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Toiling with teeth: an integrated dental analysis of sheep and cattle dentition in Iron Age and Viking-Late Norse Orkney

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Keywords

Palaeodiet Dental Microwear Stable Isotopes Dental pathologies Atlantic Iron Age Norse Orkney

Abstract

A key goal for archaeozoology is to define and characterise pastoral farming strategies. In the last decade, some of the most innovative approaches for addressing these questions have centered on the mammalian dentition, including *inter alia* sequential sampling of stable isotopes, dental microwear analysis and the study of dental pathologies. It is when these techniques are integrated and combined with more traditional approaches, such as tooth eruption and wear, however, that their full potential is realised. In this article we demonstrate how such an integrated dental analysis combining isotopes, microwear, dental development, dental pathologies, tooth eruption and wear can be used to elucidate changing pastoral practices and their impacts on the landscape from the Iron Age and Viking-Late Norse periods in the North Atlantic islands, a period of significant socio-economic and cultural change in this region. Analysis focuses on two case study sites, Mine Howe, dating to the Atlantic Middle Iron Age (MIA) and the Earls' Bu, one of the residences of the Orkney Earl's from the 10th to 13/14th centuries AD. Each of the techniques applied to the sheep/goat and cattle dentition identifies clear differences between the two sites, in diet, in culling season, herd health and stress levels, all of which point to potential differences in underlying husbandry practices. These are related to wider socio-economic developments in Orkney at these periods, specifically increasing control of pastoral resources and economic production by North Atlantic elites in the MIA and the emergence of manorial estates in Late Norse/Early Medieval Scandinavia.

1. Introduction

In 1986, Chang and Koster argued that faunal analysis will only allow a partial understanding of pastoralism and urged archaeologists to look 'beyond bones' to find physical traces of animals and their herders within the landscape. In the intervening decades, landscape-based approaches have provided diverse insights into the interaction between herds, herders and the wider environment surrounding archaeological sites. Nevertheless, these approaches remain limited by one fundamental issue, that of attribution. The study of shieling structures (Lucas 2008; Vickers and Sveinbjarnardóttir 2013), field boundaries (Madsen 2012; Yates 2007), sediments or palaeoecological biota associated with livestock (Ledger et al. 2013; Simpson et al. 2004; Shahack-Gross 2011) enable the presence of herds to be detected in the landscape: it is, however often difficult to relate such sources of evidence to specific herd species, to particular age and sex groups or, for grazing areas and shielings, etc., to identify the duration (eg all year vs. occasional) and timing (i.e. seasonality) of use. In the last decade some of the most innovative approaches for addressing these questions have started to look again ***within*** animal bone assemblages, with a particular emphasis on the impact of 'lifestyle' or husbandry practice on ungulate dentition (Mainland 2008). Techniques such as stable isotope and dental microwear analysis are now beginning to provide detailed insights into diverse aspects of prehistoric herding: the scale and intensity of pastoralism (Mainland 2006; Henton 2012; et al. 2014); strategies for grazing management (McGovern et al. 2010; Muldner et al. 2014; Britton et al. 2008; Ascough et al. 2014), for foddering (Vanpouke et al. 2009; Wilkie et al. 2007; Balasse et al. 2012); the movement and the impact of herds and herders across the landscape (Henton et al. 2010; Chase et al. 2014; Buxon and Simonetti 2013). Yet, with some notable exceptions (Henton 2012; Henton et al. 2014), relatively few studies have gone on to explore the combined potential of these methodologies for understanding herding systems in the past. Moreover, there is often an emphasis on dietary reconstruction and the potential of other aspects of the dentition, e.g., tooth eruption/wear (Jones 2006) , dental pathologies (Davies 2005; Upex and Dobney 2012) or dental development (Davis 2011), as ancillary sources of evidence on herding practice in such palaeodietary analyses has been less well addressed.

In this article, we aim to demonstrate the potential for the study of pastoral and mixed-farming societies of an integrated dental analysis which brings together a range of techniques using as a case study two archaeological sites from Scotland, Mine Howe and the Earls' Bu. These date to the Atlantic Iron Age and Viking-Late Norse periods, respectively and are both located on the Mainland of Orkney, one of the Northern Isles of Scotland. Analysis has two broad objectives: to explore what can be inferred about livestock husbandry practices in the later prehistory of Orkney from an integrated dental analysis of sheep and cattle dentition at these two sites; and, what wider inferences can be made about the nature of Iron age and Viking/Late Norse society and in particular the role of feasting therein from the evidence of livestock husbandry practices?

2. Archaeological background

Mine Howe, dating to the Atlantic Middle Iron Age (c. 3rd century BC to 5th century AD) is a non-domestic, non-residential, site with evidence of ritual activity, structured deposition, fine 'prestige' metalworking and feasting debris (Card et al. 2006). The latter comprises large dumps of animal bone and ceramics found mainly in the upper levels of the partially excavated monumental ditch which surrounds a subterranean stone –built chamber. Currently unique within the context of the Scottish Iron age, Mine Howe has been interpreted as a site of communal gathering and feasting. Atlantic Scotland at this time, saw the emergence of local elites, who exerted increasing control over agricultural resources, prestige goods and traded items (Dockrill and Bond 2014; Parker Pearson et al. 1996); feasting is likely to have played a significant role in forming and maintaining these elites (Dockrill and Bond 2014; Parker Pearson et al. 1996; Mulville et al. 1999), as has been argued for other Iron age societies in Britain (Ralph 2007). The Mine Howe mammal bone assemblage (n=41,000 fragments) is one of the largest dating to the MIA in Atlantic Scotland (Card and Downes forthcoming). It is dominated by the domesticates cattle, sheep and pig, in that order, but with a greater emphasis on cattle than is evident elsewhere in the Atlantic Iron Age (Mainland et al. in press; Bond 2007; Smith 1994; Mulville 1999).

In the Northern and Western Isles of Scotland, the Iron Age was brought to an end by a period of major social and cultural change: the Viking expansion, which from c. 800AD onwards saw the colonization of these islands by settlers largely from Norway, impacting society at all levels from material culture, to settlement organization and genetics (Barrett 2012; Crawford 2013, Chpt. 3). The Northern Isles became the centre for the powerful Early Medieval Earldom of Orkney which had influence and connections across the Scandinavian world. The Earl's Bu, sited in Orphir on the Mainland of Orkney, is known historically to be one of the residences of the Orkney Earls and would have functioned as a meeting place and feasting hall for successive Earls and their retainers, as well as an estate or manorial farm (Crawford 2013, Chpt 4.6; Taylor 1938, Chap LXVI; Batey 1993; Mainland et al. 2015). Excavations at the Earl's Bu recovered rich middens comprising c. 90, 000 fragments of mammal bone dating from the late 800s – mid 1100s AD underneath and overlying a horizontal mill (Batey 2003). Cattle is the most frequently occurring species which, as is typical for assemblages of this period, is dominated by livestock species (Mainland 1995; Bond 2007; McGovern et al. 2010).

3. Methodology

A total of 264 cattle and 159 mandibles of sheep/goat were available for study at Mine Howe and a further 37 cattle and 53 sheep/goat mandibles from the Earl's Bu. Culling strategies and the underlying goals of herding economies at the two sites were assessed through analyses of tooth eruption and wear. Sequential sampling of stable isotopes and dental microwear analysis provided the nutritional background while an analysis of developmental enamel defects in lambs and tooth development in foetal/neonatal calves enabled insight into herd health and other environmental stresses. Analysis also drew on previously published research undertaken on oxygen and carbon stable isotopes in the Earl's Bu and Mine Howe sheep/goat populations (Balasse et al. 2009). The sample sizes selected for each analytical approach are summarised in Tables 1-2 which also detail stratigraphic and dating pertinent to the samples considered. Although human activity at Mine Howe spans over 500 years, where possible, samples for palaeodietary analysis were selected from the likely contemporaneous large bone deposits in the upper phases of the enclosure ditch representing c. 300 years (AD50-350). At Earls Bu sampling was largely concentrated in the Late Norse middens (ie c. AD1050-1300).

3.1 Age and season-of-death

Tooth eruption and wear at Mine Howe and Earl's Bu was recorded and analyzed using Payne (1973) for sheep and Halstead (1985) for cattle using all available mandibles. For mandibles with incomplete molar rows, Payne's (1973) system of proportional allocation was adopted, which results in age classes being represented by fractions of individuals. Jones (2006) eruption wear categories for juvenile sheep which enable age assessment in c. 6 monthly stages up until c. 25 months was employed to assess season-of-death . A birthing season in late April/May is assumed. This is the optimal period for sheep herders in the Northern Isles, both historically and currently, as it co-incides with the spring vegetation growth (Mainland per comm.; Fenton 1978). Jones and Sadler's (2012) system for assigning cattle season-of-birth could not be applied here due to the possibility of multiple birthing seasons for this species (Towers 2013; Towers et al. in press).

3.2 Diet

3.2.1 Sequential sampling of oxygen and carbon stable isotopes in cattle teeth

For oxygen and carbon isotope ratio analysis, enamel samples were prepared and analysed at the Stable Light Isotope Facility at the University of Bradford. Intra-tooth powdered enamel samples were collected from the lingual lobes of 11 third molars, eight second molars and seven first molars from 12 Mine Howe cattle of the Mid Iron Age (Phases D9, D10 and D11; c. 75 AD – c. 380AD) and of nine third and three second molars from nine Earl's Bu cattle of the Viking to Late Norse periods. Details of sample preparation, involving treatment with NaOCl solution and acetic acid, are summarised in Towers et al (2011). Prepared sample were weighed into septa-capped vials which were loaded into a Finnigan Gasbench II, an 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, released through the reaction between the acid and the carbonate fraction of enamel, was analysed by the mass spectrometer. Included in each batch of enamel samples were several samples of each of two different internal laboratory standards (Merck Suprapur $CaCO_3$ and OES1) and one international laboratory standard (NBS-19). The resulting $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ measurements obtained for the enamel samples 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. These values were determined for an internal standard consisting of homogenised, enamel powder, one or two samples of which were included in most sample batches.

3.2.2 Dental microwear in sheep

A total of 29 mandibles was examined for microwear, 14 from Earl's Bu and 15 from Mine Howe with a representative spread of ages sampled from each site (Earls' Bu: Payne (1973) stage B - n=1, D - n=6, E- n=5, F- n=1); Mine Howe, C - n=6, D n=4, F – n=1, G – n=4). Season-of-death could be assigned for 4 of the Earl's Bu mandibles with 1 dying in the first summer of life (EB7) and three in winter as yearlings (EB32, EB10, EB7). At Mine Howe, seasonality could only be assessed for three of the mandibles sampled for microwear, with one culled during the sheep's first summer (MH75), one in the first winter (MH161) and one as a winter yearling (MH58).

All available dP4 and M1 were replicated and analysed for microwear patterning following the methodology outlined in McGovern et al. (2010) and Mainland (2006), giving sample sizes of for Earl's Bu and Mine Howe, respectively, 13 (M1 = 8; dP4 =5) and 16 (M1=9; dP4 = 7). Only one individual was represented by both M1 and dP4 (MH 7). Combining the dP4 and M1 in this way enables a broader spread of ages to be examined than by focusing on a single tooth (McGovern et al. 2010). As defect size and frequency varies along the molar row, separate analyses were undertaken for each tooth.

In the dP4, identification of dietary signatures was achieved statistically using the discriminant analysis model for caprines outlined in Mainland (2006) which distinguishes between modern grazing caprines on high and low abrasive diets (reflecting pasture type and stocking density) and between grazing sheep and those housed and fed on soft-textured diets (Mainland 2003; 2006; Mainland and Halstead 2005). DA is a multivariate statistical technique which can be used both to evaluate the ability of a set of variables (here microwear statistics such as feature size and frequency) to distinguish between known groups (here the modern diets) and then to classify cases of unknown origin (here archaeological mandibles) according to the model derived. The first axis (61% of between group variability), separates soft-textured fodders (leafy-hay/milled cereals) from grazing individuals and can be attributed to five microwear variables: length of rounded pits, length of narrow striations, breadth of narrow striations, defect frequency and length of ovoid pits (Mainland 2006) (Fig. 2). The second axis separates the low abrasive grazers and leafy-hay/milled cereal-fed individuals from the high abrasive grazers on the basis of two variables: the ratio of pits to striations and the relative frequency of rounded pits.

Analysis of microwear trends in the M1 considered variability in the size, relative and absolute frequencies of pits and striations, where pits are defined as features with a length to breadth ratio of less than 4:1 and striations, greater than 4:1. The ratio of pits to striations is the basis axis of variation within ungulate microwear providing insight into relative frequencies of browse and graze species in the diet, consumption of exogenous abrasives and stocking densities (Solounias and Semprebon 2003; Henton 2012; Mainland 2006; McGovern et al. 2010).

3.3 Animal health and environmental stress

3.3.1 Developmental defects in sheep enamel

6 sheep mandibles from Earl's Bu and 8 from Mine Howe were assessed for the presence of developmental enamel defects using a combination of histological and macroscopic approaches. Developmental enamel defects are systematic disturbances of the hard tissue secretion and mineralization process (Clarkson 1989) that cause defective enamel formation (Miles and Grigson 1990; 437) reflecting environmental and other stress events during dental development (ie. in the early life of animal), including weaning, nutritional stress and parasitism. These range in severity from enamel hypoplasia, visible as pits and grooves in the surface of the tooth surface, to accentuated striae of Retzius (incremental enamel growth bands), visible in longitudinal section as broad darkened bands running perpendicular to enamel prisms from the dentine enamel junction (DEJ) and found alone or in association with hypoplastic lesions (Goodman et al. 1984).

Sampling was focused on developmental defects occurring during the first 6 months of life, which are optimally visible in the first molar, to assess environmental stresses associated with weaning and the nutritional status of lambs. Longitudinal sections were taken in a buccal-lingual direction through the centre of the posterior cusp using a Leica SP 1600 saw microtome, polished to a thickness of 100-200um and then viewed using an Olympus BX51 transmitted light microscope with pololarizing facility. The distribution of accentuated striae within a tooth was assessed by measuring the distance of each defect from the CEJ. The position of each defect in relation to mean crown height of unworn sheep first molars was then used to assess the timing of an incident, following Blakey et al. (1994) and Dobney et al. (2002). All measurements were undertaken using AnalySIS. The Mine Howe samples derive from the later phases of bone deposition at Mine Howe (first to fourth centuries AD); the Earl's Bu samples span the 11th to 12th centuries AD. To aid interpretation, comparison was made with developmental defects observed in modern sheep reared under different husbandry regimes and environments: an Orkney meat herd, pastured on semi-indigenous pastures (n=8) (Balasse et al. 2009); seaweed-grazing sheep from Orkney with no additional dietary supplements (n=6); a meat herd from Greenland grazing on indigenous grassland (n=8) (Mainland 2003; 2006). For the two meat herds, weaning was achieved at 5-6 months; for the seaweed grazing population this occurred naturally, at a similar age.

3.3.2 Tooth development in foetal and neonatal calves

Brown and Chapman's (1991) scoring system for ungulate crown and root development was used to distinguish foetal and neonatal mandible dentition in calves and to refine the age of calves dying within the first month of life. Application of the approach to a modern control group of 43 pre-term (3 to 9 months gestation) and 33 postnatal (birth to 20 weeks) calves indicates a good correspondence between tooth development score and known age (Table 3) (Davis 2011). All Mine Howe and Earl's Bu cattle mandibles (i.e. excluding loose dP4) within the appropriate age group, i.e. Halstead stages A and B, and with sufficiently intact roots/crowns were analysed, giving a total of 35 and 2 mandibles, respectively. Two derive from the earlier occupation of Mine Howe (mid first century BC to early first century AD; phases D5 and E3); otherwise the remainder are from the upper layer of the ditch and workshop area, dating from the 1st C to the fourth centuries AD. The Earl's Bu calf mandibles date to the Later Norse period (11th to 12th centuries AD).

4. Results

4.1 Tooth eruption and wear in sheep/goat and cattle

Mortality profiles at Earl's Bu and Mine Howe indicate an emphasis on the culling of sheep and cattle of prime meat age, ie 1-3/4 years (Fig. 3) (Table 4), a point at which optimum growth would have been reached for the smaller and likely slower growing livestock prevalent in the Northern Isles during the first millennium AD (Harland 2012; Bond 2007; Smith 1994). This is especially pronounced for the Earl's Bu sheep where over 80% of the assemblage is derived from animals at Payne age stages D or E (1-3 years). This is a culling strategy indicative of 'consumption' rather than of subsistence herding where a broader spectrum of ages would be expected (O' Connor 2003; Groot and Lentjes 2013; Holmes 2014). The focus on meat-aged animals at these two sites is atypical: in Atlantic Iron Age and Viking/Norse periods, mortality profiles for cattle are more normally dominated by neonates and older adults, argued to reflect a specialized dairying economy and a heavy reliance on cow's milk and milk products while culling patterns for Iron Age and Viking/Norse sheep point to a mixed economic strategy, emphasising milk, meat and to a lesser extent wool (Fig. 3) (Ewens 2010; Mulville et al. 2005).

An all-year round culling of at least some lambs and yearlings is indicated at both sites though with some degree of seasonal preference (Table 5). At Mine Howe, a greater proportion of lambs and yearling were culled during spring and summer (35% and 25%, respectively) while at Earl's Bu there is a greater emphasis on winter slaughtering (86%) and in particular on winter-culled yearlings (72%).

