^{13}\text{C}$ amplitude variance intra-tooth is 0.5‰ (0.3‰ to 0.8‰).

The inter-specimen comparison of the carbon isotopic sequences reveals some potential sub-grouping between individuals, based upon the isotopic composition of the M1s (Figure 338). Mean M1 carbon values of BO01, BO02 (male) and BO05 are relatively similar to each other (-21.5‰ to -21.7‰), and different to the mean values of the female specimens (BO03 mean: $-22.4\text{‰} \pm 0.28$; BO04 mean: $-22.4\text{‰} \pm 0.14$). A student's t-test was performed on the gained means between the enriched initial grouping and the comparatively depleted group of BO03 and BO04, presenting a $P = 0.00926\%$, indicating these sub-groups hold statistical significance (De Winter 2013, 3).

Comparative analysis of the M2 sequences reveals different sub-groups change, with BO04 holding a mean inter-tooth enrichment of 0.2‰ (mean: $-21.9\text{‰} \pm 0.21$), grouping its sequence closer to that of BO01, BO02 and BO05 (mean range: -21.4‰ to -21.6‰). The M2 sequence of BO03 remains comparatively depleted ($-22.4\text{‰} \pm 0.25$), although values begin to enrich towards the end of the sequence, with an enrichment peak observed within last increment (BO03: M2.7D: -22.1‰) (Figure 337 F).

$\delta^{15}\text{N}$ results

Serial nitrogen isotopic values (analytical error: 0.072‰) for each sampled tooth are depicted graphically in Figure 337 A–F. All nitrogen values have been plotted for inter-individual comparison along a constructed timeline of dentine growth in Figure 339.

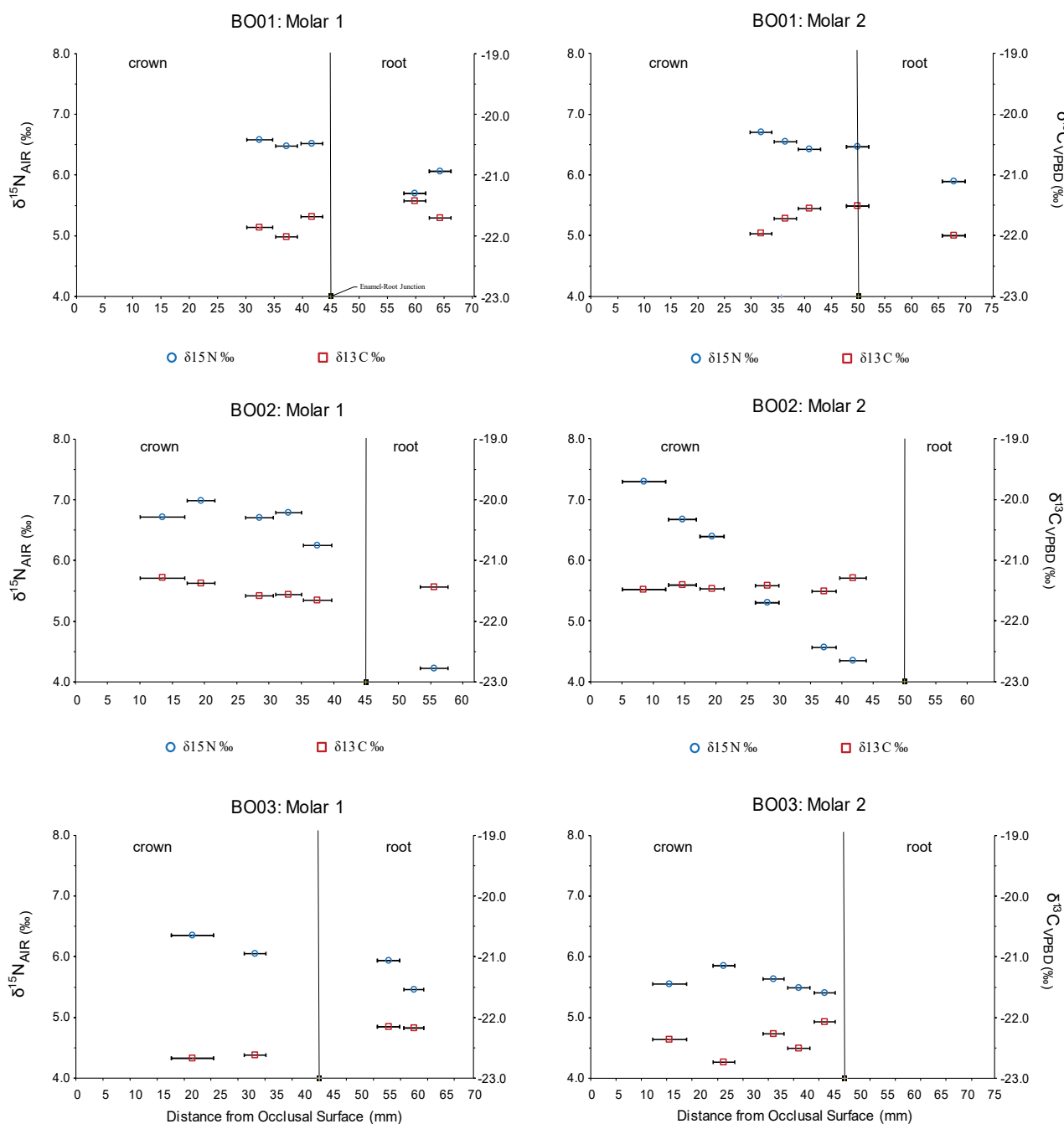


Figure 337. (continued on next page) Measured dentine collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for each first tooth and second molar from the five cattle specimens. Samples positioned on each tooth lobe by distance from the estimated unworn occlusal surface (unworn crown height estimated: M1 45 mm, M2 50 mm). Increments represented by their mid-point. Parameter bars represent total increment diameter across growth axis. Analytical error $\delta^{13}\text{C}_{\text{VPDB}}$ 0.090‰; $\delta^{15}\text{N}_{\text{AIR}}$ 0.072‰

Nitrogen results present a far greater value range than those observed in the carbon dataset, ranging from 4.2‰ to 7.3‰; r^2 : 3.1‰. The range presents no bias towards molar types, with both M1 samples (4.2‰ to 7.0‰; r^2 : 2.80) and the M2 samples (4.4‰ to 7.3‰; r^2 : 3.0‰) presenting a broad series of nitrogen values. The calculated average amplitude of variation within a single tooth is 1.2‰ (0.1‰

to 3.0‰), with an average amplitude of variation within an individual being 1.5‰ (0.4‰ to 3.1‰).

