An isotopic investigation into the origins and husbandry of Mid-Late Bronze Age cattle from Grimes Graves, Norfolk

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Abstract

Bioarchaeological evidence suggests that the site of Grimes Graves, Norfolk, characterised by the remains of several hundred Late Neolithic flint mineshafts, was a permanently settled community with a mixed farming economy during the Mid-Late Bronze Age (c. 1400 BC – c. 800 BC). The aim of this study was to investigate, through isotope ratio analysis (^{87}Sr/^{86}Sr, δ^{13}C and δ^{18}O), the origins and husbandry of Bronze Age cattle (*Bos taurus*) excavated from a mineshaft known as the "1972 shaft". Strontium isotope ratios from the molar enamel of ten Grimes Graves cattle were compared with eight modern animals from the Chillingham Wild White cattle herd, Northumberland. The range of ^{87}Sr/^{86}Sr values for the modern cattle with known restricted mobility was low (0.00062) while the values for the Grimes Graves cattle varied much more widely (range = 0.00357) and suggest that at least five of the cattle were not born locally. Two of these animals were likely to have originated at a distance of $\geq$ 150 km. Intra-tooth δ^{13}C profiles for eight of the Grimes Graves cattle show higher δ^{13}C values compared to those of Early Bronze Age cattle from central England. Most of these profiles also display pronounced shifts in δ^{13}C during the period of enamel formation. One possible interpretation is that the cattle were subject to dietary change resulting from movement between habitats with different vegetation δ^{13}C values. More comparative data, both archaeological and modern, is required to validate this interpretation. The multi-isotope approach employed in this study suggests that certain cattle husbandry and/or landscape management practices may have been widely adopted throughout central Britain during the Mid-Late Bronze Age.

Keywords

Strontium; Carbon; Oxygen; Isotope analysis; Tooth enamel; Intra-tooth sampling; Cattle husbandry

1. Introduction

Grimes Graves, in the Breckland region of Norfolk, lies within a swathe of Upper Cretaceous chalk geology (Figure 1). The site covers an area of approximately 9 ha and is characterised by several hundred depressions that are the remains of Late Neolithic flint mineshafts (Mercer, 1981). Evidence from excavations carried out in the 1970s suggests that by the Middle Bronze Age flint mining had ceased and the site had been re-occupied after a period of abandonment (Mercer, 1981). During the Bronze Age the mineshafts were used for the disposal of midden material, the contents of which indicate a range of activities: textile production (possible chalk spindle whorls, bone needles and pins); leatherworking (bronze awls and flint boring tools); woodworking (various flint implements and oak charcoal); and metalworking (clay moulds for casting spearheads, small pieces of metalworking debris and items fabricated from copper alloy such as jewellery and small tools) (Mercer, 1981; Needham et al., 1991a, 1991b). The middens also contained evidence of agricultural activity through the presence of charred grains and a large quantity of animal bones (Mercer, 1981). The aim of this study was to gain information about the origins and husbandry of Mid-Late Bronze Age cattle (*Bos taurus*) from Grimes Graves through stable isotope analysis of molar enamel. Analysis of enamel from the modern Chillingham Wild White cattle herd, Northumberland (Figure 1) was also undertaken. Chillingham cattle were chosen to provide comparative data because they represent a non-mobile herd of semi-feral cattle with minimal human interference. They remain in one location throughout their lives, graze on the locally available vegetation year round and are given no supplementary food apart from hay in winter.

1.1. Grimes Graves, Norfolk (NGR: TL818898, alt. 25m)

The cattle mandibles selected for this study were from the Bronze Age midden deposits of the "1972 shaft", a 10.5 m diameter mine shaft excavated in 1972. The midden material appears to have been deposited over several centuries: radiocarbon dates for two of the cattle mandibles, identified in this study as GG120 and GG92, are 1416-1302 cal BC, 95 % confidence (MAMS-14361, 3084 ± 21 BP) and 908-820 cal BC, 95 % confidence (MAMS-14362, 2722 ± 20 BP) respectively, calibration having been carried out using the INTCAL09 dataset (Reimer et al., 2009) and SwissCal 1.0 (L. Wacker, ETH-Zürich). Unfortunately, it is not possible to estimate the dates of the remaining mandibles because there is no stratigraphic information relating to them.

Bioarchaeological evidence suggests that Grimes Graves was a permanently settled community during the Bronze Age with a mixed farming economy. Counts of animal mandibles from the 1972 shaft deposits indicate that cattle were the dominant domestic species, followed by sheep/goat (thought to be mainly sheep) with pig mandibles much less numerous (Legge, 1981). Mortality profiles for Mid-Late Bronze Age cattle show that approximately 50 % of the animals were less than eight months old at death suggesting an emphasis on dairying (Legge, 1992). Carbonised cereal grains are dominated by six-row hulled barley (*Hordeum vulgare*) and emmer wheat (*Triticum dicoccum*), whilst carbonised weed seeds include species associated with cereal crops, pasture and waste ground (Legge, 1981). The picture of a mixed farming economy is supported by the local soil types: slope soils which are calcareous, easily worked and suitable for cereal production despite limited fertility; dry valley and upland soils which are acidic and unsuitable for cereal production but may be utilised for grazing; and wet valley soils along the Little Ouse river suitable for pasture (Legge, 1981). Animal husbandry would have been necessary not only to make use of the poorer,

acidic soils but also to provide manure to maintain the fertility of those soils suitable for cereal production.

1.2. Chillingham Park, Northumberland (NGR: NU073258, alt. 98-235 m)

The Chillingham Wild White cattle herd live in Chillingham Park, Northumberland, a 130 ha enclosure of well-managed grassland and open woodland. The bedrock geology consists of Mississippian sandstone, siltstone and mudstone (Inverclyde Group) and Mississippian sandstone with subordinate argillaceous rocks and limestone (Border Group) largely overlain with Quaternary Diamicton till. From 1980 until 2004, the principal areas of grassland were fertilized with magnesian limestone (from the Permian geological period) to alleviate magnesium deficiency within the herd (Bunce and Hall, 2013).

The cattle are free from direct human husbandry apart from the provision of hay during winter which may constitute between approximately one half to two thirds of what they eat during that period depending upon the severity of the weather (Leyland, pers. comm.). Cattle numbers have risen from 13 in 1947 (Hall and Hall, 1988) to approximately 100 strong by 2011 (Chillingham Wild Cattle Association, 2008-2016), indicating that they have been well-provisioned in recent years. Mandibles were obtained from the carcasses of cattle that had died between 2007 and 2010. For these cattle, during the period of tooth formation, hay was sourced from the neighbouring county to the north, Scottish Borders, and purchased through a dealer. The species content of the hay and a more precise provenance are not known and may have varied between batches.

1.3. Isotopic analysis of cattle molar enamel

This study employed two isotopic techniques to analyse molar enamel from Grimes Graves: strontium isotope ratio analysis (^{87}Sr/^{86}Sr) to investigate cattle origins and mobility, and carbon and oxygen isotope ratio analysis (δ^{13}C, δ^{18}O) of the carbonate fraction of enamel to investigate husbandry.

Strontium ^{87}Sr/^{86}Sr values measured in tooth enamel are determined by an animal's food and drinking water which are strongly dependent on the geology of the region in which they are sourced. The geology and associated biosphere ^{87}Sr/^{86}Sr values of the British Isles are sufficiently varied (Evans et al., 2010) to utilise strontium isotope ratio analysis in archaeology as a method to investigate the origins and movements of animals (e.g. Minniti et al., 2014; Montgomery et al., 2007; Sykes et al., 2006; Towers et al., 2010; Viner et al., 2010). Like calcium, strontium is absorbed into blood plasma from the intestine and subsequently becomes incorporated into the bioapatite lattice of forming enamel (Ezzo, 1994). A fraction of this strontium may originate from bone bioapatite which, unlike enamel, remodels during life. Such recycled strontium can be resident in the body for several months or years (Papworth and Vennart, 1984). Thus, an animal's enamel ^{87}Sr/^{86}Sr values may reflect strontium ingested in the past in addition to strontium ingested during enamel formation (Montgomery et al., 2010).

Carbon and oxygen isotope ratios are expressed in the δ notation (units are permil, ‰). The δ^{13}C value of tooth enamel carbonate is derived from dissolved inorganic carbon in blood (Passey et al., 2005; Sullivan and Krueger, 1981) and is largely determined by the δ^{13}C of the whole diet (Sullivan and Krueger, 1981). For prehistoric herbivores in the British Isles, diet would have been predominantly composed of C$_3$ plants. The δ^{13}C value of vegetation is influenced by species, growth form, plant part and environmental factors such as irradiance, salinity, water availability and the

"canopy effect" whereby the δ^{13}C values of plants growing at ground level under dense tree cover tend to be lower than for plants growing in open environments (comprehensive summaries by Heaton, 1999; Tieszen, 1991). Environmental factors such as water availability and irradiance tend to vary throughout the year leading to seasonally varying vegetation δ^{13}C values (Dungait et al., 2010; Smedley et al., 1991). The δ^{13}C value of herbivore enamel may also be influenced by digestive physiology (Hedges, 2003; Passey et al., 2005; Towers et al., 2014). Tooth enamel δ^{18}O values are primarily determined by the δ^{18}O value of drinking water, which tends to be related to the δ^{18}O value of precipitation (Longinelli, 1984; Luz and Kolodny, 1985; Luz et al., 1984). The latter varies seasonally at British latitudes with higher values in summer, due to various climatic variables including air temperature (Dansgaard, 1964).