4.2 Diet

4.2.1 Sequential sampling of oxygen and carbon stable isotopes in cattle teeth

Intratooth enamel $\delta^{18}O$ and $\delta^{13}C$ results for 12 Mine Howe and nine Earl's Bu cattle are presented in Table 6. In Fig. 4, which shows $\delta^{18}O$ and $\delta^{13}C$ profiles for the 12 Mine Howe cattle, isotopic values are plotted versus time to enable the combining of first, second and third molar data onto a single axis. Conversion between distance from the cervix, given in Table 6, and time was achieved using a method detailed by Towers (2013; Towers et al. 2014) which uses the chronology of cattle molar crown formation published by Brown et al. (1960) and predictions of unworn crown heights. In each case the $\delta^{18}O$ profile is approximately sinusoidal, strongly controlled by the $\delta^{18}O$ value of precipitation via ingested drinking water which tends to vary seasonally at mid- to high latitudes with the highest values occurring in summer and the lowest in winter (Dansgaard 1964; Luz and Kolodny 1985). The $\delta^{18}O$ profiles for all but one of the cattle are similar in magnitude, falling between 23.1 and 26.9 ‰. The exception is the profile of MH133 which varies between 21.1 and 25.7 ‰ (Fig. 5). The larger range and lower mid-range value suggest that this animal originated at a location with a cooler climate on average and more seasonally variable water sources than to be found on Orkney.

Examination of the Mine Howe cattle intra-tooth enamel $\delta^{13}C$ profiles (Fig. 4) reveals a variety of patterns that may indicate different husbandry regimes based upon terrestrial C_3 vegetation. Six of the 12 plots (MH03, MH125, MH128, MH138, MH140 and MH0604) display a common feature: their third molar $\delta^{13}C$ and $\delta^{18}O$ profiles co-vary, but with a temporal shift of ~1-3 months between the two. $\delta^{13}C$ maxima or minima that co-vary in this way with equivalent $\delta^{18}O$ features are indicated by dashed lines in the relevant plots (Fig. 4). Such seasonal patterning may be reflecting the seasonal variation in vegetation $\delta^{13}C$, which is influenced by factors such as water availability, irradiance and the seasonally varying $\delta^{13}C$ value of atmospheric CO_2 (Smedley et al 1991; Dungait et al 2010; Farquhar et al 1989, Ciais et al 1995) and has been demonstrated for cattle-grazed meadowland in Orkney, Somerset and Northumberland (Balasse et al 2009; Dungait et al 2010; Towers 2013). For MH128, the form of the δ^{13}C profile appears to be seasonal throughout both the second and third molars , resembling the profiles of modern sheep from Rousay, Orkney (Balasse et al. 2009) that grazed outside all year round. However, it is possible that a similar pattern may arise from grazing during the summer months and the consumption of fodder with lower δ^{13}C values during the winter months. Other cattle show co-varying δ^{13}C and δ^{18}O in their third molar enamel but different patterns in earlier forming enamel, perhaps indicating different husbandry regimes involving both grazing and the use of fodder, or movement between habitats. Pattern variation in first and second molar enamel may also reflect different weaning strategies.

Comparison of the Mine Howe cattle with δ^{13}C values obtained from Iron Age/Scandinavian Interface cattle at the site of Pool on the island of Sanday shows overall mid-range δ^{13}C value for the third molars to be 0.5 ‰ lower in the Mine Howe individuals (-12.4 ‰ for Mine Howe; -11.9 ‰ for Pool)(Table 6)(Towers 2013). However, two Mine Howe cattle, MH162 and MH163, show δ^{13}C profiles that are comparable in shape and magnitude to the profiles of a number of Pool cattle (Towers 2013). The soil in the vicinity of Pool on the small island of Sanday was probably drier and more saline than the soils on much of Mainland Orkney, which would have elevated the δ^{13}C values of Pool vegetation (Guy et al 1986; van Groenigen and van Kessel 2002). Perhaps MH162 and MH163 were also raised in a saline coastal environment using a similar husbandry regime. The δ^{13}C profiles of the Mine Howe cattle suggest that seaweed was not a significant dietary component, unlike the δ^{13}C profile of an Iron Age sheep from Mine Howe which does show evidence for seaweed consumption through significantly elevated enamel δ^{13}C values (Balasse et al 2009).

The overall range of third molar enamel δ^{13}C values (1.4 ‰, 9 cattle)for Earl's Bu cattle is smaller than for either the Mine Howe cattle (2.3 ‰, 11 cattle) or Pool cattle examined by Towers (2013) (1.7 ‰, 8 cattle) (Figs. 6a-b). Detailed examination of their intra-tooth enamel δ^{13}C profiles also reveals little internal variation (Fig. 7). In fact, the range for Earl's Bu cattle is comparable to that of the wild Chillingham cattle that live together as a single herd in Chillingham Park, Northumberland (1.3 ‰, 5 cattle) (Towers 2013). Therefore, it is possible that the Earl's Bu cattle were raised within a similarly restricted geographical area, probably local to Earl's Bu, and/or under a common husbandry regime. The consumption of winter fodder with higher δ^{13}C values than winter grazing, perhaps hay, straw or grains harvested during the summer, for example, might act to reduce the amount of variation in a $\delta^{13}C$ profile.

4.2.2 Dental microwear and stable isotopes in sheep dentition

The sheep sampled from both Mine Howe and Earl's Bu are characterised by heavily striated enamel surfaces (Fig. 2; Table 7). For the dP4, all but one individual from Mine Howe is classed as a 'high abrasive' grazer using DA, reflecting microwear in which striations are the dominant feature. Plotting individual samples according to their discriminant score, however, separates Earl's Bu from Mine Howe on the first discriminant function. In addition, the Mine Howe group exhibiting greater intra-group variability on the second function while the Earls' Bu is more closely clustered (Fig. 2). Descriptive statistics for defect frequencies and striation dimensions on the M1 and the dP4 also indicate between site differences with a higher absolute frequency of defects (pits and striations) and of larger striations (length and breadth) at Mine Howe. Overall, the Earl's Bu samples are unusual in exhibiting very few microwear features (mean number of defects = 26). This is apparent on both M1 and dP4, and across the range of ages sampled, indicating that it cannot merely be attributed to length of time in wear. Standard deviations for microwear dimensions and frequencies are larger for the Mine Howe variables, suggesting, as is evident in the DA, greater within group variability in microwear, and hence diet, than at Earl's Bu.

Previous research on microwear in known diet sheep populations has demonstrated that a high percentage of striations is evident in grazing environments where soil minerals are consumed in quantity, reflecting season-of-grazing and grazing intensity (Mainland 2006; McGovern et al. 2010; Henton 2012) and in phytolith-rich pastures/fodders such as grass- and sedge-based grazing, cereal straws and stubble (Henton 2012). Henton (2012) has also noted higher overall frequencies of striations and of defects in general where soil ingestion is high, in wet and muddy pastures or wet seasons; conversely, sheep grazing phytolith rich wheat and barley stubble with minimal soil ingestion exhibit fewer defects, though a greater proportions of these are striations (Henton 2012). Microwear in the Mine Howe sheep, which shows a high absolute and relative frequency of striations, is consistent with sheep pastured in grass or sedge-rich grazing environments where the potential for soil ingestion is high, e.g., through high stocking levels , pasturage on areas of patchy ground cover (eg machair, edges of cultivated fields) or grazing outdoors during the winter months. Outwintering of sheep and cattle on grassland in Orkney has to be carefully managed to avoid vegetation loss, puddling and muddying of pastures (Simpson et al. 1995). The Earl's Bu sheep also exhibit striations indicative of the presence of dietary abrasives such as phytoliths or soil grits, but here the very low feature frequencies suggest limited soil ingestion, perhaps indicating that the animals were housed and fed on a phytolith-rich fodder, such as wheat or barely straw, before being culled. The emphasis on winter-culled sheep at Earl's Bu (Table 4) would support this suggestion. The low standard deviation exhibited by microwear variables in the Earl's Bu population may also be consistent with the use of a single species cereal fodder, as free-grazing sheep will tend to select from a wide range of grasses and forbs (Bullock 1985). The grazing of sheep outdoors at low stocking density, on phytolith rich vegetation, such as wheat or barely stubble fields (eg Henton 2012) is considered less likely for Orkney given the potential for such pastures to become rapidly muddied in autumn and winter. The use of other fodders such as leafy-hay, milled cereals or seaweed is also considered unlikely because these diets are also associated with pits in domestic sheep (Mainland and Halstead 2005; Mainland 2000).

Although not part of the current study, Balasse et al. (2009) have presented $\delta^{13}C$ and $\delta^{18}O$ profiles for sheep dentition at the Earl's Bu (n=3) and Mine Howe (n=3). Smaller samples are involved, but this data also hints at potentially contrasting dietary regimes at these two sites. The Mine Howe sheep again show a greater variability in diet, with one individual providing evidence for occasional winter seaweed consumption and the others being consistent with a largely terrestrial diet (Balasse et al. 2009, fig. 3, table 1 ($\delta^{13}C$ mean amplitude of variation 2.4). In contrast, a more even dietary profile is represented by the Earl's Bu sheep with all 3 individuals sampled consuming a terrestrial grazing environment. Like the cattle, ranges and standard deviations for $\delta^{13}C$ values at Earls' Bu are smaller, reflecting little inter-individual variability, with $\delta^{13}C$ presenting a relatively 'flat' profile (Balasse et al. 2009 fig 3, table 1) ($\delta^{13}C$ mean amplitude of variation 1) through the chronological sequence of the tooth. As with the cattle, this could again be indicative of foddering although an equivalent narrow range of variation in $\delta^{13}C$ is evident in modern grazing sheep from Orkney raised as a single herd and outwintered ($\delta^{13}C$ mean amplitude of variation 1.5).

4.3 Animal health and environmental stress

4.3.1 Developmental enamel defects in sheep

Seven of the 8 Mine Howe sheep teeth displayed defects with an average of 2.6 accentuated striae per individual. In addition, two exhibited hypoplastic lesions. These stress events occurred throughout the first six months of life in the sampled population and although the majority of defects were formed between birth and 4 months, no clear age-related trend were observed. The incidence of developmental defects was slightly lower in the Earl's Bu samples (average of 2 striae per teeth) and no hypoplasia (ie major stress events) were observed. Occurrence was primarily associated with the latter period of tooth development examined, ie between 4-6 months. This is comparable with incidences found in modern grass-fed meat herds raised under relatively good nutritional conditions and where weaning is delayed, with separation from the mother only occurring towards the end of the natural cycle (Fig. 8) (Ewens 2010). In contrast, the more dispersed distribution of developmental defects in the Mine Howe population indicates greater and more persistent levels of stress throughout early life, suggesting checks to animal growth from factors such as a poorer diet and heavier parasite burdens and/or early weaning within the first few months of life.

4.3.2 Tooth development in calves

A high rate of infant mortality is evident in cattle at Mine Howe with 38% (n=13) of calves at Halstead age stages A to B dying before reaching full gestation, and likely representing still births or abortions (Table 8). A further 10 individuals died (29%) during the first two weeks of life. This could represent a culling of neonates as part of a specialised dairying economy, as is evident elsewhere in the Atlantic Iron Age (Mulville et al. 2005). However, it is usually assumed that herders will allow calves to suckle for c. 10 days before slaughtering calves under such a regime to ensure that milk production is established in the cow (eg. the Infant category in Table 8) (Halstead 1998). This raises the possibility of an even higher frequency of natural deaths occurring at or around birth in the Mine Howe population. Present-day aetiologies could include: third trimester - Listeriosis, Mycotic abortion, Salmonellosis, A. pyogenes, Brucellosis, Leptospirosis, Neospora caninum; 1-2 weeks post natal - Cryptosporidiosis, Salmonellosis (Davis 2010). It seems reasonable to infer ancient correlates to some if not all of these abortifacients and neonatal pathogens. The two mandibles examined from the Earl's Bu assemblage derived from calves aged older than 2 weeks. Interpretation of this assemblage is difficult because of the general lack of mandibles in the relevant age groups, but as preservation conditions were comparable at the two sites, the lack of foetal material may indicate generally better husbandry at Earl's Bu. A similar absence of foetuses was observed at the site of Snusgar in Orkney, also of Viking to Late Norse date though here a greater frequency of neonatal and infant calves was also present (Davis 2010). However, the ageing methodology by tooth development is probably only valid for foetuses from mid-late pregnancies since very young foetal material is usually insufficiently ossified and/or too fragile to survive taphonomic processes (Davis 2010,252).

5. Discussion

There are many similarities between the faunal assemblages deposited at Mine Howe and the Earl's Bu. Both are very large midden deposits, amongst the biggest assemblages recovered from sites of a Middle Iron Age and Viking/Late Norse date in the Northern Isles; they are cattle dominated, exhibit mortality profiles indicative of consumption (ie of 'meat'), in both cattle and sheep, and as such are each atypical for their respective periods where secondary products and in particular milk production are emphasized. The importance of dairy specialization in the Northern and indeed Western isles of Scotland is well attested by both mortality profiles and pottery residue analysis from this region which shows an emphasis on milking economies from the Neolithic onwards (Cramp et al. 2014; Mulville et al. 2005). Earls Bu is also unusual in showing a high relative frequency of pig, a species traditionally associated with feasting and high status consumption in early Medieval Europe (Woolgar et al. 2006;). An emphasis on pig is only apparent at one other site in Viking/Norse Orkney, the Brough of Birsay which was also an Earldom estate (Mainland et al. 2015). At Mine Howe, the sheer quantity of bone deposited in the upper phases of the partially excavated enclosure ditch is consistent with large scale consumption events with three of the larger individual contexts excavated in this area alone representing bone dumps in excess of 11, 000 fragments in total. Moreover, both sites have been interpreted as sites of communal gathering/ feasting on the basis of ancillary archaeological and for Earl's Bu, historical evidence. Nevertheless, each of the techniques applied to the sheep/goat and cattle dentition have identified clear differences between the two sites, in diet, in culling season, herd health and stress levels, all of which point to potential differences in underlying husbandry practices. Furthermore, the Earl's Bu livestock consistently shows less variability in these indicators than do the Mine Howe cattle and sheep, which emerge as rather more diverse populations in terms of diet, health and culling strategy.

Palaeodietary analysis indicates that cattle and sheep at Mine Howe had been reared under several different grazing and foddering systems. For the cattle these may have included outwintering, summer grazing combined with winter foddering and pasturage in saline grasslands, perhaps coastal heaths or machairs. Sheep may additionally have foraged along the foreshore with an occasional consumption of seaweed apparent in one individual. Jones et al. (2012) also report bone collagen enriched in ^{13}C in Iron Age sheep samples from Mine Howe and other sites in Orkney, suggesting a more widespread use of seaweed and foreshore grazing by sheep herds at this time though again some variability is evident in the extent to which this resource was utilised. Potential locations of such activities in the hinterland of Mine Howe are illustrated in Fig. 1.

Culling strategies are also more diverse at Mine Howe. Although the tendency is towards a summer slaughter in the lambs and yearlings, this was not focused on a specific age group as was evident at the Earl's Bu. Likewise, environmental stresses were dispersed throughout the first 6 months of life, again unlike the Earl's Bu where, as in modern meat flocks, development defects occur almost exclusively in the 4-6 months age-bracket.

The results from the Earl's Bu cattle and sheep are more akin to what might be expected from a single herd, or, more likely, given that the samples did not derive from one context but could potentially span a period of 100-150 years, a specific management practice. Inter-individual isotopic variability, e.g., is comparable to that found in modern cattle and sheep herds where animals are routinely pastured in a confined geographical area (Balasse et al. 2009; Towers 2013), suggesting the use of designated grazing locations in the hinterland of the Earl's Bu (Fig. 1). The absence of any evidence for prolonged foreshore and seaweed grazing in either the microwear and isotopic data also indicates carefully managed herds which were not allowed to roam freely (Balasse et al. 2009; Mainland 2000). Winter housing of sheep, perhaps on a cereal-based fodder, is also indicative of well husbanded flocks and may reflect the fattening-up of livestock for consumption. An increase in the cultivation of oats is noted between the Viking and Late Norse periods in Orkney (Bond 2007; Barrett 2012), including at the Earl's Bu (Huntley pers comm.) which has been argued reflects greater use of this cereal as animal fodder (Bond 2007; Barrett 2012, 205). Dental development shows the Earl's Bu herds were not stressed, in early life at least, indicating good maternal nutrition and adequate fodder/grazing for lambs and calves prior to weaning. The culling strategy employed for sheep at the Earl's Bu is also more systematic, being focused on a particular age group and season, namely 1-3 year olds slaughtered predominately during the winter months (October/November to April). An emphasis on winter feasting is recorded in historical accounts of the Orkney earldom, which relate how in summer the earls and their followers left Orkney on raiding, and trading expeditions, returning home in autumn to entertain their followers and retinue with the proceedings of these activities (Barrett 2005).