Comparative analysis of individual sequences reveals little consistency between the nitrogen isotopic profiles of the cattle. The individual sequences of BO01, BO03 and BO05 present relative uniformity in their amplitude of variation (0.4‰ to 1.0‰), varying little across the

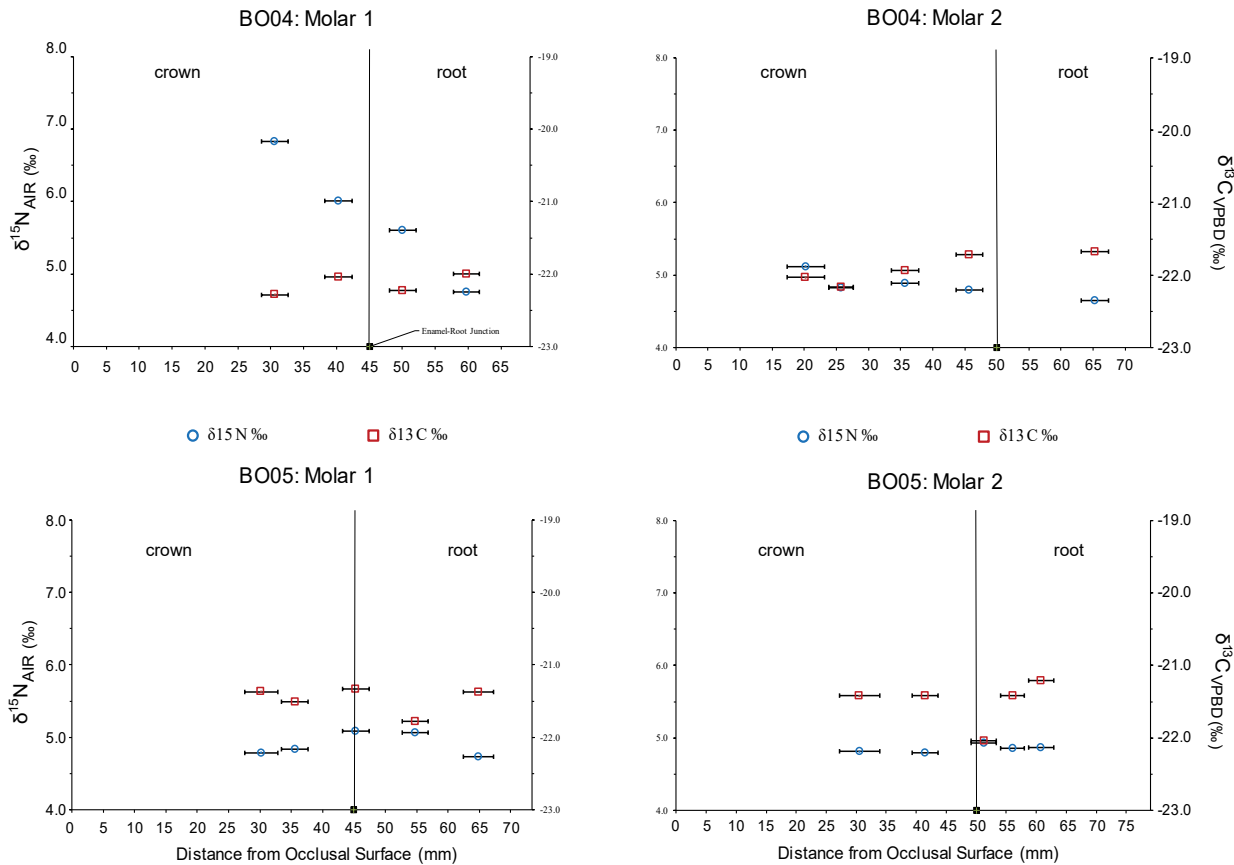


Figure 337.(continued)

dentine growth axis of their two successional molars (Figure 339). However, the sequences do all vary in their encompassing values, with BO01 presenting a comparably enriched sequence (mean: $6.3‰ \pm 0.33$) to that of BO05 (mean: $4.9‰ \pm 0.12$). The individual sequence of BO03 holds a mean of $5.8‰ \pm 0.32$, with values noted to gradually decline from the start to the end of the individual's dentine formation timeline ($6.4‰$ to $5.4‰$; r^2 : 1.0‰).

In comparison, individuals BO02 and BO04 hold sequences with significant amplitudes of variation. BO04's sequence depletes by $2.1‰$ in a linear fashion along the axis of growth of the M1, from its earliest increment (BO04: M1.8D: $6.8‰$) to its last increment (BO04: M1.2D: $4.8‰$) (Figure 337 B, G). As the sequence moves to the M2, it stabilises and varies little in range ($0.5‰$), presenting a similar profile (mean: $4.9‰ \pm 0.17$) to the M2 of BO05 (mean: $4.9‰ \pm 0.05$).

A sequential depletion is also observed on the M1 of BO02. The beginning of the M1 sequence (5–30 mm from the occlusal surface, *in utero* to postnatal <2–3 months) is relatively uniform (r^2 : 0.3‰), before rapidly depleting ($6.8‰$ to $4.2‰$) along the successional axis of growth, into the root. The age (postnatal, <2–3 months) at which the sequences begin to diminish (33 mm from

the occlusal surface) is similar to that of BO04 (30 mm from the occlusal surface). Unusually, the M2 sequence of BO02 presents an almost identical linear depletion to that observed on its M1; from its first increment (BO02: M2.12D: $7.3‰$) to its last (BO02: M2.5D: $4.4‰$), with a value decrease of $3.0‰$. The repetition of a similar linear decrease indicates the sequence is probably not a continuous timeline, but rather the sequenced re-recording of dentine tissue that formed simultaneously. Similarities between BO02's M1 and M2 carbon sequences (M1 mean: $-21.5‰ \pm 0.15$; M2 mean: $-21.4‰ \pm 0.08$) also suggest this timeline repetition (Figure 337 A, C–D).