It is the formation process of cattle molars that enables sub-annual variation in enamel δ^{13}C and δ^{18}O values to be observed. Enamel mineralization follows two principal phases: matrix formation and maturation. The matrix, an organic framework, is secreted ahead of maturation and becomes lightly mineralized as it is laid down (Hillson, 2005; Suga, 1982). It is initially deposited at the enamel-dentine junction (EDJ) then outwards to what eventually becomes the outer surface of the enamel. Once the matrix has reached its final thickness, maturation begins which is a complex process both temporally and spatially initially consisting of an increase in mineralization from the surface to the innermost layer followed by a further increase in the opposite direction, then finally an increase in mineralization of the narrow outer surface layer (Hoppe et al., 2004; Robinson et al., 1995; Suga, 1982; Tafforeau et al., 2007). The matrix progresses sequentially from cusp to cervix over a number of months which means that sub-annual variation in δ^{13}C and δ^{18}O may be revealed by analysing a series of intra-tooth enamel samples from the length of a molar crown. Cattle second molars form between the ages of 1 and 12-13 months while third molars form between the ages of 9-10 and 23-24 months, each of these timings being approximations (Brown et al., 1960). They are related to matrix progression and do not take account of the complex nature of enamel mineralization. For cattle molar enamel, a sample from any position on the crown, extracted through the bulk of its thickness, will have taken at least 6-7 months to complete mineralization (Balasse, 2002; Montgomery et al., 2010; Zazzo et al., 2005). Thus, the δ^{13}C and δ^{18}O values of each intra-tooth sample are time-averaged values for mineral incorporated during both the matrix and maturation phases (Passey and Cerling, 2002). The 6-7 month period was estimated from intra-tooth isotopic analysis (Balasse, 2002) and does not include the final stage of mineralization of the narrow outer surface layer which tends to be discarded during enamel sampling.

2. Sample preparation and analysis

Mandibular molars from ten Grimes Graves cattle and eight Chillingham cattle were selected for isotopic analysis (Table 1). The Grimes Graves mandibles comprised six left mandibles and four right mandibles; care was taken to establish that they originated from ten different individuals: they had to be distinguishable, either visually with respect to wear or isotopically after analysis. The Chillingham mandibles were known to be from different animals.

Table 1: Summary of cattle molars included in this study. M_2 = Mandibular 2nd molar, M_3 = Mandibular 3rd molar. Wear stages after Grant (1982), age stages after Halstead (1985).

Animal ID	Radiocarbon date (95% confidence)	Teeth analysed (+ wear stage)		Estimated age at death (+ age stage)	Enamel sampled for $^{87}Sr/^{86}Sr$, Sr ppm	Enamel sampled for $\delta^{18}O$, $\delta^{13}C$
Grimes Graves						
GG92	908-820 cal BC	M_2 (g)	M_3 (c)	30-36 mo. (E)	√	√
GG120	1416-1302 cal BC	M_2 (a/b)		8-18 mo. (C)	√	√
GG121		M_2 (j)	M_3 (g)	adult (G)	√	√
GG614		M_2 (f)	M_3 (E)	18-30 mo. (D)	√	√
GG621		M_2 (f)		18-30 mo. (D)	√	
GG677		M_2 (f)		18-30 mo. (D)	√	
GG681		M_2 (j)	M_3 (g)	adult (G)	√	√
GG743		M_2 (g)	M_3 (e/f)	young adult (F)	√	√
GG839		M_2 (g)	M_3 (d)	30-36 mo. (E)	√	√
GGT10		M_2 (g)	M_3 (f)	young adult (F)	√	√
Chillingham						
CHIL1		M_2 (g)	M_3 (f)	30-36 mo. (E)	√	√
CHIL5			M_3 (l)	senile (I)	√	
CHIL6		M_2 (l)	M_3 (k)	senile (I)	√	√
CHIL7		M_2 (k)	M_3 (j)	old adult (H)	√	√
CHIL8			M_3 (l)	senile (I)	√	
CHIL9			M_3 (l)	senile (I)	√	
CHIL10		M_2 (k)	M_3 (j)	old adult (H)	√	√
CHIL14		M_2 (k)	M_3 (h)	adult (G)	√	√

2.1. Strontium isotope ratio analysis of enamel

Enamel preparation was initially performed at the Stable Light Isotope Facility at the University of Bradford. In order to assess the level of variation in $^{87}Sr/^{86}Sr$ values for cattle from a single herd, cleaned solid chips of cuspal enamel (~1mm x 2mm) were collected from the third molars of eight Chillingham cattle. Samples of cleaned enamel, in the form of chips or in powdered form (10-20 mg), were obtained from the molars of ten Grimes Graves cattle. For each of these animals, samples of second molar cuspal enamel were collected to investigate cattle origins. Additional samples were also obtained from eight of the ten Grimes Graves cattle to explore mobility. The selection of these samples, from both second and third molar crowns, was based upon the intra-tooth $\delta^{13}C$ profiles obtained for these teeth. Their purpose was to determine any correspondence between significant shifts in $\delta^{13}C$ and changes in $^{87}Sr/^{86}Sr$.

Further details regarding sample preparation may be found in Towers et al. (2010, 2011). Subsequent chemical processing and analysis were performed at the clean laboratory suite at the NERC Isotope Geosciences Laboratory at Keyworth, Nottinghamshire (NIGL). The procedure, involving cation exchange chromatography, is described by Montgomery (2002). Prepared samples, in the form of a dry chloride salt, were analysed by means of a Thermo Triton multi-collector thermal ionisation mass spectrometer (TIMS). During run time, all $^{87}Sr/^{86}Sr$ results were normalised to $^{86}Sr/^{88}Sr$ = 0.1194 to correct for fractionation. The international standard material NBS-987 gave a value of 0.710253 ± 0.000006 (1σ, n = 350) during the period in which the enamel samples were analysed. Analytical precision for $^{87}Sr/^{86}Sr$ was ± 0.0017 % (2σ) while for strontium concentration it

was estimated to be ± 10 % (2σ), as suggested by Montgomery et al. (2000). Procedural blank values (≤ 100 pg) were considered insignificant.

2.2. Oxygen and carbon isotope ratio analysis of enamel

Enamel samples from second and third molars were prepared and analysed at the Stable Light Isotope Facility at the University of Bradford. For each molar crown, the surface of a single lobe was cleaned using a diamond dental burr. Where possible, lingual lobe enamel was sampled unless it appeared to be of poorer quality than buccal lobe enamel. Any influence on the measured $\delta^{13}C$ and $\delta^{18}O$ profiles due to lobe selection is expected to be minimal and not affect the interpretation of data in this study. Intra-tooth powdered enamel samples were collected from the cusp to the cervix by drilling through the bulk of the enamel thickness. In total, 15 molars from eight Grimes Graves cattle and ten molars from five Chillingham cattle were sampled. Details of subsequent sample preparation, involving treatment with NaOCl solution and acetic acid, are described in Towers et al. (2011). Treatment was identical for both modern and archaeological enamel. Prepared samples were weighed into septa-capped vials which were loaded into a Finnigan Gasbench II automated carbonate preparation device connected to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer. The automated system added anhydrous phosphoric acid sequentially to each sample at 70 °C and the resulting CO_2 was analysed by the mass spectrometer. Included in each batch of enamel samples were multiple samples of two internal laboratory standards (Merck Suprapur $CaCO_3$ and OES1) and one international laboratory standard (NBS-19). The resulting enamel $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ measurements were normalised by means of a linear calibration equation derived from a plot of accepted versus measured values for the three standards. Analytical precision was ± 0.2 ‰ (1σ) and ± 0.1 ‰ (1σ) for $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ respectively, determined for an internal standard consisting of homogenised enamel powder, included in analyses performed over a 15 month period (n = 33).

3. Results and Discussion

3.1. Strontium analysis and cattle origins

$^{87}Sr/^{86}Sr$ and strontium concentration values for eight Chillingham and ten Grimes Graves cattle are presented in Table 2. Figure 2 is a plot of $^{87}Sr/^{86}Sr$ versus strontium concentration for Grimes Graves second molar cuspal enamel and Chillingham third molar cuspal enamel. Because second molar cuspal enamel is the earliest forming enamel that may be sampled from either the second or third molar, its $^{87}Sr/^{86}Sr$ value is the most appropriate to investigate the origins of the Grimes Graves cattle. The Chillingham cattle remained in the same location for all of their lives. Therefore molar type was unimportant. Cattle data from the Early Bronze Age barrows of Irthlingborough and Gayhurst in central southern England are also displayed (data from Towers et al., 2010). Figure 3 displays the four $^{87}Sr/^{86}Sr$ datasets in the form of a simple box plot.

Table 2: Strontium isotope ratios and concentrations of Chillingham and Grimes Graves cattle molar enamel. M_2 = Mandibular 2nd molar, M_3 = Mandibular 3rd molar. Distance from cervix values were not recorded for the Chillingham molars, GG621 and GG677.