Mine Howe may arguably be reflecting a less organised form of husbandry, primarily subsistence based, perhaps with smaller numbers of animals per household, and in which stress events such as weaning are more randomly spread over the life of the animal, responding to herding decisions based on immediate needs rather than specialised production goals (Halstead 2014). The higher incidence of enamel defects together with high rates of foetal and neonatal deaths under 2 weeks also suggest a less productive and more marginal farming system, with poorer nutrition and heavier parasite burdens. The use of foreshore grazing by sheep and outwintering of cattle, which both imply a lack of conserved fodder (Mainland 2000; Balasse et al. 2009), may be further indicators of marginality (Amorosi et al. 1996). The variability at Mine Howe could equally be attributed to its function, ie a place of communal gathering. Here, the animals deposited within the feasting debris of the enclosure ditch would represent individuals derived from more than one household and/or herding system brought to Mine Howe by participants in the feast, perhaps suggesting that the host(s) of feasts held at Mine Howe were able to draw on resources from a wide area, in tribute or other forms of obligation (Card and Downes forthcoming). The presence of one cow from Mine Howe with $\delta^{18}O$ values atypical for Orkney and suggestive of a location of a cooler climate and more seasonally variable water sources indicates that these potential contacts and influences may well have gone beyond the islands (Towers 2013). Similar arguments of centralised control over resources and the role of feasting therein have been made for the MIA domestic settlements of the Northern and Western Isles, the broch villages (Dockrill et al. 2005; Dockrill and Bond 2014). These have, however, been difficult to prove equivocally (e.g. Armit 2003; Hill 2011) because of a reliance on zooarchaeological and/or archaeobotanical production/consumption models for identifying movement and exchange of foodstuffs, sources which are affected by issues of taphonomy and equifinality (Halstead 1998; Holmes 2014). The methodological approach used on the Mine Howe and Earl's Bu assemblages in which techniques enabling insight into the life histories of individuals are combined with analyses of herd demographics to explore both animal management strategies and the economic outcomes, or products, of pastoral farming provides an alternative way into the question of redistribution and control of resources in the Iron Age. Wider application on a regional basis holds much potential. A similar approach to herding economies was used to explore centralised control of resources at Danebury, an early first century AD hillfort in southern England, but only considered stable isotopes in bone collagen (Stevens et al. 2013).

Feasting in Viking and Late Norse Orkney, as across the Norse world, was an underpinning mechanism used by powerful men and women to both acquire and legitimse power through commensal hospitality (Byock 2001; Zori et al 2011; Barrett 2005; Steinsland 2011). On analogy with practices elsewhere in Medieval Scandinavia and Scotland (Lucas and McGovern 2007; Zori et al. 2011; Woolf 2007, 23-34), foods consumed at such events could potentially derive from renders owed by tenants and/or others obligated to the Earls or from the Earls own farms and estates, of which the Earls' Bu was one of several in Orkney (Thomson 2008; Crawford 2013, Chpt. 4.6). In potentially deriving from diverse farms, of differing economic status and from locations across the Earldom which during the early 11th century AD stretched from Shetland to the Western Isles, it could be argued that foodstuffs originating as rent or food in kind would reflect a greater diversity of diet and the other proxies for husbandry practice considered (see eg Stevens et al. 2013; McGovern et al. 2010; Madgwick et al. 2012). Rather, the overall impression for the Earl's Bu is of an organised system of pastoral farming with specialist herds of sheep and cattle pastured and fattened up on established home fields and/or specific upland zones tied to the estate (eg Fig. 1) and an economy geared towards specific products, in this case meat: to sustain the Earl's retinue, his 'hird' and meet any other commensal obligations while the Earls were in residence. There is currently much debate about the antiquity of aristocratic estates in a Scandinavian context (Poulsen and Sindbaek 2011), which during the early Medieval period included the Orkney earldom. Formerly believed to have their origins in the 12th and 13th centuries AD as a consequence of changing power systems with the advent of Christianity, the rise of state-level kinship and feudalism, there is increasing evidence that the elite had control over large manorial estates from the Viking period onwards, displacing the view of 9-11th century AD agricultural landscapes as one dominated by free peasant farmers with varying degrees of obligation to chieftains and larger farmers (Poulsen and Sindbaek 2011). The herding system identified at the Earl's Bu hints at the presence of tracts of land under one management systems from at least the 11th century AD. This potentially supports the argument for an earlier development of manorial estates in the Orkney Earldom, as indeed has often been previously been mooted for this region with some authors even suggesting continuity in estate management from the pre-Viking Pictish period (Thomson 2008; Dockrill and Bond 2014). As well as potentially enabling insight in resource redistribution and control in the Iron Age, the methodologies presented here offer an alternative approach to another intractable question, the antiquity of estate farming in Medieval Scandinavia, a premise which is currently being explored through application to a wider range of sites in Orkney, spanning the Pictish, Viking and Late Norse periods.

Conclusions

Our approach to integrated dental studies within zooarchaeology which comprises a comparative analysis of trends in husbandry practice derived from the application of a suite of different methodological approaches to cattle and sheep dentition has provided significant new insights into social practice and animal husbandry in Orkney during the first and early second millennium for the case study sites considered. Extension of this methodology on a regional scale to incorporate sites of differing size and status, both within the Scottish Isles and further afield, has the potential to address questions relating to the movement and control of animals and animal-derived resources during later prehistory in Western Europe and Scandinavia which have hitherto been difficult to explore using conventional palaeodietary, zooarchaeological or archaeological methodologies alone (Stevens et al. 2013; Thomson 2008; Dockrill and Bond 2014; Poulsen and Sindbaek 2011). In this article, however, application of each technique was largely undertaken independently of one other reflecting the developmental nature of several of the methodologies discussed (Towers 2012; Ewens 2010; Davis 2009). In only a few examples was more than one applied per animal (Balasse et al. 2009) and as a result it was not possible to explore the life histories of specific individuals (eg. Henton et al. 2010). A more nuanced approach to integration which brings together microwear, isotopes and the analysis of developmental defects at the level of an individual animal, enabling 'animal biographies' to be compiled showing seasonal movement, intra- and inter-annual variability in diet and in nutritional status for animals of similar age, sex or species within specific chronological time spans is a logical next step.

Ultimately, however, the potential of integrated dental analyses such as these to explore the spatial and temporal distribution of grazing and foddering activities within the landscape is dependent on an accurate understanding of how key parameters such as stable isotopes, dietary texture and abrasivity vary between different habitats, altitudes and seasons and/or with management practice (eg. Riveaux 2015; Stevens et al. 2013). For Orkney, as indeed for most other regions (see eg. Stevens et al. 2013; Henton et al. 2010; Mueldner et al. 2014; Riveaux 2015), this has yet to be achieved and any reconstruction of pastoral land-use around the case study sites is by necessity rather generalised, in this case based on pre-modernisation land-use maps (Fig. 1). The difficulty of mapping more accurately pastoral activity within landscapes is perhaps one of the most significant challenges facing future development of isotope and microwear studies within zooarchaeology (eg Stevens et al 2013; Muldner et al. 2014; Henton et al. 2014; Riveaux 2015) and will arguably require a better understanding, using modern baseline studies, of the relationship between specific animal management practices (eg grazing of low productivity grassland vs. manured fields; dried grasses or leaves vs. fresh graze or browse), stable isotopes and dietary composition between and across different geographic regions.

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Table captions

Table 1 Lists for each methodological approach the individual cattle mandibles sampled. Mandibular reference nos. given first are the unique codes used in the data archives for the Mine Howe and Earls Bu faunal assemblages (Mainland et al. in press; in prep); reference nos. in brackets prefixed by EB, MINE and MH are those used by Towers (2013), Ewens (2010) and Balasse et al. (2009).

Table 2 Lists for each methodological approach the individual sheep mandibles sampled. Mandibular reference nos. given first are those used in the data archives for the Mine Howe and Earls Bu faunal assemblages (Mainland et al. in press; in prep); reference codes in brackets prefixed by EB, MINE and MH are those used by Towers (2013), Ewens (2010) and Balasse et al. (2009).

Table 3 Correspondence between Brown & Chapman (1991) tooth development score and age in modern foetal/neonatal cattle mandibles: represents the combined score of each tooth in the mandibular arcade (dP2, dP3, DP4, M1) using the ten sequential dental development stages outlined in Brown & Chapman (1991).

Table 4 Data for sheep/goat (a) and cattle (b) mortality profiles from Earl's Bu and Mine Howe
Table 4a Data for sheep/goat mortality profiles from Earl's Bu and Mine Howe (after Payne (1973) with juvenile sheep ages according to Jones (2006)).
Table 4b Data for cattle mortality profiles from Earl's Bu and Mine Howe (after Halstead 1985).

Table 5 Season and year of death for juvenile sheep mandibles from Mine Howe (a) and Earls Bu (b) based on Jones (2006) wear stages. A May birth for lambs is assumed (Fenton 1978); attribution of age-at-death to season takes into account the short growing season for vegetation in Orkney (located 50^{o} North) with late September/October to April classed here as winter.
Table 5a Season and year of death for juvenile sheep mandibles from Earls's Bu
Table 5b Season and year of death for juvenile sheep mandibles from Mine Howe

Table 6 Intra-tooth oxygen and carbon isotope ratios of enamel from Earl's Bu (a) and Mine Howe (b) cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal. Wear stages after Grant (1982).
Table 6a Intra-tooth oxygen and carbon isotope ratios of enamel from Earl's Bu cattle mandibular molars.
Table 6b: Intra-tooth oxygen and carbon isotope ratios of enamel from Mine Howe cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal (Results for MH84, MH138 and MH0604 have previously been published in Towers et al. 2014)

Table 7 Statistics for microwear variables for the dP4 (a) and M1 (a) in the Earl's Bu and Mine Howe sheep; lists mean values, range and standard deviation (Std. Dev.) for total defect frequency, striation frequency, the ratio of pits to striations (expressed a percentage of total defects), striation length, breadth and orientation. Statistically significant differences (Student's T-test, $p<0.05$) are indicated by an asterisk.
Table 7a Statistics for microwear variables for the dP4 in the Earl's Bu and Mine Howe sheep
Table 7b Statistics for microwear variables for the M1 in the Earl's Bu and Mine Howe sheep

Table 8 Frequencies of foetal and neonatal cattle mandibles at Earl's Bu and Mine Howe based on dental development stages outlined in Brown & Chapman (1991) and the modern known-age foetal/neonatal mandibles summarised in Table 3.

Figure captions

Figure 1 Location map for Mine Howe, the Earl's Bu and Pool. The insets show the potential for different pastoral management strategies within the hinterland of these sites and is based on the 1931-5 land utilization map for Scotland (National Library of Scotland 2015) which will reflect the pre- modernization farming landscape of Orkney. These are intended to give a general indication of resource potential rather than be a reconstruction of actual land-use (see text for further details). Likewise the area mapped are topographic in nature and as such do not reflect definitive boundaries of these settlements.

Figure 2. Stepwise discriminant analysis plot for known diet sheep/goat used in the classification of the juvenile archaeological mandibles from Earl's Bu and Mine Howe (after Mainland 2006). Function 1 separates fodder-fed (leafy-hay/cereal, ie 'soft-diet') from grazing individuals such that feature dimensions (length rounded pits, length narrow striations, breadth narrow striations) and pit length orientation decrease and the absolute frequency of defects increases towards the LHS of the diagram; function 2 separates the low abrasive grazers and the fodder-fed ('soft-diet') individuals from the high abrasive grazers, such that the relative frequency of pits and of rounded pits increases towards the top of the diagram.

Figure 3 Sheep/goat (a) and cattle (b) mortality profiles from Earl's Bu and Mine Howe (see also Table 2)
Fig. 3a Sheep/goat mortality profiles for Earl's Bu and Mine Howe (after Payne 1973). Ages in adults (greater than c. 4 years) are an approximation.
Fig. 3b Cattle mortality profiles for Earl's Bu and Mine Howe. Ages in adults (greater than c. 36 months) are an approximation.

Figure 4. Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from 12 Mine Howe cattle. The dashed lines indicate features discussed in the text. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

Figure 5. $\delta^{18}O$ profiles for first, second and third cattle molar enamel from 12 Mine Howe cattle. Each line represents an individual animal. The dashed profile is for MH133. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

Figure 6a. Intra-tooth enamel $\delta^{13}C_{VPDB}$ values versus distance from cervix for Mine Howe and Earl's Bu cattle third molars. Each line represents an individual animal. Analytical error is ± 0.1 ‰ (1σ).
Figure 6b. Intra-tooth enamel $\delta^{18}O_{VSMOW}$ values versus distance from cervix for Mine Howe and Earl's Bu cattle third molars. Each line represents an individual animal. Analytical error is ± 0.2 ‰ (1σ).

Figure 7. Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for second and third cattle molar enamel from nine Earl's Bu cattle. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

Figure 8. Prevalence of enamel development defects in modern and archaeological sheep from Orkney and Greenland. Vertical bars show the frequency of accentuated striae by distance from the CEJ (cementum-enamel junction) in millimetres in modern and archaeological sheep. Horizontal bars indicate the approximate position of hypoplasia (see text for further explanation of terminology).
Figure 8a. Modern grazing sheep (n=8) from Orkney, meat-flock, weaned at 5-6 months
Figure 8b. Modern seaweed- grazing sheep (n=8) from Orkney, weaned naturally at c. 5-6 months
Figure 8c. Modern grazing sheep (n=8) from Greenland, meat-flock weaned at 5-6 months
Fig. 8d Earl's Bu sheep (n=6)
Fig. 8e Mine Howe sheep (n=8)

Site and period	**Microwear**	**Enamel developmental defects**	**Stable isotopes**	**Tooth development**
Earls Bu Viking (Phase M)	Not analysed	Not analysed	14 (EB1); 34 (EB13); 51 (EB4); 37 (EB8); 46 (EB21); 33 (EB23); 56 (EB14); 17 (EB28)	25
Earls Bu Late Norse (N-X)	Not analysed	Not analysed	33 (EB9)	31
Mine Howe lower ditch and contemporary deposits (Phases D1-6; E1-4.3)	Not analysed	Not analysed	Not sampled	6.17; 6.08; 6.05
Mine Howe upper ditch and contemporary deposits (Phases D7-11; E4.4-8)	Not analysed	Not analysed	3; 128; 138; 125; 133; 140; 149; 162; 163; 174; 6.04; 84	71; 78; 85; 92; 1; 98; 6.15; 72; 93; 79; 67; 81; 94; 75; 65; 91; 89; 68; 69; 74; 84; 99; 86; 97; 90; 66; 96; 72; 77; 88; 6.07; 6.16

Table 1. Lists for each methodological approach the individual cattle mandibles sampled. Mandibular reference nos. given first are the unique codes used in the data archives for the Mine Howe and Earls Bu faunal assemblages (Mainland et al. in press; in prep); reference nos. in brackets prefixed by EB, MINE and MH are those used by Towers (2014), Ewens (2010) and Balasse et al. (2009).

Site and period	Microwear	Enamel developmental defects	Stable isotopes	Season-of-death	Tooth development
Earls Bu Viking (Phase M)	14; 15; 44	Not sampled	Not sampled	14; 30; 34; 36; 44	Not analysed
Earls Bu Late Norse (N-X)	7; 9; 10; 19; 31; 32; 37; 55; 58; 60	1; 10; 15; 43; 60	5; 9	1; 2; 5; 6; 7; 10; 12; 16; 20; 21; 23; 24; 43; 45; 58; 60	Not analysed
Mine Howe lower ditch and contemporary deposits (Phases D1-6; E1-4.3)	Not sampled	Not sampled	Not sampled	Not sampled	Not analysed
Mine Howe upper ditch and contemporary deposits (Phases D7-11; E4.4-8)	28; 44; 48; 49; 50;51; 58; 76; 75; 81; 88; 91; 130; 133; 161	163 (MINE3); 167 (MINE7); 162 (MINE2); 165 (MINE5); 168 (MINE8); 166 (MINE6); 164 (MINE4)	44 (MH1); 50 (MH2); 58 (MH3)	3; 4; 13; 21; 22; 58; 57; 52; 75; 119; 128; 150; 161; 162; 163; 164; 165; 166; 167; 168	Not analysed

Table 2. Lists for each methodological approach the individual sheep mandibles sampled. Mandibular reference nos. given first are those used in the data archives for the Mine Howe and Earls Bu faunal assemblages (Mainland et al. in press; in prep); reference codes in brackets prefixed by EB, MINE and MH are those used by Towers (2014), Ewens (2010) and Balasse et al. (2009).

Category	**Age-range**	**Tooth development score**	**Number of modern known age mandibles**
FOETUS (F)	Less than 7-8 months gestation	3-6	11
LATE FOETUS-NEWBORN (LFNB)	Between 7-8 months gestation and birth	7-24	32
NEWBORN-NEONATE (NBNN)	Between birth and 2 weeks	25-26	26
INFANT (INF)	Between 2 and 4 weeks	27-28	2
JUVENILE (JUV)	More than 1 month	29 plus	5

Table 3 Correspondence between Brown & Chapman (1991) tooth development score and age in modern foetal/neonatal cattle mandibles: represents the combined score of each tooth in the mandibular arcade (dP2, dP3, DP4, M1) using the ten sequential dental development stages outlined in Brown & Chapman (1991).

Table 4 Data for sheep/goat (a) and cattle (b) mortality profiles from Earl's Bu and Mine Howe

Age stage	**Age**	**Earl's Bu**			**Mine Howe**		
		n	%	%surv	n	%	%surv
A	0-1 months	0	0.0	100.00	0	0.0	100.00
B	1-4 months	3	5.7	94.34	8.67	5.5	94.55
C	3-13 months	1	1.9	92.45	42.15	26.5	68.04
D	10-25 months	22.3	42.1	50.38	22.6	14.2	53.82
E	3-4 years	22.7	42.8	7.55	27.04	17.0	36.82
F	young adult	4	7.5	0.00	35.13	22.1	14.72
G	adult	0	0.0	0.00	20.92	13.2	1.57
H	adult	0	0.0	0.00	2.49	1.6	0.00
I	senile adult	0	0.0	0.00	0	0.0	0.00
TOTAL		53			159		

Table 4a Data for sheep/goat mortality profiles from Earl's Bu and Mine Howe (after Payne (1973) with juvenile sheep ages according to Jones (2006)).

