AN ISOTOPIC INVESTIGATION INTO CALVING SEASONALITY, DIET AND DAIRYING IN BRITISH PREHISTORIC CATTLE

Reconstructing animal husbandry at a sub-annual resolution using multi-isotope analysis and intra-tooth sampling

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submitted for the degree
of Doctor of Philosophy

Division of Archaeological Sciences

University of Bradford

2013

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Keywords

Oxygen, carbon, strontium, enamel, collagen, Northern Isles, Grimes Graves, Chillingham

Abstract

The detection of dairying is essential to understand prehistoric economies, particularly in northwest Europe, where a high degree of lactose tolerance implies that fresh milk has long been a significant dietary component. Domestic cattle (*Bos taurus*) are biologically able to breed year-round, potentially enabling farmers to select a calving strategy to suit their economic focus. Published literature and interviews with farmers suggests that spring calving would have been favoured by economies focussed on meat or storable dairy products, whereas the year-round provision of fresh milk would have required two calving seasons, in spring and autumn, or an extended period through spring, summer and autumn.

This thesis uses intra-tooth isotope ratio analysis of cattle tooth enamel to predict birth seasonality as an indicator of dairying. Analysis was performed on first, second and third cattle molars from the archaeological sites of Mine Howe, Pool and Earl's Bu (Iron Age and Viking period Orkney), Old Scatness (Iron Age Shetland) and Grimes Graves (Bronze Age Norfolk). Modern molars from Chillingham Wild White cattle were also analysed.

A new method to determine cattle birth seasonality has been proposed utilising the isotopic patterning ($\delta^{13}C$, $\delta^{18}O$) recorded within first and second molar enamel. Results suggest that birth seasonality estimates are of sufficient accuracy to discriminate between single-and multiple-season calving. Although Pool and Grimes Graves have been interpreted as dairying sites from their age-at-death slaughter patterns, birth seasonality predictions imply an economy focussed on year-round fresh milk at Pool but an emphasis on storable dairy products at Grimes Graves.

In addition, it has been demonstrated that intra-tooth enamel data can provide information regarding sub-annual variation in diet and environment. A new method to investigate weaning strategy has also been proposed.

Acknowledgements

This research would never have taken place without the enthusiastic encouragement of my MSc and PhD supervisor Dr Janet Montgomery who inspired me to take the plunge. Many, many thanks to Janet who has continued to provide invaluable support, advice and expertise throughout my four years of study, despite her move from Bradford to Durham University. I am also indebted to my other supervisors: Dr Julie Bond for her insightful guidance during the difficult writing phase; Dr Ingrid Mainland (Orkney College UHI) for her in-depth knowledge of Orkney and organisational help with all things Orcadian; and Professor Carl Heron for his encouragement and expertise in tracking down funding. I am also very grateful to the Arts and Humanities Research Council for funding my research and the Division of Archaeological and Environmental Sciences at the University of Bradford for enabling me to pursue it.

Many other people have contributed to this research. With respect to obtaining archaeological samples, I am grateful to the British Museum and Tankerness House Museum, Orkney, for permission to sample cattle molars in their collections, particularly Gillian Varndell and Marianne Eve (British Museum), and Linda Aiano (Tankerness House Museum). Thanks also to Dr Ingrid Mainland, Dr Julie Bond and Dr Julia Cussans for the provision of cattle molars stored at the University of Bradford, and to the late Professor Tony Legge (University of Cambridge) for facilitating sampling at the British Museum. Regarding the sampling of modern materials, I am indebted to Chris Leyland (Chillingham Park Manager) Professor Stephen Hall (University of Lincoln), Del Ross and Ben Leyland for their help in the collection of Chillingham material; Louisa Gidney (Durham University) for the provision of modern Dexter mandibles; Tommy and Mary Isbister (Trondra, Shetland), Ronnie Eunson and Sue White (both of Uradale Farm, Shetland), Dr Ingrid Mainland, Fay McKenzie and Dr Peter Martin (all of Orkney College UHI), Alan Leitch (RSPB Orkney) and Cliff Bichan (Swanbister Farms, Orkney) for their help in the collection of vegetation and water samples from Orkney and Shetland.

Thanks are also due to the following people for their time and insightful comments when interviewed about cattle husbandry: Cyril Annal (South Ronaldsay, Orkney), Jim Chalmers (Orkney College UHI), Ronnie Eunson and Sue White (both of Uradale Farm, Shetland), James Foubister (Tankerness, Orkney), Louisa Gidney (Durham University), Mick Grummitt (Allington, Lincolnshire), Tommy and Mary Isbister (Trondra, Shetland), John Mainland (Rousay, Orkney), Kenny Meason (Shapinsay, Orkney), Neal Stephenson (Snizort, Isle of Skye) and Rona Towrie (Sanday, Orkney).

On the technical side, I am very grateful to Andrew Gledhill (University of Bradford) for his invaluable analytical expertise and support; Professor Jane Evans (NIGL) for both her analytical support and constant encouragement; Carol Arrowsmith (NIGL) for the analysis of water samples; Dr Maura Pellegrini (Oxford University) for providing an enamel laboratory standard; and Dr Mandy Jay (Durham University) and Professor Michael Richards (University of British Columbia) for their help in obtaining radiocarbon dates (thanks also to Mandy for her useful comments regarding my Grimes Graves data). I would like to express my gratitude to Dr Marie Balasse and Dr Antoine Zazzo (both of CNRS/MNHN, Paris) for their suggestions as reviewers of a paper submitted to the journal Archaeometry, which resulted in a significant improvement of both paper and thesis.

Finally, many thanks to my friends and family for their steadfast support and encouragement during the last four years. Particularly my fellow PhD students Dr Julia Beaumont and Dr Eline Schotsmans – I wish them the very best for their future academic careers; Sophie Boual who helped me with French translation; and Dean Holdaway for his IT support, infinite patience and willingness to participate in PhD-related “holidays”.

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1 Introduction

If we are to gain more than a superficial understanding of prehistoric communities, it is essential that reliable archaeological methods are available to investigate that most important and time-consuming of human activities in the past: the management of food resources. In northwest Europe, including the British Isles, there is a high degree of lactose tolerance, suggesting that fresh milk from domestic animals has long been a significant dietary component. Thus, an ability to detect prehistoric dairying and determine its economic significance would be particularly useful in this region of the world.

Currently, prehistoric dairying is investigated using two well-established methods: the examination of faunal skeletal remains and compound-specific stable isotope analysis of lipids in archaeological pottery residues. Examination of faunal remains to determine age-at-death slaughter patterns (mortality profiles) and female to male ratios allows the economic role of a particular species (i.e. for meat, wool, milk or traction) to be inferred. However, faunal remains may be misinterpreted due to equifinality, whereby several possible taphonomic processes, pre- and post-deposition, result in similar animal bone assemblages (Halstead 1998). The second method, lipid analysis, provides information on when and where dairying was practised through the identification of milk products in the archaeological record (e.g. Dudd and Evershed 1998, Copley et al 2005a). Unfortunately, this particular technique is unable to distinguish milk fats originating from different ruminants (Copley et al 2005a). However, recent developments in the analysis of archaeological organic residues using the technique of proteomics, have allowed the identification of milk proteins to species (e.g. Hong et al 2012, Buckley et al 2013). Neither lipid nor protein analyses are able to predict the *intensity* of milk production and, consequently, its significance to ancient economies.

This thesis explores an alternative approach by which prehistoric dairying might be identified, that focusses specifically on the economic role of domestic cattle (*Bos taurus*). The basis of this approach is a possible link between economic goal and

cattle birth seasonality, the latter defined in this thesis as the distribution of births throughout the year. Cattle are biologically able to breed year-round (King 1978 pp124), potentially giving farmers the freedom to choose a calving strategy to best meet their economic goals. However, cattle living under feral conditions tend to breed seasonally in spring (e.g. Hall and Moore 1986, Berteaux and Micol 1992, Gómez et al 1997), their breeding behaviour being influenced by climate and the seasonal availability of food (Peters and Ball 1995 p150). Thus, if calving outside this "natural" season were to be favoured by a prehistoric community, it is likely to have required considerable effort in terms of fodder provision at the very least (Balasse and Tresset 2007). One possible impetus might have been the continuous supply of fresh milk, providing nutritious food even in winter. Certainly, if the duration of lactation for prehistoric cows was significantly shorter than for modern dairy cows, as might be expected, then calving over several seasons would have been necessary for a year-round supply of milk. In contrast, the ability to supply meat throughout the year would not have been dependent on the time of year calves were born. Thus, for an economy based on meat production, a more restricted calving period timed to coincide with spring growth and mimicking the breeding behaviour of most feral herds, may have been favoured. Even in the British Isles today, calves raised for meat tend to be born in spring, whereas dairy cows are often managed to calve year-round or in spring and autumn in order to produce a more evenly distributed supply of milk.

Increasingly, during recent years, birth seasonality of prehistoric domestic herbivores has been investigated through oxygen isotope ratio analysis by mass spectrometry of molar enamel (e.g. Balasse et al 2003, Balasse and Tresset 2007, Henton et al 2010, Blaise and Balasse 2011, Stevens et al 2011, Towers et al 2011, Balasse et al 2012a, Balasse et al 2012b). The technique appears ideally suited to this application for three principal reasons: 1) the molar teeth of many herbivorous mammals are high-crowned (hypsodont), each molar forming sequentially over a period of time from the cusp at the occlusal surface to the cervix, where the root and crown meet (Brown et al 1960, Hillson 2005 pp8); 2) tooth enamel tends to survive well in the archaeological record, preserves its biogenic integrity during

burial and does not continually remodel once formed; and 3) the isotope composition of oxygen incorporated into enamel during its formation tends to vary seasonally. Thus, by analysing a series of intra-tooth enamel samples extracted along the length of a molar crown from cusp to cervix, the seasonal variation in oxygen isotope composition (measured as the ratio $^{18}O/^{16}O$) becomes evident (Fricke and O'Neil 1996). For cattle raised at mid- and high latitudes, the form of this variation generally follows a sinusoidal-like pattern recorded along the molar crown with minima corresponding to winter and maxima to summer (Fricke et al 1998). The positioning of this pattern along the crown depends on the time of year the animal was born. Therefore, by comparing the results for several cattle present in an archaeological assemblage, seasonality of birth may be estimated.

However, there is another potential influence on the positioning of the sinusoidal-like pattern along the molar crown: the timing of molar crown formation relative to birth. Any inter-animal variability in molar crown formation will introduce a degree of uncertainty into estimates of birth seasonality. If there is a link between birth seasonality and the economic role of domestic cattle, it is critical that the distribution of births throughout the year can be determined to a reasonable degree of accuracy such that different calving strategies, e.g. single-season and multiple-season calving, can be discriminated.

Thus, a principal aim of this thesis is to propose a reliable method based on intra-tooth isotope ratio data to estimate cattle birth seasonality. The approach taken to achieve this comprises two activities: 1) the evaluation of the existing method, described above, based on oxygen isotope ratio data; and 2) the pursuit of alternative methods. The second of these activities involves a broader range of data than used by the existing method, including the analysis of first molars in addition to second and third molars, and the examination of carbon isotope ratio patterning in molar enamel. A secondary aim of this thesis is to evaluate the effectiveness of intra-tooth isotope ratio data in providing useful information regarding the diet and environment of prehistoric cattle. Although such information is encoded within the carbon isotope ratio data of enamel, interpretation of intra-tooth data is not

straightforward due to the averaging inherent in enamel mineralization (Balasse 2002) and the relatively small degree of variation in carbon isotope ratio of a C_3-only environment such as prehistoric Britain.

This thesis will present intra-tooth isotope ratio data for cattle molar enamel from five British archaeological sites with varying mortality profiles. These sites are: Pool, Mine Howe and Earl's Bu, located in Orkney; Old Scatness, Shetland; and Grimes Graves, Norfolk. For comparative purposes, it would be highly beneficial to analyse enamel from modern cattle of known birth dates and closely controlled dietary and drinking water sources. However, obtaining such material would require a long-term biological study with experimental animals, which would be beyond the scope of this thesis. Nevertheless, data will be presented for enamel from modern feral cattle residing at Chillingham Park, Northumberland, and a modern Dexter bull raised for beef in County Durham. Although analysis of molar enamel is the primary focus of this study, results of supplementary analyses including intra-tooth analysis of dentine collagen, bulk analysis of bone collagen and strontium isotope analysis of enamel will be included for selected sites to aid interpretation.

1.1 Research questions, aims and objectives

Two principal research questions are addressed by this study:

- Can intra-tooth isotope ratio data recorded in enamel be used to investigate prehistoric cattle dairying?
- Can intra-tooth isotope ratio data recorded in enamel provide useful information regarding sub-annual variation in the diet and environment of prehistoric cattle?

The following aims and objectives have been devised to attempt to answer these research questions:

Aim 1: To investigate the likelihood that prehistoric farmers manipulated cattle birth seasonality to suit economic focus such that calving strategies for milk and meat production were distinct.

Objectives:

a) Comprehensively review modern, scientific, ethnographical and historical literature to investigate the feasibility of manipulating cattle birth seasonality and possible motivating factors.
b) Discuss calving strategy with modern farmers.

Aim 2: To increase understanding of intra-tooth carbon isotope ratio data recorded in cattle enamel, i.e. possible interpretation in terms of physiological changes in early life, diet and environment.

Objectives:

a) Obtain and analyse intra-tooth enamel samples from molars and fourth deciduous premolars of modern Chillingham cattle and of the modern Dexter bull from County Durham.
b) Obtain and analyse intra-tooth dentine collagen samples from the molars of modern Chillingham cattle and of the modern Dexter bull from County Durham.
c) Collect vegetation samples from Chillingham Park seasonally and analyse for carbon isotope ratio. Also obtain and analyse samples of the dietary components of the Dexter bull.
d) Make comparisons between these three datasets.

Aim 3: To determine whether intra-tooth isotope ratio data recorded in cattle enamel can be used to estimate birth seasonality with a degree of accuracy that will enable the investigation of different economic goals. The degree of accuracy is defined here as an ability to discriminate between one-, two-, three- and four-season calving.

Objectives:

a) Obtain and analyse intra-tooth enamel samples from the molars of archaeological mandibles containing first and second molars or all three molars.
b) Examine both oxygen and carbon isotope ratio data from the selected molars and attempt to identify any possible new methods to estimate cattle birth seasonality.
c) Attempt to identify and quantify the principal sources of uncertainty for the methods to estimate birth seasonality (both published methods and any methods that are newly formulated).
d) Apply each method to the selected dataset and compare results. Determine their relative effectiveness and whether any can be used to estimate birth seasonality with an acceptable degree of accuracy.

Aim 4: To devise a method to predict the actual season of birth of an animal from its intra-tooth isotope ratio data.

Objectives:

a) Determine whether intra-tooth enamel isotope ratio data produced for the modern Dexter bull from County Durham may be used to calibrate equivalent datasets from other cattle. The Dexter bull is the only animal included in this study with a known date of birth.

Aim 5: To determine whether the economic focus of an archaeological site inferred from an estimate of cattle birth seasonality concurs with the interpretation of its mortality profile.

Objectives:

a) Obtain cattle age-at-death statistics and inferred economic goals from relevant literature sources.

b) Obtain and analyse intra-tooth enamel samples from all archaeological molars selected for this study.
c) For each site, apply any of the identified methods to estimate birth seasonality that are considered to have an acceptable degree of accuracy.

Aim 6: To determine whether intra-tooth carbon isotope ratio data recorded in cattle enamel can provide useful information about the diet and environment of the archaeological cattle included in this study.

Objectives:

a) Obtain and analyse samples of indigenous vegetation and traditional crops from Orkney and Shetland. Determine whether crop grains are distinguishable isotopically from indigenous vegetation.
b) Make comparisons between enamel carbon isotope ratio data of archaeological cattle and modern Chillingham cattle.
c) For each archaeological site, assess enamel carbon isotope ratio data for possible indications of seaweed consumption. Also look for recurring patterns in the datasets that might indicate common husbandry practices.

1.2 Thesis structure

Following this introduction, the thesis consists of 13 further chapters. Chapters 2-6 are literature reviews aimed at providing background information, beginning with Chapter 2 which discusses the feasibility of manipulating cattle birth seasonality and the motivation for doing so. Chapters 3-5 focus on various aspects of stable isotope ratio analysis. Chapter 3 discusses stable isotopes in environmental and biological systems and includes a section on isotope ratio mass spectrometry. Chapter 4 is concerned with the skeletal tissues selected for stable isotope ratio analysis, and discusses the formation, composition, physical properties and susceptibility to diagenesis of cattle molar enamel, molar dentine and mandibular bone. Chapter 5 reviews previous studies involved in the development and application of isotopic techniques used to investigate domestic cattle husbandry, predominantly, but not

exclusively, at a sub-annual resolution. Chapter 6 provides descriptions of the archaeological sites included in the present study, focussing on those factors directly or indirectly relevant to cattle husbandry.

The selection of archaeological and modern cattle mandibles and the collection of vegetation and water samples for this study are outlined in Chapter 7, while the subsequent preparation and analysis of enamel, dentine, bone, vegetation and water samples are described in Chapter 8. Chapter 9 provides a comprehensive summary of the results for all isotopic analyses and presents them in graphical form and compares them, where possible, with published values. Chapter 10 is concerned with data handling and describes how intra-tooth data may be plotted versus time, a requirement for Chapters 11-13. Chapter 11 attempts to further understand intra-tooth carbon isotope ratio data recorded in enamel through comparison between modern enamel, dentine and vegetation data. In Chapter 12, three methods to estimate cattle birth seasonality are described and an attempt is made to identify and quantify the principal sources of uncertainty associated with each. The methods are compared and their effectiveness assessed. The chapter also outlines a method to determine the actual season of birth of an animal. Intra-tooth enamel oxygen and carbon isotope ratio data are presented for each archaeological site in Chapter 13 and interpreted with respect to seasonality and season of birth, diet and environment. Finally, the conclusions of the study are presented in Chapter 14 with reference to the original aims. The potential for further research is also included in the final chapter.

2 Human management of cattle birth seasonality: feasibility and economic motivation

Before investigating a possible relationship between cattle birth seasonality and economic focus in prehistory, it is necessary to consider two fundamental questions: a) would it have been feasible to manage cattle birth seasonality, i.e. the distribution of births throughout the year; and b) what would have been the motivation for doing so. These questions are addressed in this chapter.

2.1 Feasibility of manipulating cattle birth seasonality

2.1.1 Cattle reproduction

Biologically, domestic cows are polyoestrous animals, meaning that they ovulate more than once a year. In fact, having reached sexual maturity, a healthy, well-nourished cow should proceed to ovulate at regular intervals of approximately 21 days indefinitely throughout the rest of her life (Peters and Ball 1995 p25). This cycle is known as the *oestrous cycle*. For a short period of time, known as *oestrus*, just before each ovulation, a cow will become sexually receptive and it is then that she should mate if pregnancy is to be achieved. A cow in oestrus can be detected through changes in behaviour, such as bellowing and being mounted by other cows, and through changes in physiology, particularly mucus secretion from the vagina (Peters and Ball 1995 pp51). Oestrus usually continues for six to 30 hours depending on the season (King 1978 p125). The oestrous cycle is interrupted by pregnancy, which usually lasts around 280 to 285 days (Peters and Ball 1995 p5), and there is also a period of ovarian and sexual inactivity after calving before the cycle recommences (ibid p145). The period of time between calving and re-establishment of the oestrous cycle is known as *postpartum anoestrus*. Since sperm production in a healthy bull is also a continuous process (Perry et al 2008), it is biologically possible for domestic cattle to breed, and therefore calve, throughout the year. Theoretically, then, it would have been feasible for prehistoric cattle farmers to manipulate cattle birth seasonality to achieve calving during a particular season, over an extended period or all year round. However, would these options have

been readily achievable in practice? To address this question it is informative to begin by investigating the reproductive behaviour of feral cattle or those reared in extensive, outdoor conditions with minimal human management.

2.1.2 Reproductive behaviour of feral herds

Of particular interest to this study are feral and semi-feral *Bos taurus* cattle of temperate regions where the climate is not too dissimilar to that of the British Isles. The few examples of such herds where calving season is mentioned in the literature are listed in Table 2.1. Two of these herds are found in the British Isles, on the small Orcadian island of Swona and at Chillingham in Northumberland. All but one of the herds in Table 2.1 calve seasonally, with the majority of births occurring during the season of spring. Thus, in temperate regions, calving tends to coincide with the spring flush of grass as temperatures rise after winter. Similarly, in tropical regions, where seasons are defined by the amount of rainfall, calving of traditionally managed cattle is often seasonal and related to the timing of the rainy season when vegetation regenerates after a period of dry conditions (e.g. Dahl and Hjort 1976 pp149, Abeygunawardena and Abayawansa 1995, Madibela et al 2001, Kanuya et al 2006). Where there are two rainy seasons in a year, as in Ankole, Uganda, a bimodal distribution of births is observed (Dahl and Hjort 1976 p152).

The breeding behaviour of feral cattle herds in temperate regions and traditionally managed herds in the tropics suggests a strong relationship between calving seasonality and the seasonal availability of food, which is related to climate. Therefore, it might be expected that an adequate supply of food throughout the year would result in year-round calving. Of the herds included in Table 2.1, only the Chillingham cattle of Northumberland calve throughout the year (Figure 2.1), although, from 1953 to 1984, there were still more spring and summer births, with 65% occurring between March and August (Hall and Hall 1988). The number of Chillingham cattle, rising from 13 in 1947 (ibid) to approximately 100 strong at the beginning of 2012 (Chillingham Wild Cattle Association 2012), indicate that they are well-provisioned and thriving. They are given hay in winter and have access to 130

ha of extremely well-managed mixed permanent grassland and open woodland. In contrast, the Swona animals, which calve in spring, are not given any supplementary food in winter and, although they have access to all 113 ha that form the island, only 13.5 ha of that area are described as containing “species of grazing value” with the remainder being rough grazing (Hall and Moore 1986). Their numbers have reduced and now average around 17 (Ringland 2012) from a high point of 33 in 1985 (Hall and Moore 1986), supporting the suggestion that food supply is limited and inadequate for year-round calving. Like the Chillingham cattle, the Highland cattle of Rhein-Taunus Naturpark (Table 2.1) were given supplementary food in the winter. However, the Highland cattle, numbering 9 – 19 animals during the period of observation (Reinhardt et al 1986), had a very short calving period with most births in March and April. Despite the supplementary feeding, the amount of food available to the animals was likely to have been limited, particularly in winter when snow generally covers the ground from December to February (Reinhardt et al 1986). In addition, the 5 ha of grazing at Rhein-Taunus Naturepark may not have provided as much food per animal as the much larger well-managed area at Chillingham.

Figure 2.1: Winter calf at Chillingham Park, Northumberland (photograph by J. Towers, taken 07/02/2011).

Table 2.1: Seasonality of calving for five feral or semi-feral herds living in temperate regions. Information from Hall and Moore 1986 (Swona), Reinhardt et al 1986 (Rhein-Taunus), Vitale et al 1986 (Maremma), Hall and Hall 1988 (Chillingham), Berteaux and Micol 1992 (Amsterdam Island), Lazo 1995 (Doñana), Gómez et al 1997 (Basque Country), Annal, pers comm (Swona).

Herd location and breed	**Supplementary food?**	**Seasonality of calving**
Swona, Orkney, UK (mixed breeding)	No	March and April
Chillingham, Northumberland, UK (Chillingham cattle)	Hay in winter	Year round
Rhein-Taunus Naturpark, Hesse, Germany (Highland cattle)	Hay, straw and silage in winter	91 % births in March and April
Basque Country, Navarre and Pyrénées Atlantiques (Betizu cattle)	No	Around March
Doñana National Park, Andalusia, Spain (Mostrenca cattle)	No	February – August (60% births March – May)
Maremma National Park, Tuscany, Italy (Maremma cattle)	Not mentioned in publication	March – June
Amsterdam Island, southern Indian Ocean (mixed breeding)	No	90 % births between September and January

2.1.3 The influence of nutrition on cattle birth seasonality

The relationship between the calving seasonality of feral and traditionally managed cattle and food availability suggests that reproductive functions in adult cattle are affected by nutritional status. From the middle of the 20th century an increasing number of scientific studies were conducted to determine exactly how nutrition influences reproduction, the impetus being to improve efficiency in the cattle industry. One early study was carried out by Joubert (1954) using cattle on an experimental farm in Pretoria, South Africa, where there are two seasons: cool, dry winters and hot, wet summers. In that study, one group of heifers was kept on a low plane of nutrition from a young age, which consisted of natural grazing with no supplementary feeding, while a second group was kept on a high plane of nutrition, which also consisted of natural grazing but with supplementary feeding throughout the winter period. Sexual activity was monitored by visual observation of signs of oestrus. For most high plane animals, the onset of oestrous cycling at puberty began earlier than for low plane animals, in winter, whereas for low plane animals, it did not start until the following summer. For the low plane heifers, sexual activity

was found to fluctuate widely between complete inactivity in winter to maximum activity in summer, whereas for the high plane animals, sexual activity continued throughout the year with a peak in activity in late summer. One manifestation of this difference was that conception occurred in the summer for all low plane heifers but was more variable for the high plane animals. In another study, Durrell (1955) observed the conditions of heifers on working farms in western Quebec. Here, food rations were often meagre and the incidence of anoestrus high, tending to commence in December. However, by actively increasing the plane of nutrition of anoestrous animals, oestrous cycling could be restored within six weeks (Durrell 1955).

These and subsequent studies (e.g. Wiltbank et al 1962, Dunn et al 1969, Richards et al 1986, Louw et al 1988) clearly demonstrated that oestrous cycling is the reproductive function most strongly influenced by nutrition. For male animals, nutritional stress can lead to a reduction in sperm quality and quantity but reproductive function does not cease (Dunn and Moss 1992, Brown 1994). In experimental studies investigating the relationship between nutrition and oestrous cycling, the plane of nutrition is usually formulated according to the amount of energy the food provides. Food energy tends to be prioritised for survival rather than reproduction. According to Short and Adams (1988), the order of priority from greatest to lowest is: 1) basal metabolism, 2) activity, 3) growth, 4) basic energy reserves, 5) pregnancy, 6) lactation, 7) additional energy reserves, 8) oestrous cycles and initiation of pregnancy and 9) excess reserves. Thus, when food becomes limited, the oestrous cycle will be one of the first physiological functions to become inactive. Whether this happens depends on the quantity and quality of the available food (i.e. the energy input), the competing energy demands of other physiological functions such as lactation, how much activity is required to forage for food and water, whether the animal is growing and how much body fat the animal has as a stored energy supply.

The climate will also affect the food energy available for reproduction. In temperate winters under certain conditions, maintenance of body temperature may require

heat production through shivering. Food energy would be prioritised for this vital body function and diverted from other body functions (McDonald et al 1988 pp293). Returning to the feral herds discussed in Section 2.1.2, the difference in climate between Swona and Chillingham, although not large, may be a contributing factor to the difference in calving seasonality of their feral cattle. Swona is a windier location than Chillingham and wetter in the autumn and winter (Wheeler and Mayes 1997). There are no trees and shrubs on Swona to provide both food and shelter for the cattle. Although the animals have limited shelter in the form of stone walls, they are likely to suffer much greater exposure to wet, cool and windy conditions than the Chillingham cattle who have access to areas of woodland. As a result, more food energy will be required to maintain body temperature. A similar argument holds for the Highland cattle of Rhein-Taunus Naturpark. Here the winters are also harsher than at Chillingham, with colder temperatures and frequent snow (Reinhardt et al 1986).

Although it is believed that domestic cattle have retained a residual sensitivity to photoperiod, which would predispose towards mating in summer and calving in spring (Peters and Ball 1995 p150), the dominant factors influencing calving seasonality are those described above: the seasonal variation in food availability and the seasonally dependent energy demands due to climate, both of which affect oestrous cycling. These factors also predispose towards mating in summer if there is little supplementary food during the winter because the only time of year when females can restore their body reserves to a level sufficient for oestrous cycling is during the spring and summer when there is a greater supply of good quality feeding. Even then, some animals may not reach this condition before the vegetation starts to reduce in quality and quantity, particularly those that are lactating. For these cows, lactation will take precedence over oestrous cycling in terms of energy prioritisation. In addition, the act of suckling itself tends to delay the onset of oestrous cycling (Peters and Ball 1995 p147). Limited food availability not only predisposes towards spring calving but towards calving every other year.

If prehistoric cattle farmers wanted their animals to calve outside the "natural" period of spring, they would have had to work hard to ensure that food of sufficient quantity and quality was available outside the growing season. Provision of shelter may also have been necessary. Even for herds under modern management where year-round calving is achieved, constant effort is required to prevent a concentration towards spring calving, which would otherwise occur because of the tendency for postpartum intervals to be longer for autumn-calving cows than for spring-calvers (Hewett 1968, Hammond et al 1983 pp57, Hansen 1985). The importance of husbandry effort is illustrated by an 18th century description of cattle by James Burnett, Lord Monboddo, in the third volume of his work "Antient Metaphysics": "the cattle in the West Highlands of Scotland are never housed, but run out, summer and winter; whereas, in other parts of Scotland, and, I believe, all over England, they are housed, if not all the year, at least a great part of it. Now, the cows that run out always never take the bull till they are three years old, and very often not till they are four; and they seldom have a calf two years running, but generally only one every other year: Whereas the housed heifers admit the bull when they are two years old, and sometimes when they are only one; and they have regularly a calf every year" (Burnett 1784 p224). Columella, a Roman writer of agriculture of the First Century AD, stated that "where there is a great luxuriance of fodder, a calf can be reared from the same cow every year, but, where food is scarce, the cow must be used for breeding only every other year" (Forster and Heffner 1954 p185). Both Columella and Burnett concluded that better care, in terms of nutrition and shelter provision, results in a higher reproductive efficiency. The same argument would hold true for the manipulation of calving seasonality.

2.1.4 Other husbandry-related factors influencing cattle birth seasonality

Apart from nutrition, detection of oestrus is a very important element of herd management that can influence cattle birth seasonality. If a bull lives amongst a herd of cows, he will have no problem detecting oestrous cows and will mate with them accordingly. In this situation, if impregnation is not required, it can be prevented by simple methods such as the use of an apron on a bull, as seen recently

in the Italian Alps (Figure 2.2), or by means of a covering over the rear end of a cow, as practised in Shetland (Eunson, pers comm). Alternatively, control over reproductive activity may be achieved by keeping the bull physically separate from the cows and only allowing contact with each individual cow when she is in oestrus. However, detection of oestrus is then dependent on human observation, which may not be easy under certain conditions, for example in winter when the oestrus period tends to be shorter than in other seasons at temperate latitudes (King 1978 p125), nights are long and cattle may be housed in buildings with poor lighting. Even if an oestrous cow is detected, she has to be with a bull within a few hours if mating is to be successful. This may depend on whether the bull is kept close by and is available at all times or whether he is shared between several communities. For example, in Orkney during the middle of the 20th century, oestrous cows were often taken to bulls kept on the bigger farms of the district (Foubister, pers comm, Towrie, pers comm). Alternatively, the bull was taken to the herd and may have remained with the cows for a period of time and at a time of year dictated by circumstances rather than the requirements of the cow owner. One example of this practice occurred on the island of Swona, Orkney, in the 1930s where the ancestors of the now feral cattle were being actively reared at a farm on the island. However, there was no resident bull at the farm. Instead, the bull was a shared resource with farms on South Ronaldsay, and he was only brought over in a boat to Swona during the summer months (Annal, pers comm). As a result, the calving season was restricted to spring on Swona.

Calving strategy may also require organisation in relation to the other farming activities occurring throughout the year in terms of manpower and resources. Examples include the provision of food for other domestic animals such as sheep for which there might be competition for limited resources, activities such as harvest which require a concentration of manpower, and the season of birth of other domestic animals.

Figure 2.2: A method of controlling reproductive activity, currently practised in the Italian Alps (photograph by J. Towers, taken 19/09/2010).

2.2 Motivation to manage cattle birth seasonality: economic goals

Described above are a range of factors such as the ability to provide sufficient fodder and the availability of a bull that could have seriously limited the choice of calving strategy for some prehistoric communities. However, without such limitations, the principle motivation of a community to manage its calving season is likely to have been the economic goal for rearing the cattle. This section considers how different economic goals may have motivated calving strategy.

The economic goal for rearing cattle is often presented in terms of meat or milk. However, in Britain, with its long dairying heritage, it is probable that both products were utilised in many locations but with an *emphasis* on one or the other. It is also likely that the production of draught animals would have been a useful by-product of a meat- or milk-focussed economy, similar to non-food products such as hides, hair, horn, tallow and manure, rather than a goal in its own right.

2.2.1 Meat-focussed production

For a prehistoric community focussed on meat production, a major motivation behind the choice of calving strategy would have been the desire to produce the most meat for the least effort in terms of both fodder provision and manpower. Spring calving would have fulfilled this requirement since cattle naturally revert to it if food is seasonally limited (Sections 2.1.2 and 2.1.3). Calving in spring also has the practical advantage that, since it requires mating during the summer, a bull can live outside amongst the cows during that period, alleviating the need for human effort in the detection of oestrous cows.

Younie (2001) recommended spring calving for modern organic beef production. The system he described is a forage-based management system in Scotland which is likely to be a closer analogue to prehistoric cattle rearing than many other modern, more intensive systems. He listed the following advantages: a) calves are at least six months old at the onset of winter and are therefore better able to withstand the harsh weather conditions of that season; b) peak grass productivity maximises milk yield for the calf; c) calves begin to graze when the quality, palatability and productivity of grass is high; d) the rising plane of nutrition during the spring maximises the fertility of the cow for summer mating; e) later in the grazing season, when producing less milk, cows are able to build up body reserves, thus reducing fodder requirements for the following winter; f) cows calve when in their leanest condition which reduces the likelihood of dystocia (difficulty in calving); g) spring is too early in the year for flies, reducing the incidence of mastitis (an infection of the udder which is potentially fatal) (Younie 2001). North American studies of rangeland beef cattle have investigated the variation of forage nutrients throughout the year and the energy and protein requirements of a cow through her breeding cycle. They have concluded that if calving is synchronized to the growing season, the period of highest energy and protein requirements for a cow, during early to mid-lactation, will coincide with the period of maximum nutrient content in the forage. As a result, utilisation of grazed forages is optimised and fodder costs are reduced (e.g. Adams et al 1996, Clark et al 1997, McInnis and Vavra 1997). Later in the year, during the

summer, the vegetation matures. It produces seed heads and becomes more fibrous, and nutrient content reduces. In Orkney and Shetland, spring calving is adopted by modern beef farmers precisely because it maximises calf growth while minimising effort and cost (Chalmers, pers comm, Eunson, pers comm, Isbister, pers comm, Meason, pers comm).

Since one object of rearing cattle for meat is to provide as many healthy animals as possible, the times of year for calving and breeding should be adjusted to avoid stressful weather conditions, which would lead to increased calf mortality (Sprott et al 2001). In Britain, late winter and early spring can be difficult for young calves, particularly if the weather is wet, as Hall and Hall (1988) discovered when examining calf mortality rates for the Chillingham Wild Cattle in Northumberland.

The disadvantage of mating and, therefore, calving too early by a few weeks was recognized by Hebridean cattle farmers in the 18th century. In his "Report on the Hebrides", the Reverend Dr John Walker noted that the vetch growing on the sandy soils of North and South Uist and Benbecula was esteemed "highly for Pasture, as it has the remarkable Property of making the Cows who feed plentifully upon it, to take the Bull Readily, and early in the Season, which is a matter of great Consequence in a breeding Country, where they have great Difficulty to support and preserve their Calves in the Winter" (McKay 1980 p75). The problem in this case was the shortage of winter food for the cows. Later in his report, when referring to the cattle kept on Skye, he stated "If the Cows calve before the first of March, it will be sometimes a Month or Six Weeks before they have Milk Sufficient to feed the Calves" (McKay 1980 p209).

Thus, if the emphasis of cattle rearing in prehistoric Britain was meat production, the most efficient way to achieve this would have been to employ a calving strategy in which the calves were born after the start of vegetation regrowth but before it reached maturity. Provided the calves were sufficiently large and healthy by their first winter, they could be kept on minimum rations through that and subsequent

winters without compromising the quality of the meat available after a single period of spring and summer grazing. Martin (1703) commented in his description of the Western Isles of Scotland that cattle are "expos'd to the rigour of the coldest Seasons, and become meer Skeletons in the Spring, many of them not being able to rise from the Ground without help, but they recover as the Season becomes more favourable, and the Grass grows up, then they acquire New-beef, which is both sweet and tender".

2.2.2 Production of fresh milk for consumption

Milk is more nutritionally complete than most other food products. It is a rich source of proteins, fats, calcium, phosphorus, iodine and vitamins B_{12} and B_2 (riboflavin). It also contains vitamins A and C together with other B vitamins, and essential minerals such as zinc, potassium and magnesium at lower but appreciable levels (The Dairy Council 2007-2013). There are several possible reasons why communities in prehistoric Britain might have focussed their cattle husbandry efforts towards the production of milk. Firstly, milk pastoralism is the most efficient way of utilising uncultivable grazing land (Ingold 1980 p176). For modern cattle, milk production is three to four times more efficient in terms of energy and protein produced per unit area than beef production (Holmes 1970), as shown in Table 2.2, although the full benefit would only be obtained if surplus calves, as competitors for the milk, were removed soon after birth, which may not have been possible for prehistoric cattle (see Section 6.6 for a discussion about calf slaughter and dairying). Another major advantage for a subsistence economy is that milk is a renewable resource. As a result, it is better suited to be a substitute food at times of crop failure than meat. Increasing the consumption of meat as a response to crop failure may either compromise the viability of the cattle herd through reduction in numbers or require the rearing of surplus animals for such an eventuality (Bogucki 1986). In prehistoric northwest Europe, the winter months would have been times of food scarcity and the provision of fresh milk or storable dairy products made earlier in the year may have been a significant factor determining the survival of a community. If the provision of fresh milk in winter was an objective of a

settlement's cattle husbandry regime then, in order to determine the calving strategy that might have achieved this, the duration of lactation for prehistoric cattle must be estimated.

Table 2.2: Energy and protein yields for 20th century cattle (from Holmes 1970).

	Energy per hectare (Mcal/ha)	**Protein per hectare (kg/ha)**
Dairy cows	2500	115
Beef cattle	750	27
Ratio dairy : beef	3.3	4.3

Milk production commences with the birth of a calf, increases rapidly to peak production within the first four to 11 weeks then reduces more gradually over several months (Jenkins and Ferrell 1992, Peters and Ball 1995 p141) until lactation ceases naturally or the cow is deliberately dried off. These changes in milk production may be visualized by producing a lactation curve where daily milk yield is plotted against time elapsed since calving. The shape of a lactation curve depends on a range of factors including breed, energy intake and season of calving (Jenkins and Ferrell 1992, Garcia and Holmes 2001), and differences are also seen between lactation curves for first-lactation heifers and mature cows (Barnard et al 1970 p202). For cattle of the modern era, the duration of lactation can be very variable, from three or four months for early weaning beef cattle (Brody et al 1923) to more than two years (Fitzgerald 1989 p65).

Although it is impossible to predict the duration of lactation for the prehistoric cattle of north-west Europe with any degree of accuracy, it may still be possible to make an estimate by studying data from the more recent past. Figure 2.3 shows the lactation curves of a beef breed (Hereford) and a dual purpose breed (Braunvieh) from the late 20th century, together with those from the early part of the same century for two dairy breeds (Holstein and Jersey) and for cattle that have not been selectively bred (scrub cattle). Curves for modern dairy cows are not included because recent increases in milk yields and lactation duration are due to

recent scientific advances in breeding methodology. The lactation curves of the dairy breeds from the early 20th century are noticeably flatter than those for the modern beef and dual purpose breeds, undoubtedly the result of years of selective breeding for their milk producing characteristics. In contrast, the curves of the non-dairy breeds decline more rapidly after peak daily yield.

Further back in history, variation in daily milk yield can only be gleaned from the few descriptions that break down total yields into shorter time frames. For example, Sinclair (1813 p115) estimated that Ayrshire cows, on average, produced 5 gallons per day for the first 90 days after calving, then 3 gallons per day for the next 90 days and finally 1½ gallons per day for 120 days. Similarly, Petty (1719 p51), in his political survey of Ireland of 1672, wrote that "in Ireland a Milch-Cow, if English breed, may be fed upon two Acres of Pasture, and with as much Hay as will grow upon half an Acre of Meadow, will yield præter propter 3 Gallons of Milk for 90 days, one with another, and one Gallon at a Medium for 90 more, and for 90 more scarce 1 quarter of a Gallon one day with another, and for 90 more dry". In Robert Loder's farm accounts for 1618 (Fussell 1936), the lactation period is split into two time periods, between Whitsun eve (23rd May) and Michaelmas (29th September) and between Michaelmas and St. Thomas's Day (21st December). Milk yields have been calculated from the value of the milk, cheese and butter produced during these two periods using methods proposed by Slicher van Bath (1958). These 17th and early 19th century examples are shown graphically in Figure 2.4. Curves have been fitted visually using an equation developed by Jenkins and Ferrell (1984). Whilst acknowledging the inaccuracies inherent in this approach, it is interesting to compare these curves with those of the 20th century animals shown in Figure 2.3. Generally speaking, the rate of decline of the curves for the Ayrshire cows and Robert Loder's cows are similar to that of 20th century Hereford cows, despite differences in total yield. The curve of the English milch-cows of 17th century Ireland shows a greater rate of decline. Table 2.3 gives the approximate weeks of lactation by which the yield has dropped to 50% of peak yield for each case. This occurs between 16 and 27 weeks (around four to six months).

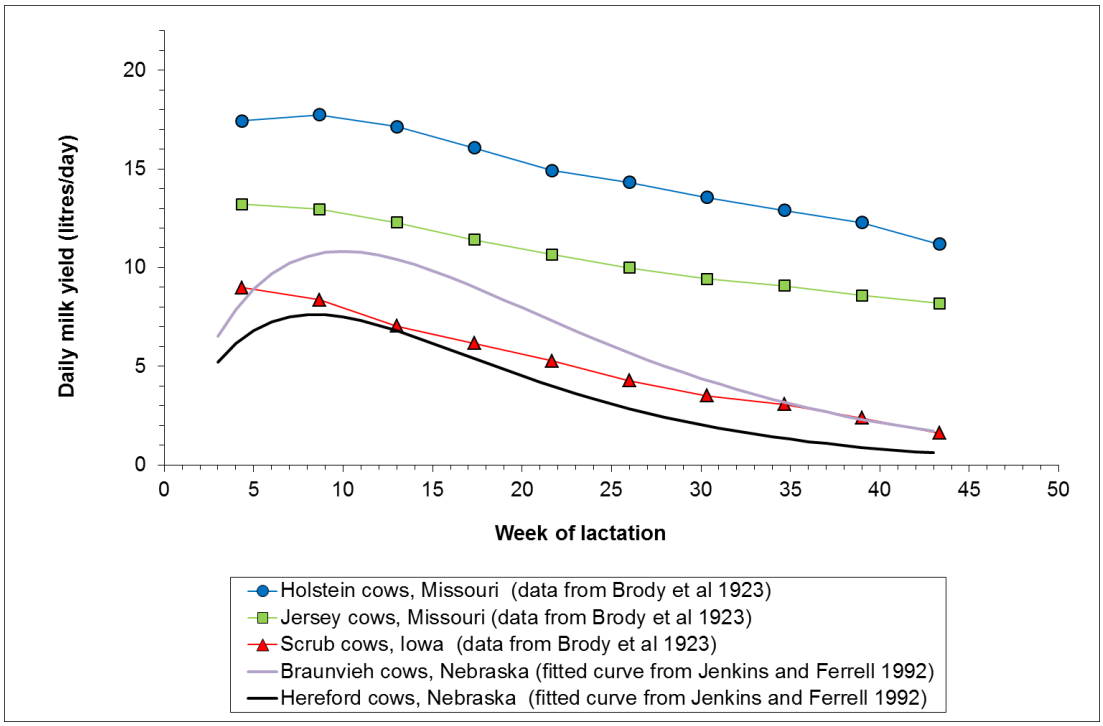


Figure 2.3: 20th century lactation curves.

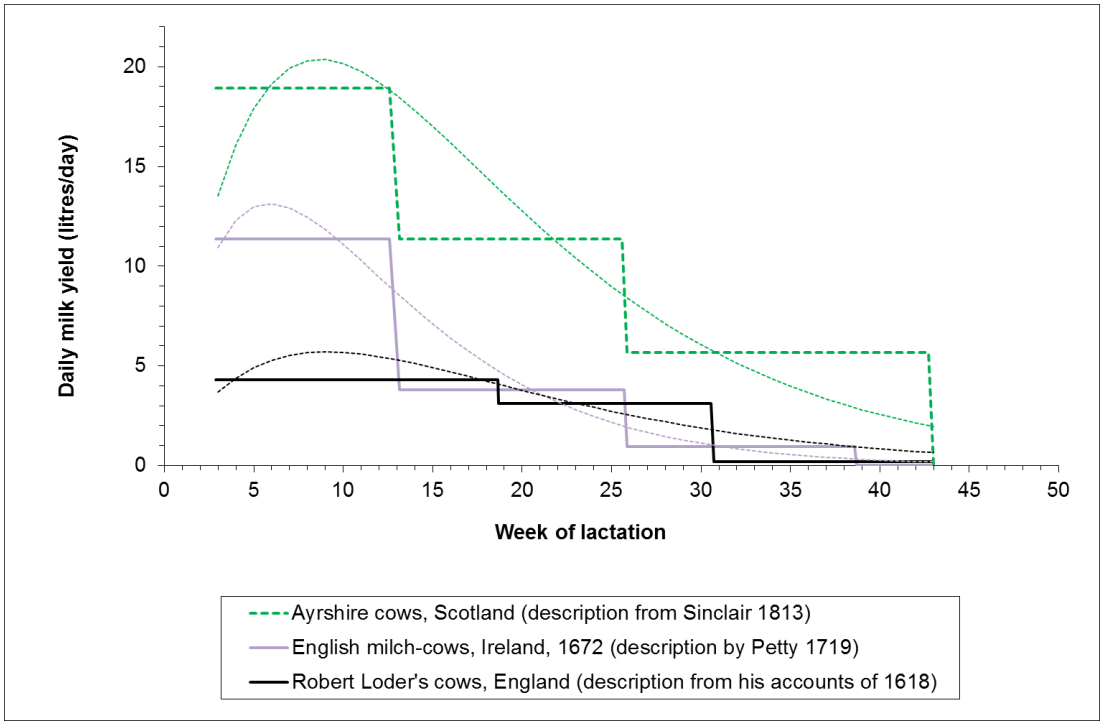


Figure 2.4: 17th and 19th century lactation plots based on descriptions (curves fitted visually using an equation from Jenkins and Ferrell 1984).

It would be unwise to assume that the duration of lactation would have been even shorter for prehistoric cattle, especially for dairying communities, some of whom would have benefited from centuries of experience in managing cattle for milk production, given the Neolithic origins of dairying (Copley et al 2005b). A possible example of early cattle breeding, by Irish aristocrats of the early First Millennium AD, is suggested in the Táin Bó Cúailnge (The Cattle Raid of Cooley) (McCormick 1983). This may have been for milking capability since milk, rather than beef, was the major dietary component derived from cattle (Lucas 1989 p4).

In conclusion, calving in autumn is likely to have been required in prehistoric Britain to produce fresh milk during the winter months and through the lean period immediately prior to vegetation growth in spring. In order to achieve a continuous supply of milk throughout the year, calving in spring and autumn would have been necessary, either as two distinct calving seasons or perhaps as a single calving period through spring, summer and autumn. The milk-related advantage of an extended calving season was certainly acknowledged in several 17th and 18th century books on farming. For example, Richard Bradley (1732 p132), professor of botany at the University of Cambridge, recommended that "To order them so as that they may have Plenty of Milk, let your Kine go to Bull from the Spring to Winter, whereby you may always milk some". According to farmer William Ellis (1744 p134) "At Over, where they make the best Butter for the Colleges, seven Miles from Cambridge, they sell off their driest Cows, and buy in others, that will calve in each Winter-month". More than a century earlier, the French agronomist Olivier de Serres (1617 p 251) wrote that the time of year for breeding cattle was a carefully considered choice for farmers with some wanting their cows to calve at the beginning of winter, a little before the worst of the cold weather, while they could be fed with good hay, and others preferring their cows to calve in spring to coincide with the new grass. The choice, as stated by de Serres, varied according to climate, the quality of grass and the continuation of milking in winter. Even in the early to mid-20th century, some Orcadian farmers producing milk for home use would stagger the calving of their milk cows throughout the year to ensure a continuous supply (Mainland, pers comm). In the words of James Foubister: "it was

an awful bad business not to have enough milk for the porridge" (Foubister, pers comm). In a description of her childhood on the small island of Eilean nan Ròn, which lies off the north coast of Sutherland, Scotland, Mina MacKay Stevens recalled that "Most families had two cows. One cow would calve in the spring, for milk through the summer, and one would calve in the autumn, to give milk through the winter" (Neat 2000 p67).

Table 2.3: Comparison of different lactation curves in terms of approximate week of lactation for 50% of peak milk yield (information derived from Jenkins and Ferrell 1992, Brody et al 1923, Sinclair 1813, Petty 1719 and Fussell 1936).

Cows (date of study/description)	Approximate week of lactation for 50 % of peak yield
Braunvieh (1992)	27
Hereford (1992)	23
Scrub (1923)	26
Ayrshire (1813)	24
English milch-cows, in Ireland (1672)	16
Robert Loder's cows (1618)	25

2.2.3 Production of storable dairy products

For a prehistoric dairying community producing storable dairy products such as cheese and butter, the necessity to calve in autumn to provide winter sustenance is removed through the nature of the products themselves. Since both butter and cheese may be stored in cool conditions for several months if salted (other possible preservation processes for cheese are pressing and smoking), it may have been possible to produce them in the spring and summer for consumption during autumn and winter. A major motivation behind the choice of calving strategy would have been the desire to maximise the quantity of milk and, hence, storable dairy product, for the least effort in terms of both fodder provision and manpower. Spring calving would have fulfilled this requirement, as explained by the English writer Gervase Markham (1668 p142): "The best time for a Cow to Calve in for the Dairy, is in the later end of March and all April: for then the grass beginneth to spring to its perfect

goodness, which will occasion the greatest increase of Milk that may be, and one good early Cow will countervail two later". Thomas Hale, writing in the 18th century concurred: "The best and most favourable time for calving, in order to yielding the greatest plenty of milk is when the pasturage is springing in all its strength, for then it will make the greatest supply. Therefore those who wish for abundance of milk, are happy if their calves fall in the end of March, or the beginning of April, for at that season the grass is in its fullest springing strength" (Hale 1758 p245). The entry on husbandry in the 1811 edition of Encyclopædia Londinensis was of the same opinion, highlighting the regional variation of the start of the growing season across Britain: "From the end of March to the end of April is the best time in the more northern districts that a cow can drop her calf, as she soon gets into good condition on the early grass, and yields a greater quantity of milk in the course of the season than those that calve either considerably earlier or later. But in the southern parts of the island it is an advantage for them to calve much earlier" (Encyclopædia Londinensis 1811 p510).

2.2.4 Summary

If a prehistoric community's calving strategy was chosen on the basis of the economic goal for rearing cattle rather than any logistical limitation such as the availability of a shared bull, then spring calving would have offered the greatest efficiency in terms of husbandry effort for an economy focussed on the production of meat or storable dairy products such as cheese and butter. Only the provision of fresh milk during the winter would have necessitated calving outside of the spring period. Autumn calving would have been required for winter milk. For fresh milk all year round, two calving seasons, in spring and autumn, or an extended period of calving through spring, summer and autumn would have been necessary. To achieve this, a high degree of effort and management would have been required to provide food of sufficient quantity and quality throughout the year and, perhaps, shelter during winter. In addition, human detection of oestrous cows may have been necessary at certain times of year, and a bull had to be organised to ensure mating at the appropriate times for the calving strategy.

3 Stable isotopes in environmental and biological systems

3.1 Introduction to stable isotopes

Stable isotope ratio analysis of animal remains in archaeology is a technique based on the principle that, during formation, body tissues record the isotopic composition of ingested food and water. Thus, through isotopic analysis of archaeological remains, it is possible to gain insights into the past lives of animals, whether wild or domestic, and the environment in which they lived. However, the only remains of body tissues usually represented in the archaeological record are bone, tooth enamel and dentine, and it is the analysis of enamel and, to a lesser extent, bone and dentine that is the focus of this study.

Many elements occur naturally in at least two isotopic forms, each of which has the same number of protons, the property determining the element itself, but a different number of neutrons; i.e. the isotopes of an element have the same atomic number (Z) but different mass numbers (A). Z and A are related by the equation: A = Z + N where N is the number of neutrons. If X represents any element having several isotopic forms, each of its isotopes may be represented symbolically by ^{A}X. Isotopes may be stable or radioactive. For example, the two main isotopes of carbon, ^{12}C and ^{13}C, are stable, whereas a third, ^{14}C, is radioactive and its decay over time forms the basis of radiocarbon dating. The measurement of stable rather than radioactive isotopes in this study means that the isotopic composition of an archaeological specimen remains as it was at the time of death, unless there has been diagenetic alteration. Stable isotopes of oxygen, carbon and strontium are measured in this study. Oxygen and carbon are particularly prevalent in environmental and biological systems, constituting between them a significant proportion of the body tissue present in the archaeological record. The natural abundances and atomic data for the three elements are given in Table 3.1.

Because the isotopes of an element have the same number of protons and, therefore, electrons, their chemical behaviour is qualitatively similar. However,

because their masses are not identical, their physical behaviour is very slightly but quantitatively different, resulting in different bond strengths and reaction rates (Sulzman 2007). Therefore, during low temperature physical, chemical and biological processes, differences tend to arise between the isotopic compositions of products and reactants. Such differential isotopic behaviour is termed *fractionation*. Because strontium is a heavy element, the relative mass difference between the two isotopes measured in archaeological material (^{87}Sr and ^{86}Sr) is relatively small and fractionation resulting from the types of processes mentioned above is negligible. However, for a light stable element such as oxygen or carbon, it is fractionation and the resulting differences in isotopic composition between various reservoirs of the element within environmental and biological systems that allow information about an animal's life history to be derived from its archaeological remains (Schoeller 1999).

The isotopic composition of an environmental or archaeological sample is measured in terms of the abundance ratios $^{13}C/^{12}C$, $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$. However, for carbon and oxygen, these ratios are very small (0.002055 for the natural abundance ratio of ^{18}O to ^{16}O) as are any changes in the ratios due to fractionation. As a result, the delta notation, expressed in parts per thousand (‰, permil), has been adopted for these elements and, taking oxygen as an example, is defined as:

$$\delta^{18}O = (R_{sample} / R_{standard}) - 1$$

where R_{sample} and $R_{standard}$ are the ratios of ^{18}O to ^{16}O measured in the sample being analysed and an internationally agreed standard material (Coplen 2011). For this study the standard for $\delta^{18}O$ is VSMOW (Vienna Standard Mean Ocean Water) and for $\delta^{13}C$ it is VPDB (Vienna Pee Dee Belemnite).

Table 3.1: Natural abundances and atomic data for the isotopes of carbon, oxygen and strontium (abundance values for carbon and oxygen are taken from Table 1 of Berglund and Wieser 2011, those for strontium are from Capo et al 1998).

Element	Isotope	Atomic number Z	Mass number A	Natural Abundance (%)
Carbon	^{12}C	6	12	98.93
	^{13}C	6	13	1.07
Oxygen	^{16}O	8	16	99.757
	^{17}O	8	17	0.038
	^{18}O	8	18	0.205
Strontium	^{84}Sr	38	84	0.56
	^{86}Sr	38	86	9.87
	^{87}Sr	38	87	7.04
	^{88}Sr	38	88	82.53

3.2 Herbivore $\delta^{18}O$: environmental inputs and sources of variation

A herbivore's three principal sources of oxygen are inhaled atmospheric O_2, ingested liquid water, either as drinking water or free water in vegetation, and chemically bound oxygen in plant material. Kohn (1996) has estimated the relative amounts of oxygen in these three sources to be 24 %, 65 % and 8 % respectively. Since $\delta^{18}O$ values of atmospheric O_2 vary very little worldwide (Dole et al 1954) and most of the oxygen entering a herbivore's body does so through the ingestion of water, it is this source that is of greatest significance when interpreting oxygen isotope ratios of animal remains.

Ingested water originates as precipitation which, before its addition to an animal's local water source, has already been subjected to fractionating processes, primarily evaporation and condensation, occurring within the global water cycle (Gat 1980, Sharp 2007 p67). The process of condensation favours the isotopically heavier $H_2{}^{18}O$ over the lighter $H_2{}^{16}O$ molecules whereas it is the lighter molecules that preferentially evaporate (Sharp 2007 p74). The degree of fractionation in such processes tends to be temperature dependent. Indeed, a strong, positive, linear correlation between the mean annual $\delta^{18}O$ value of precipitation, $\delta^{18}O_{precipitation}$, and

surface air temperature has been demonstrated for high latitude locations (Dansgaard 1964), the surface air temperature reflecting the temperature of the precipitation bearing air mass above (Darling and Talbot 2003). One consequence of this "temperature effect" is a seasonal variation in $\delta^{18}O_{precipitation}$ at higher latitudes with values in summer being more positive than in the winter (Dansgaard 1964). Further consequences are a decrease in $\delta^{18}O_{precipitation}$ with increasing latitude and increasing altitude (Dansgaard 1954, cited in Dansgaard 1964), the latter effect having been observed in many regions of the world including the British Isles, averaging -0.28 ‰ per 100 m worldwide (Poage and Chamberlain 2001, Darling and Talbot 2003). In addition, as air masses move inland, the value of $\delta^{18}O_{precipitation}$ decreases for a given surface air temperature (Dansgaard 1964). This is the "continental effect". It occurs because, as an air mass moves away from its ocean source, it undergoes a succession of precipitation cycles. During each cycle, the value of $\delta^{18}O_{precipitation}$ is more positive than that of the vapour from which it originates. As a result of this preferential rainout of the heavier isotope, ^{18}O, the value of $\delta^{18}O_{vapour}$ and $\delta^{18}O_{precipitation}$ become progressively more negative after each successive precipitation cycle (Cuntz et al 2002, Sharp 2007 p80).

Closer to the equator, $\delta^{18}O_{precipitation}$ tends to be negatively correlated with the amount of precipitation. Values of $\delta^{18}O_{precipitation}$ are more negative in the rainy season than in the dry season (Dansgaard 1964). This "amount effect" may be observed at locations at higher latitudes, such as the British Isles, but only during the summer months (Darling and Talbot 2003). Generally, at higher latitudes the temperature effect is dominant.

Thus, $\delta^{18}O_{precipitation}$ is dependent on a range of different climatic and geographic variables. In the British Isles, the values of $\delta^{18}O$ for groundwaters, which preserve long-term average rainfall values (Darling et al 2003), tend to decrease from west to east (Figure 3.1). As a result, the $\delta^{18}O$ value of water ingested by an animal is strongly related to the location of the source. It may also be seasonally dependent. However, the nature of the source itself may influence both its average $\delta^{18}O$ value and the degree of seasonal variability. Possible inputs to surface waters such as

lakes, rivers and streams are rainfall runoff and groundwater discharge. Surface waters originating primarily from rainfall runoff tend to show higher degrees of seasonal variation in $\delta^{18}O$ than those originating primarily from groundwater discharge (Darling et al 2003). The $\delta^{18}O$ values of surface waters are also affected by evaporative fractionation to a greater or lesser degree; standing or slow moving bodies of water such as lakes tend to be more affected than rivers and streams in this respect (Darling et al 2003). Average wind velocity is a contributing factor. The highest $\delta^{18}O$ values for lakes in the British Isles have been measured in lochs located on Scottish islands such as Unst, Shetland (Darling et al 2003) where average wind velocities are high and lochs are relatively small and shallow.

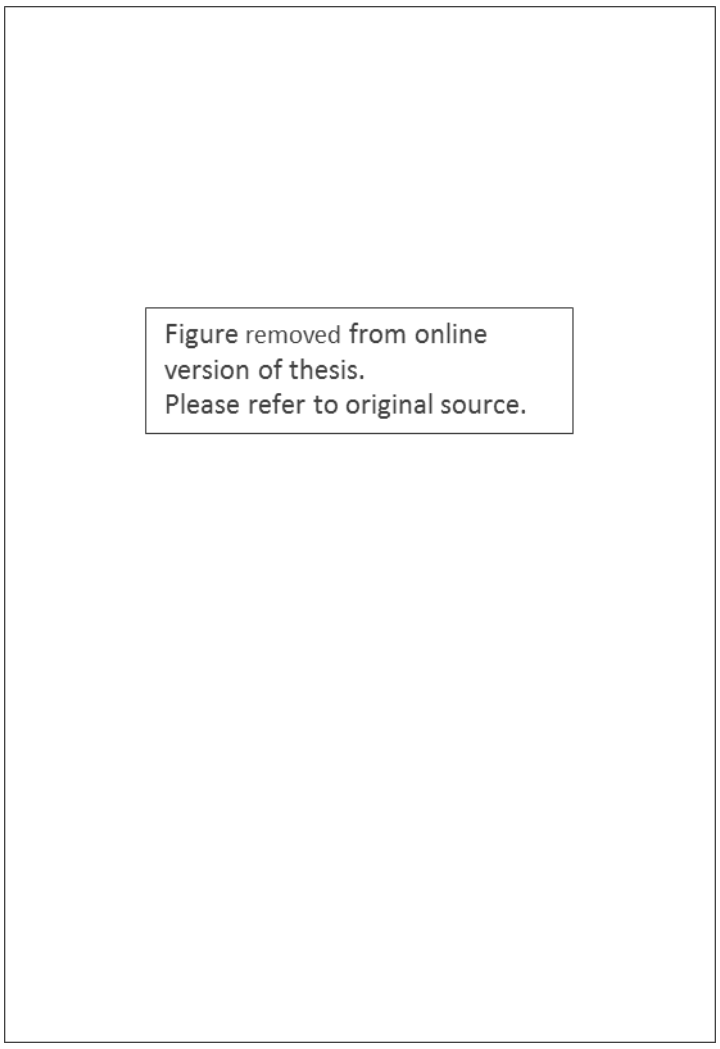


Figure 3.1: Contour map of groundwater $\delta^{18}O$ values for the British Isles. Taken from Darling et al 2003.

In addition to open water sources such as lakes and streams, a further source of water available to herbivores is plant material. In fact, some herbivores, such as non-lactating adult domestic sheep, may obtain all the water they require from vegetation and from any dew forming thereon (King 1978 p201). In contrast, domestic cattle require a source of open water since they are obligate drinkers. Mature modern beef animals require more than 50 litres per day and younger animals proportionally less depending on body weight (King 1978 p161). Since oxygen isotope fractionation does not occur during the uptake of water from soil into a plant's root system (Zundel et al 1978), the $\delta^{18}O$ value of water in the root and stem tends to be similar to that of precipitation. However, because of the process of transpiration from leaves, which is evaporative in nature, the $\delta^{18}O$ value of leaf water is more positive than that of root and stem water (Gonfiantini et al 1965, Dongmann et al 1974, Epstein et al 1977).

Thus, the $\delta^{18}O$ value of a herbivore's body water, $\delta^{18}O_{body\ water}$, which is principally controlled by $\delta^{18}O_{precipitation}$ (Longinelli 1984), is similarly influenced by climate, season and geography but is also dependent on the animal's drinking behaviour and by the nature of its water source. The turnover of body water oxygen has been shown to have a half-life of between 3 and 6 days for small mammals (Podlesak et al 2008) and it is likely that the turnover within larger mammals is complete within a month (Sharp and Cerling 1998). As a result of the isotopic values and proportions of the various inputs and outputs of an animal's body water and the fractionation of some of these inputs and outputs, $\delta^{18}O_{body\ water}$ is more positive than $\delta^{18}O_{precipitation}$ (Longinelli 1984, D'Angela and Longinelli 1990, Kohn 1996). One consequence of this is that the $\delta^{18}O$ values of milk are more positive than those for drinking water (Lin et al 2003, Renou et al 2004, Camin et al 2008) because it is derived from the mother's body water.

In this study, oxygen isotope ratios are measured in tooth enamel, which is largely composed of the mineral hydroxyapatite, the chemical formula of which is $Ca_{10}(PO_4)_6(OH)_2$. This mineral, also a constituent of bone and dentine, is never in its pure form due to the substitution of other ions including carbonate (CO_3^{2-}) for

phosphate (PO_4^{2-}) and hydroxyl (OH^-), and strontium (Sr^{2+}) for calcium (Ca^{2+}) (Hillson 2005 p146-147). In this biological, impure form, the mineral is referred to as biological apatite or "bioapatite". It is possible to obtain $\delta^{18}O$ values for both the carbonate and phosphate components of enamel bioapatite. During enamel formation, both components precipitate from body water, a process involving fractionation, and their resulting $\delta^{18}O$ values, $\delta^{18}O_{carbonate}$ and $\delta^{18}O_{phosphate}$, are dependent on both the value of $\delta^{18}O_{body\ water}$ and temperature; for homeothermic mammals, enamel mineralizes at a constant body temperature of ~ 37 °C and $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ are approximately 18 ‰ and 26 ‰ more positive than $\delta^{18}O_{body\ water}$ respectively (Longinelli 1984, Luz and Kolodny 1985, Bryant et al 1996a, Iacumin et al 1996, Kohn 1996, Koch 2007). It follows that $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ are influenced by all the factors controlling $\delta^{18}O_{body\ water}$. Hence, it is possible to investigate climate, migration, diet and birth seasonality through the measurement of $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ in archaeological animal remains (e.g. Fricke et al 1998, Sponheimer and Lee-Thorp 1999, Balasse et al 2003, Pellegrini et al 2008).

3.3 Herbivore $\delta^{13}C$: environmental inputs and sources of variation

The food consumed by an animal determines the carbon isotope ratios of its body tissues (DeNiro and Epstein 1978), and for a herbivore, vegetation of one form or another is usually the sole dietary input. Ultimately, the source of carbon for vegetation is atmospheric CO_2, which is incorporated through the process of photosynthesis. Currently, the average global $\delta^{13}C$ value of atmospheric CO_2 is < -8 ‰ (Keeling et al 2010), a value that has become increasingly more negative since the industrial revolution as a result of anthropogenic fossil fuel combustion and biomass destruction (Keeling et al 1979, Friedli et al 1986). Pre-industrial levels were ~ -6.4 ‰ according to measurements of atmospheric CO_2 trapped within ice cores (Friedli et al 1986). Atmospheric CO_2 enters a plant by diffusion through the plant's stomata, during which fractionation occurs due to the differential diffusivities of $^{13}CO_2$ and $^{12}CO_2$. There is further fractionation during the process of photosynthesis itself. As a result, $\delta^{13}C$ values measurements of plant material are

more negative than the $\delta^{13}C$ value of atmospheric CO_2, the degree of difference depending on the photosynthetic pathway used by the plant (Bender 1968, Smith and Epstein 1971, Farquhar et al 1989). Most of the world's terrestrial plants, including the staple crops barley, oats, rice, rye and wheat, photosynthesize by the Calvin-Benson or C_3 pathway, in which carbon is initially fixed into a 3-carbon compound (Sealy 2001 p270). Worldwide, the $\delta^{13}C$ values of C_3 plants are highly variable, measurements ranging from –37 ‰ to –20 ‰ (Kohn 2010). Of more relevance to this study are the results of a study by Dungait et al (2010) where a mean value of -28.7 ± 1.2 ‰ and a range of 4.2 ‰ were obtained for grasses and herbs from cattle-grazed meadowland in Somerset, UK.

A second group of plants, consisting mostly of a variety of tropical grasses including the crops maize, millet, sorghum and sugarcane, photosynthesize by the Hatch-Slack or C_4 pathway for which a 4-carbon compound is the first product of photosynthesis (Sealy 2001 p270). $\delta^{13}C$ values for C_4 plants range from -16 ‰ to -9 ‰ (Deines 1980). The terrestrial plants available as food to herbivores of prehistoric Britain would have been predominantly C_3 plants. C_4 plants were unlikely to feature in their diet and the same argument may be applied to a third, small group of mainly succulent plants designated CAM plants after their mode of photosynthesis (Crassulacean Acid Metabolism). CAM plants switch between C_3 photosynthesis during daylight hours and C_4 photosynthesis during the night (Deines 1980).