Animal ID	Tooth	Position on tooth lobe	Distance from cervix (mm)	$^{87}Sr/^{86}Sr$ normalised	Sr concentration (ppm)
CHIL1	M_3	cusp	-	0.710555	98
CHIL5	M_3	cusp	-	0.710451	126
CHIL6	M_3	cusp	-	0.710593	100
CHIL7	M_3	cusp	-	0.710318	118
CHIL8	M_3	cusp	-	0.710751	85
CHIL9	M_3	cusp	-	0.710467	121
CHIL10	M_3	cusp	-	0.710936	79
CHIL14	M_3	cusp	-	0.710451	85
GG92	M_2	cusp	39.0	0.708945	107
GG92	M_3	cusp	40.0	0.709035	88
GG92	M_3	cervix	9.5	0.709164	88
GG120	M_2	cusp	47.0	0.711993	333
GG120	M_2	cervix	8.0	0.711870	238
GG121	M_2	cusp	38.0	0.709190	284
GG121	M_2	cervix	6.5	0.709298	165
GG121	M_3	cervix	7.5	0.708835	114
GG614	M_2	cusp	46.0	0.710962	192
GG614	M_3	cusp	47.5	0.710592	142
GG614	M_3	cervix	7.0	0.712418	175
GG621	M_2	cusp	-	0.708909	169
GG677	M_2	cusp	-	0.708415	113
GG681	M_2	cusp	26.5	0.708745	161
GG681	M_3	mid-lobe	19.5	0.708523	113
GG743	M_2	cusp	42.5	0.709588	287
GG743	M_3	cusp	46.0	0.710363	210
GG743	M_3	mid-lobe	22.0	0.711273	189
GG743	M_3	cervix	8.0	0.710831	143
GG839	M_2	cusp	42.0	0.708517	155
GG839	M_3	mid-lobe	19.0	0.708608	84
GGT10	M_2	cusp	38.0	0.709833	162
GGT10	M_3	mid-lobe	29.0	0.709766	118
GGT10	M_3	cervix	7.0	0.708989	99

As might be expected for cattle living within a restricted area, the results for the Chillingham cattle form a tight cluster. Concentrations lie between 79 and 126 ppm while $^{87}Sr/^{86}Sr$ values vary between 0.71032 and 0.71094 (a range of 0.00062) (Figure 2). This level of $^{87}Sr/^{86}Sr$ variation may reflect spatial variation in the underlying geology and hence vegetation values within Chillingham Park. It

may also relate to inter-animal differences in the amount of water consumed via ingested vegetation and as drinking water. In maritime regions, rainwater has a similar $^{87}Sr/^{86}Sr$ value to that of seawater, ~0.7092 (McArthur et al., 2001). Other possible contributing factors are the grassland liming carried out between 1980 and 2004, which may have caused spatial and temporal variation in vegetation by lowering $^{87}Sr/^{86}Sr$ values, and inter-animal differences in the winter consumption of hay sourced from the neighbouring county, the precise provenance of which is unknown. Despite this variation in $^{87}Sr/^{86}Sr$, the total and interquartile ranges for the Chillingham data are markedly smaller than those for the Grimes Graves, Irthlingborough and Gayhurst datasets (Figure 3).

The results for the Grimes Graves cattle vary widely in both $^{87}Sr/^{86}Sr$ value and concentration (Figure 2). $^{87}Sr/^{86}Sr$ values lie between 0.70842 and 0.71199 (a range of 0.00357) while concentrations vary from 107 to 333 ppm, suggesting diverse origins. Because Grimes Graves lies in a region of chalk geology, second molar cuspal enamel $^{87}Sr/^{86}Sr$ values are expected to lie between ~0.708 and ~0.709 for locally-born cattle (the grey band in Figure 2), based on plant measurements (Evans et al., 2010). Plant $^{87}Sr/^{86}Sr$ values are used to define the biosphere range for a particular geological terrain because they reflect the bioavailable strontium in their immediate locality which is derived from a mixture of sources, principally the local geological substrate, rainwater and sea water if coastal. They tend to compare favourably with measurements for archaeological samples of known local provenance (Evans et al., 2010). Results from five of the cattle (GG120, GG121, GG614, GG743 and GGT10) lie above the proposed biosphere range for chalk and are likely to have originated elsewhere. GG121, GG743 and GGT10 may have been born in a region of Jurassic geology which at its closest is only ~20 km to the west of Grimes Graves. Their $^{87}Sr/^{86}Sr$ values are similar to the majority of values for Irthlingborough and Gayhurst, both of which are located on Jurassic terrain (Figure 2). It should be noted that large swathes of Britain, not only Jurassic regions, can produce biosphere values between 0.709 and 0.710 (Evans et al., 2010). The $^{87}Sr/^{86}Sr$ values for GG120 and GG614 (0.71199 and 0.71096) suggest distant places of birth. Such biosphere values have been proposed for much of western and northern Britain (Evans et al., 2010), of which parts of the West Midlands and Derbyshire are closest to Grimes Graves at distances of ~150 km. Second molar cuspal enamel $^{87}Sr/^{86}Sr$ values for the remaining five cattle (GG92, GG621, GG677, GG681 and GG839) are consistent with local origins although non-local origins cannot be ruled out. For example, the $^{87}Sr/^{86}Sr$ value obtained for third molar cervical enamel from GG92 (Table 2) may indicate that this animal spent its first two years in a region of Jurassic rather than chalk geology.

The presence of cattle at Grimes Graves with distant origins suggests that long-distance cattle trading networks from western to eastern Britain were in operation during the Mid-Late Bronze Age, as they may have been during the Early Bronze Age given the two $^{87}Sr/^{86}Sr$ values > 0.711 from Irthlingborough and Gayhurst (Figure 2). One implication is that prehistoric people recognized the importance of fresh bloodlines to their livestock. Alternatively, cattle may have been used as pack animals for transport, and the diverse origin of the Grimes Graves cattle is a reflection of human mobility during the Mid-Late Bronze Age. Cattle are widely used as pack animals within ethnographic contexts (eg. Woodhouse, 1987) and figurines depicting pack oxen are known in Late Neolithic contexts in Greece (Halstead, 1981; Toufexis, 2003).

Although strontium concentration values are presented here, interpretation is not straightforward. Strontium concentration in tooth enamel can vary because of a number of different reasons none of which are well defined. It can vary geographically, which could be due to variations in bedrock geology (Turekian and Kulp, 1956). Calcium content of food and water is also a factor with high

calcium diets tending to suppress strontium uptake (Underwood, 1977). In coastal areas, the strontium concentration of food and water may be influenced by sea-splash and sea-spray which have considerably higher strontium concentrations than rainwater and terrestrial surface waters (Capo et al., 1998; Whipkey et al., 2000). In Figure 2, the Grimes Graves cattle with $^{87}Sr/^{86}Sr$ values consistent with local origins have lower strontium concentration values than three of the non-local animals (GG121, GG743 and GG120). This difference may reflect the relatively high calcium content of food and water from a chalk-based environment. It is possible that GG743 and GG121 had coastal origins; their $^{87}Sr/^{86}Sr$ values may have been modified by the presence of marine strontium. Alternatively, their relatively high strontium concentration values and that of GG120 may derive from different geological substrates.

3.2. Intra-tooth $\delta^{18}O$ and $\delta^{13}C$ profiles

Intra-tooth enamel carbonate $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ results for five Chillingham and eight Grimes Graves cattle are presented in Tables 3 and 4. Results for GG120, GG614 (M_2), GG743, GG839 and GGT10 have been published previously in a methods-related study (Towers et al., 2014). The data are also displayed in Figures 4 and 5 where $\delta^{18}O$ and $\delta^{13}C$ values are plotted versus distance from cervix. For each animal, data from the second and third molars are shown on the same plot such that the earliest forming enamel (second molar cuspal enamel) is at the left of the plot and the latest forming enamel (third molar cervical enamel) is at the right. Second molars begin to grow at the age of one month while third molars complete their growth at the age of 23-24 months (Brown et al., 1960). Thus, the x-axis, in terms of matrix progression, represents approximately the first two years of life. Each y-axis value ($\delta^{18}O$ or $\delta^{13}C$) is an average value representing ~6-7 months of mineralization occurring after initial matrix deposition (Balasse, 2002). Figure 5 also includes intra-tooth $^{87}Sr/^{86}Sr$ values obtained for the Grimes Graves cattle.

Table 3: Intra-tooth oxygen and carbon isotope ratios of enamel from Chillingham cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal, BM = buccal mesial. Wear stages after Grant (1982).

Sample no.	Distance from cervix (mm)	$\delta^{18}O_{VSMOW}$ normalised (‰)	$\delta^{13}C_{VPDB}$ normalised (‰)	Sample no.	Distance from cervix (mm)	$\delta^{18}O_{VSMOW}$ normalised (‰)	$\delta^{13}C_{VPDB}$ normalised (‰)
Third molars							
CHIL1 (M_3), BM, wear stage f				CHIL6 (M_3), LM, wear stage k			
cusp to cervix 45.5 mm				cusp to cervix 25.5 mm			
1	43.5	23.3	-15.1	1	23.5	23.4	-14.6
2	40.0	23.1	-15.3	2	21.0	23.9	-14.4
3	36.5	22.9	-15.5	3	18.5	24.1	-14.3
4	33.0	22.7	-15.5	4	16.0	24.2	-14.2
5	30.0	22.8	-15.4	5	13.5	23.9	-14.2
6	26.0	22.8	-15.2	6	11.0	24.0	-14.4
7	23.0	23.1	-15.2	7	8.5	23.4	-14.5
8	19.5	23.5	-15.2	8	6.0	23.2	-14.7
9	15.5	23.8	-15.0	9	3.5	22.7	-14.8
10	12.0	23.8	-15.1				
11	8.0	23.4	-14.9				
12	4.0	22.7	-15.0				

CHIL7 (M$_3$), BM, wear stage j
cusp to cervix 33.0 mm

1	31.5	23.6	-14.7
2	28.5	24.1	-14.5
3	25.5	24.4	-14.4
4	22.5	24.2	-14.2
5	20.0	23.9	-14.2
6	17.0	23.5	-14.3
7	14.0	23.2	-14.4
8	10.5	22.5	-14.4
9	7.0	22.1	-14.6
10	3.5	22.0	-14.7