Age stage	**Age**	**Earl's Bu**			**Mine Howe**		
		n	%	%surv	n	%	%surv
A	0-1 month	0	0.0	100	37.2	14.1	86
B	1-8 months	2	5.4	95	67.0	25.4	61
C	8-18 months	1	2.7	92	4.0	1.5	59
D	18-30 months	5.33	14.4	77	25.0	9.5	50
E	30-36 months	10.67	28.8	49	49.2	18.6	31
F	young adult	7.41	20.0	29	34.7	13.1	18
G	Adult	3.53	9.5	19	24.4	9.2	9
H	old adult	3.53	9.5	10	11.4	4.3	4
I	Senile	3.53	9.5	0	11.4	4.3	0
TOTAL		37			264		

Table 4b Data for cattle mortality profiles from Earl's Bu and Mine Howe (after Halstead 1985).

Table 5 Season and year of death for juvenile sheep mandibles from Mine Howe (a) and Earls Bu (b) based on Jones (2006) wear stages. A May birth for lambs is assumed (Fenton 1978); attribution of age-at-death to season takes into account the short growing season for vegetation in Orkney (located 50° North) with late September/October to April classed here as winter.

Jones (2006) wear stages	**Age**	**Season of Death**	**n**	**%**
B-C1/2	1-5m	1st spring/summer	3	14
C3/4 – C5	5-9m	1st winter	0	0
C6+	8-12m	1st winter	0	0
D1/2	10-13m	1st winter (2nd spring)	3	14
D3/4	12-17m	2nd spring/summer	0	0
D5	14-20m	2nd summer/early winter	0	0
D6+	18-24m	2nd winter	15	72
Total			21	

Table 5a Season and year of death for juvenile sheep mandibles from Earls's Bu

Jones (2006) wear stages	**Age**	**Season of Death**	**n**	**%**
B-C1/2	1-5m	1st spring/summer	7	35
C3/4 – C5	5-9m	1st winter	0	0
C6+	8-12m	1st winter	2	10
D1/2	10-13m	1st winter (2nd spring)	2	10
D3/4	12-17m	2nd spring/summer	5	25
D5	14-20m	2nd summer/early winter	0	0
D6+	18-24m	2nd winter	4	20
Total			20	

Table 5b Season and year of death for juvenile sheep mandibles from Mine Howe

Table 6 Intra-tooth oxygen and carbon isotope ratios of enamel from Earl's Bu (a) and Mine Howe (b) cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal. Wear stages after Grant (1982).

Third molars							
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 (‰)
EB1 (M_3), LM, wear stage a cusp to cervix 47.5 mm				EB4 (M_3), LM, wear stage f cusp to cervix 43.5 mm			
1	45.0	25.1	-12.2	1	40.0	22.9	-12.4
2	41.0	24.5	-12.2	2	37.0	22.6	-12.3
3	37.0	24.3	-12.1	3	33.5	23.1	-12.5
4	33.5	23.8	-12.1	4	30.0	23.4	-12.5
5	29.5	23.6	-12.0	5	23.0	24.2	-12.2
6	26.0	23.9	-12.0	6	19.5	24.3	-12.2
7	22.0	24.1	-12.1	7	16.5	24.8	-12.2
8	19.0	24.3	-12.2	8	13.5	24.4	-12.2
9	16.0	24.5	-12.2	9	10.5	24.1	-12.2
10	12.5	25.4	-12.3	10	7.5	24.2	-12.1
11	9.0	25.4	-12.3	11	4.0	23.7	-12.5
12	5.5	25.7	-12.1				
EB8 (M_3), LM, wear stage f cusp to cervix 44.0 mm				EB9 (M_3), LM, wear stage d cusp to cervix 46.5 mm			
1	39.5	25.9	-12.0	1	43.0	23.9	-12.2
2	35.0	25.8	-11.7	2	39.0	23.9	-12.1
3	32.0	25.8	-11.7	3	36.0	23.4	-12.2
4	28.0	25.2	-11.8	4	32.5	23.4	-12.3
5	24.5	24.9	-11.7	5	29.0	23.7	-12.3
6	21.0	24.5	-11.9	6	25.5	24.3	-12.2
7	18.0	23.7	-11.9	7	22.0	24.5	-12.1
8	15.0	23.6	-12.0	8	18.5	24.9	-11.9
9	12.0	23.6	-12.1	9	15.0	25.2	-11.9
10	8.5	23.4	-12.0	10	11.5	24.9	-11.9
11	5.0	23.1	-12.3	11	7.5	24.2	-11.8
				12	4.5	23.7	-11.9
EB13 (M_3), LM, wear stage a/b cusp to cervix 50.0 mm				EB14 (M_3), LM, wear stage j cusp to cervix 33.0 mm			

1	47.0	24.0	-12.1	1	28.5	23.0	-13.1
2	44.5	23.9	-12.0	2	25.5	23.1	-13.0
3	41.5	23.6	-12.2	3	21.5	23.6	-12.9
4	38.5	23.6	-12.2	4	17.0	24.4	-12.8
5	35.5	23.6	-12.3	5	14.5	24.9	-12.6
6	32.0	24.0	-12.4	6	11.0	25.0	-12.6
7	28.5	24.4	-12.4	7	8.0	24.5	-12.5
8	24.5	24.4	-12.2	8	5.0	23.9	-12.6
9	21.0	25.0	-12.2	9	2.5	23.8	-12.8
10	17.0	25.1	-12.1				
11	14.0	25.2	-12.2				
12	10.5	24.9	-12.2				
13	7.5	24.7	-12.2				
EB21 (M$_3$), LM, wear stage f cusp to cervix 43.0 mm				EB23 (M$_3$), LC, wear stage d cusp to cervix 47.5 mm			
1	39.5	25.5	-12.3	1	44.5	24.4	-12.5
2	35.5	26.5	-12.1	2	40.0	25.1	-12.5
3	31.5	26.6	-12.0	3	32.5	24.9	-12.6
4	28.0	26.5	-11.9	4	29.0	25.1	-12.4
5	25.0	26.2	-11.9	5	25.5	25.3	-12.4
6	21.0	25.6	-11.9	6	21.0	24.6	-12.5
7	17.5	24.7	-12.1	7	17.0	24.3	-12.6
8	14.5	24.1	-12.2	8	13.0	23.8	-12.7
9	11.5	23.8	-12.4	9	9.5	23.8	-12.7
10	8.5	23.7	-12.5	10	6.5	23.4	-12.7
11	5.5	23.4	-12.5	11	4.0	23.4	-12.7
EB28 (M$_3$), LM, wear stage a cusp to cervix 47.0 mm							
1	43.5	25.2	-12.0				
2	40.0	24.7	-11.9				
3	36.0	24.3	-12.0				
4	32.0	23.8	-11.9				
5	28.0	23.5	-11.9				
6	24.5	23.5	-11.9				
7	21.0	23.9	-11.9				
8	17.5	24.4	-12.0				
9	14.5	24.8	-12.1				
10	11.0	25.1	-12.1				
11	8.0	25.5	-12.0				
12	5.0	25.5	-12.0				

Second molars							
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 (‰)
EB1 (M_2), LM, wear stage f cusp to cervix 41.5 mm				EB4 (M_2), LM, wear stage g cusp to cervix 37.5 mm			
1	38.0	24.1	-12.4	1	35.0	23.1	-12.4
2	34.5	23.9	-12.3	2	31.0	23.4	-12.1
3	30.5	23.5	-12.3	3	27.5	23.6	-12.1
4	27.0	24.0	-12.5	4	24.5	24.3	-11.9
5	23.5	24.1	-12.2	5	21.5	24.1	-11.9
6	20.5	24.4	-12.1	6	18.0	24.6	-11.9
7	17.0	25.3	-12.2	7	15.5	24.9	-12.0
8	13.5	25.9	-12.2	8	12.0	24.4	-12.0
9	10.5	26.4	-12.3	9	8.5	24.2	-12.0
10	7.0	26.5	-12.3	10	6.0	23.7	-11.9
11	3.5	26.1	-12.3	11	3.0	23.7	-12.0
EB13 (M_2), LD, wear stage f cusp to cervix 45.5 mm							
1	42.0	23.8	-13.0				
2	37.0	23.9	-12.6				
3	33.0	24.5	-12.6				
4	29.5	24.8	-12.5				
5	26.0	24.8	-12.5				
6	22.5	25.5	-12.4				
7	19.0	25.9	-12.3				
8	15.5	25.6	-12.2				
9	12.0	25.4	-12.0				
10	9.0	25.1	-11.9				
11	5.0	24.7	-11.8				

Table 6a Intra-tooth oxygen and carbon isotope ratios of enamel from Earl’s Bu cattle mandibular molars.

Third molars							
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 (‰)
MH03 (M_3), LM, wear stage g cusp to cervix 32.0 mm				MH125 (M_3), LM, wear stage g cusp to cervix 32.0 mm			
1	29.5	24.8	-12.1	1	30.0	23.6	-13.0
2	26.5	24.6	-12.1	2	27.0	23.8	-13.1
3	23.5	24.7	-11.8	3	24.0	23.6	-13.0
4	20.0	23.9	-12.1	4	21.0	23.5	-13.3
5	17.5	23.4	-12.1	5	18.0	23.9	-13.4
6	13.5	23.7	-12.2	6	15.0	24.0	-13.5
7	10.5	23.6	-12.4	7	12.0	24.7	-13.5
8	7.0	24.0	-12.7	8	9.0	25.2	-13.5
9	4.0	24.4	-12.7	9	6.0	25.8	-13.4
				10	3.5	26.3	-13.1
MH128 (M_3), LM, wear stage g cusp to cervix 33.5 mm				MH133 (M_3), LM, wear stage d cusp to cervix 50.0 mm			
1	31.5	23.2	-13.2	1	43.5	21.5	-12.6
2	28.0	24.1	-13.1	2	38.0	21.1	-12.6
3	25.0	24.8	-13.1	3	33.0	21.5	-12.6
4	22.5	25.5	-12.9	4	28.0	22.5	-12.8
5	19.0	25.8	-12.7	5	23.5	24.0	-12.7
6	16.0	26.2	-12.5	6	18.0	25.0	-12.4
7	12.5	26.0	-12.4	7	13.0	25.7	-12.2
8	10.0	25.7	-12.3	8	7.5	25.2	-12.3
9	7.0	25.0	-12.4	9	2.5	24.2	-12.3
10	3.5	24.2	-12.5				
MH138 (M_3), LM, wear stage f cusp to cervix 44.5 mm				MH140 (M_3), LM, wear stage f cusp to cervix 46.5 mm			
1	42.5	24.8	-12.8	1	38.5	23.6	-12.0
2	39.5	24.4	-12.9	2	31.0	23.4	-12.1
3	36.0	24.2	-12.8	3	27.0	23.3	-12.2
4	33.0	23.9	-12.9	4	24.0	23.2	-12.3
5	30.0	23.6	-13.0	5	20.5	23.1	-12.4
6	27.0	24.3	-12.9	6	17.0	23.5	-12.5
7	24.0	24.5	-13.2	7	13.5	23.8	-12.4
8	21.0	24.6	-13.0	8	10.5	23.9	-12.4

9	18.5	25.0	-12.6
10	15.5	25.5	-12.4
11	12.5	25.9	-12.4
12	9.5	25.0	-12.3
13	7.0	24.8	-12.4
14	3.5	23.9	-12.5

MH149 (M_3), LM, wear stage h
cusp to cervix 30.5
mm

1	28.5	23.6	-12.1
2	25.0	23.4	-12.1
3	22.0	23.4	-12.1
4	19.0	23.9	-12.2
5	16.0	24.2	-12.1
6	13.0	24.4	-12.1
7	10.0	24.9	-12.2
8	7.0	25.4	-12.3
9	4.0	25.7	-12.3

MH163 (M_3), LM, wear stage b
cusp to cervix 44.0
mm

1	41.5	25.9	-12.0
2	38.5	25.6	-11.6
3	34.0	24.9	-11.5
4	28.5	24.2	-11.7
5	25.0	24.0	-11.7
6	21.5	23.7	-11.8
7	18.0	23.7	-11.9
8	14.5	23.7	-12.1
9	11.0	24.0	-12.2
10	8.0	24.5	-12.4
11	4.5	25.1	-12.3

MH0604 (M_3), LM, wear stage f
cusp to cervix 45.0
mm

1	42.0	26.0	-11.9
2	38.5	26.1	-11.8
3	35.5	26.3	-11.8

9	7.0	24.0	-12.1
10	3.0	25.7	-11.9

MH162 (M_3), LM, wear stage d
cusp to cervix 43.5
mm

1	42.0	25.1	-11.7
2	39.0	25.5	-11.4
3	36.0	25.0	-11.2
4	33.0	24.2	-11.2
5	29.5	23.8	-11.3
6	26.0	23.8	-11.3
7	23.0	23.6	-11.5
8	20.0	23.8	-11.7
9	16.5	23.8	-11.7
10	10.5	24.7	-12.0
11	7.0	25.3	-12.1
12	4.0	25.8	-12.0

MH174 (M_3), LM, wear stage f
cusp to cervix 40.0
mm

1	37.5	25.8	-12.2
2	34.0	24.8	-12.2
3	31.0	24.6	-12.2
4	28.0	24.0	-12.2
5	25.0	23.8	-12.4
6	22.0	23.5	-12.5
7	19.0	23.6	-12.5
8	16.0	23.6	-12.8
9	13.0	23.8	-12.9
10	10.0	24.3	-12.7
11	7.0	24.7	-12.6
12	4.0	25.5	-12.3

4	32.5	26.0	-11.8				
5	29.5	25.6	-11.7				
6	27.0	25.4	-11.8				
7	24.0	24.9	-11.8				
8	21.0	24.4	-11.8				
9	18.0	24.2	-11.9				
10	15.5	23.8	-12.1				
11	12.5	23.6	-12.1				
12	9.5	23.5	-12.2				
13	6.5	23.6	-12.3				
14	3.5	23.7	-12.4				

Second molars

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 (‰)
MH03 (M_2), LM, wear stage k cusp to cervix 28.5 mm				MH84 (M_2), LD, wear stage c cusp to cervix 48.5 mm			
1	25.5	23.5	-12.8	1	46.0	23.7	-13.2
2	22.0	23.5	-12.7	2	43.0	23.9	-12.9
3	18.5	24.0	-12.6	3	40.0	23.9	-12.7
4	15.5	23.9	-12.7	4	36.5	23.8	-12.6
5	12.5	24.1	-12.7	5	33.0	23.7	-12.6
6	9.5	24.4	-12.6	6	30.0	23.8	-12.4
7	6.5	24.5	-12.6	7	27.0	24.3	-12.3
8	3.5	25.4	-12.5	8	24.0	24.2	-12.3
				9	20.5	24.7	-12.2
				10	17.5	25.4	-12.2
				11	14.0	26.0	-12.1
				12	11.0	26.4	-12.1
				13	8.0	26.4	-12.1
				14	4.5	26.0	-12.3
MH125 (M_2), LD, wear stage k cusp to cervix 28.0 mm				MH128 (M_2), LM, wear stage k cusp to cervix 22.0 mm			
1	26.0	23.7	-12.9	1	20.0	25.0	-12.7
2	23.0	24.2	-12.9	2	17.0	25.4	-12.4
3	20.0	24.6	-12.7	3	14.0	25.5	-12.3
4	17.5	25.0	-12.6	4	11.0	25.0	-12.2
5	14.5	25.8	-12.6	5	5.5	23.7	-12.4
6	11.5	26.4	-12.6	6	3.0	23.6	-12.6
7	8.0	26.9	-12.5				

8	5.0	26.7	-12.6				
9	2.5	26.8	-12.6				
MH133 (M_2), LM, wear stage j cusp to cervix 42.5 mm				MH138 (M_2), LM, wear stage k cusp to cervix 35.0 mm			
1	34.0	21.3	-12.9	1	33.0	24.4	-12.6
2	30.5	21.6	-12.9	2	30.0	24.9	-12.4
3	27.5	22.3	-12.9	3	27.0	25.0	-12.2
4	24.0	22.7	-12.7	4	24.0	25.4	-12.3
5	20.5	23.8	-12.7	5	21.0	26.4	-12.3
6	17.0	24.6	-12.4	6	18.5	26.6	-12.4
7	13.0	25.6	-12.2	7	15.5	26.3	-12.3
8	9.0	25.4	-11.9	8	12.5	26.3	-12.6
9	5.5	24.7	-12.0	9	9.5	25.9	-12.6
10	2.0	24.3	-11.9	10	6.5	25.3	-12.6
				11	3.5	24.9	-12.6
MH140 (M_2), LM, wear stage j cusp to cervix 42.0 mm				MH0604 (M_2), LM, wear stage j cusp to cervix 32.5 mm			
1	38.0	23.2	-12.1	1	29.0	24.6	-12.7
2	33.5	23.2	-11.8	2	26.0	24.4	-12.8
3	30.0	23.9	-11.8	3	23.5	24.4	-12.7
4	26.5	23.9	-11.8	4	20.5	24.1	-12.6
5	23.0	24.6	-11.8	5	18.0	24.2	-12.6
6	19.5	24.8	-11.8	6	15.0	24.4	-12.5
7	16.0	25.5	-11.6	7	12.0	24.6	-12.6
8	12.5	25.6	-11.7	8	9.0	24.7	-12.5
9	9.0	25.5	-11.8	9	6.0	24.6	-12.6
10	6.0	25.4	-11.9	10	3.0	25.6	-12.4
11	3.0	24.4	-12.0				