The wide range of $\delta^{13}C$ values measured for C_3 vegetation results from a variety of factors that affect the stomatal conductance of CO_2 and the rate of photosynthesis including plant physiology and morphology. Differences in vegetation $\delta^{13}C$ values have been observed between species, growth forms (e.g. herbaceous or woody) and different varieties of the same species (e.g. Körner et al 1988, Smedley et al 1991, Senbayram et al 2008). Differences have also been measured between plant parts such as grains, stems and roots (e.g. Lowdon and Dyck 1974, Winkler et al 1978, Leavitt and Long 1982, Badeck et al 2005) and between biochemical constituents such as sugars, amino acids and fatty acids (Deines 1980, Ambrose and Norr 1993, Dungait et al 2008). A range of environmental factors may also affect

stomatal conductance and the rate of photosynthesis, thus, influencing the $\delta^{13}C$ values of plants. These are summarised by Heaton (1999) and Tieszen (1991) and include: light level: plant $\delta^{13}C$ values become more positive as light intensity increases (e.g. Ehleringer et al 1986, Yakir and Israeli 1995); water availability: plant $\delta^{13}C$ values become more negative with increasing water availability (e.g. Stewart et al 1995, Schnyder et al 2006); soil salinity: plant $\delta^{13}C$ values become more positive with increasing soil salinity (e.g. Guy et al 1986, van Groenigen and van Kessel 2002); and soil nitrogen content: plant $\delta^{13}C$ values become more positive with increasing nitrogen content (e.g. Sparks and Ehleringer 1997). Environmental factors such as water availability and irradiance tend to vary seasonally leading to seasonally varying plant $\delta^{13}C$ values (Smedley et al 1991, Dungait et al 2010). In addition, the $\delta^{13}C$ value of atmospheric CO_2 varies seasonally in the Northern Hemisphere with $\delta^{13}C$ increasing in the summer months and decreasing during the winter (Farquhar et al 1989, Ciais et al 1995). This has been attributed to the much larger landmass and associated vegetation of the Northern Hemisphere which acts as a CO_2 sink during the growing season when $^{12}CO_2$ is preferentially taken up by vegetation through photosynthesis and relatively more $^{13}CO_2$ remains in the atmosphere. In winter, when there is little photosynthesis, there is a net release of CO_2 from vegetation into the atmosphere through respiration which acts to lower the $\delta^{13}C$ value of atmospheric CO_2 (NOAA nd). An annual cycle of approximately ± 0.3 ‰ has been measured for British latitudes (Ciais et al 1995) and could contribute to the seasonal variation of plant $\delta^{13}C$ values. Temperature has also been suggested as a factor affecting plant $\delta^{13}C$ values. However, studies have not been conclusive in this respect (Heaton 1999). Two additional influences on plant $\delta^{13}C$ values are altitude: plant $\delta^{13}C$ values become more positive with increasing altitude, which may be related to changes in soil characteristics with altitude (e.g. Körner et al 1988, Sparks and Ehleringer 1997); and the "canopy effect" where the $\delta^{13}C$ values of plants growing at ground level under dense tree cover tend to be lower by 2-5 ‰ than for plants growing in open environments, which may be partly due to the re-assimilation of CO_2 from soil decomposition and respiration trapped by the tree canopy (Da Silveira et al 1989, van der Merwe and Medina 1991). However, reduced light levels are likely to be a significant contributing factor (Heaton 1999).

In addition to terrestrial C_3 vegetation, herbivores of prehistoric Britain living close to the seashore would have had access to marine vegetation. Seaweed was certainly given to cattle on Orkney in the 19th century as fodder (Fenton 1997 p428). On the Isle of Rum in the Inner Hebrides red deer, hill ponies and Highland cattle all include seaweed in their diets (Gordon et al 1987, Conradt 2000) and on the small island of Swona, Orkney, feral cattle have also been observed to eat seaweed (Hall and Moore 1986). Sheep on North Ronaldsay, Orkney, feed almost entirely on seaweed. $\delta^{13}C$ values measured for seaweed obtained from North Ronaldsay range from –21.2 ‰ to –14.0 ‰, significantly more positive than the range of between –32.8 ‰ and –29.0 ‰ measured for the local terrestrial vegetation (Balasse et al 2009). The $\delta^{13}C$ values for seaweed result from the uptake of dissolved carbon from the seawater (Farquhar et al 1989, Raven et al 2002).

For new-born mammalian herbivores, milk is the sole source of dietary carbon. Studies that have measured $\delta^{13}C$ values of milk, $\delta^{13}C_{milk}$, produced by cattle feeding on a C_3 diet have obtained varying differences between $\delta^{13}C_{milk}$ and the $\delta^{13}C$ value of the whole diet, $\delta^{13}C_{diet}$, ranging from $[\delta^{13}C_{milk} - \delta^{13}C_{diet}] = -0.5$ ‰ to $[\delta^{13}C_{milk} - \delta^{13}C_{diet}] = +2.9$ ‰ (Minson et al 1975, Boutton et al 1988, Metges et al 1990).

Carbon enters an animal's body as a molecular component of three principal types of nutrient: proteins, carbohydrates and lipids. Through a variety of metabolic processes, including respiration and protein synthesis, carbon atoms originally present in dietary molecules become bound within the molecular constituents of body tissues. Fractionation produces a shift in $\delta^{13}C$ value between body tissue and whole diet which varies from tissue to tissue (DeNiro and Epstein 1978). In this study, carbon isotope ratios are measured in two body tissue types: tooth enamel, largely composed of bioapatite, and collagen, which is the main proteinous component of both bone and dentine. Experimental studies have demonstrated that the $\delta^{13}C$ value of bioapatite, $\delta^{13}C_{bioapatite}$, is strongly correlated with $\delta^{13}C_{diet}$, whereas the $\delta^{13}C$ value of collagen, $\delta^{13}C_{collagen}$, primarily reflects the value of the dietary protein, $\delta^{13}C_{diet\text{-}protein}$, although the degree of correlation tends to be poor for low protein diets where a larger proportion of the carbon present in collagen is

routed from dietary carbohydrates and lipids (Ambrose and Norr 1993, Tieszen and Fagre 1993, Jim et al 2004, Kellner and Schoeninger 2007). Fractionation involved in routing carbon from the diet to newly-forming collagen results in an offset between $\delta^{13}C_{collagen}$ and $\delta^{13}C_{diet}$, with $\delta^{13}C_{collagen}$ being more positive than $\delta^{13}C_{diet}$ by around 3.5 – 6.5 ‰ (Ambrose and Norr 1993, Tieszen and Fagre 1993, Howland et al 2003, Hedges 2003). The carbon present in body tissue proteins such as collagen and hair is derived from both dietary and endogenous sources. Through isotopic analysis of horse tail hair, Ayliffe et al (2004) have estimated that ~56 % of the carbon present in hair protein is derived from a pool governed mainly by dietary sources, with a fast turnover rate and a half-life of ≤ 4 days, while the remaining ~44 % is derived from an endogenous pool with a very slow turnover rate and a half-life of 4-5 months, governed by the breakdown of proteins in bodily tissues such as skeletal muscle tissue. It is likely that the formation of collagen would be similar to hair protein.

Carbon present in the carbonate component of bioapatite is derived from dissolved inorganic carbon (CO_2, CO_3^{2-}, H_2CO_3 and HCO_3^-) in blood (Sullivan and Krueger 1981, Passey et al 2005). Again, the experimental work on horses by Ayliffe et al (2004) has shown that this blood dissolved inorganic carbon is derived from several pools with different turnover rates. They estimate that ~84 % is derived from a pool governed mainly by diet, with a fast turnover rate and a half-life of < 3 days, while the remaining ~16 % has a slower turnover rate and a half-life of ~50 days and is derived from endogenous sources. Thus, the dissolved inorganic carbon in blood appears to be more responsive to diet than the amino acids in blood, which are the building blocks of tissue protein (Ayliffe et al 2004).

As for collagen formation, the process of bioapatite formation also involves fractionation. In this case, $\delta^{13}C_{bioapatite}$ is substantially more positive than $\delta^{13}C_{diet}$. Offsets measured in various studies for herbivores range from around 9-15 ‰ (Ambrose and Norr 1993, Tieszen and Fagre 1993, Cerling and Harris 1999, Balasse 2002, Jim et al 2003, Passey et al 2005). The larger offsets have been measured for ruminants. It is postulated that the increase in bioapatite-diet offset in these animals over other herbivore species results largely, but perhaps not solely, from

the fermentation of food brought about by micro-organisms in the rumen (Hedges 2003, Passey et al 2005). The fermentation process produces methane and CO_2. The $\delta^{13}C$ value of the methane is significantly more negative than the food by more than 30 ‰ (Rust 1981, Metges et al 1990, Schulze et al 1997). As a consequence, the CO_2 becomes enriched in ^{13}C. It is argued that if a proportion of this ^{13}C-enriched CO_2 enters the blood stream, the average $\delta^{13}C$ value of dissolved carbon in the blood will be more positive than for a non-ruminant with a comparable diet and will therefore lead to more positive values of $\delta^{13}C_{bioapatite}$ (Hedges 2003, Passey et al 2005). The amount of methane produced by the fermentation process depends on both the quantity and quality of ingested food, with the rate of methane production higher for a low-quality fibre-rich diet than for a protein-rich diet (Crutzen et al 1986). This was demonstrated by Harper et al (1999) who found that methane emission was approximately four times higher for cattle fed a pasture-only diet than for cattle fed a grain-rich diet (80 % grains). Thus, it is possible that the quality of a ruminant's diet will influence the $\delta^{13}C$ value of forming bioapatite. However, to date, there has been no detailed exploration of this suggestion in the published literature.

3.4 Herbivore $^{87}Sr/^{86}Sr$: environmental inputs and sources of variation

A herbivore's principal sources of strontium are its food and drinking water. Before the introduction of modern fertilizers, all strontium present in vegetation and water would have had a geological origin. Strontium has four naturally occurring stable isotopes, three of which are non-radiogenic: ^{88}Sr, ^{86}Sr and ^{84}Sr. The fourth, radiogenic ^{87}Sr, is produced through the radioactive β-decay of ^{87}Rb (rubidium), which occurs naturally in many minerals and rocks and has a half-life of ~4.88×10^{10} years (Capo et al 1998). From the time of formation, the amount of ^{86}Sr, ^{88}Sr and ^{84}Sr in a rock or mineral will remain constant but the amount of ^{87}Sr will increase over time. Thus, the value of $^{87}Sr/^{86}Sr$ measured for a rock or mineral will depend on the relative abundances of strontium and rubidium at the time of formation and the time elapsed since formation (Bentley 2006). Consequently, $^{87}Sr/^{86}Sr$ values of rocks tend to vary between 0.703 for recently formed volcanic rocks and ≥ 0.750 for old

rocks with a high initial abundance of rubidium with respect to strontium (Graustein 1989).

Physical and chemical weathering of rocks allows strontium to become biologically available in soils, groundwaters and stream waters (Graustein 1989, Åberg 1995, Capo et al 1998). Other sources of strontium entering soils and surface waters are atmospheric dust and aerosols (e.g. Dymond et al 1974) and precipitation, which is more significant in temperate, maritime regions such as the British Isles (Montgomery 2010). Rainfall is derived from the ocean and, in maritime regions, has a similar value of $^{87}Sr/^{86}Sr$ to that of seawater, ~0.7092 (McArthur et al 2001). This is the average value for the continental crust, which is continuously entering the oceans as sediment through the processes of weathering (Bentley 2006). In coastal areas, additional, and significant, sources of marine-derived strontium are sea-splash and sea-spray (Whipkey et al 2000), the strontium concentration of which is considerably higher than for rainwater and terrestrial surface waters (Capo et al 1998). Thus, the strontium available to vegetation in soil water may result from the mixing of several different sources. Because strontium and calcium are both alkaline earth metals and have similar ionic radii, strontium tends to substitute for calcium in a variety of biochemical and physiological contexts (Ezzo 1994), which enables it to become incorporated into vegetation tissues and, thence, animal tissues. Using a mixing equation, the $^{87}Sr/^{86}Sr$ value of vegetation may be calculated as a weighted mean of the various strontium sources present within the soil water, provided the strontium concentration and $^{87}Sr/^{86}Sr$ value of each source are known (Capo et al 1998, Bentley 2006). Similarly, the $^{87}Sr/^{86}Sr$ value of herbivore tissue is a weighted mean of its sources of strontium.

Usually, the $^{87}Sr/^{86}Sr$ value of vegetation is dominated by strontium derived from the local bedrock. Indeed, a map of biosphere $^{87}Sr/^{86}Sr$ values drawn up for Britain, using plant and water values obtained from a wide range of locations, shows a strong relationship with the underlying bedrock geology (Figure 3.2) (Evans et al 2010). Nevertheless, in some areas of western Britain, where rainfall is high, and in coastal areas, biosphere values of $^{87}Sr/^{86}Sr$ are often modified by rainwater or

seawater. Despite this damping effect in certain areas, the geology and associated biosphere values of $^{87}Sr/^{86}Sr$ of the British Isles are sufficiently varied to utilise strontium isotope ratio analysis in archaeology as a method to investigate the origins and movements of animals, both wild and domestic (e.g. Sykes et al 2006, Montgomery et al 2007a, Towers et al 2010, Viner et al 2010). Similar studies have been carried out elsewhere in the world (e.g. Hoppe et al 1999, Balasse et al 2002, Pellegrini et al 2008, Britton et al 2009).

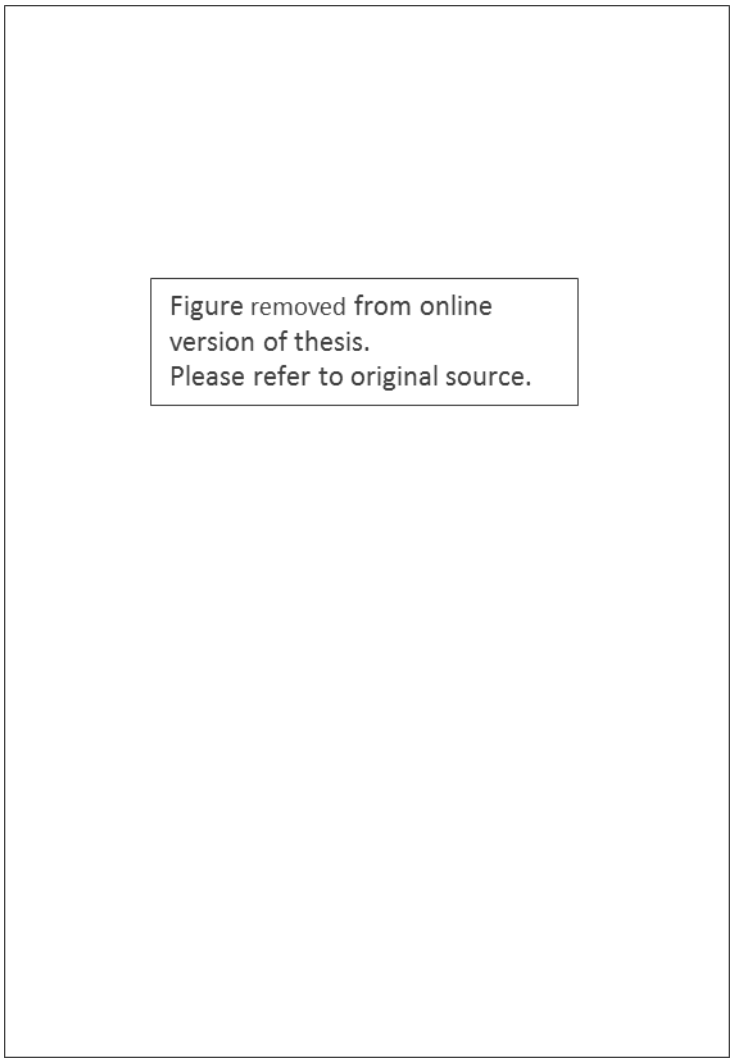


Figure 3.2: A map of biosphere $^{87}Sr/^{86}Sr$ values for Britain. Taken from Evans et al 2010.

In the present study, $^{87}Sr/^{86}Sr$ values are measured in cattle tooth enamel. Like calcium, strontium originating in food and drink is absorbed from the intestine into blood plasma from where it becomes incorporated into forming enamel, Sr^{2+} ions substituting for Ca^{2+} cations in the bioapatite lattice (Ezzo 1994). A proportion of strontium incorporated into bioapatite may originate from bone. Like enamel, strontium substitutes for calcium in bioapatite but, unlike enamel, bone is a living tissue which remodels during life, releasing calcium and strontium back into the blood plasma. This recycled strontium may have been resident in the body for several months or years, depending on a number of factors including age, calcium intake and bone turnover rates (Papworth and Vennart 1984). Thus, $^{87}Sr/^{86}Sr$ values measured in enamel may not only reflect the $^{87}Sr/^{86}Sr$ values of an animal's food and drink at the time of enamel formation, but also $^{87}Sr/^{86}Sr$ values stored in the body from the past (Montgomery et al 2010).

3.5 Isotope ratio mass spectrometry

Isotope ratios of body tissues and environmental samples may be measured through the use of mass spectrometry. The technique of isotope ratio mass spectrometry, initially developed in the 1920s, has evolved during subsequent decades to produce a range of different instruments, designed and optimised to suit the analyses of particular isotopes, with applications in the fields of ecology, geochemistry, nuclear engineering, nutrition and pharmacology (Newman 1996), in addition to archaeology. The generic design of all these instruments includes some form of ionization facility, a single magnetic sector that separates and focusses the resulting ion beams according to their mass to charge ratios and an array of collectors to count the separated ions (Figure 3.3) (Brenna et al 1997). By sacrificing the flexibility and high resolution present in other types of mass spectrometer and limiting the range of ions that may be detected, high-precision isotope ratio measurements may be obtained (ibid).

Figure 3.3: The general layout of an isotope ratio mass spectrometer. Taken from Brenna et al 1997.

The particular technique of mass spectrometry used predominantly in the present study is known as continuous flow isotope ratio mass spectrometry in which the samples are transformed into a gaseous form and transported by a carrier gas, high-purity helium, through various stages of on-line chemistry into the ionization facility of the mass spectrometer. For tooth enamel, the sample gas is CO_2 which is carried by helium into the mass spectrometer, enabling the measurement of both $\delta^{18}O$ and $\delta^{13}C$ for the carbonate fraction of the enamel. For this study, the extraction of CO_2 from enamel carbonate was carried out in a Thermo Finnigan GasBench II, an automatic, online, carbonate preparation device connected directly to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer (Figure 3.4).

The use of this type of preparation device requires that the enamel samples, usually chemically treated beforehand to remove any exogenous carbonate and organic matter, are in powdered form. They are weighed into septa-capped vials which are placed in the autosampler of the GasBench II and flushed with high-purity helium to remove air. By adding a few drops of anhydrous phosphoric acid (H_3PO_4, 103 %) to each sample, CO_2 is released following the reaction:

$$CaCO_3 + H_3PO_4 = CO_2 + H_2O + CaHPO_4$$

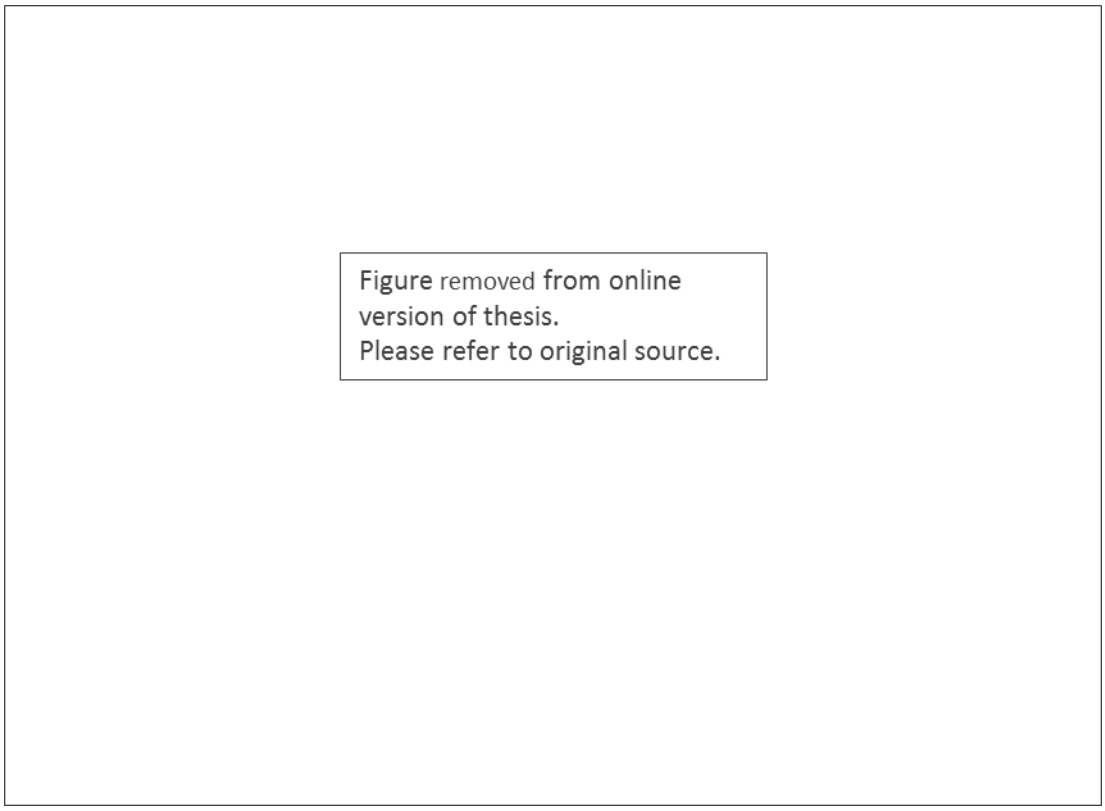


Figure 3.4: Thermo Finnigan GasBench II. Taken from the Thermo Finnigan GasBench II product brochure 2007 with additions.

Paul and Skrzypek (2007) found that allowing the enamel carbonate and phosphoric acid to react at 70 °C for 30 minutes produced accurate results. Fractionation of oxygen isotopes between the carbonate and the CO_2 means that $\delta^{18}O$ for the enamel has to be calculated using a known fractionation factor (Paul and Skrzypek 2007). To ensure that pulses of pure CO_2 enter the mass spectrometer, the released CO_2, carried by the helium carrier gas, passes through two water removal units and is injected into a gas chromatography (GC) column by means of a sampling loop (Figure 3.4). The CO_2 enters the ion source of the mass spectrometer where it is ionized by means of electron impact. A high quality reference supply of CO_2 with known isotopic composition is also introduced into the mass spectrometer and $\delta^{18}O$ and $\delta^{13}C$ values for both reference and sample CO_2 are determined. The Thermo Delta V Advantage has three Faraday collectors to detect several species of CO_2 with different mass to charge ratios (m/z): $^{12}C^{16}O^{16}O$ (m/z = 44), $^{13}C^{16}O^{16}O$ and $^{12}C^{17}O^{16}O$ (m/z = 45) and $^{12}C^{16}O^{18}O$ (m/z = 46). Ion counts at the three collectors enable the calculation of $^{18}O/^{16}O$ and $^{13}C/^{12}C$ for both the sample and reference

CO_2. Values of $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ for the sample CO_2 may then be calculated using known values of $\delta^{18}O_{VSMOW}$ and $\delta^{13}C_{VPDB}$ for the reference CO_2.

A second isotope ratio mass spectrometry system has also been employed in this study to obtain $\delta^{13}C$ values for vegetation samples and for bone and dentine collagen: a Thermo Finnigan Flash EA 1112 elemental analyser connected to a Thermo Finnigan Delta Plus XL continuous flow isotope ratio mass spectrometer. In this type of analysis, both CO_2 and N_2 are produced from the samples and transported by a flow of helium into the mass spectrometer. As a result, $\delta^{15}N$ values are also generated but are not discussed in this thesis.

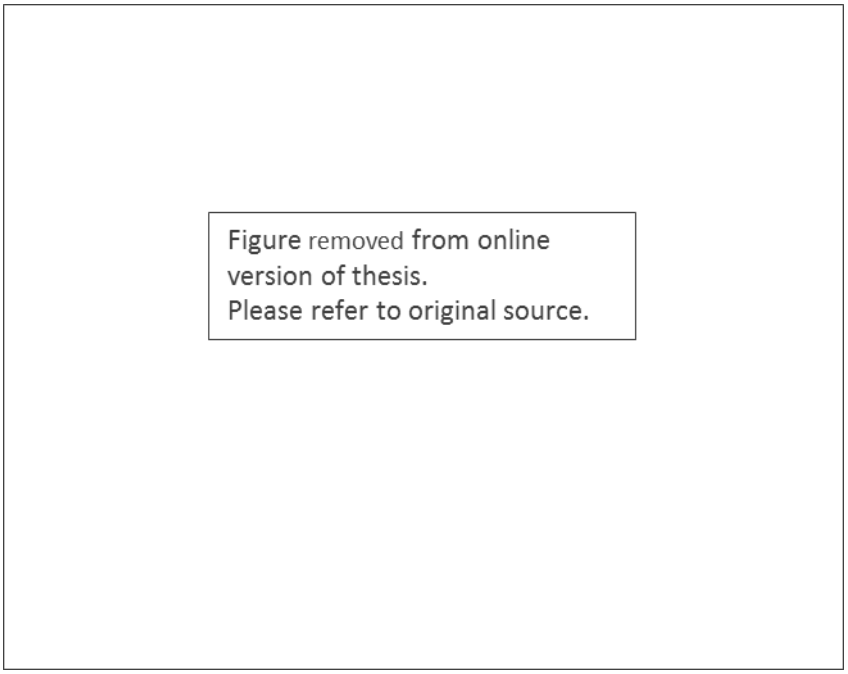


Figure 3.5: A schematic diagram of a Thermo Finnigan Flash EA 1112 elemental analyser. Taken from Oesselmann et al 2001.

Samples of collagen or powdered vegetation are weighed into tin capsules which are then sealed and loaded into an autosampler. Each sample is dropped sequentially into an oxidation furnace within the elemental analyser where it is combusted in the presence of oxygen together with various oxidants and catalysts, including the tin capsule itself, such that the combustion temperature is ~1800 °C (Figure 3.5). The resulting gaseous molecules are transported by the helium carrier

gas through silver wool, also present in the oxidation furnace, to remove halides and sulphides, and then through a reduction chamber where compounds of carbon and nitrogen are reduced to CO_2 and N_2. Water is removed and a GC column separates the two gases so that they enter the mass spectrometer consecutively rather than together. The Thermo Finnigan Delta Plus XL mass spectrometer is similar in design to the Thermo Delta V Advantage: ionization is by means of electron impact and it has three Faraday collectors to detect CO_2 with mass to charge ratios of 45, 46 and 47. The same three collectors may be used to detect three different species of N_2: $^{14}N^{14}N$ (m/z = 28), $^{14}N^{15}N$ (m/z = 29) and $^{15}N^{15}N$ (m/z = 30). Again, high quality reference supplies of CO_2 and N_2 with known isotopic compositions are also introduced into the mass spectrometer to enable $\delta^{13}C_{VPDB}$ and $\delta^{15}N_{AIR}$ values for each collagen or vegetation sample to be determined.

The majority of samples included in this study were analysed using the two isotope ratio mass spectrometry systems described above. However, a relatively small number of enamel samples were analysed to obtain $^{87}Sr/^{86}Sr$ and strontium concentration values. The method used was thermal ionisation mass spectrometry (TIMS) because it produces $^{87}Sr/^{86}Sr$ values with a sufficiently high level of precision (Crews et al 1994). In this type of analysis, each sample must first be converted to a chloride salt of sufficient purity by means of a time-consuming and rigorous chemical procedure. The salt is deposited onto a rhenium filament which is loaded onto a carousel-like magazine holding up to 21 filaments. The carousel is introduced into a Thermo Triton multi-collector TIMS where each salt sample is successively evaporated and ionized by electrical heating of the filament. The ions are accelerated and collimated to form a beam, which is directed into the magnetic sector of the TIMS and, thence, to the collectors.

A fourth isotope ratio mass spectrometry system was also used in this study to obtain $\delta^{18}O$ values for a small number of water samples. The system consisted of a VG Isoprep 18 H_2O-CO_2 equilibration device connected to a VG Sira 10 isotope ratio mass spectrometer. In this system, the $\delta^{18}O$ values of water samples are obtained using a H_2O-CO_2 equilibration method for oxygen (Epstein and Mayeda 1953). For

each water sample, 2 ml is pipetted into a 14 ml conical equilibration glass vessel which is then attached to the Isoprep 18 device. Two banks of 24 such vessels are enclosed in a temperature-controlled cabinet. Included amongst the batch are four pairs of two isotopically different internal standards. The air in each vessel is replaced by CO_2 of known isotopic composition and the H_2O-CO_2 mixture equilibrated through constant shaking of the vessel for 6 hours at 25 °C. After equilibration, the CO_2 passes into a cold trap at -80 °C for 60 s to remove water vapour and then into the Sira 10 isotope ratio mass spectrometer, which is similar in design to the Thermo instruments described above. The $\delta^{18}O$ value of the CO_2 is measured and the $\delta^{18}O$ value for the water sample calculated by interpolation from the $\delta^{18}O$ values measured for the internal standards.

4 Choice of skeletal tissues for stable isotope ratio analysis

The skeletal tissues analysed isotopically in this study are cattle molar enamel and collagen, the latter from both cattle bone and molar dentine. This chapter describes the formation processes of these tissues, which determine the temporal resolution at which isotopic measurements may be interpreted. It also describes their composition and physical properties together with their susceptibility to diagenesis.

4.1 Cattle molar enamel

When fully mineralized, fresh tooth enamel is an unusual body tissue in that it contains no cells, is 96 % inorganic and crystalline in form, the remainder being protein (<1 %) and water (Williams and Elliott 1979 p204). The inorganic fraction, known as biological apatite or "bioapatite", is an impure form of the mineral hydroxyapatite, the chemical formula of which is $Ca_{10}(PO_4)_6(OH)_2$. The impurity of bioapatite is due to the substitution of ions such as carbonate (CO_3^{2-}) for phosphate (PO_4^{2-}) and hydroxyl (OH^-), and strontium (Sr^{2+}) for calcium (Ca^{2+}) (Hillson 2005 p146-147). Crystals of bioapatite are estimated to be at least 1600 nm in length (ibid p155). After the completion of mineralization, during an animal's early life, enamel is not renewed or remodelled. Consequently, isotope ratios measured in enamel are representative of a relatively short, well-defined period of its life.

Cattle molars are hypsodont (high-crowned) teeth and their crowns form sequentially, progressing from the cusp at the occlusal surface to the cervix where crown and root meet (Figure 4.1; see also Table A.1 and Figure A.1, Appendix 1). Such a description is simplistic, however, and crown formation is, in reality, a very complex process. Amelogenesis (the formation of enamel) is brought about by a layer of narrow, cylindrical cells known as ameloblasts (Hillson 2005 p155) and has been shown, through radiographic and optical examination of hypsodont molars from sheep and goat, to follow two distinct phases: matrix deposition and maturation (Suga 1982). The matrix, an organic structure that acts as a framework for the ensuing maturation process, is secreted from cusp to cervix and is lightly

mineralized during deposition (Hillson 2005 p155). The percentage wet weight composition of the matrix before maturation commences is 66 % protein, 29 % bioapatite and 5 % water, as measured for rat incisors, the bioapatite being present in the form of thin crystallites (Nanci 2003 p154). The matrix front progresses with a periodicity that is observable through incremental structures known as the brown striae of Retzius (Hillson, 2005 p161). At any position on the crown, the matrix is initially deposited at the enamel-dentine junction (EDJ) and subsequently outwards to what will eventually become the outer surface of the fully mineralized enamel. Only after the matrix has reached its final thickness, which will be the thickness of the fully mineralized enamel, does maturation begin (Suga 1982). The ameloblasts change shape and physiology as they switch from matrix secretion to maturation, the latter involving the removal of protein and water and the significant increase in thickness of the thin bioapatite crystallites (Boyde 1997, Mann 1997). In fact, most of the mineralization occurs during the maturation phase (Robinson et al 1995). Maturation is a complicated process both spatially and temporally (Suga et al 1979, Suga 1982, Hoppe et al 2004, Tafforeau et al 2007), in contrast to the relatively simple progression of matrix deposition. There appears to be three phases to the maturation process, the first being an increase in mineralization from the surface to the innermost layer, the second a further increase in the reverse direction, and the third and final phase an increase in mineralization of a narrow subsurface layer (Suga 1982). A consequence of this complex process for cattle molar enamel is that 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, Zazzo et al 2005, Montgomery et al 2010). Hence, measured isotope ratios for enamel will be the result of averaging over that period of time. There is also the possibility that the time taken for enamel mineralization is variable within a single tooth, as observed in deciduous bovine incisors (Deutsch et al 1979), and between different tooth types with similar crown heights, as observed in equine premolars and molars (Hoppe et al 2004).

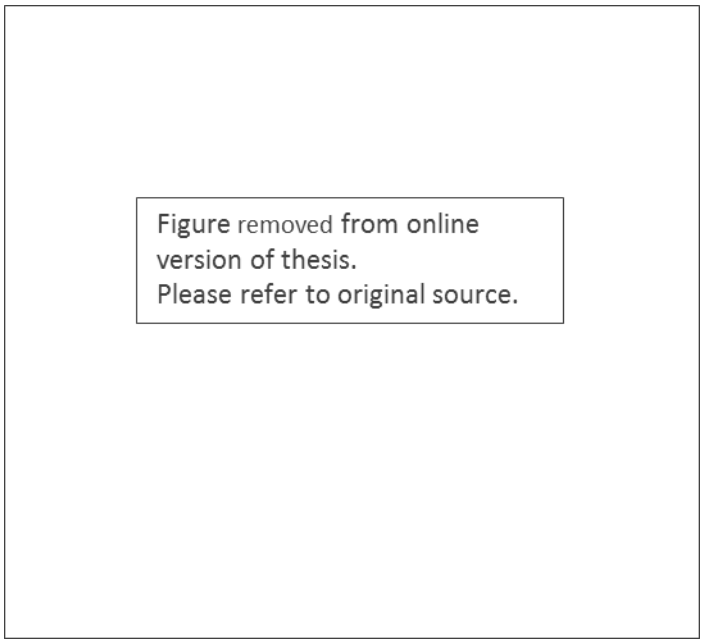


Figure 4.1: Cross section of a cattle molar. Taken from Reitz and Wing 1999 p48, with additions.

Brown et al (1960) have determined through radiography a chronology of molar development for modern cattle, as shown in Table 4.1. However, these timings are related to matrix progression and do not take account of the maturation process. There is some uncertainty in the start and finish times shown in Table 4.1, since they are given as ranges and described by Brown et al (1960) as “approximations”. In cattle teeth, the striae of Retzius, observable at the enamel surface as troughs known as perikymata, tend to be regularly spaced along most of the crown height (Hillson 2005 p163), suggesting a reasonably constant rate of matrix progression. However, a reduction in the rate of matrix progression towards the cervix has been reported in studies of molars from different bovid species (sheep, goats and the extinct *Myotragus balearicus*) (Jordana and Köhler 2011, Kierdorf et al 2012, Zazzo et al 2012).

Table 4.1: Chronology of development of mandibular cattle molars (from Brown et al 1960), related to matrix progression. * Foetal age of 140 days (Soana et al 1997), equivalent to approximately 4.7 months before birth.

	First molar (months)	Second molar (months)	Third molar (months)
Start of crown formation	In utero*	1	9 – 10
Completion of crown formation	2 – 3	12 – 13	23 – 24
Completion of root formation	13	24 – 25	38

4.2 Cattle molar dentine

By weight, fresh dentine is 72 % inorganic and 20 % organic, the remainder being water. The major organic component is the protein collagen (Williams and Elliott 1979 p204). The inorganic fraction is bioapatite, as it is in enamel. However, the crystals in dentine are considerably shorter, their lengths ranging from 20 to 100 nm (Hillson 2005 p184). Dentine is a living tissue, the cells of which are known as odontoblasts. Its formation is a two stage process with a phase of organic matrix secretion followed by mineralization. The organic matrix, known as predentine, consists of collagen fibrils and first forms at what will become the EDJ a short time before the adjacent enamel begins to form (ibid p185). Collagen is an insoluble fibrous protein comprising polypeptide chains of amino acids (predominantly glycine, proline and hydroxyproline) that form triple-stranded helical macromolecules bound together into fibrils (ibid p148). The organic matrix is mineralized almost immediately after deposition, through the seeding of thin crystallites which then expand radially (Hillson 2005 p185), but is not removed during mineralization, unlike in enamel.

Dentine is deposited as a series of stacked cone-shaped layers, and later as sleeve-shaped layers (Figure 4.2), a process that acts to increase the thickness of the dentine and cause its progression from cusp to root tip (Hillson 2005 p185), the timing of which is given in Table 4.1. After completion, during the early life of an animal, dentine is not renewed or remodelled. One consequence of the formation process of dentine in cattle molars is that a dentine sample from any position in the

crown or root, if extracted through the bulk of its thickness, will comprise a mixture of layers that, together, have taken several months to form; 8-9 months of time averaging has been estimated for second molar cattle molar coronal dentine (Zazzo et al 2006). The timings in Table 4.1 relate to the initial matrix formation of the earliest layer and do not take account of the subsequent accumulation of layers.

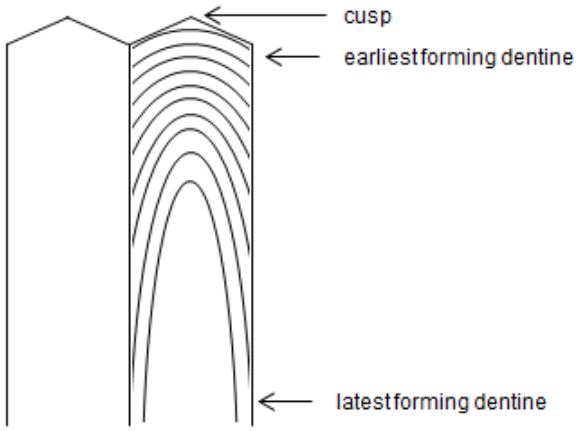


Figure 4.2: Schematic diagram showing dentine formation as a series of growth layers progressing from cusp towards the root tip (based on a figure in Balasse et al 2001).

4.3 Cattle mandibular bone

Living bone is similar to dentine in its composition: by weight it is 22 % protein, predominantly collagen, and 70 % bioapatite, the remainder being water (Williams and Elliott 1979 p204). Bioapatite crystals in bone are small and plate-like with dimensions approximately 3 x 50 x 25 nm (Weiner and Wagner 1998). At the macrostructural scale, bone has two predominant forms: cortical (or compact) bone and cancellous (or trabecular) bone. Outer layers of bone consist of dense, hard cortical bone whilst the interior material consists of spongy, porous cancellous bone containing marrow (Rho et al 1998).

The formation of bone is a complex process, the details of which are not pertinent to this particular study. However, one important property of bone is that it is constantly remodelled through life, whereby old bone is removed through resorption and replaced by new bone, a process referred to as “bone turnover”. As

a consequence, isotope ratios measured in bone collagen are likely to reflect an animal's diet averaged over a long period, perhaps several years.

4.4 Diagenesis and degradation of skeletal material

4.4.1 Bioapatite

The diagenesis of skeletal bioapatite – its chemical and physical alteration after deposition in the burial environment – may result from several different processes. The two principal diagenetic processes liable to attack the biogenic integrity of skeletal bioapatite are the addition of new material and the alteration of the bioapatite crystals themselves (Krueger 1991). The former includes precipitation of secondary minerals such as carbonates into pores and spaces at the bioapatite surfaces, and ionic exchanges at those surfaces, which is considered to be a principal mechanism for strontium incorporation into bioapatite (Pate and Hutton 1988, Montgomery 2002). The latter may result from either re-crystallization or crystal growth, enabling ions from the burial environment to be incorporated into the crystal structure of the bioapatite (Pate and Hutton 1988, Lee-Thorp 2002).

Such diagenetic processes tend to have a much greater effect on dentine and bone than enamel. This is due to enamel having larger bioapatite crystals and a reduced organic content, resulting in fewer and smaller pores and spaces. As a result, the diffusion of groundwater into the material and the precipitation of secondary minerals are much reduced. Ionic exchange is also reduced because of the lower surface area per unit volume of the larger enamel bioapatite crystals (Neuman and Neuman 1953). The smaller crystals of bone and dentine and the greater porosity of these skeletal materials, increased by any diagenetic decay of the organic content between the crystals, also makes them more susceptible to re-crystallization or crystal growth, which has been observed through X-Ray diffraction and IR spectroscopy (Koch et al 1997).

Thus, it might be expected that diagenetic processes occurring after death may alter the isotopic composition of skeletal biopapatite such that it no longer reflects the

diet and environment of an animal during its life. This has been demonstrated in a study by Nelson et al (1986) that measured oxygen, carbon and strontium isotope ratios in prehistoric and modern animal bones. For all three isotope ratios, distinctions were clearly observable between terrestrial and marine feeders for modern material but not for the prehistoric material. Measurements of strontium isotope ratios and concentrations have indicated that dentine apatite is similarly susceptible to diagenesis, whereas enamel, in general, is not (Budd et al 2000). In fact, the different diagenetic susceptibility of dentine and enamel may be exploited to determine the strontium isotope ratio of the local burial environment (Montgomery et al 2007b).

Several pre-treatment procedures to remove the effects of diagenesis on bone and dentine apatite have been proposed. Leaching with a weak acid, usually acetic acid, is a favoured method. However, the results have been mixed with some researchers claiming success (e.g. Krueger 1991, Grupe et al 1997) and others failure (e.g. Koch et al 1997, Tuross et al 1989, Trickett et al 2003, Hoppe et al 2003). Such differences in outcome strongly suggest that weak acid pre-treatment may only remove diagenetic material that has been added through precipitation of secondary minerals and ionic exchange at crystal surfaces, but cannot reverse the effects of diagenetic re-crystallization (Nielson-Marsh and Hedges 2000). The uncertain effectiveness of pre-treatment procedures for bone and dentine has prompted the recommendation of only using tooth enamel for isotope ratio analysis of bioapatite (Lee-Thorp and van der Merwe 1991, Koch et al 1997, Hoppe et al 2003).

When measuring oxygen isotope ratios in tooth enamel there is an additional consideration to be made regarding possible diagenetic effects. Oxygen isotope ratios may be obtained from carbonate oxygen or phosphate oxygen and there has been an assumption in the past that the stronger P-O bond is less susceptible to diagenesis than the weaker C-O bond, as discussed by Lee-Thorp (2002). However, isotopic studies suggest that enamel carbonate oxygen is not particularly susceptible to diagenesis, although acetic acid pre-treatment is routinely carried out to remove any exogenous carbonates derived from the burial environment. For

example, the same oxygen isotopic patterning has been observed in Pleistocene hippo and Miocene giraffid enamel and in modern African animal enamel (Bocherens et al 1996, Cerling et al 1997). In addition, more recent studies involving intra-tooth oxygen isotope ratio analysis of archaeological ruminant molar enamel have shown clear seasonal patterning indicating insignificant diagenetic alteration (e.g. Balasse et al 2003, Blaise and Balasse 2011, Towers et al 2011, Balasse et al 2012a). Intra-tooth sampling, where sequential samples are extracted from the length of a tooth crown, is described in Section 5.1.

4.4.2 Collagen

Collagen is one of the most stable organic components of bone and dentine. Nevertheless, after death, it is susceptible to two principal mechanisms of diagenesis: degradation and contamination (van Klinken 1999). Degradation involves the breakage of peptide bonds within the polypeptide chains that form the helical macromolecules of collagen. It is brought about by microbial attack and by chemical hydrolysis, which is catalysed by hydrogen and hydroxyl ions and accelerated by alkaline conditions (Collins et al 1995, Collins et al 2002). Owing to the close structural association between collagen and bioapatite, microbial enzymes cannot gain access to the collagen until small zones of apaptite have been dissolved, which may be brought about through microbially-mediated processes (Child 1995, Collins et al 2002) or chemically as a result of groundwater action. Bone preservation tends to be poor in burial environments with fluctuating groundwater content (Nielson-Marsh et al 2000).

Degradation of collagen results in the removal of peptides and amino acids, a process that leads to the progressive reduction of bone and dentine collagen content over time (Collins et al 2002). One possible consequence of microbial degradation is that the $\delta^{13}C$ value of biodegraded archaeological collagen may differ from its $\delta^{13}C$ value at the time of death. This is because the amino acid building blocks of collagen have varying $\delta^{13}C$ values and microorganisms tend to extract

certain amino acids preferentially, thus altering the overall $\delta^{13}C$ value of collagen (Grupe 2001).

Collagen may be contaminated by a variety of substances found in the burial environment including humic substances. These are highly complex, large organic molecules produced by the decomposition of biological matter (White 2006 p50). They can originate from the soil or from the auto-humification of the collagen itself and are able to bind with collagen (van Klinken and Hedges 1995). Luckily, many collagen contaminants may be removed in the laboratory through the use of appropriate treatment techniques, such as ultrafiltration, during collagen extraction (see Section 8.2.2). In addition, quality indicators may be used to identify and discard collagen samples affected by contamination or severe degradation. A set of quality indicators used in the Oxford Radiocarbon Accelerator Unit at the University of Oxford has become established (van Klinken 1999). Samples are potentially suitable for isotopic interpretation provided they satisfy all the following criteria:

1) Collagen yield. This should be ≥ 0.5 %, although samples with yields between 0.5 and 1.0 % should be treated with caution.

$$\text{Collagen yield} = (\text{weight}_{\text{collagen}} / \text{weight}_{\text{bone/dentine}}) \times 100$$

2) Carbon content (%C). This should be around 35 wt % [Oxford Radiocarbon Accelerator Unit measurements of bone of indiscriminate quality: 34.8 ± 8.8 (1σ) wt %, n = 2146 (van Klinken 1999)].

3) Nitrogen content (%N). This should be between 11 and 16 wt %.

4) C:N ratio. This is the atomic ratio and should be between 3.1 and 3.5.

$$\text{C:N ratio} = (\%C / \%N) \times (14/12)$$

5 Investigating domestic animal husbandry practices through isotope ratio analysis

The study described in this thesis employs various isotopic techniques to investigate domestic cattle husbandry, predominantly, but not exclusively, at a sub-annual resolution. This chapter describes these techniques and previous studies involved in their development and application. The majority of analyses included in the current study were performed on the carbonate fraction of enamel bioapatite because: 1) enamel is highly resistant to diagenesis, as discussed in Section 4.4.1; 2) $\delta^{18}O$ and $\delta^{13}C$ values are obtained concurrently; and 3) enamel forms sequentially from cusp to cervix and, by analysing a series of samples along the length of a molar crown, it is possible to gain time-related information. Thus, investigating animal husbandry through sequential (or "intra-tooth") sampling of enamel is the focus of this study and, consequently, this chapter. Section 5.1.1 describes the development of intra-tooth isotope ratio analysis as a technique, including the information it can provide and the resolution it can achieve, while Section 5.1.2 presents a review of relevant previous studies in which intra-tooth oxygen and carbon isotope ratio analysis have been used to investigate the birth seasonality and diet of domestic herbivores.

Intra-tooth analysis of dentine collagen and bulk analysis of bone collagen are also performed in this study, but, in both cases, there are far fewer analyses than for enamel. Therefore, the techniques are described briefly in Sections 5.2 and 5.3 respectively, the two sections focussing on different aspects. For dentine collagen it is the development of the intra-tooth sampling technique itself since there have been very few archaeological applications, while for bone collagen, the emphasis for this well-established technique is on previous archaeological studies investigating domestic animal husbandry in prehistoric Britain. Although analysis of collagen produces $\delta^{13}C$ and $\delta^{15}N$ values concurrently, interpretation of $\delta^{15}N$ values is beyond the scope of the present study. Instead the focus is on the $\delta^{13}C$ values of collagen.

The final section of this chapter is concerned with strontium isotope ratio analysis of tooth enamel. Since the application of this particular analytical technique also forms a relatively minor part of this study, only a brief description will be given in Section 5.4, focussing on the combined effect of enamel mineralization and bone turnover on the temporal resolution of the technique, together with previous studies investigating the origins of domestic cattle found at a number of British archaeological sites.

5.1 Intra-tooth analysis of tooth enamel ($\delta^{18}O$, $\delta^{13}C$)

5.1.1 The technique

Because the hypsodont (high-crowned) molars of domestic herbivores such as cattle and sheep form sequentially from cusp to cervix, time-related isotopic data may be obtained by analysing a series of samples taken along the length of a molar crown. This type of sampling is referred to as "intra-tooth" sampling. The earliest studies utilising intra-tooth sampling applied the technique to the teeth of wild animals, the first notable demonstration being carried out by Koch et al (1989) who drilled a sequence of individual dentine samples along the lengths of several Pleistocene mastodont and mammoth tusks. Oxygen isotope ratio analysis performed on the carbonate fraction of dentine bioapatite revealed sinusoidal-like patterning of $\delta^{18}O$ along each tusk, interpreted as reflecting the seasonal variation of $\delta^{18}O_{precipitation}$ via the animal's drinking water. This interpretation was supported by the fact that the lower (winter) $\delta^{18}O$ values corresponded to slow-growth areas in the tusk, as indicated by the relatively narrow incremental features present in the dentine. Thus, Koch et al (1989) successfully demonstrated that sub-annual information could be extracted from teeth using intra-tooth sampling.

By the mid-1990s, the focus of intra-tooth sampling had turned to enamel, doubts having been raised about the susceptibility of dentine bioapatite to diagenesis (Lee-Thorp and van der Merwe 1991, Koch et al 1997). In addition, oxygen isotope ratio analysis of enamel phosphate rather than carbonate was the preferred method of

analysis because the phosphate fraction was thought to be less susceptible to diagenesis, as discussed by Lee-Thorp (2002). Initially, intra-jaw rather than intra-tooth sampling was carried out, where single enamel samples were extracted from each of a number of selected teeth within a single jaw. Using this technique, Bryant et al (1996b, 1996c) obtained patterns of intra-jaw $\delta^{18}O$ variation from fossil and modern equids from which season of birth was inferred. At that time, the principal motivation behind many studies involving oxygen isotope ratio analysis of animal teeth was palaeoclimate reconstruction. Through a mixture of intra-jaw and intra-tooth sampling of a modern sheep and an archaeological bison, Fricke and O'Neil (1996) concluded that interpretation of palaeoclimate would not be straightforward using a single sample per tooth approach since each measured enamel $\delta^{18}O$ value was influenced by short-term seasonal variation in the $\delta^{18}O$ value of ingested water. They recognized that, through comparison between animals of different regions or time periods, the seasonal cycle recorded in molar enamel could itself provide more reliable information on palaeoclimates, long-term climate change and season of birth.

Building on this work, Fricke et al (1998) devised a larger, more comprehensive study involving intra-tooth sampling of third molars from archaeological cattle and sheep and modern cattle and elk, originating from a range of locations around the world. For each tooth, between four and 11 samples were extracted depending on the size of the tooth, each sample comprising ~6 mg of enamel drilled from a narrow band perpendicular to the tooth growth direction. Oxygen isotope ratio analysis demonstrated that the variation of $\delta^{18}O$ recorded in molar enamel depended on location, drinking water supply and species. For example, cattle third molar enamel from York and Iowa displayed very different patterns of $\delta^{18}O$ values. The former clearly recorded the seasonal variation of $\delta^{18}O_{precipitation}$ while the latter showed no seasonal variation at all, the cattle from Iowa deriving their drinking water almost exclusively from groundwater supplies. The $\delta^{18}O$ value of groundwater tends to be constant, equating to long-term average precipitation values (Darling et al 2003). In addition, $\delta^{18}O$ patterns in sheep third molar enamel from York and Iceland, while both displaying seasonal variation, differed in both

mean value and amplitude, reflecting the different climatic conditions of the two locations. The influence of species was also observed. Differences between the seasonally varying $\delta^{18}O$ patterns of cattle and sheep from York were interpreted as being due to sheep obtaining more of their drinking water from plant leaves. Leaf water tends to have a higher value of $\delta^{18}O$ than $\delta^{18}O_{precipitation}$ as a result of evaporative transpiration (Gonfiantini et al 1965, Dongmann et al 1974, Epstein et al 1977).

Towards the end of the 1990s isotope ratio analysis of the carbonate fraction of enamel was gaining popularity, the concurrent production of $\delta^{18}O$ and $\delta^{13}C$ data an obvious advantage. Sharp and Cerling (1998) obtained intra-tooth $\delta^{18}O$ and $\delta^{13}C$ data from fossil equid third molars by laser ablation, the carbon being derived from the carbonate fraction and the oxygen from both the carbonate and phosphate fractions of enamel. The authors suggested that the resulting sinusoidal $\delta^{18}O$ and $\delta^{13}C$ patterns indicated a lack of diagenetic alteration. Wiedemann et al (1999) obtained intra-tooth samples of powdered enamel from archaeological bovid and equid molars and analysed them for $\delta^{18}O$ and $\delta^{13}C$ after suitable treatment to remove organic material and exogenous carbonate. These authors recognized that the temporal resolution achieved by intra-tooth isotopic analysis depends upon the enamel mineralization process. A landmark isotopic study which has contributed greatly to our understanding in this respect was carried out by Balasse (2002). In that study, intra-tooth samples of powdered enamel were collected from the first and second molars of five cattle raised on an experimental farm under strict dietary control. From birth until weaning at the age of 9 or 10 months, the calves were given a C_3-only diet, predominantly as milk initially, their mothers being fed on a C_3 plant diet. After weaning, the calves' diet comprised significant amounts of maize, a C_4 plant. The enamel samples were treated to remove organic material and exogenous carbonates, then analysed for carbon isotopic composition. The resulting data demonstrated that the abrupt change in diet was not resolved in a plot of intra-tooth $\delta^{13}C$ values. Instead, it was manifest as a slope in the isotopic patterning, as shown in Figure 5.1. In fact, the influence of the C_4 diet was evident in an intra-tooth sample that started forming some 6-7 months *before* the diet switch

from C_3 to C_4. This led to the important conclusion that cattle molar enamel takes ~6-7 months to complete mineralization.

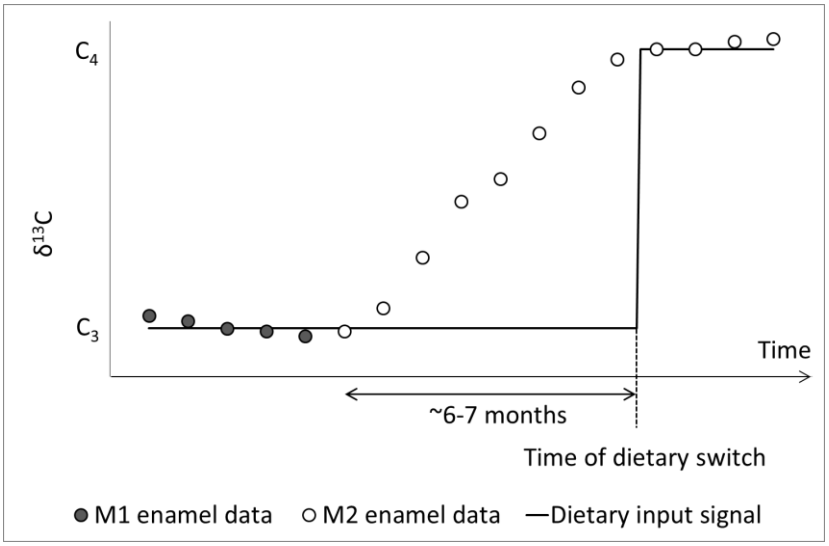


Figure 5.1: Sketch of intra-tooth $\delta^{13}C$ data recorded in cattle molar enamel and the dietary input signal that produced it. $\delta^{13}C$ data taken from Balasse 2002. Each enamel data-point is plotted according to the time of initial matrix formation. Its $\delta^{13}C$ value is of the completed enamel which took ~6-7 months to mineralize following initial matrix deposition.

A model of enamel mineralization in ungulate hypsodont teeth developed by Passey and Cerling (2002) allows prediction of intra-tooth isotopic patterning from a given input signal. Applying the model to a sinusoidal input signal, such as the seasonal variation in $\delta^{18}O_{precipitation}$, led to the following observations: 1) the process of enamel mineralization causes attenuation between the input and recorded signals (Figure 5.2); 2) there is a time shift between the input and recorded signal (Figure 5.2); and 3) the recorded signal is not greatly influenced by the intra-tooth sampling density provided that the time interval between neighbouring samples in terms of matrix progression is several times shorter than the time taken for each sample to complete mineralization (Passey and Cerling 2002, Kohn 2004).

In order to test the model by Passey and Cerling (2002) on cattle molar enamel, Zazzo et al (2005) re-analysed the molars previously used in the study by Balasse (2002), from modern cattle on a strictly controlled diet. They collected microsamples through the enamel thickness, from the surface to the enamel-

dentine junction, and, as a result, were able to determine mineralization parameters, allowing the model developed by Passey and Cerling (2002) to be used to predict isotopic signals in cattle enamel. Zazzo et al (2005) concluded that isotopic patterning along the innermost layer of enamel, next to the enamel-dentine junction, potentially offered the most accurate representation of the input signal, a suggestion also proposed by Balasse (2003) based on the conclusions of a histological study by Suga (1982). Nevertheless, analysis of molar enamel from modern sheep on controlled diets has suggested that conventional intra-tooth sampling, with each sample comprising enamel from the whole thickness of the enamel layer, can provide useful information regarding diet despite the averaging effects of mineralization (Zazzo et al 2010), particularly in studies using a consistent sampling procedure and focussed on inter-animal comparisons (Balasse 2003). More recently, conventional intra-tooth sampling has been applied to pig enamel (Frémondeau et al 2012). The authors recommended the use of first and second incisors and male canines rather than molars because they produced clearer, less damped isotopic profiles (ibid).

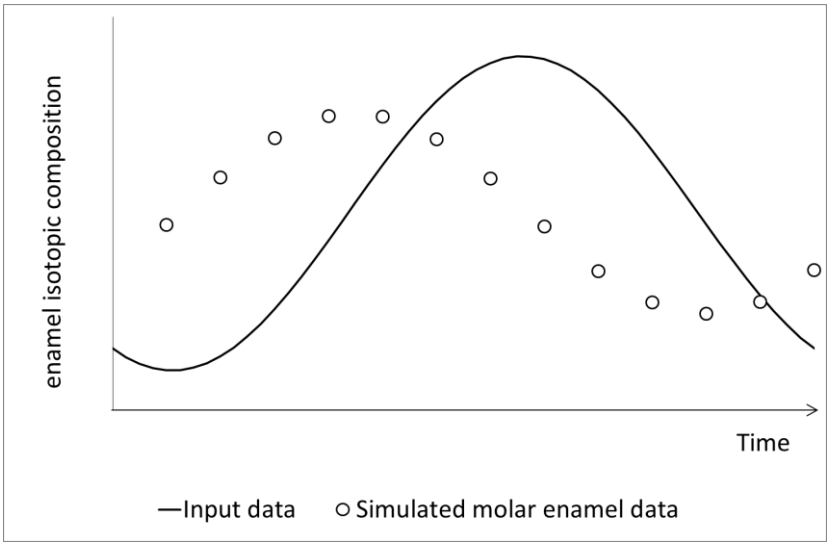


Figure 5.2: Sketch of simulated intra-tooth isotopic data recorded in hypsodont enamel and the input signal that produces it. Each enamel data-point is plotted according to the time of initial matrix formation. Its isotopic composition is of the completed enamel, the result of several months of mineralization following initial matrix deposition.

5.1.2 A review of previous isotopic investigations into domestic animal husbandry practices using intra-tooth analysis of molar enamel

During the last decade, oxygen isotope ratio analysis of intra-tooth enamel samples has increasingly been used to investigate birth seasonality in prehistoric domestic animals, i.e. how their births were distributed throughout the year. Knowledge of this is important when considering the possible husbandry practices of a prehistoric site, the feasibility and consequences of such practices and the motivation to pursue them. An early study of this type by Balasse et al (2003) was an investigation into sheep birth seasonality at the Late Stone Age site of Kasteelberg in South Africa. In that study, second molar $\delta^{18}O$ data from several sheep were combined onto the same plot of $\delta^{18}O$ versus distance from the cervix. Birth seasonality was assessed through visual inspection of the combined plot, which showed two distinct groups of overlying $\delta^{18}O$ profiles. Third molar data also showed two groups. The conclusion was that there were two lambing seasons, probably in spring and autumn, which is certainly possible for some breeds in some parts of the world. Balasse et al (2003) considered how this might have been achieved: did ewes lamb twice a year or were the ewes split into two groups lambing at different times? They also suggested that two lambing seasons may have had consequences for the human community. For example, milk would have been available for human consumption over a longer period of the year than for a single lambing season, and their degree of mobility may have been restricted.

In a similar study of Neolithic sheep from the Knap of Howar, Orkney and Er Yoh, Brittany, birth seasonality was again assessed through visual inspection of the $\delta^{18}O$ profiles (Balasse and Tresset 2007). The profiles from the earlier site, Knap of Howar, coincided almost exactly, suggesting a single restricted season of birth, whereas those from Er Yoh were more variable. $\delta^{18}O$ profiles obtained for cattle molars from the Knap of Howar and Er Yoh showed the same disparity, with those from Knap of Howar overlying one another and those from Er Yoh more varied. Balasse and Tresset (2007) acknowledged that the datasets were too small to draw firm conclusions (each dataset comprising between three and five molars) and

collection of more data was necessary. They also suggested that if the small datasets really are representative of birth seasonality at the two sites, then the difference between them for both sheep and cattle could have been the result of climate, husbandry practices and/or genetics. However, it was not possible to be more precise and determine the extent to which each of these factors was responsible. A related study that compared the $\delta^{18}O$ profiles of Neolithic sheep from Knap of Howar and the Holm of Papa Westray, Orkney, showed that, although the summer $\delta^{18}O$ maxima were similar in magnitude, the winter minima of the Holm of Papa Westray profiles were significantly higher than those of the Knap of Howar by 1.8 ‰ on average (Balasse et al 2006). The difference was attributed to significant ingestion of seawater via seaweed in the diet of the Holm of Papa Westray sheep, which was indicated by their $\delta^{13}C$ results. Similar $\delta^{18}O$ profiles were obtained for modern seaweed-eating sheep from North Ronaldsay, Orkney. Unlike $\delta^{18}O_{precipitation}$, the $\delta^{18}O$ value of seawater is fairly uniform and does not vary seasonally (Epstein and Mayeda 1953).

Towers et al (2011) applied the technique to cattle molars from Early Bronze Age barrows at Irthlingborough, Northamptonshire, and Gayhurst, Buckinghamshire. Instead of plotting the $\delta^{18}O$ data versus distance from the cervix, they produced plots of $\delta^{18}O$ versus time, where distance from the cervix was converted to time by predicting unworn crown heights and using the chronology of molar crown development suggested by Brown et al (1960) (Table 4.1). In this way, data from second and third molars were displayed together in relation to a single time-related x-axis. The assumption was that crown formation times were constant between different animals, unlike the earlier studies that had implicitly assumed a constant rate of formation (mm per unit time). Comparison of the timings of the $\delta^{18}O$ maxima from the different animals suggested that births were distributed over approximately nine months of the year. The possibility of autumn- or winter-born calves led to speculation that the provision of fresh milk in winter was the impetus. To achieve calving at those times of year would have required considerable husbandry effort in the provision of food of sufficient quantity and quality.

In each of the studies described above, both mandibular and maxillary molars were used. Because of a possible timing offset in crown formation between mandibular and maxillary molars, however small, more recent studies have tended to use mandibular molars exclusively. In a study by Blaise and Balasse (2011), the second and third mandibular molars of eight modern sheep of the southern pre-Alps breed from southeast France, born at different times of year, were analysed to produce a reference dataset which would help determine the actual season of birth of archaeological sheep. An important observation was that the resulting $\delta^{18}O$ profiles showed that inter-animal variability in crown formation appeared to be low in second molars but more pronounced in third molars. $\delta^{18}O$ profiles were obtained for the second molars of four sheep from the Late Neolithic site of Collet-Redon, also in southeast France. Through comparison with the reference dataset, the authors estimated that lambing occurred during late winter and early spring.

A second reference dataset was produced by Balasse et al (2012b) using mandibular second molars from ten modern Shetland cross sheep raised on the island of Rousay, Orkney, and born towards the end of April and at the beginning of May. By comparing plots of $\delta^{18}O$ data versus distance from the cervix, earlier studies had implicitly assumed that the rate of crown formation did not vary between different animals. However, the study by Balasse et al (2012b) suggested that this was unlikely, revealing great variability in crown height for the reference set of second molars despite the animals being slaughtered at the same age. In order to remove inter-animal variability in crown height and rate of molar formation, the authors have proposed that these sources of potential uncertainty may be removed through normalisation to period. The procedure involves fitting a cosine curve to each $\delta^{18}O$ profile to determine the period in mm, X, then scaling the whole profile relative to X. The distance from the cervix of each $\delta^{18}O$ maximum or minimum can then be defined as a fraction of the period. More details on this procedure are given in Section 12.1. The $\delta^{18}O$ profiles for the Rousay sheep were shown to have $\delta^{18}O$ maxima and minima with normalised distances 0.28X and 0.78X from the cervix on average, providing reference values for sheep born towards the end of April or at the beginning of May.

This normalisation procedure was applied to sheep mandibular second molars from the Neolithic settlement of Bercy, Paris, France (Balasse et al 2012a). Normalised distances from the cervix of $\delta^{18}O$ maxima ranged between 0.19X and 0.43X, which translates to a lambing period of approximately 3 months since X represents 12 months. The mean normalised distance, 0.31X, is similar to the value of 0.28X found for the modern reference data, suggesting that lambing at Bercy was centred around the same time of year as lambing at Rousay. Balasse et al (2012a) also applied the normalisation procedure to cattle mandibular third molars from Bercy. In this case, normalised distances ranged between 0.12X and 0.62X, translating to a calving period of approximately six months. If this is representative of the Bercy herd as a whole, one consequence would have been year-round provision of fresh milk (Balasse et al 2012a). In addition, the normalisation procedure was applied to the $\delta^{18}O$ data from the Neolithic Knap of Howar cattle published by Balasse and Tresset (2007). A distribution of births of less than two months was calculated, corroborating, in this case, the conclusion drawn using visual inspection. To date, no reference dataset has been published using molars from modern cattle.

Ideally, carbon isotope ratio analysis of intra-tooth enamel samples from domestic animals should be able to provide dietary information at a sub-annual resolution. The consumption of different plant species or plant parts at different times of the year, the movement of animals between habitats, fodder provision at certain times of the year and any seasonal variation in growing conditions have the potential to influence enamel $\delta^{13}C$ profiles. Unfortunately, if the diet is solely composed of C_3 vegetation, the magnitude of $\delta^{13}C$ variation revealed by intra-tooth sampling is often small and difficult to interpret. For this reason, previous studies have tended to focus on both wild and domestic animals living in environments that include both C_3 and C_4 plants, where large changes in enamel $\delta^{13}C$ are possible because the mean $\delta^{13}C$ value for C_4 plants is ~14 ‰ higher than the mean $\delta^{13}C$ value for C_3 plants (Sealy 2001). Typical examples of wild animal studies were carried out by Feranec et al (2009) and Souron et al (2012). Feranec et al (2009) analysed horse and bison molar enamel from Late Pleistocene deposits in California to investigate resource partitioning between the two species, concluding that, although the diets of both

species were dominated by C_3 species, bison incorporated more C_4 plants into their diets particularly during winter. Similarly, Souron et al (2012) applied the technique to the canine teeth of modern hippopotami in Chad. They were able to show that the animals' diet was dominated by C_4 grasses during the dry season but comprised a greater proportion of C_3 vegetation during the rainy season.

By analysing sheep and cattle molar enamel from the coastal site of Kasteelberg, South Africa, Balasse et al (2002) tested a hypothesis that Late Stone Age pastoralists were seasonally mobile. The difference in vegetation between the coastal area, dominated by C_3 plants, and the interior, where C_4 plants are more prevalent, provided the basis upon which mobility could be investigated. Seasonal variation was observed in the sheep $\delta^{13}C$ profiles, but it was not possible to determine, using only the $\delta^{13}C$ measurements, whether this was due to seasonal variation in the local C_3 vegetation or seasonal movement inland. Strontium isotope ratio analysis, employed to resolve the issue, suggested that some animals did indeed move between the different areas whereas others remained local. Combined $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ results for a single cow indicated that that animal had also moved from the interior, but not on a seasonal basis (Balasse et al 2002).

Studies exploiting the large difference in isotopic composition between C_3 and C_4 vegetation are not possible for prehistoric Britain where the terrestrial vegetation available as food to herbivores would have comprised predominantly of C_3 plants. However, a second strand of studies is of potential interest, particularly to coastal archaeological sites in Britain. These studies have investigated the consumption of seaweed by domestic animals, utilising the difference in $\delta^{13}C$ values between terrestrial C_3 vegetation and seaweed. The $\delta^{13}C$ values measured for seaweed are very variable but are often significantly higher than $\delta^{13}C$ values for terrestrial C_3 vegetation (Raven et al 2002). This is certainly true for the seaweed consumed by modern sheep living in North Ronaldsay, Orkney, the focus of a study by Balasse et al (2005), where $\delta^{13}C$ values for seaweed ranged from –21.2 ‰ to –14.0 ‰, while those for the local terrestrial vegetation ranged between –32.8 ‰ and –29.0 ‰ (Balasse et al 2009). $\delta^{13}C$ profiles obtained from mandibular second molar enamel

by Balasse et al (2005) clearly demonstrated that North Ronaldsay sheep consumed seaweed throughout the year, with one group feeding exclusively on seaweed while the diet of a second group included terrestrial vegetation during the summer. $\delta^{13}C$ profiles of Neolithic sheep and cattle from Knap of Howar and sheep from the Holm of Papa Westray, Orkney, showed that while the former grazed terrestrial vegetation throughout the year, the latter consumed terrestrial vegetation during the summer but relied on seaweed during the winter (Balasse et al 2006). Intra-tooth sampling was also applied to sheep molars from Neolithic Point of Cott, Iron Age Mine Howe and Late Norse Earl's Bu, all sites in Orkney (Balasse et al 2009). The resulting $\delta^{13}C$ profiles showed that one sheep from Mine Howe and one sheep from Point of Cott consumed seaweed during the winter while the remaining animals from all three sites were year-round consumers of terrestrial C_3 vegetation (ibid).