Interestingly, the most enriched sequence belongs to BO01, the only individual dating to the Late Norse period, whilst the most depleted sequence belongs to the single individual dating to the Early Norse period (BO05).

Covariances in the $\delta^{15}N$ & $\delta^{13}C$ profiles

Intra-individual comparisons between sequenced $\delta^{15}N$ and $\delta^{13}C$ chronologies largely indicate minimal covariance between the two. A Pearson correlation coefficient statistical test determined a correlation value of $r = -0.1413$ between

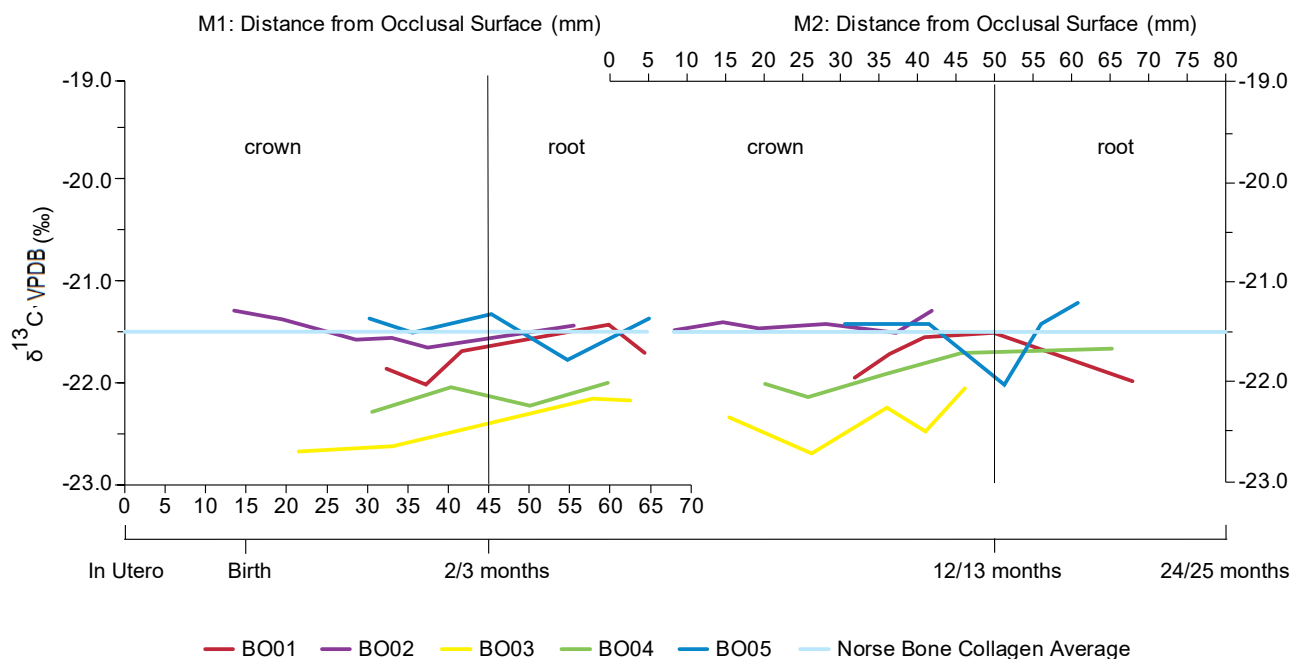


Figure 338. Combined $\delta^{13}\text{C}$ profiles for all first and second cattle molars measured against the estimated tooth eruption timeline. The horizontal purple line denotes the ERJ. Analytical error 0.090%

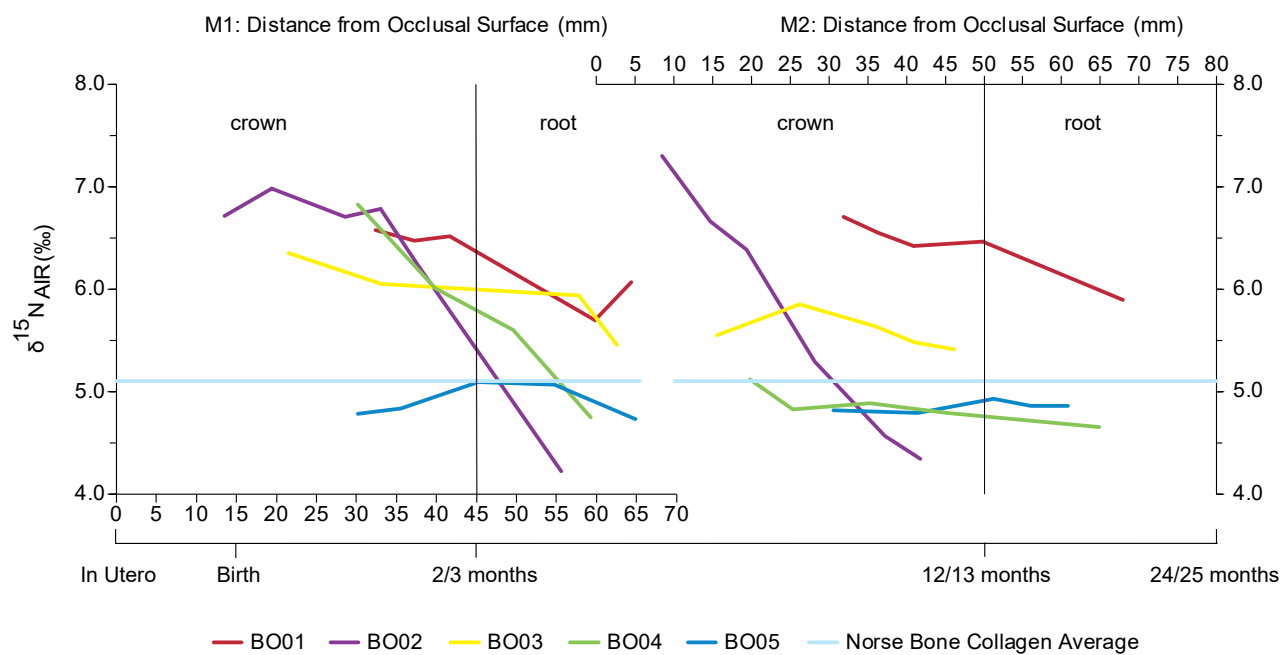


Figure 339. Combined $\delta^{15}\text{N}$ profiles for all first and second cattle molars measured against the estimated tooth eruption timeline. The horizontal purple line denotes the ERJ. Analytical error 0.072%

the $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values, indicating an insignificant negative correlation (Alexopoulos 2010). Some positive correlations are observed within enrichment/depletion patterns, *i.e.* the simultaneous depletion of carbon (0.5‰) and nitrogen (0.6‰) values from the ERJ through the root (>12–13 months) within the M2 of BO01 (Figure 337 A,