CHIL10 (M$_3$), LM, wear stage j
cusp to cervix 30.5 mm

1	28.5	22.8	-15.2
2	26.0	22.8	-15.1
3	23.0	22.9	-15.1
4	20.0	23.0	-15.0
5	17.0	23.2	-14.9
6	14.0	23.5	-14.7
7	12.0	24.0	-14.6
8	9.5	24.5	-14.6
9	7.0	24.6	-14.5
10	4.5	24.7	-14.5
11	2.0	24.4	-14.4

CHIL14 (M$_3$), LM, wear stage h
cusp to cervix 43.0 mm

1	40.0	22.2	-14.8
2	36.0	21.9	-14.8
3	32.0	21.9	-14.7
4	28.5	21.7	-14.8
5	25.0	21.7	-14.8
6	21.0	21.9	-14.8
7	17.0	22.5	-14.8
8	12.5	23.4	-14.7
9	9.0	23.2	-14.5
10	5.0	23.6	-14.5
11	2.0	23.9	-14.7

Second molars

CHIL1 (M$_2$), BM, wear stage g
cusp to cervix 39.0 mm

1	37.0	23.1	-16.1
2	33.5	23.1	-16.0
3	30.5	23.3	-15.9
4	27.5	23.6	-15.6
5	24.0	23.9	-15.3
6	20.5	24.2	-15.1
7	16.5	24.4	-14.8
8	12.5	24.4	-14.8
9	9.0	24.0	-14.8
10	6.0	23.9	-14.8
11	3.0	23.5	-15.1

CHIL6 (M$_2$), LM, wear stage l
cusp to cervix 16.0 mm

1	15.0	24.2	-14.3
2	13.0	24.4	-14.3
3	10.5	24.2	-14.4
4	8.5	23.8	-14.3
5	6.0	23.8	-14.4
6	3.0	23.5	-14.7

CHIL7 (M$_2$), BM, wear stage k
cusp to cervix 27.5 mm

1	25.5	24.8	-14.9
2	22.0	24.2	-14.9
3	18.5	23.8	-14.9
4	15.0	23.5	-14.9
5	11.5	22.8	-14.9
6	8.5	22.7	-14.8
7	6.0	22.3	-14.9
8	3.0	22.4	-14.8

CHIL10 (M$_2$), LD, wear stage k
cusp to cervix 25.5 mm

1	24.0	22.0	-15.4
2	20.5	22.2	-15.3
3	15.0	22.8	-15.1
4	12.0	23.3	-14.9
5	9.0	23.5	-14.8
6	6.5	23.6	-14.6
7	3.5	24.1	-14.6

CHIL14 (M$_2$), LM, wear stage k
cusp to cervix 33.5 mm

1	30.0	22.1	-15.4
2	26.0	22.2	-15.2
3	22.5	22.7	-15.1

4	19.0	23.3	-15.1
5	15.5	23.5	-15.0
6	12.0	24.0	-15.1
7	9.0	24.2	-15.0
8	5.5	24.2	-14.8
9	2.0	23.9	-14.9

Table 4: Intra-tooth oxygen and carbon isotope ratios of enamel from Grimes Graves cattle mandibular molars. Sampled lobe: LM = lingual mesial. Wear stages after Grant (1982). Results for GG120, GG614 (M_2 only), GG743, GG839 and GGT10 have been published previously by Towers et al. (2014).

Sample no.	Distance from cervix (mm)	$\delta^{18}O_{VSMOW}$ normalised (‰)	$\delta^{13}C_{VPDB}$ normalised (‰)	Sample no.	Distance from cervix (mm)	$\delta^{18}O_{VSMOW}$ normalised (‰)	$\delta^{13}C_{VPDB}$ normalised (‰)
Third molars							
GG92 (M_3), LM, wear stage c				GG121 (M_3), LM, wear stage g			
cusp to cervix 52.0 mm				cusp to cervix 47.0 mm			
1	46.0	26.2	-11.6	1	36.5	23.4	-12.1
2	41.0	25.2	-11.5	2	33.0	23.5	-12.3
3	36.5	25.1	-11.6	3	29.5	23.1	-12.4
4	33.0	24.8	-11.7	4	26.0	23.5	-12.3
5	29.0	24.6	-11.7	5	22.0	24.1	-12.4
6	25.5	24.2	-11.6	6	18.0	25.1	-12.5
7	21.5	23.7	-11.8	7	14.5	25.5	-12.6
8	17.5	23.7	-12.0	8	10.5	25.9	-12.3
9	13.5	23.5	-12.2	9	6.5	25.7	-12.1
10	10.0	23.6	-12.3	10	3.0	25.4	-12.1
11	6.5	24.5	-12.3				
12	3.5	25.1	-12.3				
				GG681 (M_3), LM, wear stage g			
				cusp to cervix 42.5 mm			
1	45.0	25.4	-12.0	1	37.5	23.8	-12.4
2	41.0	24.4	-12.1	2	33.5	24.5	-12.3
3	36.0	24.2	-12.1	3	28.5	25.3	-12.0
4	31.5	24.1	-12.2	4	25.0	25.8	-11.8
5	27.0	23.9	-12.3	5	21.0	26.3	-11.7
6	23.0	24.0	-12.4	6	17.0	26.2	-11.7
7	18.0	25.0	-12.5	7	13.5	26.0	-11.9
8	14.0	25.5	-12.7	8	10.0	25.4	-12.0
9	8.5	26.5	-12.4	9	6.5	24.6	-12.3
				10	3.5	23.6	-12.9
GG743 (M_3), LM, wear stage e/f				GG839 (M_3), LM, wear stage d			
cusp to cervix 51.0 mm				cusp to cervix 49.5 mm			
1	46.0	23.9	-12.3	1	45.0	24.9	-13.0
2	41.5	24.1	-12.4	2	41.0	25.6	-12.7
3	37.5	23.4	-12.7	3	37.5	26.2	-12.4
4	33.5	23.3	-13.0	4	34.0	26.5	-12.1
5	29.5	23.5	-13.3	5	30.5	26.3	-11.6
6	26.5	23.9	-13.5	6	27.5	25.5	-11.6
7	19.0	24.7	-13.3	7	24.0	24.9	-11.6
8	15.5	25.1	-13.1	8	20.5	24.3	-11.6
9	12.0	25.3	-12.6	9	17.0	23.9	-11.6
10	8.0	25.3	-12.2	10	13.5	24.0	-11.6

11	4.0	25.1	-12.2

11	10.0	23.6	-11.8
12	6.5	23.2	-11.8
13	3.0	23.5	-11.8

GGT10 (M₃), LM, wear stage f
cusp to cervix 49.0 mm

1	42.0	24.9	-12.8
2	38.0	24.5	-12.8
3	34.0	24.0	-12.9
4	30.5	23.5	-13.0
5	26.5	23.4	-13.0
6	23.0	23.3	-12.8
7	20.0	23.3	-12.8
8	16.5	23.7	-12.6
9	13.0	24.8	-12.3
10	10.0	25.9	-11.8
11	6.5	26.9	-11.3
12	3.5	27.2	-11.3

Second molars

GG92 (M₂), LM, wear stage g
cusp to cervix 43.0 mm

1	35.5	23.7	-12.3
2	31.5	23.5	-12.3
3	27.5	23.6	-12.3
4	24.0	23.4	-12.2
5	20.0	23.5	-12.4
6	16.5	24.1	-12.3
7	13.0	24.8	-12.3
8	9.0	25.3	-12.2
9	5.5	25.7	-12.1
10	2.5	26.4	-12.1

GG120 (M₂), LM, wear stage a/b
cusp to cervix 50.0 mm

1	44.0	23.3	-14.2
2	40.0	23.4	-14.2
3	36.0	22.7	-14.3
4	32.5	22.8	-14.3
5	29.5	23.0	-14.4
6	26.0	23.1	-14.4
7	22.0	23.4	-14.3
8	18.0	23.9	-14.1
9	14.5	24.7	-13.8
10	10.5	24.6	-13.2
11	6.0	24.8	-12.9
12	3.0	24.9	-12.9

GG121 (M₂), LM, wear stage j
cusp to cervix 41.0 mm

1	31.5	24.8	-13.5
2	28.5	25.5	-13.3
3	25.5	26.0	-13.3
4	22.0	26.5	-13.0
5	18.0	26.5	-12.8
6	14.5	26.5	-12.5
7	11.0	26.1	-12.2
8	7.5	25.9	-12.0
9	3.5	25.2	-12.0

GG614 (M₂), LM, wear stage f
cusp to cervix 48.5 mm

1	42.5	24.0	-13.6
2	37.5	23.6	-13.6
3	33.0	23.7	-13.6
4	28.5	24.1	-13.4
5	23.5	25.0	-13.5
6	19.5	25.9	-13.2
7	15.5	26.7	-12.9
8	11.5	27.0	-12.7
9	7.0	26.4	-12.1
10	3.5	26.1	-12.0

GG681 (M₂), LM, wear stage j
cusp to cervix 31.5 mm

1	24.0	26.2	-12.7
2	21.0	26.2	-12.9
3	17.0	25.8	-12.6
4	10.0	25.4	-12.5
5	6.5	24.3	-12.4
6	3.5	23.5	-12.5

GG743 (M₂), LM, wear stage g
cusp to cervix 45.5 mm

1	38.5	23.8	-13.6
2	34.0	24.0	-13.3
3	30.0	24.5	-13.4
4	26.5	24.9	-13.1
5	23.0	25.5	-12.8
6	19.0	26.1	-12.4
7	15.5	25.7	-12.1
8	12.0	25.6	-11.8
9	8.5	25.2	-11.9
10	2.5	24.4	-12.2