The study by Balasse et al (2009) also included $\delta^{13}C$ data for modern sheep from Rousay, Orkney that grazed on terrestrial pasture at a single farm. Their $\delta^{13}C$ and $\delta^{18}O$ profiles tended to co-vary, albeit with a temporal shift of ~2-3 months between the two, and the $\delta^{13}C$ profiles were interpreted as reflecting the seasonal variation of the pasture $\delta^{13}C$ value (Balasse et al 2009) (Figure 5.3). Two of the three sheep from Iron Age Mine Howe showed similar patterning whereas the three sheep from Earl's Bu did not (ibid). Blaise (2009 pp155) produced intra-tooth second molar $\delta^{13}C$ and $\delta^{18}O$ profiles for four modern sheep of known dietary history from southeast France. Two of the animals were born in winter, the other two in autumn. Despite the differences in birth date, all the $\delta^{13}C$ profiles showed the same pattern of variation with maxima 11-17 mm from the cervix. Blaise (2009 pp155) concluded that this feature probably reflected a known dietary change from starter food and hay to grazing at pasture when the sheep were finally weaned aged ~70 days, rather than the seasonal variation of vegetation in one location.

Figure 5.3: Intra-tooth second molar enamel $\delta^{13}C$ and $\delta^{18}O$ profiles for a modern sheep from Rousay, Orkney. Taken from Balasse et al 2009. $\delta^{13}C$ data are represented by black symbols, $\delta^{18}O$ data by white symbols.

Intra-tooth $\delta^{13}C$ profiles for cattle from the Early Bronze Age barrows at Irthlingborough and Gayhurst in central southern England were obtained by Towers et al (2011). Plots combining second and third molar $\delta^{13}C$ and $\delta^{18}O$ data onto the same time-related x-axis showed a variety of patterning in the $\delta^{13}C$ profiles, some of which appeared to show seasonal variation. For example, for one animal from Irthlingborough, the $\delta^{13}C$ and $\delta^{18}O$ profiles co-varied, maximum aligning with maximum, whereas for an animal from Gayhurst, the maximum in the $\delta^{13}C$ profile corresponded to a minimum in the $\delta^{18}O$ profile (Figure 5.4) (ibid). Similarity to the Rousay sheep profiles obtained by Balasse et al (2009) suggested that the former example may be reflecting the seasonal variation of the local vegetation $\delta^{13}C$ value due to environmental factors such as water availability (Section 3.3), whereas the latter example may have been related to movement between habitats or fodder provision at certain times of year. Such interpretations are highly speculative, however. Towers et al (2011) have suggested that only after increasing the dataset substantially and including analysis of enamel from animals of known history might recurring patterns be identified and less speculative interpretation be made.

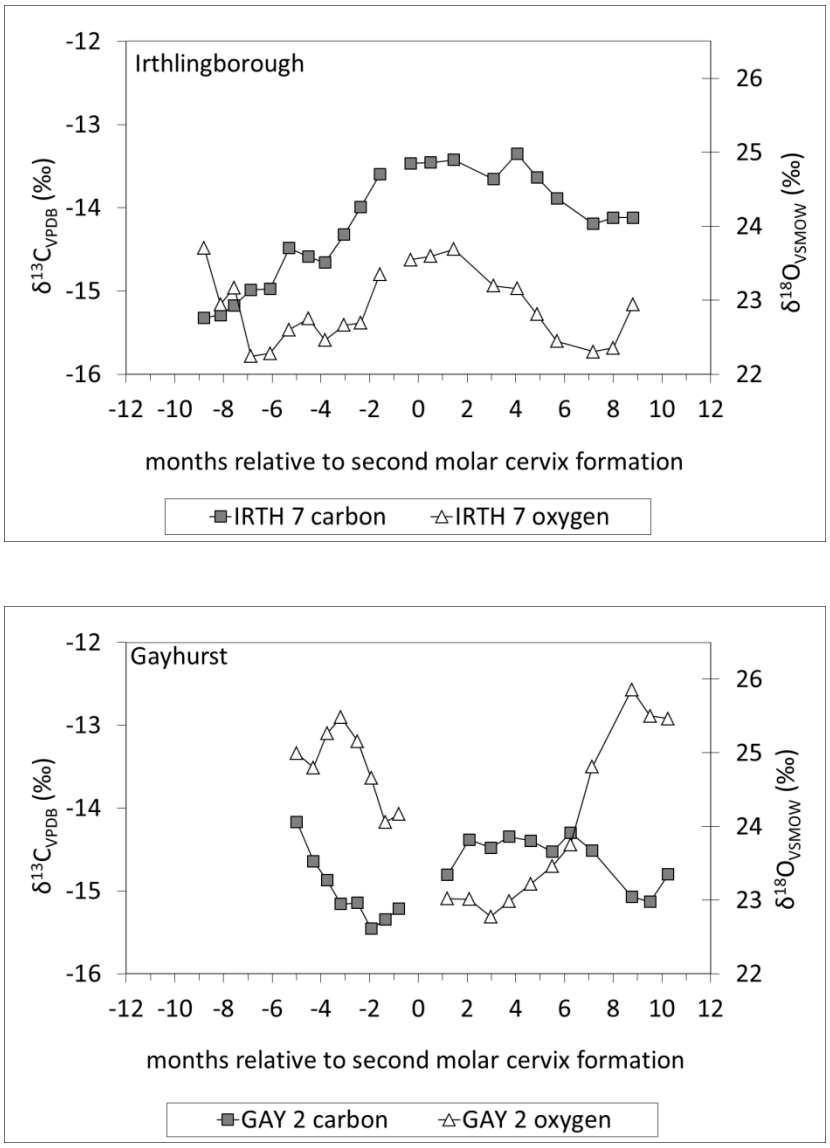


Figure 5.4: $\delta^{13}C$ and $\delta^{18}O$ profiles for Early Bronze Age cattle from Irthlingborough and Gayhurst showing different patterns of seasonal variation in $\delta^{13}C$. Data taken from Towers et al 2011.

Further work on cattle has been carried out by Balasse et al (2012a), third molar $\delta^{13}C$ profiles being obtained for ten animals from Neolithic Bercy, Paris, France. Most of the profiles showed seasonal variation and co-varied with their corresponding $\delta^{18}O$ profiles, similar to the profile for the Irthlingborough animal shown in Figure 5.4. However, in this case, it was suggested that some of the animals may have consumed leafy fodder during the winter. Leaves from vegetation growing at ground level under dense tree cover tend to be depleted in ^{13}C due to the "canopy effect" (Section 3.3). Balasse et al (2012a) have proposed that such leafy fodder was available in the dense oak forest that, according to

archaeobotanical data, existed near to the settlement. Either this fodder was brought to the animals or the animals were taken to the forest (Balasse et al 2012a). The studies by Towers et al (2011) and Balasse et al (2012a) demonstrate how similar $\delta^{13}C$ profiles can lead to a number of possible interpretations and determining the most likely can only be achieved, if at all, through knowledge of the local environment at the period in question.

5.2 Intra-tooth analysis of dentine collagen ($\delta^{13}C$)

Given that intra-tooth sampling of enamel and isotope ratio analysis of bone and bulk dentine collagen are now well-established techniques to explore the past lives of animals and the environment in which they lived, it is rather surprising that so few studies have combined carbon and nitrogen isotope ratio analysis of dentine collagen with intra-tooth sampling. Of course, the cost of analysis per animal is increased, particularly in comparison to single sample analysis of bone and bulk dentine collagen. Nevertheless, after recent development of the technique for human tooth enamel by Beaumont et al (2013), the advantage of higher resolution isotopic data in reconstructing the lives of prehistoric people has clearly been demonstrated by Montgomery et al (in press) who applied the technique to Shetland's first Neolithic farmers and revealed short-term periods of marine resource consumption during childhood, information that was not discernible in adult bone collagen data.

The first notable study applying a similar technique to animal dentine was carried out by Hobson and Sease (1998). They analysed dentine micro-samples from Stellar sea lion canines, extracted from sequential growth increments. In that study $\delta^{13}C$ and $\delta^{15}N$ values were obtained from the inorganic and organic fractions respectively. A little later, Balasse et al (2001) applied the technique to molars from five modern cattle raised on an experimental farm. The animals were under strict dietary control involving a switch from C_3- to C_4- based diets (tooth enamel from the same animals was analysed in a study by Balasse (2002), described above in Section 5.1.1). In order to obtain intra-tooth dentine samples from first and second molars,

each tooth was quartered lengthwise to include both crown and root dentine, initially into posterior and anterior halves, then into lingual and buccal quarters. One of the quarters was demineralized, after which the collagen isomorph was sectioned from cusp to root tip into 4 mm samples using a scalpel. Each intra-tooth sample was gelatinized, filtered and freeze-dried (a standard procedure for collagen preparation) then analysed for $\delta^{13}C$ and $\delta^{15}N$ by mass spectrometry (Balasse et al 2001). Like the $\delta^{13}C$ results for intra-tooth enamel, those for intra-tooth dentine demonstrated that an abrupt change from a C_3- to a C_4-based diet was not resolved in a plot of intra-tooth $\delta^{13}C$ values, but instead was manifest as a slope in the isotopic patterning. The authors suggested that this might have been due to a proportion of the carbon in collagen being derived from body pools with slow turnover rates (Section 3.3). Alternatively, the effect might have resulted from the sampling strategy in relation to the pattern of dentine growth, each intra-tooth sample comprising a number of growth layers (Figure 4.2) (Balasse et al 2001). Analysis of the inorganic fraction of powdered intra-tooth dentine samples, also obtained from the same experimental cattle, was carried out by Zazzo et al (2006). The resulting $\delta^{13}C$ profiles indicated that a typical dentine intra-tooth sample from a second molar crown takes ~8-9 months to form due to the build-up of growth layers. Thus, the isotopic patterning produced by Balasse et al (2001) is more likely to have resulted from the sampling strategy in relation to the pattern of dentine growth. In addition, for fast-growing young animals such as these, a greater proportion of the carbon present in collagen may derive from dietary sources, with a fast turnover rate, rather than from endogenous sources with slower turnover rates (Balasse et al 2001).

Balasse and Tresset (2002) used the method described by Balasse et al (2001) to investigate weaning of Neolithic domestic cattle from Bercy, Paris, France. An additional stage in the process, soaking the collagen isomorphs in sodium hydroxide, was added to remove humic acids. By comparing the pattern of $\delta^{15}N$ values in the archaeological first molars to equivalent data collected by Balasse et al (2001) for modern cattle, the authors concluded that the cattle from Bercy were weaned at an earlier age than the modern animals. These two studies appear to be

the only widely available published studies where intra-tooth dentine collagen data have been obtained for domestic animals. Of particular interest to the present research project is $\delta^{13}C$ patterning in dentine. However, intra-tooth dentine collagen $\delta^{13}C$ data from Bercy have not been published.

Such data have been produced for a small number of wild animal studies which, in some cases, can be useful when attempting to interpret data from domestic animals. For example, Britton (2009) obtained intra-tooth $\delta^{13}C$ data for molar dentine collagen from modern North American caribou and bison. Seasonal fluctuation in caribou intra-tooth $\delta^{13}C$ profiles was interpreted as most likely reflecting the seasonal consumption of ^{13}C-enriched lichen during the winter, whereas variation in bison profiles was related to the relative proportions of C_3 and C_4 vegetation in the animals' diets. These effects were more obvious in intra-tooth enamel carbonate $\delta^{13}C$ profiles and the author suggested that the dentine collagen profiles were being influenced by the contribution of carbon from endogenous sources with slower turnover rates (Britton 2009). In addition, Rountrey et al (2007) extracted and demineralized sequential dentine samples from the tusk of a juvenile woolly mammoth and analysed the organic component, principally collagen, for $\delta^{13}C$ (and $\delta^{15}N$). The resulting plot of $\delta^{13}C$ versus time revealed seasonal patterning, interpreted as seasonal variation in the relative proportions of plant and milk proteins in the animal's diet (Rountrey et al 2007). There have also been several studies centred on various species of marine mammal that have built upon the work by Hobson and Sease (1998) described above. Analysis of the organic fraction of individual dentine growth increments for $\delta^{13}C$ and $\delta^{15}N$ has enabled investigations into such topics as temporal change in diet, mobility, dietary differences between sexes and lactation period and weaning age (e.g. Newsome et al 2006, Mendes et al 2007, Hanson et al 2009, Martin et al 2011).

5.3 Analysis of bone collagen ($\delta^{13}C$)

Because isotope ratios measured in bone are long-term average values due to continual bone turnover, isotopic analysis of bone collagen is somewhat of a blunt

tool in comparison to intra-tooth analysis of dentine collagen. Nevertheless, because of its relatively low cost and straightforward method, the technique to extract and analyse archaeological bone collagen to determine $\delta^{13}C$ and $\delta^{15}N$ has become well-established, and it has been applied extensively to human material. In order to gain a meaningful interpretation of the human data from a particular archaeological site, it is essential to obtain isotope ratios for herbivores living at the same location in the same period. $\delta^{13}C$ values measured in herbivore bone collagen reflect the local growing conditions, affected by factors such as climate, soil properties and salinity (Section 3.3). Hence, they provide a baseline against which human data may be compared. Jay and Richards (2007) have provided a useful description and demonstration of the benefits of such an approach.

Isotopic datasets obtained for herbivores, including those collected as baseline data for human studies, have increasingly been used to investigate inter-site, regional and temporal differences in animal diet, husbandry and habitat. For example, bone collagen $\delta^{13}C$ was measured for a substantial number of domestic animals from Danebury Iron Age hillfort, Hampshire (Stevens et al 2010). Because archaeozoological and botanical evidence suggest that Danebury was a regional centre for food redistribution, the authors speculated that the high level of intra-population variability in $\delta^{13}C$ (and particularly $\delta^{15}N$) observed for each species was the result of animals being brought to the hillfort after being raised in a number of distinct ecological zones within the local area, such as river valleys, dry valleys and upland pasture. To test this idea, similar isotopic datasets were obtained for a further five Iron Age sites within a 7 km radius of Danebury (Stevens et al 2013), with the expectation that each site would show a narrower range of isotopic variation than Danebury. Comparisons between Danebury and the other sites showed that all six sites had similar levels of intra-population variability suggesting that each site had access to a variety of different habitats (Stevens et al 2013).

Mulville et al (2009) measured bone collagen $\delta^{13}C$ from domestic animals and red deer from Late Iron Age Bornais, South Uist, Outer Hebrides. The authors compared mean $\delta^{13}C$ values for each species with other published values from Iron Age sites

around Britain. Mean $\delta^{13}C$ values for cattle varied by < 1 ‰, ranging from -22.4 ‰ to -21.5 ‰. Interpretation of the observed inter-site differences was not possible (Mulville et al 2009). In order to investigate inter-regional differences, Jones et al (2012) amalgamated faunal data from a number of archaeological sites in the Outer Hebrides and made comparisons with a similar pooled dataset from Orkney. Comparisons were also made between the Neolithic, Iron Age and Norse periods. Iron Age and Norse pigs were the only domesticates with isotope ratios suggestive of marine resource consumption. Mean $\delta^{13}C$ values for cattle ranged from -21.9 ‰ (Iron Age Orkney) to -21.1 ‰ (Iron Age Outer Hebrides) and were always higher for the Outer Hebrides than for Orkney whatever the time period. Suggested reasons were slight differences in plant communities, whether anthropogenically determined or naturally occurring, or the effect of increased salinity due to sea-spray for the Outer Hebridean sites. Temporal differences were noted for sheep from the Outer Hebrides for which additional data for the Bronze Age and Beaker Period were available. Sheep appeared to have been subject to different foddering practices through time, possibly involving relocation from inland pastures to the more saline coastal machair in the Beaker period, for which $\delta^{13}C$ values were relatively elevated (Jones et al 2012). Similarly, salt-marsh grazing was the interpretation suggested for domestic herbivores from Middle and Late Bronze Age sites in the Severn Estuary by Britton et al (2008): bone collagen $\delta^{13}C$ (and particularly $\delta^{15}N$) values were relatively high compared to a selection of published faunal data, cattle $\delta^{13}C$ values ranging from -21.2 ‰ to -19.9 ‰.

Temporal variation in human diet was the focus of a study by Stevens et al (2012). The mean $\delta^{13}C$ value for Late Neolithic human bone collagen from the Thames Valley archaeological site at Eton College Rowing Course, Dorney, Buckinghamshire, was found to be lower than for equivalent Late Bronze Age, Iron Age and Roman values measured for the same site, the difference being statistically significant. This trend was also observed for cattle data but was not statistically significant. The number of results for humans and cattle from each time period in the Eton College Rowing Course study was small, < 8 (Stevens et al 2012). However, the isotopic analysis carried out in the much more extensive multi-site Beaker People Project

has revealed a similar chronological shift in human bone collagen $\delta^{13}C$ values (Jay et al 2012). The mean $\delta^{13}C$ value for 158 Beaker humans from England and eastern Scotland was 0.6 ‰ lower than the mean value for 164 Middle Iron Age humans from a similar geographical spread (Jay and Richards 2006, 2007), the difference being statistically significant (Jay et al 2012). According to Jay et al (2012), a mixture of published and unpublished data for domestic herbivores also shows the same trend, the temporal shift in $\delta^{13}C$ being generally greater than for humans. A change in husbandry and/or foddering possibly combined with deforestation has been tentatively suggested as the cause rather than climate change (ibid).

The potential influence of forest cover in lowering herbivore bone collagen $\delta^{13}C$ values due to the canopy effect has been exploited as a means to discriminate between aurochs and domestic cattle, the assumption being that aurochs lived in dense woodland while domestic cattle lived in more open environments. Balasse et al (2000) used this criterion to select the bones of immature domestic cattle for isotopic analysis from a mixed assemblage containing aurochs remains. Similarly, a study by Noe-Nygaard et al (2005) showed a clear distinction in bone collagen $\delta^{13}C$ between the earliest domestic cattle (~4000-5200 BP) and the most recent aurochs (~8000-9000 BP) living on the Danish island of Sjælland. The lower $\delta^{13}C$ values of the aurochs appeared to reflect the predominance of dense forest in the earlier period, evident from pollen analysis, while the higher values of the domestic cattle were indicative of the increased amount of open grassland in the later period (Noe-Nygaard et al 2005). Lynch et al (2008) observed a similar trend in their isotopic comparison of British aurochs and domestic cattle, suggesting that aurochs may have favoured wetland habitats rather than heavily forested environments based on observed behaviour of modern cattle and historical aurochs. Plant $\delta^{13}C$ values decrease with increasing water availability (e.g. Stewart et al 1995, Schnyder et al 2006).

5.4 Strontium isotope ratio analysis of molar enamel

Because of the high cost of strontium isotope ratio analysis, it is rarely combined with high density intra-tooth sampling when investigating the origins of domestic animals. Instead, it is more usual to obtain a single discrete sample or, perhaps, a small number of such samples from a crown, each sample being approximately the same size as an intra-tooth sample for oxygen and carbon isotope ratio analysis. Due to the complex mineralization process of enamel, it is expected that the $^{87}Sr/^{86}Sr$ value recorded in such a sample is an average value resulting from several months of strontium incorporation. For cattle molar enamel, ~6-7 months of averaging might be assumed following the $\delta^{13}C$ study by Balasse (2002) (Section 5.1.1). However, Balasse et al (2002) discussed the possibility that $^{87}Sr/^{86}Sr$ results obtained for sheep and cattle molars from the Late Stone Age site of Kasteelberg, South Africa, may have been influenced by a reservoir effect where strontium ions, having substituted for calcium ions in bone, are subsequently released back into the blood plasma (Section 3.4).

The incorporation of strontium in cattle molar enamel was explored in more depth by Montgomery et al (2010). In their study, 13 consecutive 2 mm wide intra-tooth samples were obtained through the full thickness of the enamel from the length of an archaeological third molar crown and analysed by thermal ionisation mass spectrometry (TIMS) (Section 3.5). The method of laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) was also utilised to obtain a second set of measurements from the length of the same enamel lobe using 400 µm diameter craters. The two datasets were indistinguishable, showing a gradual increase in $^{87}Sr/^{86}Sr$ from cusp to cervix, the overall difference between the cusp and cervix values being substantial. The authors suggested that the most likely scenario to have produced such a pattern was a single change of location. Based on this assumption, two principal conclusions were drawn: 1) reduction of the sampling volume did not improve the temporal resolution of the resulting $^{87}Sr/^{86}Sr$ profile and, therefore, long-term averaging occurred even at a microscopic scale; and 2) the gradually increasing form of the profile suggested that strontium was

incorporated over a period of at least one year, the combined effect of enamel mineralization and the recycling of "old" strontium due to bone turnover (Montgomery et al 2010).

To date there have been few studies using strontium isotope analysis to investigate domestic animal origins in Britain. In one such study, Evans et al (2007) compared $^{87}Sr/^{86}Sr$ and strontium concentration data for cattle molar enamel from Ketton and Empingham, two Anglo-Saxon sites in Rutland, central England. Although both groups of animals were interpreted as having been raised locally, the Ketton dataset was very dispersed in both $^{87}Sr/^{86}Sr$ and concentration while the data from Empingham formed a very tight cluster. The authors suggested that the Ketton cattle grazed on a range of varied soil types related to the underlying heterogeneous geology of the local area whereas feed and grazing must have been restricted and controlled for the Empingham cattle despite the similar local geology (Evans et al 2007). In contrast, second molar enamel isotope ratios for cattle from the ditch of an Iron Age chariot burial at Ferry Fryston, Yorkshire, were very variable, indicating a diversity of non-local origins (Montgomery et al 2007a). Similarly, measurements of second molar cuspal enamel by Towers et al (2010) revealed the presence of non-local animals in the large cattle assemblages from the Early Bronze Age barrows of Irthlingborough and Gayhurst in central southern England. The authors proposed regions in western Britain with more radiogenic geologies as possible birthplaces for the non-local cattle, suggesting the existence of long-distance communication and trade links in the Early Bronze Age. By increasing the number of samples to include cuspal, mid-lobe and cervical enamel from both second and third molars, it was possible to determine that the non-local animals were brought to the Irthlingborough or Gayhurst local area on the hoof well before they were slaughtered (Towers et al 2010). Evidence for long-distance prehistoric cattle movement was also presented by Viner et al (2010). In that study, third molars from Late Neolithic Durrington Walls, Wiltshire, were sampled for enamel. For each tooth, cuspal, mid-lobe and cervical samples were analysed for $^{87}Sr/^{86}Sr$ and strontium concentration. Eleven out of the 13 cattle included in the study produced $^{87}Sr/^{86}Sr$ values that were inconsistent with origins on the local chalkland.

Instead, cattle appear to have been driven to Durrington Walls, probably for feasting activities, from a range of localities, some of which were at least 100 km distant. For some animals, enamel mineralization from the three molar samples indicated movement towards the chalkland area during the period of enamel mineralization, while for others, movement occurred after mineralization was complete; i.e. cattle of different ages were brought to Durrington Walls (Viner et al 2010).

6 Archaeological sites

The archaeological sites included in this study are described in this chapter. Included in each description, where information is available, are the factors that are directly or indirectly relevant to cattle husbandry: the environment in which the cattle lived, possible water sources, the husbandry of other domestic animals, crops that were grown and the exploitation of wild resources. These particular sites and phases were selected because of their varying cattle mortality profiles. These are discussed in the final section of this chapter (Section 6.6) together with proposed interpretations regarding economic goal. Site phases and their estimated date ranges are given in Table 6.1 and the locations of the sites are shown in Figure 6.1.

Table 6.1: Summary of sites and phases from which the cattle molars selected for this study were recovered. Date ranges are estimated from information in Morris 1985 (Earl's Bu), Hunter et al 2007 p140 (Pool), Davis 2010 p417 (Mine Howe), Dockrill et al 2010 pp10 (Old Scatness). For Grimes Graves, the date range is estimated from the radiocarbon dates presented in Section 6.5.

Archaeological site	**Period and phase of cattle teeth**	**Estimated date range of period**
Pool	Iron Age/Scandinavian Interface (7)	c. 800 AD – c. 950 AD
Mine Howe	Mid-Later Iron Age (D9, D10 and D11)	c. 50 AD – c. 400 AD
Earl's Bu	Viking	c. 800 AD – c. 1050 AD
Old Scatness	Middle Iron Age (5 and 6)	c. 200 BC – c. 400 AD
Grimes Graves	Mid-Late Bronze Age (Groups 1, 2 and 3)	c. 1400 BC – c. 850 BC

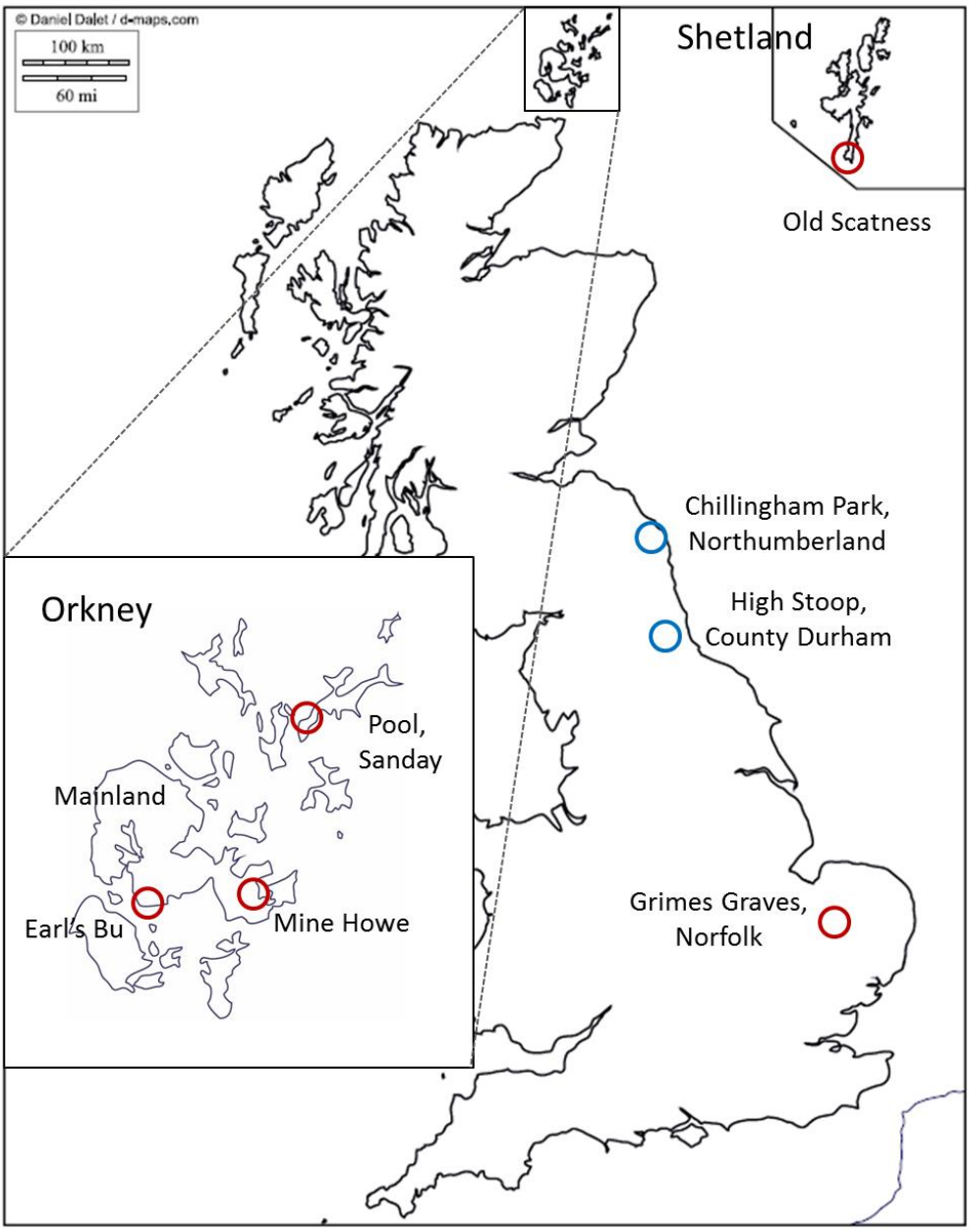


Figure 6.1: Locations of the British archaeological sites included in this study (red symbols). Also shown are two locations, Chillingham Park and High Stoop, from which modern material has been collected and analysed (blue symbols).
Map outlines taken from
http://dmaps.com/carte.php?lib=scotland_map&num_car=15859&lang=en (Orkney)
http://d-maps.com/carte.php?lib=united_kingdom_map&num_car=2557&lang=en (United Kingdom).

6.1 Pool, Orkney

Pool (NGR: HY619379, alt. 5m) is a multi-period settlement site located on the south-western peninsula of the island of Sanday, Orkney. There is evidence of occupation in the Neolithic period and from the Iron Age through to the Late Norse period (Bond 2003). The cattle teeth analysed in this study were from deposits exhibiting the earliest signs of Scandinavian influence in the archaeological record (Table 6.1). Scandinavian influence is evident in new artefact types such as steatite vessels and in differently worked implements such as pins and combs. It is also evident in building style, with Iron Age cellular structures co-existing with Scandinavian sub-rectangular buildings (Hunter et al 2007 pp121). This period may be regarded as the "Interface" period between the pre-existing Iron Age culture and the incoming and eventually dominant Scandinavian culture.

The bioarchaeological evidence indicates that Pool was a settlement with a mixed farming economy. A detailed analysis and discussion of the environment around Pool and the bioarchaeological evidence recovered from the site is presented by Bond et al (2007). A brief summary of the principal conclusions is presented here. Cattle and sheep were the dominant domestic animal species during the Interface period. Relative proportions of the domestic species present, predicted from bone counts corrected for minimum number of individuals, are 36 % cattle, 35 % sheep/goat, 20 % pig and 9 % horse. A few fragments of domestic goat bone appear in the archaeological record for the first time suggesting that goats were a Scandinavian introduction. Both terrestrial and marine wild species were also exploited, including red deer, which may not have lived on Sanday, seal, gannet, cormorant, shag and large gadids such as cod, saithe and ling.

Carbonised cereal grains recovered from Interface period contexts are dominated by six-row hulled barley (*Hordeum vulgare*) and oats (*Avena* sp.). The hulled variety of barley appears to have been favoured over naked barley (*Hordeum vulgare* var. *nudum*), which was also grown during the Interface period but to a lesser extent. It is possible that the hulled variety was better suited to storage in the damp

conditions of an Orcadian winter. Having first arrived in Pool during the early part of the 1st Millennium AD, oats appear to have been cultivated increasingly more intensively from the Interface period. Limited diagnostic evidence suggests that these oats more closely resembled the traditional black oats (*Avena strigosa*) of the Northern Isles rather than common oats (*Avena sativa*). Also, during the Interface period, flax (*Linum usitatissimum*) was introduced as a new crop to the settlement. Having arrived in Mainland Orkney several centuries before, flax could have provided both linseed oil from its grains and fibrous stems for linen production. Its appearance at Pool during the Interface period strongly suggests a Scandinavian influence to its introduction there. Despite the intensification of oats and the introduction of flax, barley production does not seem to have reduced significantly, implying that more land was transferred to arable use. Since oats are a hardy crop, they can be grown on poor land and do not require a great deal of manuring (Bond 2003).

Carbonised weed seeds from the Interface period support the idea of arable intensification with the appearance for the first time of wild radish (*Raphanus raphanistrum*), small nettle (*Urtica urens*) and black bindweed (*Polygonum convolvulus*) in addition to species already present such as chickweed (*Stellaria media*), fat hen (*Chenopodium album*) and corn spurrey (*Spergula arvensis*). Some of these arable-associated weeds are nitrogen-loving, preferring manured soil, while others grow readily in dry, sandy soils. The presence of both may support the idea that barley and flax, crops that require a rich, manured soil, were grown in a well-cultivated "infield" area close to the settlement while oats were grown further afield on poorer, sandier land that had previously been uncultivated. Sources of manure were likely to have been animal waste and, perhaps, seaweed, which was used in the 18th century. According to the description of Sanday in the Statistical Account of Scotland 1791-1799 (OSA 1799 p28), "the general manure is the seaweed or ware, which is driven ashore in storms".

To the southwest of Pool is a band of boulder clay producing an area of wet ground. The presence of damp grassland in the Interface period is suggested by the

carbonised remains of common sorrel (*Rumex cf. acetosa*). In fact, the name "Pool" itself probably refers to what was once a pool of brackish or fresh water. It is thought to have still existed as open water in the middle of the 1st millennium AD although at that time it was reducing in size due to peat growth. At some unknown time later blown sand covered the remains of the pool completely. The pool was probably still present in the Interface period providing a possible water source for livestock and flax fibre production. There also appears to have been areas of moorland and scrub woodland as suggested by the charred remains of crowberry (*Empetrum nigrum*), heather (*Calluna vulgaris*), alder (*Alnus*), hazel (*Corylus*) and willow (*Salix*).

6.2 Mine Howe, Orkney

The Iron Age site of Mine Howe (NGR: HY511060, alt. 25m), situated in eastern Mainland, Orkney, consists of a central complex of underground chambers within a natural mound, surrounded by a substantial ditch with a single entrance. The underground structure and ditch are currently interpreted as a single monument dating to around the 4th or 3rd century BC (Card and Downes 2003, Harrison 2005 p8). The ditch was initially detected by geophysics as were several buildings outside the ditch that included a circular building constructed amongst the demolished remains of earlier structures. The building, interpreted as a workshop specialising in the production of metal objects, contained a central hearth, archaeomagnetically dated to 100 BC – 110 AD, a clay-lined furnace, crucibles for melting copper alloy and anvils. An iron smelting furnace, on the central mound, was also located by geophysics and excavated (Harrison 2005 pp10). Domestic settlement structures have not been found at Mine Howe or in its vicinity, and the site has been interpreted as having religious significance (ibid pp18).

As time passed the ditch gradually filled in and by c. 500 AD it was probably no longer visible. Animal bones were found in the ditch infill and in the workshop area (Davis 2010 p99). The cattle teeth analysed in this study were from Mid-Later Iron Age ditch deposits (Table 6.1). According to a preliminary, unpublished report on

the animal bone recovered from the ditch during the 2003 excavation, cattle and sheep/goat dominated the assemblage (63 % and 24 % respectively according to number of identified specimens) followed by pig, red deer and horse (9 %, 4 % and 0.5 % respectively) (Mainland and Ewens nd). There is also evidence from the Mine Howe ditch deposits that shellfish, particularly common periwinkles (*Littorina litorrea*) were being exploited in the Later Iron Age as a food source but perhaps also as bait for fishing (Anon nd, unpublished report).

Very few carbonised cereal grains have been recovered from Mine Howe. Those that have include a single specimen of six-row hulled barley (*Hordeum vulgare*) from a context roughly contemporary with the cattle teeth analysed in this study, and a single oat grain (*Avena sp.*) which may date to a slightly later period (Miller and Ramsay 2001). Other carbonised plant remains include heather (*Ericaceae*) and small quantities of grass or sedge, suggesting the burning of heathy turf, together with willow (*Salix*), probably a low-growing, bushy species rather than a tall tree (ibid). Further information regarding the local environment may be derived from the 18th century description of St Andrews, the parish in which Mine Howe is located. According to the Statistical Account of Scotland 1791-1799 (OSA 1799 p202), St Andrews, "is in general flat; and the soil is loam and moss interspersed with stones, upon a deep cold clay and tilly bed. Hence it is naturally wet and boggy in many places. It is stiff to plough". In the Iron Age it is thought that the water table was generally higher than at present and that much of the land around Mine Howe was boggy or wet. The soils surrounding the mound at Mine Howe have been interpreted as Iron Age plaggen soils (Guttmann 2001, cited in Card and Downes 2003). Plaggen manuring was a system in which grass or heather turfs were cut from areas of wasteland, used as bedding material for domestic animals and then applied, together with the accumulated animal dung, to land used for growing crops (Blume and Leinweber 2004). It is possible that seaweed was also used as a source of manure. Certainly, in the 18th century, seaware (seeweeds such as wrack used as fertilizer) "is the most common manure, and where it is scarce, a compost formed of ware and earth" (OSA 1799 p202). The latter description of a mixture of seaweed and earth may be referring to a type of plaggen manuring.

6.3 Earl's Bu, Orkney

The site of Earl's Bu (NGR: HY335044, alt. 5m) is situated at Orphir in Mainland, Orkney on the north coast of Scapa Flow. It is thought to have been the early 12th century seat of Earl Haakon Paulsson and visible remains consist of Late Norse structures including a round church and excavated foundations of a large hall (Johnson and Batey 2003). Close to these remains a stone-lined passageway was discovered in 1978. Subsequent excavations revealed a chamber at one end, and these two structures, the passageway and chamber, have been interpreted as the leat and underhouse of a horizontal mill. They had been covered over and filled in by Late Norse midden material. Below these structures were midden deposits of an earlier, Viking, date (Batey and Morris 1992). The cattle teeth analysed in this study were from these Viking midden deposits (Table 6.1).

A detailed site report including the analysis of bioarchaeological evidence has yet to be published although initial, unpublished assessments of the faunal and botanical remains from the Late Norse deposits have been carried out. The Late Norse midden material contained large amounts of bone not only from cattle but also from sheep, goat, pig, horse, domestic fowl and goose (Mainland 1995, cited in Davis 2010 p124). Wild species were also present, including seal, whale, duck and cormorant, together with an abundance of fish bones particularly from the gadids cod, saithe, pollack and haddock (Batey and Morris 1992, Mainland 1995, cited in Davis 2010 p124). Carbonised seeds recovered from the midden material are dominated by oats (*Avena* sp.). Barley (*Hordeum vulgare*), probably the six-row hulled variety, and flax are also present as are the carbonised remains of heather wood, flowers, leaves and shoots (Batey and Morris 1992).

It is possible to gain an idea of the environmental setting and agricultural potential of Earl's Bu from an 18th century description of the parish of Orphir. According to the Statistical Account of Scotland 1791-1799 (OSA 1799 p155), "the face of the parish is diversified with hills and dales through which many rivulets flow. The soil, in a few places near the coast, is a rich loam, mixed with stones, and tolerably

fertile; but, in general, it is clay or moss, or a mixture of both; and when well manured, though but indifferently cultivated, is more than sufficient to maintain the inhabitants. The upper part of the parish, except for a few small farms, near a lake, called the Loch of Kirbister is hilly, and chiefly covered with heath, intermixed with coarse grass, and well adapted for the breeding of sheep and small cattle. The lower part, towards the S.E.S. and W. and extending about a mile from the hills to the sea-shore, is in general plain, and beautifully diversified with corn-fields, meadows, and green pasture".

6.4 Old Scatness, Shetland

Old Scatness (NGR: HU390106, alt. 10m) is a multi-period settlement site located at the southern tip of Mainland, Shetland. At the centre of the site are the remains of a broch tower, dating from the 3rd or 4th century BC (Outram et al 2010). A complex of other buildings of similar or later dates cluster around the broch and the whole settlement is enclosed by a ditch and rampart. There is evidence of occupation through the Iron Age, Viking, Late Norse and Post-Medieval periods until the 20th century (Bond et al 2004). However, the settlement may date from the Bronze Age or earlier, as suggested by cultivated soils beyond the ditch, dated using optically stimulated luminescence (Burbidge et al 2001). The cattle teeth analysed in this study were recovered from occupation and midden deposits in a series of Middle Iron Age structures (Table 6.1). Archaeological evidence, in the form of drains, a possible tether stone and hay- or straw-like deposits, suggests that the southern half of one of the buildings from this period (Structure 21, Phase 6) may have been used as a byre (Dockrill et al, in press).

An analysis and discussion of the bioarchaeological evidence recovered from Old Scatness is presented by Bond et al (in press). A brief summary of the principal conclusions is presented here. Analysis of faunal remains indicates that during the Middle Iron Age, cattle and sheep were the two dominant domesticates. Pigs were present but in considerably lower numbers. Wild species were also exploited, including seal, whale, shag, gannet, auk, gull and wildfowl, and shellfish were

utilised, either for human consumption or as fishing bait. Evidence for fishing during the Middle Iron Age is dominated by first and second year saithe which could have been caught close to the shore using a rod and baited line. Such fish could have provided conserved food supplies for times of crop failure in the form of fish oil or as dried fish.

Carbonised cereal grains recovered from the Middle Iron Age period are dominated by six-row hulled barley (*Hordeum vulgare*). However, naked barley (*Hordeum vulgare* var. *nudum*) has a significant presence particularly in contexts from the later part of the period. It has been hypothesised that the two varieties were grown as complementary crops, either to reduce the likelihood of complete crop failure resulting from disease, or to be utilised for different purposes. According to Zohary and Hopf (2000 p60), traditional farming communities tend to favour hulled barleys for animal feed and brewing beer, and naked barleys for food preparation. Smaller amounts of domesticated oat grains (*Avena* sp., probably *Avena strigosa*) are also present in the Middle Iron Age deposits. This is a very early appearance of oats in the Northern Isles and may represent the start of cultivation on a small scale rather than presence as a barley crop weed.

Carbonised weed seeds from plants such as common chickweed (*Stellaria media*), mouse ear (*Cerastium* sp.), knotgrass (*Polygonum aviculare*), fat hen (*Chenopodium album*), docks (*Rumex* sp.) and brassicas (*Brassica* sp.) indicate soils that were both sandy and fertile. Soil analysis suggests that the soils were improved considerably throughout the Iron Age with ash-based manure being replaced by domestic animal manure possibly utilising a plaggen system during the Middle Iron Age (Simpson et al 1998, Guttmann et al 2003). Carbonised seeds from heath grass (*Danthonia decumbens*), bell heather (*Erica cinerea*) and ling (*Calluna vulgaris*) indicate areas of heathland while the existence of wetland habitat is suggested by blinks (*Montia fontana*) and sedges (*Carex* sp.). Between 1½ and 2 km to the south of the site of Old Scatness, on the peninsula of Scat Ness is an area of small lakes, including the Loch of Gards, marshy ground and springs where water would have been available for cattle. Close to the settlement itself, given the sandy nature of the natural soils,

a well may have been required, as is evident at the broch site of Jarlshof 1½ km to the southeast (Fojut 1982). During the excavation of Old Scatness Broch waterlogged material was recovered, suggesting the former presence of a pond, pool or well in the vicinity of the broch (Bond, pers comm).

6.5 Grimes Graves, Norfolk

The site of Grimes Graves (NGR: TL818898, alt. 25m), located in the Breckland region of Norfolk and covering an area of approximately 9 hectares, is characterised by several hundred depressions, 6-20 m in diameter, that are the remains of Late Neolithic flint mineshafts (Mercer 1981 p1). Evidence from excavations carried out in the 1970s suggests that by the Middle Bronze Age the flint mining had ceased as an activity and the site re-occupied after a period of abandonment (ibid p113). During the Bronze Age the mineshafts were used for the disposal of midden material, the contents of which include spinning and weaving artefacts, charred grains and a large quantity of animal bones, indicating that the settlement during that period was agricultural in nature (ibid p114). The cattle mandibles analysed in this study were from the Bronze Age midden deposits of the "1972 shaft", a 10.5 m diameter mine shaft excavated in 1972. Three midden deposits separated by layers of chalky material, were identified and designated Groups 1, 2 and 3. The Group 3 midden material, at the bottom of these deposits, accumulated first, followed by Group 2 and then Group 1 (ibid pp36). Unfortunately, only one of the cattle mandibles used in this study can be ascribed to a particular midden group. Archaeological evidence (ibid pp36) and radiocarbon dates for two of the mandibles suggest that the midden material was deposited over several centuries: 1416-1302 cal BC, 95 % confidence (MAMS-14361, 3084 ± 21 BP) and 908-820 cal BC, 95 % confidence (MAMS-14362, 2722 ± 20 BP). Calibration was carried out using the INTCAL09 dataset (Reimer et al 2009) and SwissCal 1.0 (L. Wacker, ETH-Zürich).

Detailed discussions of the bioarchaeological evidence recovered from Grimes Graves and the local environment are presented by Legge (1981). A brief summary of the principal conclusions is given here. Counts of identified animal mandibles

from these midden deposits indicate that cattle were the dominant domestic species, followed by sheep/goat (thought to be mainly sheep) with pig mandibles much less numerous and horses only visible in the archaeological record by a few loose teeth. Relative proportions of the main domesticates, predicted from mandible counts corrected for minimum number of individuals, are 57 % (cattle), 37 % (sheep/goat) and 6 % (pig). Similar figures were obtained from the Bronze Age midden deposits of a second mine shaft ("shaft X") excavated in the same decade (Legge 1992 p 17). Relatively small numbers of roe and red deer remains were recovered from both the 1972 shaft and shaft X (ibid).

Carbonised cereal grains recovered from the Bronze Age midden deposits of the "1972 shaft" are dominated by barley, which has been identified as six-row hulled barley (*Hordeum vulgare*) for most specimens, and emmer wheat (*Triticum dicoccum*). These two species account for 74 % and 25 % of all cereal grains found. A single specimen of pea (*Pisum sativum*) suggests the possibility that this legume was also cultivated. Carbonised weed seeds were also recovered from the midden deposits. They include species associated with cereal crops, e.g. cleavers (*Galium aparine*), black bindweed (*Polygonum convolvulus*) and knotgrass (*Polygonum aviculare*), and those more commonly associated with pasture or waste ground, e.g. ribwort plantain (*Plantago lanceolata*), fescue grasses (*Festuca* sp.) and medick (*Medicago* sp.).

Overall, the bioarchaeological evidence suggests that Grimes Graves in the Bronze Age was a permanently settled community with a mixed farming economy. This picture is also supported by the soil types evident in and around Grimes Graves today. The Breckland is an area of sandy heathland with soils that drain very readily. As a consequence, drought conditions are possible, particularly in dry summers. Legge (1981) has simplified an earlier mapping of Breckland soils by Corbett (1973) to show that there are three main soil groupings within the vicinity of Grimes Graves: 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 (Figure 6.2). The areas of the three groupings within a 3 km radius of Grimes Graves are currently 45 %, 50 % and 5 % respectively. A mixed farming economy would have been the most efficient method of land utilisation in prehistoric times and animal husbandry would have been a necessary component to not only make use of the poorer, acidic soils but also to provide manure to maintain the fertility of those soils better suited for cereal production.

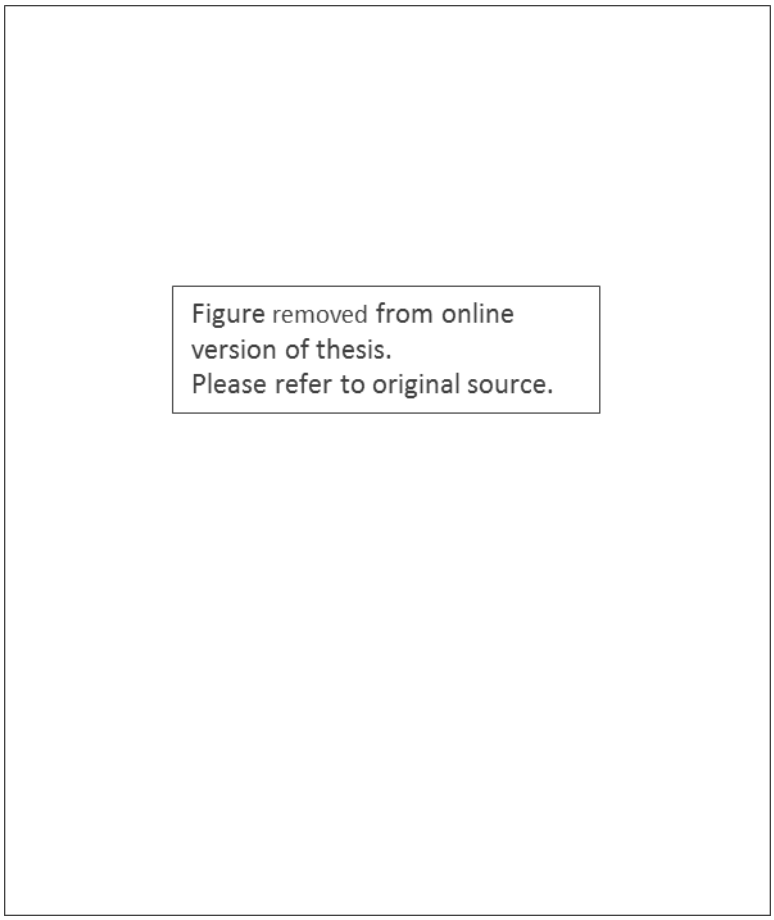


Figure 6.2: Soil types in the vicinity of Grimes Graves. Taken from Legge 1981 p95.

6.6 Mortality profiles and inferred cattle husbandry goals

For the sites and phases included in this study (Table 6.1), tooth eruption and wear analysis have been carried out previously by other researchers in order to investigate the economic goals motivating domestic animal husbandry (Legge 1981, Davis 2010 pp367, Bond et al, in press). Following Grant's (1982) wear stage definitions and age-at-death classes assigned by Halstead (1985), mortality profiles have been constructed for each assemblage which show graphically the percentage of animals surviving at each age group and hence the slaughter pattern. They are reproduced here in Figure 6.3 and show a variety of forms leading to differing interpretations regarding economic strategy, based upon models developed by Payne (1973) for meat and milk production for sheep (Figure 6.4). In Payne's meat model, lambs are reared until they just reach adult weight, a strategy that produces the greatest amount of meat for the amount of feed consumed. At that point, most of the males are killed together with a proportion of the females, some females being retained as breeding stock. Thus, Payne's meat production mortality profile shows a clear increase in slaughter between the ages of one and three years, after which the profile declines steadily reflecting the removal of sheep that are injured, barren or ill. In Payne's milk model, lambs having no future use are slaughtered as early as can be achieved without threatening the milk yield of their mothers. As a result, Payne's milk production mortality profile shows the greatest increase in slaughter for sheep less than two months old. Similar arguments may be made for cattle.

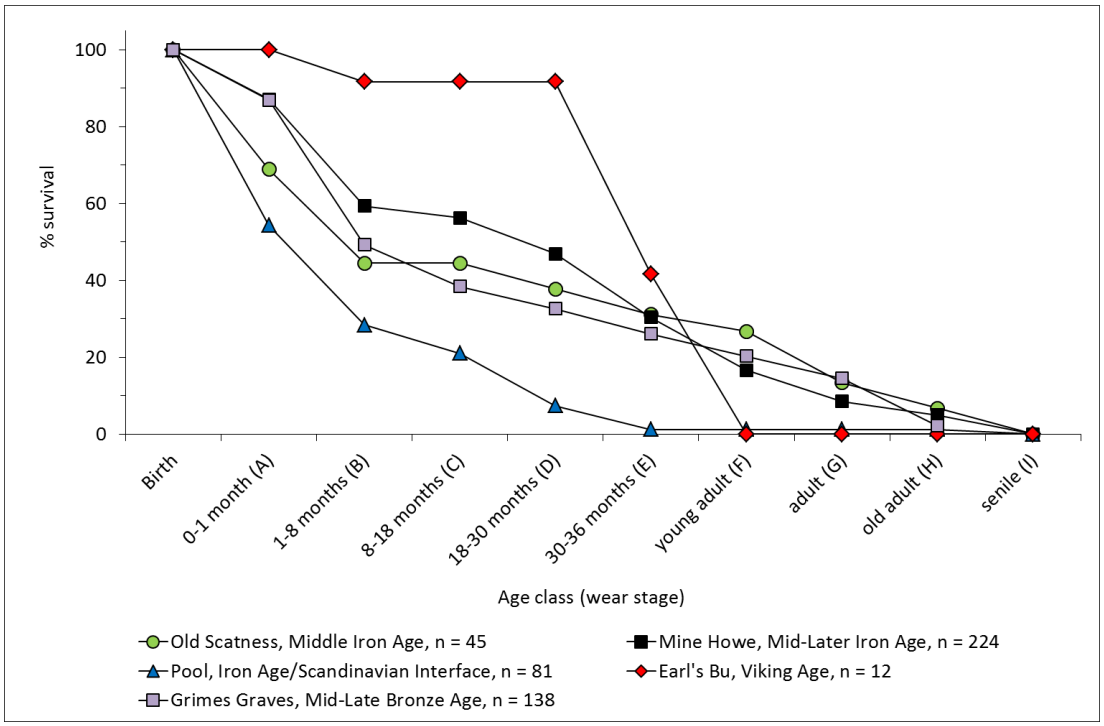


Figure 6.3: Mortality profiles for the archaeological sites and phases included in this study. Data from Legge 1992 p24 (Grimes Graves), Davis 2010 pp367 (Pool, Mine Howe and Earl's Bu) and Bond et al, in press (Old Scatness).

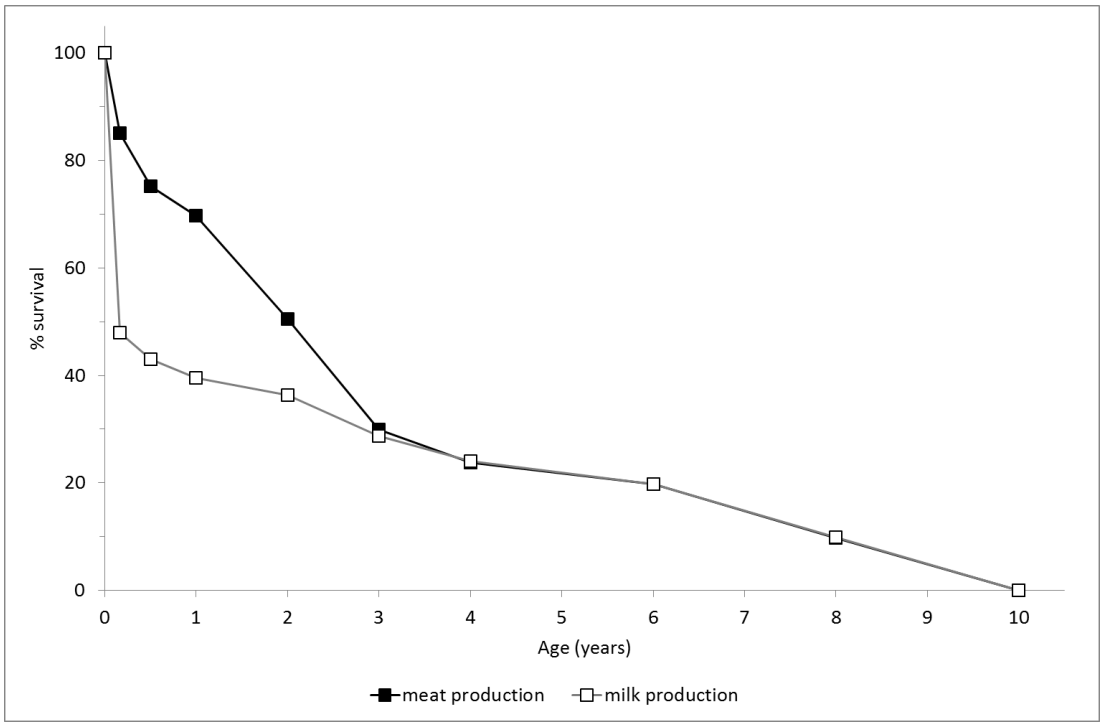


Figure 6.4: Mortality profile models for sheep/goat proposed by Payne (1973). Data from Payne 1973.

The Iron Age/Scandinavian Interface mortality profile for Pool cattle shows that more than 40 % of the assemblage were very young calves, aged less than one month, and more than 70 % were animals less than eight months old (Figure 6.3). Such a high level of juvenile mortality resembles Payne's (1973) milk model (Figure 6.4). Thus, Pool has been interpreted as having a dairy-based economy (Serjeantson and Bond 2007a). Legge (1981, 1992 pp25) argues, using data from Holmes (1970), that, by killing most calves and retaining much of the milk for human consumption, significantly more food energy may be obtained per unit area of grazing than if the calves are reared for beef. If grazing was limited at Pool and meat was available from alternative sources such as pig and sheep, for which a meat-focussed husbandry strategy is interpreted (Bond 2007), it is plausible that a more energy efficient system based on intensive cow's milk dairying was practised (Serjeantson and Bond 2007a). An estimated female to male ratio of between 4:1 and 7:1 amongst adult animals also supports an emphasis on milk rather than meat (Bond 2007). The intensification of oat production during the Interface Period through expansion into newly-cultivated poorer quality land, as suggested by carbonised grain and weed seed deposits, again appears to support the idea of a dairy-based economy at Pool since it would have provided a source of high-energy fodder for dairy cattle (Bond 2003). Returning to the mortality profile, it is noticeable that the number of older animals in the Pool assemblage is negligible, perhaps implying that old milk cows ended their working lives elsewhere. In that case, Pool may have been a producer settlement in a network of several interdependent settlements (Serjeantson and Bond 2007a).

The mortality profile for Viking Earl's Bu has a completely different form to that of Pool (Figure 6.3). A high proportion of the cattle in the assemblage were killed at wear stages E and F, almost certainly for their beef since the prime age for meat is around 1½ - 3½ years (Hambleton 1999 p78). In this respect the mortality profile for Earl's Bu resembles Payne's (1973) meat model (Davis 2010 p450) (Figure 6.4).However, the cattle remains were likely to have been debris from a high-status building on the site of the Late Norse hall (Batey and Morris 1992), and not necessarily representative of a local herd structure, given the lack of older and

younger animals as might be expected from Payne's (1973) meat model (Davis 2010 p450). It is possible that beef was supplied by one or more local farms that may or may not have specialised in its production.

Between the two extremes of mortality profile for Pool and Earl's Bu are the profiles for Mine Howe, Old Scatness and Grimes Graves (Figure 6.3). The mortality profile for Middle Iron Age Old Scatness is similar to that of Pool in that there are a large number of juveniles. More than 30 % of the assemblage were very young calves aged less than one month, and more than 50 % were animals less than eight months old. Thus, it is similar in form to Payne's (1973) milk model (Figure 6.4) suggesting that dairying was important to the Old Scatness economy (Bond et al, in press). Unfortunately, a lack of sexually diagnostic bones means that the ratio of female to male animals is not known. During the Middle Iron Age period oats were introduced and appear to have been cultivated on a small scale, perhaps to provide additional fodder for dairy cattle. From approximately 18 months of age, the mortality profile shows a steady drop off perhaps reflecting natural deaths and the deliberate removal of cattle that were injured, barren or ill (Payne 1973). This would have provided beef for consumption. Meat was also obtained from sheep, for which the mortality profile indicates an emphasis on wool but with some consumption of lamb (Bond et al, in press). Pork would also have been consumed, although probably to a lesser extent given the lower frequency of pig remains (ibid).

The mortality profile for Mid-Late Bronze Age Grimes Graves shown in Figure 6.3 has been constructed for the Shaft X cattle assemblage, for which detailed wear stage information is readily available (Legge 1992 p24), rather than for the 1972 shaft cattle assemblage from which the molars analysed in this study are derived. However, the two assemblages result in very similar mortality profiles (ibid p25). The profile resembles that of Old Scatness for wear stages B-I but differs from it in the percentage of very young animals less than one month of age (13 % for Grimes Graves, 31 % for Old Scatness). Legge (ibid p24) provides a more detailed breakdown of Grimes Graves animals at wear stage B from which it is possible to calculate that 38 % of the assemblage were less than three months of age. In total,

51 % of the Grimes Graves were animals less than eight months old compared to 56 % for Old Scatness. Despite the differences between age classes, the high proportion of juveniles less than eight months old suggests the same interpretation as Old Scatness, an emphasis on dairying (Legge 1981, Legge 1992 pp 25). This idea is supported by a female to male ratio amongst adult animals of approximately 5:1 (Legge 1992 p31).

The mortality profile for Mid-Later Iron Age Mine Howe is similar to that of Grimes Graves in that there is a high proportion of animals between one and eight months of age (28 % of the assemblage for Mine Howe compared to 38 % for Grimes Graves). Given that Mine Howe has been interpreted as having religious significance (Harrison 2005 pp18), the cattle remains may have been the debris of religious rituals or feasting, and not necessarily representative of a local herd structure. Thus, the high proportion of juveniles may reflect a dairy-based economy, but alternatively, it may represent ritual slaughter at a certain age, perhaps autumn slaughter of spring-born calves (Davis 2010 p425). There is also a second age range of increased slaughter, at wear stages E and F, corresponding to 30 % of the assemblage (cf. 12 % for Grimes Graves and 11 % for Old Scatness). It appears that these animals were killed at the prime age for beef (Hambleton 1999 p78).

In summary, through comparison with Payne's (1973) mortality models for milk and meat production, economic goals regarding cattle husbandry have been inferred for the archaeological sites included in this study. It is likely that Earl's Bu and Mine Howe were consumer sites and their cattle remains may not have been representative of a particular herd structure, with those at Earl's Bu the debris of a high-status hall and those at Mine Howe perhaps the debris of ritual activities. In contrast, Pool, Old Scatness and Grimes Graves have been interpreted as self-sufficient communities with cattle husbandry focussed on dairying because of the high proportions of young calves present in their cattle assemblages. There has been much debate on whether or not the presence of these young animals really does represent a policy of deliberate slaughter associated with dairying. Legge's (1981, 1992 pp25) efficiency argument, that killing most of the calves to retain the

milk for human consumption yields more food energy per unit area of grazing than rearing the calves for beef, appears straightforward and logical. In the intensive dairy industry of Britain today, superfluous, mainly male, calves are slaughtered within hours of birth (McVeigh 2012). However, it has been assumed that for the "primitive" cattle of prehistoric Britain, the presence of the calf was necessary for a cow to release her milk (e.g. Clutton-Brock 1981, Entwistle and Grant 1989, Noddle 1990). This would appear to render the slaughter of calves at a young age counterproductive since it would reduce the amount of milk available for humans.

The "let-down" of milk is a conditioned reflex. Farmers are able to condition their cows to release milk as a result of external stimuli associated with suckling rather than through direct stimulation from suckling (Amoroso and Jewell 1963). For modern dairy cows, the environment of the milking parlour is sufficient to act as the stimulus for milk let-down whereas many unimproved cows of Africa and Asia need to be able to see and smell their calves (ibid). The supposition regarding prehistoric British cattle is based largely upon the behaviour of these African and Asian cattle together with historical reports of cattle in Ireland. For example, Camden, writing about Ireland in the 16th century, commented that "Cows are the most valuable treasure here. Of which, this is remarkable that cows are certain to give no milk in Ireland, unless either their own calves be set by them alive, or the skin of it stuff'd with straw, to represent the live one; in which they meet with the scent of their own Matrix" (Camden 1722 p1419). Interestingly, Camden has described a method to induce milk let-down in the event of a calf dying. Potentially, this would have allowed the slaughter of young calves to maximise the amount of milk for human consumption. Fynes Moryson (1735 p376), in his description of early 17th century Ireland, suggests that such a strategy was not an unusual occurrence: "These wild Irish as soon as their Cows have calved, take the Calves from them, and thereof feed some with Milk to rear for Breed, some of the rest they fley, and seeth them in a filthy Poke, and so eat them, being nothing but Froth, and send them for a Present one to another: But the greatest Part of these Calves they cast out to be eaten by Crows and Wolves, that themselves may have more Abundance of Milk. And the Calves being taken away, the Cows are so mad among them, as they will give no

Milk till the Skin of the Calf be stuffed and set before them, that they may smell the Odour of their own Bellies."

Thus, it is possible that the high numbers of juveniles in the cattle assemblages of Pool, Old Scatness and Grimes Graves were the result of deliberate slaughter for dairy-focussed economies, even if milk let-down was more problematic than for modern dairy cows. There has been much debate on the subject (e.g. Halstead 1998, McCormick 1998, Mulville et al 2005, Davis 2010 pp478) and it has been argued that the young calves in these assemblages died of natural causes or were slaughtered for alternative reasons. Davis (2012 pp493) re-examined calf mandibles at wear stage classes A and B (after Halstead 1985) from six Orcadian sites from the Neolithic to the Norse period and has re-assigned each to one of five newly defined age classes. He estimated that 43 % of the calves were either foetuses or less than 2 weeks old and suggested that they died of natural causes, based on ethnographic research on unimproved dairy cattle in Greece during the 1940s and 1950s where cows required their calves to suckle for around 10-15 days before lactation was established. Davis (2010 pp480) has suggested that disease through poor hygiene, dystocia (difficulty in calving) and insufficient fodder were possible causes of death. It is possible that a dairying economy might lead to higher rates of calf mortality through natural causes than a meat-focussed economy. In order to maximise milk yields, dairy cows are often given priority if winter shelter is limited (Halstead 1998). Unfortunately, housing several animals in a confined space can easily lead to unhygienic conditions, resulting in an increased risk of disease and calf mortality (ibid).

An alternative viewpoint is that high calf mortality reflects deliberate slaughter, as a pragmatic approach to fodder conservation in marginal environments rather than a strategy related to economic focus (McCormick 1998). A study by Mulville et al (2005), comparing mortality profiles from the Western and Northern Isles of Scotland, supports the suggestion that calf slaughter was deliberate, but questions whether the intention was to conserve fodder. In that study, cattle mandible wear stage data from a number of Western Isles sites were combined to produce

mortality profiles that showed the proportion of animals dying in their first month of life decreasing through time. In the Bronze Age, 72 % of cattle died in that age group, whereas in the Iron Age and Norse period, the proportions were 43 % and 8 % respectively. In contrast, the proportions calculated for Pool, Orkney, increased through time: 14 % in the Neolithic, 36 % in the Late Iron Age and 48 % in the Norse period (Mulville et al 2005). It may be argued that the provision of fodder would have been determined ultimately by the climate, which is likely to have changed in a similar manner for the two island groups. Therefore, if calves were slaughtered to conserve fodder, the expectation would be of a trend in the same direction for both the Western and Northern Isles. Likewise, natural mortality rates, affected by climate and husbandry expertise, would be expected to follow similar trends for both island groups. Therefore, deliberate slaughter for economic purposes appears to be the most plausible explanation for the opposing trends in calf mortality, with different mortality profiles reflecting different economic foci.

7 Archaeological and modern materials

7.1 Archaeological skeletal material

Skeletal material was selected from cattle assemblages excavated from each of the archaeological sites described in Chapter 6. Because the emphasis of this study is intra-tooth isotope ratio analysis of molar enamel, mandibles comprising at least two molars in sequence, i.e. those comprising first and second molars or second and third molars, were prioritised in order to maximise the period of time during which enamel was mineralizing and, thus, the length of time represented by the intra-tooth isotopic profiles (see Table 4.1 for the chronology of development for mandibular cattle molars; see also Figure A.1, Appendix 1, for an example of a mandible comprising molars in sequence). Since individual first and second molars are difficult to distinguish, easily identifiable loose third molars were also selected. For two sites, Earl's Bu and Old Scatness, the material collected for this study consists principally or solely of loose third molars. For each site, care was taken to ensure that the mandibles and loose third molars were from different individuals; i.e. for every combination of left and right mandibles, equivalent molars had to be distinguishable, either visually in terms of wear or isotopically after analysis. Mandibles and loose third molars were also selected on the basis of enamel quality. Crumbly enamel with a high degree of internal cracking was avoided on the premise that it might be more susceptible to diagenesis. Also rejected were mandibles in which the molars had been badly damaged and those with very worn third molars (and, therefore, very worn first and second molars) which would produce intra-tooth isotopic profiles with large data-free sections, resulting in limited interpretation. Because of possible discrepancies in development chronology between equivalent mandibular and maxillary molars, mandibular molars were used for all analyses so that direct comparisons could be made between the intra-tooth isotopic profiles of different animals.

Selection of the Pool material was kindly facilitated by Linda Aiano of Tankerness House Museum, Kirkwall, Orkney, where the Pool assemblage is stored. Three of

the assemblages, Mine Howe, Earl's Bu and Old Scatness, were easily accessible during the period of this study, being temporarily stored at the University of Bradford for post excavation work. Selection of the Grimes Graves material was kindly facilitated by Gillian Varndell and Marianne Eve of the British Museum where the Grimes Graves assemblage (Mercer's Excavations 1971-2) is stored. Details of the mandibles and loose teeth selected for the five archaeological sites are given in Tables A.2-A.6, Appendix 1.

7.2 Modern skeletal material

Mandibles were obtained from the carcasses of eight Chillingham Wild White cattle. The Chillingham Wild White cattle herd live in Chillingham Park, Northumberland, a 130 ha enclosure of well-managed mixed permanent grassland and open woodland (NGR: NU073258, alt. 98-235 m). The cattle are free from direct human husbandry apart from the provision of hay during the winter months. During that period, hay may constitute between approximately one half to two thirds of what an animal eats in total depending upon the severity of the weather (Leyland, pers comm). Because the Chillingham cattle are not slaughtered but die of natural causes, most of the mandibles obtained for this study comprise the very worn molars of old adult or senile animals, using the age class descriptions given by Halstead (1985). All eight mandibles are from cattle that died between 2007 and 2010. Acquisition of the eight cattle mandibles was kindly facilitated by Chris Leyland, Chillingham Park manager, and Professor Stephen Hall, University of Lincoln. Details of the mandibles are given in Table A.7, Appendix 1.