D), but these examples are limited. There is an occasional relationship between the enrichment of one isotopic variant and the depletion of the other, *i.e.* the sequences of BO04, where the nitrogen values deplete by 2.1‰ along the dentine growth axis of the M1, and the carbon values, though slight, enrich by 0.3‰ (Figure 337). The best

example of this trend, however, is the comparison of the carbon and nitrogen M2 sequences of BO03. Although this individual presents the most depleted carbon sequence (mean: $-22.4‰ \pm 0.25$) of all sampled individuals, its nitrogen is the second most enriched (mean: $5.6‰ \pm 0.17$) (Figure 337 E–F).

Discussion

The isotopic profiles of the five analysed cattle provide evidence for the seasonality of birth, weaning age and fodder variations that may indicate transhumance. Integrated with the results of the zooarchaeological analyses, this provides information on cattle management techniques practised by the inhabitants of Bornais.

Birthing seasonality

Within this study, birth seasonality is assessed through the inter-individual variability in positioning of the lowest and highest oxygen values along the growth axis of M1 and M2 molars (Balasse *et al.* 2011). As the lowest values are thought to represent the winter months, and the highest the summer (Sharma *et al.* 2004), the location along the postnatal growth axes at which the first season is experienced can be used to estimate the season of birth (Brown *et al.* 1960). To determine this, a relatively complete sinusoidal patterning is necessary (Balasse *et al.* 2011). Unfortunately, this was absent in the unsexed individuals BO01 (Late Norse) and BO05 (Early Norse) and discussion is therefore limited to the three individuals from the Middle Norse period (BO02, BO03 and BO04).


In BO02 and BO03 the lowest $\delta^{18}\text{O}$ values, assumed to represent winter, were experienced towards the end of the M1 growth axis, within the first 2–3 months of life (Figure 336). As both individuals' $\delta^{18}\text{O}$ profiles demonstrate a sinusoidal decline around the time of birth, this suggests that they were born in the autumn; for BO03 this is early autumn and for BO02 slightly later. For BO04 the M1 sequence, although notably enriched, still depletes around the same point as BO03 (37 mm from occlusal surface), also suggesting an early autumn birth. For both BO03 and BO04 O^{18} -enrichment, indicating the succeeding summer season, is visible on the M2 (at 25 mm). There is a relationship between O^{18} -enrichment and mother's milk consumption (Gron *et al.* 2015), and therefore this enriched M1 sequence may indicate BO04 was still suckling during the winter months.

Although the interpretation of this demographic trend in the Middle Norse period is limited to the analysis of three cattle, the oxygen values suggest an autumn birth profile for one male and two female animals, which would have required careful management (see below). Cattle have an average nine-month gestation period (Richardson *et al.* 1990; Gidney 2013), so a winter breeding season is suggested.

IMPACT OF AUTUMN BIRTHING RHYTHMS FOR CATTLE

Despite being aseasonal breeders, with the ability to conceive all year-round (Peters and Riley 1982), in the absence of human intervention cattle in northern European climates are assumed to have a natural single-season birthing rhythm (Gron *et al.* 2015). Natural birthing rhythms are difficult to ascertain given the absence of true wild cattle in contemporary times (Van Vuure 2005). However, comparisons can be drawn with feral populations, such as the feral cattle inhabiting the island of Swona, Orkney, which have a spring birthing rhythm (Hall and Moore 1986). The preference for spring/summer births has been attributed to the availability of fodder to sustain both mothers and suckling calves (Reinhardt *et al.* 1986) and the lack of shelter during winter months (Pucek *et al.* 2004).

Some treatises on medieval husbandry have an indication of a second calving period in late August or early September (Thompson 2005, 135) but an autumn birthing rhythm appears to be infrequent in antiquity (Balasse *et al.* 2012; Towers *et al.* 2011). However, analysis of cattle specimens from the Neolithic site of Almhov, Sweden (Gron *et al.* 2015), uncovered a bi-annual birthing rhythm in the spring and autumn months.

Writing in the late thirteenth century about autumn or 'Michaelmas' calves, Walter suggests that unless fed on good fodder these animals would have consumed more milk per day than was available for cheese and butter production. By the late eighteenth century, a winter hay-fed animal was reported as producing three gallons of milk per day (Fussell 1949, 164). An autumn breeding cycle at Bornais would, therefore, have required supplementary feeding and shelter to maintain both mothers and calves over the winter. A restricted ability to provide these would have contributed to the high mortality of young calves observed in the faunal assemblage (Ingrem  and would have reduced milk yields. However, three individuals in this dataset survived being born in winter and went on to thrive for at least a year and a half (the male) and three years (the females). The evidence for specific seasons of births also implies that by the Middle Norse period sexually mature males and females were segregated during non-breeding seasons (Walde 2006).

The principal reason for controlling cattle breeding is the importance of milk as a subsistence source. As the estimated lactation period of cattle in antiquity is 6–7 months (Gregg 1988; Peske 1994; Thompson 2005, 135), an autumn birthing season at Bornais could have provided a substantial dairy yield for human consumption throughout the winter and spring. An autumn cattle birthing season in the Middle Norse period would have made economic sense, with autumn-calving cows coming into full milk as the yield of spring calvers fell, providing supplementary subsistence at a time when other food-stocks are low.

Weaning profiles

Within this project, weaning ages/periods have been determined through the analysis of $\delta^{15}\text{N}$ biographies, with supporting evidence for seasonality taken from serial $\delta^{18}\text{O}$ values. When suckling, the calf holds a ^{15}N -enrichment of 2‰–4‰ over the mother (Minagawa and Wada 1984), with values depleting by this amount during the weaning period (Balasse *et al.* 2001). By identifying where on the tooth ^{15}N -depletion begins ('weaning signature') and ends, and the rate of change, it is possible to determine whether calves were allowed to wean naturally or had suckling artificially terminated (Vigne and Helmer 2007; Makarewicz *et al.* 2017, 119).