GG839 (M$_2$), LM, wear stage g				GGT10 (M$_2$), LM, wear stage g			
cusp to cervix 44.5 mm				cusp to cervix 41.0 mm			
1	39.0	26.6	-13.7	1	35.0	24.0	-13.1
2	34.5	26.2	-13.6	2	31.0	23.7	-13.2
3	30.5	25.2	-13.7	3	26.5	23.8	-13.2
4	27.5	24.5	-13.5	4	22.5	24.2	-13.1
5	24.0	24.0	-13.6	5	19.0	24.8	-13.1
6	20.0	23.8	-13.6	6	15.5	25.6	-12.9
7	16.5	23.7	-13.6	7	12.5	26.3	-12.8
8	12.5	23.9	-13.7	8	8.5	26.5	-12.7
9	9.0	24.1	-13.7	9	5.0	26.2	-12.5
10	5.0	24.8	-13.5	10	2.0	25.7	-12.6
11	2.5	26.2	-13.2				

A common feature of the plots is the sinusoidal-like shape of the $\delta^{18}O$ profile for each animal, reflecting the seasonal variation of $\delta^{18}O$ of ingested drinking water. $\delta^{18}O$ values vary between 21.7 and 24.8 ‰ (mid-range = 23.2 ‰) for the Chillingham cattle and between 22.7 and 27.2 ‰ (mid-range = 24.9 ‰) for the Grimes Graves cattle. The difference in mid-range values may indicate slightly warmer climatic conditions on average for the Grimes Graves cattle during the Mid-Late Bronze Age compared to current conditions at Chillingham. $\delta^{13}C$ values vary between -16.1 and -14.2 ‰ (mid-range = -15.2 ‰) for the Chillingham cattle and between -14.4 and -11.3 ‰ (mid-range = -12.9 ‰) for the Grimes Graves cattle. The difference in mid-range value (2.3 ‰) may be largely explained by the fossil fuel effect. As a result of anthropogenic fossil fuel combustion and biomass destruction, the $\delta^{13}C$ value of atmospheric CO_2 has fallen since the Industrial Revolution (Friedli et al., 1986; Keeling et al., 1979). It was ~-8.4 ‰ during the period of enamel mineralization for the Chillingham cattle (Keeling et al., 2010), whereas the pre-industrial value was ~ 2.0 ‰ higher at ~-6.4 ‰ (Friedli et al., 1986).

In principal, it should be possible to estimate calving seasonality for the Grimes Graves cattle using first and second molar $\delta^{18}O$ and $\delta^{13}C$ profiles (Balasse et al., 2012; Towers et al., 2014). Knowledge of calving seasonality can potentially provide information regarding economic focus (fresh milk, storable milk products or meat) (Balasse et al., 2012; Gron et al., 2015; Towers et al., 2017). However, the Grimes Graves cattle molars were excavated from contexts spanning more than 500 years. In addition, strontium isotope ratio analysis suggests that the cattle originated from a variety of locations. Therefore, they were not born into a single herd and any estimate of calving seasonality cannot add further detail to Legge's (1981) suggestion of a dairying economy derived from the mortality profile.

3.3. Diet and environment

An interesting comparison may be made between the $\delta^{13}C$ values recorded in cattle enamel from Mid-Late Bronze Age Grimes Graves and Early Bronze Age Irthlingborough and Gayhurst (data from Towers et al., 2011). Figure 6 shows the third molar $\delta^{13}C$ profiles for all three sites together with those for Chillingham. Third molar results have been selected to ensure that $\delta^{13}C$ values are unaffected by suckling which may influence values recorded in enamel forming at an early age (Towers et al., 2017). The mid-range value for the Chillingham profiles when corrected for the fossil fuel effect (-12.8 ‰) is similar to that for the Grimes Graves cattle (-12.4 ‰). Despite the possibility

of slightly warmer conditions at Grimes Graves as suggested by the δ^{18}O profiles, differences in climate and elevation (~150 m) between the two sites are not expected to produce significantly different vegetation δ^{13}C values for similar growing conditions (Heaton 1999). Thus, it may be speculated that the grazing and fodder growing environments for the Grimes Graves and Chillingham cattle were reasonably similar in terms of environmental factors affecting vegetation δ^{13}C values such as tree cover and water availability. There are wooded areas within Chillingham Park but vegetation from those areas does not form a significant proportion of the animals' diet (Leyland, pers. comm.). In addition, vegetation preferences of the Chillingham cattle were studied by Hall (1988) who determined that the cattle showed a preference for lowland "good grassland" (39.8 Ha, of which 10 % was described as "wet") whereas "second-rate grassland" and "upland grassland" (41.9 Ha combined, of which 59 % was described as "damp" or "flushed") was less attractive to the animals although they did not discriminate strongly against those areas. If any of the Grimes Graves cattle spent a significant amount of time during their second year of life grazing in dense woodland or very wet environments, it is likely that their third molar δ^{13}C values would have been lower than those of the Chillingham cattle.

Third molar mid-range values for the Irthlingborough and Gayhurst δ^{13}C profiles are -14.3 ‰ and -14.1 ‰ respectively, and there is little overlap between the Early and Mid-Late Bronze Age profiles (Figure 6). These lower values may indicate grazing under forest cover and/or the consumption of leafy fodder brought to the animals from the forest, as suggested by Balasse et al. (2012) for cattle from Neolithic Bercy, Paris. They may also indicate grazing in more waterlogged conditions. It is possible that the δ^{13}C values for Irthlingborough, Gayhurst and Grimes Graves reflect a temporal trend observed in several bone collagen studies. The δ^{13}C value of collagen is also determined by diet, although it primarily reflects the value of dietary protein in contrast to the bioapatite value which is strongly correlated with the value of the whole diet (Ambrose and Norr, 1993; Jim et al., 2004). The mean δ^{13}C value for Late Neolithic human bone collagen from the Thames Valley archaeological site at Eton College Rowing Course, Dorney, Buckinghamshire (-21.1 ‰ , n = 6) was found to be lower than equivalent values for Late Bronze Age (-20.3 ‰ , n = 6) and Iron Age (-20.0 ‰ , n = 5) individuals from the same site (Stevens et al., 2012). Similarly, in the more extensive multi-site Beaker People Project, the mean δ^{13}C bone collagen value for Beaker humans from England and eastern Scotland (-21.2 ‰ , n = 158) was found to be 0.6 ‰ lower than the mean value for Middle Iron Age humans from a comparable geographical spread (-20.6 ‰ , n = 164) (Jay and Richards, 2006, 2007; Jay et al., 2012). A mixture of published and unpublished data for domestic herbivores also shows the same trend, and a change in husbandry and/or foddering possibly combined with deforestation has been tentatively suggested as the cause rather than climate change (Jay et al., 2012).

3.4. Cattle mobility

Before attempting to interpret the Grimes Graves isotopic profiles (Figure 5) in terms of mobility, it may be constructive to analyse the Chillingham profiles obtained from animals restricted to a 130 ha enclosure (Figure 4). Unfortunately, the Chillingham cattle are not an ideal control group because: 1) they died of natural causes and most of the mandibles collected for this study comprise very worn molars from old animals which produce shorter isotopic profiles; and 2) they were given hay during winter in varying amounts and from varying external sources depending on the year.

A visual comparison between the enamel $\delta^{13}C$ and $\delta^{18}O$ profiles of animal CHIL1 shows that they co-vary, suggesting that the $\delta^{13}C$ profile is seasonally influenced. Similar correlations between the $\delta^{13}C$ and $\delta^{18}O$ profiles of CHIL6, CHIL10 and the third molar of CHIL7 are also apparent. In a previous study, co-varying $\delta^{13}C$ and $\delta^{18}O$ profiles, albeit with a temporal shift of ~2-3 months between the two, were obtained from the molar enamel of sheep from Rousay, Orkney, and were interpreted as reflecting the seasonal variation of the pasture $\delta^{13}C$ value (Balasse et al., 2009). Thus, it is possible that the aforementioned Chillingham $\delta^{13}C$ profiles are reflecting the $\delta^{13}C$ values of Chillingham Park vegetation, shown to be seasonally variable with higher values in summer (August 2010, mean = -29.8 ‰, n = 28) and lower values in winter (February 2011, mean = -30.6 ‰, n = 28) (Towers, 2013). In addition, observations by Hall (1988) showed a preference by the Chillingham cattle during the summer months for "good grassland" which tends to be drier than the alternative grazing areas of "second-rate grassland" and "upland grassland". Thus, the seasonally varying $\delta^{13}C$ profiles recorded in the Chillingham enamel may also have been influenced by a seasonally varying pattern of grazing. Interpretation is complicated by the provision of hay in winter. If the hay $\delta^{13}C$ value was higher than the mean $\delta^{13}C$ winter value of the Chillingham Park vegetation, then hay consumption would reduce the amplitude of the enamel $\delta^{13}C$ profiles. It is possible that the unvarying $\delta^{13}C$ profiles of CHIL14 and the second molar of CHIL7 are examples in which hay consumption reduced the amplitude to zero. Alternatively, they may represent years when mean $\delta^{13}C$ values of vegetation varied very little or reflect feeding behaviour where the sequence of vegetation types and feeding locations throughout the year did not produce a seasonal pattern.