In addition to the modern Chillingham material, one complete mandible was obtained from a modern Dexter bull raised for beef by Louisa Gidney, Durham University. The animal, named Karst (animal ID: KAR), was born on the 8th February 2010 in a barn at High Stoop, Tow Law, County Durham (NGR: NZ104401, alt. 310 m). He remained in the barn until the 5th March 2010 when he was turned out onto pasture, also at High Stoop, with his mother. Water sources available at High Stoop were rain water and ditch water. Tap water was used as a supplementary source if

there was a shortage of rain and ditch water. On the 26th May 2010 he was transported to pasture at Snowsfield Farm, Stanhope, County Durham (NGR: NY981387, alt. 215 m) approximately 13 km from High Stoop. Water at Stanhope was available from a stream and from a borehole. On the 13th November 2010 he was transported back to Tow Law where he remained in a barn at Dapple Farm (NGR: NZ103391, alt. 250m) until the 26th June when he was slaughtered. Tap water was the only source of water at Dapple Farm. Karst's diet varied with location and is listed in Section 7.3.3 below. Details of the mandible obtained from Karst are found in Table A.7, Appendix 1.

7.3 Modern vegetation samples

Samples were collected from a variety of locations as outlined below. In general, each consisted of a small handful of vegetation. They were stored in individual paper bags and, as soon as possible after sample collection, the bags were air dried in a warm environment in order to avoid rotting and possible alteration of the vegetation $\delta^{13}C$ values.

7.3.1 Orkney and Shetland

Samples of vegetation were collected from various locations around Sanday and Mainland, Orkney and around southern Shetland (Figures 7.1 and 7.2). All samples were collected in August 2011. Unimproved, indigenous vegetation was targeted and a large proportion of the Orcadian samples were collected from RSPB reserves. In Shetland, advice regarding suitable sampling locations was given by local ecologist and environmental advisor Sue White. Crop samples were also obtained. Whole plant samples of traditional bere barley and black oats together with a modern oat variety "Belinda" were provided by Dr Peter Martin, Orkney College UHI. In addition, samples of bere barley and black oat grains were donated by Shetland farmers Tommy and Mary Isbister, Burland Croft, Trondra (NGR: HU393369, alt. 10m).

Figure 7.1: Vegetation sampling locations in Orkney. The location of the stream from which water samples were taken is also shown. The green triangle marks the location where crops sampled for this study were grown. Map data © OpenStreetMap contributors (www.openstreetmap.org/copyright).

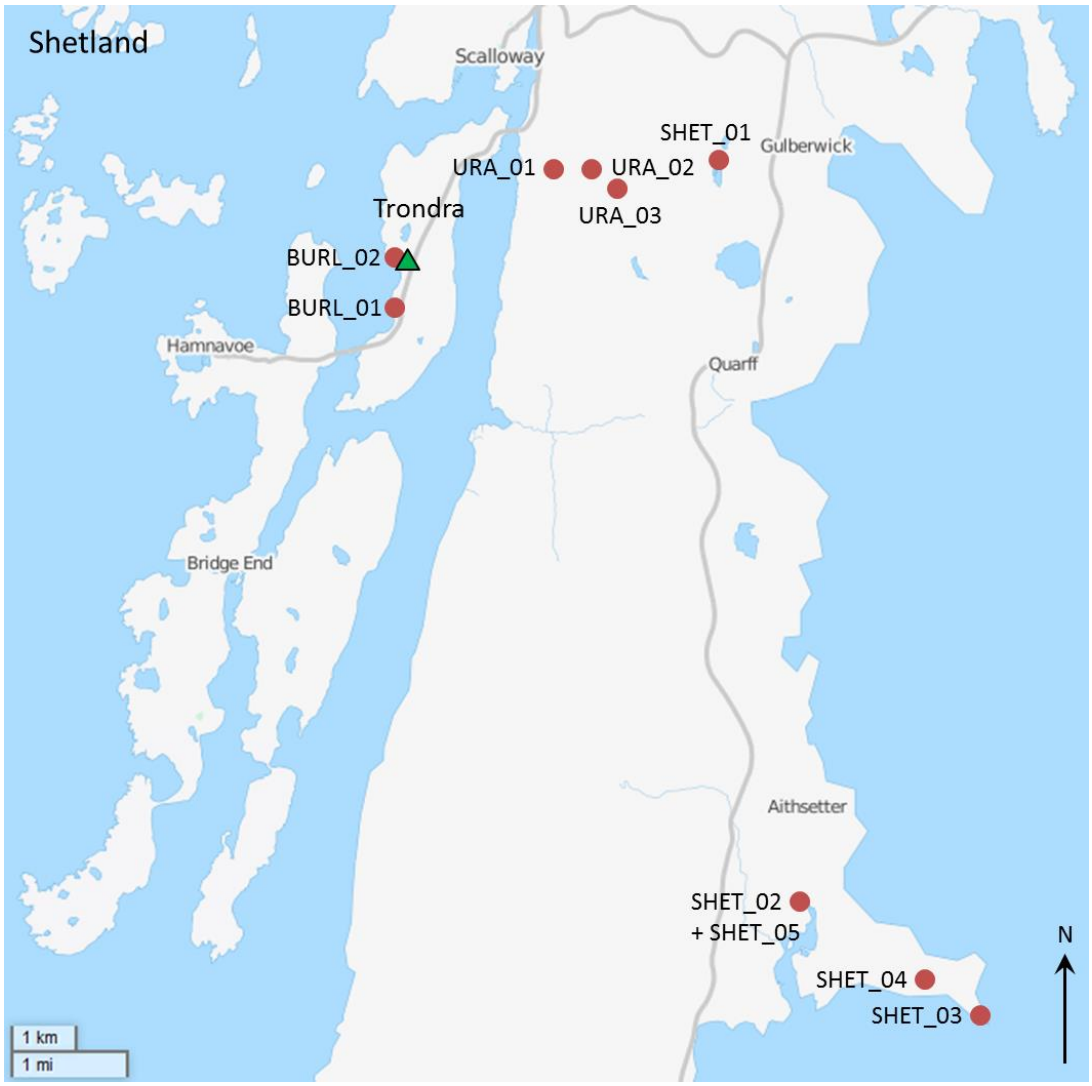


Figure 7.2: Vegetation sampling locations in Shetland. The green triangle marks the location where crops sampled for this study were grown. Map data © OpenStreetMap contributors (www.openstreetmap.org/copyright).

7.3.2 Chillingham Park

Vegetation samples were collected from Chillingham Park, Northumberland during a 12 month period in 2010/2011. Collection dates were the 10th May 2010 (spring), the 9th August 2010 (summer), the 15th November 2010 (autumn) and the 7th February 2011 (winter). The samples were from 28 GPS-located positions scattered around the park (Figure 7.3). 15 of these positions were in the western part of the park (mainly designated "good" grassland by Hall and Bunce (1984) and at an altitude < 130m), while 13 were in the eastern part (designated "second-rate" and "upland" grassland by Hall and Bunce (1984) and at an altitude > 130m). Each sample was picked by hand over a small area of ground to simulate a mouthful of vegetation for an animal. Thus, samples tended to be a mixture of grass and herb species. Thistles and bracken were avoided as were bracken-rich locations, since the cattle do not eat these genera (Leyland, pers comm). Leaves from trees and shrubs were not sampled either because they do not form a significant proportion of the animals' diet (Leyland, pers comm). Because of the limited accuracy of the GPS unit used, the sampling positions were not identical from season to season. However, this should not be detrimental to the study. Given that the cattle are able to roam freely, it is the seasonal change in $\delta^{13}C$ of the whole park or large areas of it rather than at any single location that is of interest, which may be estimated by averaging the results from all or several of the nominal sampling positions. Unfortunately, it was not possible to obtain representative samples of winter hay. During the period when the cattle teeth analysed in this study were forming, which comprised a number of years, hay was sourced from various locations outside Chillingham Park.

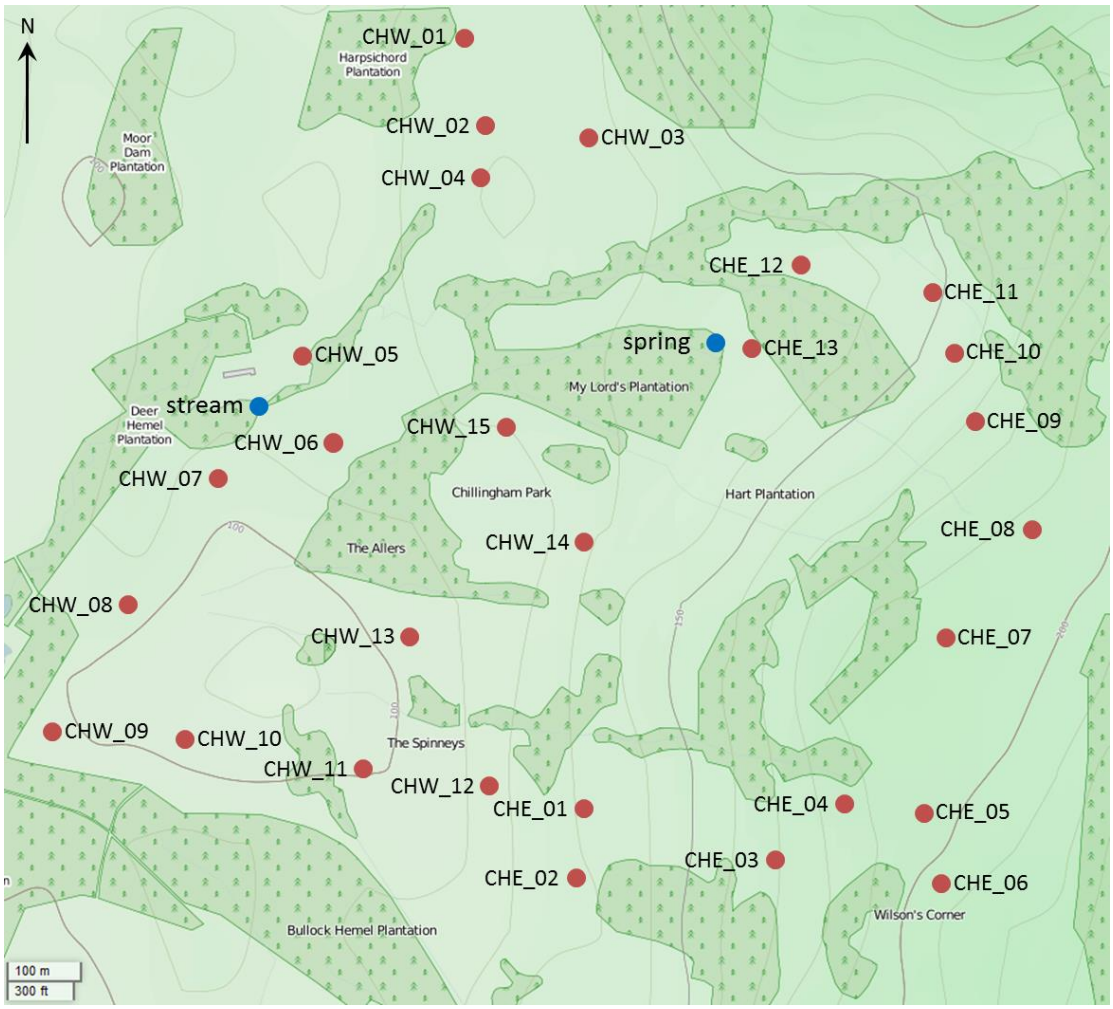


Figure 7.3: Vegetation sampling locations in Chillingham Park, Northumberland. The locations of the stream and spring from which water samples were taken are also shown. Map data © OpenStreetMap contributors (www.openstreetmap.org/copyright).

7.3.3 Dexter bull's dietary components

Representative samples of the Dexter bull's dietary components were collected on the 25th May 2011. Diet, initially via his mother's milk, varied with location (Section 7.2 above): sugar beet pellets and "Darlington" hay in the barn at High Stoop; pasture at High Stoop; pasture at Stanhope; and barley feed, haylage and bedding straw in the barn at Dapple Farm.

7.4 Water samples

Water samples were collected from a stream on the island of Rousay, Orkney (NGR: HY397278, alt. 10 m) and from a stream (NGR: NU069259, alt. 105 m) and spring (NGR: NU075260, alt. 135 m) in Chillingham Park (Figures 7.1 and 7.3). Nine samples were collected from Rousay during a 12 month period in 2010/2011, while ten samples were collected from Chillingham Park during a different 12 month period in 2010/2011. Samples were stored in 30 ml clear polypropylene containers with screw lids. Each container was filled completely to avoid the exchange of oxygen between the water sample and air.

8 Methods

For oxygen and carbon isotope ratio analysis, all enamel, dentine, bone and vegetation samples were prepared and analysed at the Stable Light Isotope Facility at the University of Bradford. For strontium isotope ratio analysis, initial preparation of enamel was carried out at the University of Bradford. However, subsequent chemical processing and analysis were done at the clean laboratory suite at the NERC Isotope Geosciences Laboratory at Keyworth, Nottinghamshire (NIGL) under the supervision of Professor Jane Evans. Analysis of water samples was also undertaken at NIGL, by Carol Arrowsmith. The methods employed for each sample type are described below. A summary of the sampling undertaken for each animal included in this study is provided in Table A.8, Appendix 1.

8.1 Sample preparation and analysis of tooth enamel

8.1.1 Intra-tooth powdered enamel samples for oxygen and carbon isotope ratio analysis

All intra-tooth enamel samples were from cattle molars and deciduous premolars. Before intra-tooth sampling could proceed, the required teeth, if still retained within mandibles, were extracted using a dental saw. The cementum from the targeted lobe of each tooth was then removed and the underlying enamel cleaned using a diamond dental burr. For comparative purposes, lingual mesial lobes were targeted for archaeological molars unless the enamel appeared of poorer quality than that of alternative lobes, in which case lingual distal lobes for second molars and lingual central lobes for third molars were sampled (see Table A.1 and Figure A.1, Appendix 1, for molar terminology). Lingual mesial and distal/central lobes are very similar in terms of length and enamel thickness and the timing of crown development is assumed to be very similar also. Buccal lobes tend to be shorter than lingual lobes and have thicker enamel which may alter the timing of crown development slightly. Powdered enamel samples from the cusp to the cervix of the targeted lobe were collected using a clean diamond burr, the drilling of each sample, through the bulk of the enamel thickness, forming a groove approximately

2 mm wide (Figure 8.1). Each powdered sample was placed in a 2 ml microtube and weighed approximately 15 mg, which provided sufficient material to enable several repeat analyses if required. To prevent cross-contamination, the dental burr was cleaned with acetone between successive intra-tooth samples.

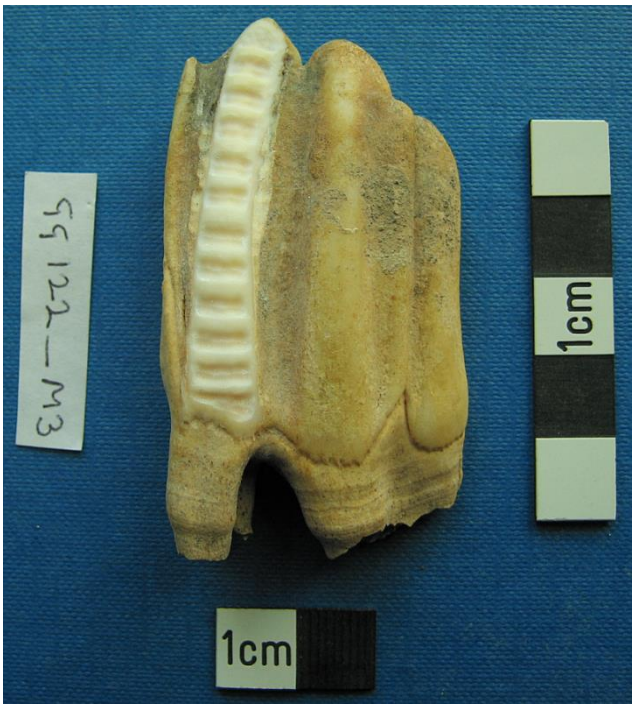


Figure 8.1: Intra-tooth enamel sampling of a cattle third molar lingual mesial lobe.

Preparation of the powdered enamel samples continued following a protocol modified by Sponheimer (1999) for finely powdered samples with particle sizes < 50 µm, as obtained using a diamond dental burr. The method was as follows: 1.8 ml of 1.7 % sodium hypochlorite (NaOCl) was added to each sample in order to remove any residual organic material. The mixture was agitated to form a suspension and any reaction between the NaOCl and enamel, as indicated by bubbling, was generally complete within 1 hour. The samples were then centrifuged enabling the NaOCl to be removed by pipette and replaced by deionised water. This procedure of centrifuging followed by replacement by fresh deionised water was carried out three times to rinse the samples. They were centrifuged once more and the deionised water was removed. In order to remove any exogenous carbonate 1.8 ml of 0.1M acetic acid was added to each sample. The samples were then centrifuged,

enabling the acetic acid to be removed by pipette and replaced by deionised water. The time between adding the acetic acid to the enamel and subsequently removing it was limited to ≤ 10 minutes to avoid excessive sample loss. After rinsing three times with deionised water, the water was removed and the samples were dried in an oven at low heat (~40 °C) overnight. The samples were then freeze-dried to complete the drying process.

Each sample was weighed into a septa-capped vial (~1.3 mg) which was loaded into a Finnigan Gasbench II, an automated carbonate preparation device connected to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer (Section 3.5). Batches of up to 72 samples could be loaded into the Finnigan Gasbench II. Included in each batch 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 automated system added anhydrous phosphoric acid (103 %) 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. 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, BES, one or two samples of which were included in most sample batches (45 normalised measurements obtained over a 23 month period). See Appendix 2 for more details regarding the standards and normalisation.

8.1.2 Enamel samples for strontium concentration and isotope ratio analysis

All enamel samples for strontium concentration and isotope ratio analysis were extracted from cattle molars. For reasons of cost, only one sample was obtained per tooth. Apart from a single sample of cervical enamel, cuspal enamel was sampled. For each molar, cementum was removed from the target area of the crown using a

diamond dental burr, after which a sample of enamel was cut using a rotary dental saw. In general, sample weights were approximately 10-20 mg. Discoloured or cracked areas of crown enamel, which may have been affected by diagenetic contamination, were avoided during sampling. For each sample, all surfaces were cleaned using a dental burr. Because dentine is generally much more susceptible to diagenesis than enamel (Section 4.4.1), it was important to remove it completely from the enamel's inner surface. After sampling from one molar, before moving onto the next, the dental burr and saw were cleaned by swabbing with 4M HNO_3, rinsing three times in deionised water, cleaning ultrasonically for 5 minutes in diluted Decon 90 and rinsing three times once more in deionised water.

At this stage in the procedure, the samples were taken to NIGL where further processing took place under laminar flow conditions, using high purity reagents and deionised water and following an adaptation of a method developed by Royse et al (1998). The samples were cleaned in acetone to remove grease, then ultrasonically in deionised water to remove any adhering particulates. Each enamel sample, once dried, was weighed into a Teflon beaker. Several standard samples (NIST-1486) were also weighed into Teflon beakers. All samples were spiked with a known amount of Oak Ridge Dilute Sr, a ^{84}Sr enriched tracer. Procedural blanks were also produced, consisting of spike solution only. 2 ml of Teflon-distilled 8M HNO_3 was added to each sample beaker to remove organic compounds and exogenous carbonates, and homogenise the samples. The beakers were then placed, without lids, on a hotplate at ~110 °C in order to dry down the samples. This part of the procedure was repeated using 2 ml of quartz-distilled 6M HCl to convert cations such as Ca^{2+} and Sr^{2+} to chlorides. After drying down, the samples were left for approximately 30 minutes to dissolve in 2 ml of quartz-distilled 2.5M HCl.

The samples were then ready for strontium extraction which was achieved through cation exchange chromatography by means of quartz columns containing Dowex AG 50W-X12 resin. 1 ml from each sample solution was retained for future use in the event of analysis failure while the remaining 1 ml was poured into a cation exchange column. A different column was used for each sample. By this method,

cations in any sample solution become attached to the column resin and, through calibration of the columns, may be separated and released in a controlled manner. The columns at NIGL were calibrated such that 45 ml of quartz-distilled 2.5M HCl washed the major unwanted cations such as Ca^{2+} through the column, leaving the strontium cations attached to the resin. A further 12 ml of quartz-distilled 2.5M HCl could then be added to wash the strontium cations through the column into clean Teflon collection beakers. The beakers were placed, without lids, on a hotplate to dry down the samples, which were then ready for loading into a Thermo Triton multi-collector TIMS (Section 3.5). Full details of the preparation method described above are found in Montgomery (2002).

Each sample, now in the form of a dry chloride salt, was mixed with a tantalum oxide activator to enable more efficient and controlled thermal ionisation in the mass spectrometer. Approximately 1-1.5 ml of each sample/activator mixture was dried onto a separate rhenium filament. Batches of 21 filaments were variously loaded with enamel samples, NIST-1486 standard samples, procedural blanks and machine standards (NBS-987).

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. Thus, 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.

8.2 Extraction and analysis of collagen

8.2.1 Collagen from modern intra-tooth dentine samples

All intra-tooth dentine samples were from modern cattle first and second molars. For first molars, a whole lobe was removed from cusp to root tip using a dental

circular saw (Figure 8.2). Each lobe was then sectioned into ~2 mm wide sequential samples along its whole length. Alternatively, for second molars, where crown dentine was not required, one half of a root was removed from cervix to root tip. Each sample was cleaned by means of the circular saw and a dental burr. This included the removal of enamel and cementum if present. The resulting intra-tooth dentine samples, whether from crown or root, weighed between 10 and 81 mg.

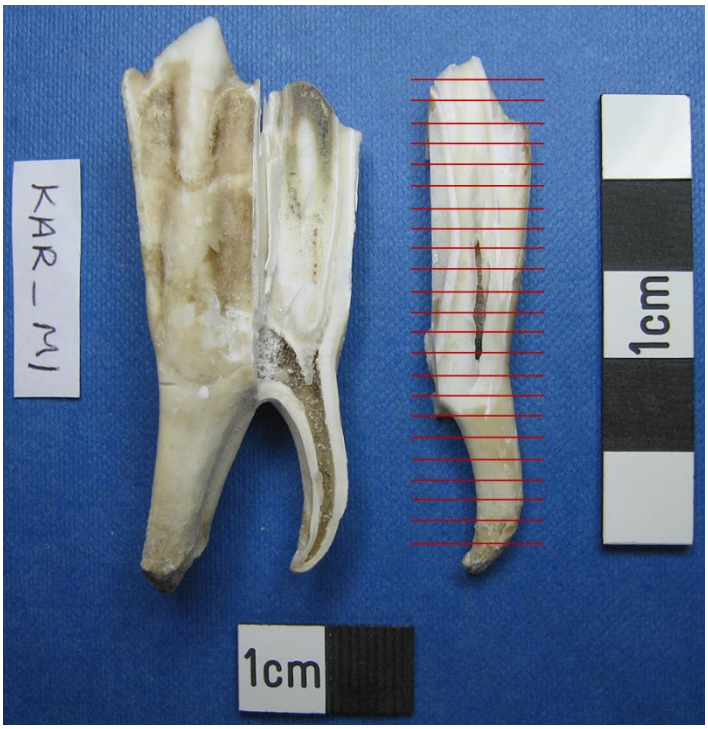


Figure 8.2: Removal of lobe from cusp to root tip, followed by intra-tooth dentine sampling (indicated by horizontal lines).

Collagen was extracted from each dentine sample using a protocol based on the modified Longin method but adapted for small samples (Longin 1971, Brown et al 1988, Collins and Galley 1998, Richards and Hedges 1999, Beaumont et al 2013). Each sample was placed in a 2 ml microtube where it remained for the whole of the collagen extraction procedure. Initially, the samples were demineralized in 0.5 M hydrochloric acid (HCl) refrigerated at a temperature of approximately 4 °C, the lids of the microtubes open to allow the CO_2 produced by the reaction to escape. Demineralization tended to be complete by around 5-6 days after which the samples were rinsed three times with de-ionised water. A pH 3 aqueous solution of

HCl was added to each sample (around ¾ full to allow for expansion during subsequent freezing) and the sealed microtubes were placed in a heating block at 70 °C for approximately 24 hours. Such conditions act to denature the collagen by separating its triple helix structure, thus allowing it to become soluble. After this stage of the collagen extraction process (gelatinization), insoluble contaminants, such as humic acid, could be separated from the dissolved collagen through centrifugation. The centrifuged samples were frozen solid before being freeze-dried.

The resulting collagen samples were weighed into tin capsules (~0.5 mg) and loaded into a Flash EA 1112 elemental analyser connected to a Thermo Finnigan Delta Plus XL continuous flow isotope ratio mass spectrometer (Section 3.5). Batches of up to 99 samples could be loaded into the elemental analyser. Included in each batch were several samples of each of two different internal laboratory standards, fish gelatine and BLS (bovine liver standard), and one international laboratory standard, IAEA-600. The resulting $\delta^{13}C_{VPDB}$ (and accompanying $\delta^{15}N_{AIR}$) measurements obtained for collagen 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) for $\delta^{13}C_{VPDB}$ (and $\delta^{15}N_{AIR}$), determined by multiple analyses of standard materials by the instrument manufacturer. For each collagen sample, two tin capsule samples were prepared in order to obtain isotopic measurements in duplicate from which average measurements were calculated. See Appendix 2 for more details regarding the standards and normalisation.

8.2.2 Collagen from archaeological cattle bone

All cattle bone samples were cut using a dental circular saw from archaeological cattle mandibular bone. Each sample weighed approximately 0.7-0.9 g. Collagen was extracted using the modified Longin method described above for intra-tooth dentine samples but with the addition of two filtering stages (Longin 1971, Brown et al 1988, Collins and Galley 1998, Richards and Hedges 1999). Also, microtubes could not be used due to the larger sample size for bone. The bone samples were cleaned

using air-powered powder abrasion. After demineralization and gelatinization each sample of denatured collagen solution was filtered with an 8 µm Ezee® filter (Elkay Laboratory Products) to remove insoluble residues, followed by centrifugal filtering with an Amicon® Ultra-4 filter (Millipore Corporation) to remove smaller molecules with atomic masses < 30kD and retain the larger collagen molecules. Before using the ultrafilters it was necessary to rinse them through with 0.1M sodium hydroxide followed by three rinses with deionised water in order to remove trace amounts of glycerine present on the filter membranes. For each sample, the liquid retained by the ultrafilter containing the collagen was carefully removed by pipette and placed into a labelled tube. Each tube was covered with Parafilm and laid at a shallow angle in a freezer, producing a thin layer of frozen sample along the inside of the tube. Such an arrangement enables more efficient freeze-drying, which is the next stage in the procedure. The frozen samples were freeze-dried for 48 hours, the Parafilm lids having been pierced to allow the water to escape. Subsequent preparation for analysis is identical to that described above for dentine collagen.

8.3 Sample preparation and analysis of vegetation samples

At the start of the preparation process each vegetation sample consisted of a handful of dried matter that often included more than one plant species. A sub-sample from each, weighing approximetaly 300-400 mg, was homogenised by means of a freezer mill (SPEX CertiPrep 6750 Freezer/Mill) as follows: the sub-sample was placed in a closed vial (SPEX CertiPrep 6751 Vial) together with a steel impactor rod. The vial was loaded into the freezer mill, which uses liquid nitrogen as a coolant. In order to prepare the vegetation sub-sample for homogenisation through the process of grinding, the vial remained immersed in the liquid nitrogen for four minutes to cool down. This allowed the sub-sample to become brittle and suitable for grinding. Grinding was achieved by means of the steel impactor rod which was driven back and forth by two electromagnets at high frequency between the steel end-plugs of the vial. The grinding time was two minutes. Each powdered sample was transferred into a polypropylene container and freeze-dried.

The powdered samples were weighed into tin capsules (~1.5 mg) and loaded into a Flash EA 1112 elemental analyser connected to a Thermo Finnigan Delta Plus XL continuous flow isotope ratio mass spectrometer (Section 3.5). Batches of up to 99 samples could be loaded into the elemental analyser. Included in each batch were several samples of each of two different internal laboratory standards, fish gelatine and Elemental Microanalysis B2157 (Wheat Flour), and one international laboratory standard, IAEA-600. The resulting $\delta^{13}C_{VPDB}$ (and accompanying $\delta^{15}N_{AIR}$) measurements obtained for the vegetation 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) for $\delta^{13}C_{VPDB}$ (and $\delta^{15}N_{AIR}$), determined by multiple analyses of standard materials by the instrument manufacturer. For each powdered vegetation sample, two tin capsule samples were prepared in order to obtain isotopic measurements in duplicate from which average measurements were calculated. See Appendix 2 for more details regarding the standards and normalisation.

8.4 Oxygen isotope ratio analysis of water samples

2 ml aliquots were pipetted from the 30 ml stream and spring water samples collected from Chillingham, Northumberland and Rousay, Orkney, and introduced into separate conical vessels connected to a VG Isoprep 18 device for equilibration with CO_2 (Section 3.5). Vessels containing calibrated laboratory standards were also connected to the VG Isoprep 18 device. After equilibration, CO_2 from each vessel was analysed by means of a VG Sira 10 isotope ratio mass spectrometer. The analytical precision of the resulting $\delta^{18}O_{VSMOW}$ measurements was ± 0.08 ‰.

9 Results and initial observations

In this chapter, the results of all isotopic analyses are presented in graphical form and summarised. For oxygen and carbon results, differences between various environmental (vegetation and water) and cattle (enamel and collagen) $\delta^{18}O$ and $\delta^{13}C$ datasets have been calculated and compared with published values. In this way, the validity of the datasets may be assessed. In addition, strontium results have allowed the identification of cattle born remotely to where they were buried, which is useful knowledge when evaluating $\delta^{18}O$ and $\delta^{13}C$ isotopic datasets.

9.1 Modern vegetation and water results

9.1.1 $\delta^{13}C$ results for Chillingham vegetation samples

$\delta^{13}C$ results for vegetation samples collected from Chillingham Park, Northumberland are presented in Table A.9 (Appendix 1) and displayed in Figure 9.1. Results from four collection dates are included (10th May 2010, 9th August 2010, 15th November 2010 and 7th February 2011). Overall, $\delta^{13}C$ values range between -31.4 and -28.7 ‰ (range = 2.7 ‰), and the mean value for the whole dataset is -30.3 ± 0.6 ‰ (1σ, n = 112). The range is smaller and the mean $\delta^{13}C$ value lower than those measured for cattle-grazed meadowland in Somerset where the range was 4.2 ‰ and the mean value was -28.7 ‰ (Dungait et al 2010). The disparity between the two sites is probably due to differences in species mix and growing conditions.

$\delta^{13}C$ values range between -30.6 and -29.3 ‰ for May, between -30.4 and -28.7 ‰ for August, between -31.3 and -29.6 ‰ for November and between -31.4 and -29.6 ‰ for February. The mean $\delta^{13}C$ values for the May, August, November and February datasets are -29.9 ± 0.3 ‰, -29.8 ± 0.4 ‰, -30.7 ± 0.4 ‰ and -30.6 ± 0.5 ‰ respectively (1σ, n = 28 for each dataset). Similar results for subsets of the whole dataset, comprising samples designated “CHW” and “CHE” from the western and eastern areas of the park respectively, are shown in Table 9.1, together with those for the whole park. Figure 9.2 shows how the mean $\delta^{13}C$ values vary seasonally, with higher values in May and August and lower values in November and February.

This seasonal variation appears to be a real effect as there is a significant difference between the mean values of August and November [2 tailed unpaired t-test, $t(54) = 7.59$, $p < 0.001$]. The pattern is essentially the same for vegetation in the western part of the park (mainly designated "good" grassland by Hall and Bunce (1984) and at an altitude < 130 m) and in the eastern part (designated "second-rate" and "upland" grassland by Hall and Bunce (1984) and at an altitude > 130 m). A similar seasonal variation in vegetation $\delta^{13}C$ has been measured for cattle-grazed meadowland in Somerset where the mean $\delta^{13}C$ values for grasses and herbs were -30.1 ‰, -28.7 ‰ and -28.3 ‰ for October 1998, July 1999 and May 2000 respectively (Dungait et al 2010). Such seasonal variation is likely to result from several environmental factors acting on stomatal conductance and rate of photosynthesis such as light level and water availability, as well as reflecting the seasonal $\delta^{13}C$ cycle of atmospheric CO_2 (Section 3.3).

Table 9.1: $\delta^{13}C$ mean values and ranges for Chillingham vegetation.

	Samples from the whole park (n = 28)		**Western area samples ("CHW", n = 15)**		**Eastern area samples ("CHE", n = 13)**	
Collection date	**$\delta^{13}C$ (‰) mean**	**$\delta^{13}C$ (‰) range**	**$\delta^{13}C$ (‰) mean**	**$\delta^{13}C$ (‰) range**	**$\delta^{13}C$ (‰) mean**	**$\delta^{13}C$ (‰) range**
May 2010	-29.9 ± 0.3	-30.6 to -29.3	-29.9 ± 0.4	-30.6 to -29.5	-30.0 ± 0.2	-30.2 to -29.3
August 2010	-29.8 ± 0.4	-30.4 to -28.7	-30.0 ± 0.3	-30.4 to -29.5	-29.5 ± 0.4	-30.1 to -28.7
November 2010	-30.7 ± 0.4	-31.3 to -29.6	-30.8 ± 0.3	-31.3 to -30.2	-30.5 ± 0.5	-31.1 to -29.6
February 2011	-30.6 ± 0.5	-31.4 to -29.6	-30.8 ± 0.4	-31.4 to -30.2	-30.4 ± 0.6	-31.3 to -29.6
The four datasets combined	-30.3 ± 0.6	-31.4 to -28.7	-30.4 ± 0.5	-31.4 to -29.5	-30.1 ± 0.6	-31.3 to -28.7

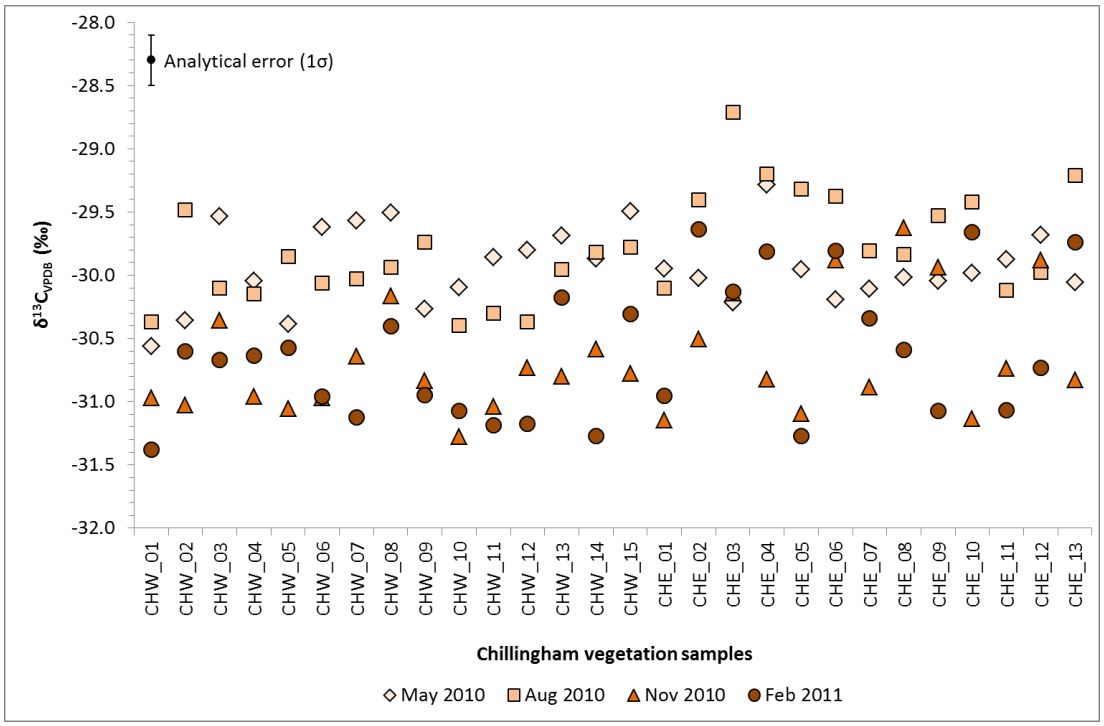


Figure 9.1: $\delta^{13}C_{VPDB}$ values for vegetation samples collected seasonally from Chillingham Park, Northumberland. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates.

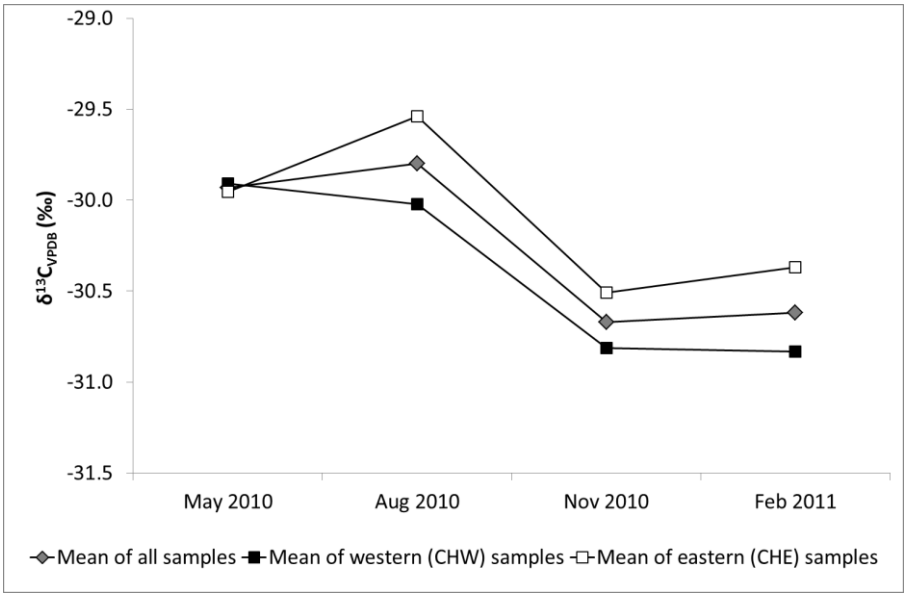


Figure 9.2: Mean seasonal $\delta^{13}C_{VPDB}$ values for Chillingham vegetation samples.

9.1.2 $\delta^{13}C$ results for the Dexter bull's dietary components

Table A.10 (Appendix 1) shows the $\delta^{13}C$ results for the dietary components of the modern Dexter bull from County Durham. This data is also displayed graphically in Figure 9.3. For most of the feed items, several different samples were analysed and are shown as separate data-points in Figure 9.3. Mean $\delta^{13}C$ values are -29.4 ‰ for Darlington hay (n = 3), -28.0 ‰ (n = 1) for sugar beet pellets, -30.5 ‰ (n = 4) for High Stoop field vegetation, -29.3 ‰ (n = 5) for Stanhope field vegetation, -28.3 ‰ (n = 2) for bedding straw, -27.8 ‰ (n = 3) for barley feed and -29.5 ‰ (n = 3) for haylage. Overall, $\delta^{13}C$ values range from -30.9 ‰ (one of the Stanhope field vegetation samples) to -27.6 ‰ (one of the barley feed samples).

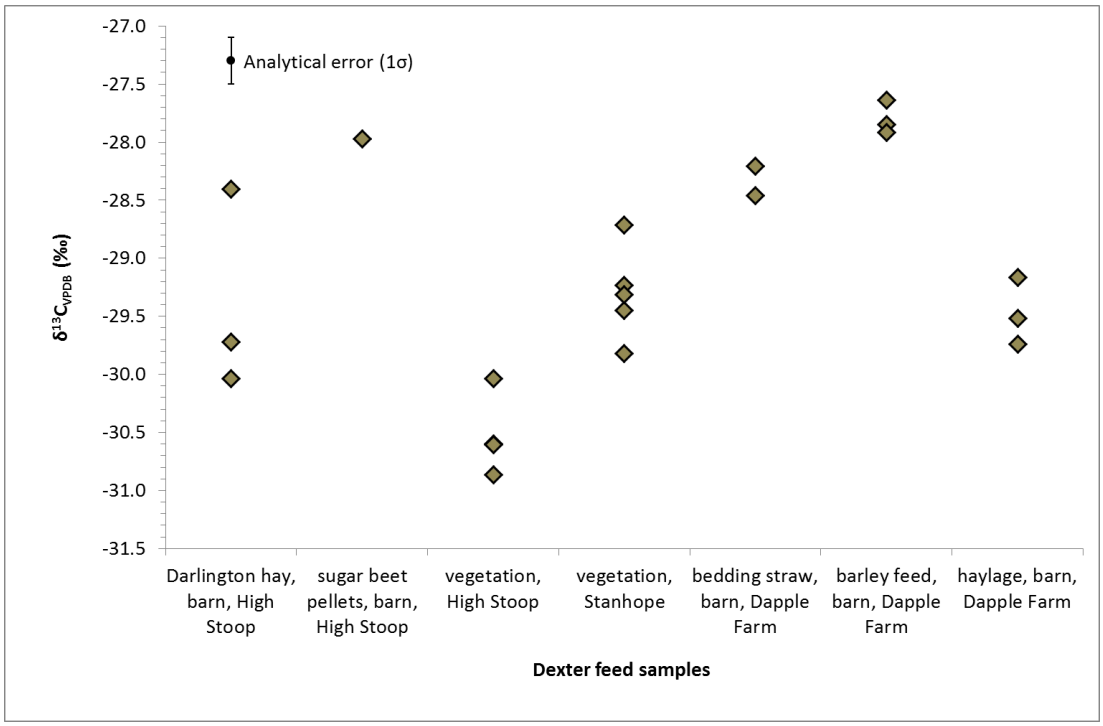


Figure 9.3: $\delta^{13}C_{VPDB}$ values for the dietary components of the modern Dexter bull from County Durham, collected in May 2011. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates.

9.1.3 $\delta^{13}C$ results for Northern Isles vegetation and crop samples

$\delta^{13}C$ results for vegetation samples collected from Orkney are presented in Table A.11 (Appendix 1) and displayed in Figure 9.4. $\delta^{13}C$ values range between -30.3 and

-24.8 ‰, and the mean value is -28.6 ± 1.4 ‰ (1σ, n = 18). The highest $\delta^{13}C$ value, -24.8 ‰ for sample SAND_01, is more than 2σ above the mean and if it is regarded as an outlier and excluded, the $\delta^{13}C$ values range between -30.3 and -26.6 ‰, and the mean becomes -28.8 ± 1.1 ‰ (1σ, n = 17). The high $\delta^{13}C$ value for sample SAND_01 appears to be environment- rather than species-related. SAND_01 comprised one species, identified as red fescue (*Festuca rubra*). Sample SAND_02, a mixed sample, also included red fescue. The $\delta^{13}C$ value of the red fescue of SAND_02, when analysed separately, was -28.6 ‰, which is 3.8 ‰ lower than the measurement for SAND_01. The environmental factor responsible for this difference may be the salinity of the soil. $\delta^{13}C$ values of single species, ranging over several permil, have been found to be positively correlated with increasing soil salinity (e.g. Guy et al 1986, van Groenigen and van Kessel 2002). Although samples SAND_01 and SAND_02 were both obtained from a coastal environment, the level of salinity may have been greater for SAND_01.

$\delta^{13}C$ results for vegetation samples collected from southern Shetland are presented in Table A.12 (Appendix 1) and displayed in Figure 9.5. $\delta^{13}C$ values range between -30.6 and -28.2 ‰ with a mean $\delta^{13}C$ value of -29.4 ± 0.8 ‰ (1σ, n = 10). In addition, results for crop samples grown in the Northern Isles are presented in Table A.13 (Appendix 1) and displayed in Figure 9.6. These include bere barley and black oats, traditional crop varieties that may show similar characteristics to those grown during the First Millennium AD, together with the modern oat variety “Belinda”. $\delta^{13}C$ values range between -30.0 ‰ for Shetland black oat grains and -27.2 ‰ for Orkney bere grains. For each crop from Orkney, grains and stems have been measured for the same plant. In each case, the $\delta^{13}C$ values measured for the grains are higher, by ≥ 0.9 ‰, than those for the stems, as was demonstrated by Winkler et al (1978) for modern varieties of wheat and oats. Nevertheless, the $\delta^{13}C$ values for the traditional Orkney crop samples, whether grains or stems, lie within two standard deviations of the mean value for unimproved vegetation from Orkney. Similarly, the $\delta^{13}C$ values for the traditional Shetland crop samples lie within two standard deviations of the mean value for unimproved vegetation from Shetland.

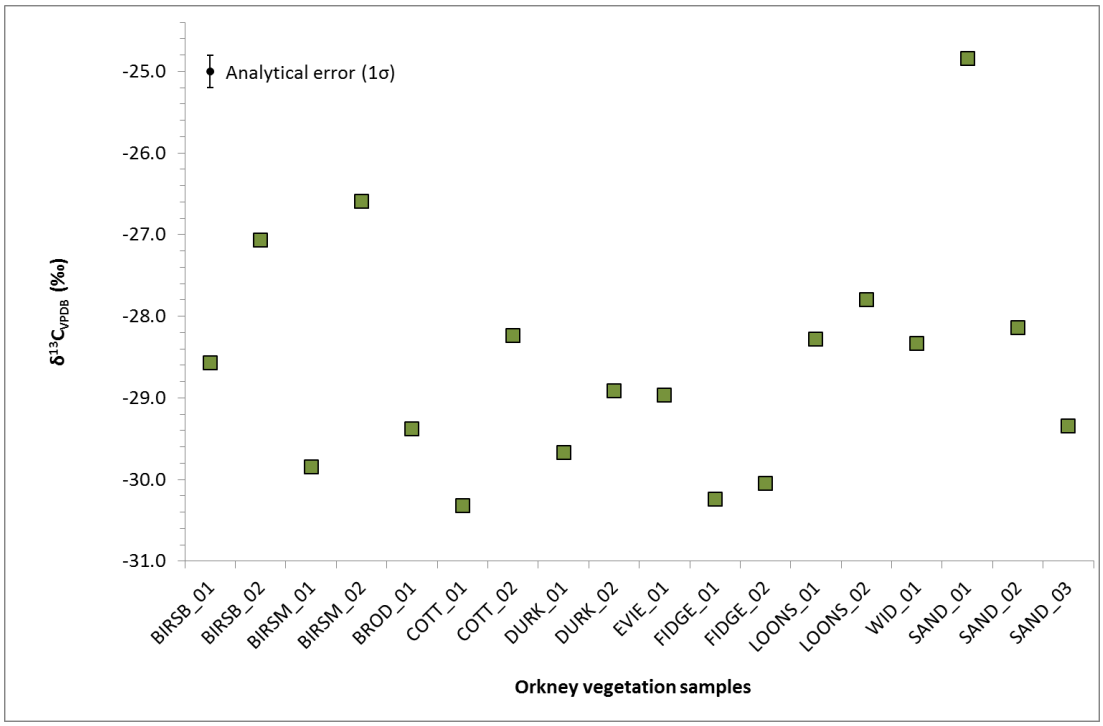


Figure 9.4: $\delta^{13}C_{VPDB}$ values for unimproved vegetation samples collected from various locations in Orkney in August 2011. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates.

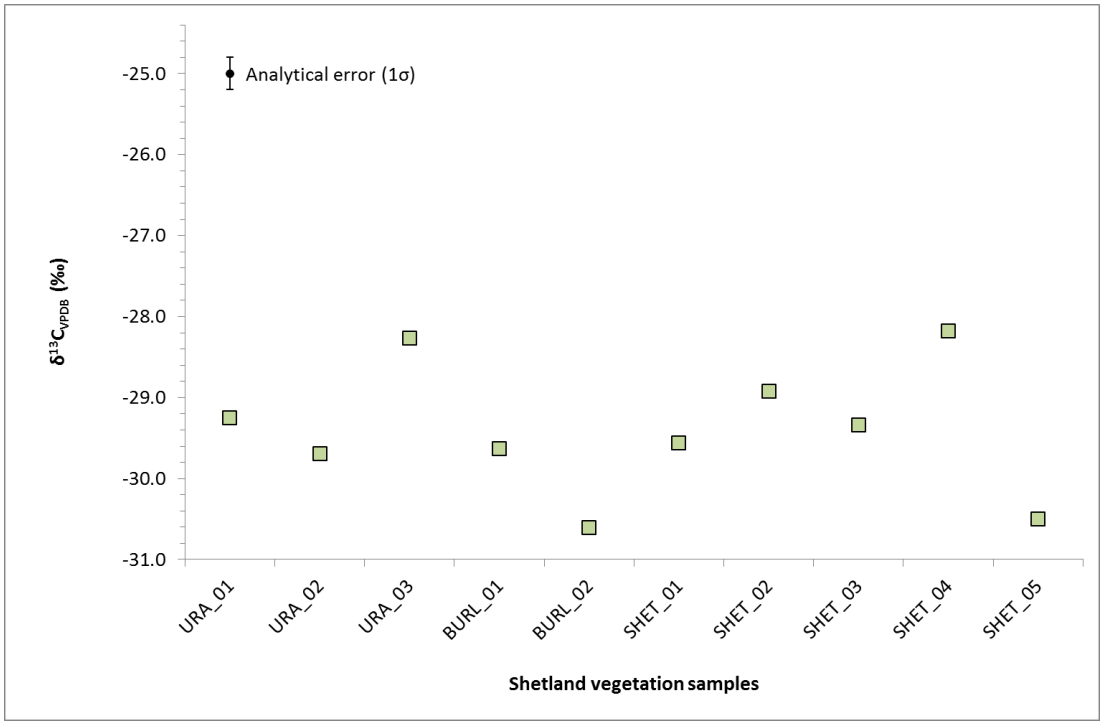


Figure 9.5: $\delta^{13}C_{VPDB}$ values for unimproved vegetation samples collected from various locations in southern Shetland in August 2011. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates.

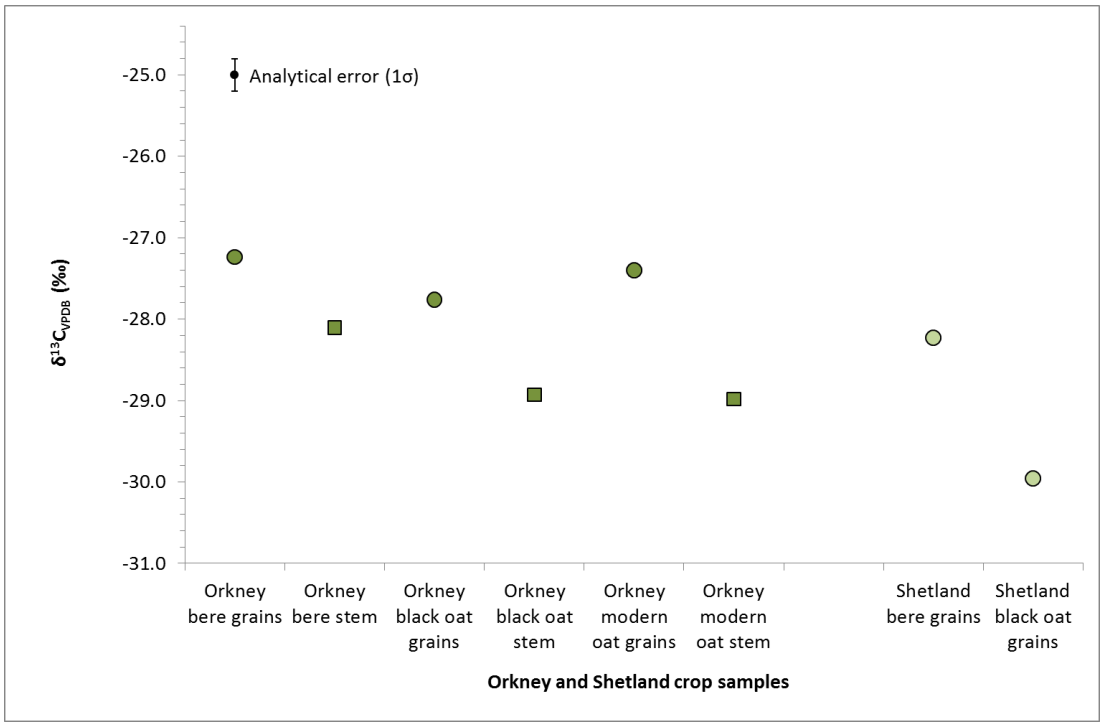


Figure 9.6: $\delta^{13}C_{VPDB}$ values for crop samples collected from Orkney and Shetland in August 2011. The samples from Orkney were grown in 2011 at the Agronomy Institute, Orkney College UHI, Kirkwall and the samples from Shetland were grown in 2010 at Burland Croft, Trondra. For each crop from Orkney, grains and stems are from the same plant. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates.

9.1.4 $\delta^{18}O$ results for Chillingham and Rousay water samples

The $\delta^{18}O$ results for water samples collected from a stream and spring within Chillingham Park, Northumberland and from a stream on the island of Rousay, Orkney, are presented in Table A.14 (Appendix 1) and displayed in Figure 9.7. $\delta^{18}O$ values vary between -8.54 and -7.74 ‰ for the Chillingham stream water (range = 0.80 ‰), between -8.30 and -7.73 ‰ for the Chillingham spring water (range = 0.57 ‰), and between -6.76 and -6.03 ‰ for the Rousay stream water (range = 0.73). Samples were collected regularly throughout a period of approximately one year but do not reflect the seasonal variation observable in measurements of rainwater $\delta^{18}O$ (e.g. Darling and Talbot 2003, Tyler et al 2007). Instead, as might be expected for the spring water, the $\delta^{18}O$ values of all three water sources appear strongly influenced by groundwater, which tends not to vary seasonally in $\delta^{18}O$ (Darling et al 2003). A similar magnitude of variation has been measured in river water (ibid). The mean annual $\delta^{18}O$ values for the Chillingham stream and spring waters combined

and the Rousay stream water are -8.1 ‰ and -6.4 ‰ respectively. These values are in reasonable agreement with the contour map of groundwaters shown in (Figure 3.1), the Chillingham value being a little more negative than suggested by the map.

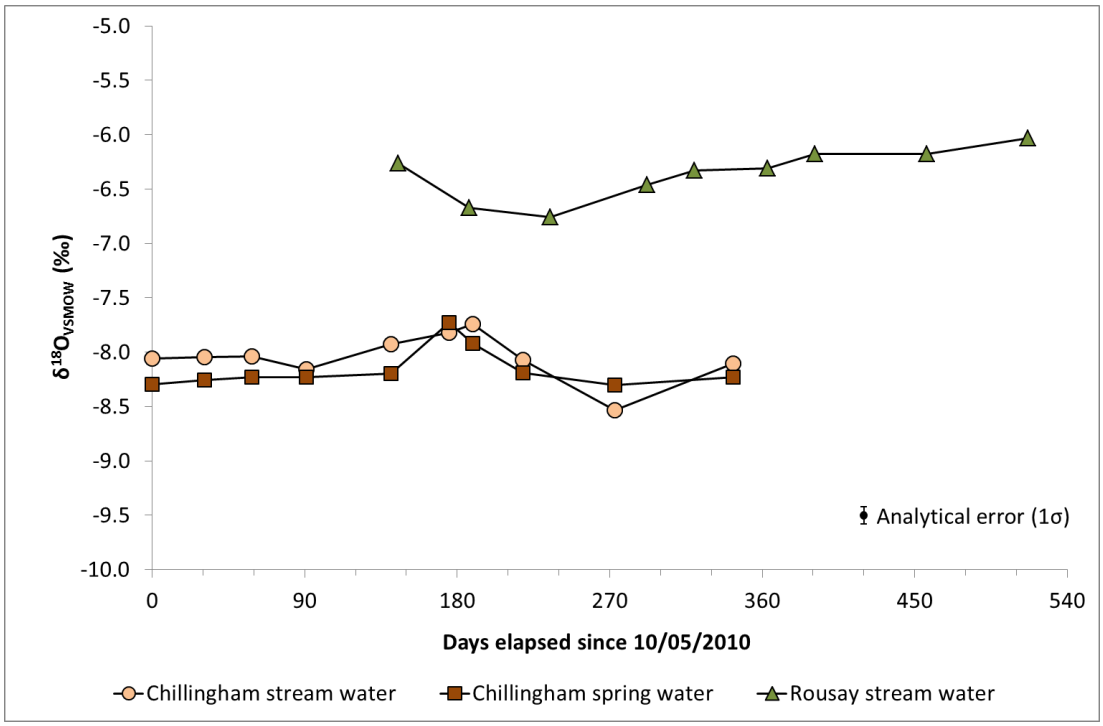


Figure 9.7: $\delta^{18}C_{VSMOW}$ values for vegetation samples collected from Chillingham Park, Northumberland and Rousay, Orkney during 2010 and 2011. Analytical error is ± 0.08 ‰ (1σ).

9.2 Enamel $^{87}Sr/^{86}Sr$ values and strontium concentration results

$^{87}Sr/^{86}Sr$ values and strontium concentrations for cattle molar enamel from Mine Howe, Grimes Graves and Chillingham are presented in Table A.15 (Appendix 1). Also included are results from a single animal from Pool, PL0444, for which the $^{87}Sr/^{86}Sr$ value and strontium concentration are 0.709352 and 943 ppm respectively. The Mine Howe, Grimes Graves and Chillingham results are displayed in Figure 9.8 which shows a plot of $^{87}Sr/^{86}Sr$ versus strontium concentration. There are noticeable differences between these three datasets. As might be expected for cattle able to roam freely but within a restricted area, the results for third molar cuspal enamel from eight modern Chillingham cattle form a tight cluster. $^{87}Sr/^{86}Sr$

values vary between 0.71032 and 0.71094, a range of 0.00062 while concentrations for Chillingham lie between 79 and 126 ppm.

The $^{87}Sr/^{86}Sr$ values for second molar cuspal enamel from eight Mine Howe cattle also fall within a limited range, varying between 0.70973 and 0.71051 (a range of 0.00078) (Figure 9.8). However, concentrations for Mine Howe are higher than for Chillingham and vary much more widely, lying between 129 and 555 ppm. The range reduces to 362-555 ppm if the data-point for second molar cuspal enamel from animal MH133 is excluded. The high strontium concentrations measured for the Mine Howe cattle are consistent with other studies showing elevated values for herbivores and humans in island and coastal regions of Scotland (Montgomery et al 2003, Evans et al 2012). It has been proposed that the high strontium concentration in enamel from this type of environment derives from seawater through sea-spray and sea-splash, and perhaps the use of seaweed as fertilizer (Montgomery 2010, Evans et al 2012). The geology of Orkney is Old Red Sandstone throughout. Other areas of Old Red Sandstone in Britain that are not coastal have produced biosphere $^{87}Sr/^{86}Sr$ values ≥ 0.712 (Evans et al 2010). However, the lower $^{87}Sr/^{86}Sr$ values of the Mine Howe cattle enamel are likely to have been heavily influenced by marine-derived strontium for which the $^{87}Sr/^{86}Sr$ value is ~0.7092 (McArthur et al 2001). Therefore, the $^{87}Sr/^{86}Sr$ and strontium concentration values measured for all but one of the Mine Howe cattle are consistent with an Orcadian birthplace. The uniformity of the Orcadian geology and the strong coastal effect do not allow the investigation of possible origins at a higher resolution. The relatively low strontium concentration for the second molar cuspal enamel of animal MH133, which commenced formation during the first six months of life, does suggest that this animal may not have been born on an island such as Orkney. In contrast, the concentration of its third molar cervical enamel is consistent with the second molar enamel values obtained for the other Mine Howe cattle, suggesting a move to Orkney sometime before the animal was two years of age. Compared to the Mine Howe results, the higher concentration of 943 ppm and lower $^{87}Sr/^{86}Sr$ value of 0.709352 for the animal from Pool (PL0444, Table A.15, Appendix 1, not shown in Figure 9.8) imply an even greater influence of marine-derived strontium through

sea-spray and sea-splash. This is consistent with the location of Pool on a small island, facing the sea and the prevailing weather to the west. In contrast, the closest coastline to Mine Howe was more sheltered, forming part of an inlet, and to the east of the site.

The results for second molar cuspal enamel from ten Grimes Graves cattle vary widely in both $^{87}Sr/^{86}Sr$ and concentration (Figure 9.8). $^{87}Sr/^{86}Sr$ values lie between 0.70842 and 0.71199 (a range of 0.00357) and concentrations range from 107 to 333 ppm. In terms of concentration values, most Grimes Graves data-points lie between the Chillingham cluster and the bulk of the Mine Howe data-points. Grimes Graves lies in a region of chalk geology and $^{87}Sr/^{86}Sr$ values are expected to fall between ~0.708 and ~0.709, based on values measured for plants and water (Evans et al 2010). Therefore, cattle born locally to Grimes Graves should show $^{87}Sr/^{86}Sr$ values below the dotted line indicated in Figure 9.8. Results from five of the Grimes Graves cattle (GG120, GG614, GGT10, GG743 and GG121) lie above the proposed biosphere range for chalk and are likely to have originated elsewhere. GGT10, GG743 and GG121 may have been born in an area of Jurassic geology, the nearest point of which is only ~20 km to the west of Grimes Graves. However, for GG120 and GG614, places of birth are likely to have been further afield. Given the time taken for enamel to mineralize, ~6-7 months according to Balasse (2002), the $^{87}Sr/^{86}Sr$ values for each of these animals may represent a mixing of strontium from both the animal's place of birth and the Grimes Graves area, depending on the age at which the animal was brought to Grimes Graves. Therefore, the ratios of strontium ingested by GG120 and GG614 at their places of birth would have been ≥ 0.712 and ≥ 0.711 respectively. 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 a distance of ~150 km. Thus, for two of the archaeological sites included in this study, Grimes Graves and Mine Howe, results suggest that some cattle had non-local origins.

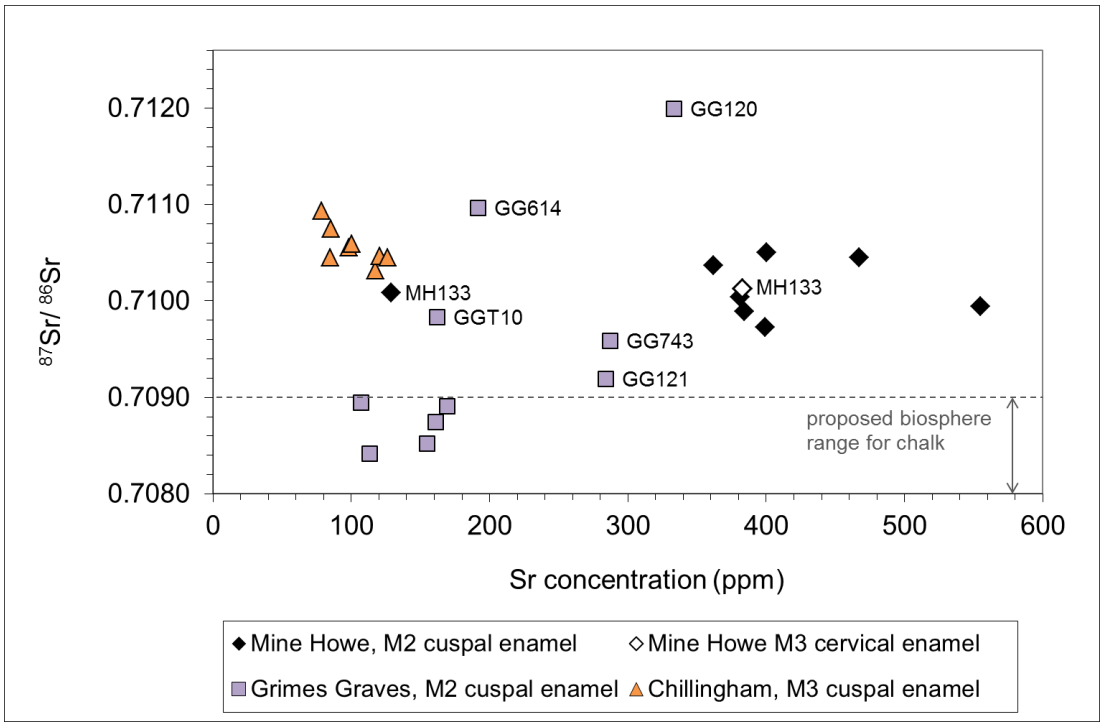


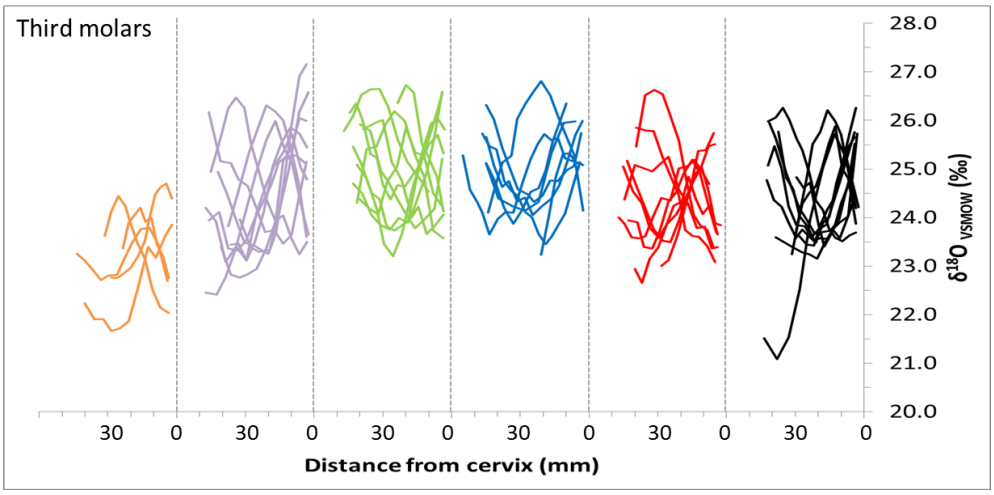
Figure 9.8: $^{87}Sr/^{86}Sr$ versus strontium concentration for cattle molar enamel samples. The 2σ error for $^{87}Sr/^{86}Sr$ is contained within the symbols. The 2σ error for strontium concentration is estimated to be ± 10 %. Proposed biosphere range for chalk taken from Evans et al 2010.

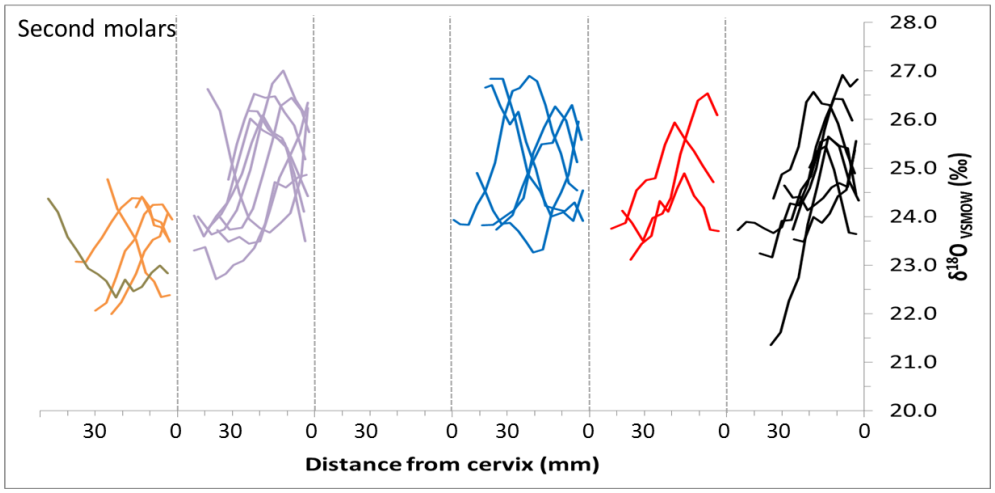
9.3 Intra-tooth enamel carbonate $\delta^{18}O$ and $\delta^{13}C$ results

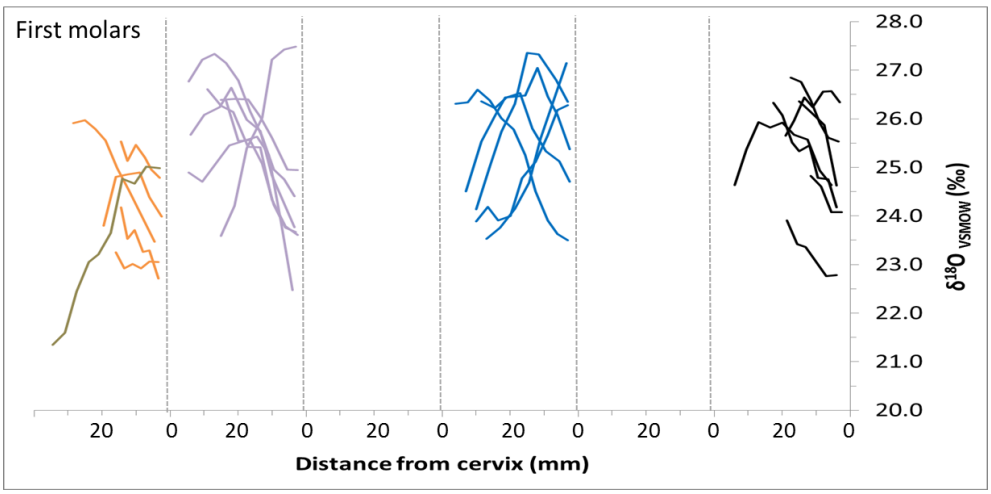
The intra-tooth enamel carbonate $\delta^{18}O$ and $\delta^{13}C$ results for all molars and deciduous premolars analysed in this study, both archaeological and modern, are presented in Tables A.16-A.21 (Appendix 1). These tables also include the position along the tooth lobe (distance from cervix) at which each sample was extracted. The $\delta^{18}O$ and $\delta^{13}C$ datasets are summarised separately below.