Only two cattle, BO02 and BO04, exhibit $\delta^{15}\text{N}$ weaning signatures, with the M1 sequence indicating rapid weaning, beginning at <2–3 months of age (with crown dentine) and ending at >2–3 months of age (within root dentine) (Figure 339). Both date to the Middle Norse period, and hold ^{15}N -depletion amplitudes of 2.1‰ (BO04) and 2.8‰ (BO02). These individuals were also born in the autumn and survived this weaning period, living until at least three and two years. A similar rapid ^{15}N -depletion is observed in the M2, but at a slightly later estimated age. This suggests that the estimates for the timing of the overlapping dentine formation timeframe in the root of the M1 and the start of the M2 (Brown *et al.* 1960) may be slightly incorrect.

BO03, the other female from the Middle Norse period, and BO01, unsexed and Late Norse, present contrasting nitrogen profiles, with no obvious weaning signature. Instead the $\delta^{15}\text{N}$ inter-tooth sequence gradually depletes over the 12–13-month timeline (Figure 339). This biography suggests a prolonged cessation to suckling and may represent natural weaning, with the calf gradually transitioning to plant foods (Reinhardt and Reinhardt 1981, 309), or limited access to milk with the bulk removed for human consumption (Makarewicz *et al.* 2017, 119). The length of the period of weaning is perplexing, with both animals continuing to demonstrate enriched sequences to the end of the sampled time frame; in the case of BO01 this extend to over 12–13 months. These animals may have continued to suckle for extended periods, and in the case of BO01, this individual's mother would not have bred in the following season. The season of birth could only be estimated for BO03, for which the data indicate that this occurred in autumn, whilst the value for BO01 do not reveal seasonal changes.

These signatures could provide evidence for cattle lactation periods that extended beyond the 6–7 months estimated for antiquity (Gregg 1988; Peske 1994) and support the theorised increase in lactation time to around 305 days during the medieval period in Europe (Makowiecki 2006). Another possibility is that these animals were weaned within the recorded timeframe but simultaneously pastured onto a protein source with high ^{15}N -enrichment, *i.e.* coastal-grown vegetation or manured fields (Nitsch *et al.* 2017). Such an enriched food source could mask the expected weaning depletion curvature.

BO05, the Early Norse individual, presents a constant, though considerably depleted nitrogen inter-tooth sequence, similar in value range to the post-weaning M2 sequence of BO02. This indicates the individual was probably artificially weaned earlier in life (less than 2 to 3 months), in a period not represented in the isotopic biography. The nature and exact point of weaning cannot be determined, although a projected rapid protocol is likely, given the short period on the dentine growth axis that is missing between estimated birth and the beginning of the sequence represented (at 30 mm, or less than 2 to 3 months).

The identification of artificial early-weaning profiles in three of the five individuals suggests this practice was a regular part of livestock management during the Middle and Late Norse periods; whilst the extended weaning profiles for the two other individuals point to additional, and previously unexpected, strategies employed in calf-rearing.

SUPPORTIVE EVIDENCE FOR WEANING AGE FROM $\Delta^{18}\text{O}$ PROFILES

Suckling and weaning periods can contribute to changes in serial $\delta^{18}\text{O}$ values much as they do to $\delta^{15}\text{N}$ profiles. *In utero* and suckling calves ingest water from their mother, leading to an ^{18}O -enrichment of 2‰–3‰ (Robert *et al.* 1988), due to fractionation processes within the mother's digestive tract (Fricke and O'Neil 1996). Determining at which age a 2‰–3‰ depletion occurred can be used to ascertain weaning age (Dupras and Tocheri 2007).

However, locating a weaning or suckling period within $\delta^{18}\text{O}$ isotopic biographies is difficult since it is masked by the effect of seasonal water cycles (Gron *et al.* 2015). During gestation and suckling, calves have a consistent water source, causing minimal change to their $\delta^{18}\text{O}$ values, but biographies still display a sinusoidal patterning caused by variations in the meteoric water intake of the mother (Gadbury *et al.* 2000). This often makes it problematic to discern whether a $\delta^{18}\text{O}$ depletion is associated with the winter season or whether it indicates a period of weaning. Furthermore, if the calf is weaned during autumn/winter, then $\delta^{18}\text{O}$ values will accentuate the natural meteoric winter depletion but may be masked by natural seasonal variance (Gron *et al.* 2015). For these reasons, most zooarchaeological studies utilising sequential $\delta^{18}\text{O}$ analysis will often omit weaning from their discussions, considering its determination too variable (Tsutaya and Yoneda 2015).

$\delta^{18}\text{O}$ evidence for suckling and weaning periods within the five Bornais biographies is minimal, although BO02 and BO03 may present evidence of an early weaning age (<2–3 months) identified along the growth axis of the M1, that accents the winter decline of $\delta^{18}\text{O}$ values along the sinusoidal curvature (BO02: 2.4‰; BO03: 2.1‰). The absence of an accompanying $\delta^{15}\text{N}$ weaning signature on the M1 dentine growth axis of BO03 suggests

these changes are probably attributable to environmental sinusoidal patterning rather than weaning. Although restricted, the comparatively depleted $\delta^{18}\text{O}$ values of BO05 (M1) complement the depleted $\delta^{15}\text{N}$ sequence, supporting the theory that BO05 was weaned at an early age. The lack of sinusoidal curvature means that it is difficult to deduce whether these low values represent a weaned individual or a natural winter depletion.

For BO04, suckling has already been identified by the dampening of the $\delta^{18}\text{O}$ negative sin-curvature during the autumn/winter months (see above 000). This supports the observed weaning signature in the $\delta^{15}\text{N}$ sequence occurring around the ERJ, ending at over 2 to 3 months of age; indicating that the individual was likely weaned during late winter. The enriched M1 sequence for BO01 supports a theorised later weaning, displayed in their $\delta^{15}\text{N}$ biography, but the lack of sinusoidal curvature makes clarification difficult, as the sequence may also be biased towards a late spring/early autumn season of weaning.