Milk consumption may also influence the $\delta^{13}C$ profiles recorded in enamel formed during the first months of life. The Chillingham cattle wean their calves naturally and, in general, the amount of milk consumed by a calf will gradually decrease as time passes. In practice, the calf's access to milk is determined by its mother: some cows terminate suckling after a few months, others after a much longer period, perhaps nine months or a year (Leyland, pers. comm.). Suckling from a teat will stimulate a reflex action that channels milk into the abomasum for digestion similar to that of a non-ruminant (McDonald et al., 1988). As the proportion of milk in the diet gradually decreases and the proportion of vegetation increases, the carbon incorporated into enamel carbonate is expected to become progressively more enriched in ^{13}C due to an increasing contribution of ^{13}C-enriched CO_2 in the bloodstream from methanogenetic fermentation in the rumen (Towers et al., 2017). Thus, for the Chillingham cattle, a gradual transition from a milk-rich diet to a vegetation-only diet is predicted to produce a rise in the $\delta^{13}C$ profile recorded in earliest forming second molar enamel. This is possibly what is observed in the second molar profile of CHIL1 (Figure 4), the least worn of the Chillingham second molars, where the profile rises from a value of -16.1 ‰, which is ≥ 0.7 ‰ lower than any of the other second molar cuspal values for Chillingham.

Turning to the Grimes Graves $\delta^{13}C$ data in Figure 5, several of the profiles display noticeable shifts in $\delta^{13}C$. The largest shift, for GG839, is 2.1 ‰ which is larger than any observed in the Chillingham profiles, although consumption of hay in winter may have modified the latter. The plot shows a slope that is similar in shape to $\delta^{13}C$ patterning observed in a study by Balasse (2002), in which the diet of five cattle was abruptly changed from a C_3-based diet to a C_4-based diet at the age of 9-10 months: the resulting enamel $\delta^{13}C$ profiles show a linear, rising slope with evidence for dietary change being first recorded in enamel that started to mineralize ~6-7 months previously. Figure 7 shows the $\delta^{13}C$ profile for GG839 in which the $\delta^{13}C$ values are plotted against time of initial enamel matrix formation relative to birth. Conversion from distance from cervix to time is described in detail

elsewhere (Towers, 2013; Towers et al., 2014). If the plot does reflect an abrupt change between two distinct diets, then it is predicted to have occurred when the animal was approximately 16 months old (from that age the enamel only comprises mineral incorporated after the dietary change). As for the plots obtained by Balasse (2002), the second diet is first detected in enamel starting to form approximately six months earlier. The time of year at which the change of diet occurred may be predicted from season of birth analysis described by Towers et al. (2014) suggesting that GG839 was born during late winter. This would imply that dietary change occurred in early summer, approximately 16 months later. However, this prediction should be treated with caution because the season of birth estimate relies on a single modern control animal with a known date of birth but access to a variety of water sources throughout its life (Towers et al., 2014).

It is possible that dietary change was brought about by movement between different habitats. $^{87}Sr/^{86}Sr$ measurements for GG839 (Figure 5) indicate that this animal may have remained in the vicinity of Grimes Graves all its life. In that case, the low and high $\delta^{13}C$ levels may reflect local differences in environmental factors such as water availability or tree cover. Perhaps the $\delta^{13}C$ profile is due to movement between the wet valley and dry valley/upland environments described by Legge (1981). Like Grimes Graves, Danebury Iron Age hillfort and several neighbouring Iron Age sites are situated in an area of chalk geology. Bone collagen $\delta^{13}C$ data for domestic cattle from these sites show a high level of intra-population variability (cattle from five sites in the Danebury Environs: n = 148, $\delta^{13}C$ range = 2.2 ‰), which has been interpreted as reflecting the local diversity of ecological feeding zones such as wet valley, dry valley and upland pasture environments (Stevens et al., 2013).

The $\delta^{13}C$ profile of GGT10 also shows a pronounced shift in $\delta^{13}C$ (1.7 ‰) in the cervical half of its third molar enamel (Figure 5). For this animal, a dietary change brought about by movement is likely since the shift in $\delta^{13}C$ corresponds to a shift in $^{87}Sr/^{86}Sr$, suggesting relocation to a chalk-based terrain, possibly moving to Grimes Graves itself. For GG743, the $\delta^{13}C$ profile shows oscillatory patterning, which may indicate seasonal movement between habitat types. Movement between geological regions was certainly involved according to $^{87}Sr/^{86}Sr$ measurements, although such movement may have occurred only once within the time frame of enamel formation. Possible incorporation into this animal's tooth enamel of recycled strontium from bone may mean that the cuspal third molar $^{87}Sr/^{86}Sr$ value is lower than expected due to the influence of strontium originally ingested at its place of birth (Montgomery et al., 2010), in which case the cuspal, mid-lobe and cervical third molar values may represent the same location.

The $\delta^{13}C$ profiles of GG120, GG121 and GG614 also show noticeable shifts in $\delta^{13}C$ (Figure 5). For these animals, the $\delta^{13}C$ shifts are recorded entirely within their second molar enamel. If we are again observing abrupt dietary change, then it appears to have occurred before the age of one year, a younger age than that estimated for GG839 (~16 months). The $^{87}Sr/^{86}Sr$ values before and after these shifts in $\delta^{13}C$ differ by < 0.0004 (cf. the range of 0.00062 for the modern Chillingham cattle) suggesting that if movement was involved, it may have been local between different habitats, as proposed for GG839. Third molar $^{87}Sr/^{86}Sr$ measurements for GG614 indicate relocation to a more radiogenic geological region by the end of its second year, while those for GG121 may represent movement to Grimes Graves (although we cannot rule out the possibility that it remained close to its birthplace since the difference in $^{87}Sr/^{86}Sr$ value is only 0.0005).

For any of the Grimes Graves cattle showing pronounced shifts in $\delta^{13}C$ that do not correspond to significant shifts in $^{87}Sr/^{86}Sr$, there are alternative interpretations that are not based upon

movement: a switch between fodder and grazing or vice versa (although this could involve movement); the seasonal variation in vegetation δ¹³C values in one location; and, in earliest forming second molar enamel, the possible influence of the transition from a milk-rich diet to a vegetation-only diet (cf. the second molar δ¹³C profiles of GG121 in Figure 5 and CHIL1 in Figure 4).

Although the Grimes Graves δ¹³C profiles, with their pronounced shifts in δ¹³C, differ in form from equivalent profiles obtained for Early Bronze Age Irthlingborough and Gayhurst (Towers et al., 2011) and Iron Age and Viking Age Orkney (Mainland et al., 2016; Towers et al., 2017), it is not known whether they are typical for Mid-Late Bronze Age cattle from central Britain due to a lack of comparative data. The diversity of their enamel ⁸⁷Sr/⁸⁶Sr values together with the similarities between their δ¹³C profiles may indicate possible widespread adoption of certain common cattle husbandry and landscape management practices during the Mid-Late Bronze Age. Additional radiocarbon dates would allow a more nuanced interpretation of herd management since the cattle analysed in this study derive from contexts spanning several centuries and their origins and management may have varied within this time period.

4. Conclusions

Strontium isotope ratio analysis of cattle molar enamel indicates diverse origins for the ten Grimes Graves cattle included in this study. The range of ⁸⁷Sr/⁸⁶Sr measurements contrasts with a narrow range of 0.00062 obtained for eight modern cattle that spent their lives within Chillingham Park, Northumberland. Results suggest that at least five of the Grimes Graves cattle were not born locally to Grimes Graves; two of these animals are likely to have originated ≥ 150 km from Grimes Graves. Their presence at Grimes Graves suggests that long-distance cattle trading networks from western to eastern Britain were in operation during the Mid-Late Bronze Age, as they had been during the Early Bronze Age according to ⁸⁷Sr/⁸⁶Sr data from Irthlingborough and Gayhurst (Towers et al., 2010). One implication is that prehistoric people recognized the importance of fresh bloodlines to their livestock. Alternatively, cattle may have been used as pack animals for transport, and the diverse origin of the Grimes Graves cattle is a reflection of human mobility during the mid-late Bronze Age.

δ¹³C profiles recorded in third molar enamel from eight of the Grimes Graves cattle show higher δ¹³C values compared to those of Irthlingborough and Gayhurst cattle (Towers et al., 2011) suggesting a change in husbandry and/or foddering between the Early and Mid-Late Bronze Age, possibly combined with deforestation (Jay et al., 2012). Pronounced shifts in δ¹³C are a feature of most of the Grimes Graves δ¹³C profiles. One interpretation is that the cattle were subject to dietary change resulting from movement between habitats with different vegetation δ¹³C values influenced by environmental factors such as water availability or tree cover. However, alternative interpretations such as dietary change between fodder and grazing or the seasonal variation of vegetation δ¹³C values cannot be ruled out. A multi-isotope approach has allowed us to speculate that certain cattle husbandry and perhaps landscape management practices may have been widely adopted throughout central Britain during the Mid-Late Bronze Age. Much more comparative data, both archaeological and modern, and additional radiocarbon dates would be required to improve our interpretation of this dataset.