First molars							
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 (‰)
MH03 (M_1), LM, wear stage l/k cusp to cervix 17.5 mm				MH84 (M_1), LD, wear stage g cusp to cervix 38.5 mm			
1	15.0	26.4	-13.8	1	34.0	24.6	-16.5
2	11.5	26.1	-13.3	2	30.5	25.4	-16.3
3	7.5	25.9	-12.9	3	27.0	25.9	-15.9

4	4.0	24.6	-12.6	4	23.5	25.8	-15.2
				5	20.0	25.9	-14.5
				6	16.5	25.7	-13.9
				7	12.5	25.6	-13.4
				8	9.0	24.9	-13.3
				9	5.5	24.6	-13.1
MH125 (M_1), LD, wear stage k cusp to cervix 19.5 mm				MH128 (M_1), LM, wear stage l cusp to cervix 13.5 mm			
1	17.5	26.8	-14.3	1	11.5	24.8	-13.1
2	14.5	26.8	-13.6	2	8.5	24.6	-12.8
3	11.5	26.4	-13.1	3	5.5	24.1	-12.6
4	9.0	25.9	-12.7	4	2.5	24.1	-12.7
5	6.5	25.6	-12.6				
6	3.5	25.5	-12.6				
MH133 (M_1), LD, wear stage ? cusp damaged				MH138 (M_1), LM, wear stage k cusp to cervix 23.5 mm			
1	18.5	23.9	-13.4	1	22.5	26.3	-14.9
2	15.5	23.4	-13.2	2	20.0	26.1	-14.2
3	13.0	23.4	-12.9	3	17.0	25.5	-13.7
4	7.0	22.8	-13.0	4	15.0	25.3	-13.5
5	4.0	22.8	-13.0	5	12.0	25.5	-13.5
				6	9.5	24.8	-13.3
				7	6.5	24.8	-13.2
				8	4.0	24.2	-13.3
MH0604 (M_1), LM, wear stage k cusp to cervix 22.0 mm							
1	19.0	25.6	-15.6				
2	16.5	26.0	-15.3				
3	13.5	26.4	-14.9				
4	11.0	26.2	-14.5				
5	8.0	26.6	-14.1				
6	5.5	26.6	-13.7				
7	3.0	26.3	-13.9				

Table 6b: Intra-tooth oxygen and carbon isotope ratios of enamel from Mine Howe cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal (Results for MH84, MH138 and MH0604 have previously been published in Towers et al. 2014)

Table 7 Statistics for microwear variables for the dP4 (a) and M1 (a) in the Earl's Bu and Mine Howe sheep; lists mean values, range and standard deviation (Std. Dev.) for total defect frequency, striation frequency, the ratio of pits to striations (expressed a percentage of total defects), striation length, breadth and orientation. Statistically significant differences (Student's T-test, $p<0.05$) are indicated by an asterisk.

	Earl's Bu (n=5)		**Mine Howe (n=7)**	
Variable	mean	Std. Dev	mean	Std. Dev
Total number of defects (dn)*	26.4	17.16	87	97.43
Total number of striations (sn)*	26.0	16.75	82.14	93.3
Percentage of pits (%pits)*	1.06	1.53	6.9	5.61
Striation length (sl)	46.82	10.63	69.32	22.61
Striation breadth (sb)	1.31	.22	2.08	0.64
Striation long axis orientation (slo)	71.18	19.73	107.12	38.78

Table 7a Statistics for microwear variables for the dP4 in the Earl's Bu and Mine Howe sheep

	Earl's Bu (n=9)		**Mine Howe (n=8)**	
Variable	mean	Std. Dev	mean	Std. Dev
Total number of defects (dn)*	18.88	5.67	88.78	62.85
Total number of striations (sn)*	18.13	5.96	86.33	62.84
Percentage of pits (%pits)	5.44	8.54	3.77	3.61
Striation length (sl)	77.49	22.98	80.34	18.05
Striation breadth (sb)	2.14	0.22	1.76	0.40
Striation long axis orientation (slo)	70.0	34.05	96.45	34.31

Table 7b Statistics for microwear variables for the M1 in the Earl's Bu and Mine Howe sheep

Category	**Age**	**Mine Howe (n=35)**		**Earls Bu (n=2)**	
		n	%	n	%
Foetus	<7-8 m gestation	3	9		
Late Foetus – Newborn	7-8m gestation – birth	10	29		
Newborn-Neonate	Birth- 2 weeks	8	22		
Infant	2-4 weeks	3	9	1	50
Juvenile	>1 month	11	31	1	50

Table 8 Frequencies of foetal and neonatal cattle mandibles at Earl's Bu and Mine Howe based on dental development stages outlined in Brown & Chapman (1991) and the modern known-age foetal/neonatal mandibles summarised in Table 3.

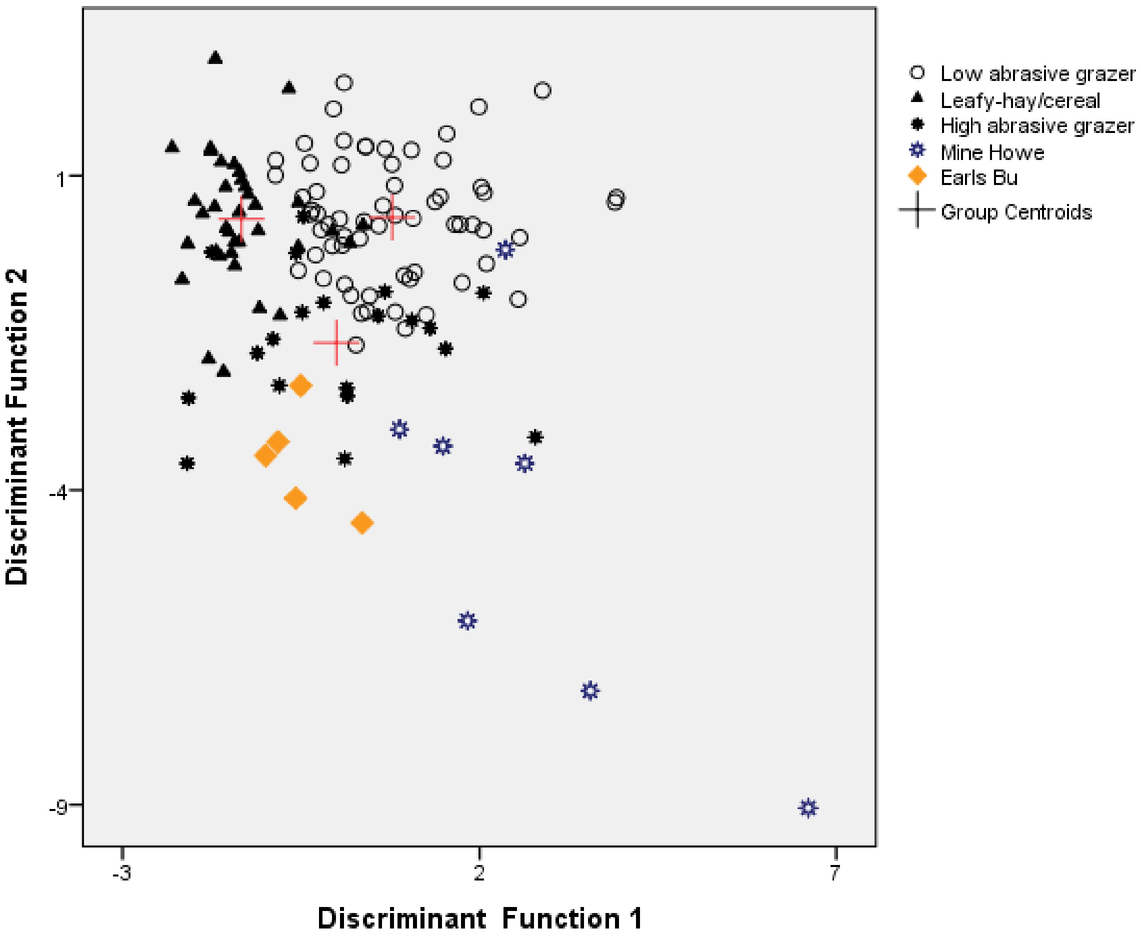


Figure 1. Stepwise discriminant analysis plot for known diet sheep/goat used in the classification of the juvenile archaeological mandibles from Earl's Bu and Mine Howe (after Mainland 2006).

Figure 2 Sheep/goat (a) and cattle (b) mortality profiles from Earl's Bu and Mine Howe (see also Table 2)

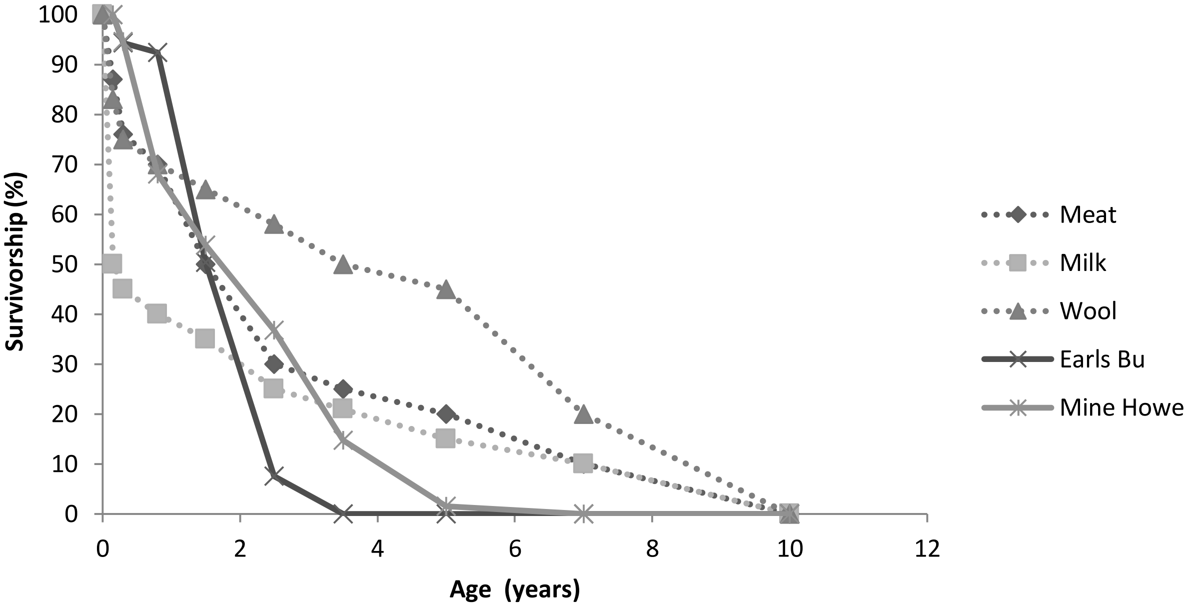


Fig. 2a Sheep/goat mortality profiles for Earl's Bu and Mine Howe (after Payne 1973). Ages in adults (greater than c. 4 years) are an approximation.

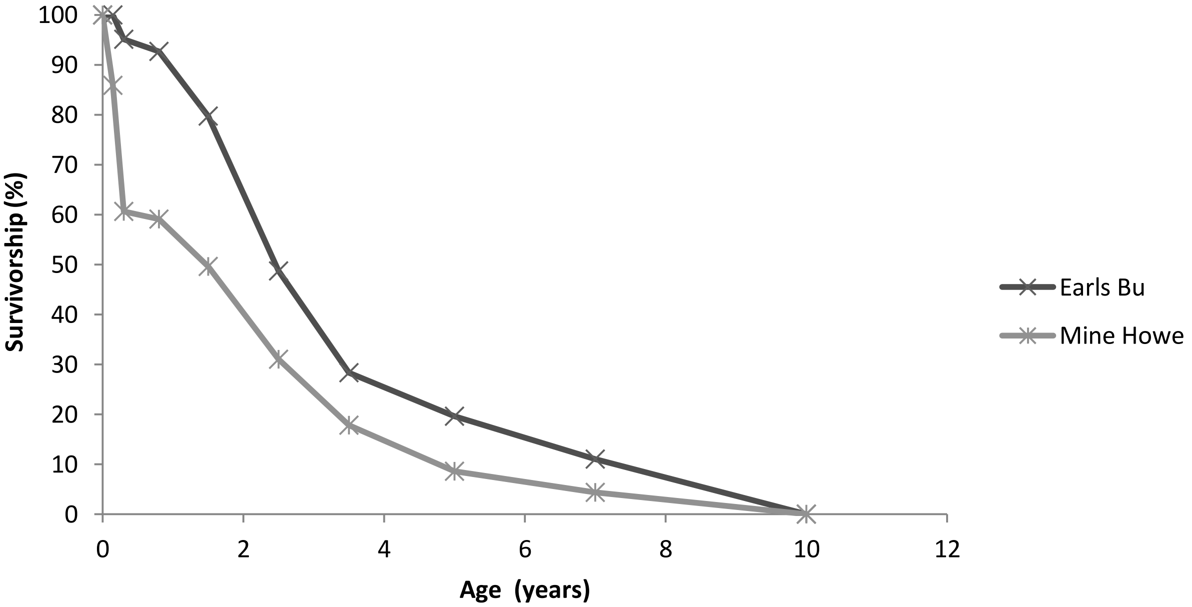
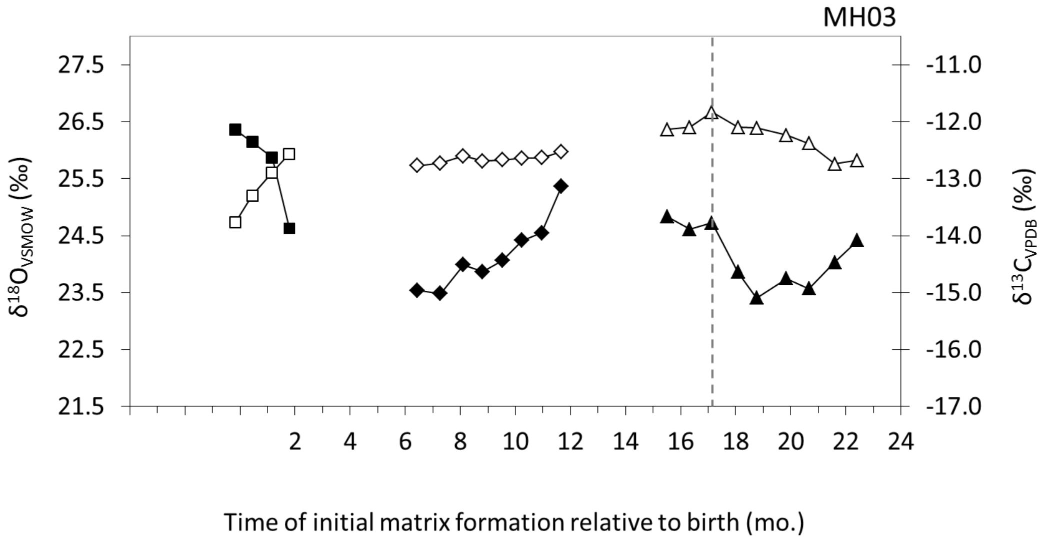
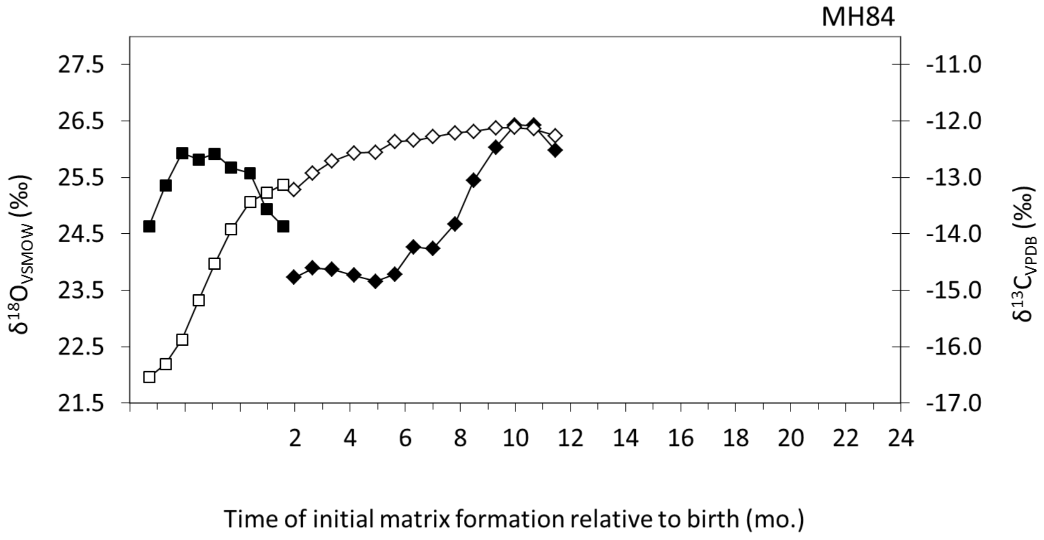
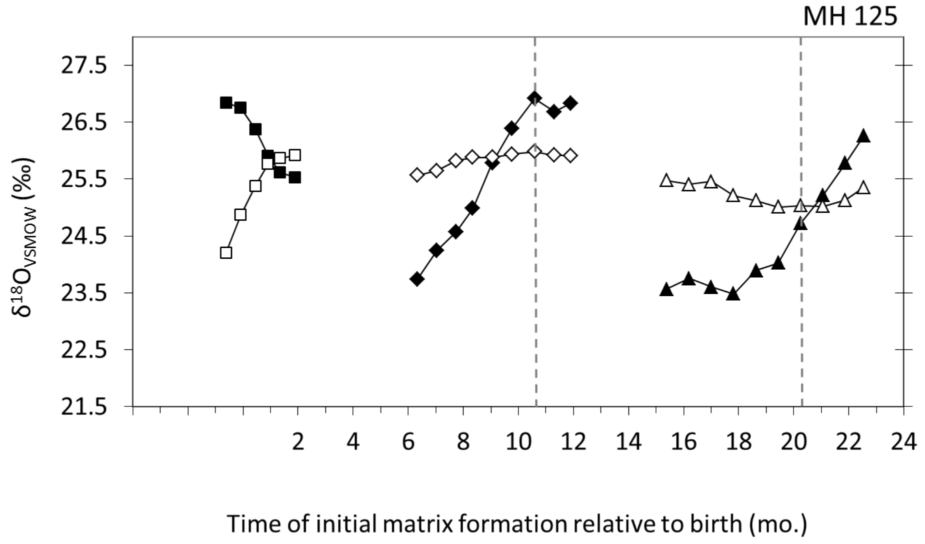
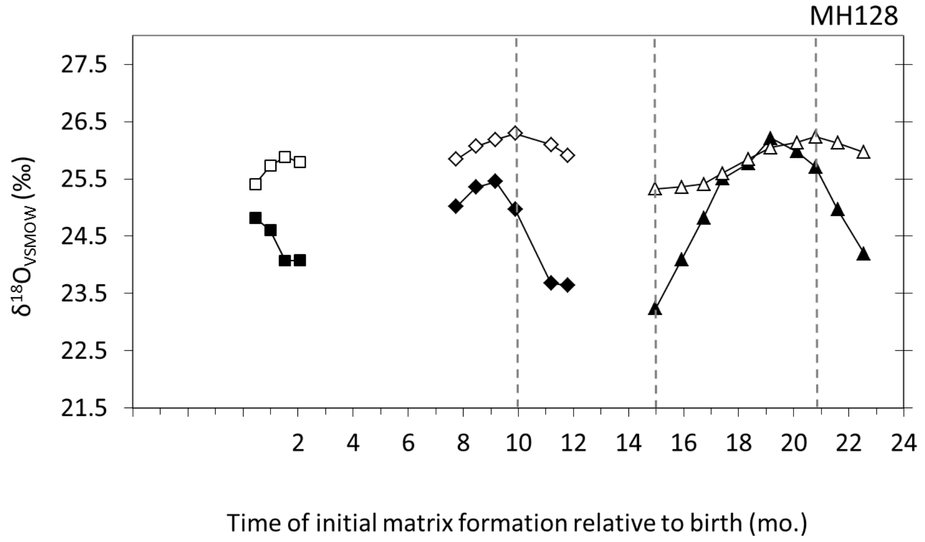