Consequently, it is evident that determining suckling and weaning periods within $\delta^{18}\text{O}$ profiles is significantly restricted, but that most evidence supports observed trends in the $\delta^{15}\text{N}$ biographies.

CAVEATS IN DETERMINING WEANING PROFILES

Unlike enamel mineralisation, the process of dentine formation in cattle has been heavily reviewed (e.g. Zazzo *et al.* 2006; Koenigswald 2011; Klevezal 2017). Hypsodont dentine matrices form in analogous incremented cones within the eruption timeline (Fisher and Fox 1998), with minimal remodelling after initial deposition (Hillson 1986; Lee-Thorp 2002). This means that the location of a weaning signature on the M1 or M2 can indicate the point at which individuals stopped ingesting their mother's milk (less than 2 to 3 months, or 1 to 10 months, considering maximum cattle lactation periods; Metge *et al.* 1990; Zazzo *et al.* 2006). However, incremental dentine analysis is limited by the variable rate of dentine formation, which makes establishing the exact age of weaning difficult. Although generally considered continuous, the rate-fluctuating process is dependent on multiple environmental variables (Kierdorf *et al.* 1993).

In modern studies, the rate of dentine formation in cattle was found to vary according to season (Klevezal and Pucek 1987) and was correlated with temperature: as temperature decreased, so did the rate of tissue formation. As the sinusoidal $\delta^{18}\text{O}$ profiles of BO02, BO03 and BO04 reveal that winter was experienced within the formation of the M1, the reduction in temperature may have slowed the rate of dentine tissue formation during this time, suggesting that weaning periods/age may have been longer or later than concluded through Brown *et al.*'s (1960) tissue formation timelines.

SUMMARY

Despite difficulties in calculating the exact age of weaning signatures, uniformity in dentine growth within the eruption timelines has enabled the conclusion that artificial early weaning strategies were employed during the Early and Middle Norse periods at mounds 2 and 2A. The removal of calves from their mothers suggests that a high milk yield was valued over the possibility of the increased survival of some calves, and this strategy probably contributed to the observed high mortality of neonate/young calves at the settlement.

The early weaning ages of BO02 and BO04, combined with their birthing season profiles, suggest autumn calving in the Middle Norse period was linked with the production of milk over the winter season. The absence of a weaning signature in BO03 indicates that this autumn-born female was deliberately allowed to suckle for longer, possibly in order to increase the survival chances of a future milk producer. BO03 and BO01 may provide evidence that domestic cattle lactation periods were longer than the originally hypothesised 6–7 months.

However, this analysis reveals caveats in the investigation of weaning profiles. First, the analysis of $\delta^{18}\text{O}$ profiles alone cannot provide conclusive evidence for weaning profiles, given the dominating effect that the seasonal water cycle has on values. Secondly, there is a need for further sequential dentine analysis to be undertaken on modern cattle from a similar environment to the Bornais cattle, to understand the formation rate of cattle dentine, thus enabling a more accurate determination of weaning ages, as well as a better integration of enamel $\delta^{18}\text{O}$ weaning evidence with dentine $\delta^{15}\text{N}$ evidence.

Seasonal foddering changes & evidence for transhumance

Variations in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values relate to diet and time and provide evidence for seasonal changes in grazing, which may relate to movement of livestock in the landscape (Makarewicz 2014). As this analysis does not require a true age for each animal, but rather analyses value patterning over the teeth's growth axis, the discussion of possible seasonal dietary changes is less restricted than the discussion of weaning and birthing seasons.

Serial $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from all the tooth samples were compared to the mean bulk bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of Early to Late Norse cattle specimens taken from Bornais and Cille Pheadair on South Uist, and Bostadh on Lewis (Jones 2014, 94). The combined mean Norse cattle bone collagen values from the three sites are $\delta^{13}\text{C}$: -21.5‰ and $\delta^{15}\text{N}$: 5.1‰.

Review of the $\delta^{13}\text{C}$ biographies suggests little evidence for changing intra-individual dietary protein sources during the animal's life. It is unsurprising to observe only nominal $\delta^{13}\text{C}$ value changes from the *in utero*/suckling periods to post-weaning ages, as the mother's digestive

tract causes minimal fractionation to carbon isotopic ratios. If the mother was consuming a similar source of $\delta^{13}\text{C}$ at the time of gestation and calf suckling to that consumed by the calf after weaning, then $\delta^{13}\text{C}$ sequences would be seen to be balanced over the timeline (Beaumont 2014).

All the cattle in the dataset have values consistent with an herbivorous diet of C^3 plants within the northern European region, typically falling between the range of -19.0‰ to -29.0‰ (Pollard and Heron 2015). The cattle present value ranges $<-21.0\text{‰}$, indicating that they were not consuming plants grown within a coastal region. Previous isotopic investigations within the north Atlantic region (Barrett and Richards 2004; Richards *et al.* 2006; Mulville *et al.* 2009) have suggested that consumption of coastal plants would enrich $\delta^{13}\text{C}$ values to $>-20.0\text{‰}$ within herbivorous fauna, as a result of the influence of sea spray (Van Groenigen and Van Kessel 2002). The settlement at Bornais was situated fairly close to the sea and, though coastal erosion during the last millennium may have reduced slightly the distance from the settlement to the coast, it is unlikely to have had a dramatic effect. The depleted $\delta^{13}\text{C}$ sequences therefore indicate that the plant material used for fodder was probably grown further inland, although a $\delta^{13}\text{C}$ plant baseline for the site would be necessary to confirm this.

Despite the consistency in dietary carbon sources comparisons between the individual biographies may suggest segregated foddering of cattle. Individuals BO01, BO02 and BO05 all present $\delta^{13}\text{C}$ biographies that cluster close to the mean bone collagen value from the three Norse settlements (Figure 338). BO03, and the M1 sequence of BO04, present comparatively depleted sequences, although values are still consistent with the bone collagen isotopic data (cattle bone collagen $\delta^{13}\text{C}$ values hold a range of 3‰ around the mean; Jones 2014, 94). BO03 is believed to be suckling throughout its dentine biography, and the period of suckling/weaning of BO04 also coincides with the period of $\delta^{13}\text{C}$ depletion. It is possible that a husbandry practice involving segregated grazing of mother and calf away from the rest of the herd was implemented in the Middle Norse period at mounds 2 and 2A, with the mothers grazing on different plant sources.