9.3.1 $\delta^{18}O$ results

Plots of $\delta^{18}O$ versus distance from cervix for all molars and deciduous premolars analysed in this study are shown in Figure 9.9, which has been devised to show at a glance the overall characteristics of each dataset and inter-site differences rather than details of each individual profile.


Third molars
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
δ18OVSMOW (‰)
30 0 30 0 30 0 30 0 30 0 30 0
Distance from cervix (mm)


Second molars
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
δ18OVSMOW (‰)
30 0 30 0 30 0 30 0 30 0 30 0
Distance from cervix (mm)


First molars
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
δ18OVSMOW (‰)
20 0 20 0 20 0 20 0 20 0 20 0
Distance from cervix (mm)


Modern animals
Chillingham, Northumberland
Dexter, County Durham
Archaeological animals
Grimes Graves, Norfolk
Old Scatness, Shetland
Pool, Orkney
Earl's Bu, Orkney
Mine Howe, Orkney

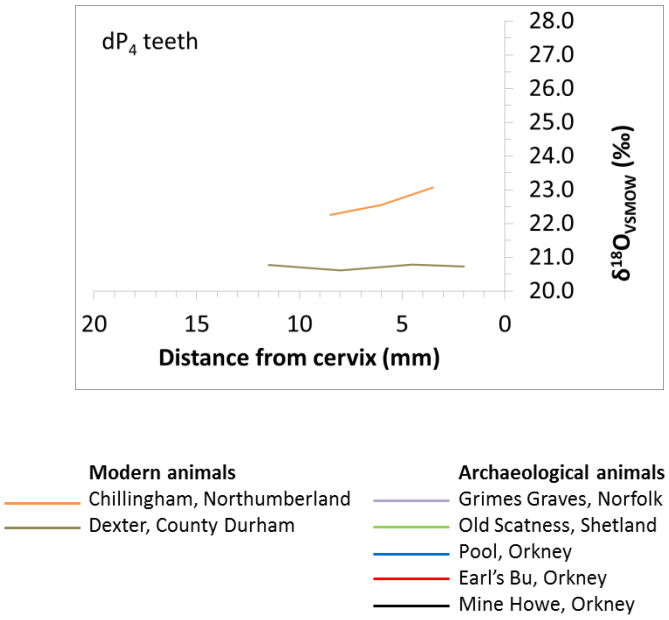


Figure 9.9: Intra-tooth enamel $\delta^{18}O_{VSMOW}$ values versus distance from cervix for cattle first, second and third molars and fourth deciduous premolars. Analytical error is ± 0.2 ‰ (1σ).

$\delta^{18}O$ results are also summarised in Table 9.2 which shows the lowest and highest values for each site, together with calculated ranges and mid-range values. For each molar type, ranges are smallest for Chillingham cattle (between 2.8 and 3.3 ‰), at an intermediate level for Old Scatness, Pool and Earl's Bu cattle (between 3.4 and 4.0 ‰) and largest for Mine Howe and Grimes Graves cattle (between 4.0 and 5.6 ‰). The ranges measured in enamel are related to the seasonal variation in $\delta^{18}O$ of the animals' drinking water (Section 3.2). For the Chillingham cattle, drinking water may be sourced from the streams and springs within the Park. However, isotopic measurements of stream and spring water indicate little seasonal variation in $\delta^{18}O$ (Figure 9.7). Therefore, the cattle must be obtaining a significant proportion of their water from additional sources that do exhibit seasonal variation in $\delta^{18}O$, for example rainwater pools and water present in vegetation. The relatively small ranges exhibited within Chillingham cattle enamel may be a consequence of the smaller sample size for that site. Alternatively, water from a seasonally unvarying source forms a greater proportion of their ingested water than for the cattle from archaeological sites.

The ranges in enamel $\delta^{18}O$ for Mine Howe are expected to be similar to those of the other Orcadian sites and this is true if the animal producing noticeably lower $\delta^{18}O$ values in all three molar types in Figure 9.9 is excluded (bracketed values in Table 9.2). This animal is MH133, for which strontium concentration results suggest origins outside of Orkney (Section 9.2). The noticeably larger ranges and lower mid-range values exhibited by the second and third molar $\delta^{18}O$ values of MH133 (Figure 9.9) support this suggestion, indicating a birth place with a cooler climate on average and more seasonally variable water sources than to be found in the Northern Isles. Similarly, the range of $\delta^{18}O$ values measured for Grimes Graves may be influenced by cattle originating from diverse regions of Britain, as indicated by the $^{87}Sr/^{86}Sr$ values for Grimes Graves (Section 9.2).

Table 9.2: A summary of enamel $\delta^{18}O$ values for the cattle teeth sampled in this study. Values in brackets for Mine Howe are produced by excluding animal MH133, for which strontium concentration results suggest origins outside Orkney.

	$\delta^{18}O_{VSMOW}$ (‰)			
Dataset	**Lowest**	**Highest**	**Range**	**Mid-range**
Third molars				
Chillingham (53 samples, 5 animals)	21.7	24.7	3.0	23.2
Grimes Graves (111 samples,10 animals)	22.4	27.2	4.8	24.8
Old Scatness (107 samples, 10 animals)	23.2	26.7	3.5	25.0
Pool (96 samples, 8 animals)	23.2	26.8	3.6	25.0
Earl's Bu (102 samples, 9 animals)	22.6	26.6	4.0	24.6
Mine Howe (120 samples, 11 animals)	21.1 (23.1)	26.3	5.2 (3.2)	23.7 (24.7)
Second molars				
Chillingham (41 samples, 5 animals)	22.0	24.8	2.8	23.4
Modern Dexter (14 samples, 1 animal)	22.3	24.4	2.1	23.4
Grimes Graves (89 samples, 9 animals)	22.7	27.0	4.3	24.9
Pool (69 samples, 6 animals)	23.3	26.9	3.6	25.1
Earl's Bu (33 samples, 3 animals)	23.1	26.5	3.4	24.8
Mine Howe (79 samples, 8 animals)	21.3 (23.2)	26.9	5.6 (3.7)	24.1 (25.1)
First molars				
Chillingham	22.7	26.0	3.3	24.3

(32 samples, 5 animals)				
Modern Dexter (10 samples, 1 animal)	21.4	25.0	3.6	23.2
Grimes Graves (54 samples, 7 animals)	22.5	27.5	5.0	25.0
Pool (52 samples, 6 animals)	23.5	27.4	3.9	25.4
Mine Howe (43 samples, 7 animals)	22.8 (24.1)	26.8	4.0 (2.7)	24.8 (25.5)
Fourth deciduous premolars				
Chillingham (4 samples, 1 animal)	22.3	23.1	0.8	22.7
Modern Dexter (4 samples, 1 animal)	20.6	20.8	0.2	20.7

For each molar type, mid-range $\delta^{18}O$ values are lowest for Chillingham, at an intermediate level for Mine Howe and highest for Old Scatness, Pool, Earl's Bu and Grimes Graves. Again, the presence of data from MH133 has strongly influenced the mid-range value for Mine Howe. If MH133 is excluded, the mid-range for Mine Howe becomes similar to the other Orcadian sites (bracketed values in Table 9.2).

In order to assess the validity of the $\delta^{18}O$ values for enamel and water presented in this chapter, it is helpful to compare them to previously published data. Only two significant studies have been carried out to determine the relationship between cattle bioapatite $\delta^{18}O$ values and drinking water $\delta^{18}O$ values. The results of the earlier of the two studies, by D'Angela and Longinelli (1990) for modern domestic cattle, are regarded as unreliable because of the possible influence of water derived from both food and water that are not locally sourced (Delgado Huertas et al 1995). The second study, by Hoppe (2006) for modern wild bison, is used here for comparative purposes for three principal reasons: bison are physically similar to domestic cattle and have similar diets; the bison were wild which means their water sources were local; enamel carbonate was analysed allowing direct comparison. Figure 9.10 shows a plot of mean $\delta^{18}O$ values for third molar enamel for nine wild North American bison populations versus mean $\delta^{18}O$ values for environmental waters (Hoppe 2006). Added to the plot is a data-point for Chillingham third molar enamel for which the mid-range $\delta^{18}O$ value, 23.2 ‰, has been plotted versus the

mean annual $\delta^{18}O$ value for Chillingham stream and spring water, -8.1 ‰ (Section 9.1.4). A data-point encompassing all three Orcadian sites has also been added by plotting the overall mid-range $\delta^{18}O$ value for third molar enamel, 24.7 ‰ (MH133 excluded from the Mine Howe data), versus the mean annual $\delta^{18}O$ value for Rousay stream water, -6.4 ‰. The groundwater contour map shown in Figure 3.1 suggests that the $\delta^{18}O$ value for water at Old Scatness, Shetland, would be similar to that measured for the Rousay stream. Therefore, the Old Scatness cattle would plot very closely to the Orcadian cattle in Figure 9.10.

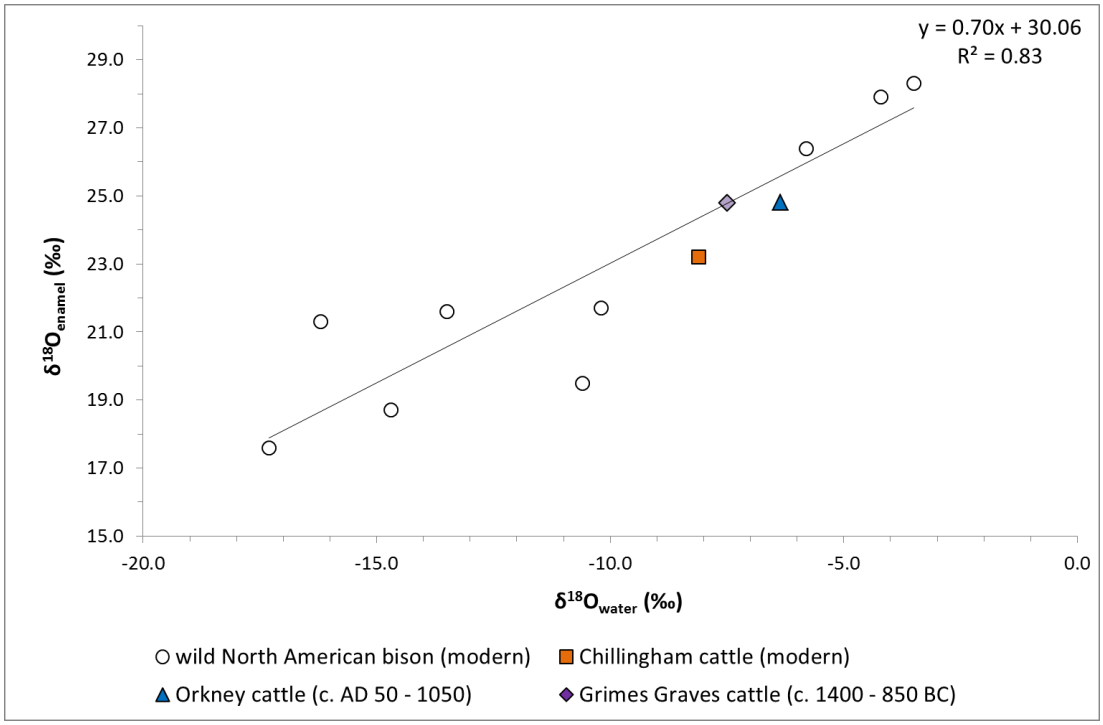


Figure 9.10: Mean $\delta^{18}O$ values of third molar enamel carbonate for a number of wild bison populations versus mean $\delta^{18}O$ values of environmental waters (data and best fit line equation from Hoppe 2006). Each bison data-point is the mean of ≥ 4 animals. Equivalent data have been added for Chilllingham, Orkney and Grimes Graves cattle. $\delta^{18}O$ values for water have been measured for Chillingham and Orkney but estimated for Grimes Graves (see text).

A data-point for Grimes Graves cattle has also been included in Figure 9.10. In this case, the $\delta^{18}O$ value for water, -7.5 ‰, has been estimated from the groundwater contour map in Figure 3.1 and the $\delta^{18}O$ value for third molar enamel is the mid-range value, 24.8 ‰ (Table 9.2). The Grimes Graves data-point may carry more uncertainty than those for Chillingham and Orkney because the $\delta^{18}O$ value for

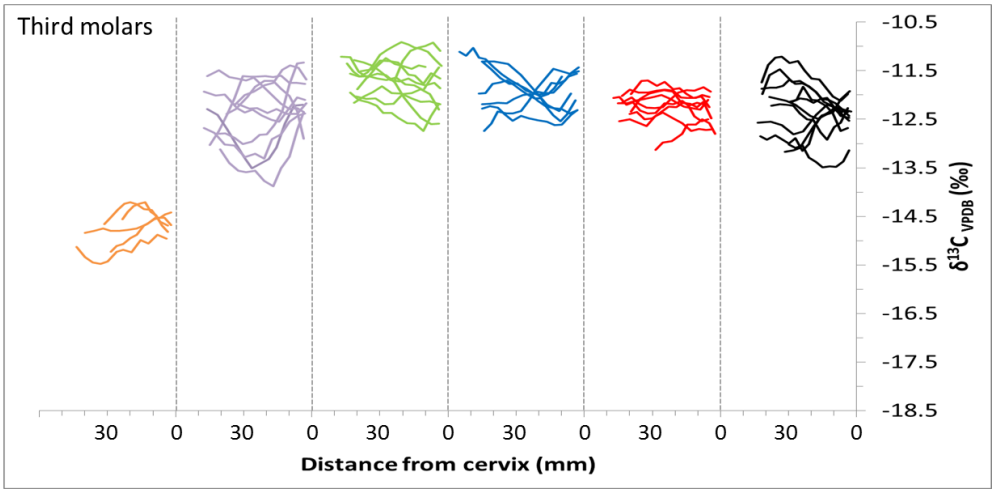
water is predicted rather than measured, and the $\delta^{18}O$ value for enamel might be influenced by the presence of animals born elsewhere. In addition, a $\delta^{18}O$ value for *archaeological* enamel has been plotted against a $\delta^{18}O$ value for *modern* water, which is also true for the Orkney data-point. Nevertheless, all three British data-points broadly conform to the correlation demonstrated by Hoppe (2006) for wild North American bison populations.

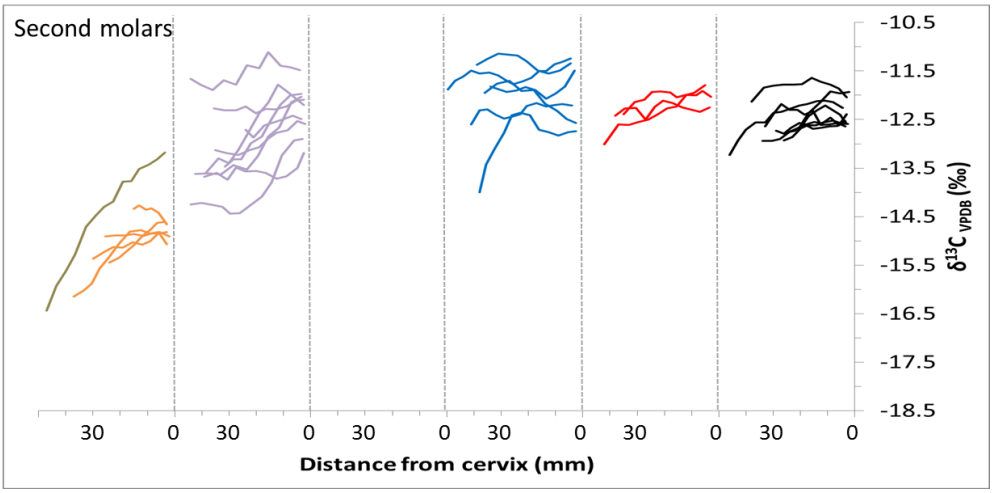
Returning to Table 9.2, a further observation is that the highest $\delta^{18}O$ values for first molar enamel are higher than those for third molar enamel for all sites. This may be related to milk being a principal source of water for a calf during the first few weeks of life, a period during which first molar enamel is in the process of mineralizing. $\delta^{18}O$ values of milk tend to be higher than $\delta^{18}O$ values for the local drinking water (Lin et al 2003, Renou et al 2004, Camin et al 2008) because it is derived from the mother's body water.

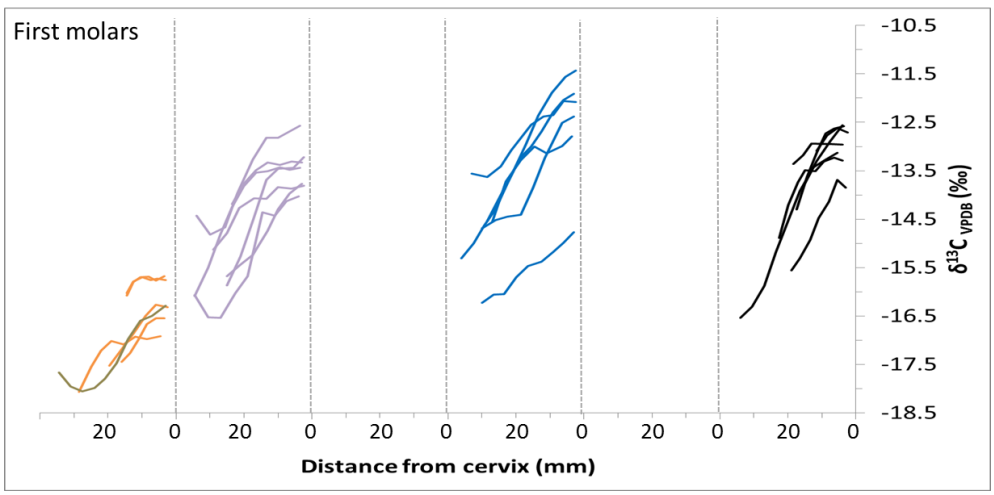
$\delta^{18}O$ data for molar enamel from the modern Dexter bull reared in County Durham are also included in Table 9.2 and in Figure 9.9, where they are shown with the Chillingham data. It might be expected from the groundwater contour map in Figure 3.1 that drinking water $\delta^{18}O$ values at Chillingham would be comparable to those in County Durham, producing similar $\delta^{18}O$ values in the molar enamel of the Dexter and Chillingham cattle. Mid-range values are identical for the second molar enamel $\delta^{18}O$ values. However, the Dexter first molar mid-range value is 1.1 ‰ lower than the Chillingham value, which may be related to the particular dietary components and sources of drinking water available to the animals' mothers when the first molar enamel was mineralizing. $\delta^{18}O$ data were also obtained for fourth deciduous premolar enamel from the Dexter bull and one of the Chillingham cattle (CHIL1).

9.3.2 $\delta^{13}C$ results

Plots of $\delta^{13}C$ versus distance from cervix are shown in Figure 9.11, which, like Figure 9.9, has been devised to display the overall characteristics of each dataset and inter-site differences rather than details of each individual profile.







Modern animals
- Chillingham, Northumberland
- Dexter, County Durham

Archaeological animals
- Grimes Graves, Norfolk
- Old Scatness, Shetland
- Pool, Orkney
- Earl's Bu, Orkney
- Mine Howe, Orkney

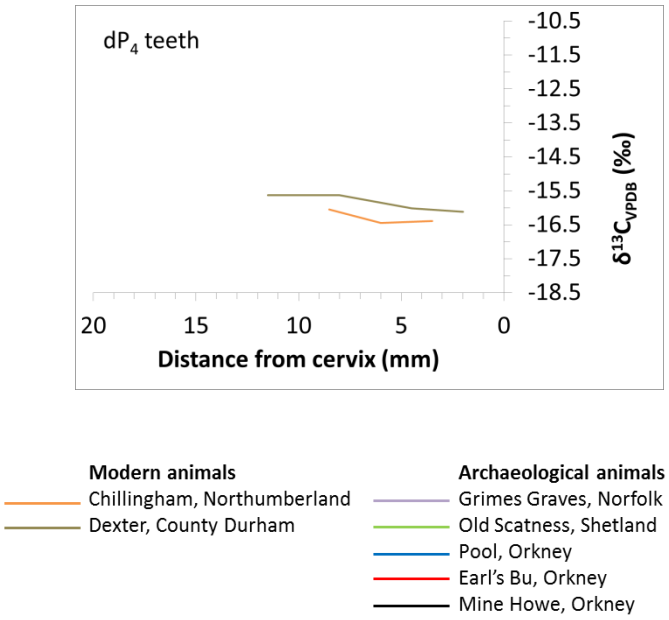


Figure 9.11: Intra-tooth enamel $\delta^{13}C_{VPDB}$ values versus distance from cervix for cattle first, second and third molars and fourth deciduous premolars. Analytical error is ± 0.1 ‰ (1σ).

$\delta^{13}C$ results are also summarised in Table 9.3 which shows the lowest and highest values for each site, together with calculated ranges and mid-range values. Ranges vary between sites and between molars types. This may result from several causes: for example, differing amounts of seasonal variation in vegetation $\delta^{13}C$ (e.g. Figure 9.2) or different husbandry practices with respect to diet. The latter may involve the consumption of different plant species at different times of year, perhaps as fodder brought to the cattle, or the movement of animals between areas with different habitats and/or growing conditions. The rise in the second molar enamel $\delta^{13}C$ values of the modern Dexter bull is likely to be influenced by dietary changes throughout life, which involved grazing in two different locations and the provision of fodder when housed (Sections 7.2 and 7.3.3). Since the archaeological cattle molars analysed in this study are from sites spanning several hundred years, ranges of enamel $\delta^{13}C$ values may also be influenced by long term changes in dietary regime. Grimes Graves cattle exhibit larger ranges of $\delta^{13}C$ values in their second and third molar enamel, 2.6 and 3.3 ‰ respectively, than cattle from the Northern Isles. Earl's Bu cattle show the smallest range, 1.4 ‰ for third molars (the range for second molars may be influenced by the small number of animals), which is comparable to the range for Chillingham third molars. For first and second molar

enamel from Pool, there is one animal that has noticeably lower $\delta^{13}C$ values in each case, which might suggest that the animal originated elsewhere. However, the animal in question is PL0444 for which strontium analysis has been carried out. Results are consistent with PL0444 being born at a coastal site in Orkney such as Pool.

A noticeable feature of Figure 9.11 is that the $\delta^{13}C$ results for first molar enamel show a distinctly different form to those of second and third molar enamel. Furthest from the cervix, $\delta^{13}C$ values are relatively low compared to values obtained for second and third molar enamel, in most cases by several permil. Moving towards the cervix there is a noticeable increase in $\delta^{13}C$ followed by a reduction in gradient to values more typical of second molar enamel. This pattern is important regarding the investigation of cattle birth seasonality and is discussed in detail in Section 11.1. $\delta^{13}C$ data were also obtained for fourth deciduous premolar enamel from the Dexter bull and one of the Chillingham cattle (CHIL1). Values are comparable with the values obtained for first molar cervical enamel and will be discussed further in Section 11.1.

Table 9.3: A summary of enamel $\delta^{13}C$ values for the cattle teeth sampled in this study.

	$\delta^{13}C_{VPDB}$ (‰)			
Dataset	**Lowest**	**Highest**	**Range**	**Mid-range**
Third molars				
Chillingham (53 samples, 5 animals)	-15.5	-14.2	1.3	-14.8
Grimes Graves (111 samples,10 animals)	-13.9	-11.3	2.6	-12.6
Old Scatness (107 samples, 10 animals)	-12.7	-10.9	1.8	-11.8
Pool (96 samples, 8 animals)	-12.7	-11.0	1.7	-11.9
Earl's Bu (102 samples, 9 animals)	-13.1	-11.7	1.4	-12.4
Mine Howe (120 samples, 11 animals)	-13.5	-11.2	2.3	-12.4
Second molars				
Chillingham (41 samples, 5 animals)	-16.1	-14.3	1.8	-15.2
Modern Dexter (14 samples, 1 animal)	-16.4	-13.2	3.2	-14.8
Grimes Graves	-14.4	-11.1	3.3	-12.8

(89 samples, 9 animals)				
Pool (69 samples, 6 animals)	-14.0	-11.1	2.9	-12.6
Earl's Bu (33 samples, 3 animals)	-13.0	-11.8	1.2	-12.4
Mine Howe (79 samples, 8 animals)	-13.2	-11.6	1.6	-12.4
First molars				
Chillingham (32 samples, 5 animals)	-18.1	-15.7	2.4	-16.9
Modern Dexter (10 samples, 1 animal)	-18.1	-16.3	1.8	-17.2
Grimes Graves (56 samples, 7 animals)	-16.5	-12.6	3.9	-14.6
Pool (52 samples, 6 animals)	-16.2	-11.4	4.8	-13.8
Mine Howe (43 samples, 7 animals)	-16.5	-12.6	3.9	-14.6
Fourth deciduous premolars				
Chillingham (4 samples, 1 animal)	-16.4	-16.0	0.4	-16.2
Modern Dexter (4 samples, 1 animal)	-16.1	-15.6	0.5	-15.9

For each molar type, mid-range $\delta^{13}C$ values calculated for Chillingham cattle enamel are noticeably lower than those for the archaeological sites. This is due to the fossil fuel effect whereby the $\delta^{13}C$ value of atmospheric CO_2 has become increasingly more negative since the Industrial Revolution (Section 3.3). Levels during the first decade of the 21st century, the approximate time of mineralization for the Chillingham cattle molars analysed in this study, were ~-8.4 ‰ (Keeling et al 2010), whereas pre-industrial levels were ~-6.4 ‰ according to measurements of atmospheric CO_2 trapped within ice cores (Friedli et al 1986). Thus, a difference of ~ 2.0 ‰ is expected between the mid-range $\delta^{13}C$ values for Chillingham and those for the archaeological sites. Applying a correction of +2.0 ‰, Chillingham values for first, second and third molars become -14.9, -13.2 and -12.8 ‰ respectively, which are closer to the equivalent archaeological values, particularly the Grimes Graves values, but still a little more negative. Possible reasons for inter-site variation in mid-range $\delta^{13}C$ values are differences in grazed vegetation species and/or growing conditions, and differences in fodder provision.

The isotopic separation between enamel and diet $\delta^{13}C$ values has been calculated in previous studies and such calculations may be made for the Chillingham data obtained in the current study. To allow comparisons between datasets using different isotopic scales (e.g. VSMOW, VPDB), Passey et al (2005) and Cerling and Harris (1999) recommend the use of isotopic enrichment, ε*, to express offsets in $\delta^{13}C$:

$$\varepsilon^*_{\text{enamel-diet}} = (\alpha_{\text{enamel-diet}} - 1) \times 1000$$

where

$$\alpha_{\text{enamel-diet}} = (1000 + \delta^{13}C_{\text{enamel}}) / (1000 + \delta^{13}C_{\text{diet}})$$

Applying these formulae to the Chillingham data, using the mid-range $\delta^{13}C$ value for third molar enamel, -14.8 ‰, for $\delta^{13}C_{\text{enamel}}$ and the mean annual $\delta^{13}C$ value for vegetation, -30.3 ‰, for $\delta^{13}C_{\text{diet}}$, $\alpha = 1.01598$ and $\varepsilon^* = 16.0$ ‰. The value of ε* is a little larger than those calculated by Passy et al (2005) for domestic cattle, 14.6 ± 0.3 ‰, and by Cerling and Harris (1999) for a variety of large ruminants, 12.9-14.8 ‰. The reason for this discrepancy is not clear. It is possible that the mean annual $\delta^{13}C$ value for Chillingham vegetation is not particularly representative of the actual vegetation consumed by the animals involved in the analysis. The grazing behaviour of these individuals within Chillingham Park is not known. Therefore, using a mean value for the whole park may not be valid. Similarly, using the mean $\delta^{13}C$ value for vegetation collected in 2010 and 2011 may not be representative of values prevalent during the period of enamel formation several years earlier. In contrast, Passey et al (2005) performed a controlled diet study where the animals' diet was known during the period of enamel formation. Another explanation for the discrepancy between the values of ε* for the Chillingham cattle and the cattle in the study by Passey et al (2005) may be the difference in diet, the latter being fed a mono-specific diet of alfalfa or bermuda-grass. The diet of the Chillingham cattle may have produced more methane through fermentation in the rumen (Section 3.3) than the mono-specific diet, leading to the higher isotopic enrichment in the

Chillingham enamel. It is also possible that inter-laboratory differences in sample treatment and analysis have contributed to the discrepancy, although there are no published inter-laboratory comparisons pertinent to this discussion.

Isotopic enrichment, ε*, may also be calculated for the archaeological Orcadian cattle enamel. Using the overall mid-range $\delta^{13}C$ value for Pool, Earl's Bu and Mine Howe third molar enamel, -12.3 ‰, for $\delta^{13}C_{enamel}$ and the mean annual $\delta^{13}C$ value for vegetation collected in Orkney in August 2011, -26.8 ‰ (-28.8 ‰ corrected for a fossil fuel offset of 2.0 ‰), for $\delta^{13}C_{diet}$, α = 1.01490 and ε* = 14.9 ‰. Similar calculations may be made for Old Scatness using the mid-range $\delta^{13}C$ value for Old Scatness third molar enamel, -11.8 ‰, and the mean annual $\delta^{13}C$ value for vegetation collected in Shetland in August 201, -27.4 ‰ (-29.4 ‰ corrected for a fossil fuel offset of 2.0 ‰), resulting in values for α and ε* of 1.01604 and 16.0 ‰ respectively. The same arguments that were made for the Chillingham ε* value may be made for the Northern Isles ε* values when compared to the controlled-diet study (Passey et al 2005).

9.4 Intra-tooth dentine collagen $\delta^{13}C$ results

Intra-tooth dentine collagen $\delta^{13}C$ results were obtained for modern cattle only. They are presented in Table A.22 (Appendix 1) and displayed in Figure 9.12. As expected for modern dentine, collagen yields are generally high with the majority of values ranging between 11 and 24 %. The other three quality criteria proposed by van Klinken (1999) and outlined in Section 4.4.2 (C:N ratio, %C and %N) are also met.

For the two Chillingham cattle for which results have been obtained, $\delta^{13}C$ values range between -25.1 and -24.4 ‰ with a mid-range value of -24.8 ‰ (first and second molars combined). The offset between collagen and the mean $\delta^{13}C$ value for Chillingham vegetation, -30.3 ‰, is 5.5 ‰ (or 5.7 ‰ in terms of isotopic enrichment ε*) which is in agreement with the collagen-diet spacing suggested by Hedges (2003) of 5 ± 1.5 ‰. An offset of identical magnitude exists between the mid-range

collagen $\delta^{13}C$ value for the Dexter animal (first and second molars combined), -23.8 ‰, and the mid-range $\delta^{13}C$ value for diet, -29.3 ‰.

The offset between enamel and collagen for Chillingham, using the mid-range $\delta^{13}C$ value for third molar enamel, -14.8 ‰, is 10.0 ‰ (ε* = 10.3 ‰), which is at the high end of the range of values presented by Lee-Thorp et al (1989) for modern African herbivores and comparable to the value of 10.1 ‰ (ε* = 10.3 ‰) obtained by Feranec (2007) for modern free-ranging North American bison. The relatively large spacing between the enamel and collagen $\delta^{13}C$ values for the Chillingham cattle appears to be related to the large spacing between the enamel and diet $\delta^{13}C$ values discussed in Section 9.3.2.

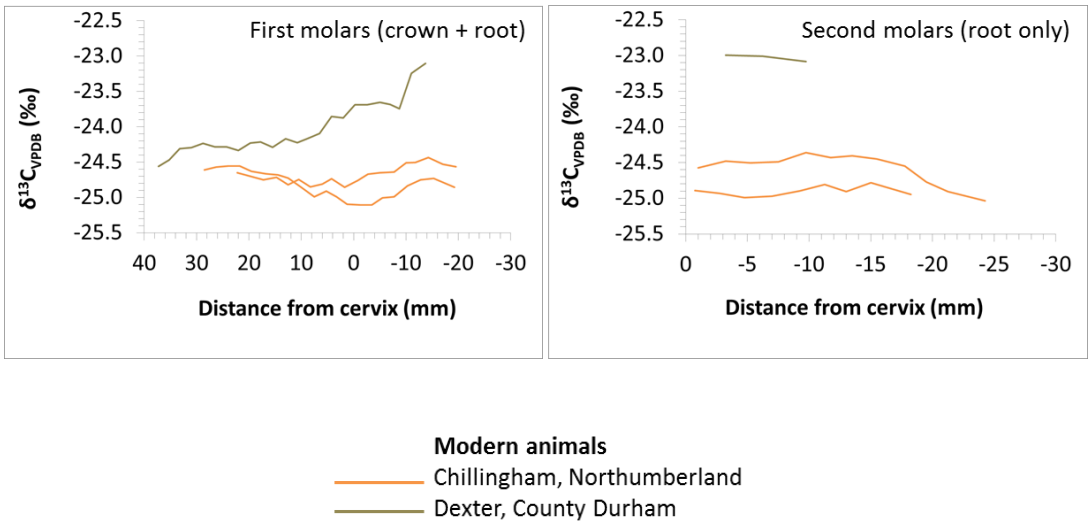


Figure 9.12: Intra-tooth dentine collagen $\delta^{13}C_{VPDB}$ values versus distance from cervix for cattle first and second molars. Positive distances are for samples from the crown, negative distances are for samples from the root. Analytical error is ± 0.2 ‰ (1σ). Each data-point is the mean of two replicates.

9.5 Bone collagen $\delta^{13}C$ results

Mandibular bone collagen $\delta^{13}C$ results were obtained for Grimes Graves cattle only. They are presented in Table A.23 (Appendix 1) and displayed in Figure 9.13. Collagen yields are < 1.0 % in most cases, which are low according to the quality criteria proposed by van Klinken (1999) and outlined in Section 4.4.2. The bones

were buried in midden deposits separated by chalky washes within an abandoned flint mine shaft in a region of chalk geology. Layers of clay were present in the midden material, particularly the Group 3 midden at the bottom of the deposits (Mercer 1981 pp36). It is possible that collagen degradation was accelerated due to a combination of fluctuating groundwater levels and alkaline conditions (Section 4.4.2). Despite the poor collagen yields, the other three quality criteria are met: C:N ratios are 3.2 or 3.3, carbon content (%C) varies between 38.7 and 41.2 % and nitrogen content (%N) varies between 13.7 and 14.8 %. Consequently, it is assumed that the results for samples with collagen yields ≥ 0.5 % are valid, as suggested by van Klinken (1999), while those with lower yields will be included in further analysis but treated with caution and highlighted. They are shown as white square symbols in Figure 9.13. The diagenetic processes leading to poor collagen yield appear not to have affected enamel isotopic values, as indicated by the low level of noise present in the intra-tooth $\delta^{18}O$ and $\delta^{13}C$ profiles and the sinusoidal nature of the $\delta^{18}O$ profiles obtained from Grimes Graves cattle molar enamel (Figure 13.15). Collagen was also independently extracted from GG120 and GG92 at the Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Leipzig, and sent to The Curt-Engelhorn-Centre for Archaeometry for radiocarbon dating. The calibrated radiocarbon dates were 1416-1302 cal BC, 95 % confidence (MAMS-14361, 3084 ± 21 BP) for GG120 and 908-820 cal BC, 95% confidence (MAMS-14362, 2722 ± 20 BP) for GG92. Calibration was carried out using the INTCAL09 dataset (Reimer et al 2009) and SwissCal 1.0 (L. Wacker, ETH-Zürich). The mandible GG120 was most likely from the Group 3 midden deposit since its radiocarbon age agrees with that obtained for a piece of charcoal known to be from that particular midden (BM-1097, 3084 ± 44 BP) (Mercer 1981 p36). GGT10, the only cattle mandible assigned to a particular midden group, was also from the Group 3 midden deposit.

The range of $\delta^{13}C$ values is -22.3 to -21.0 ‰ with nine results forming a tight group between -22.3 and -22.0 ‰. The remaining five results form a more dispersed grouping between -21.6 and -21.0 ‰. Cattle suspected to have had non-local origins according to their $^{87}Sr/^{86}Sr$ values are present in both groups: GG120,

GG614, GG743 and GG121 lie within the tight group, while GGT10 lies within the dispersed group. Since GG120 and GGT10 are both from the Group 3 midden deposit, the two groups of data do not relate to different time periods.

An approximate value for the offset between enamel and bone collagen, calculated from the mid-range $\delta^{13}C$ value for third molar enamel, -12.6 ‰, and the mean $\delta^{13}C$ value for bone collagen, -21.9 ‰, is 9.3 ‰ ($\varepsilon^* = 9.5$ ‰), which is similar, although a little smaller in magnitude, than the offset between third molar enamel and dentine collagen calculated for Chillingham cattle ($\varepsilon^* = 10.2$ ‰, see Section 9.4). It is also possible to calculate an approximate offset between enamel and bone collagen for the Orkney data using the overall mid-range $\delta^{13}C$ value for third molar enamel, -12.3 ‰, for $\delta^{13}C_{enamel}$ and a mean $\delta^{13}C$ value for bone collagen, -21.8 ‰, obtained for 33 cattle from Iron Age and Norse Orkney (sites unspecified) by Jones et al (2012). The calculated offset is 9.5 ‰ ($\varepsilon^* = 9.7$ ‰), comparable with the offsets for Grimes Graves and Chillingham.

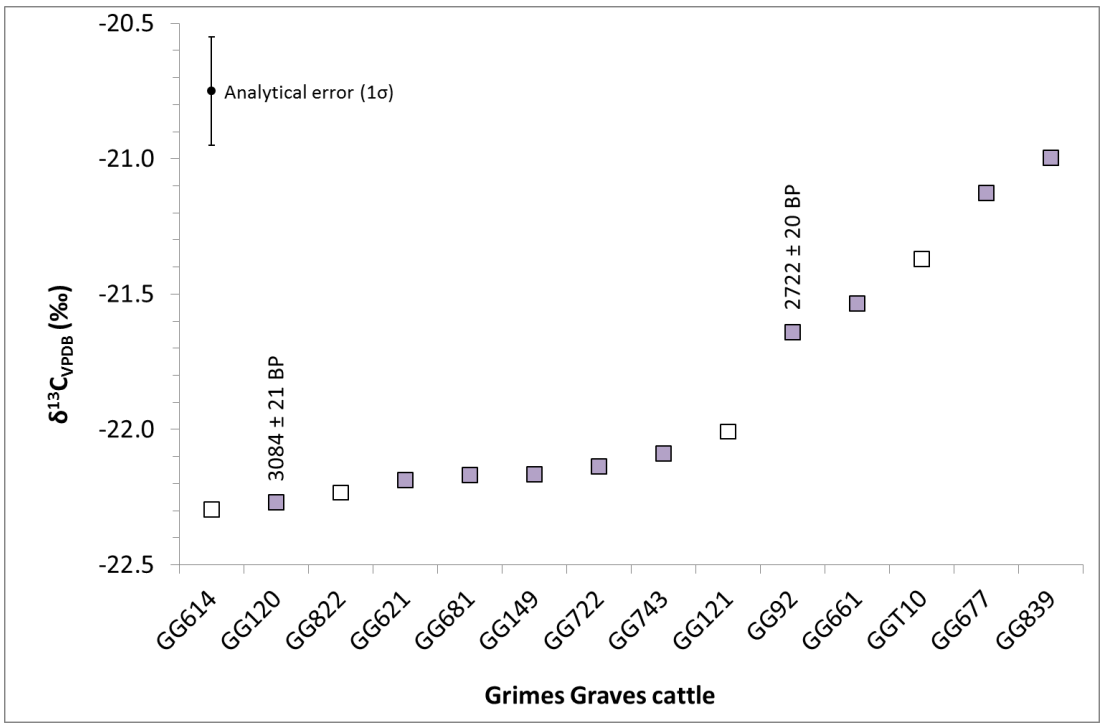


Figure 9.13: Mandible bone collagen $\delta^{13}C_{VPDB}$ values for cattle remains from Grimes Graves. Analytical error is ± 0.2 ‰ (1σ). Each result is the mean of two replicates. White squares indicate collagen yields of < 0.5 %.

10 Preliminary data handling: plotting intra-tooth data versus time

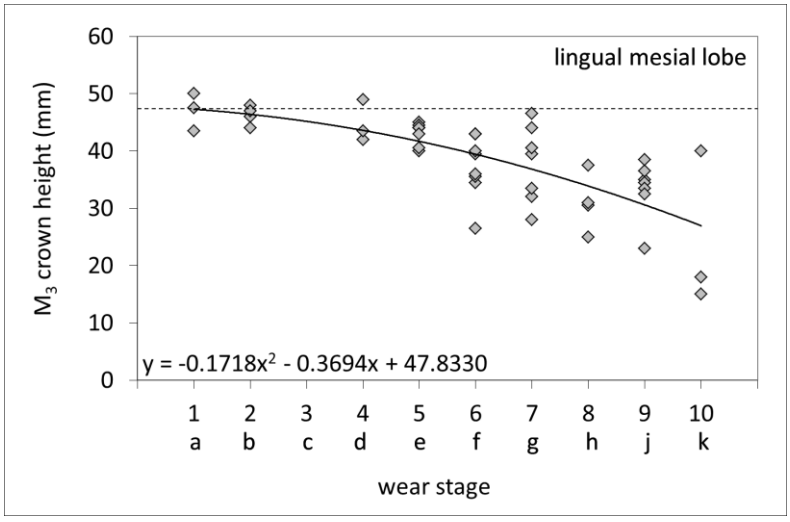
The majority of data collected for this study are intra-tooth $\delta^{18}O$ and $\delta^{13}C$ values from cattle molar enamel. Intra-tooth $\delta^{13}C$ values have also been obtained from the collagen component of cattle molar dentine. Discussion and interpretation of these datasets feature strongly in the following three chapters and, in order to aid interpretation, it has proved beneficial to plot intra-tooth data versus time rather than distance from the cervix. This allows data from first, second and third molars from the same individual to be plotted on a common x-axis. Indeed, plotting intra-tooth data versus time is a prerequisite for one of the three methods to estimate birth seasonality discussed in Chapter 12. Procedures to produce plots of intra-tooth data versus time for enamel and dentine are presented in Sections 10.1 and 10.2 below. Parts of this chapter are to be published in Towers et al (in press).

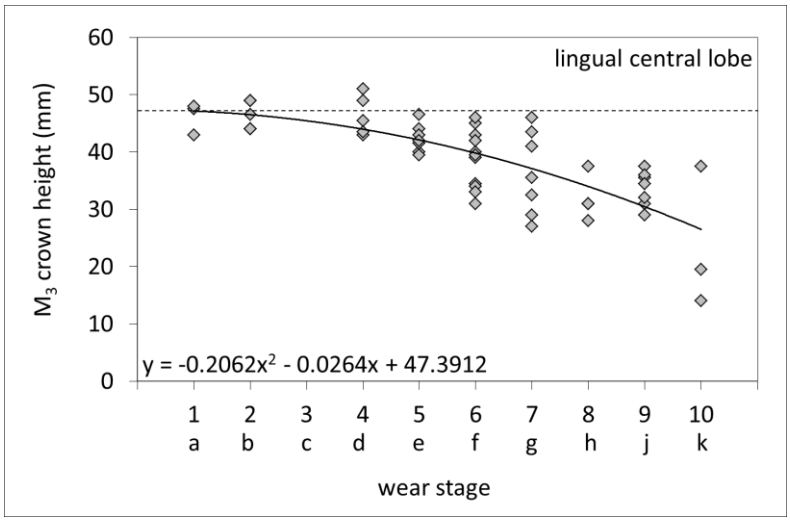
10.1 Plotting intra-tooth $\delta^{18}O$ and $\delta^{13}C$ enamel data versus time

Plots of intra-tooth $\delta^{18}O$ and $\delta^{13}C$ enamel data versus time necessitate the conversion of distance from cervix to time, a calculation requiring values for the unworn crown height of a particular molar and the start and finish time of its development. Plots of intra-tooth data versus time may be produced as follows:

1) For worn third molars at wear stages b-f as defined by Grant (1982), unworn crown heights are predicted from graphs of wear stage versus crown height (Figure 10.1) constructed using measurements of 46 mandibular third molars from Mine Howe (wear stage data from Davis 2010 Appendix V). Figure 10.1 includes graphs for both lingual mesial, lingual central and buccal mesial lobes, the three enamel lobes sampled in this study. Best-fit curves, generated in Excel, allow the determination of incremental corrections for each wear stage in mm (Table 10.1): the incremental correction for a particular wear stage is the difference in mm between the best-fit curve and the crown height for unworn wear stage a (Figure 10.1). For each third molar, the predicted unworn crown height is obtained by adding the appropriate incremental correction to the worn crown height. Despite

being derived from Mine Howe molars, the incremental corrections are used for all third molars since, whatever the original size of the unworn tooth, any difference between the actual and predicted amounts of wear will be relatively small, translating to an equally small error in the predicted unworn molar size. For animals where only first and second molars have been analysed, the similar size and morphology of second and third molars allow unworn crown heights for worn second molars to be predicted using the third molar incremental corrections for wear stages b-f.





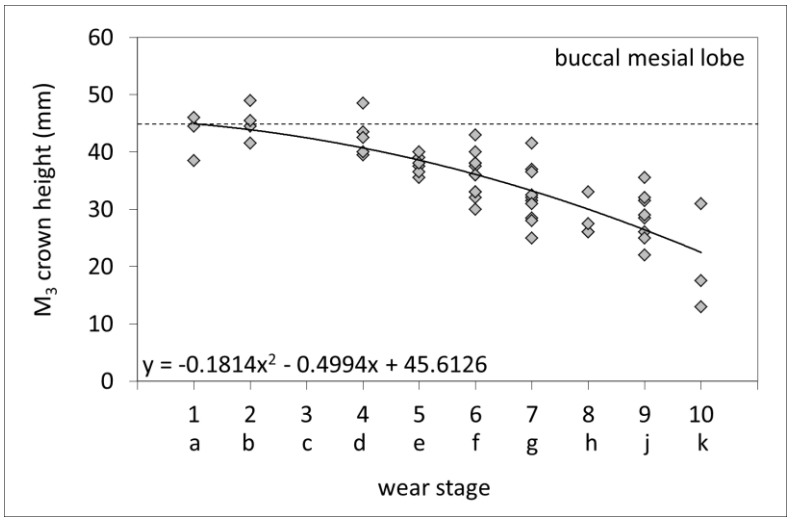


Figure 10.1: Plots of crown height versus wear stage for 46 mandibular third molars from Mine Howe, Orkney (wear stage classification from Grant 1982). The incremental correction for a particular wear stage is the difference in mm between the fitted curve and the crown height for wear stage a (indicated by the horizontal dashed line). N.B. These fitted curves do not allow for the disparity in duration of the different wear stages. Therefore, it is recommended that this method to obtain incremental corrections should not be adopted if there is a viable alternative, e.g from mean values of crown height provided such values can be calculated to a sufficient level of accuracy for all wear stages, which was not possible in this case.

Table 10.1: Incremental corrections in mm for mandibular third molar wear stages.

	Wear stage					
M_3 enamel lobe	**a**	**b**	**c**	**d**	**e**	**f**
Lingual mesial	0	0.9	2.1	3.7	5.6	7.9
Lingual central	0	0.6	1.7	3.2	5.1	7.3
Buccal mesial	0	1.0	2.5	4.2	6.4	8.8

For the remaining third molars, at wear stages g-k, unworn crown heights are not predicted using incremental corrections from plots of crown height versus wear stage because such wear stages are defined according to the height of the accessory pillar lying between the buccal lingual and central lobes. The height of this accessory pillar can vary substantially between cattle: measurements of 56 third molars from a single archaeological site by Jones (2007) produced a standard deviation of 5.3 mm, which would introduce additional uncertainty to the

prediction of unworn crown height. Instead, predicted unworn crown heights are assigned a fixed value (Table 10.2). For the archaeological third molars this is the mean value of measured and predicted unworn crown heights at wear stages a-f, which is 49.9 ± 3.0 mm (1σ, n = 30, including teeth not sampled in this study) for the Northern Isles sites, and 54.3 ± 2.4 mm (1σ, n = 8) for Grimes Graves. These two mean values apply to the lingual mesial lobe; for the Northern Isles and Grimes Graves third molars at wear stages g-k, only lingual mesial lobes were sampled. It has not been possible to calculate an equivalent mean value for the five Chillingham third molars sampled in this study because only one of these teeth, from animal CHIL1, is sufficiently unworn, at wear stage f, that the unworn crown height may be predicted by means of the incremental correction information in Table 10.1. However, estimation of birth seasonality, the efficacy of which requires minimal uncertainty in the unworn crown heights of the molars involved, is not carried out for the Chillingham animals. Therefore, accuracy is not critical and the following unworn crown height values are used: 54.3 mm and 56.9 mm for buccal mesial and lingual mesial lobes respectively. The rationale behind these values is given in Table 10.2.

Table 10.2: Unworn crown height values used for mandibular third molars at wear stages g-k.

Site	**Lobe sampled**	**Value used for unworn crown height**	**Comment**
Northern Isles (Mine Howe, Pool, Earl's Bu and Old Scatness)	Lingual mesial	49.9 mm	The mean value calculated from measured and predicted crown heights of 30 third molars at wear stages a-f from the Northern Isles sites.
Grimes Graves	Lingual mesial	54.3 mm	The mean value calculated for 8 third molars at wear stages a-f from Grimes Graves.
Chillingham	Buccal mesial	54.3 mm	The value predicted for the buccal mesial lobe of CHIL1 (wear stage f).
	Lingual mesial	56.9 mm	The value predicted for the lingual mesial lobe of CHIL1 (wear stage f).

2) For each molar series that includes a third molar, the unworn second molar crown height is calculated to be 97 % of the predicted unworn crown height of the third molar. The figure of 97 % falls between a figure of 94 % suggested by Jones (2007) and a value closer to 100 % suggested by the limited examples available to this study.

3) Unworn first molar crown heights are calculated to be 84 % of the predicted unworn second molar crown heights, as suggested by Legge (1992 p21) for Grimes Graves cattle molars.

4) For each molar, the timing, t, of each intra-tooth enamel sample relative to the timing of cervix formation is calculated proportionally from the distance of the sample from the cervix, x, the measured or calculated unworn crown height, H_C, and the duration of crown formation, T_C, given by the chronology of Brown et al (1960) (Table 4.1):

$$t = xT_C / H_C \qquad \text{(in months)}$$

These parameters are shown schematically for a third molar in Figure 10.2, which also shows the start and finish times relative to birth of each molar, assumed to be -4.7 and 2.5 months for first molars, 1 and 12.5 months for second molars and 10 and 23.5 months for third molars. These are the mid-range times given in Table 4.1 apart from the start time of 10 months for third molars, which is chosen because the mid-range start time of 9.5 months can produce visible misalignment between second and third molar isotopic data when plotted together on a time-related x-axis. The timing of each intra-tooth sample relative to birth is calculated from the age at which crown formation is complete (the timing of cervix formation); i.e. the timing relative to birth is (23.5 – t) months for a third molar, (12.5 – t) months for a second molar and (2.5 – t) months for a first molar.

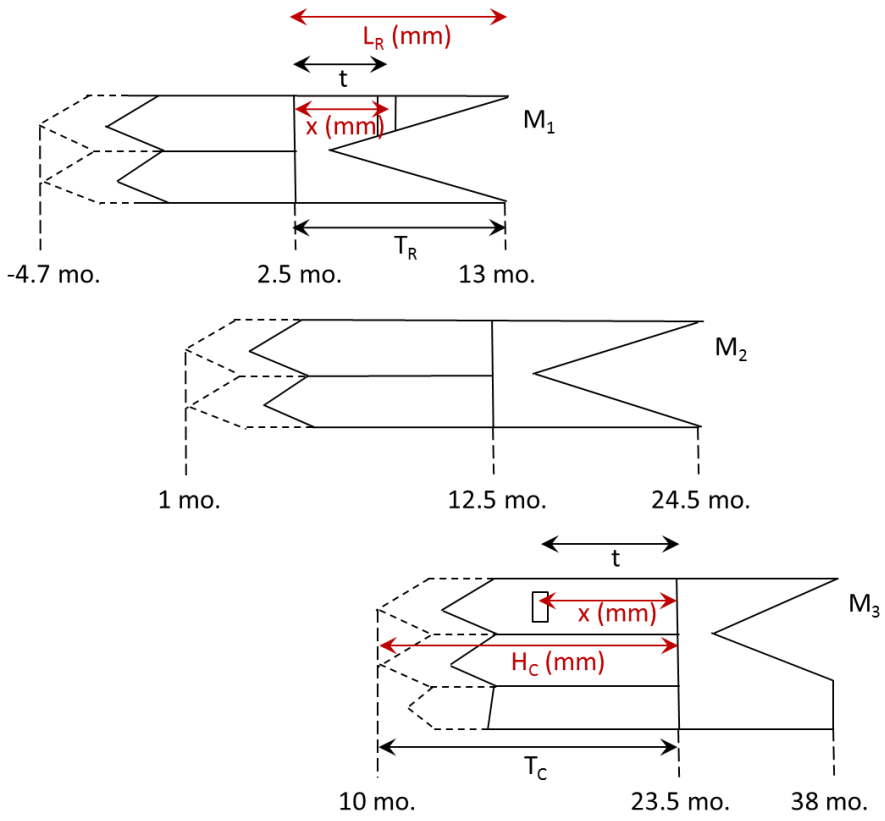


Figure 10.2: Schematic diagram showing first, second and third molar start and finish times relative to birth and the parameters required to convert distance from the cervix to time for intra-tooth samples. Dashed outlines define the unworn crown heights that must be predicted if the crowns are worn.

A typical plot constructed using the above procedure is shown in Figure 10.3. It should be emphasized that the timing of each intra-tooth data point represented in a plot of $\delta^{18}O$ or $\delta^{13}C$ versus time (its x-axis value) is related to the **initial deposition of the enamel matrix**, whereas the value of $\delta^{18}O$ or $\delta^{13}C$ (its y-axis value) is an average value of the completed enamel which took several subsequent months to mineralize following matrix deposition.

The construction of such plots, as outlined above, assumes that the crown formation times suggested by Brown et al (1960), which were derived for modern teeth, can also be applied to archaeological teeth. In addition, it is also assumed that the matrix progresses at a uniform rate, which appears not to be true for first molars. According to Brown et al (1960), only one third of the first molar crown is formed at birth; the cuspal third forms before birth over a period of approximately

4.5 months and the remaining two thirds over a shorter period of approximately 2.5 months. Thus, although the first molar isotopic data are plotted according to calculations outlined in (4) above, the x-axis time scale is removed for times earlier than 2 months because of the known non-uniformity of first molar matrix progression (Figure 10.3).

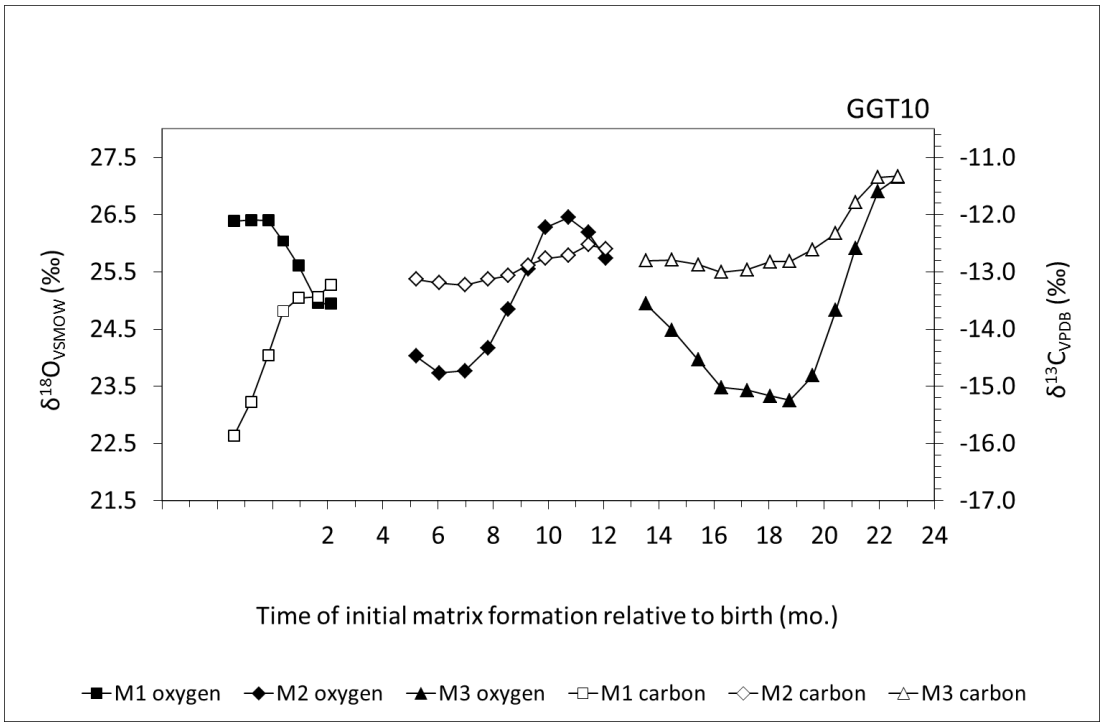


Figure 10.3: A typical plot of isotopic composition versus time of initial matrix formation relative to birth.

10.2 Plotting intra-tooth $\delta^{13}C$ dentine collagen data versus time

For intra-tooth dentine samples, the timing, t, of each sample, whether from the crown or the root, is calculated relative to the timing of cervix formation. For coronal dentine, t is calculated exactly as described for enamel in Section 10.1:

$$t = xT_C / H_C \qquad \text{(in months)}$$

The timing of each coronal intra-tooth sample relative to birth is also calculated exactly as described for enamel (Section 10.1). For root dentine, t is similarly

calculated from the distance of the sample from the cervix, x, the measured or calculated root length, L_R, and the duration of root formation, T_R, given by the chronology of Brown et al (1960) (Table 4.1):

$$t = xT_R / L_R \qquad \text{(in months)}$$

These parameters are shown schematically for a first molar in Figure 10.2. Only first molar crowns, first molar roots and second molar roots have been sampled for dentine in this study, of which one second molar root was incomplete. For cases such as this, L_R is assumed to be identical to the root length of the first molar because timing accuracy is not critical in the interpretation of the resulting plots. The timing of each root intra-tooth sample relative to birth is calculated from the age at which crown formation is complete (the timing of cervix formation); i.e. the timing relative to birth is (12.5 + t) months for a second molar and (2.5 + t) months for a first molar.

Again, the timing for each intra-tooth data point represented in a plot of $\delta^{13}C$ versus time (its x-axis value) is related to the initial deposition of the dentine, whereas the value of $\delta^{13}C$ (its y-axis value) is an average value of the completed dentine which took several subsequent months to reach its final thickness following initial deposition.

11 Preliminary investigation of intra-tooth $\delta^{13}C$ profiles

Before attempting to interpret intra-tooth $\delta^{13}C$ data collected from archaeological cattle, it is instructive to study intra-tooth data obtained from modern cattle with known histories, which, in this study, are cattle from the Chillingham Wild White Cattle herd, Northumberland and a Dexter bull (KAR) reared in County Durham. In this chapter, the intra-tooth results presented in Chapter 9 for these modern cattle are re-plotted versus time using the procedures outlined in Chapter 10. Comparisons are made between enamel and dentine collagen intra-tooth $\delta^{13}C$ profiles and between enamel $\delta^{13}C$ and $\delta^{18}O$ profiles, leading to a greater understanding of the $\delta^{13}C$ profiles themselves in terms of what they might represent regarding diet, environment and husbandry. In addition, it was observed in Section 9.3.2 that the $\delta^{13}C$ patterning in first molar enamel shows a distinctly different form to that in second and third molars. Moving from earlier forming enamel at the cusp towards later forming enamel at the cervix, first molar $\delta^{13}C$ profiles tend to start at relatively low levels, rise steeply, then level off or show a reduction in gradient to values more typical of second molar enamel. The distinctive shape of the first molar enamel $\delta^{13}C$ profile forms the basis of one of the methods to estimate birth seasonality proposed in Chapter 12. Therefore, it is important to understand its cause in order to have confidence in the proposed method. This is the first topic discussed by this chapter in Section 11.1 below. Parts of this chapter are to be published in Towers et al (in press).

11.1 First molar enamel and dentine collagen intra-tooth $\delta^{13}C$ profiles

In attempting to determine the cause of the $\delta^{13}C$ patterning within first molar enamel, it is instructive to compare the $\delta^{13}C$ profiles of enamel and dentine collagen. Figure 11.1 shows both profiles plotted together versus time for a modern animal from Chillingham (CHIL1). The $\delta^{13}C$ profile of enamel consists of intra-tooth data from first, second and third molars, the progression of the enamel matrix for these three teeth approximately spanning the first two years of the animal's life. Dentine matrix progression from first molar cusp to root tip and along the length of

the second molar root occurs during the same period (Table 4.1). Figures 11.2 and 11.3 show enamel and dentine collagen $\delta^{13}C$ profiles for two further cattle: a second Chillingham animal (CHIL14) and the Dexter bull (KAR). Because of the approximate nature of the molar formation parameters proposed by Brown et al (1960) (Table 4.1) and the different averaging processes occurring during enamel maturation and dentine formation (Sections 4.1 and 4.2), some mismatch in timing between the enamel and dentine collagen profiles is possible. A difference in body pool turnover rates may also contribute (Section 3.3), although for fast-growing young animals this may not be significant since it is likely that most of their carbon input to both enamel bioapatite and dentine collagen originates from dietary rather than endogenous sources.

It is evident from the plots in Figures 11.1-11.3 that the $\delta^{13}C$ profile of first molar enamel clearly shows a rise and subsequent reduction in gradient (indicated by the grey crossed square symbol) that is not replicated in the dentine collagen profile. Therefore, it is unlikely that the $\delta^{13}C$ rise in first molar enamel is caused by a change in the $\delta^{13}C$ value of the animals' food since such a change would be expected to influence both profiles. For the Dexter bull (KAR), the subsequent step-like appearance of the dentine profile is likely to result from the changes in location (High Stoop, Stanhope and Dapple Farm) and diet occurring during the Dexter's life, the details of which are found in Sections 7.2 and 7.3.3.

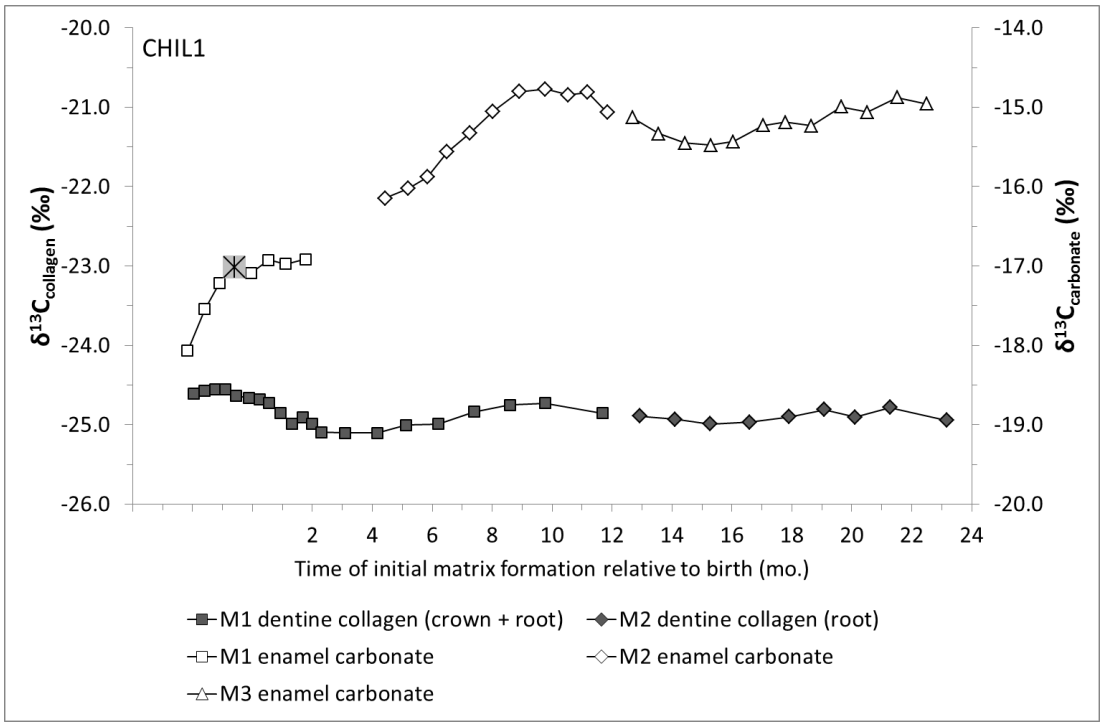


Figure 11.1: Enamel and dentine $\delta^{13}C$ profiles for modern Chillingham animal CHIL1. The grey crossed square symbol indicates the change in gradient of the enamel profile. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{carbonate}$ and ± 0.2 ‰ for $\delta^{13}C_{collagen}$.

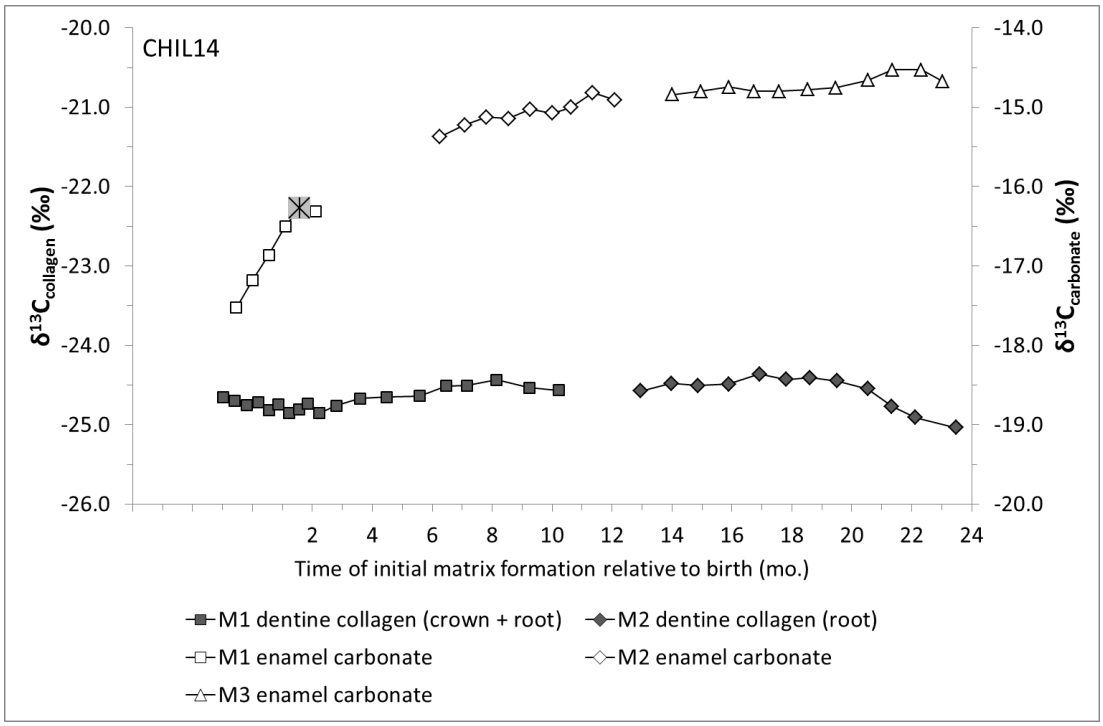


Figure 11.2: Enamel and dentine $\delta^{13}C$ profiles for modern Chillingham animal CHIL14. The grey crossed square symbol indicates the change in gradient of the enamel profile. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{carbonate}$ and ± 0.2 ‰ for $\delta^{13}C_{collagen}$.