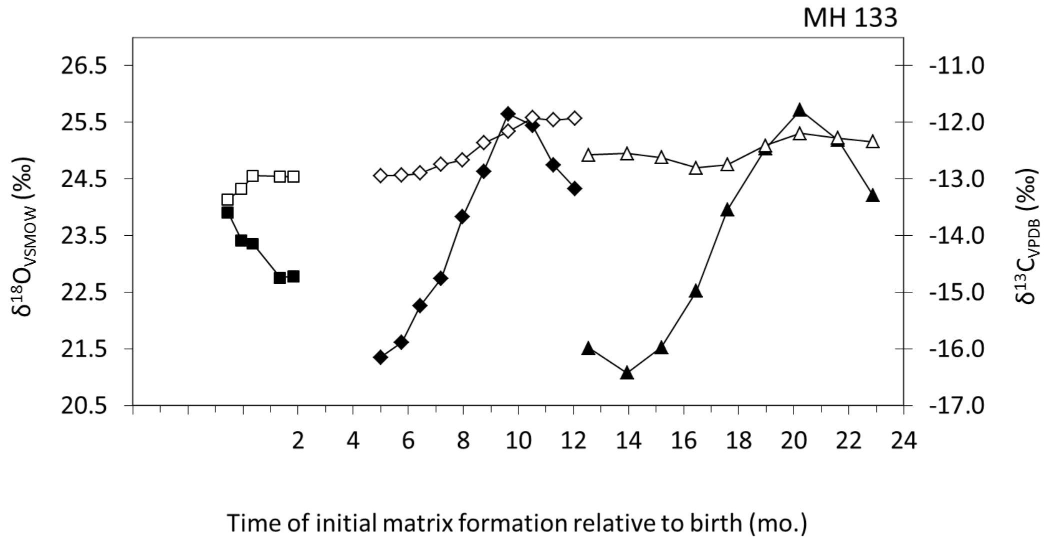
Fig. 2b Cattle mortality profiles for Earl's Bu and Mine Howe. Ages in adults (greater than c. 36 months) are an approximation.

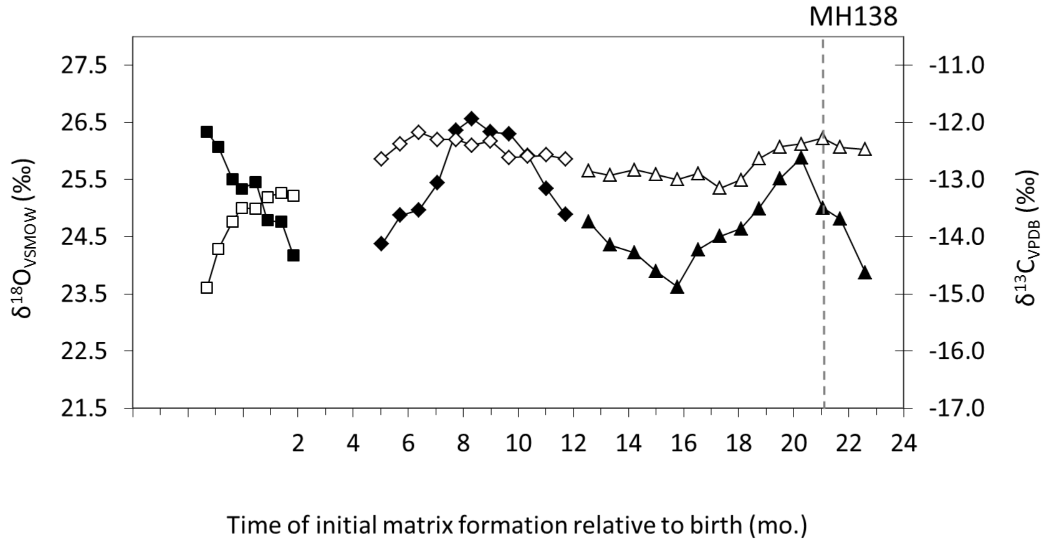

MH03
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

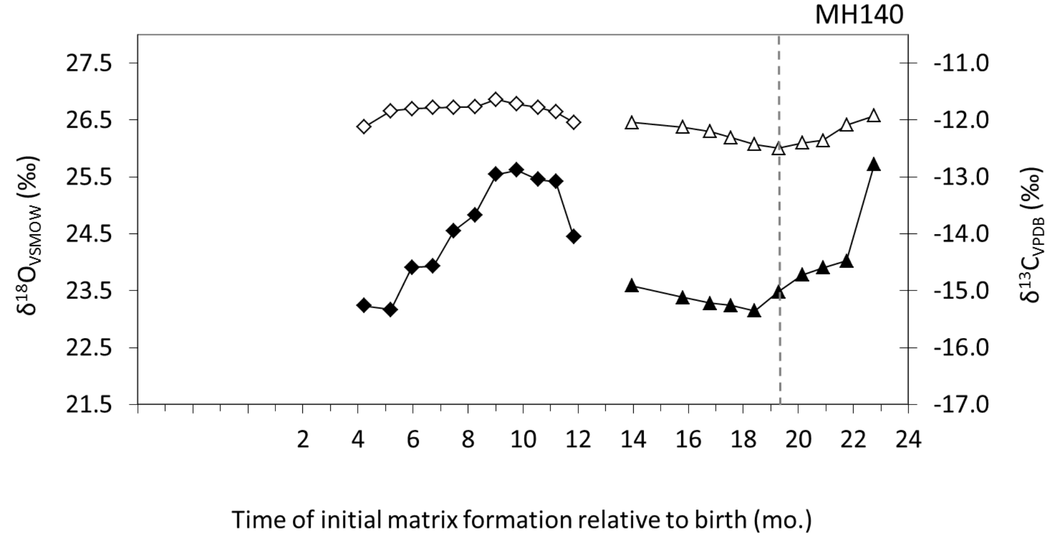

MH84
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

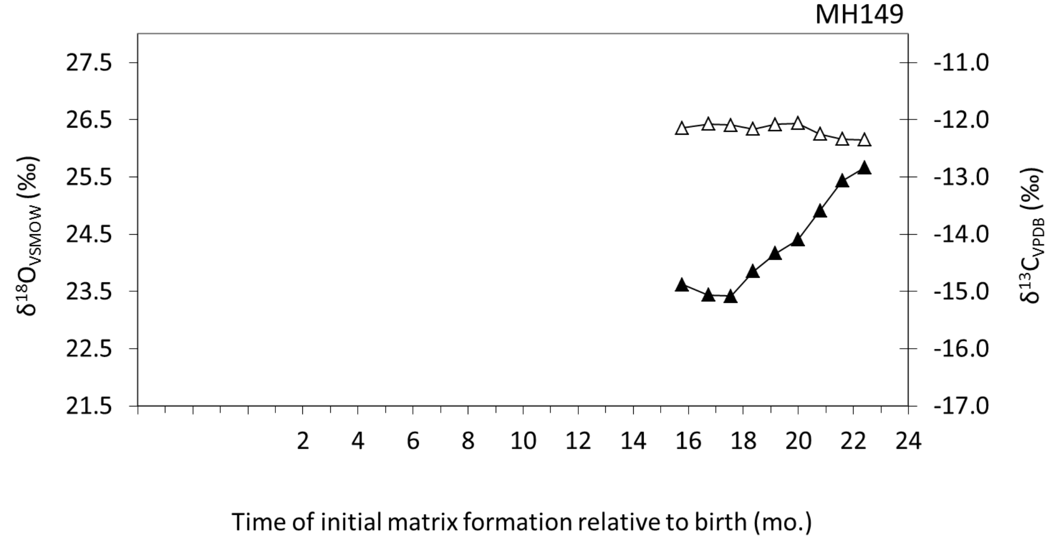

MH 125
δ18OVSMOW (‰)
δ13CVPDB (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

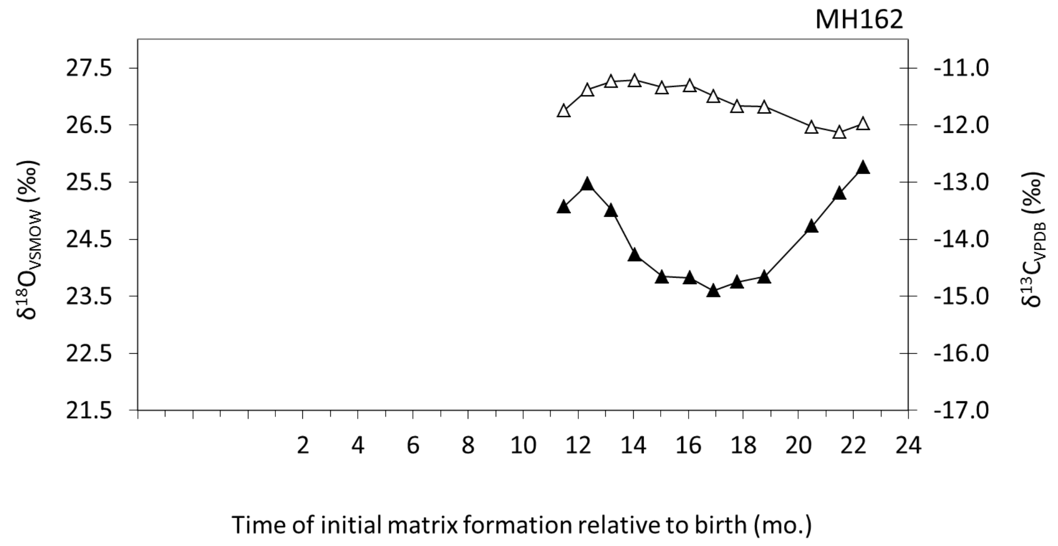

MH128
δ18OVSMOW (‰)
δ13CVPDB (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

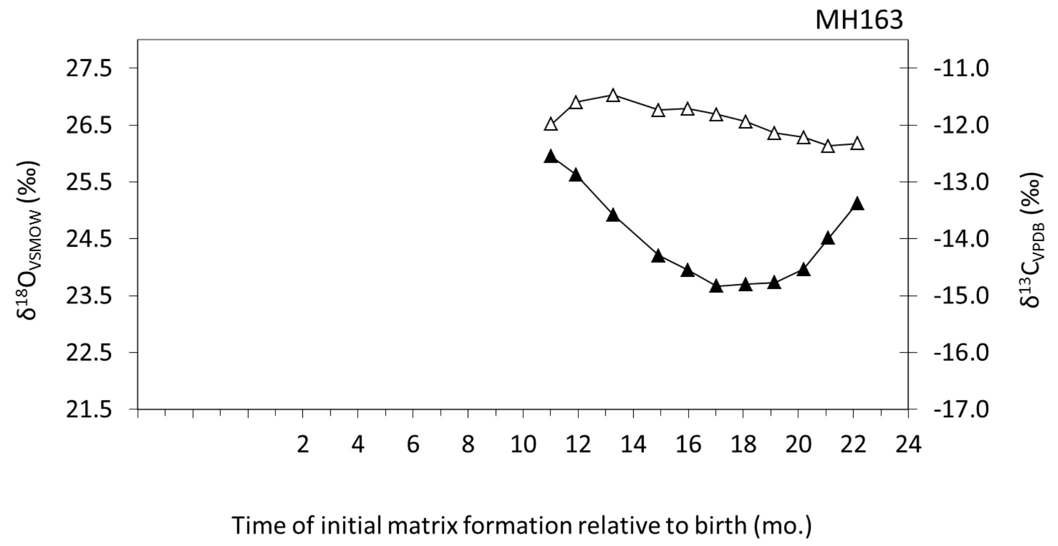

MH 133
δ18OVSMOW (‰)
26.5
25.5
24.5
23.5
22.5
21.5
20.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


MH138
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


MH140
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


MH149
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


MH162
27.5
26.5
25.5
24.5
23.5
22.5
21.5
$\delta^{18}O_{VSMOW}$ (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{13}C_{VPDB}$ (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


MH163
27.5
26.5
25.5
24.5
23.5
22.5
21.5
$\delta^{18}O_{VSMOW}$ (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{13}C_{VPDB}$ (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

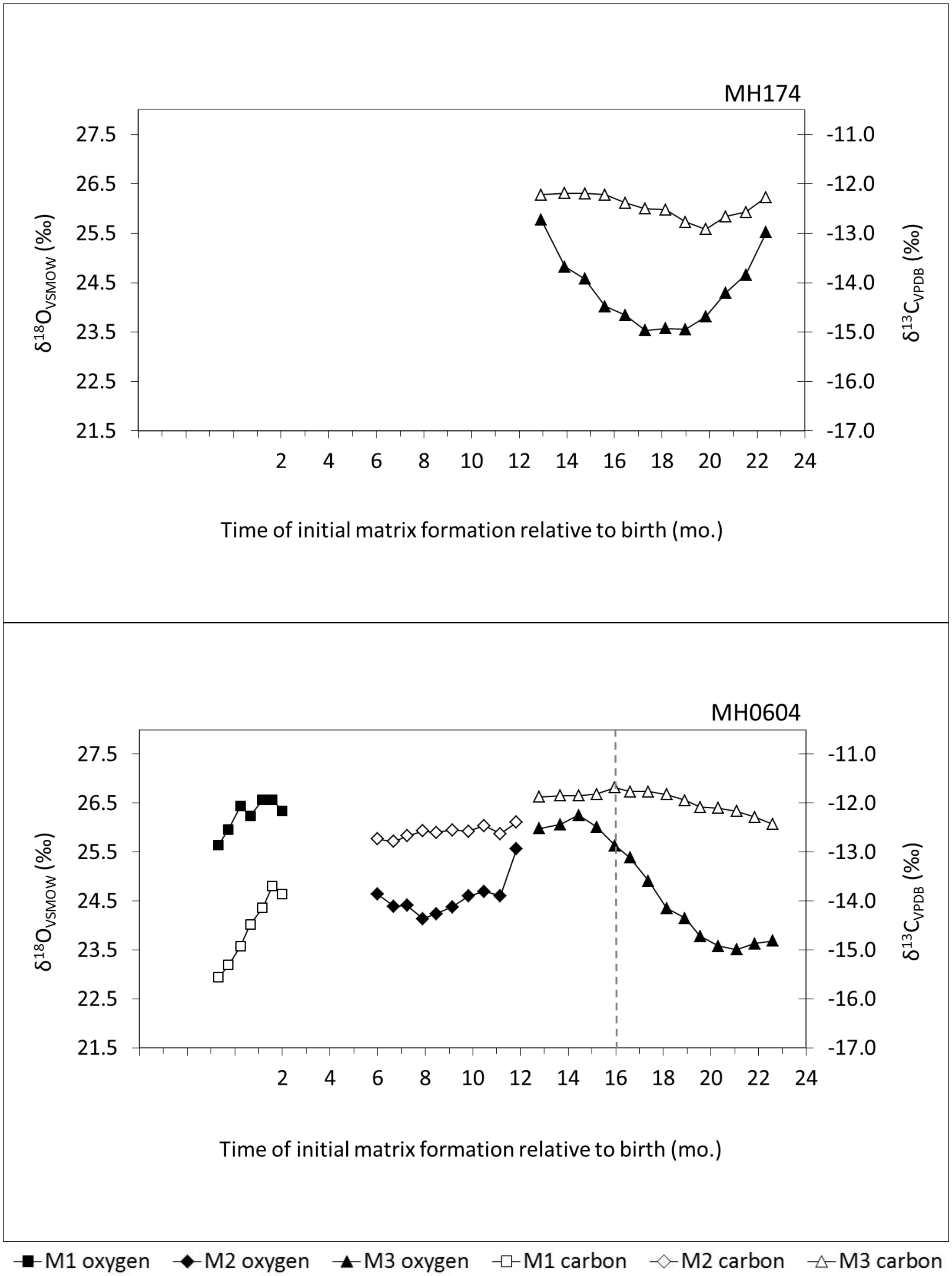


Figure 3. Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from 12 Mine Howe cattle. The dashed lines indicate features discussed in the text. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