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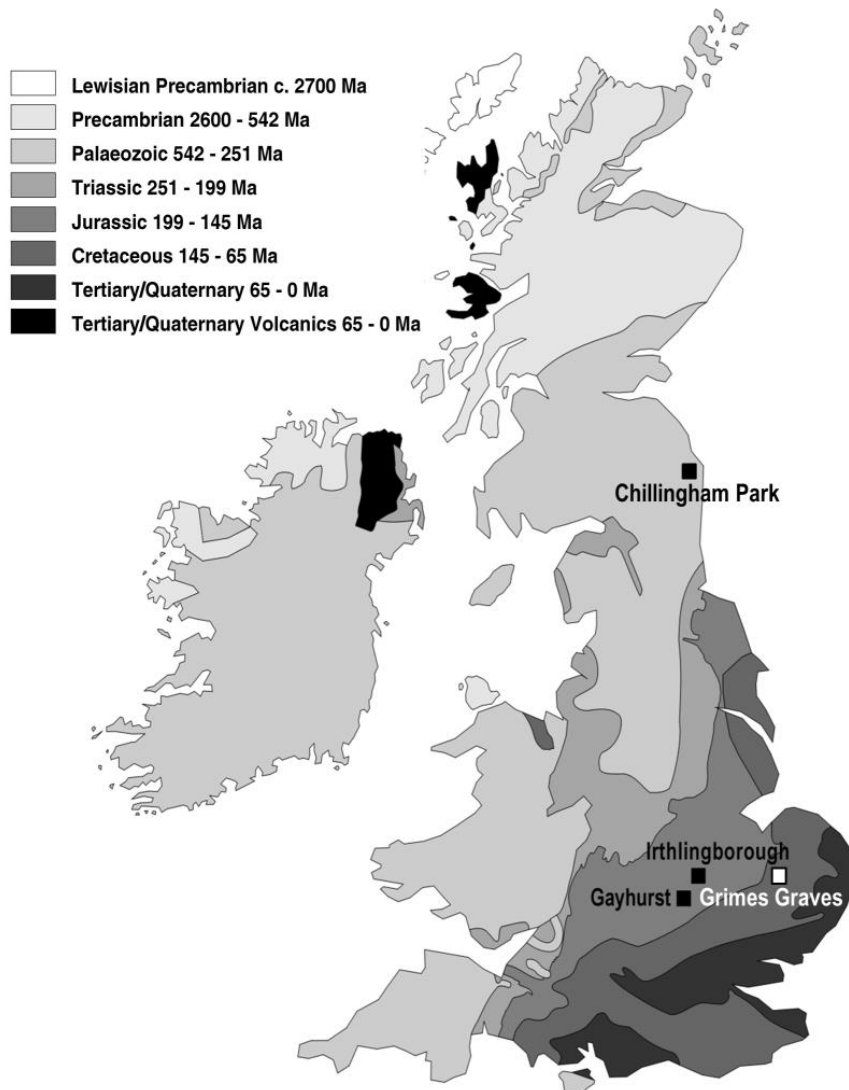
Figure 1: Simplified geology map of the British Isles showing the locations of Grimes Graves and Chillingham Park. Also shown are the locations of the Early Bronze Age sites of Irthlingborough and Gayhurst.
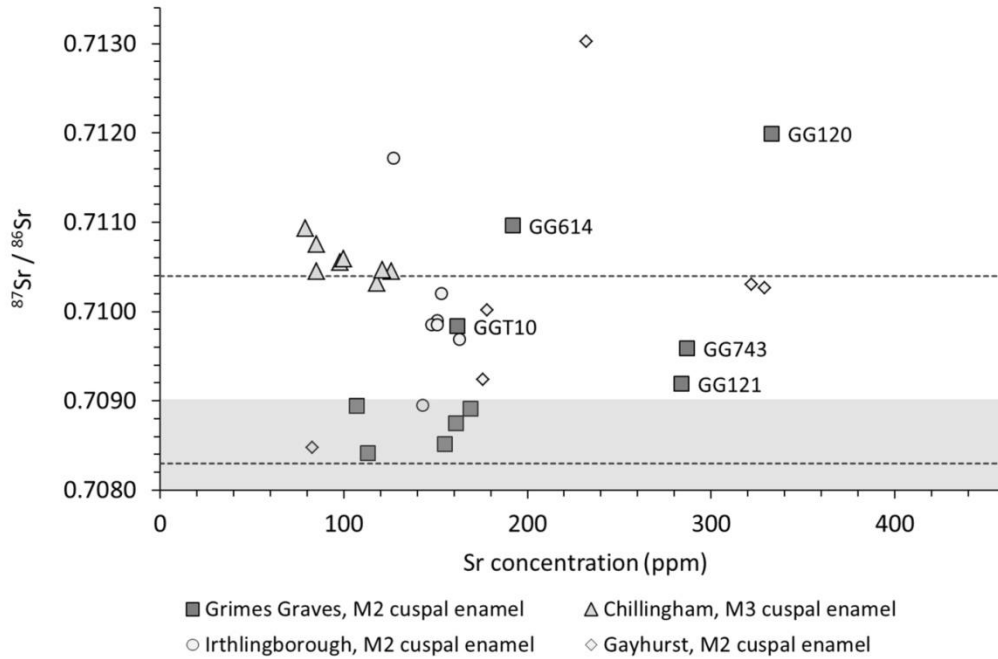
Figure 2: $^{87}Sr/^{86}Sr$ versus strontium concentration for Mid-Late Bronze Age Grimes Graves and modern Chillingham cattle molar enamel samples. The 2σ error for $^{87}Sr/^{86}Sr$ is contained within the symbols. The 2σ error for strontium concentration is estimated to be ± 10 %. The suggested biosphere range for chalk, estimated from plant data (n = 9) (Evans et al., 2010), is represented by a grey band between $^{87}Sr/^{86}Sr$ = 0.7080 and $^{87}Sr/^{86}Sr$ = 0.7090, while the suggested lower and upper values for a region of Jurassic geology are represented by the dashed lines at $^{87}Sr/^{86}Sr$ = 0.7083 and $^{87}Sr/^{86}Sr$ = 0.7104, based on plant data (n = 12) from Evans and Tatham (2004). Early Bronze Age Irthlingborough and Gayhurst data are taken from Towers et al. (2010).
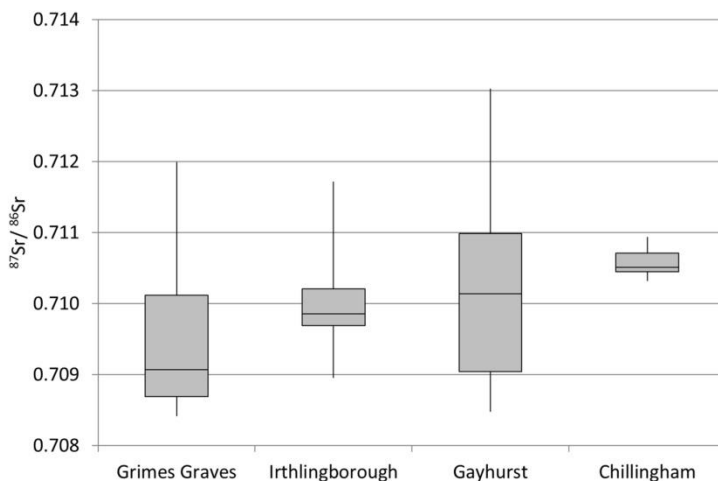
Figure 3: Simple box plot of the $^{87}Sr/^{86}Sr$ datasets. The ends of the whiskers represent minimum and maximum values. $q_L = x_{(¼(n+1))}$ and $q_U = x_{(¾(n+1))}$.
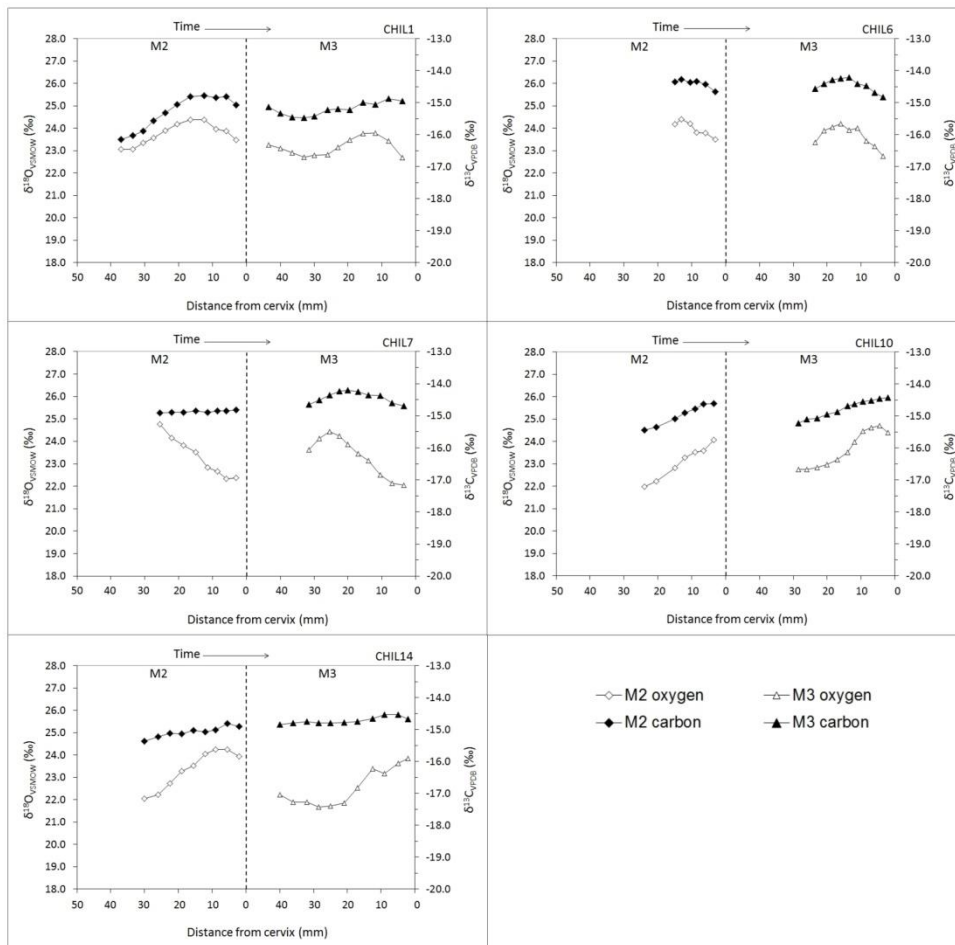