Interpretation of the $\delta^{15}\text{N}$ profiles in relation to fodder sources is limited due to the dominating effect suckling and weaning have on the sequences. Consequently, the discussion is restricted to post-weaned sequence lengths, only observable in BO04, BO05, and possibly BO01. Both BO04 and BO05 present values consistent with an herbivorous diet of terrestrial vegetation within the North Atlantic region (4.0‰ – 10.0‰ ; Schulting and Richards 2002), clustering close to the mean bone collagen value from the other Norse settlements (Figure 339). The consumption of vegetation grown in a saline-rich environment should lead to ^{15}N -enrichment of an estimated $\sim 7.0\text{‰}$ (Britton *et al.* 2008) but as the post-weaning values of BO04 and BO05

are both $<5.1\text{‰}$, this suggests the absence of machair-grown fodder, confirming the $\delta^{13}\text{C}$ patterning.

Whether the biography of BO01 represents a late suckling individual, or one weaned and grazing in a ^{15}N -enriched environment, is contentious. Enriched $\delta^{15}\text{N}$ values within herbivores have been attributed to grazing on manured soils, although expected values for this are $>8.0\text{‰}$ (Bogaard *et al.* 2007; Senbayram *et al.* 2008), a value not observed in this study. The $\delta^{15}\text{N}$ value for BO01 could be attributed to the consumption of coastal vegetation, but, taking into account the evidence from the $\delta^{13}\text{C}$ values, this is also unlikely. The cause of enrichment for this individual is therefore difficult to identify and is probably linked with continued suckling.

Overall, we see that the sequenced dentine profiles in this dataset provide evidence that foddering management practices at Bornais mounds 2 and 2A were consistent with those of other Norse settlements within the Western Isles. The isotopic data provide evidence of off-site fodder sources and segregated grazing of suckling calves and mothers away from the rest of the herd.

INTERPRETATION OF FODDERING PROFILES

The consistency of serial $\delta^{13}\text{C}$ and post-weaning $\delta^{15}\text{N}$ values suggests little seasonal change in grazing and foddering sources for cattle. The absence of evidence in the isotopic profiles for the consumption of coastal vegetation suggests that grazing occurred inland, away from the settlement. This evidence is supplemented by previous isotopic analysis of cattle bone collagen samples from the Late Iron Age/Norse phases of mound 1. Here low $\delta^{13}\text{C}$ (mean: $-21.4\text{‰} \pm 0.5$) and $\delta^{15}\text{N}$ (mean: $5.1\text{‰} \pm 1.6$) values have been attributed to the absence of coastal-grown fodder (Mulville *et al.* 2009; Jones and Mulville 2018).

Age-at-death profiles (see above 000) both challenge and support this theory. The high frequency of neonate and young calf remains observed in the faunal assemblage suggests the presence of birthing animals at the settlement (Ingrem 000), and makes year-round grazing off-site improbable. However, the scarcity of adult cattle bones within the faunal assemblages can be attributed to their removal from the settlement (Ingrem 000; Mulville 2005). The evidence of the isotopic profiles suggests inland grazing but cannot identify periods of on-site grazing during the birthing seasons.

Parallels may be drawn with the Mongolian pastoralist communities studied by Makarewicz (2014). In this region sheep are moved away from the settlement in the spring/summer and penned at the settlement during the autumn/winter, but minimal fluctuations were noted in the $\delta^{13}\text{C}$ values. This was attributed to the fact that the shepherds gathered fodder from the spring and summer meadows, dried this and brought it back to the settlement to feed the animals over the autumn/winter.

This practice of winter fodder supplementation may be considered for the cattle of Bornais. With the integration of

birthing seasonality results, the probable autumn births of the Middle Norse cattle indicate that cattle were present at the settlement over autumn and winter, a period that would have coincided with a lower availability of fresh grazing. The cattle would have required fodder to sustain both mother and new-born calf (Ingrem 000) and vegetation brought from the 'blacklands' may have been used to feed the herd through the winter. If this were the case, then the cattle could have been herded inland to graze during the spring and summer, before being moved back to the settlement in autumn for calving and over-wintering. Such seasonal movements of livestock would have maximised the use of the natural resources of the island. If the cattle were never or rarely grazed on the coastal machair, this also explains the absence of isotopic values indicating the use of saline-enriched vegetation.

TRANSHUMANCE EVIDENCE FROM $\Delta^{18}\text{O}$ PROFILES

Supporting evidence for the seasonal transhumance of cattle may be seen within the sinusoidal distribution of $\delta^{18}\text{O}$ values. Evans *et al.* (2019) state that the average $\delta^{18}\text{O}$ range between the winter and summer months in a static cattle herd within Britain is 1.2‰. In comparison, the deviation of values observed in the Middle Norse cattle at Bornais ranges from 2.3‰ to 3.1‰. The increased variation potentially indicates seasonal occupation of areas with different hydrology; the machair and the 'blacklands' (Towers *et al.* 2017).

Previous mobility studies have determined movements between different hydrogeological areas through regression conversions of $\delta^{18}\text{O}$ values against groundwater, drinking water, precipitation and surface water $\delta^{18}\text{O}_w$ base maps (Eckdart *et al.* 2009; Leach *et al.* 2009). However, recent critiques of these conversion equations have highlighted that the calibrations house significant error margins, made further problematic through the comparison of historical values against modern $\delta^{18}\text{O}_w$ sources (Pollard *et al.* 2011; Miller and Makarewicz 2018). As such, sequential $\delta^{18}\text{O}$ studies which aim to track seasonal movements will often consider calibration of values to a contemporary base map too inaccurate and rely on inter-individual and landscape comparisons to theorise geographical movements (*e.g.* Henton 2012).

Despite this limitation, this project discusses the $\delta^{18}\text{O}$ evidence for seasonal mobility based upon inter-geological comparisons of South Uist. The bedrock of the 'blacklands' causes the formation of pools of stagnating water and, during the spring and summer, high humidity results in many of them becoming ^{18}O -enriched through evaporation (Smith 1994; Fossit 1996; Henton *et al.* 2010).