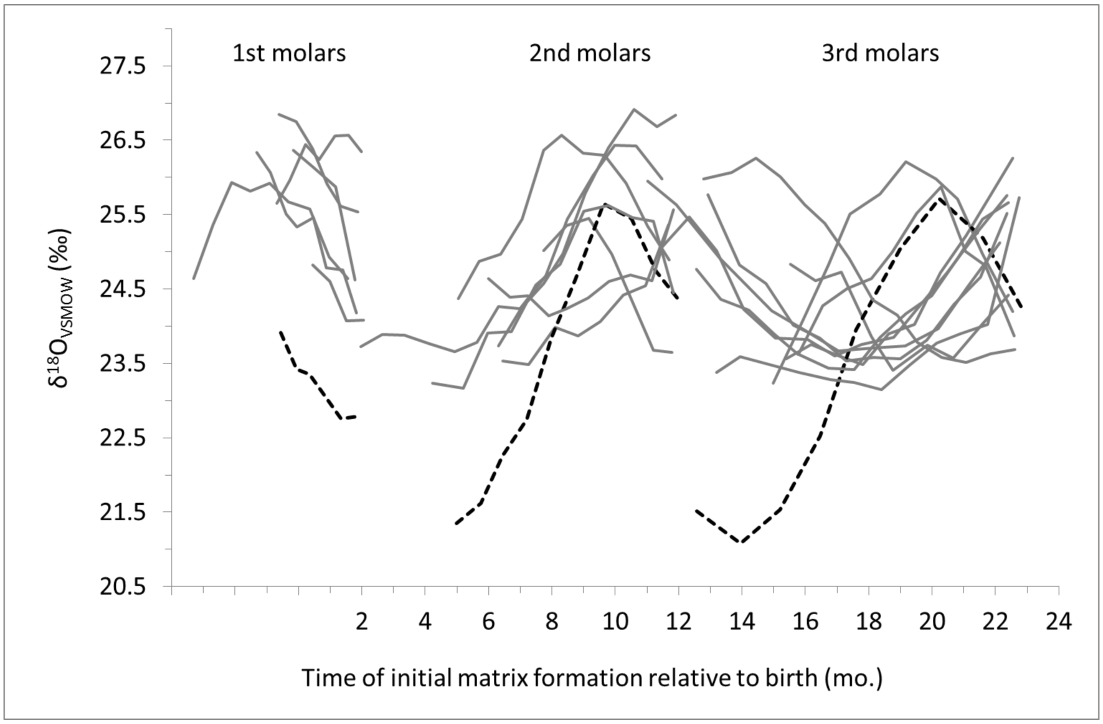


Figure 4. $\delta^{18}O$ profiles for first, second and third cattle molar enamel from 12 Mine Howe cattle. The dashed profile is for MH133. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

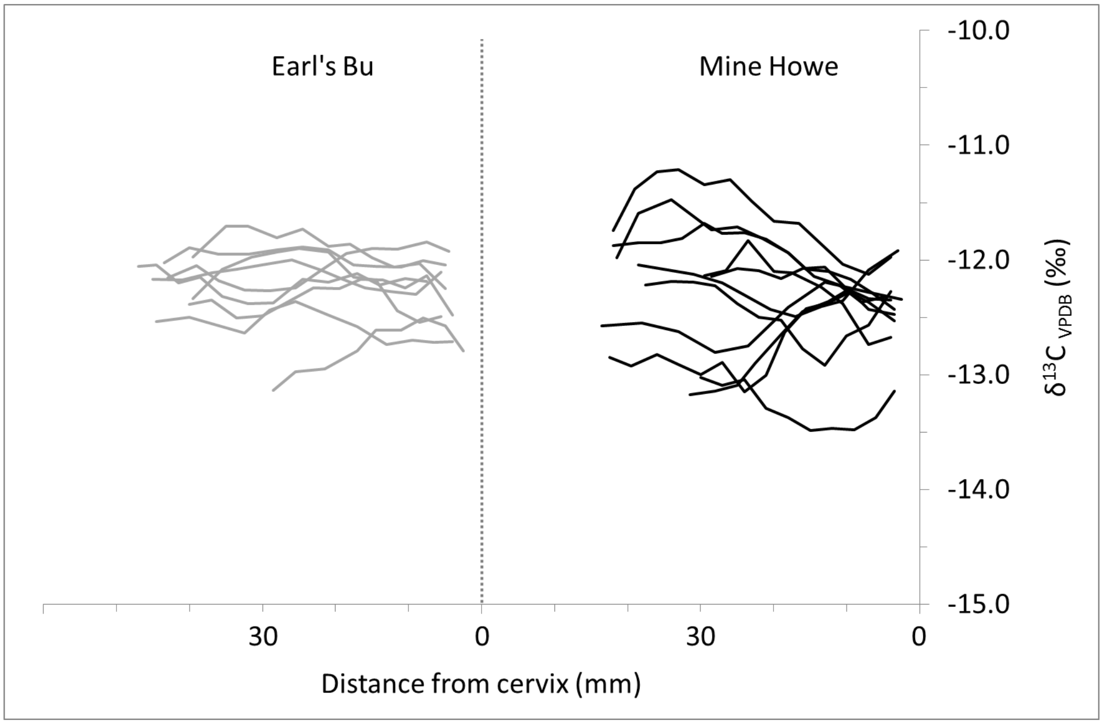


Figure 5a. Intra-tooth enamel $\delta^{13}C_{VPDB}$ values versus distance from cervix for Mine Howe and Earl's Bu cattle third molars. Analytical error is ± 0.1 ‰ (1σ).

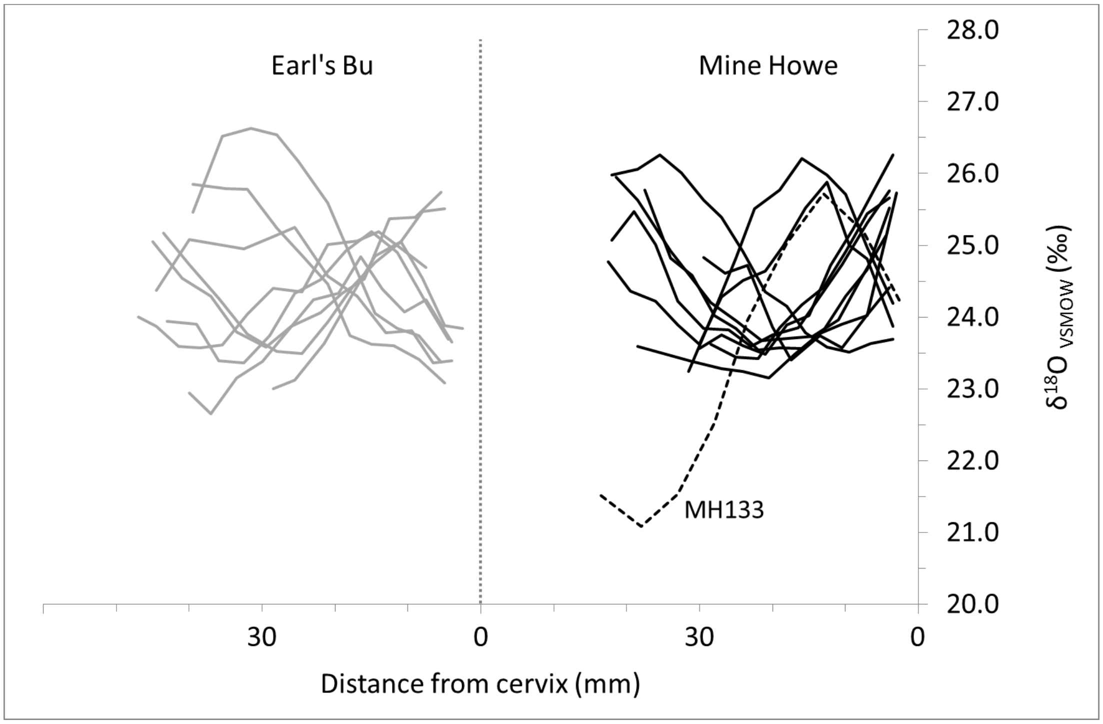
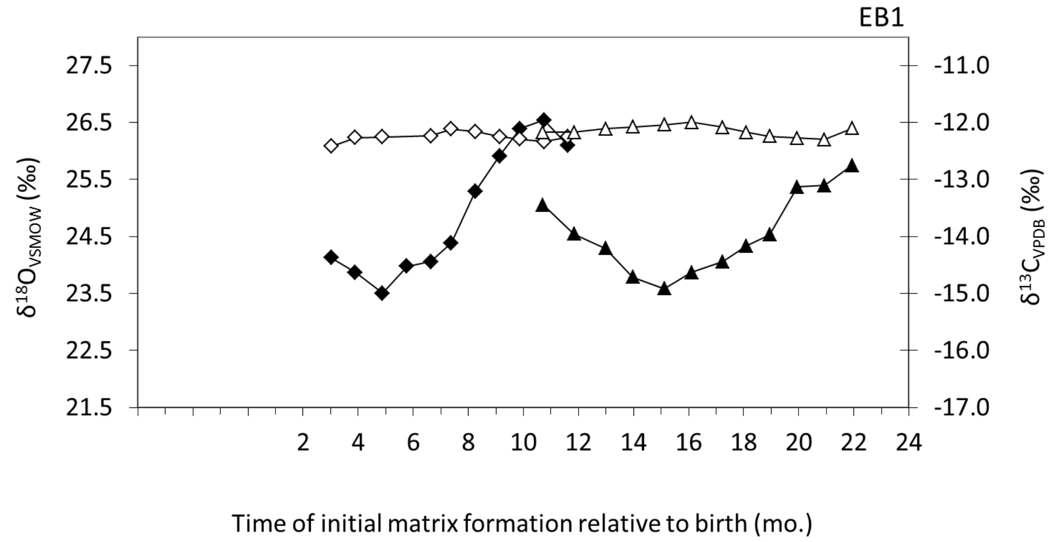
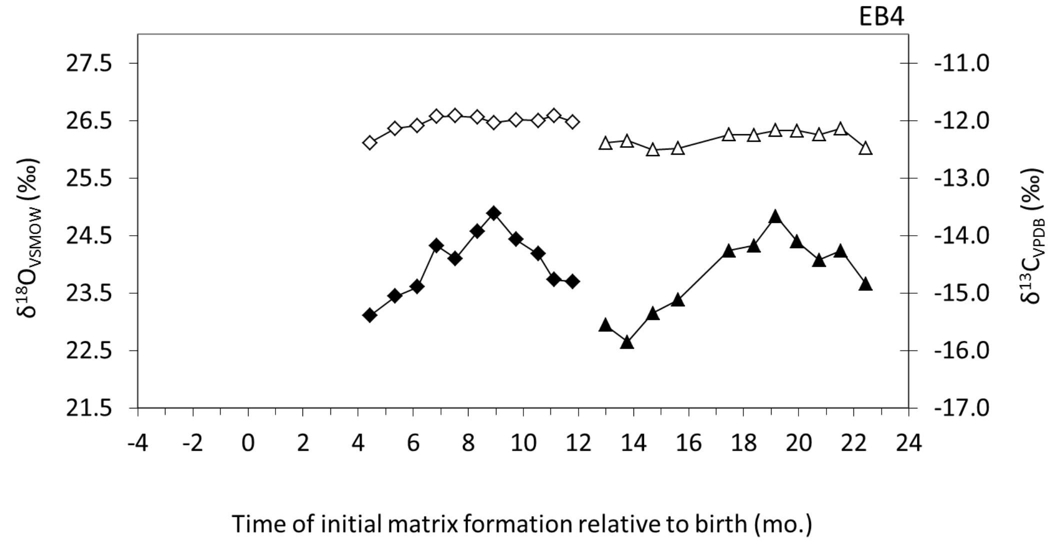
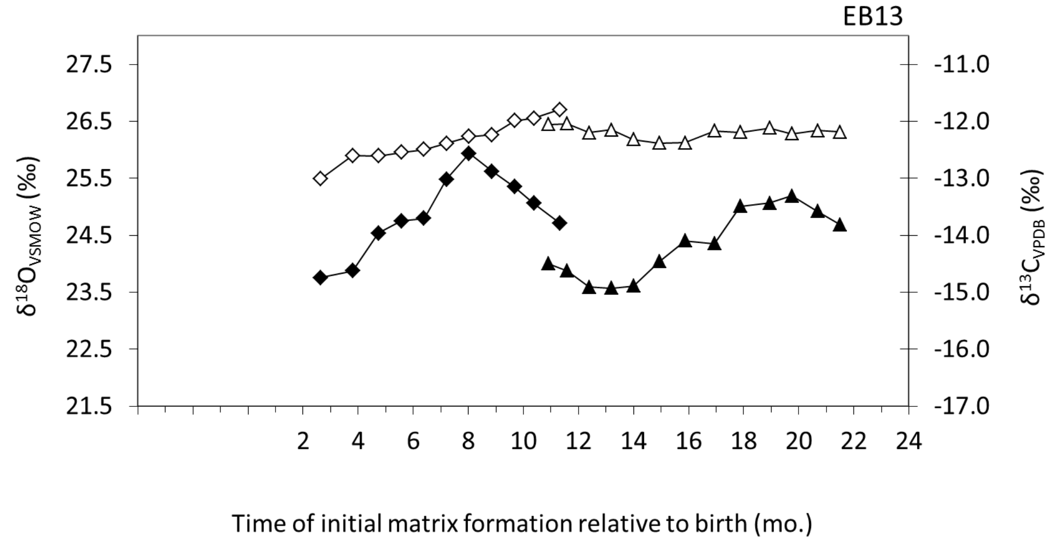
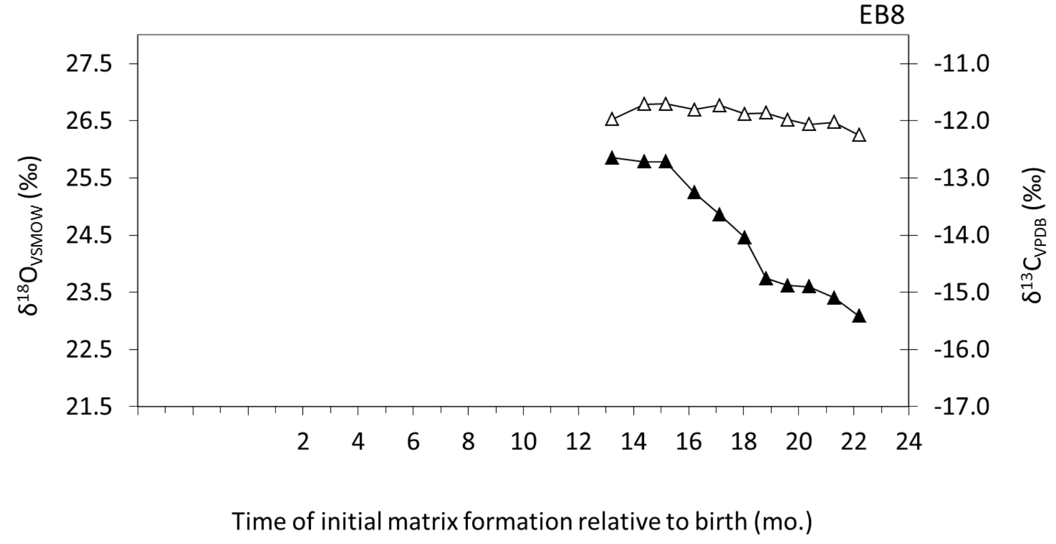


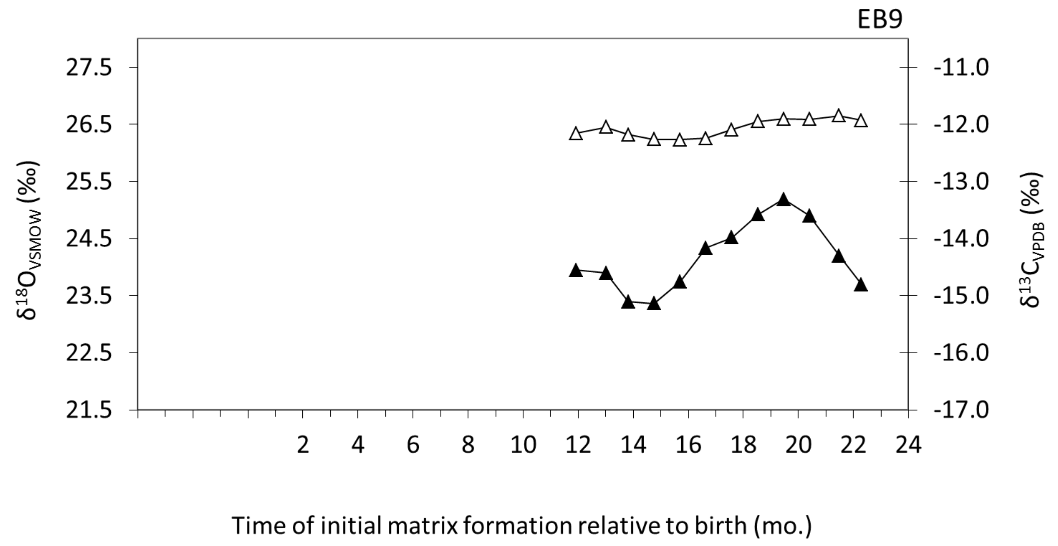
Figure 5b. Intra-tooth enamel $\delta^{18}O_{VSMOW}$ values versus distance from cervix for Mine Howe and Earl's Bu cattle third molars. Analytical error is ± 0.2 ‰ (1σ).