Figure 4: Combined δ¹⁸O and δ¹³C plots for second and third cattle molar enamel from five Chillingham cattle. Analytical error is ± 0.1 ‰ for δ¹³C$_{VPDB}$ and ± 0.2 ‰ for δ¹⁸O$_{VSMOW}$.
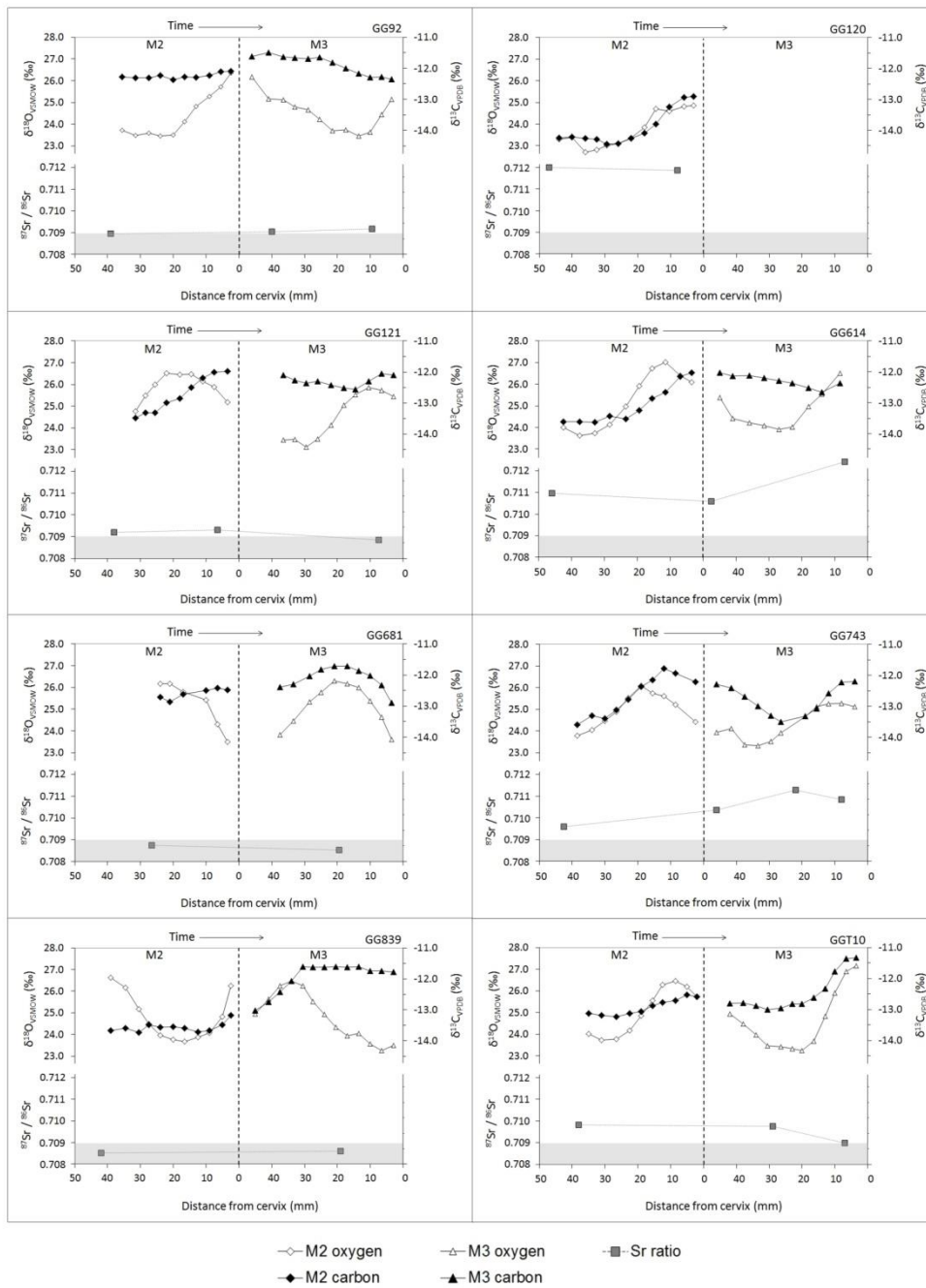
Figure 5: Combined δ^{18}O, δ^{13}C and ^{87}Sr/^{86}Sr plots for second and third cattle molar enamel from eight Grimes Graves cattle. Analytical error is ± 0.1 ‰ for δ^{13}C$_{VPDB}$ and ± 0.2 ‰ for δ^{18}O$_{VSMOW}$. The 2σ error for ^{87}Sr/^{86}Sr is contained within the symbols. The proposed biosphere range for chalk is indicated by the pale grey band between ^{87}Sr/^{86}Sr = 0.708 and ^{87}Sr/^{86}Sr = 0.709.
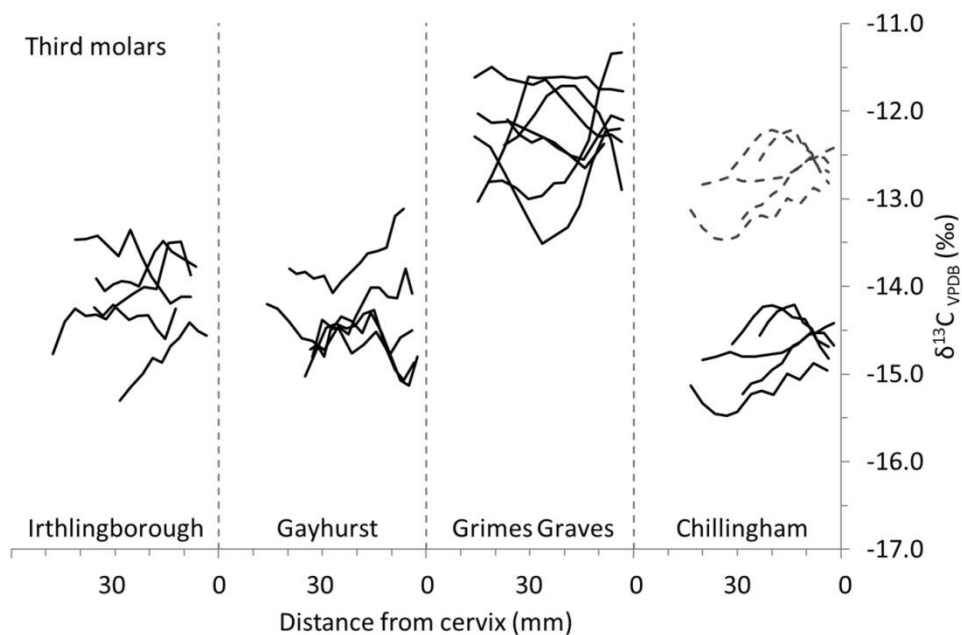
Figure 6: Third molar enamel $\delta^{13}C$ profiles for cattle from Irthlingborough (Early Bronze Age, n = 5), Gayhurst (Early Bronze Age, n = 5), Grimes Graves (Mid-Late BA, n = 7) and Chillingham (modern, n = 5). The $\delta^{13}C$ profiles for the Chillingham cattle are also shown corrected for the fossil fuel effect (dashed lines) assuming a correction of +2 ‰ (Friedli et al., 1986; Keeling et al., 2010). Irthlingborough and Gayhurst data are from Towers et al. (2011).
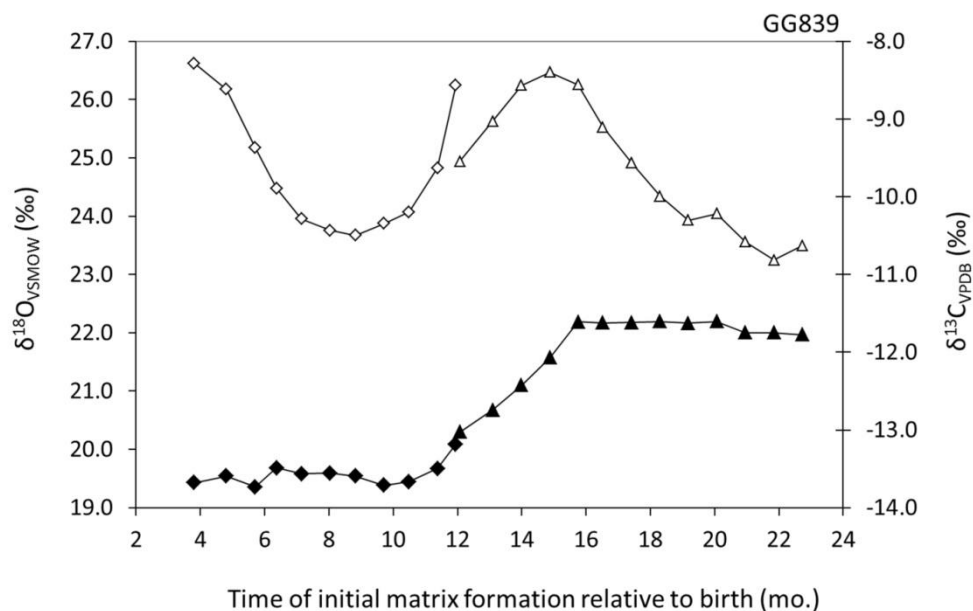

Figure 7: $\delta^{18}O$ and $\delta^{13}C$ profiles for animal GG839. $\delta^{18}O$ and $\delta^{13}C$ are plotted versus time of initial enamel matrix formation.