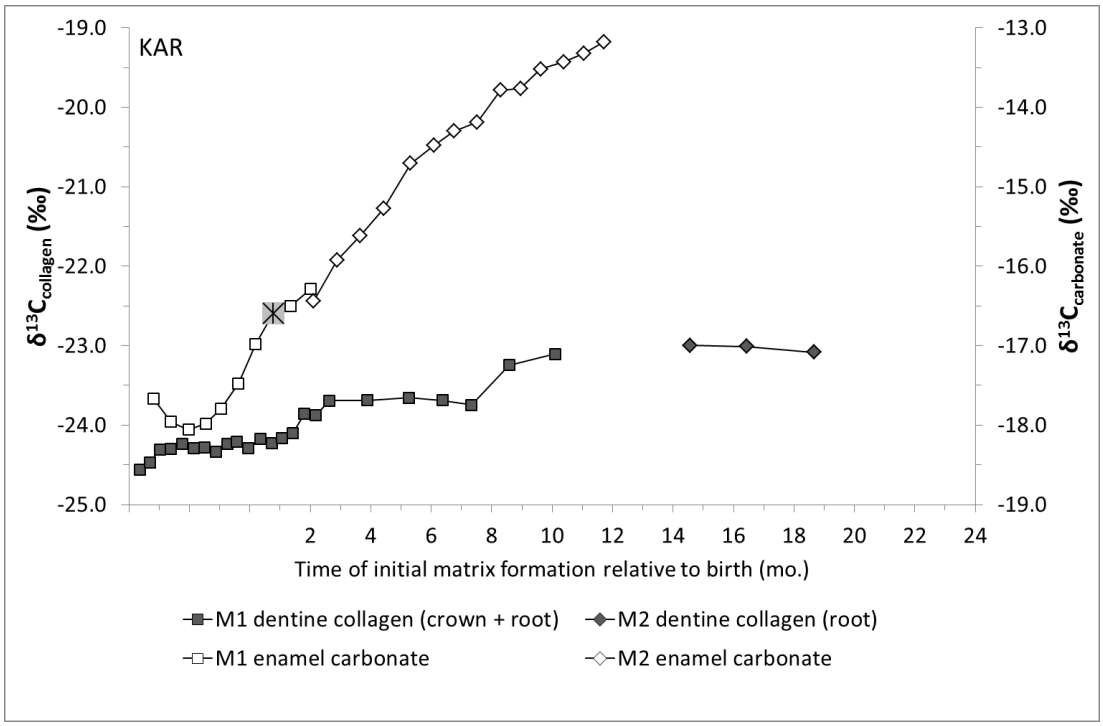


Figure 11.3: Enamel and dentine $\delta^{13}C$ profiles for the modern Dexter bull (KAR). The grey crossed square symbol indicates the change in gradient of the enamel profile. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{carbonate}$ and ± 0.2 ‰ for $\delta^{13}C_{collagen}$.

It is likely that the difference in form between the first molar enamel and dentine collagen $\delta^{13}C$ profiles relates to the source of carbon atoms in each case and the digestion processes involved. Carbon atoms incorporated into enamel carbonate derive from blood dissolved inorganic carbon (CO_2, CO_3^{2-}, H_2CO_3 and HCO_3^-). The carbon input to the latter is metabolically produced CO_2 (Passey et al 2005). However, for ruminants, there is a second input resulting from the fermentation of food by micro-organisms in the rumen, the first of four stomach compartments. The products of the fermentation process are methane and ^{13}C-enriched CO_2 (Section 3.3).

If the amount of ^{13}C-enriched CO_2 entering the bloodstream varies during a period of enamel formation, then the $\delta^{13}C$ profile recorded in enamel will reflect this. In terms of matrix progression, a cattle first molar crown starts forming several months before birth and is complete when the calf is approximately 2-3 months old (Table 4.1). Consequently, the first molar crown forms during the key stages in a

calf's digestive development, a period during which the rumen grows and becomes functional. Variation in ^{13}C-enriched CO_2 entering the bloodstream during this period is therefore expected. Initially, when the first molar crown begins forming, the dissolved carbon in the foetal calf's blood is derived from its mother's digestion processes. Hence, the $\delta^{13}C$ value of forming enamel will be typical of a ruminant. When the calf is born, its rumen is undeveloped and digestion of milk is carried out in the abomasum, the fourth stomach compartment in a ruminant, which digests food in a similar manner to the stomach of a non-ruminant. Therefore, immediately after birth, the $\delta^{13}C$ value of forming enamel is expected to be more typical of a non-ruminant; i.e. more negative. However, given the opportunity, young calves will begin to consume some solid food by the age of two weeks (Lengemann and Allen 1959, Godfrey 1961a). It is the consumption of dry food that stimulates the development of the rumen. Provided such food is available, the rumen develops quickly, anatomically, physiologically and microbially, so that by the time the calf is approximately 6-10 weeks old, it is able to digest solid food as an adult ruminant (Bryant et al 1958, Swanson and Harris 1958, Godfrey 1961b, Anderson et al 1987). Thus, from this age, the $\delta^{13}C$ value of forming enamel will be more typical of a ruminant even though the calf may not be fully weaned.

Transition of the calf from ruminant (via its mother) through non-ruminant and back to ruminant might be expected to produce relatively higher $\delta^{13}C$ values in the earliest and latest forming enamel of an *unworn* first molar with lower values between. However, most analysed first molars are worn. Because enamel mineralization takes several months (Balasse 2002) and since, according to Brown et al (1960), only one third of the crown is formed at birth, any enamel that started forming before birth is likely to be worn away or, if remaining, produce a $\delta^{13}C$ value predominantly reflecting post-birth digestion. Thus, the rise in $\delta^{13}C$ towards the cervix in first molars, evident in Figures 11.1-11.3, may indicate the transition between non-ruminant digestion immediately after birth (relatively low $\delta^{13}C$ values) and the utilisation of a fully formed rumen several weeks later (relatively high $\delta^{13}C$ values), with the reduction in gradient of the $\delta^{13}C$ profile (grey crossed square

symbols in Figures 11.1-11.3) indicating the completion of rumen functionality at the age of approximately 6-10 weeks.

The proposed relationship between the shape of the $\delta^{13}C$ profile in first molar enamel and methanogenesis arising from ruminal digestion is strengthened by $\delta^{13}C$ measurements of fourth deciduous premolar enamel. Figure 11.4 is a plot of enamel $\delta^{13}C$ versus distance from the cervix for the first molar and fourth deciduous premolar of the modern Dexter (KAR). $\delta^{18}O$ data are also shown, supporting the suggested relationship in timing between the two teeth. Moving away from the cervix, the $\delta^{13}C$ profile passes through a minimum and begins to rise again in the cuspal enamel. This earliest-forming enamel may be reflecting foetal incorporation of ^{13}C-enriched carbon resulting from the mother's ruminal digestion. Because the crown of a cattle fourth deciduous premolar is almost fully mineralized by the time of birth (personal observation), the $\delta^{13}C$ values recorded in the enamel of this tooth should be dominated by the mother's ruminal digestion. The plot in Figure 11.4 shows that the $\delta^{13}C$ values of the modern Dexter's fourth deciduous premolar enamel are relatively high. Plots for the same two teeth from one of the Chillingham cattle (CHIL1) show an equivalent pattern (Figure 11.5). Thus, together, the fourth deciduous premolar and the first molar do appear to show the three stages in a calf's digestive development from ruminant (via its mother) through non-ruminant and back to ruminant.

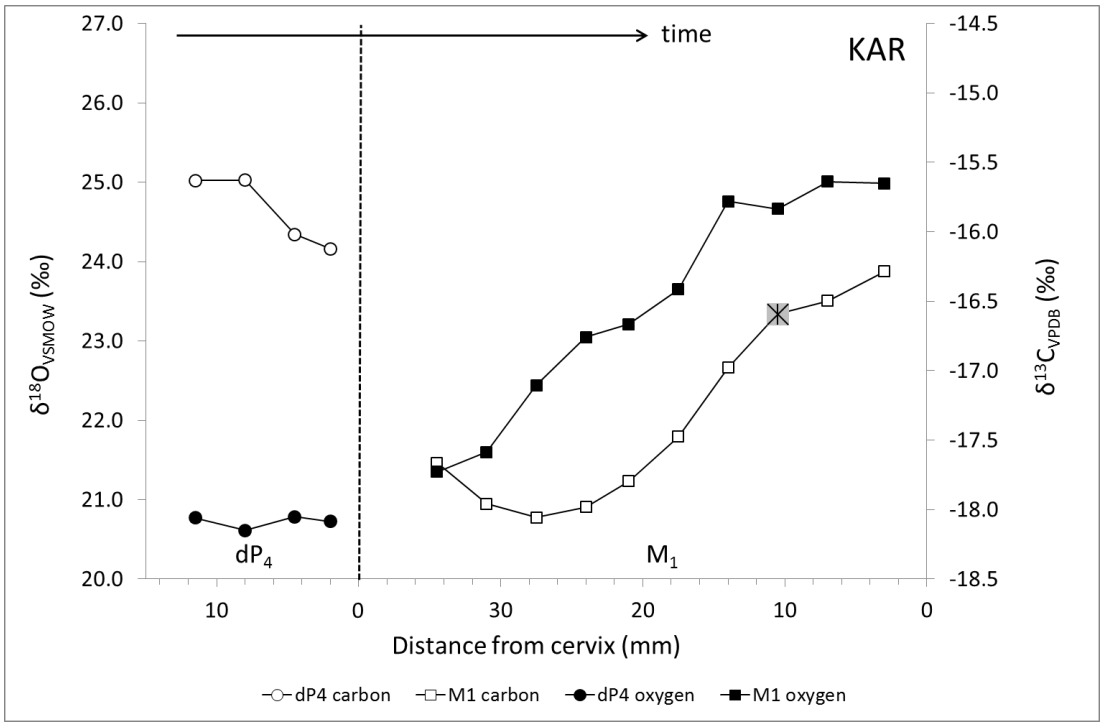


Figure 11.4: Enamel $\delta^{18}O$ and $\delta^{13}C$ versus distance from cervix for first molars and fourth deciduous premolars from the modern Dexter bull (KAR). The grey crossed square symbol indicates the change in gradient of the enamel profile. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

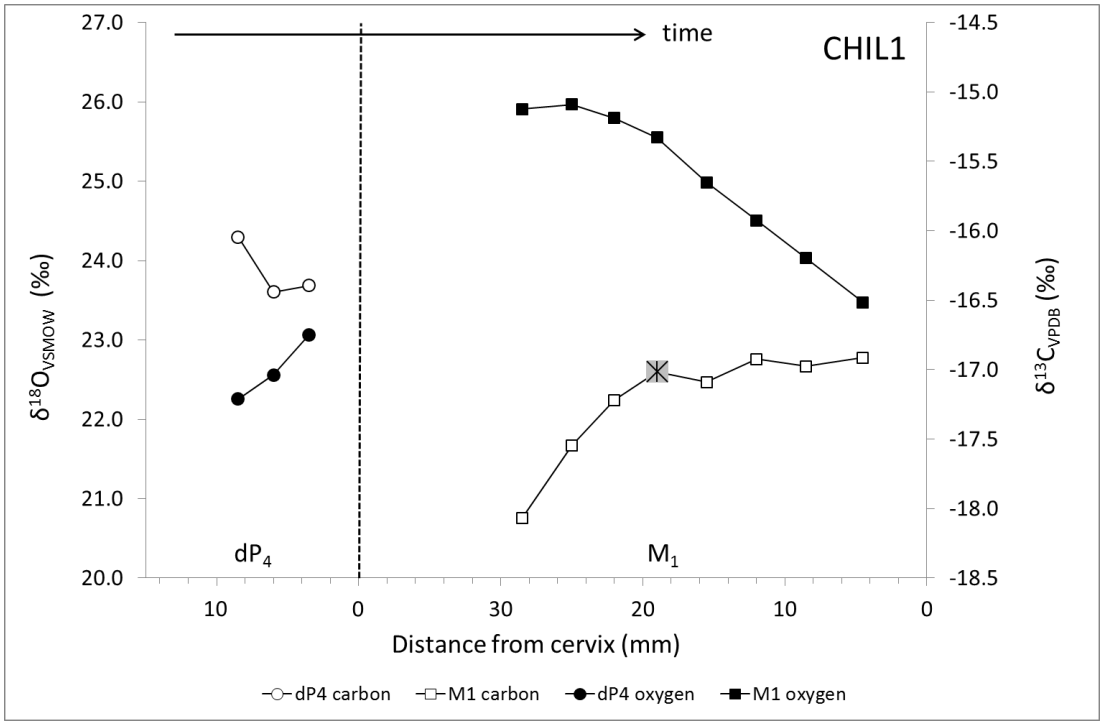


Figure 11.5: Enamel $\delta^{18}O$ and $\delta^{13}C$ versus distance from cervix for first molars and fourth deciduous premolars from a modern Chillingham animal (CHIL1). The grey crossed square symbol indicates the change in gradient of the enamel profile. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

In contrast to carbon atoms incorporated into enamel carbonate, those incorporated into dentine collagen derive predominantly from amino acids transported in the blood. In young calves with undeveloped rumens, these amino acids are produced by the digestion of milk proteins in the abomasum and small intestine (Davis and Drackley 1998 p18). In older animals, food proteins are initially broken down by micro-organisms in the rumen into amino acids and peptides. These are then synthesized into microbial proteins which are also digested in the abomasum and small intestine (McDonald et al 1988 p150). Thus, it is the protein sources of the blood-transported amino acids that change during a calf's digestive development rather than the digestion process. For a foetal calf, microbial proteins are digested by its mother's abomasum and small intestine, whereas after birth, digestion of milk proteins occurs in the calf's own digestive system. Subsequent development of the calf's rumen allows the synthesis of microbial proteins and, as the calf gets older and consumes proportionately more vegetation, the ratio of microbial to milk proteins increases. Eventually, microbial proteins become the sole source of the blood-transported amino acids that act as the building blocks of collagen. The animal is then fully weaned, the timing of which does not necessarily synchronise with the completion of rumen functionality.

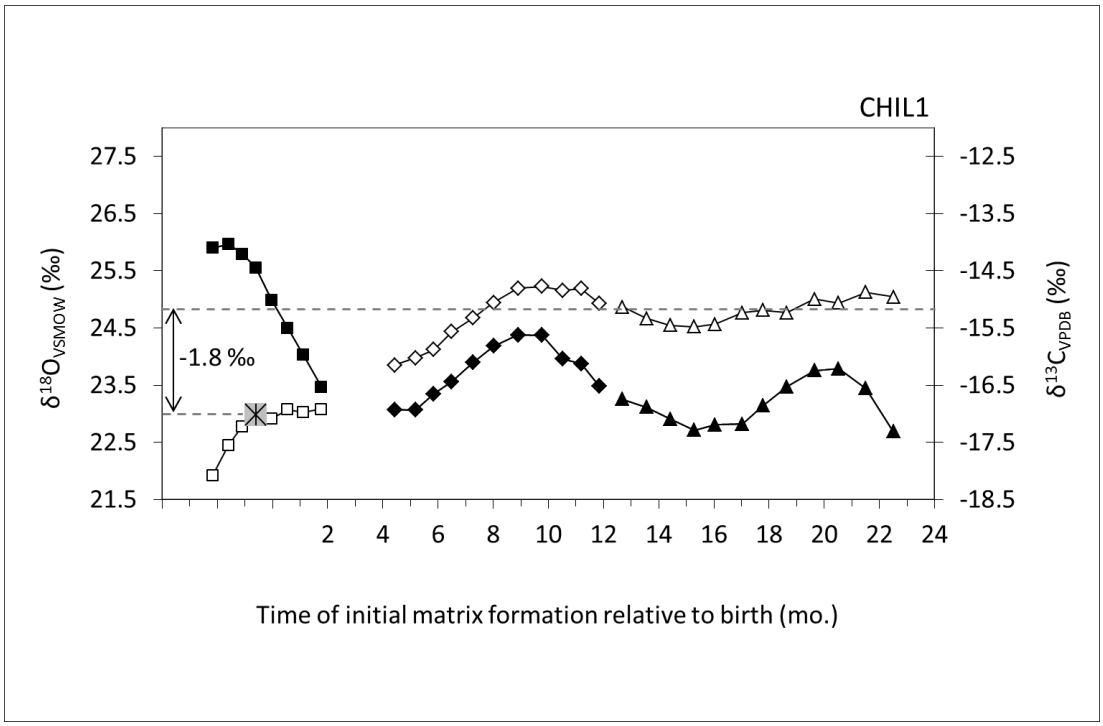
A study analysing the carbon isotope ratios of keratin from the fingernails of human mothers and infants showed that the keratin $\delta^{13}C$ values of infants that were exclusively breastfed were similar to those of their mothers when in utero, rose rapidly after birth to become more positive by ~1 ‰, then finally returned to maternal levels after a period of weaning (Fuller et al 2006). Thus, it might be expected that the dentine collagen plots in Figures 11.1-11.3 show a similar effect, although it must be borne in mind that a typical dentine intra-tooth sample takes several months to form due to the build-up of growth layers (~8-9 months for a second molar crown according to Zazzo et al (2006)), which will influence the recorded isotopic signal. The dentine collagen plot for animal CHIL1 (Figure 11.1) does appear to show a reduction in $\delta^{13}C$ values moving towards the cervix from the first molar cusp. However, this sloping $\delta^{13}C$ profile may well be reflecting the seasonal variation in vegetation $\delta^{13}C$ values, which has been observed for

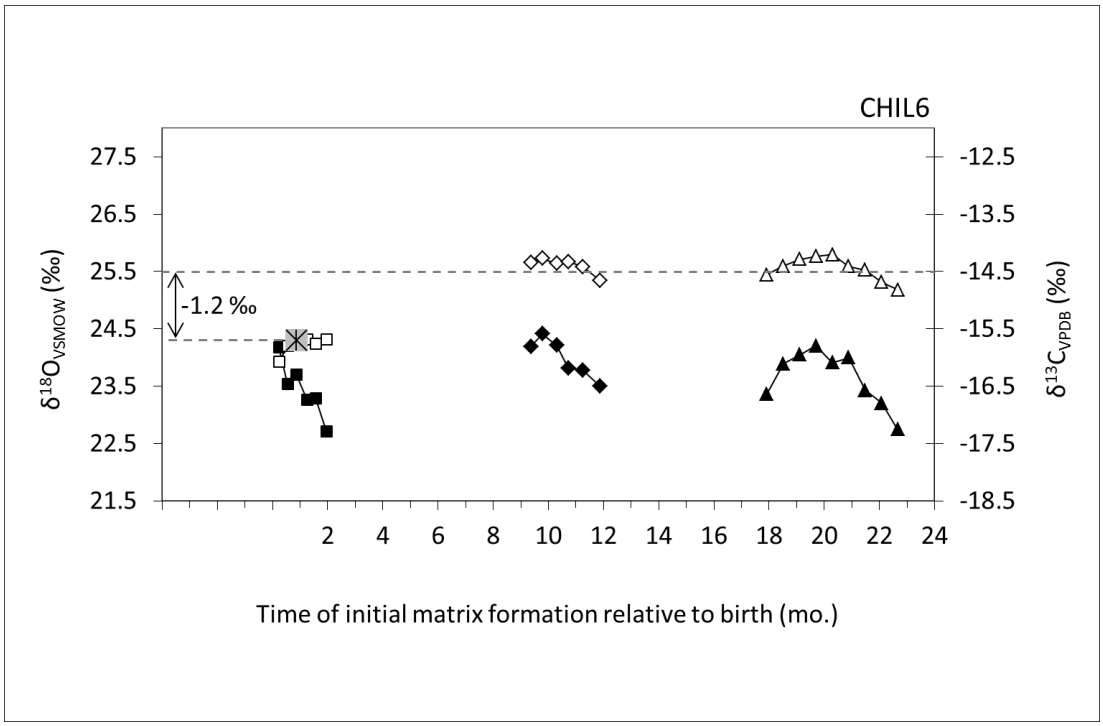
Chillingham vegetation (Figure 9.2), rather than milk consumption. There is also the hint of a downward slope in the first molar cuspal dentine of CHIL14 (Figure 11.2), although the drop in $\delta^{13}C$ is of the order of the analytical error so its validity is uncertain. Unfortunately, the first molars of both CHIL1 and CHIL14 are worn to the extent that dentine starting to form at and before birth is no longer present. Such dentine is present in the first molar of the modern Dexter bull (KAR) and the plot in Figure 11.3 does show an initial rise in the dentine collagen $\delta^{13}C$ profile which may represent the onset of suckling. However, in this case, changes in location and dietary components (Sections 7.2 and 7.3.3) may act to obscure or distort any influence by suckling on the $\delta^{13}C$ profile. Further analysis of minimally-worn first molars from modern animals with known histories would be required to investigate the effects of suckling on $\delta^{13}C$ values recorded in first molar dentine collagen.

11.2 The offset between first and third molar enamel $\delta^{13}C$ values

It is evident from Figures 11.1 and 11.2 that, for CHIL1 and CHIL14, the $\delta^{13}C$ values of third molar enamel are elevated compared to the value at which the first molar enamel $\delta^{13}C$ profile reduces in gradient (marked by the grey crossed square symbol). The plots also indicate that there is no equivalent difference between the dentine collagen $\delta^{13}C$ values of the second molar root and the first molar crown. Thus, it is unlikely that the increase evident in the enamel data is caused by a change in the $\delta^{13}C$ value of the animals' food. In fact, the rise in $\delta^{13}C$ values between first and third molar enamel is clearly observed to varying degrees for all five Chillingham animals included in this study (Figure 11.6), the offsets calculated using the mid-range $\delta^{13}C$ values for third molar enamel and varying between -0.9 ‰ for CHIL10 and -2.1 ‰ for CHIL7. Unfortunately, the second molars of several animals are worn to such an extent that a significant proportion of the enamel is missing and the $\delta^{13}C$ profile is incomplete. Nevertheless, for CHIL1, CHIL7 and CHIL14, the offset is significantly greater than any internal variation in $\delta^{13}C$ recorded within the third molar enamel, supporting the idea that the offset is unrelated to the $\delta^{13}C$ value of the animal's food.

One possible explanation might be related to weaning. The Chillingham cattle wean their calves naturally and calves will continue to suckle long after their rumens become fully functional, despite consuming increasing quantities of vegetation. 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). Potentially, suckling can continue until the next calf is born (Burthe et al 2011). Whatever the age of the calf, suckling from a teat will stimulate a reflex action that channels the milk into the abomasum for digestion similar to that of a non-ruminant. As the proportion of milk in the diet gradually decreases and the proportion of vegetation increases, the carbon incorporated into enamel carbonate will 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. Hence, for the Chillingham cattle that were naturally weaned, the $\delta^{13}C$ profiles would be expected to rise for several months after the completion of rumen functionality, which is observed in the plots of Figure 11.6. However, it is acknowledged that the interpretation proposed here is somewhat speculative. Again, this is an area of research that would benefit from a much larger study of modern animals with known histories.





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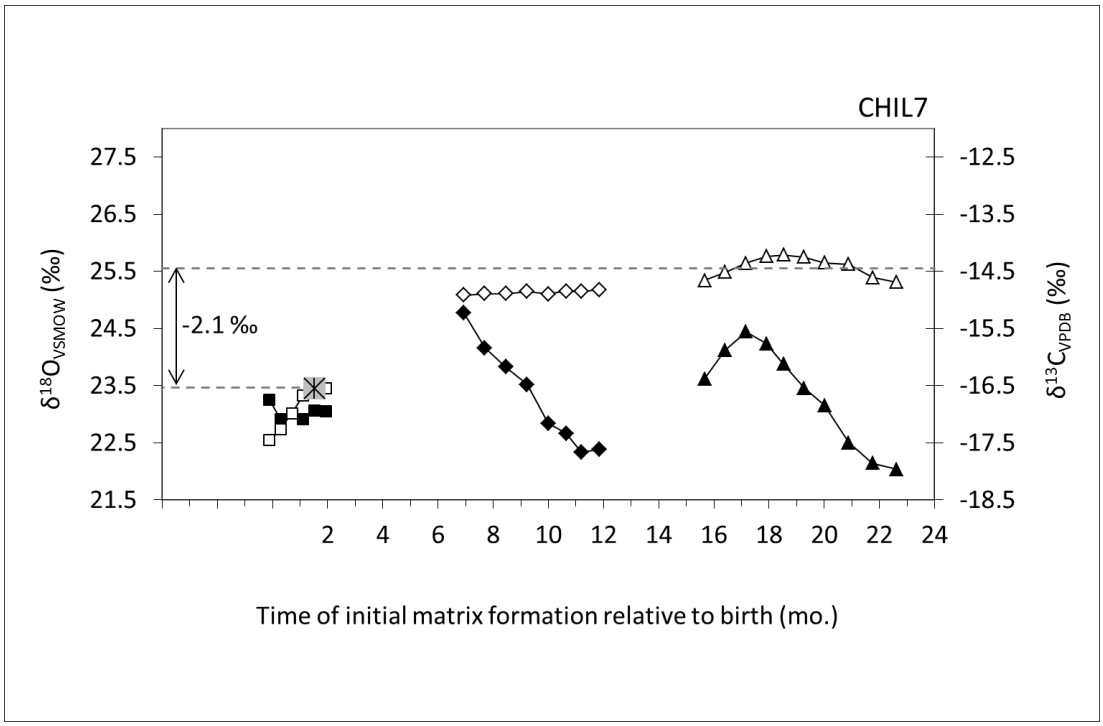
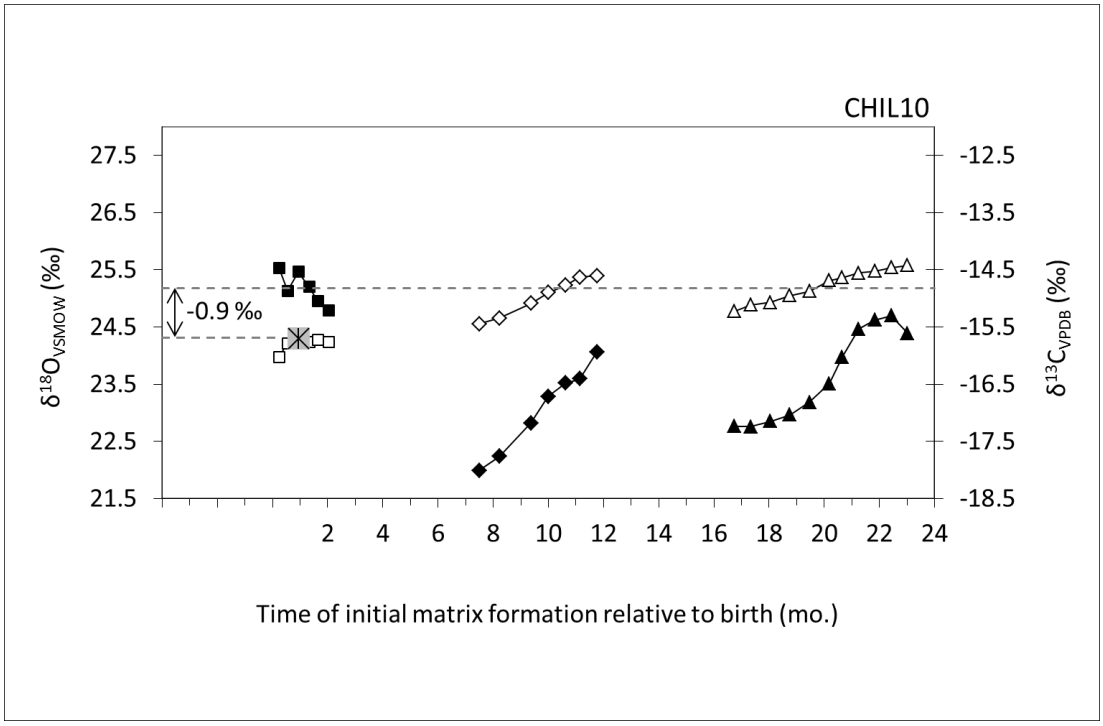




M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon

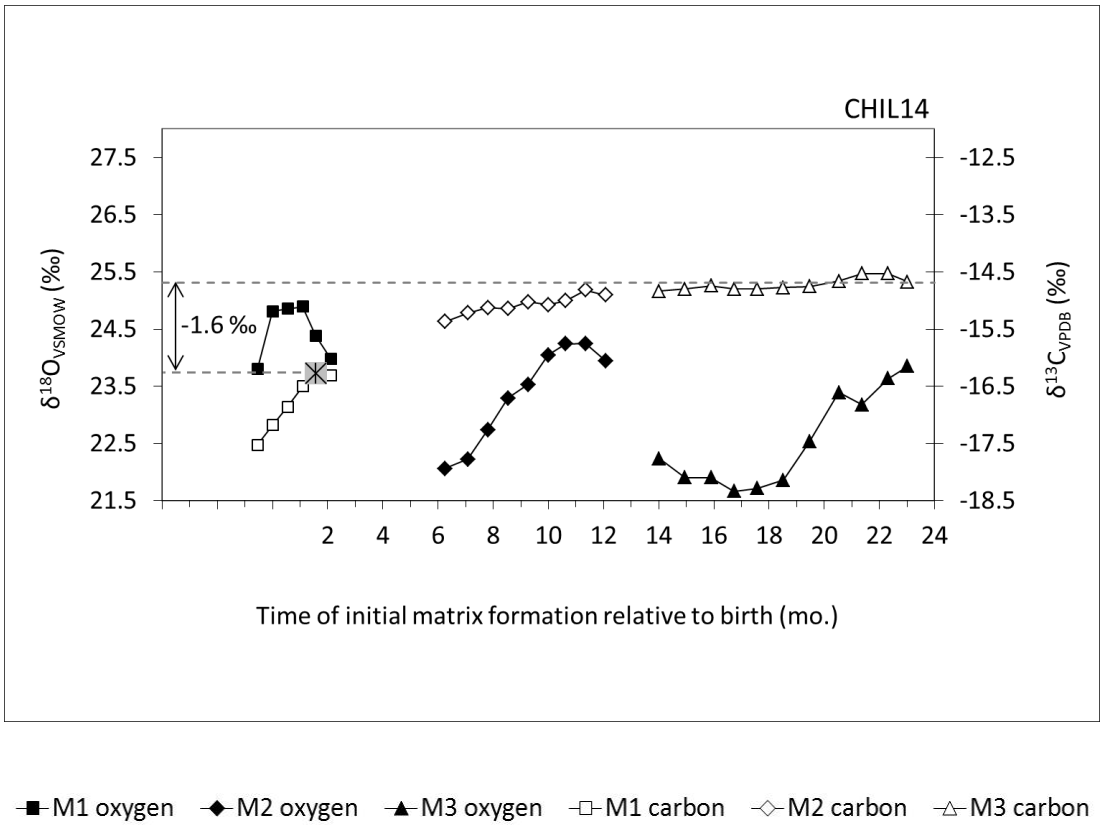


Figure 11.6: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from five Chillingham cattle. The grey crossed square symbol indicates the change in gradient of the enamel profile. The upper dashed line indicates the mid-range $\delta^{13}C$ value for third molar enamel. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

11.3 Relationship between intra-tooth $\delta^{13}C$ profiles and food $\delta^{13}C$ values

11.3.1 The Dexter bull (KAR)

The $\delta^{13}C$ values of the various dietary components of the Dexter bull (KAR) and the intra-tooth $\delta^{13}C$ profiles obtained from his enamel and dentine collagen are displayed in Figures 11.7 and 11.8 respectively. The Dexter's diet was related to location. Also included in Figure 11.8 are the three locations where he was raised: he was born at High Stoop; turned out to pasture there at 25 days old; relocated to pasture at Stanhope at 3½ months of age; and finally housed at Dapple Farm from 9 months of age. Comparison between the dentine collagen $\delta^{13}C$ profile in Figure 11.8 and the food values in Figure 11.7 suggests that the first molar coronal profile does not straightforwardly reflect the animal's food. As was discussed in Section 11.1, the first molar $\delta^{13}C$ profile would have been influenced by the averaging effect of

dentine formation and, perhaps, the act of suckling in addition to any change in the $\delta^{13}C$ values of the dietary components themselves. There is also a possibility that the $\delta^{13}C$ values measured for the food are not representative of what was actually eaten. Certainly, the study would have benefitted from more extensive sampling in this respect. Nevertheless, the dentine collagen $\delta^{13}C$ profiles recorded in the first molar root and second molar root do appear to reflect more closely changes in the $\delta^{13}C$ values of the animal's diet which increase between High Stoop vegetation and Stanhope vegetation, and between Stanhope vegetation and Dapple Farm fodder, of which barley feed was reported to be a significant component (Gidney, pers comm). The x-axis of Figure 11.8 corresponds to the timing of *initial* dentine formation whereas the y-axis represents the average $\delta^{13}C$ value of dentine collagen formed *subsequently*. Therefore, the $\delta^{13}C$ profile in Figure 11.8 suggests that the aforementioned dietary changes occurred between 2½ and 3 months of age and between 9 and 10 months of age, which corroborate sufficiently closely to the actual ages to be confident that the step changes in the dentine profile are indeed the result of relocation.

One interesting observation regarding the dentine collagen $\delta^{13}C$ profile is that the influence of Dapple Farm fodder is first evident in dentine that begins to form ~2-3 months before the relocation between Stanhope and Dapple Farm. This suggests that the 8-9 month period that a typical dentine intra-tooth sample takes to form through the build-up of growth layers, as proposed by Zazzo et al (2006) for second molar coronal dentine, does not apply to root dentine. If each intra-tooth sample did not represent the full thickness of the root, either because the root was incomplete or because of the sampling process itself, then the time period represented by each sample would be reduced. However, in this case, the first molar root of the Dexter was complete and all intra-tooth samples incorporated dentine from the outer surface to the pulp cavity. Thus, it appears that an increase in temporal resolution may be achieved through intra-tooth sampling of molar roots. The step-like pattern is not visible in the second molar enamel $\delta^{13}C$ profile. If an enamel intra-tooth sample takes ~6-7 months to mineralize, as proposed by Balasse (2002), then the period of time spent at Stanhope, 5½ months, is not

resolvable and the $\delta^{13}C$ profile will take the form of a continuously rising slope. In addition, the rise in the second molar profile may be related to weaning, an idea proposed to explain the offset between the first and third molar enamel values for the enamel $\delta^{13}C$ profiles of the Chillingham cattle (Section 11.2). Certainly, this Dexter calf remained with its mother and had access to her milk until relocation to Dapple Farm at the age of 9 months. Therefore, he would have experienced gradual weaning over a period of several months similar to the Chillingham animals.

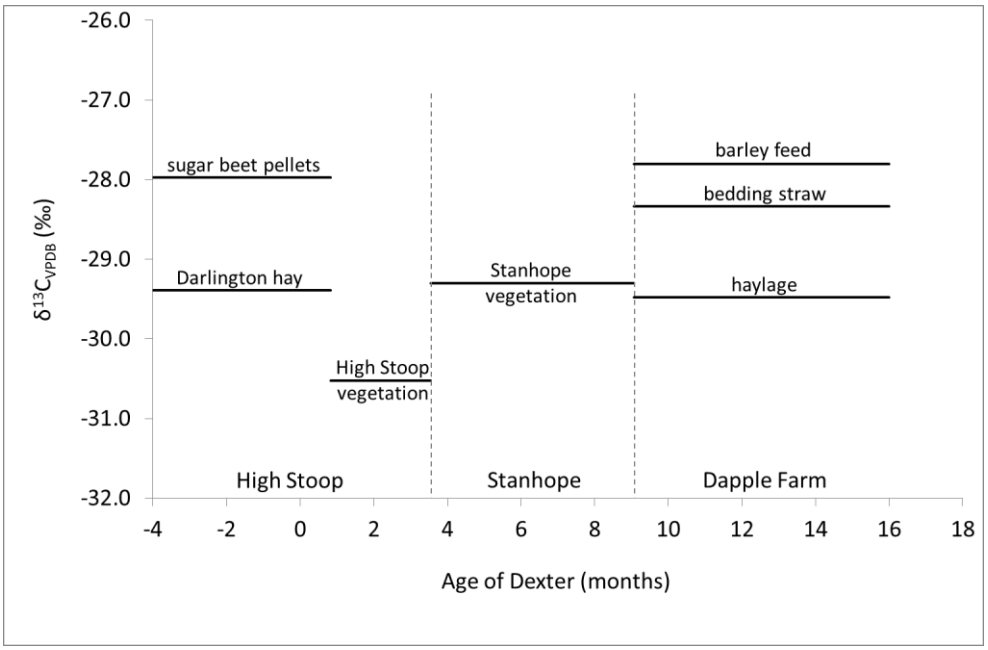


Figure 11.7: $\delta^{13}C$ values for Dexter's dietary components. The animal spent time in three locations: High Stoop, Stanhope and Dapple Farm. Analytical error is ± 0.2 ‰ (1σ) for $\delta^{13}C_{VPDB}$.

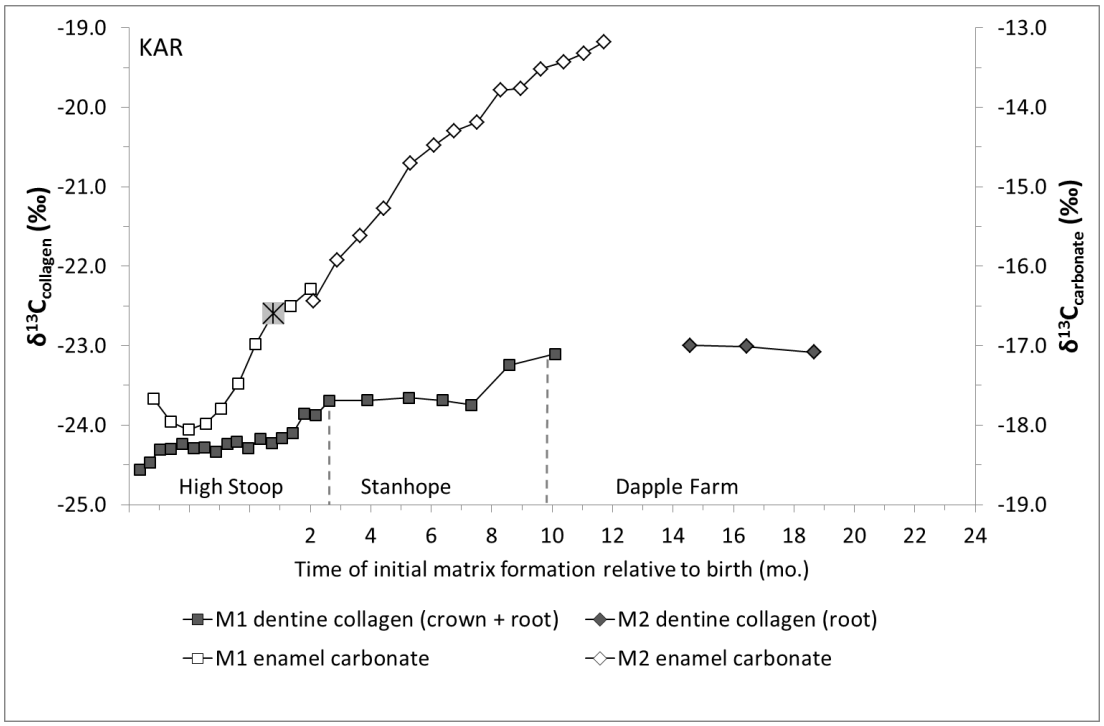


Figure 11.8: Enamel and dentine $\delta^{13}C$ profiles for the modern Dexter bull (KAR). The grey crossed square symbol indicates the change in gradient of the enamel profile. The animal spent time in three locations: High Stoop, Stanhope and Dapple Farm. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{carbonate}$ and ± 0.2 ‰ for $\delta^{13}C_{collagen}$.

11.3.2 The Chillingham cattle

With the exception of $\delta^{13}C$ patterning within the first molar crown, the intra-tooth enamel and dentine collagen $\delta^{13}C$ profiles of the two Chilllingham cattle shown in Figures 11.1 and 11.2, CHIL1 and CHIL14, generally display a similarity of form. The enamel data of CHIL1 follow a sinusoidal-like profile which is reflected in the dentine collagen data, whereas the profiles of CHIL14 show little variation, apart from the increasingly negative dentine collagen values recorded in the latest forming part of the second molar root, a trend not replicated in the third molar enamel data. The cause of this difference in the two CHIL14 profiles is possibly due to the approximate nature of the molar formation parameters used to construct the profiles, or a mismatch in timing and/or resolution resulting from the different averaging processes occurring during enamel maturation and dentine formation.

A comparison between the enamel $\delta^{13}C$ and $\delta^{18}O$ profiles of animal CHIL1 shows that they co-vary (Figure 11.6), suggesting that the sinusoidal-like patterning in the $\delta^{13}C$ profile is seasonally influenced. A similar correlation between the $\delta^{13}C$ and $\delta^{18}O$ profiles of CHIL6, CHIL10 and the third molar of CHIL7 is 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) (Figure 5.3). 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 in Section 9.1.1. The seasonal mean values calculated for all Chillingham vegetation samples suggest a summer to winter difference of ≥ 0.9 ‰ (Figure 9.2). This figure is generally consistent with the smaller maximum to minimum differences (approximately 0.5-0.8 ‰) in the enamel $\delta^{13}C$ profiles. It is expected that, due to the mineralization process of enamel, the amplitude of the $\delta^{13}C$ profile would be reduced compared to that of the vegetation. However, the two sets of data, from enamel and vegetation, are not directly comparable. Summer to winter differences in vegetation $\delta^{13}C$ values can vary from year to year and none of the cattle enamel was formed during 2010-2011, when the vegetation samples were collected. In addition, interpretation is complicated by the fact that hay is provided for the Chillingham cattle through the winter months. During that period, hay may constitute between approximately one half to two thirds of what an animal eats in total depending upon the severity of the weather (Leyland, pers comm). Unfortunately, the enamel analysed in this study was forming at a time when hay was sourced from outside Chillingham Park and it has not been possible to obtain representative samples for analysis. However, if the $\delta^{13}C$ value of the hay were more positive than the mean $\delta^{13}C$ winter value of the Chillingham Park vegetation, then consumption of hay during the winter would act to reduce the amount of variation in the $\delta^{13}C$ profiles recorded in mineralizing enamel. It is possible that the unvarying $\delta^{13}C$ profiles of CHIL14 and the second molar of CHIL7 reflect this. Alternatively, they may represent years when mean $\delta^{13}C$ values of vegetation varied very little or, perhaps, they relate to a particular feeding behaviour where the sequence of vegetation types and feeding locations

throughout the year did not produce a seasonal pattern similar to the mean values presented in Figure 9.2.

11.4 Summary

Despite the limitations of the modern cattle included in this study (e.g. the small number of individuals, the lack of knowledge regarding the Chillingham animals' dates of birth and the worn nature of their molars) and the somewhat speculative nature of the discussions above, comparisons between enamel and dentine collagen intra-tooth $\delta^{13}C$ profiles and between enamel $\delta^{13}C$ and $\delta^{18}O$ profiles do allow the following important observations to be made:

1) The shape of the first molar $\delta^{13}C$ profile recorded in enamel appears to be heavily influenced by methanogenesis resulting from ruminal digestion, and the noticeable rise in $\delta^{13}C$ values towards the cervical enamel is thought to represent the transition between purely non-ruminant digestion immediately after birth (relatively low $\delta^{13}C$ values) and the utilisation of a fully formed rumen (relatively high $\delta^{13}C$ values) several weeks later. It is proposed that the reduction in gradient indicates the completion of rumen functionality at the age of ~6-10 weeks. Consequently, this feature of the $\delta^{13}C$ profile may also be an indirect indication of birth, and its role as the basis of a possible new method to estimate cattle birth seasonality is explored in Section 12.3. The method is then applied to the archaeological cattle molars from the Northern Isles and Grimes Graves and the results discussed in Chapter 13.

2) For the Chillingham cattle, the rise in enamel $\delta^{13}C$ values continues for several months after the completion of rumen functionality such that there is a significant offset between the $\delta^{13}C$ value at which the first molar enamel $\delta^{13}C$ profile reduces in gradient and the $\delta^{13}C$ values recorded in third molar enamel. It is suggested that this is related to the process of natural weaning whereby the proportion of milk in the diet gradually decreases and the proportion of vegetation increases, resulting in an increasing contribution of enriched CO_2 in the bloodstream from methanogenetic fermentation in the rumen. If this explanation is true, then enamel

$\delta^{13}C$ profiles from cattle fully weaned at an early age through human intervention, perhaps close to the time the rumen becomes fully functional at 6-10 weeks, would be expected to show little difference between the $\delta^{13}C$ value at which the first molar enamel $\delta^{13}C$ profile reduces in gradient and the $\delta^{13}C$ values recorded in third molar enamel. Thus, investigation of weaning strategy for archaeological cattle may be possible through the measurement of such offsets. Knowledge of weaning strategy would aid interpretation regarding economic goal since calves raised for meat might be expected to suckle their mothers for a longer period of time than the calves of milk cows.

3) Seasonal variation in the $\delta^{13}C$ values of pasture, with more positive values in summer and more negative values in winter, is expected to produce a sinusoidal-like $\delta^{13}C$ profile in post weaning enamel that co-varies with the $\delta^{18}O$ profile. However, it is unlikely to be the only explanation for a sinusoidal-like $\delta^{13}C$ profile recorded in enamel. It is speculated that the provision of fodder in the winter may act to reduce the amount of variation in the $\delta^{13}C$ profiles recorded in mineralizing enamel if the $\delta^{13}C$ value of the fodder is more positive than the mean winter value of the pasture.

4) It is possible that intra-tooth isotope ratio analysis of dentine collagen samples extracted from molar roots produces $\delta^{13}C$ profiles with higher temporal resolution than profiles recorded in coronal dentine or enamel. However, applying this type of sampling and analysis to the archaeological cattle molars from the Northern Isles and Grimes Graves is beyond the scope of this study.

12 Possible methods to estimate cattle birth seasonality

In this chapter, three different methods to estimate cattle birth seasonality, i.e. the distribution of births throughout the year, are described and assessed. All are based on the patterning of intra-tooth isotopic data recorded within cattle molar enamel. For comparative purposes, the three methods are applied to data collected during this study from 13 archaeological cattle (five Pool animals, three Mine Howe animals and five Grimes Graves animals), selected because they include isotopic data from first molars. Although the first two methods described are based on $\delta^{18}O$ profiles recorded in second and third molar enamel (Sections 12.1 and 12.2), the third method, newly proposed by this study, depends upon the patterning of both $\delta^{18}O$ and $\delta^{13}C$ in first molar enamel (Section 12.3). Parts of this chapter are to be published in Towers et al (in press).

12.1 Method 1: using plots of second and third molar $\delta^{18}O$ data versus distance from the cervix with a normalisation procedure suggested by Balasse et al (2012a, 2012b)

This method is an adaptation of the basic method used in the earliest attempts to infer cattle birth seasonality from intra-tooth $\delta^{18}O$ data (e.g. Balasse et al 2003, Balasse and Tresset 2007) (Section 5.1.2). In each of those studies, the second or third molar $\delta^{18}O$ data of several animals from an archaeological site were plotted versus distance from the cervix. Birth seasonality, assessed through visual inspection, depended upon whether a particular feature of the sinusoidal-like $\delta^{18}O$ profiles, for example a minimum or maximum, occurred at a similar distance from the cervix, indicating a restricted season of birth, or was distributed more widely. To draw conclusions through such direct comparison implicitly assumed that the rate of crown formation did not vary between different animals. No attempt was made in such studies to calculate the temporal distribution of births throughout the year.

Second molar intra-tooth $\delta^{18}O$ data collected from the 13 selected cattle from Pool, Mine Howe and Grimes Graves are shown superimposed onto the same plot in

Figure 12.1. The equivalent data for third molars are shown in Figure 12.2. In both plots the $\delta^{18}O$ minima occur at a wide range of distances from the cervix, which would suggest an extended rather than restricted calving season if these animals belonged to the same herd.

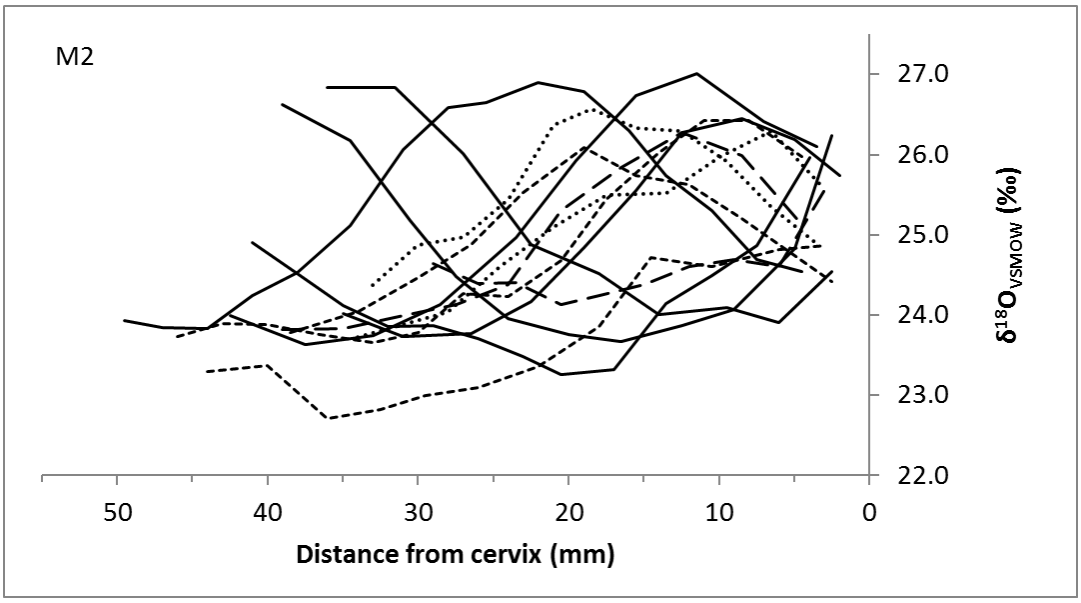


Figure 12.1: Second molar enamel $\delta^{18}O$ versus distance from cervix for 13 archaeological cattle. Analytical error is ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$. The different line styles are used to improve the clarity of the plot and do not represent different archaeological sites.

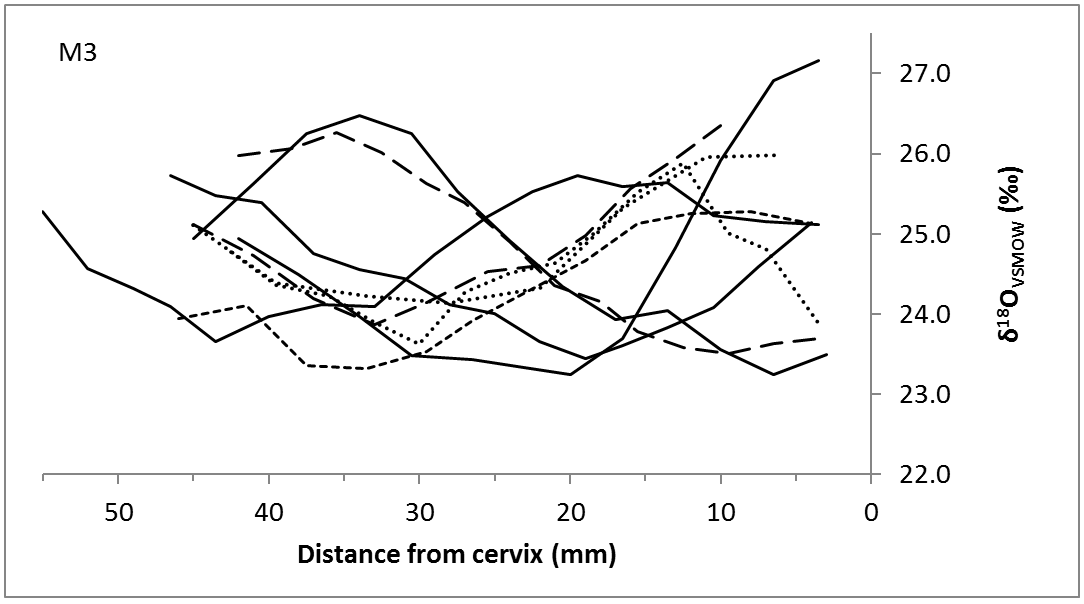


Figure 12.2: Third molar enamel $\delta^{18}O$ versus distance from cervix for 13 archaeological cattle. Analytical error is ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$. The different line styles are used to improve the clarity of the plot and do not represent different archaeological sites.

In order to calculate the distribution of births in months, the position in mm along the molar crown for each $\delta^{18}O$ minimum (or maximum) would need to be determined and the separation between the two extreme values converted to time. This would require knowledge of the rate of molar formation for each animal, calculated from the initial unworn crown height of each molar, which is not always directly measureable due to wear, and the duration of crown formation. Both crown height and duration of crown formation will vary between cattle. In addition, there may be intra-tooth variability in the rate of formation in terms of varying rates of enamel matrix formation or maturation along the crown.

A method to correct for inter-animal variability in molar growth rate by modelling the sinusoidal isotopic pattern and normalising to period has been proposed by Balasse et al (2012b). Modelling of cattle molars by Balasse et al (2012a) suggests that intra-tooth variability in the rate of formation may be insignificant. Hence, a simplified equation to model the sinusoidal pattern, proposed by Balasse et al (2012a), is applied to the data from Pool, Mine Howe and Grimes Graves molars. The procedure begins by fitting a cosine curve to each $\delta^{18}O$ profile using the equation:

$$\delta^{18}O = M + Y.\cos(2\pi.(x-x_0)/X) \qquad \text{(from Balasse et al 2012a)}$$

where

$M\ (\text{mean}) = (\delta^{18}O_{max} + \delta^{18}O_{min})/2$ (in ‰)

$Y\ (\text{amplitude}) = (\delta^{18}O_{max} - \delta^{18}O_{min})/2$ (in ‰)

x is the distance from the cervix (in mm)

x_0 is the distance between the $\delta^{18}O$ maximum and the cervix (in mm)

X is the period of the cosine curve (in mm)

These parameters are shown schematically in Figure 12.3 together with x_1, the distance in mm between the position of the $\delta^{18}O$ minimum and the cervix. Figure 12.4 shows the $\delta^{18}O$ data for each second and third molar from the 13 selected cattle together with best fit cosine curves. Each curve was fitted by the method of least squares, as proposed by Balasse et al (2012b), in which the sum of the squared discrepancies between the cosine curve and the measured data were minimized by iteratively adjusting the parameters x_o and X.

To allow comparison between method 1 and method 2 (Section 12.4), the position of the $\delta^{18}O$ minimum for each molar, x_1 must be calculated. Once the cosine curve has been fitted, x_1 is calculated as follows:

$$x_1 = x_0 \pm X/2 \qquad \text{(in mm)}$$

The addition or subtraction of X/2 depends on the order in which the $\delta^{18}O$ maximum and minimum fall within the molar crown. In terms of time, the value of X is assumed to represent 12 months. Thus, t_1, the time difference between the $\delta^{18}O$ minimum and the cervix, may be calculated using the following equation:

$$t_1 = 12x_1/X \qquad \text{(in months)}$$

The timing of each $\delta^{18}O$ minimum relative to birth is calculated using the mid-range timings of cervix formation given by Brown et al (1960), 12.5 months for second molars and 23.5 months for third molars.

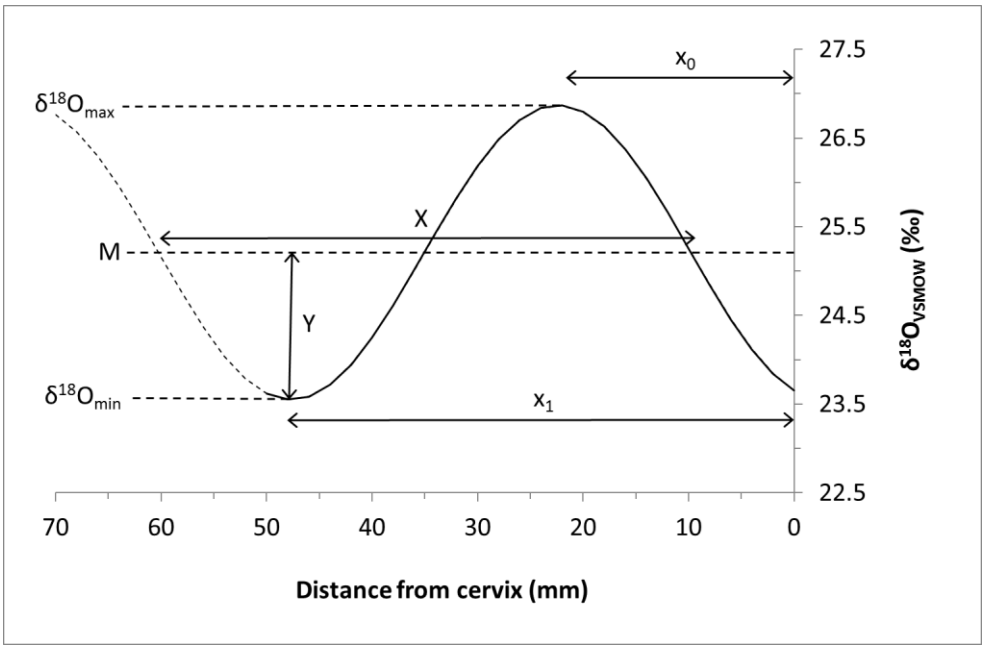
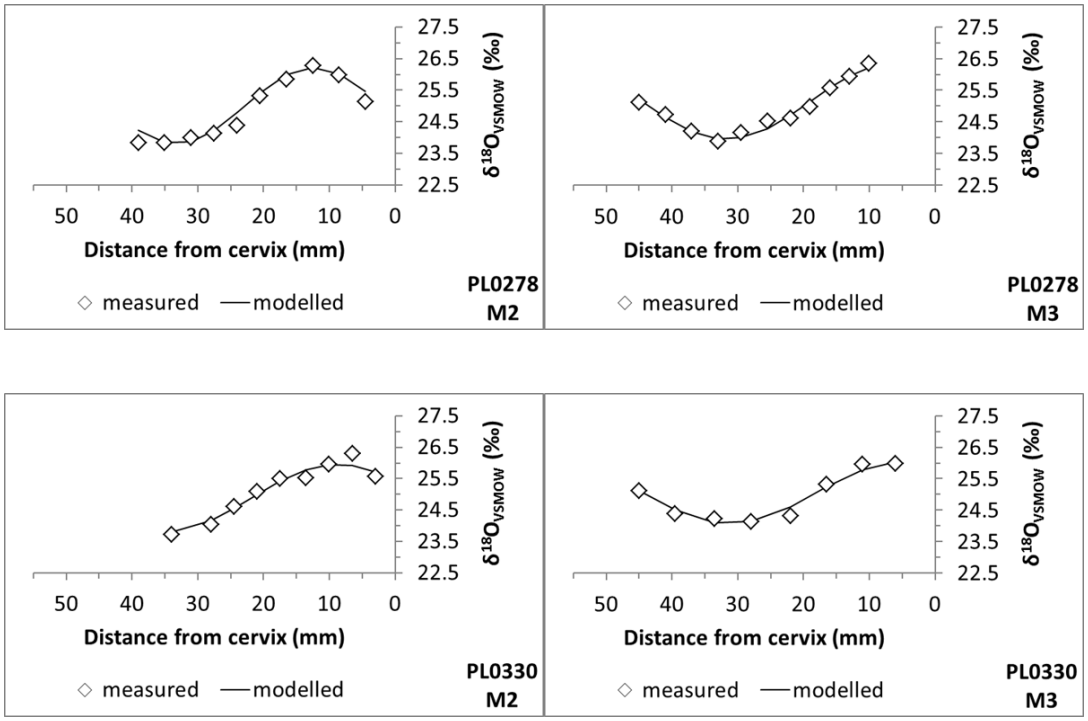
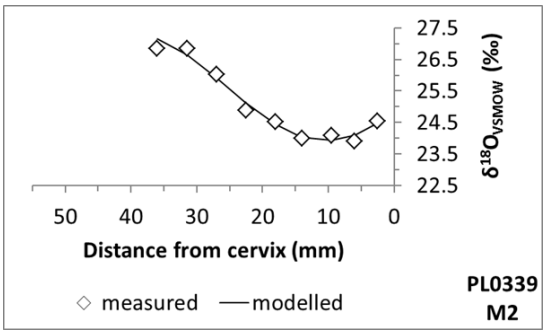


Figure 12.3: The parameters of the cosine curve fitted to each $\delta^{18}O$ profile.

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26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
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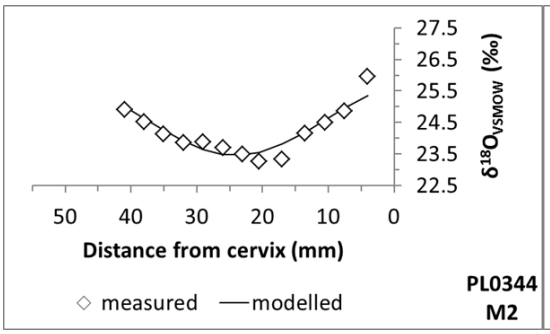
Distance from cervix (mm)
◇ measured —modelled
PL0339
M2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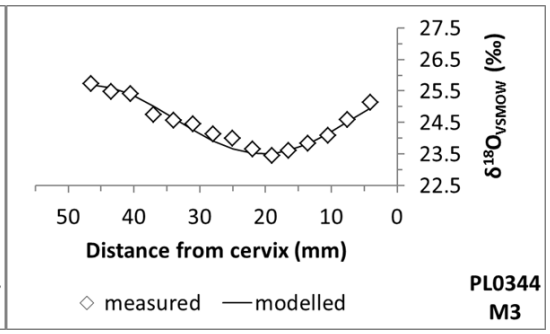
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
◇ measured —modelled
PL0344
M2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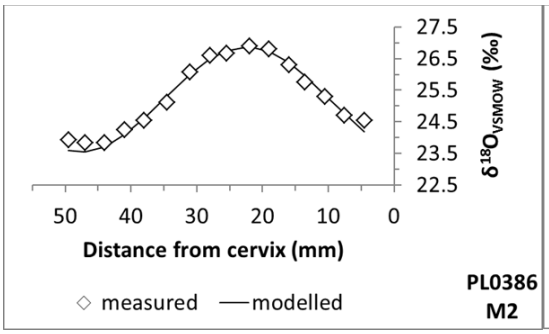
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
◇ measured —modelled
PL0344
M3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23.5
22.5
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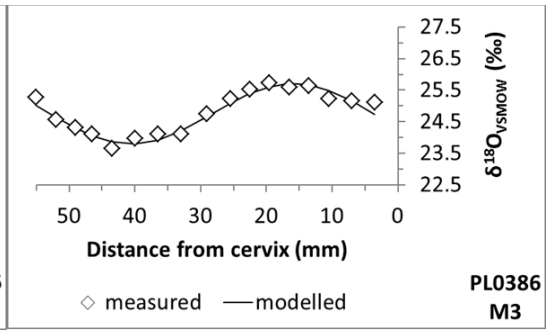
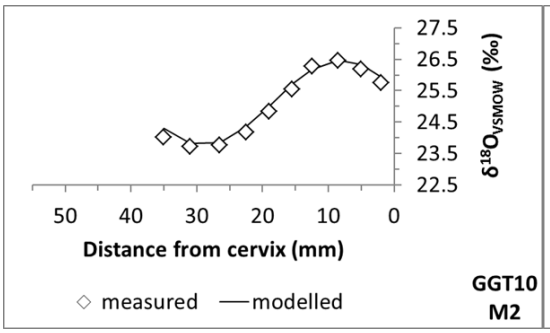
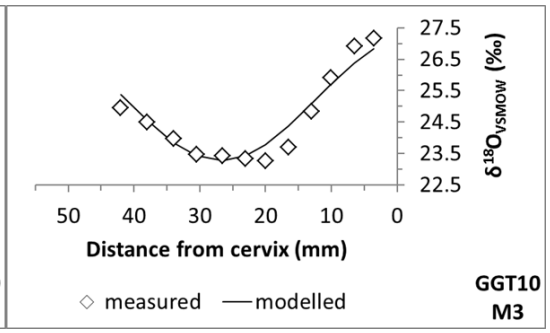
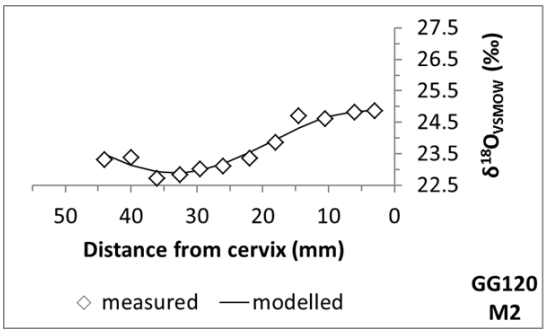
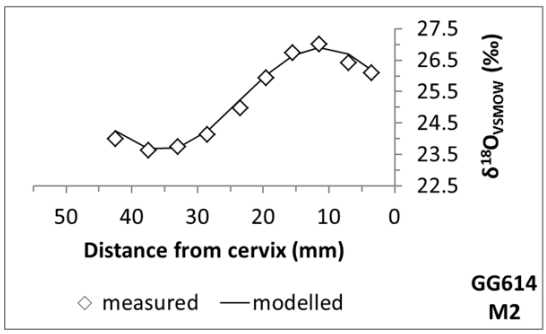
Distance from cervix (mm)
◇ measured —modelled
PL0386
M2


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
◇ measured —modelled
PL0386
M3


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
◇ measured —modelled
GGT10
M2


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
◇ measured —modelled
GGT10
M3


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
measured
modelled
GG120
M2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22.5
δ18OVSMOW (‰)
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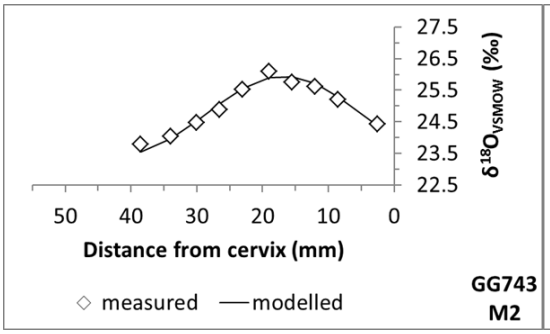
Distance from cervix (mm)
measured
modelled
GG614
M2


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
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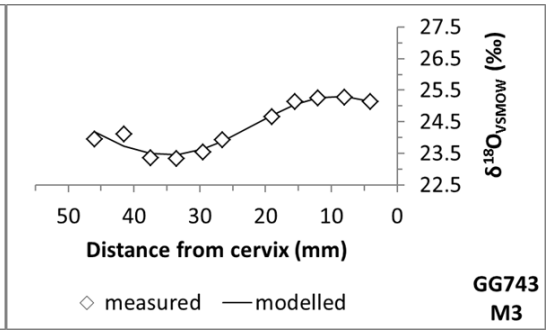
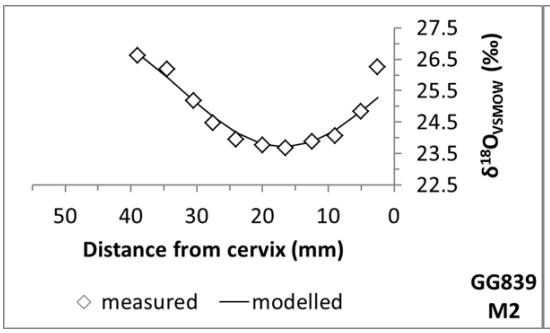
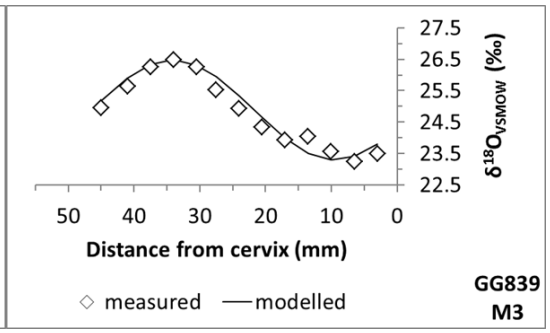
Distance from cervix (mm)
measured
modelled
GG743
M2


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
measured
modelled
GG743
M3


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
measured
modelled
GG839
M2


27.5
26.5
25.5
24.5
23.5
22.5
δ18OVSMOW (‰)
50 40 30 20 10 0
Distance from cervix (mm)
measured
modelled
GG839
M3

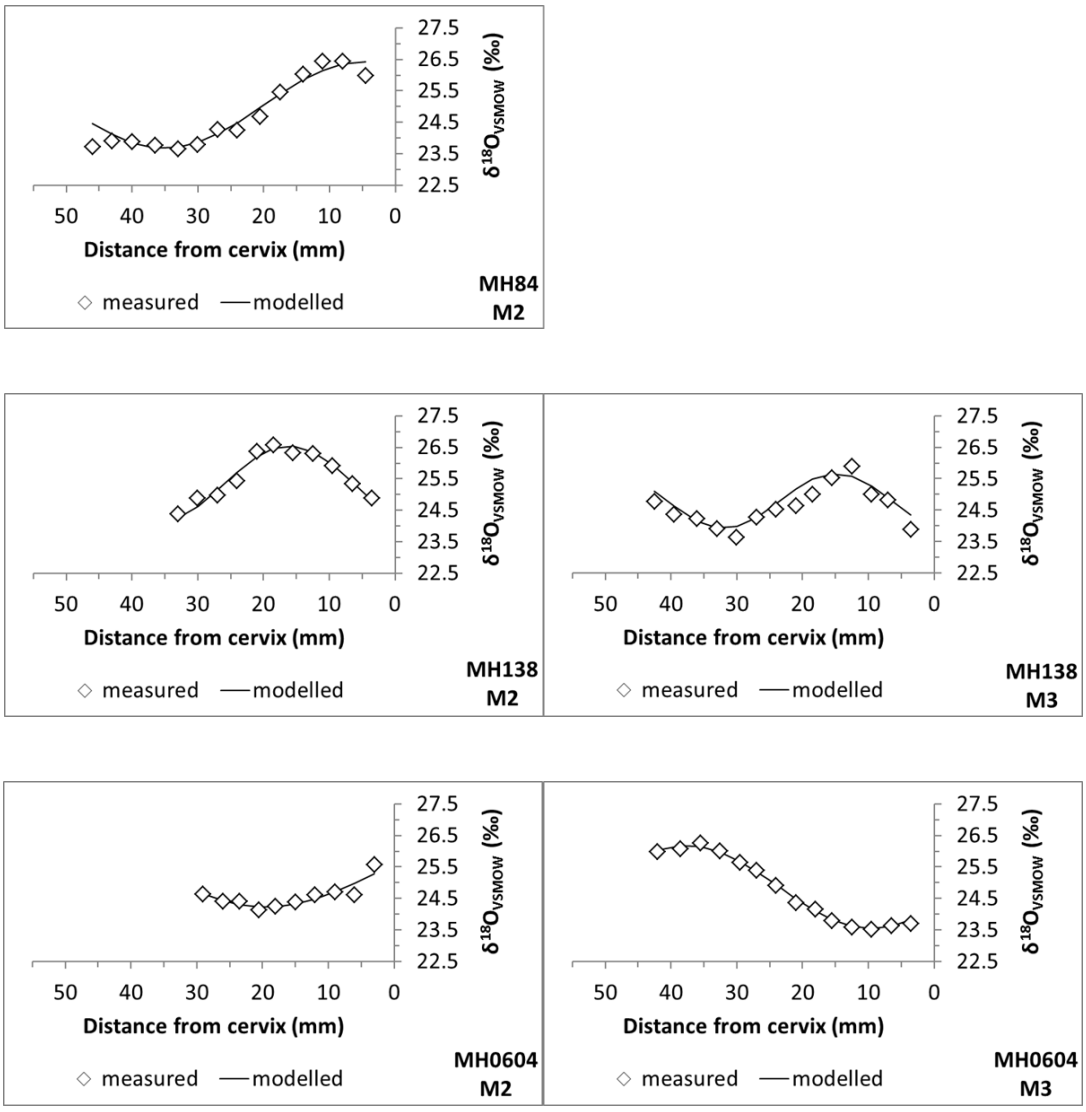


Figure 12.4: Measured enamel $\delta^{18}O$ values for each second and third molar from the 13 selected cattle together with best fit cosine curves. Analytical error is ± 0.2 ‰ for measured values of $\delta^{18}O_{VSMOW}$.