If individual cattle were ingesting water from this area in the summer and consuming water from the machair in the winter, then an increased amplitude of $\delta^{18}\text{O}$ variance between the seasons may be possible. However, without the ability to compare the $\delta^{18}\text{O}$ values to a base map, this

theory is contentious. Further, the 1.2‰ seasonal variation for a static cattle herd is an average for the whole of Britain and does not account for regions with increased seasonal precipitation, such as the Western Isles (Evans *et al.* 2019).

The amplified sinusoidal amplitude of $\delta^{18}\text{O}$ values at Bornais could be attributed to the high winter precipitation levels in the island chain, escalating the depletion of autumn/winter values and subsequently increasing the amplitude of variance (Henton *et al.* 2010). This has been recorded for cattle from the Neolithic site of the Knap of Howar, Papa Westray, Orkney. Here the sampled cattle revealed a mean sinusoidal $\delta^{18}\text{O}$ variance of 2.4‰, attributed not to mobility, since Papa Westray is an exceedingly small island, but to winter precipitation levels (Balasse *et al.* 2006). Therefore, although seasonal variation in $\delta^{18}\text{O}$ may be interlinked with movements between two hydrogeological areas, this study reinforces the need for further sequential $\delta^{18}\text{O}$ analysis to be performed on a monitored modern cattle herd, in order to determine whether seasonal variation is attributable to increased winter precipitation or to mobility.

SUMMARY

The serial $\delta^{13}\text{C}$ and post-weaning $\delta^{15}\text{N}$ values of the samples analysed indicate that the grazing cattle of mounds 2 and 2A were consuming the same source of inland vegetation on a year-round basis. Comparing the $\delta^{13}\text{C}$ and post-weaning $\delta^{15}\text{N}$ values with the combined mean bulk bone collagen values from other Norse sites in South Uist and Lewis indicates that the foddering strategy used by the Norse occupants of mounds 2 and 2A is in keeping with contemporaneous foddering protocols in use throughout the Western Isles. Further, the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data indicate a potential segregated management of grazing mothers and suckling calves away from the rest of the herd.

Integrating the isotopic data with the age-at-death profiles derived from the entire cattle bone assemblage from mounds 2 and 2A reveals that, although grazing probably occurred away from the settlement, birthing and suckling must have occurred at the settlement since there is a high frequency of neonate and young calf remains. With evidence taken from the theorised autumn birthing season of the Middle Norse period, we can deduce that cattle remained at the settlement throughout the autumn/winter period. The results of this analysis enable us to suggest that the continuous source of inland plant fodder indicates winter feeding of cattle with vegetation gathered from the 'blacklands'. It is proposed that cattle were herded to the 'blacklands' for the spring/summer months, where they were allowed to graze and breed before being moved back to the settlement for birthing, suckling and weaning, with the mothers' diet being supplemented with stored vegetation harvested from the grazing pastures.

Conclusion

This project demonstrates that the examination of tooth isotopic biographies can be used to explore animal husbandry techniques. The isotopic dataset provides evidence for four key areas of cattle management at mounds 2 and 2A: birthing season, weaning age, seasonal pasturing and seasonal fodder supplementation. A summary of this evidence is detailed below:

1. $\delta^{18}\text{O}$ enamel biographies reveal a potential autumn birthing rhythm during the Middle Norse phase of mounds 2 and 2A.
2. $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ profiles reveal evidence of an early age for artificial weaning (<2–3 months), indicating prioritisation of milk yield over calf survival, and therefore the importance of milk. An autumn birth implies a winter weaning period.
3. The discernible weaning patterns include a prolonged suckling period (<12–13 months) for two individuals in the dataset (suggesting an increased lactation period, longer than the estimated 6–7 months), and selective suckling management regimes designed to sustain certain calves.
4. $\delta^{13}\text{C}$ and post-weaning $\delta^{15}\text{N}$ values indicate the year-round grazing of cattle on a single vegetation source growing inland, as well as the possible grazing segregation of mother and suckling calf from the rest of the herd.
5. $\delta^{13}\text{C}$ and post-weaning $\delta^{15}\text{N}$ values, in combination with $\delta^{18}\text{O}$ profiles, provide evidence for the theorised transhumance of livestock to the inland ‘blacklands’ area of South Uist during spring/summer before returning to the settlement for birthing, and evidence for winter fodder being supplemented with harvested vegetation from the inland grazing pastures.

Once integrated with other zooarchaeological investigations, the isotopic data generate strong biographical accounts of the cattle’s early lives, providing evidence for an environmental rationale behind management techniques and for the economic role of cattle for the Norse inhabitants of mounds 2 and 2A. The results indicate the economic importance of milking over the winter and spring months, with early weaning during the winter maximising milk yield during a period of potential food-stock depletion. Seasonal transhumance also has an environmental rationale, with off-settlement grazing reducing competition between humans and livestock for machair-grown vegetation, whilst bringing calves and mothers to the settlement during autumn/winter would have allowed the provision of some shelter, perhaps in temporary structures.

The isotopic data complement cattle mortality profiles, with the highlighted importance of dairying and autumn birthing potentially contributing to the high infant mortality at the settlement, indicating a possible culling or natural loss of calves due to separation from their mothers and to the winter climatic conditions. To obtain the most

extensive biographies this study’s methodologies focused only on long-lived animals. Calves dying young have not been subject to analysis, so it is not yet possible to explore the seasonal and dietary biographies of such individuals. It is apparent from these results that not all early weaned animals died as a result (*e.g.* females BO02 and BO03 and unsexed BO05 all survived until adulthood), so the question of natural or deliberate mortality of calves remains unanswered.

The application of these methodologies also reveals a number of caveats as, without knowledge of dental tissue formation, isotopic biographies cannot assign isotopic values to actual age. Determination of age-related husbandry practices, such as weaning periods and birthing seasonality, always involves a degree of uncertainty. As cattle dental tissue is highly variable, and its formation is largely dependent on season and environment, it is necessary to establish accurate tissue formation timelines relating to the Western Isles environment, before isotopic values specific to age can be obtained.

Despite the limitations, the results of this study provide a vital contribution to the recreation of human–cattle interactions during the occupation of mounds 2 and 2A of Bornais. The evidence suggests that the Norse inhabitants designed cattle management techniques around their environment, in order to successfully sustain their cattle and to maximise the yield from them. This study contributes to the continuing investigation of lifeways in the Western Isles, revealing much about how past populations subsisted and survived in a challenging environment.