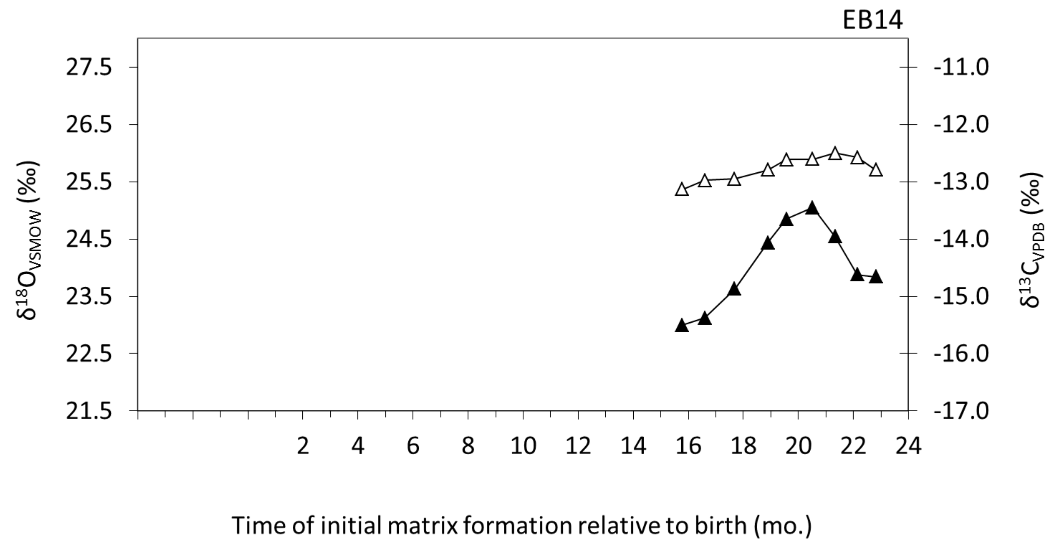

EB1
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

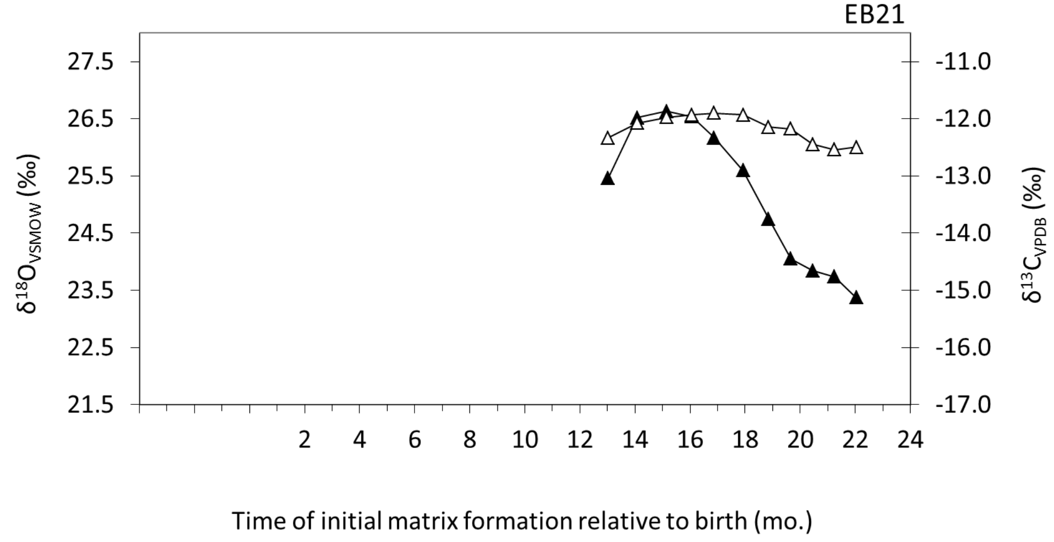

EB4
δ18OVSMOW (‰)
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ13CVPDB (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
-4
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

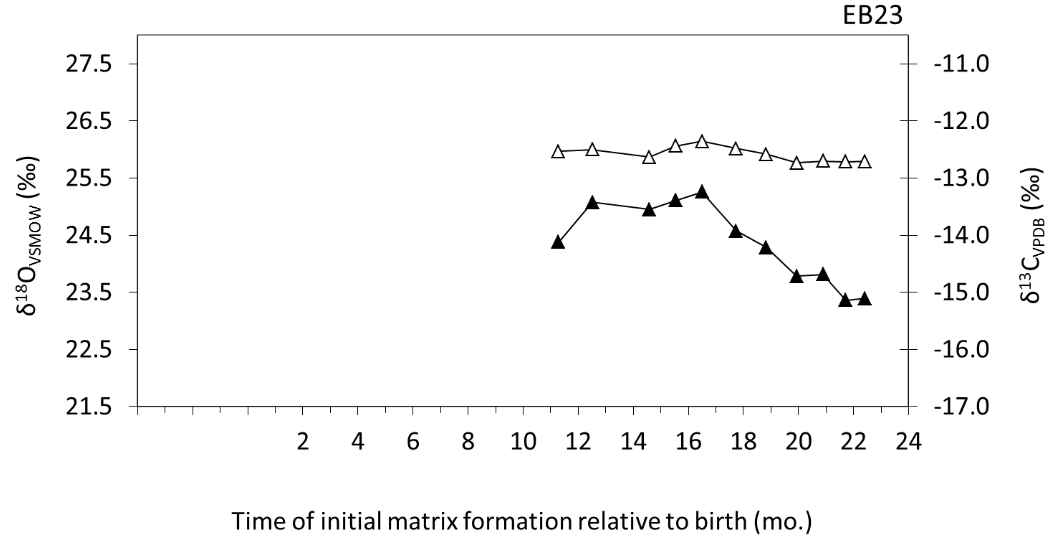

EB13
27.5
26.5
25.5
24.5
23.5
22.5
21.5
$\delta^{18}O_{VSMOW}$ (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{13}C_{VPDB}$ (‰)
2 4 6 8 10 12 14 16 18 20 22 24
Time of initial matrix formation relative to birth (mo.)


EB8
27.5
26.5
25.5
24.5
23.5
22.5
21.5
$\delta^{18}O_{VSMOW}$ (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{13}C_{VPDB}$ (‰)
2 4 6 8 10 12 14 16 18 20 22 24
Time of initial matrix formation relative to birth (mo.)


EB9
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ18OVSMOW (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
δ13CVPDB (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


EB14
27.5
26.5
25.5
24.5
23.5
22.5
21.5
δ18OVSMOW (‰)
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
δ13CVPDB (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


EB21
27.5
26.5
25.5
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{18}O_{VSMOW}$ (‰)
$\delta^{13}C_{VPDB}$ (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)


EB23
27.5
26.5
25.5
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
$\delta^{18}O_{VSMOW}$ (‰)
$\delta^{13}C_{VPDB}$ (‰)
2
4
6
8
10
12
14
16
18
20
22
24
Time of initial matrix formation relative to birth (mo.)

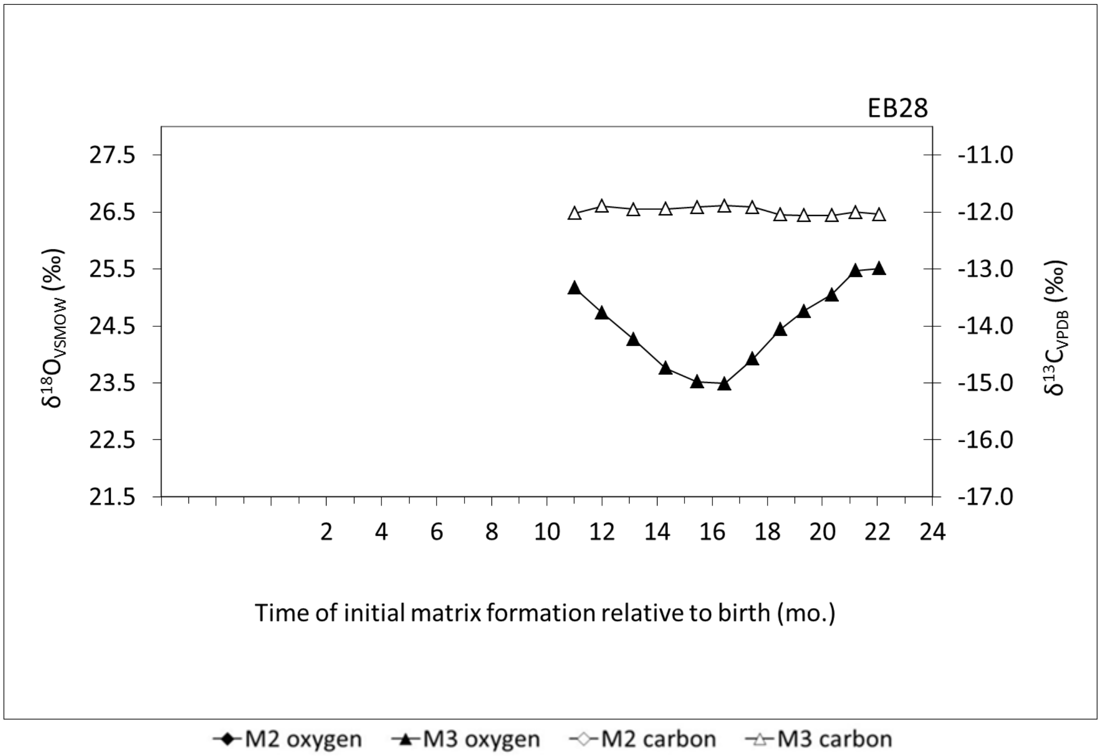


Figure 6. Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for second and third cattle molar enamel from nine Earl's Bu cattle. The x-axis time scale is removed for times earlier than 2 months because of the non-uniformity of first molar matrix progression (Brown et al 1960). Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

Figure 7. Frequency of accentuated striae by distance from the CEJ in millimetres in modern and archaeological sheep (Horizontal bars indicate the approximate position of hypoplasia)

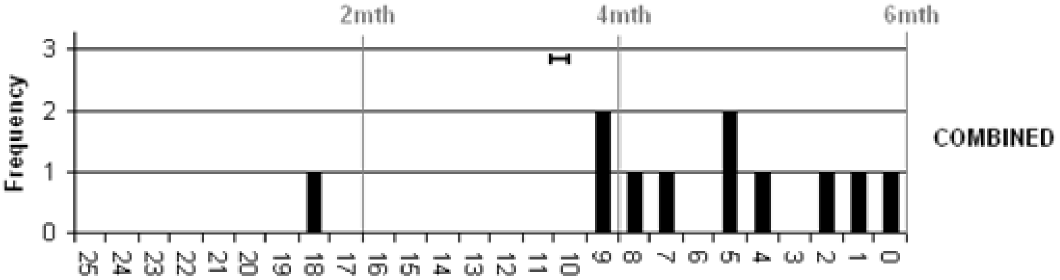


Figure 7a. Modern grazing sheep (n=8) from Orkney, meat-flock, weaned at 5-6 months

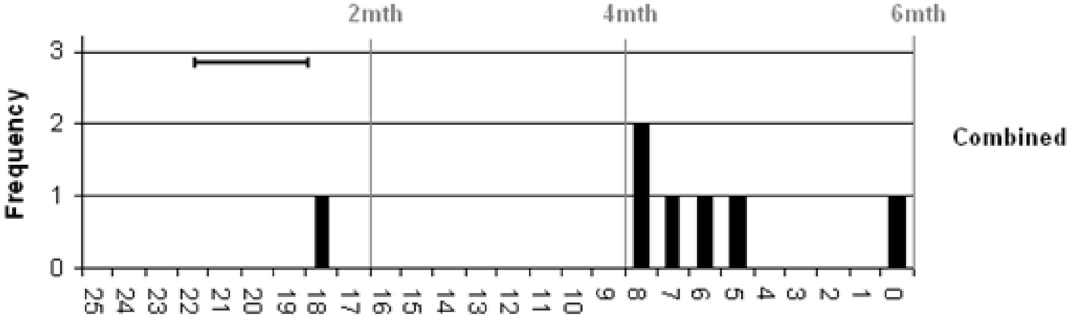


Figure 7b. Modern seaweed- grazing sheep (n=8) from Orkney, weaned naturally at c. 5-6 months

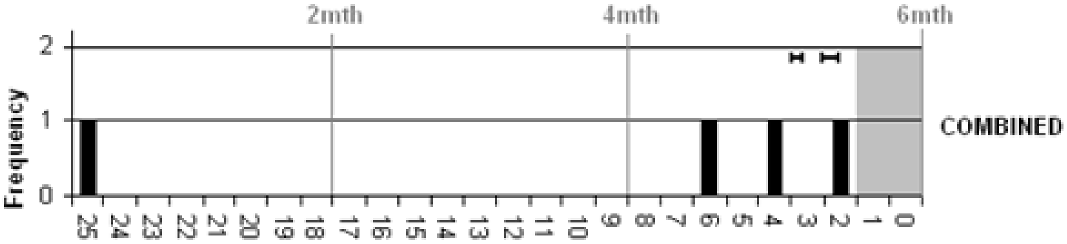


Figure 7c. Modern grazing sheep (n=8) from Greenland, meat-flock weaned at 5-6 months

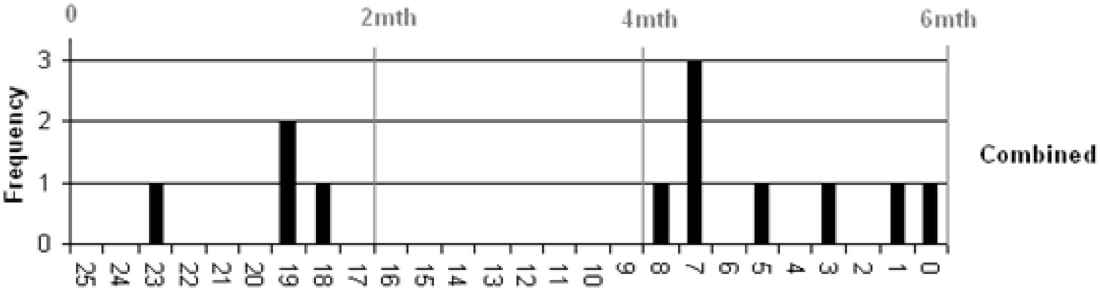


Fig. 7d Earl’s Bu sheep (n=6)

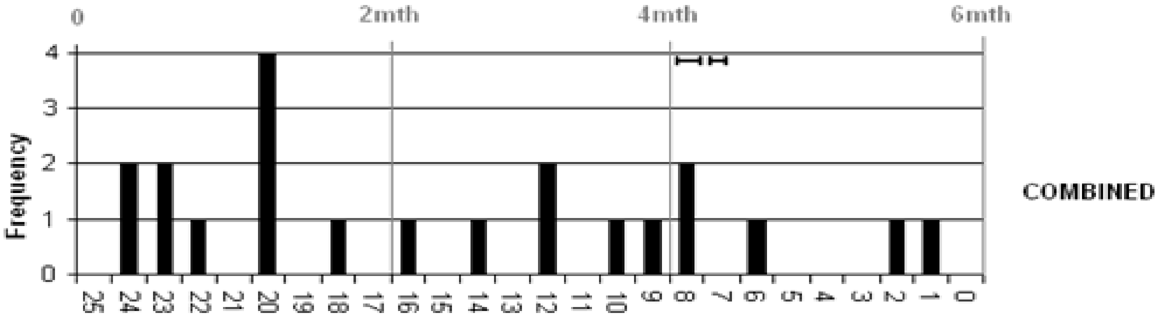


Fig. 7e Mine Howe sheep (n=8)