Timings relative to birth for all 13 cattle are presented in Table 12.1, from which the distribution of births throughout the year may be calculated. Each timing will have uncertainty associated with it arising from the assumptions made during its calculation. Two principal components of uncertainty are: (1) the timing of cervix formation for second and third molars, described by Brown et al (1960) as "approximations"; and (2) variation in the period of the body's $\delta^{18}O$ *input* signal during enamel formation, dominated by the $\delta^{18}O$ values of precipitation and demonstrated by data from Wallingford, UK, (Darling and Talbot 2003). If a six month running average is applied to monthly rainwater $\delta^{18}O$ data collected from

Wallingford between 1985 and 1991 (crudely simulating the signal recorded in enamel), the temporal separation between neighbouring maxima (or minima) is variable (Figure 12.5). Over a 14 year period, between 1982 and 1996, the mean period was 12.0 ± 1.0 months (1σ). Thus, if the Wallingford data is typical for Britain, values of t_1 calculated assuming a 12 month period ($t_1 = 12x_1/X$) may be inaccurate by ≤ ± 1.0 month (1σ), depending on the magnitude of x_1/X. Therefore, although this method to estimate cattle birth seasonality does not require knowledge of the unworn crown height of each molar and the time taken for the molar to form, it does introduce uncertainty of its own. The uncertainty associated with the timing of a $\delta^{18}O$ minimum relative to birth will incorporate the uncertainty of t_1 and the uncertainty of the timing of cervix formation relative to birth.

Table 12.1: $\delta^{18}O$ minima timings determined by method 1.

	Predicted time after birth (months)	
Animal	**second molar $\delta^{18}O$ minimum**	**third molar $\delta^{18}O$ minimum**
PL0278	2.9	16.1
PL0330	4.5	16.3
PL0339	10.4	
PL0344	7.2	19.0
PL0386	1.2	13.6
GGT10	4.2	18.0
GG120	5.6	
GG614	3.8	
GG743	2.3	15.4
GG839	9.4	21.2
MH84	5.6	
MH138	1.6	12.3
MH0604	8.8	21.5

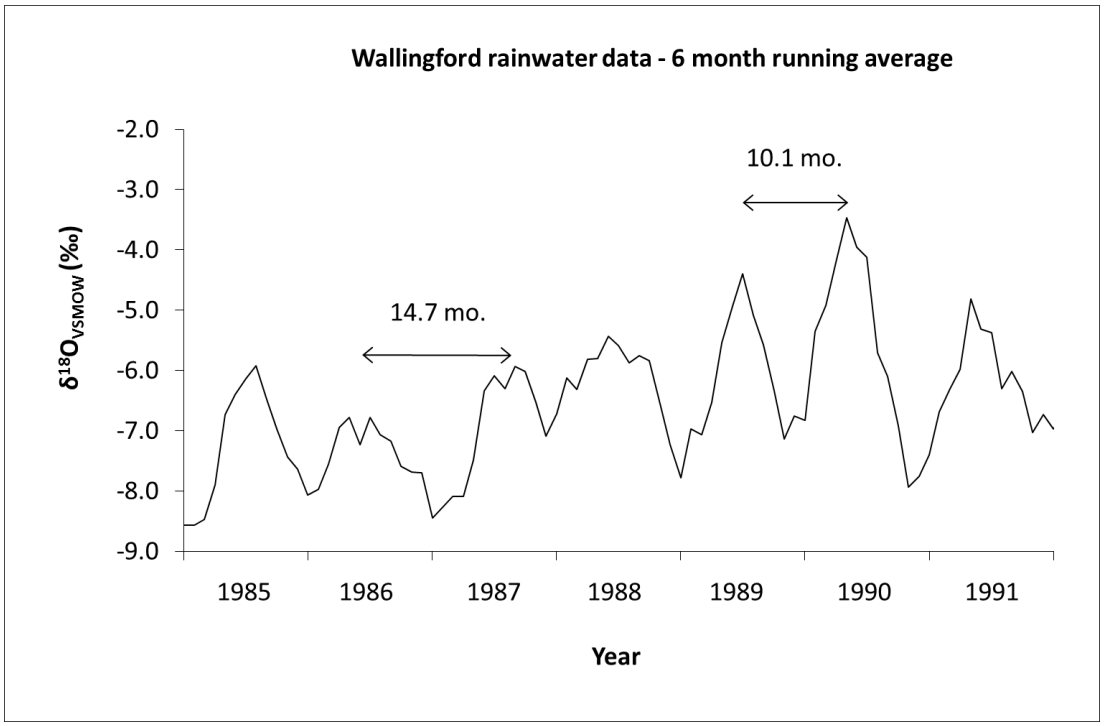


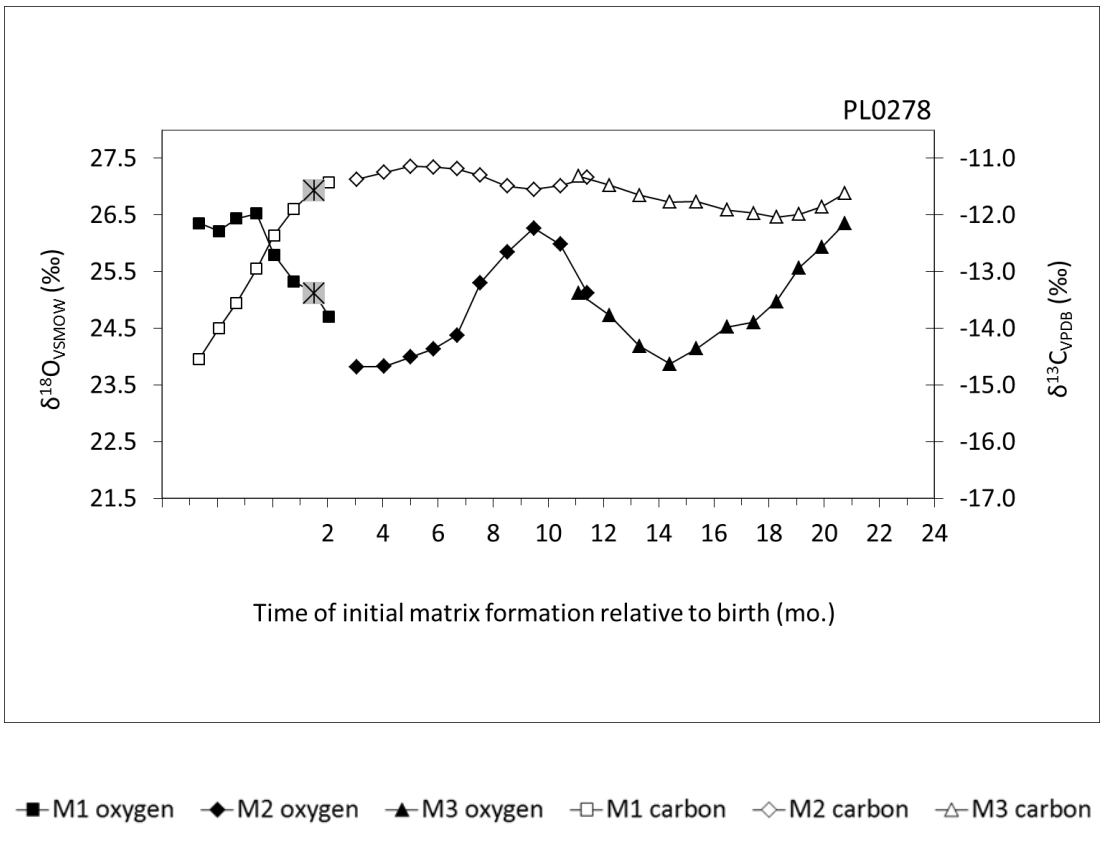
Figure 12.5: Rainwater $\delta^{18}O$ values from Wallingford, UK (data from Darling and Talbot 2003).

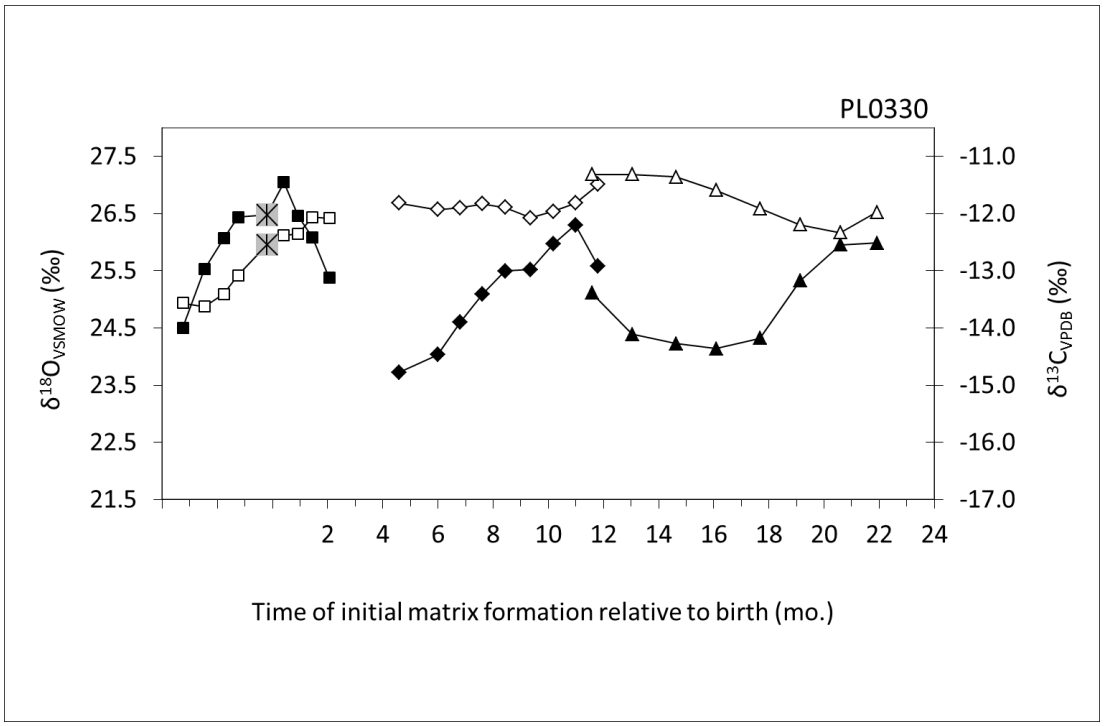
12.2 Method 2: using a combined plot of first, second and third molar $\delta^{18}O$ data versus time relative to birth

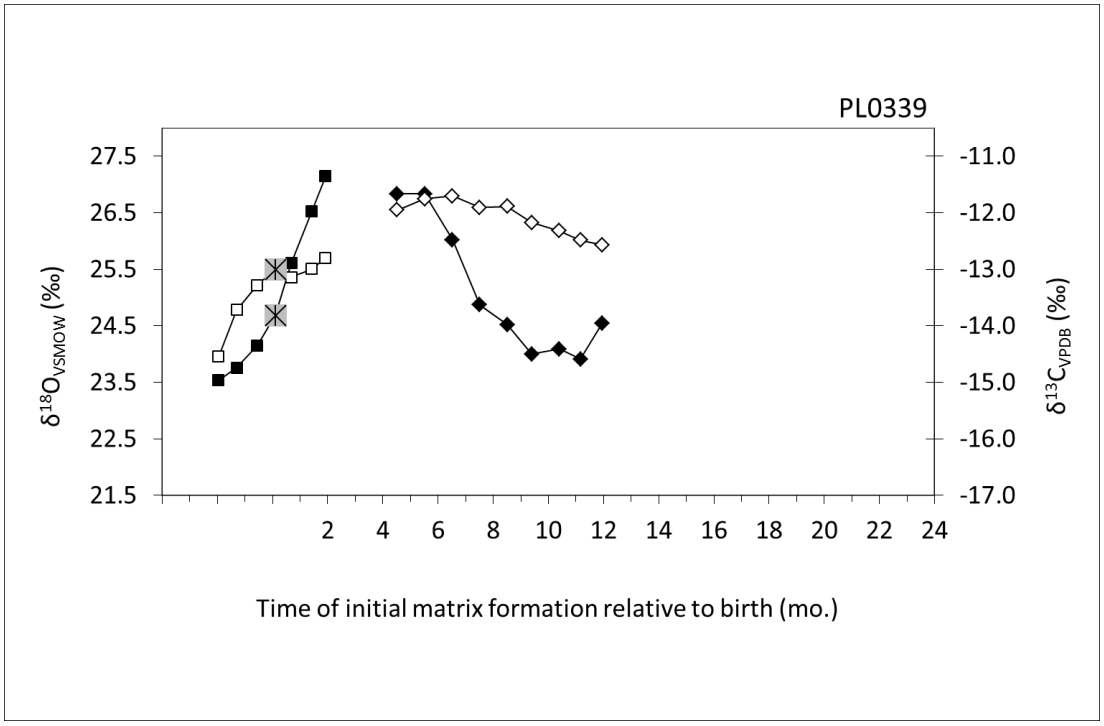
In this second method, intra-tooth $\delta^{18}O$ values are plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1. This procedure allows data from first, second and third molars from the same individual to be plotted on a common time-related x-axis. Plots for the 13 cattle from Pool, Mine Howe and Grimes Graves are shown in Figure 12.6. Intra-tooth $\delta^{13}C$ profiles are also included in the plots since they are essential for the third method to estimate cattle birth seasonality, described in Section 12.3. Selection of these particular cattle was based not only on the existence of first molar isotopic data, but also on the wear stages of their molars. For animals with first, second and third molars, their third molars were required to be at wear stages a-f because the wear stages of more worn molars depend on the accessory pillar height which can vary substantially between animals (Jones 2007), introducing more uncertainty to the conversion of distance from the cervix to time (Section 10.1). Similarly, for those animals without third molars, their second molars were required to be at wear

stages a-f. It is reiterated here that the timing of each intra-tooth data point represented in a plot of $\delta^{18}O$ or $\delta^{13}C$ versus time (its x-axis value) is related to the initial deposition of the enamel matrix, whereas the value of $\delta^{18}O$ or $\delta^{13}C$ (its y-axis value) is an average value of the completed enamel which took several subsequent months to mineralize following matrix deposition.

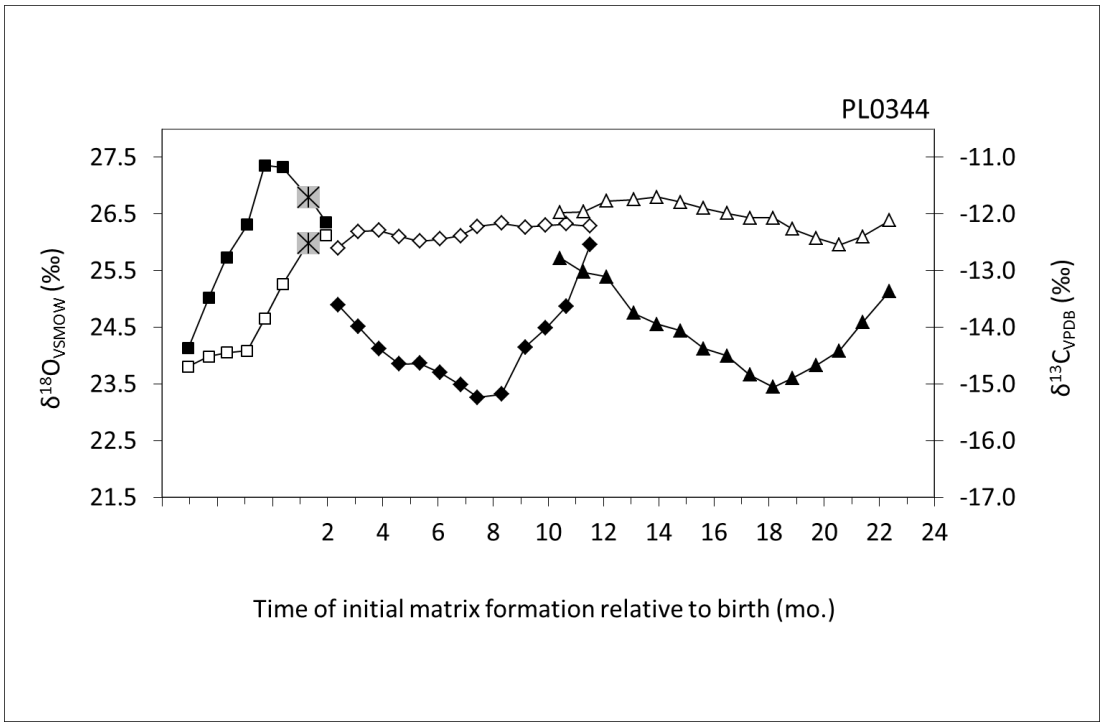
Despite the various assumptions used in the construction of the isotopic profiles, they appear to be continuous both in $\delta^{18}O$ and $\delta^{13}C$ and show little evidence of obvious discontinuity between molars (Figure 12.6). In each profile, the seasonal, sinusoidal-like variation in $\delta^{18}O$ is clearly visible. Generally, there is a minimum present in the second molar $\delta^{18}O$ profile (or straddling the first and second molar profiles), a second minimum present in the third molar $\delta^{18}O$ profile and a maximum falling between. The timing of each $\delta^{18}O$ minimum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3).







M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon


PL0344
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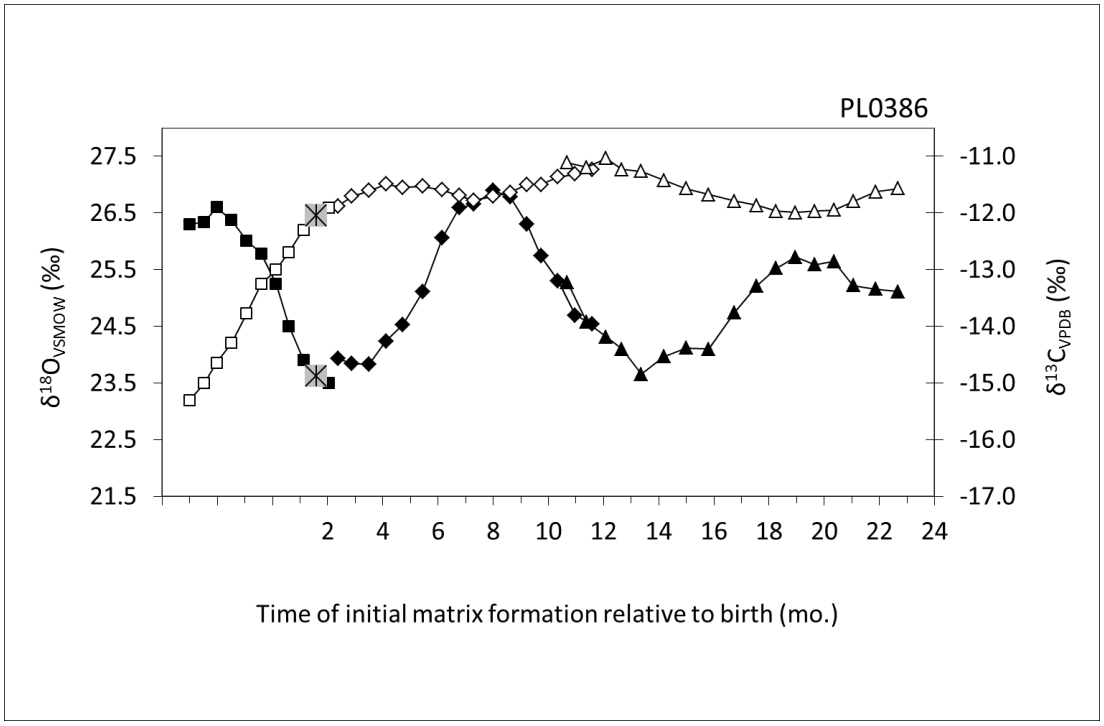
26.5
25.5
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2 4 6 8 10 12 14 16 18 20 22 24
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)


PL0386
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26.5
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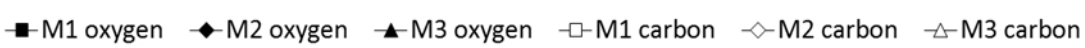
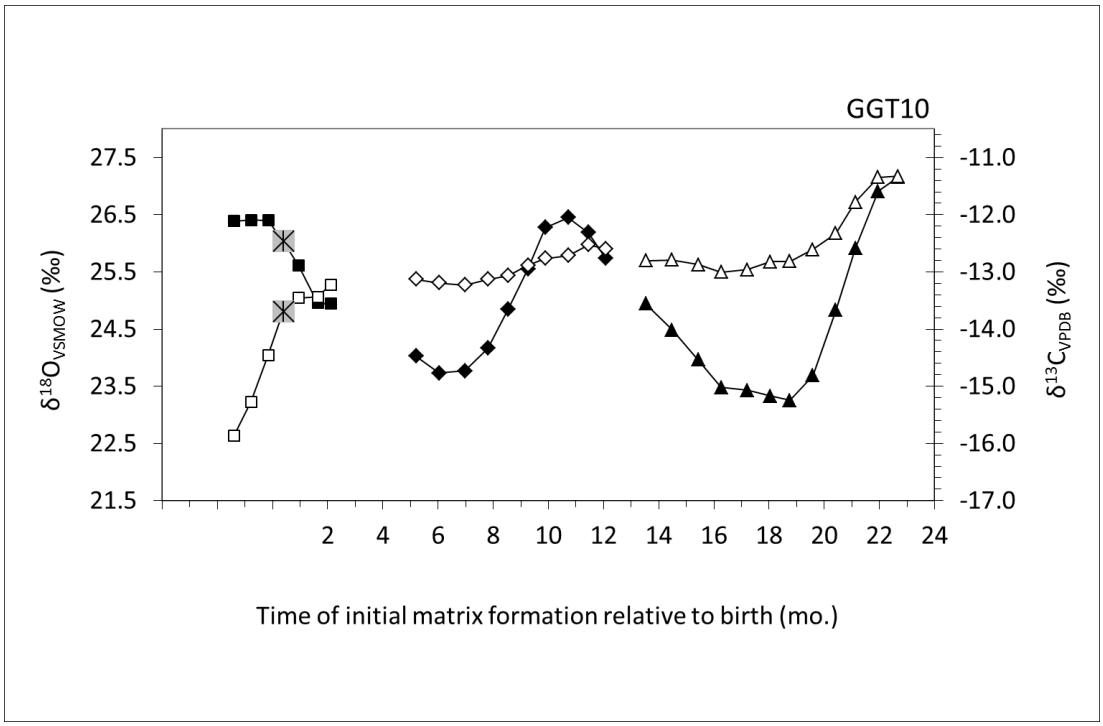
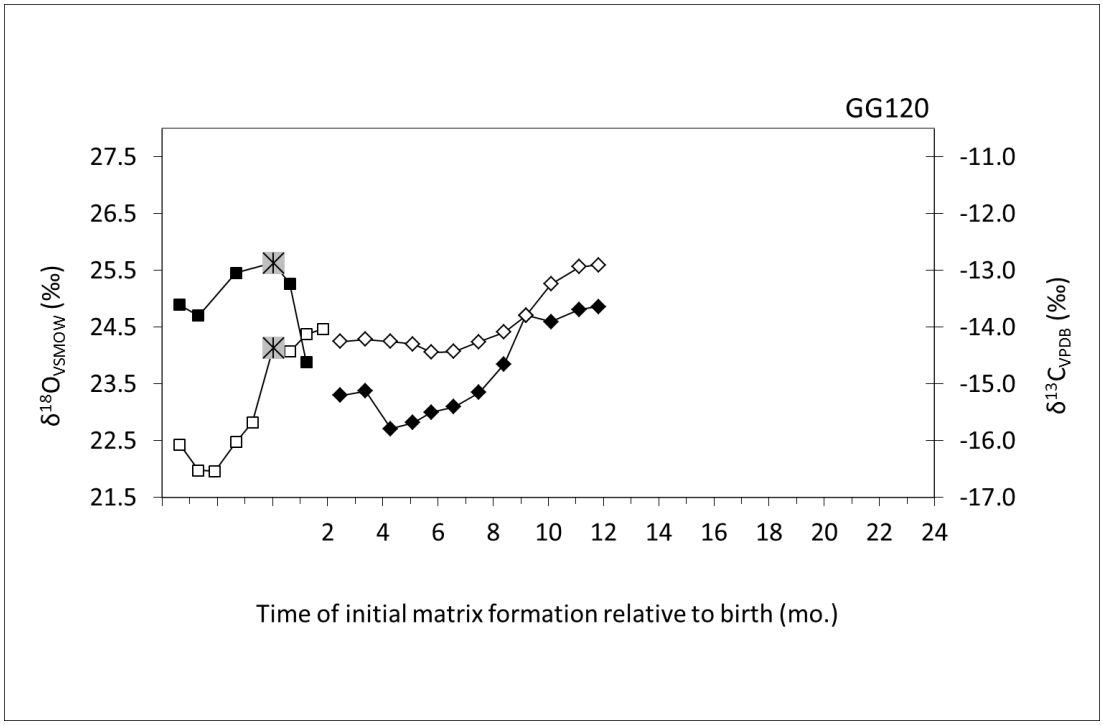
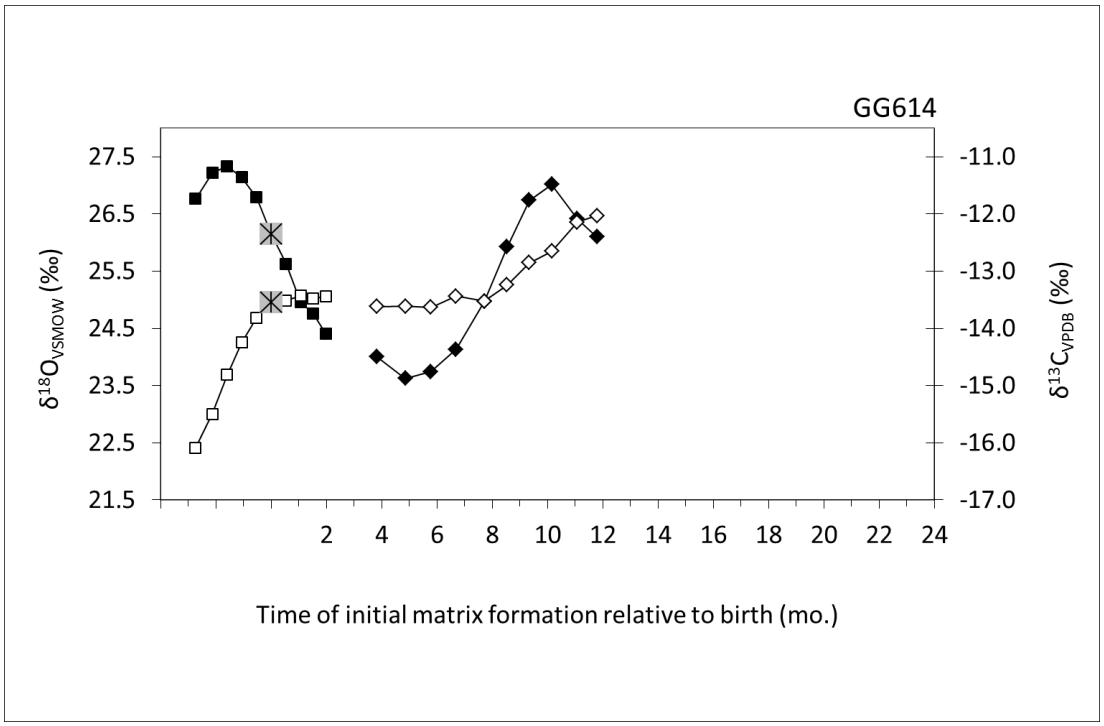
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2 4 6 8 10 12 14 16 18 20 22 24
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)

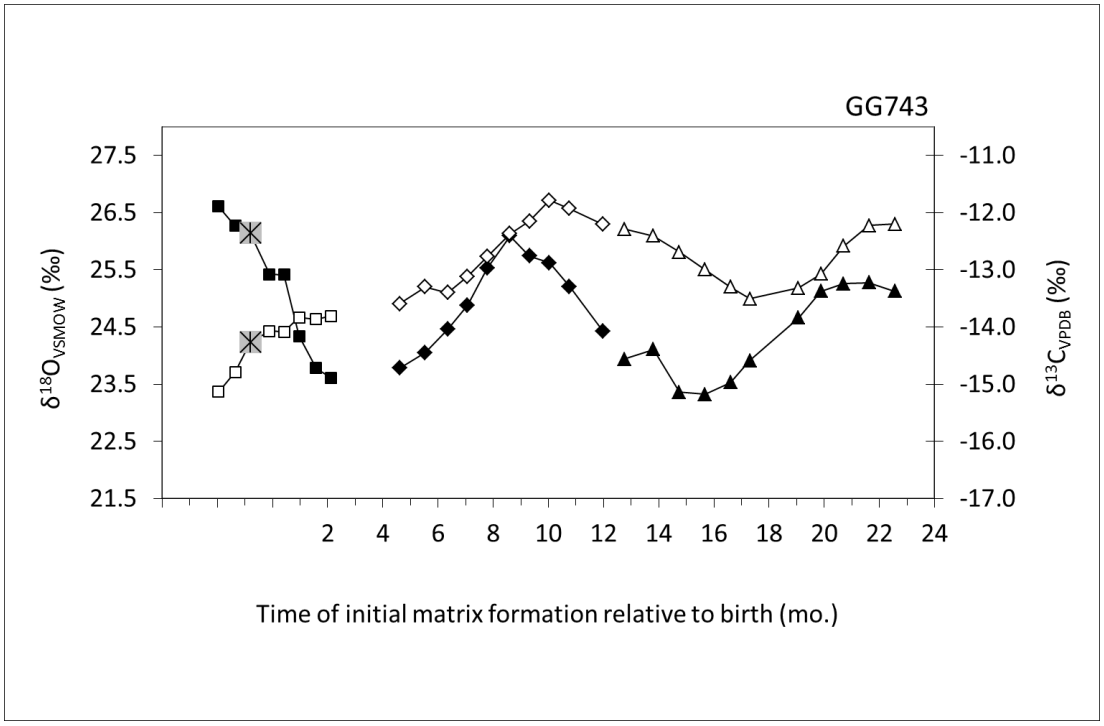

M1 oxygen
M2 oxygen
M3 oxygen
M1 carbon
M2 carbon
M3 carbon



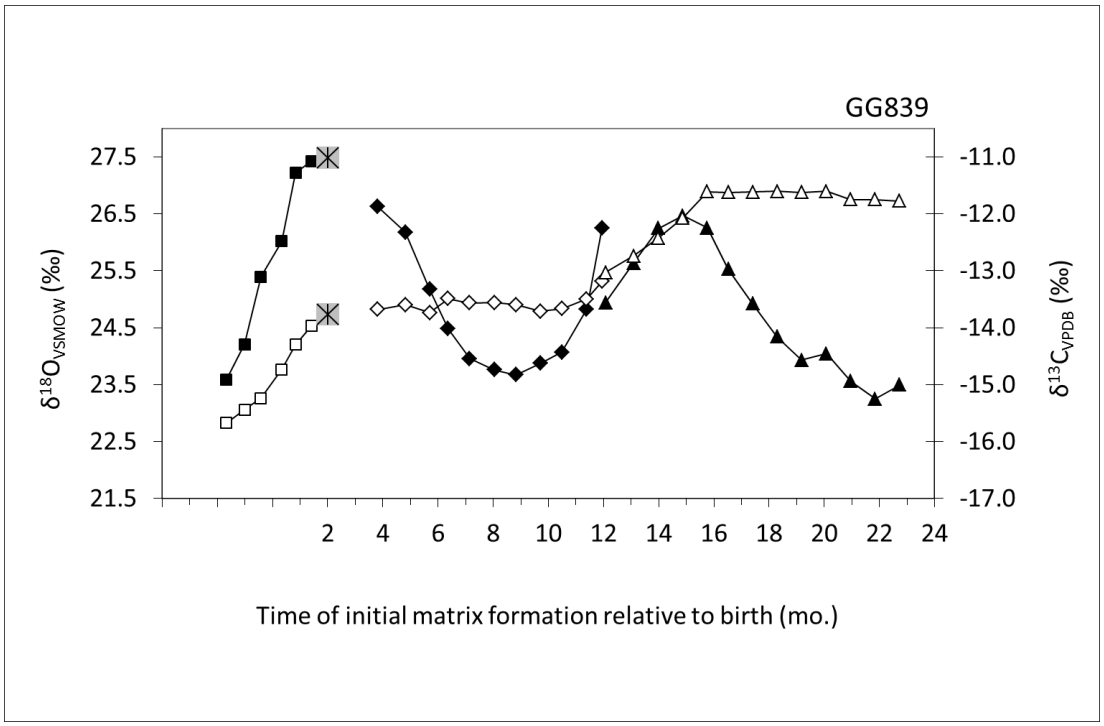


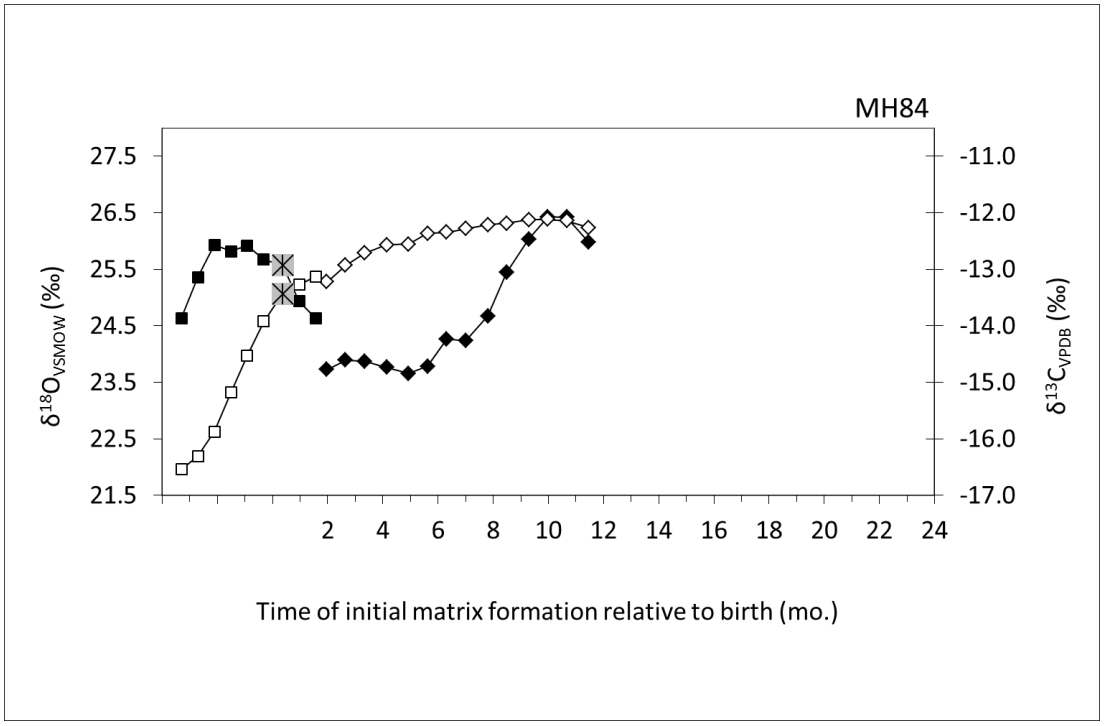
M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon





M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon





M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon

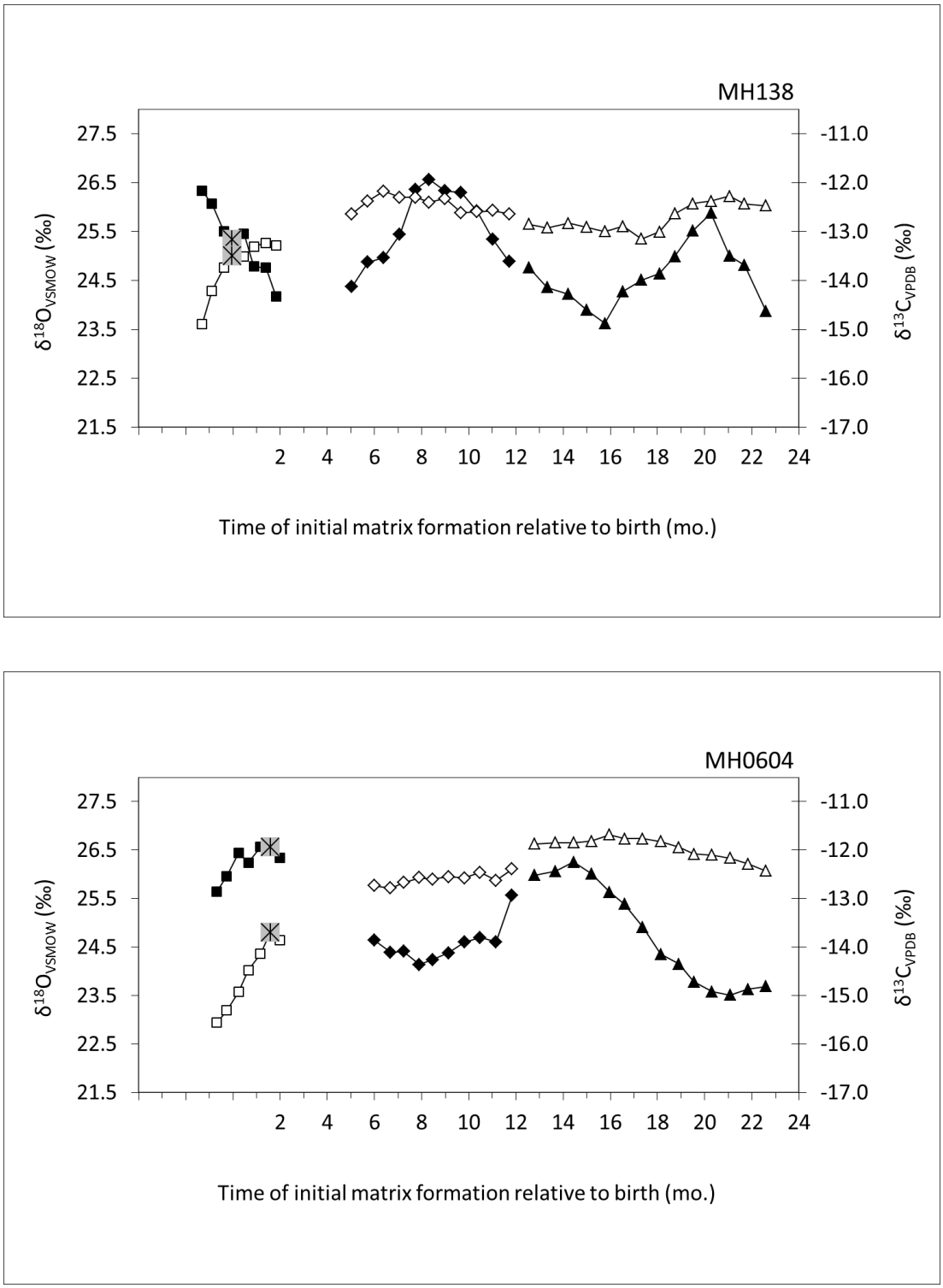


Figure 12.6: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$. The grey crossed square symbols indicate the change in gradient of the first molar $\delta^{13}C$ profile and the equivalent position in the $\delta^{18}O$ profile ($\delta^{13}C_{CG}$ and $\delta^{18}O_{CG}$, relevant to method 3, section 12.3).

Timings of $\delta^{18}O$ minima relative to birth for all 13 cattle are presented in Table 12.2, from which the distribution of births throughout the year may be calculated. The timings will have uncertainty associated with them, arising from the assumptions made when constructing the $\delta^{18}O$ profiles. Principal components of the uncertainty are: (1) the duration of crown formation and the timing of cervix formation for second and third molars; and (2) the uncertainty in the time difference, t_1, between the $\delta^{18}O$ minimum and the cervix. The latter is calculated proportionally from the distance, x_1, between the $\delta^{18}O$ minimum and the cervix, the measured or calculated unworn crown height, H_C, and the duration of crown formation, T_C (Section 10.1):

$$t_1 = x_1 T_C / H_C \qquad \text{(in months)}$$

The uncertainty in t_1 incorporates the uncertainty in T_C, which is unknown, the uncertainty in H_C and the uncertainty in x_1. For third molars, the uncertainty associated with H_{C_M3} is derived from the uncertainties associated with the measurement of the worn crown height and the incremental correction that must be added to the worn crown height to obtain a value for H_{C_M3} (Section 10.1). Worst case errors of ± 1.0 mm (2σ) and ± 2.5 mm (2σ) respectively are estimated, resulting in a combined error of $\pm \sqrt{(0.5^2 + 1.25^2)} = \pm 1.35$ mm (1σ) for H_{C_M3}, applying the sum of squares method for combining independent errors. Absolute values are used in the sum of squares expression when the variables, in this case the worn crown height and the incremental correction, are added (Berendsen 2011 p21). Because calculation of t_1 involves the multiplication and division of variables, the uncertainty associated with t_1 is calculated using percentage errors (Berendsen 2011 p21):

$$\%\ \text{error in } t_1 = \sqrt{[(\%\ \text{error in } T_{C\_M3})^2 + (\%\ \text{error in } H_{C\_M3})^2 + (\%\ \text{error of } x_1)^2]}$$

Disregarding at present the unknown error associated with T_{C_M3} and using an error of ± 0.5 mm (1σ) for x_1, an error of ± 1.35 mm (1σ) for H_{C_M3}, a value of 50mm for H_{C_M3} and a value of 13.5 months for T_{C_M3}, the uncertainty in t_1 is calculated to be ≤ ± 0.39 months (1σ), depending on the magnitude of x_1.

For second molars, the predicted unworn crown height, H_{C_M2}, is calculated to be 97 % of H_{C_M3}. Its associated error is a combination of the errors associated with H_{C_M3} and the scaling factor of 97 %. Again, since the calculation of H_{C_M2} involves multiplication, the uncertainty in H_{C_M2} is calculated using percentage errors. Suggested percentage errors are ± 2.7 % (= 100 x 1.35/50) (1σ) and ± 1.5 % (1σ) for H_{C_M3} and the scaling factor respectively, resulting in a combined percentage error of $\pm \sqrt{(2.7^2 + 1.5^2)} = \pm 3.1$ % (1σ) for H_{C_M2}. As for third molars, an error of ± 1.0 mm (2σ) is estimated for x_1. Using a value of 48.5 (=0.97 x 50) mm for H_{C_M2} and a value of 11.5 months for T_{C_M2}, the uncertainty in t_1 is calculated to be ≤ ± 0.38 months (1σ), depending on the magnitude of x_1. As mentioned above, the uncertainty in t_1 for both second and third molars should also include the uncertainty associated with the duration of crown formation, T_C, which is not known. The uncertainty associated with the timing relative to birth of a $\delta^{18}O$ minimum will incorporate the uncertainty of t_1 and the uncertainty of the timing of cervix formation relative to birth.

Table 12.2: $\delta^{18}O$ minima timings determined by method 2.

	Predicted time after birth (months)					
Animal	**M2 $\delta^{18}O$ minimum (min 1)**	**$\delta^{18}O$ maximum (max)**	**M3 $\delta^{18}O$ minimum (min 2)**	**[max – min 1] (months)**	**[min 2 - max] (months)**	**[min 2 - min 1] (months)**
PL0278	4.5	9.4	14.5	5.0	5.1	10.0
PL0330	4.9	10.5	15.3	5.6	4.8	10.4
PL0344	6.7	11.8	18.2	5.1	6.5	11.5
PL0386	2.4	7.9	13.7	5.5	5.8	11.3
GG839	8.6	14.8	21.9	6.1	7.1	13.2
GG743	3.4	9.0	15.4	5.6	6.4	12.0
GGT10	5.6	10.7	17.8	5.2	7.1	12.3
MH138	3.4	8.9	15.4	5.4	6.5	12.0
MH0604	8.0	14.0	21.2	6.0	7.2	13.2
GG614	5.1	10.2		5.1		
MH84	4.4	10.3		5.9		
PL0339	10.3					
GG120	4.9		mean =	5.5	6.3	11.8
			σ =	0.4	0.9	1.1

Table 12.2 also includes the timings of the $\delta^{18}O$ maxima lying between the second and third molar minima and values for the differences between neighbouring maxima and minima, [max – min1] and [min2 – max]. These values vary from animal to animal. Although inter-animal difference in molar crown formation may be a contributing factor, another is likely to be the variation in the enamel's $\delta^{18}O$ *input* signal during formation. For example, a six month rolling average applied to monthly precipitation $\delta^{18}O$ data from Wallingford, UK (Darling and Talbot 2003) (Section 12.1) produces summer maxima and winter minima that are not always exactly 6.0 months apart. In contrast, the mean separation between neighbouring minima and maxima is expected to be 6.0 months. This is true for the precipitation $\delta^{18}O$ data from Wallingford (Darling and Talbot 2003) for which the mean separation between neighbouring minima and maxima is 6.0 ± 1.0 months (1σ) over a 14 year period. For the molars in this study, the mean value of [max – min 1] = 5.5 ± 0.4 months (1σ, n = 11) and the mean value of [min 2 – max] = 6.3 ± 0.9 months (1σ, n = 9). This difference may be a manifestation of the small sample size. Alternatively, it may indicate that the chronology of second and third molars used here is not optimal. It is possible to obtain mean values of [max – min 1] and [min 2 – max] that are closer to 6.0 months by adjusting the start and finish times relative to birth to 0.5 and 13.5 months for second molars (rather than 1 and 12.5 months) and to 11 and 23 months for third molars (rather than 10 and 23.5). None of these revised parameters falls more than one month outside the ranges given by Brown et al (1960) for modern molars. Such discrepancies may reflect the approximate nature of those ranges or the fact that the molars are not from modern animals. Nevertheless, the original parameters are retained since they do produce mean values of [max – min 1] and [min 2 – max] that are close to the expected 6.0 months. As such, it is unlikely that this particular choice of parameters will unduly influence the conclusions of this study.

12.3 Method 3: using first and second molar $\delta^{18}O$ and $\delta^{13}C$ profiles

The third method to estimate cattle birth seasonality utilises both $\delta^{13}C$ and $\delta^{18}O$ data. In particular, the method makes use of the shape of the $\delta^{13}C$ profile recorded

in first molar enamel. Moving towards the cervix, there is a steep increase in first molar carbon isotope ratios followed by a reduction in gradient to values more typical of second molar enamel. As discussed in Section 11.1, this patterning may indicate the transition between purely non-ruminant digestion immediately after birth (relatively low $\delta^{13}C$ values) and the utilisation of a fully formed rumen (relatively high $\delta^{13}C$ values), with the reduction in gradient indicating the completion of rumen functionality at the age of approximately 6-10 weeks. Consequently, the reduction in gradient of the $\delta^{13}C$ profile may also be an indirect indication of birth recorded within the isotope data. If this is the case, this feature has the potential to provide an alternative method to estimate cattle birth seasonality, as described below.

Such $\delta^{13}C$ patterning is clearly apparent in each of the profiles included in Figure 12.6. If the reduction in gradient of the first molar enamel $\delta^{13}C$ profile is an indication of birth, albeit indirect, the relationship between the data point at which the $\delta^{13}C$ profile changes gradient and the seasonal cycle of the $\delta^{18}O$ profile is of particular importance and becomes critical to the formulation of method 3. For each of the 13 cattle represented in Figure 12.6, the data point where the $\delta^{13}C$ profile changes gradient, designated as $\delta^{13}C_{CG}$, and the equivalent point in the $\delta^{18}O$ profile, $\delta^{18}O_{CG}$, are both highlighted. In each case, $\delta^{18}O_{CG}$ has been assigned an angle relative to its position along the sinusoidal profile, A_{CG}, which is shown schematically in Figure 12.7. This was achieved as follows: the magnitudes of the summer maximum and winter minimum, $\delta^{18}O_{max}$ and $\delta^{18}O_{min}$, bracketing the data point $\delta^{18}O_{CG}$ were calculated by differentiation of second order polynomials fitted to the surrounding data points (Appendix 3). Occasionally, when a maximum or minimum was not clearly defined, as for animal MH138, values had to be estimated by visual inspection. Angle A_{CG} was calculated using the equation:

$$[\delta^{18}O_{CG} - \delta^{18}O_{min}] = 0.5\Delta[\cos(A_{CG}) + 1]$$

where $\Delta = [\delta^{18}O_{max} - \delta^{18}O_{min}]$, and $[\delta^{18}O_{CG} - \delta^{18}O_{min}]$ lies between 0 and Δ (Figure 12.7). Angles A_{CG} calculated for all of the cattle in this study are presented in Table 12.3 and Figure 12.8.

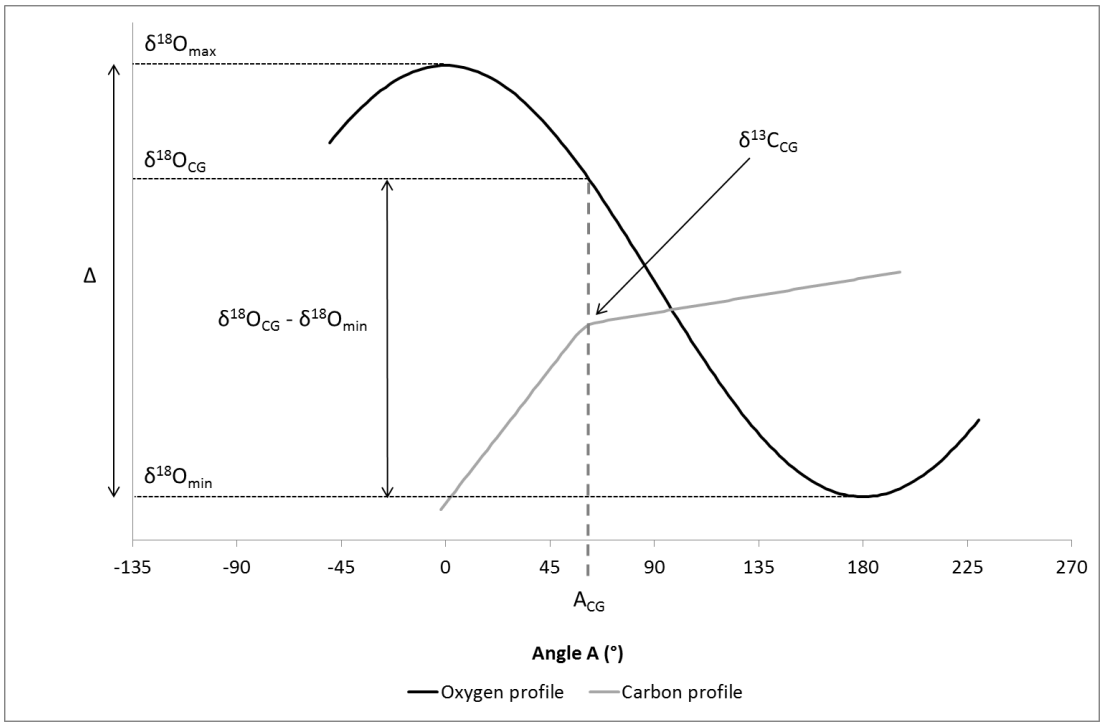


Figure 12.7: Schematic diagram showing the parameters involved in the calculation of A_{CG}.

Table 12.3: Angular positions of $\delta^{18}O_{CG}$ on the $\delta^{18}O$ profile (A_{CG}).

Animal	Angle A_{CG} (°)	Animal	Angle A_{CG} (°)
PL0278	91	GG614	68
PL0330	0	GGT10	47
PL0339	-112	GG120	12
PL0344	42	MH138	91
PL0386	161	MH0604	13
GG839	-13	MH84	49
GG743	53	KAR	-27

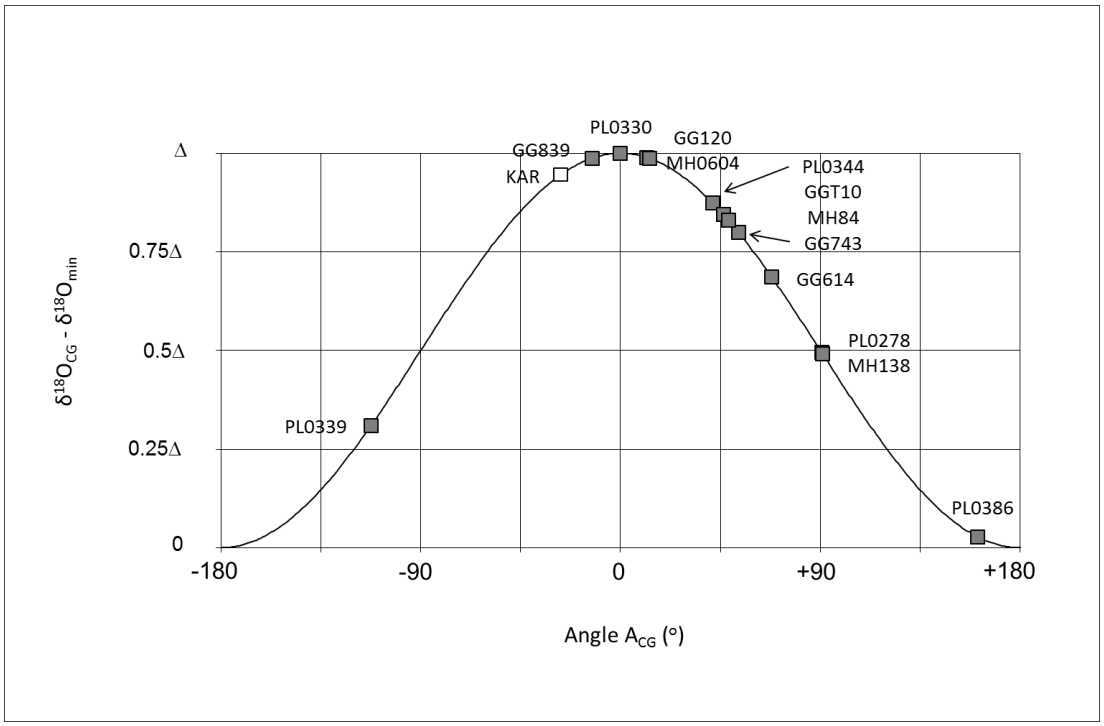


Figure 12.8: Angles A_{CG} for the 13 selected archaeological cattle and for the modern Dexter bull Karst (KAR).

Each value of A_{CG} will be subject to uncertainty. One source of error arises from the identification of the data point $\delta^{13}C_{CG}$ in the $\delta^{13}C$ profile and, from that, its equivalent in the $\delta^{18}O$ profile, $\delta^{18}O_{CG}$. This was done by visual inspection which in some cases could have led to $\delta^{13}C_{CG}$ being assigned to the wrong data point. There are approximately nine data points between neighbouring maxima and minima in the $\delta^{18}O$ profiles. Therefore, if the maximum error is ±1 data point, the error in A_{CG} is ± (180/9)° = ± 20° (2σ). There are cases where the $\delta^{18}O$ maximum or minimum is not clearly defined, e.g. MH138 (Figure 12.6) resulting in additional uncertainty in A_{CG}. This has also been estimated to be approximately ± 20° (2σ). Using the sum of squares method for combining independent errors (Berendsen 2011 p21), the total error associated with A_{CG} becomes $\pm \sqrt{(10^2 + 10^2)} = \pm 14.1°$ (1σ) which, since 360° represents 12 months, is equivalent to ± 0.47 months (1σ).

It is proposed that birth seasonality for an archaeological assemblage, i.e. the distribution of births throughout the year, may be estimated from the distribution of angles A_{CG}, which brings into play a further source of error. If the change in

gradient of the $\delta^{13}C$ profile, $\delta^{13}C_{CG}$, is an indication of the completion of rumen functionality, there will be variability in the timing of this biological event relative to birth. According to a number of studies (Bryant et al 1958, Swanson and Harris 1958, Godfrey 1961b, Anderson et al 1987), completion usually occurs at the age of approximately 6-10 weeks (i.e. 8 ± 2 weeks), provided the calf has access to some dry food. If an estimate of ± 0.75 months (2σ) is assumed, the total error associated with the timing of birth is calculated to be $\pm \sqrt{(0.47^2 + 0.375^2)} = \pm 0.60$ months (1σ), incorporating the error in estimating A_{CG}.

12.4 Comparison of all three methods

The principal sources of uncertainty associated with the timing of birth for the three different methods outlined in this chapter are summarised in Table 12.4. Estimated magnitudes of uncertainty, as calculated in the previous sections, are also included where possible. For methods 1 and 2, uncertainties related to crown formation are contributing factors. In both cases, the timing of cervix formation relative to birth is not known with any accuracy. For method 2, the duration of crown formation is also an unknown quantity. Only method 3 appears free from uncertainty related to crown formation and, consequently, may prove to be the most accurate of all three methods in estimating cattle birth seasonality, barring significant unforeseen sources of uncertainty.

Table 12.4: Comparison of the three methods to estimate cattle birth seasonality.

	Principal sources of uncertainty associated with the timing of birth and estimated magnitudes of uncertainty (± 1σ)	**Advantage of the method**
Method 1	Timing of $\delta^{18}O$ minimum relative to cervix (~± 1 mo.). Timing of cervix formation relative to birth (not known). Total uncertainty associated with the timing of birth not known.	Knowledge of unworn crown height and duration of crown formation not required (estimates of these are used in method 2).
Method 2	Timing of $\delta^{18}O$ minimum relative to cervix, which incorporates the combined uncertainty associated with the unworn crown height and the distance from the cervix (~± 0.4 mo.), and the uncertainty associated	Does not introduce uncertainty by assuming that the period of the $\delta^{18}O$ profile is exactly 12 months

	with the duration of crown formation (not known). Timing of cervix formation relative to birth (not known). Total uncertainty associated with the timing of birth not known.	(assumed in method 1).
Method 3	Angle assigned to the change in gradient of first molar $\delta^{13}C$ profile, which incorporates the combined uncertainty associated with misidentification of $\delta^{13}C_{CG}$ and estimates of the magnitudes of the $\delta^{18}O$ minimum and maximum bracketing $\delta^{13}C_{CG}$ (equivalent to ~± 0.5 mo.). Timing variability of the completion of rumen functionality relative to birth (equivalent to ~± 0.4 mo.). Total uncertainty associated with the timing of birth estimated to be ~± 0.6 mo.	Variability in the timing and rate of crown formation does not contribute to the total uncertainty associated with the timing of birth.

In order to compare method 1 with method 2 in terms of the magnitude of uncertainty involved in estimates of cattle birth seasonality, the second molar $\delta^{18}O$ minima timings obtained using methods 1 and 2 (Tables 12.1 and 12.2) have been plotted against the angles calculated using method 3 (Table 12.3). The resulting plots are shown in Figures 12.9 and 12.10. For each plot, it might be expected that the data points should approximate to a straight line of gradient –12/360 months/°. Therefore, a straight line, of the form y = -(12/360)x + c, has been fitted by adjusting the value of intercept c such that the sum of the squares of the residuals in the y direction is minimal. The plots show that there is a reasonably strong correlation between angle A_{CG} and the timings of the second molar $\delta^{18}O$ minima, supporting the idea that both types of data are related to the same factor, the timing of birth. For $\delta^{18}O$ minima timings obtained using method 1, the correlation coefficient r = -0.83 and the standard deviation of the residuals in the y direction sd_{yres} = ± 1.6 months, whereas for those obtained using method 2, the correlation coefficient r = -0.85 and the standard deviation of the residuals in the y direction sd_{yres} = ± 1.2 months. Figures 12.11 and 12.12 show equivalent plots for the third molar $\delta^{18}O$ minima, where r = -0.73 and sd_{yres} = ± 2.2 months for $\delta^{18}O$ minima timings obtained using method 1, and r = -0.72 and sd_{yres} = ± 2.0 months for those obtained using method 2.

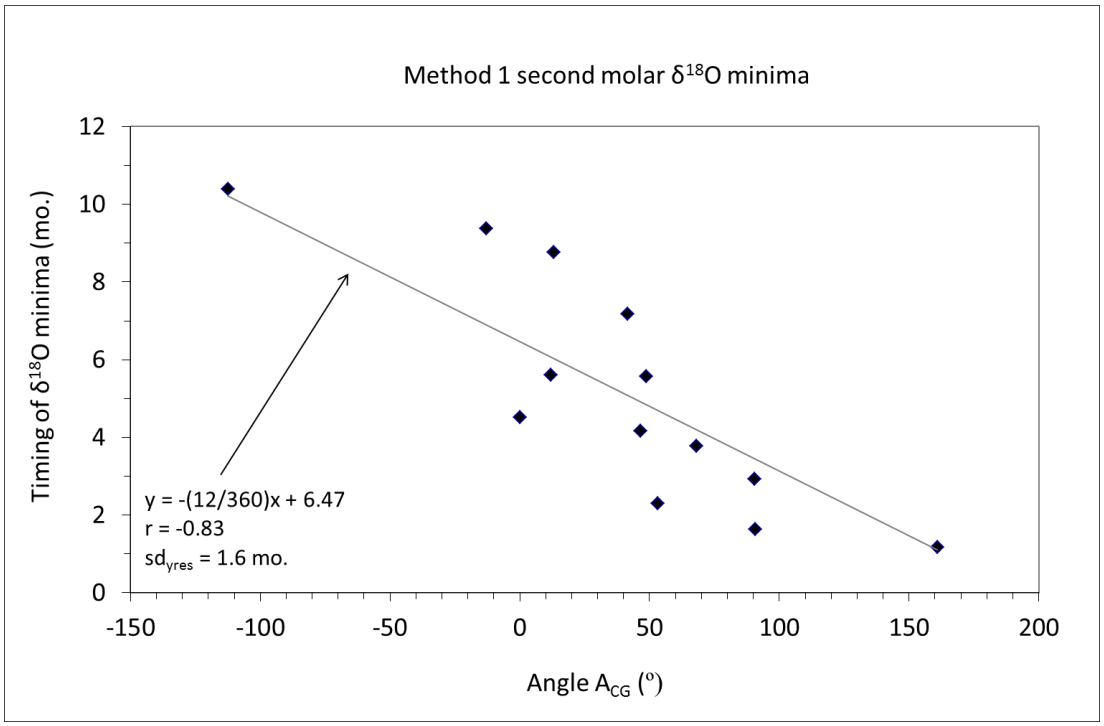


Figure 12.9: Method 1 second molar $\delta^{18}O$ minima timings versus angle A_{CG}.

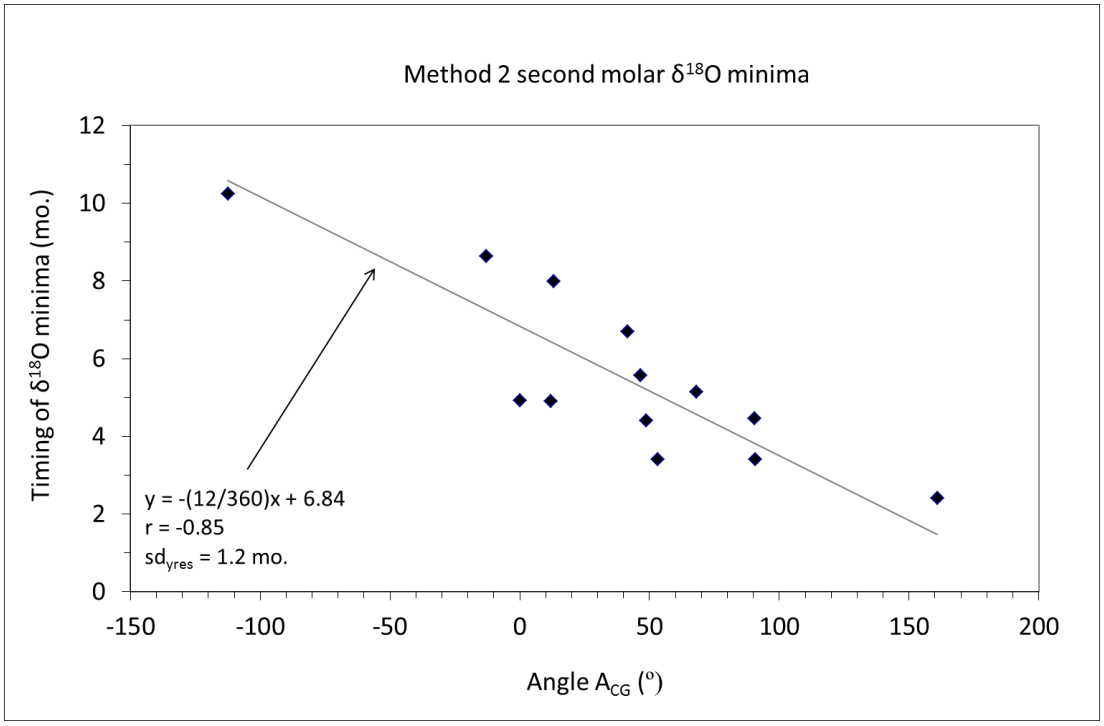


Figure 12.10: Method 2 second molar $\delta^{18}O$ minima timings versus angle A_{CG}.

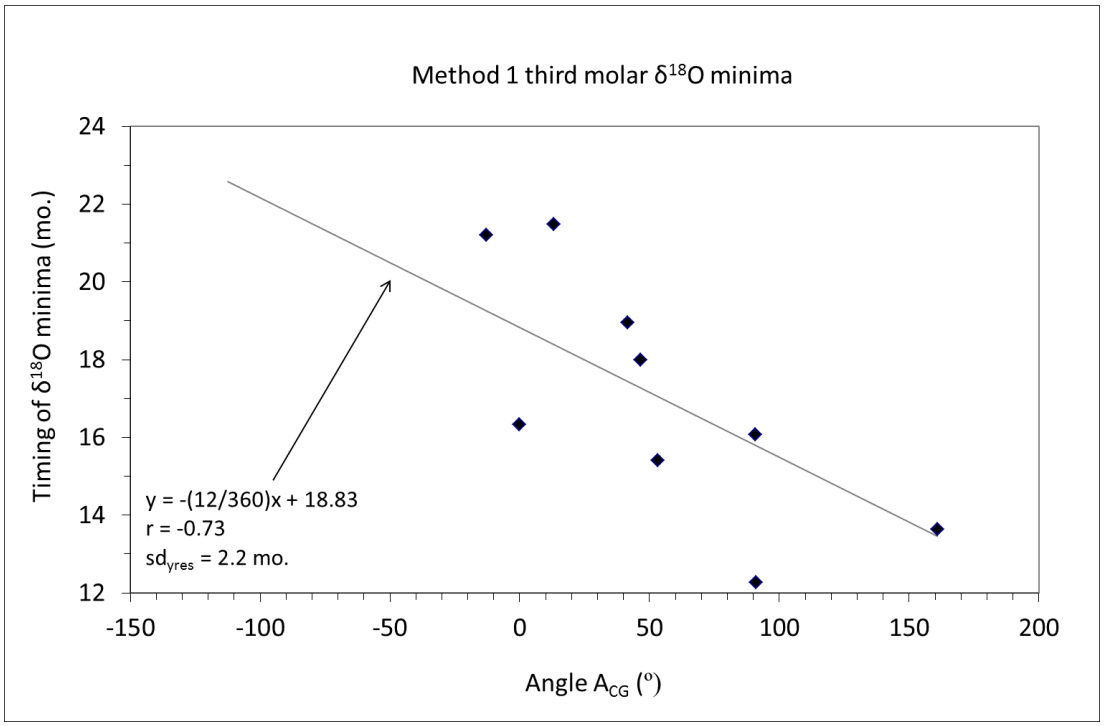


Figure 12.11: Method 1 third molar $\delta^{18}O$ minima timings versus angle A_{CG}.

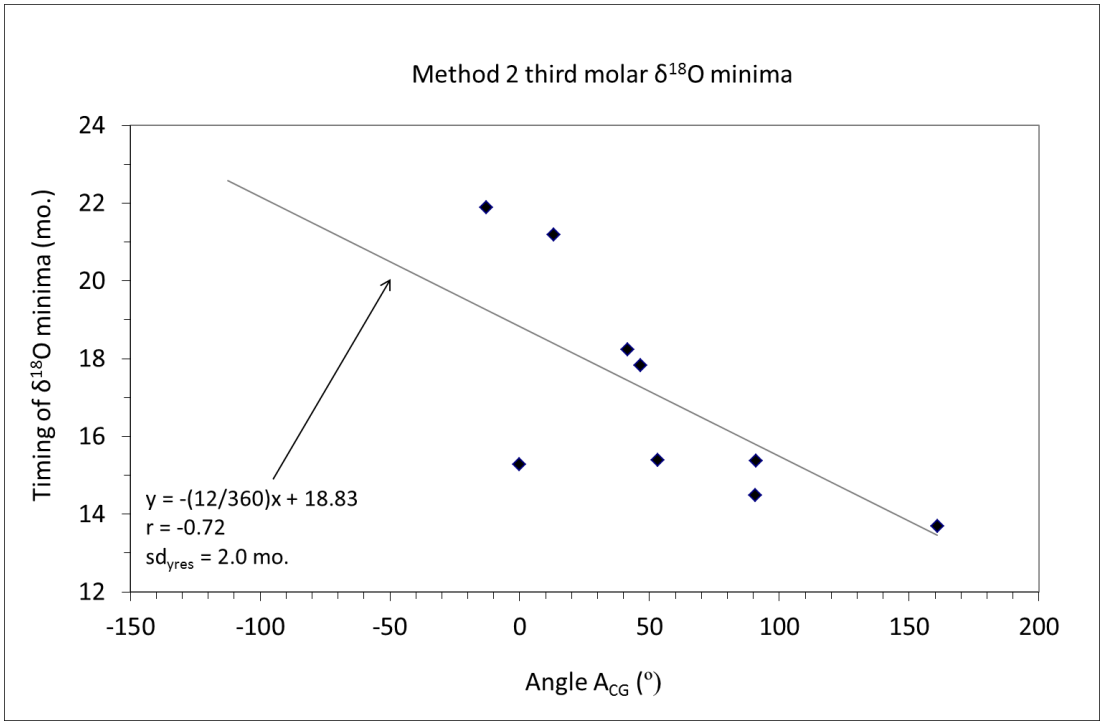


Figure 12.12: Method 2 third molar $\delta^{18}O$ minima timings versus angle A_{CG}.

Although the values of sd_{yres} for both types of molar will incorporate the annual climate-related variability in the $\delta^{18}O$ input signal and the errors associated with the

assumptions involved in calculating the timings of $\delta^{18}O$ minima, inter-animal variability in crown formation is likely to be a significant factor. This may arise from inter-animal differences in crown start and finish times, as defined by the matrix deposition process, and the time taken to complete enamel mineralization. Intra-tooth differences between animals in terms of varying rates of enamel matrix formation or enamel maturation along the crown may also be contributing factors, although, as previously mentioned in Section 12.1, modelling of cattle third molars by Balasse et al (2012b) suggests that intra-tooth variation may be insignificant. Method 1 was devised to correct for inter-animal variability in molar growth rate but application of this method here has not produced reduced values of sd_{yres}. This suggests that variability in the timing of cervix formation, a parameter required by methods 1 and 2, is a major source of error. In addition, the assumption that the period of a $\delta^{18}O$ profile is exactly 12 months may have introduced uncertainty into method 1 timing calculations. For both method 1 and method 2, variability in third molar crown formation appears to be much more pronounced than that of second molars, which is not altogether surprising since a similar trend has been observed in modern sheep second and third molars (Blaise and Balasse 2011). It is also the case that the timing of third molar formation in humans is highly variable (Hillson 1996 p136).

The advantage of method 3 is that it should be unaffected by variability in the timing and rate of molar formation. The predicted degree of uncertainty associated with the timing of birth for method 3 (± 0.6 months) is significantly smaller than the values of sd_{yres} suggesting that method 3 may be more accurate than methods 1 and 2. However, this statement cannot be accepted with a high level of confidence until the molars of more cattle have been analysed, particularly from modern animals with known histories, and the associated uncertainties investigated and evaluated thoroughly. There may be sources of error associated with method 3 not yet accounted for. For example, there may be an additional contribution to the uncertainty in A_{CG} due to distortion of the sinusoidal pattern of the first molar $\delta^{18}O$ profile caused by pre-weaning ingestion of water via milk, which tends to produce more elevated $\delta^{18}O$ values than drinking water (Lin et al 2003, Renou et al 2004,

Camin et al 2008). It is also possible that a significant change in the $\delta^{13}C$ value of a calf's diet within a month or two of the completion of rumen functionality might act to alter or obscure the position of $\delta^{13}C_{CG}$ recorded in the animal's first molar enamel.

As an illustration of how estimates of birth seasonality may depend on the method used, suppose that the animals included in this study were from the same herd and consider those 11 data points in Figures 12.9-12.12 falling in the central cluster between angles -13° and +91°. The distribution of births estimated using method 3 is (104/360) x 12 = 3.5 months. By reading along the y-axes of Figures 12.9-12.12, the distribution of births may be predicted using method 1 and method 2 for both second and third molars (Table 12.5). Method 3 produces the narrowest distribution of births, covering little more than a single season, whereas methods 1 and 2 produce wider distributions varying from 5.2 months (method 2, second molars) to 9.2 months (method 1, third molars). Thus, the choice of method and molar type may lead to very different conclusions regarding cattle husbandry and economic goals. Assuming that method 3 does provide the most accurate estimate of cattle birth seasonality and following the arguments proposed in Chapter 2 regarding birth seasonality and economic focus, the 3.5 months distribution calculated using this method would suggest an emphasis on meat or storable dairy products if these cattle were from the same herd. The same interpretation might be inferred from the 5.2 months distribution obtained by applying method 2 to second molars. However, distributions of > 7 months obtained by applying method 1 or method 2 to third molars could suggest the possibility of year-round milk production, leading to a different conclusion regarding economic focus. In Chapter 13, where each archaeological site is considered in turn, birth seasonality will be estimated using method 3, if first molar data are available, and method 2 (applied to second molars). Method 1 will no longer be considered.

The poor accuracy of birth seasonality estimates from third molar data is unfortunate as loose third molars are often the most common component in archaeozoological dental collections because they are easy to identify. In fact, third

molars are more prevalent than first and second molars in this research project and for two of the archaeological sites included (Old Scatness and Earl's Bu), they are the dominant molar type present. However, it is possible that the use of molars from different periods and geographical locations has produced a worst case scenario and that variation in the timing of third molar crown formation is reduced for cattle from a restricted time period and geographical area.

Table 12.5: Distribution of births calculated for the central cluster of 11 data points in Figures 12.9-12.12.

Method applied	**Distribution of births (mo.)**
Method 1 second molars	7.8 (= 9.4 – 1.6)
Method 1 third molars	9.2 (= 21.5 – 12.3)
Method 2 second molars	5.2 (= 8.6 – 3.4)
Method 2 third molars	7.4 (= 21.9 – 14.5)
Method 3	3.5

In order to demonstrate that this might be a possibility, it is necessary to use the $\delta^{18}O$ profiles obtained for all the archaeological cattle with second and third molars included in this study, which are displayed and examined in detail in the following chapter (Chapter 13). Like the profiles shown in the method 2 discussion above (Section 12.2), they have been produced using the procedure outlined in Section 10.1. The timing of each $\delta^{18}O$ minimum and each $\delta^{18}O$ maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3) (Tables 13.1, 13.4, 13.7 and 13.9). Of particular interest to the current discussion are the timing differences between second and third molar $\delta^{18}O$ minima, [min2 – min1], and between second and third molar $\delta^{18}O$ maxima, [max2 – max1]. These timing differences are expected to be heavily influenced by the variability of third molar formation provided that second molar formation is significantly less variable, which is probable according to Figures 12.10 and 12.12. Figure 12.13 displays [min2 – min1] and [max2 – max1] values for four archaeological sites: Earl's Bu (Orkney, c. 800 AD – c. 1050 AD), Pool (Orkney, c. 800 AD – c. 950 AD), Mine Howe (Orkney, c. 50 AD – c. 400 AD) and Grimes Graves (Norfolk, c. 1400 BC – c. 850 BC). Although the overall mean value of all [min2 –

min1] and [max2 – max1] values is 11.7 ± 1.3 months, close to the expected value of 12.0 months, the mean for Grimes Graves is 12.5 ± 0.4 months, for Pool 10.9 ± 0.6 months (excluding the outlier PL0444) and for Mine Howe 12.1 ± 1.2 months (excluding the non-local animal MH133). Apart from the single Pool outlier (PL0444), there is no overlap between the plotted values for Pool and Grimes Graves, two sites separated by distance and time. In contrast, Mine Howe values are widely distributed and act as a warning that reduced variation in crown formation cannot be assumed for third molars from a single site. Further investigation of these inter- and intra-site differences is beyond the scope of the current study but could form the basis of future work. Factors that may influence tooth crown formation are genetic make-up, sex and plane of nutrition (Hillson 2005 pp 210).

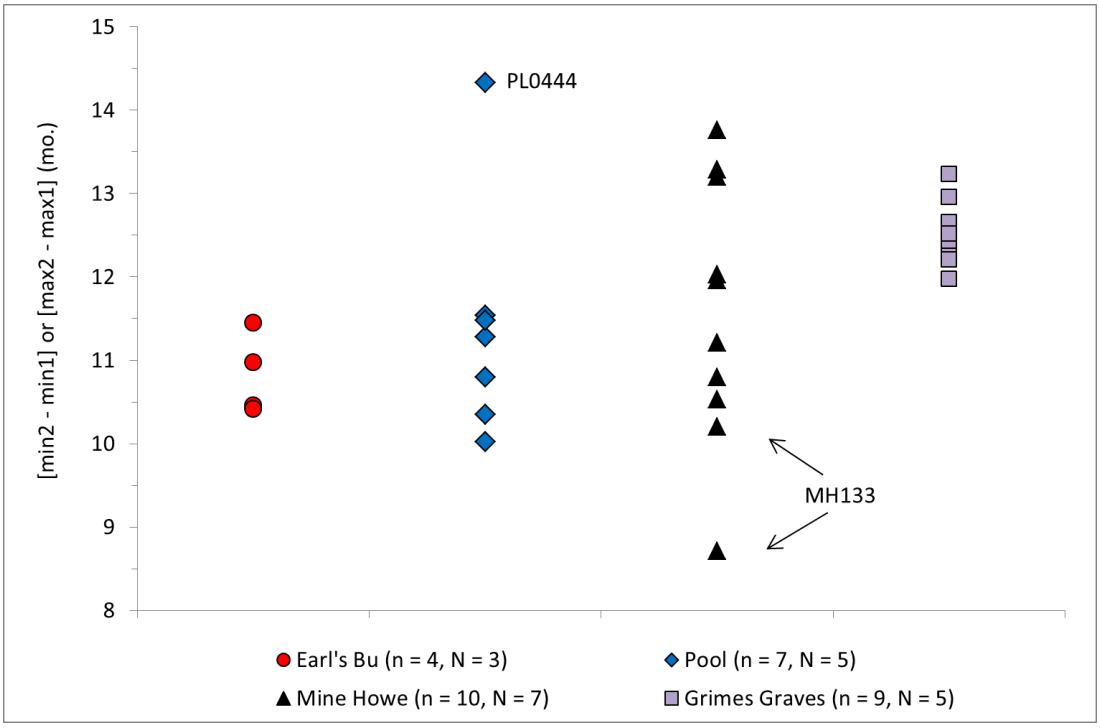


Figure 12.13: Separation between adjacent $\delta^{18}O$ minima or adjacent $\delta^{18}O$ maxima for archaeological cattle molars. n = number of measurements, N = number of cattle. Strontium concentration results suggest MH133 originated outside Orkney. The first and second molar $\delta^{13}C$ profile of PL0444 is distinct from those of the other Pool cattle although strontium results indicate origins consistent with Orkney.

12.5 Season of birth

The emphasis of this chapter has been on the seasonality of births, i.e. the distribution of births throughout the year. However, an ability to estimate the actual season of birth for an animal would contribute greatly to our understanding of past husbandry practices. In order to predict the season of birth using method 3, the analysis of molars from an animal with a known date of birth is required, which would allow calibration of angle A_{CG}. Included in this study are modern animals from the Chillingham Wild White Cattle herd and a modern Dexter reared for beef (KAR). Unfortunately, the dates of birth of the Chillingham animals are not known. The date of birth of the Dexter is known (8th February 2010), but this animal may not prove to be the ideal control animal because he moved to a location approximately 13 km from his birth place when he was 3½ months old (Section 7.2). As a result, he had access to a variety of water sources. At the first location, drinking water consisted mainly of collected rainwater and ditch water, while at the second, water was available from a stream and from a borehole. The $\delta^{18}O$ value of the borehole water may not vary appreciably with season. Despite this, the $\delta^{18}O$ profile for the first molar enamel (Figure 11.4) follows a typical sinusoidal shape, although there is a possibility of some modification by the borehole water since the enamel was still mineralizing after the move to the second location. Angle A_{CG} for the Dexter has been calculated to be -27° and is shown in Figure 12.8.

An angle of -27° might suggest simplistically that the completion of rumen functionality occurred in summer, implying birth in spring rather than February (Figure 12.8). However, the process and duration of enamel mineralization causes a temporal shift between the input and the recorded signals that depends on the shape of the input pattern, i.e. the sinusoidal profile of $\delta^{18}O$ produced by gradual seasonal change is shifted by a different amount to the step change in $\delta^{13}C$ gradient resulting from the development of the rumen. This is illustrated by the schematic diagram in Figure 12.14 which shows the $\delta^{18}O$ and $\delta^{13}C$ input signals at the time of initial enamel matrix formation for a calf born in late winter, the time of birth intersecting the $\delta^{18}O$ input signal just after a minimum in the sinusoidal curve. The

$\delta^{13}C$ input signal begins relatively high, drops at birth, then rises rapidly to the original level two months after birth, representing the three stages of the calf's development from ruminant (via its mother) through non-ruminant and back to ruminant. Subsequent dietary and locational changes specific to the Dexter (KAR) are not modelled. A simplistic prediction of the isotopic profiles subsequently recorded in the enamel are also shown in Figure 12.14, the process of mineralization modelled using a six month running average (the figure of six months is approximately the time taken for cattle molar enamel to fully mineralize as determined by Balasse (2002) for second molars, and it is possible that mineralization occurs at a different rate in first molars). The plot shows that the change in $\delta^{13}C$ gradient in the input and recorded signals are superimposed but the $\delta^{18}O$ recorded signal is ahead of the $\delta^{18}O$ input signal by three months. Consequently the change in $\delta^{13}C$ gradient aligns with the $\delta^{18}O$ recorded signal at a position just before the maximum of the sinusoidal curve. Thus, a value of -27° for angle A_{CG} is approximately as expected for a February birth.

Most of the archaeological animals included in Figure 12.8. lie between -13° (GG839) and 91° (MH138), a range of 104° which represents (104/360) x 12 months = 3.5 months. If the $\delta^{18}O$ profile of the Dexter (KAR) is truly seasonal and method 3 is a valid approach to determining cattle birth seasonality, then these animals were probably born during late winter, spring and early summer. For a random selection of animals from different sites and periods, it seems reasonable that the highest density of births (PL0344, GGT10, MH84 and GG743) would have coincided with the period of maximum grass growth in the spring.

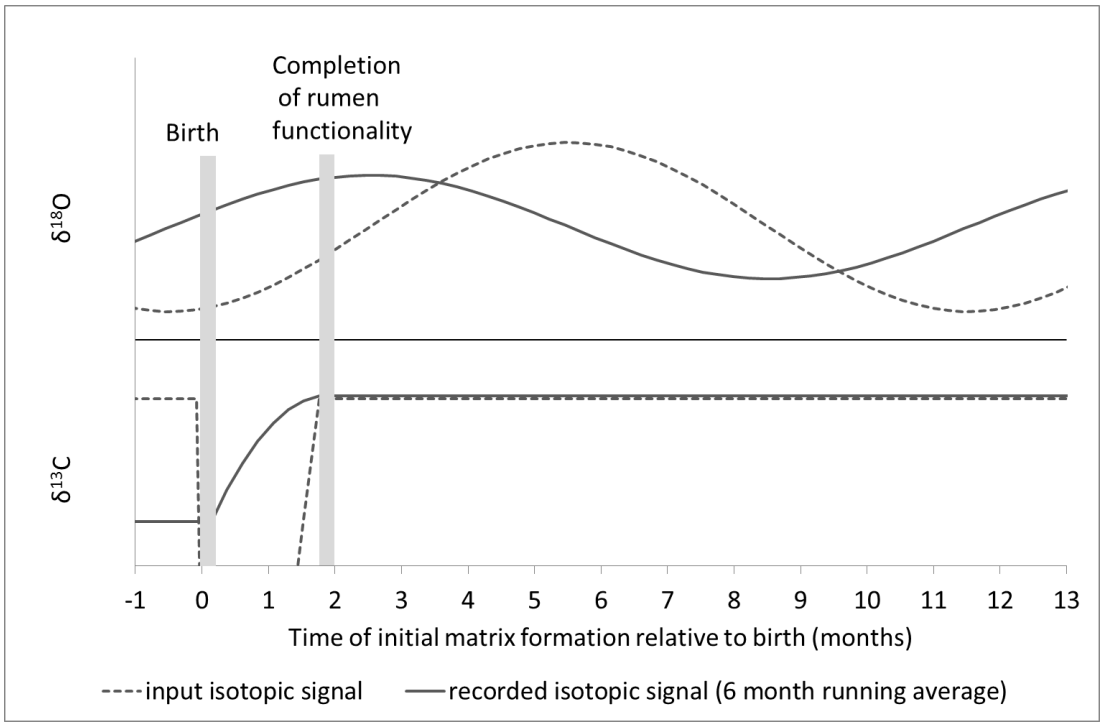


Figure 12.14: Simple model of $\delta^{18}O$ and $\delta^{13}C$ signals recorded in enamel assuming that cattle molar enamel takes approximately six months to fully mineralize, as determined by Balasse (2002) for second molars.

12.6 Summary

This chapter has introduced a possible new approach to determine cattle birth seasonality that utilises both carbon and oxygen isotope ratio measurements of cattle first molar enamel (method 3). The technique is based on the proposition that a change in gradient observed in many first molar $\delta^{13}C$ profiles is directly related to rumen development and methanogenesis and is therefore indirectly related to birth. This multiple-isotope approach, using both $\delta^{13}C$ and $\delta^{18}O$ profiles, has the advantage that prediction of cattle birth seasonality using method 3 should be unaffected by variability in the timing and rate of molar crown formation.

Initial results suggest that method 3 may produce more accurate estimates of cattle birth seasonality than methods 1 and 2, which are based on $\delta^{18}O$ maxima and minima present in second and third molar profiles. For this selection of animals, method 2, which utilises predicted unworn crown heights and crown formation timings suggested by Brown et al (1960), appears to be more accurate than method

1, which fits a cosine curve to the $\delta^{18}O$ data and normalises to period. Applying method 2 to second molars may be a viable option for estimating cattle birth seasonality. However, variability in the timing of crown formation appears to be more pronounced for third molars which could lead to inaccurate predictions of cattle birth seasonality using methods 1 and 2, and erroneous conclusions regarding cattle husbandry and economic goals.

Method 3 is still at an early stage of development and much more extensive testing is required both to verify that the patterning observed in first molar $\delta^{13}C$ profiles is indeed a result of rumen development and methanogenesis, and to further investigate and evaluate the sources of uncertainty associated with all three methods. For this purpose, the analysis of molars from modern animals with known histories would be particularly beneficial. The use of modern material would also be invaluable in the determination of season of birth, which is based in this study on only one modern animal raised in non-ideal circumstances.

In order to interpret the isotopic data from each archaeological site included in this study, which is the focus of Chapter 13, methods 2 and 3 will be utilised and the values of sd_{yres} (Figures 12.10 and 12.12) will provide estimates of uncertainty in the timings of $\delta^{18}O$ minima and maxima. These values, ± 1.2 months for second molars and ± 2.0 months for third molars, are considered approximations for three reasons: 1) variation in crown formation may be reduced for cattle from a restricted time period and geographical area, which would act to reduce sd_{yres} values; 2) they assume that values of A_{CG} are accurate, which is untrue. The magnitudes of sd_{yres} are likely to incorporate the error in A_{CG}, reducing the amount of uncertainty associated with the timings of $\delta^{18}O$ minima and maxima; and 3) for third molars at wear stages g-k, there is increased uncertainty in predicted unworn crown height (approximately ± 6 % rather than ± 3 % for third molars at wear stages b-f), which would act to increase the values of sd_{yres}, but only by a modest amount (estimated at ≤ 0.2 months).

13 Archaeological case studies: interpreting cattle husbandry using isotopic analysis

In this chapter, the cattle molar enamel $\delta^{18}O$ and $\delta^{13}C$ data obtained for each archaeological site included in this study are evaluated based on the findings of the previous two chapters with respect to birth seasonality, season of birth, diet and environment and weaning. The starting point of this evaluation is the construction of $\delta^{18}O$ and $\delta^{13}C$ profiles whereby the molar enamel $\delta^{18}O$ and $\delta^{13}C$ data are plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1. This allows first, second and third molar data from the same animal to be plotted on a common time-related x-axis.

Where possible, cattle birth seasonality, i.e. the distribution of births, is estimated using the proposed new method utilising both $\delta^{18}O$ and $\delta^{13}C$ measurements of first molar enamel, designated method 3 and described in Section 12.3. An alternative method based on the timings of $\delta^{18}O$ minima present in second molar profiles, designated method 2 and described in Section 12.2, is also applied. Although the timings of third molar $\delta^{18}O$ minima have also been calculated, they are not used in the same manner to estimate the distribution of births since third molar crown formation appears to be more variable than for second molars. Estimates of uncertainty in the timings of $\delta^{18}O$ minima and maxima are assumed to be ± 1.2 months for second molars and ± 2.0 months for third molars, based on the data analysis in Section 12.4. Season of birth is estimated with respect to isotopic data from a modern Dexter bull (KAR) of known birth date (Section 12.5). Based on this single example, any season of birth prediction for the archaeological cattle is regarded as approximate.

The $\delta^{13}C$ profiles of the archaeological cattle are also examined in order to investigate the diet and environment experienced by the animals. The approach taken here is to look for recurring patterns in the profiles. Because of the potential influence of milk consumption on $\delta^{13}C$ profiles recorded in first molar cervical enamel and second molar cuspal enamel (Section 11.2), investigation of diet and

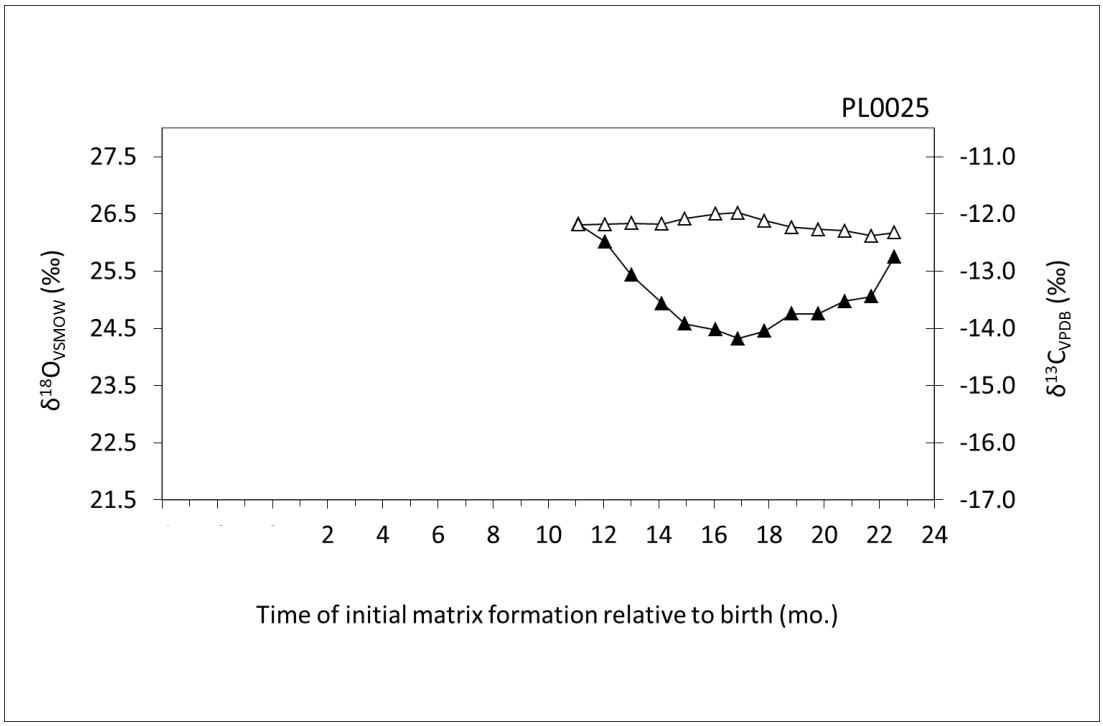
environment focusses primarily on $\delta^{13}C$ profiles recorded in second molar cervical enamel and third molar enamel. Unfortunately, absolute interpretation is not possible since similar $\delta^{13}C$ profiles may result from different dietary and environmental circumstances. Only through knowledge of the local environment and period in question can the number of possible interpretations be reduced. For $\delta^{13}C$ profiles that comprise first, second and third molar data, weaning strategy is explored using a method proposed in Section 11.2. Based on a very limited dataset, this method is highly speculative at present. Therefore, any interpretations regarding weaning strategies suggested below should be regarded similarly. Weaning cannot be investigated for Earl's Bu and Old Scatness because first molars have not been analysed for these sites.

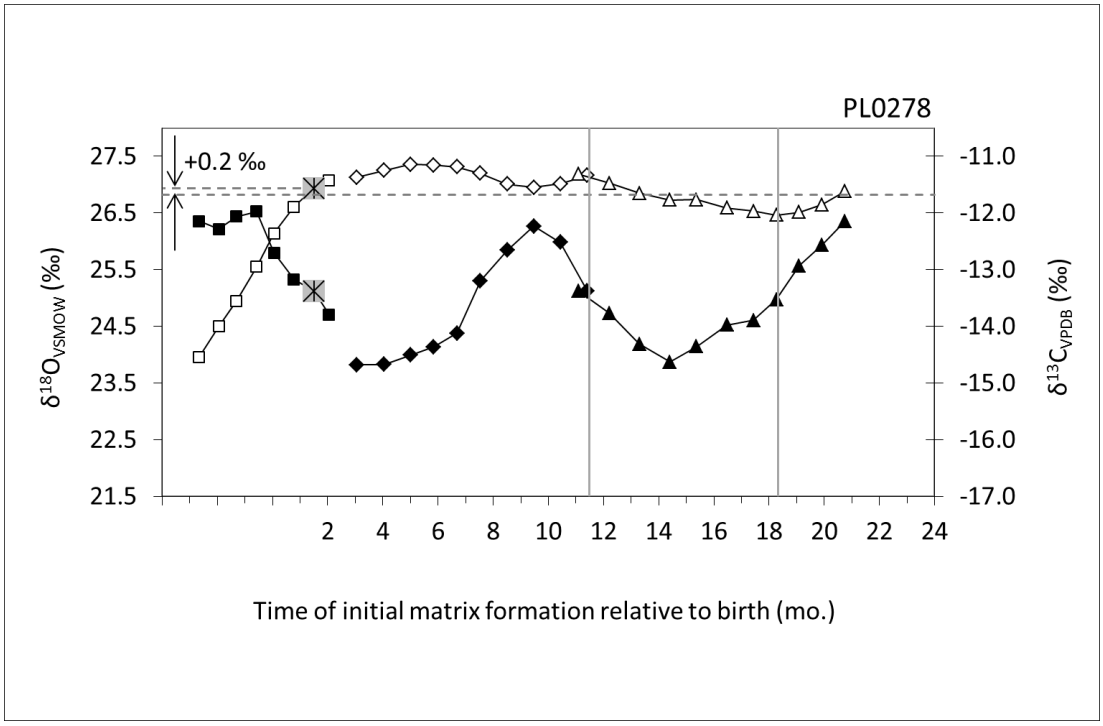
Finally, the findings related to each site are summarised and, where appropriate, considered with respect to the economic goal inferred from the mortality profile. It is acknowledged that, for each site, the number of cattle included in this study is small due to the effort required to collect, process and analyse the large number of enamel samples involved. In addition, old cattle with very worn teeth have not been included due to the incomplete nature of their isotopic profiles. Therefore, it is possible that the selected animals are not representative of the whole assemblage in terms of birth seasonality, season of birth, weaning, diet and environment, and any conclusions drawn should be regarded as provisional.

13.1 Pool, Orkney (Interface period, c. 800 AD – c. 950 AD)

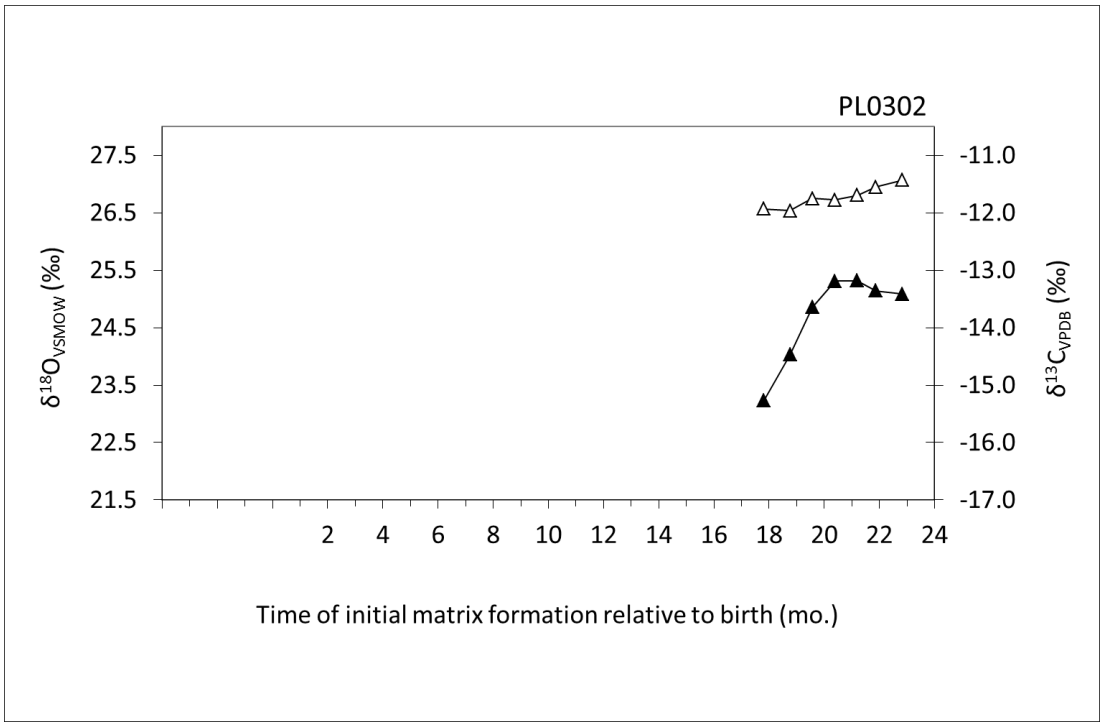
13.1.1 Intra-tooth $\delta^{18}O$ and $\delta^{13}C$ profiles

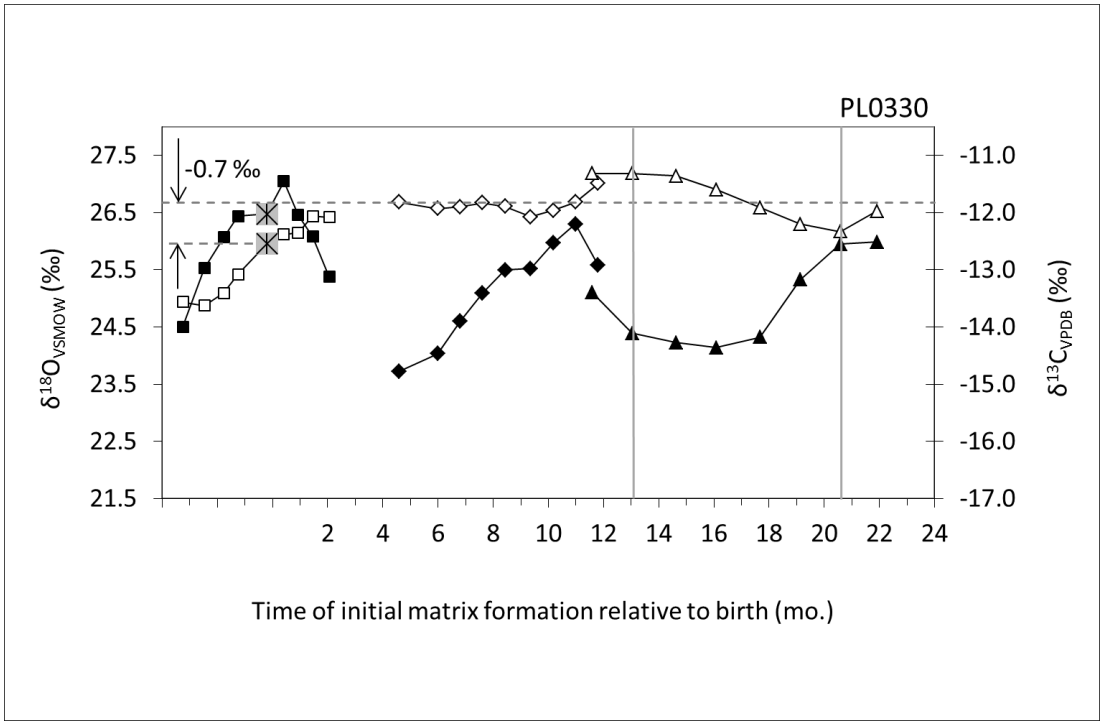
The $\delta^{18}O$ and $\delta^{13}C$ data obtained for all molars from nine Pool cattle have been plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1 (Figure 13.1).





M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon





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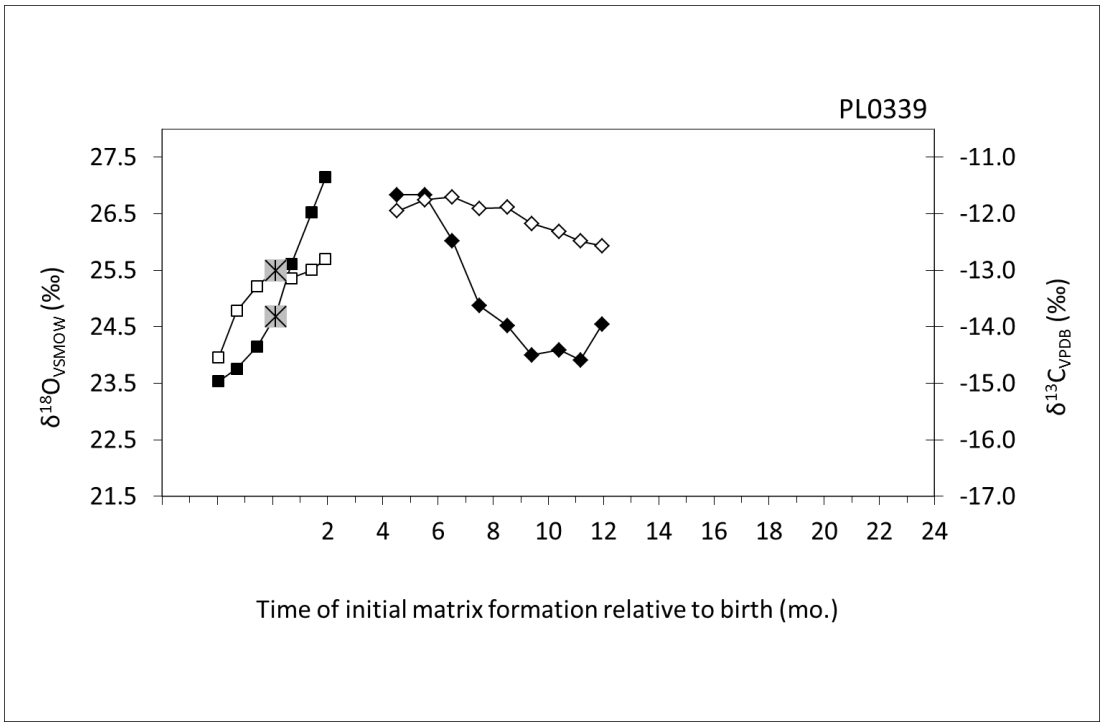

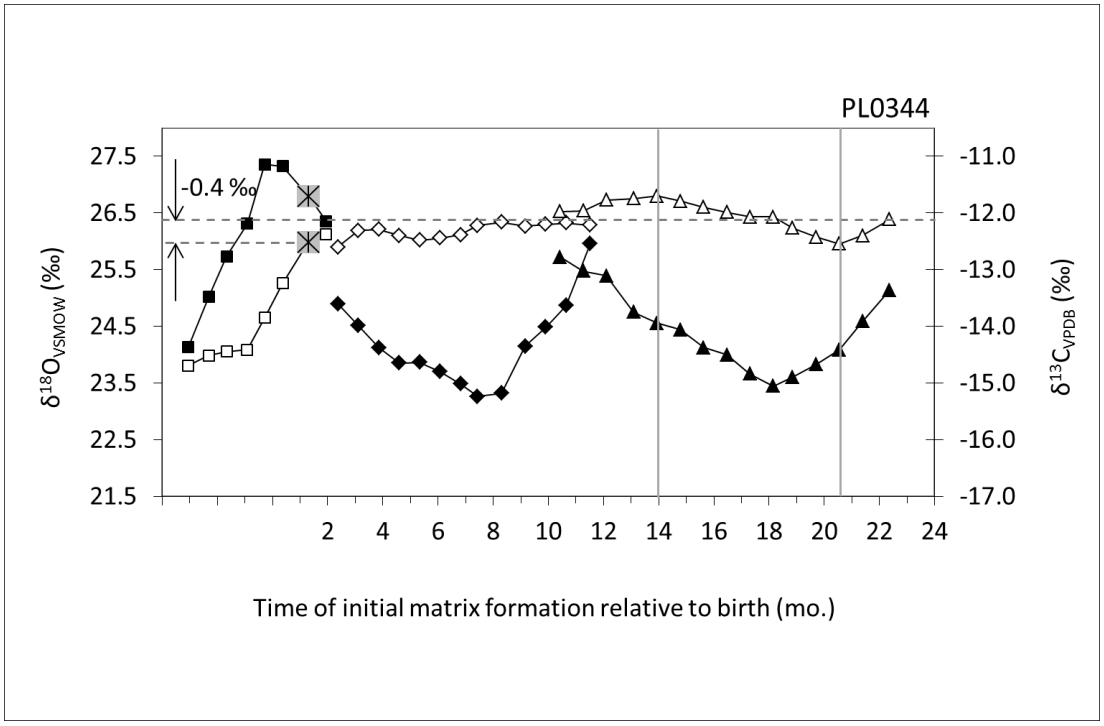

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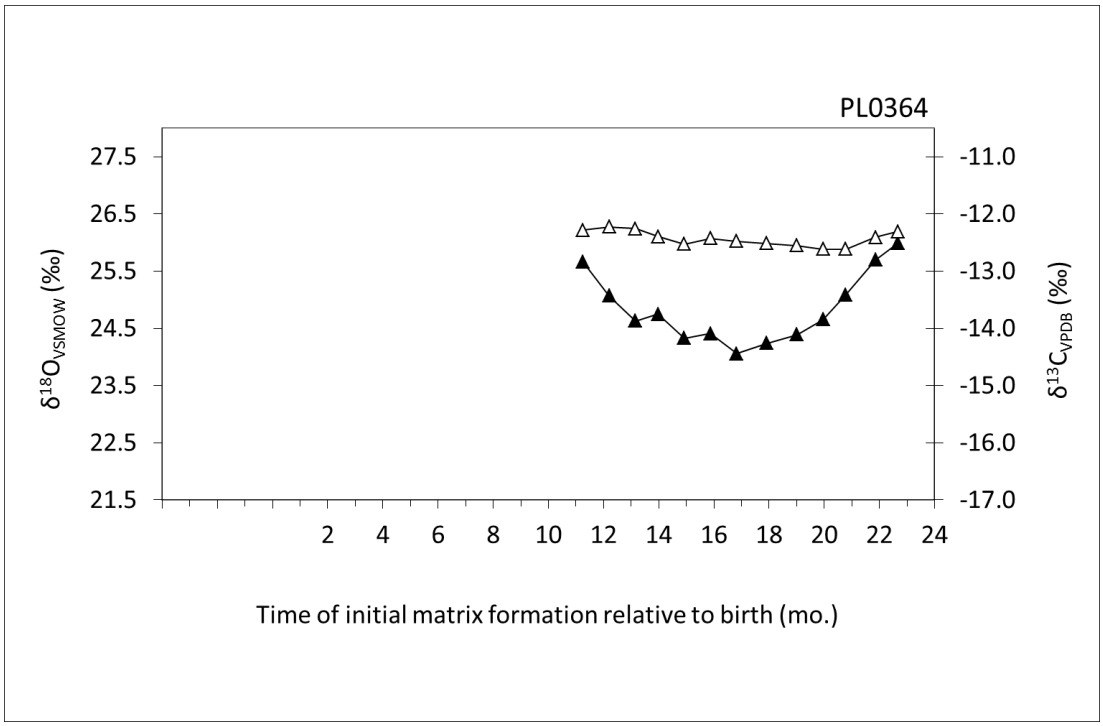

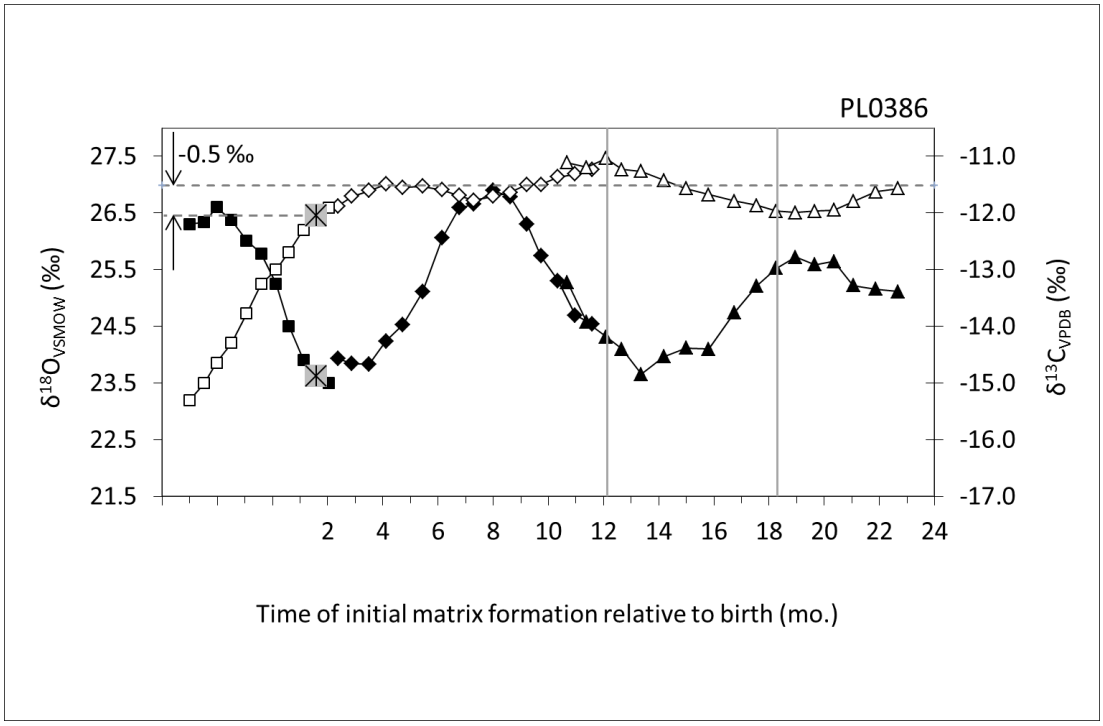

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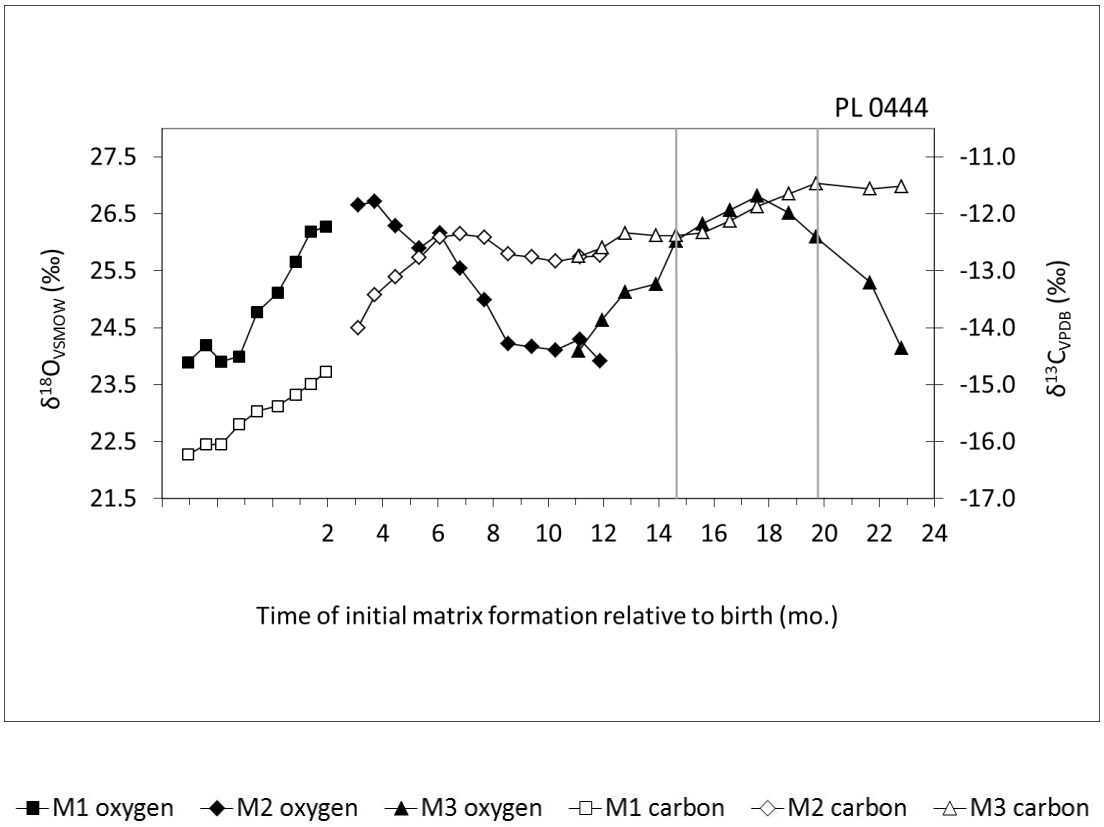


Figure 13.1: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from nine Pool cattle. The grey crossed square symbols indicate the change in gradient of the first molar $\delta^{13}C$ profile and the equivalent position in the $\delta^{18}O$ profile ($\delta^{13}C_{CG}$ and $\delta^{18}O_{CG}$). For animals with first and third molar data, the dashed lines define the value of $\delta^{13}C_{CG}$ and the mid-range $\delta^{13}C$ value for third molar enamel. The latter was calculated as follows: (maximum M3 $\delta^{13}C$ value + minimum M3 $\delta^{13}C$ value)/2. The solid lines indicate features discussed in the text. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

13.1.2 Estimation of birth seasonality and season of birth

For the Pool profiles displayed in Figure 13.1, the timing of each $\delta^{18}O$ minimum and maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3). All timings are presented in Table 13.1 and form the basis of estimating cattle birth seasonality using the method designated method 2 (Section 12.2). For each animal with first molar data, the change in gradient of the first molar $\delta^{13}C$ profile, $\delta^{13}C_{CG}$, believed to indicate the completion of rumen functionality (Section 11.1), and the equivalent position in the $\delta^{18}O$ profile, $\delta^{18}O_{CG}$, are indicated by grey crossed square symbols (excluding PL0444 for which $\delta^{13}C_{CG}$ cannot be identified). These data-points require identification in order to estimate birth seasonality using the method designated

method 3 (Section 12.3). In each case, $\delta^{18}O_{CG}$ has been assigned an angle, A_{CG}, relative to its position along the sinusoidal curve using the procedure outlined in Section 12.3 for method 3. Values of A_{CG} together with the parameters required for their calculation (Figure 12.7) are presented in Table 13.2.

Figure 13.2 is a plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Pool cattle. Second molar minima timings are also shown as a horizontal line of data-points running along the bottom of the plot. Included here is one individual, PL0444, for which there is no measured values of A_{CG} because $\delta^{13}C_{CG}$ is not identifiable. The timings of what might be regarded as the main group of four data-points lie between 2 and 7 months while those of the remaining two are approximately 10 months. Since 360° represents 12 months and there are 273° separating the two extreme individuals, PL0386 and PL0339, the distribution of births calculated from values of A_{CG} is (273/360) x 12 = 9.1 months (method 3). An alternative calculation from second molar $\delta^{18}O$ minima timings produces a distribution of 10.3 – 2.4 = 7.9 months (method 2). In this case, the results from methods 2 and 3 are in reasonable agreement, suggesting a distribution of ~ 8-9 months. Figure 13.3 is a plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Pool cattle. Again, minima timings are also shown as a horizontal line of data-points running along the bottom of the plot. Two of the eight $\delta^{18}O$ profiles comprise third molar $\delta^{18}O$ maxima only and minima timings were calculated from the maxima timings assuming a separation of 6 months. Although not used to calculate the distribution of births, the plot is broadly similar to that of second molar minima timings (Figure 13.2) and shows that timings from additional third molars lie within the main group.

Table 13.1: $\delta^{18}O$ minima and maxima timings for Pool second and third molars.

	Predicted time after birth (months)			
Animal	**M2 $\delta^{18}O$ minimum (min 1)**	**$\delta^{18}O$ maximum (max 1)**	**M3 $\delta^{18}O$ minimum (min 2)**	**$\delta^{18}O$ maximum (max 2)**
PL0025			16.7	

PL0278	4.5	9.4	14.5	
PL0302				21.3
PL0330	4.9	10.5	15.3	21.3
PL0339	10.3			
PL0344	6.7	11.8	18.2	
PL0364			16.9	
PL0386	2.4	7.9	13.7	19.3
PL0444	10.1	17.5		

Table 13.2: Angular positions (A_{CG}) of $\delta^{18}O_{CG}$ on the $\delta^{18}O$ profile for the Pool cattle. * $\delta^{18}O_{CG}$ falls at $\delta^{18}O_{max}$.

Animal	$\delta^{18}O_{max}$ (‰)	$\delta^{18}O_{min}$ (‰)	$\delta^{18}O_{CG}$ (‰)	Position of $\delta^{18}O_{CG}$ on sinusoidal curve	Angle A_{CG} (°)
PL0278	26.46	23.81	25.1	falling slope	91
PL0330		* see note		at maximum	0
PL0339	27.31	23.47	24.7	rising slope	-112
PL0344	27.28	23.46	26.8	falling slope	42
PL0386	26.47	23.55	23.6	falling slope	161

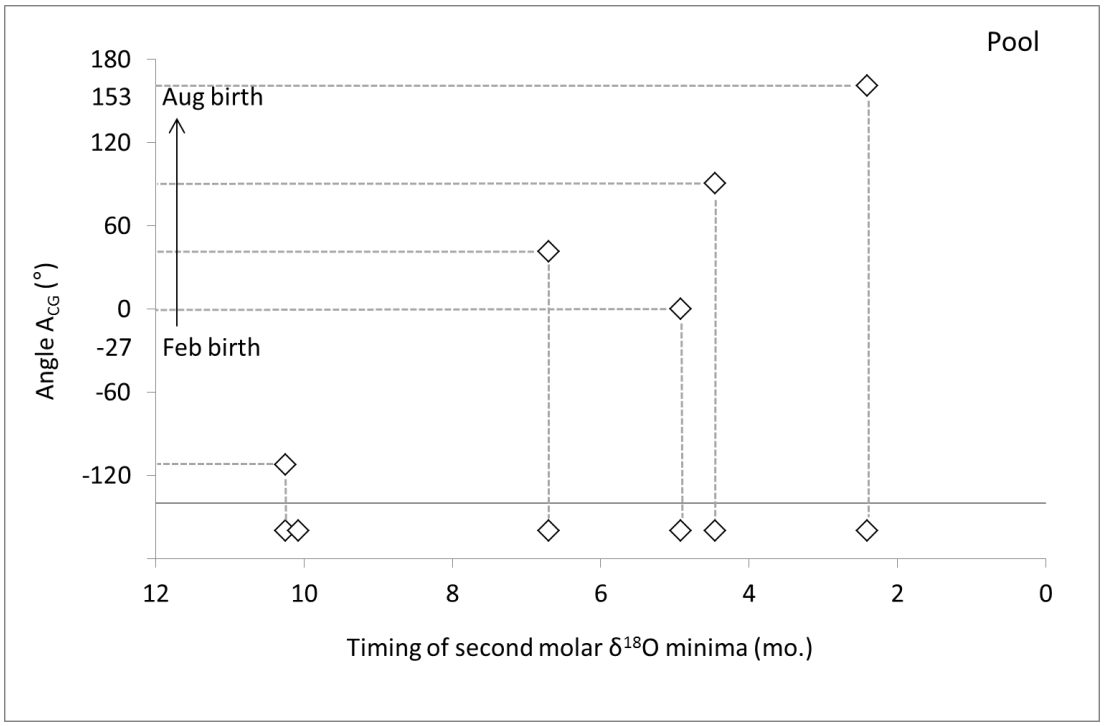


Figure 13.2: Plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Pool cattle.

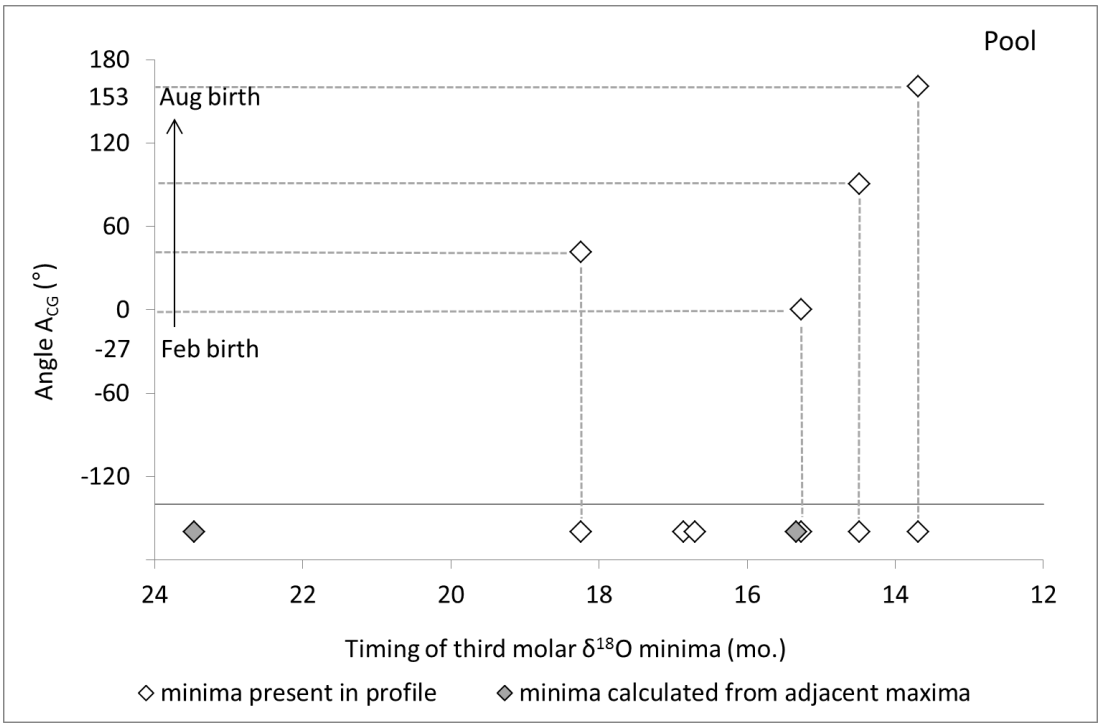


Figure 13.3: Plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Pool cattle. A six month separation is assumed for minima calculated from adjacent maxima.

To estimate season of birth for the Pool animals, it is assumed that an angle A_{CG} of -27° represents a February birth, as determined for the modern Dexter bull (KAR) of known birth date included in this study (Section 12.5). The month of birth for each Pool animal with an assigned value of A_{CG} is estimated from the difference in A_{CG} between the animal in question and the Dexter. Season of birth is then assigned using the following definitions: spring = March, April, May; summer = June, July, August; autumn = September, October, November; and winter = December, January, February. Results are displayed in Table 13.3 and show that these five cattle appear to have been born during three seasons of the year: spring, summer and autumn. Of the nine cattle included in this study, it is likely that seven were born during the six-month spring-summer period while two were born in the autumn.

Table 13.3: Estimated season of birth for each Pool animal.

Animal	Angle A_{CG} (°)	Difference in angle A_{CG} between Pool animal and the Dexter (A_{CG} = -27°) (°)	Approximate month of birth	Season of birth
PL0278	91	+118	June	summer
PL0330	0	+27	March	spring
PL0339	-112	-85	November	autumn
PL0344	42	+69	April	spring
PL0386	161	+188	August	summer

13.1.3 Diet and environment

In Section 9.3.2, the summary in Table 9.3 and the plot of third molar enamel $\delta^{13}C$ data in Figure 9.11, reproduced and expanded in Figure 13.4 below, show that the mid-range $\delta^{13}C$ value for all Pool third molars is 0.5 ‰ higher than the equivalent values for Earl's Bu and Mine Howe. There are a number of possible explanations for this difference. The relatively elevated enamel $\delta^{13}C$ values for Pool could have arisen from the consumption of seaweed. However, although the consumption of seaweed cannot be ruled out, it is unlikely to have been a significant component in the diet of the Pool cattle otherwise enamel $\delta^{13}C$ values would be higher still. Probable consumption of seaweed by two archaeological sheep, one from Iron Age Mine Howe and the other from Neolithic Point of Cott (also in Orkney), has produced enamel $\delta^{13}C$ values of > -9 ‰ (Balasse et al 2009). The $\delta^{13}C$ and $\delta^{18}O$ profiles for those animals were anti-phase suggesting seaweed consumption occurred during the winter (ibid). There are no $\delta^{13}C$ profiles amongst the Pool plots that are similar. Instead third molar levels are comparable to those measured for cattle enamel from Neolithic Knap of Howar, Orkney, interpreted as consuming C_3 terrestrial vegetation all year round (Balasse et al 2006). The relatively elevated enamel $\delta^{13}C$ values for Pool compared to those of Earl's Bu and Mine Howe may be the result of differences in local environment. Two factors likely to have been influential in raising vegetation $\delta^{13}C$ values are drier growing conditions due to the sandy soils in the vicinity of Pool (Section 6.1) and soil salinity levels (Section 3.3), which may have been very high according to the strontium concentration measurement of cattle enamel from Pool (Section 9.2). One of the modern vegetation samples collected for the present study from a coastal location in

Sanday, Orkney, had a $\delta^{13}C$ value of -24.8 ‰, > 2σ above the mean value of -28.6 ‰ for 18 samples collected from around Orkney (Section 9.1.3). Jones et al (2012) suggested increased soil salinity levels due to sea-spray as a possible cause of relatively high bone collagen $\delta^{13}C$ values for archaeological fauna from the Outer Hebrides (Section 5.3).

When attempting to obtain information from enamel $\delta^{13}C$ profiles such as those shown in Figure 13.1, a starting point might be to look for evidence of grazing the same vegetation outside all year round. The resulting enamel $\delta^{13}C$ profile might be expected to show a seasonal variation in $\delta^{13}C$ that co-varies with the $\delta^{18}O$ profile. This pattern has been observed in data obtained for this study from the Chillingham cattle, although possibly modified by the consumption of supplementary hay in winter (Section 11.3.2 and Figure 11.6) and in the profiles of modern sheep from Rousay, Orkney (Balasse et al 2009). In the latter, there was a temporal shift of ~2-3 months between the $\delta^{13}C$ and $\delta^{18}O$ profiles (Figure 5.3). In the profiles of PL0278, PL0330, PL0344 and PL0386 there is patterning that resembles the Rousay profiles, albeit at a reduced amplitude: a maximum in the $\delta^{13}C$ profile followed by a minimum approximately six months later. These $\delta^{13}C$ maxima and minima are indicated by two solid lines parallel to the y-axis in each of the relevant plots (Figure 13.1). On closer inspection, the line indicating the $\delta^{13}C$ minimum for PL0278, PL0344 and PL0386 crosses the sinusoidal curve of the $\delta^{18}O$ profile approximately 1.5 cycles after $\delta^{13}C_{CG}$, i.e. 18 months later. Therefore the $\delta^{13}C$ minima and maxima six months earlier appear to be related to age rather than the time of year, possibly indicating a change in diet through fodder provision or movement between grazing areas. PL0330 shows the same patterning but with a separation between $\delta^{13}C_{CG}$ and the $\delta^{13}C$ minimum of approximately two years. The only other Pool animal for which all three molars were analysed, PL0444, has a third molar $\delta^{13}C$ profile that is distinct from those of the four cattle discussed above. However, the two solid lines parallel to the y-axis on the plot for PL0444 in Figure 13.1 indicate $\delta^{13}C$ values that are similar to those indicated by such lines for PL0278, PL0330, PL0344 and PL0386, but occur in the reverse order. They may represent the same food sources. The $\delta^{13}C$ profile of PL0444 is distinct in other respects and may reflect a different husbandry

regime, perhaps related to the time of year the animal was born (autumn), or movement from elsewhere (see Section 13.1.4 for further discussion). The $\delta^{13}C$ profiles for PL0025 and PL0364 show very little variation, possibly indicating that husbandry is masking the seasonal variation in vegetation $\delta^{13}C$ values. Unfortunately, the seasonal variation in vegetation $\delta^{13}C$ values for Pool is not known. The $\delta^{13}C$ profile for PL0302 is too short for any interpretation to be attempted.

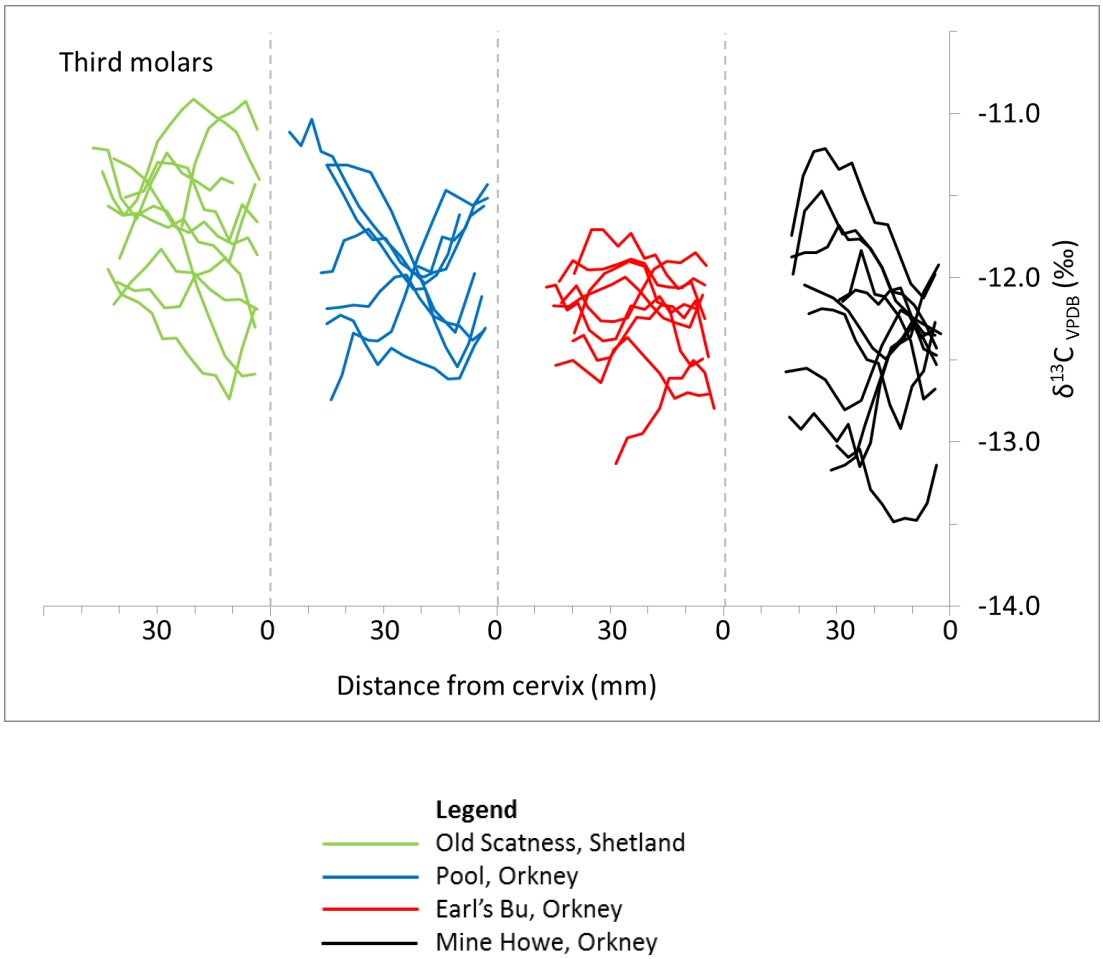


Figure 13.4: Intra-tooth enamel $\delta^{13}C_{VPDB}$ values versus distance from cervix for cattle third molars from the Northern Isles. Analytical error is ± 0.1 ‰ (1σ).

13.1.4 Exploring weaning strategy

In Section 11.2, it was observed that for each modern Chillingham animal included in this study, the mid-range $\delta^{13}C$ value for third molar enamel is elevated relative to the value of $\delta^{13}C_{CG}$. The proposed explanation is that this offset might be related to weaning, that the $\delta^{13}C$ profiles of naturally weaned animals, such as the Chillingham cattle, would be expected to rise for several months after the completion of rumen functionality as the proportion of milk in their diet gradually reduced. Conversely, much reduced offsets might be expected in the $\delta^{13}C$ profiles of cattle either fully weaned at an early age through human intervention, or allowed only restricted access to their mothers' milk from an early age, potentially from the time the rumen becomes fully functional at 6-10 weeks.

Offset values have been calculated for those Pool cattle with first and third molar data (excluding PL0444). They are shown on the relevant plots in Figure 13.1 and vary between +0.2 ‰ for PL0278, where the value of $\delta^{13}C_{CG}$ is more positive than the third molar mid-range $\delta^{13}C$ value, and -0.7 ‰ for PL0330. Figure 13.5 displays the offset values calculated for both Pool and Chillingham cattle. Comparison between the two sets of data indicates that the offsets for all four Pool cattle are less than those for the Chillingham cattle, perhaps suggesting that the Pool animals were actively weaned at a young age through human intervention. Two Pool cattle for which offset values could not be calculated are PL0339 and PL0444, the former because there is no third molar data, the latter because $\delta^{13}C_{CG}$ cannot be identified. According to the analysis in Section 13.1.2 above, these two animals are likely to have been born in the autumn. If they were born at a similar time of year, then $\delta 13C_{CG}$ for PL0444 is expected to fall approximately midway along the first molar profile. The value of $\delta^{13}C_{CG}$ for PL0339 is -13 ‰ compared to a probable value of < -15 ‰ for PL0444. The subsequent rise to third molar $\delta^{13}C$ levels is significantly greater for PL0444 than predicted for PL0339, which may be due to weaning strategy, PL0444 having had access to its mother's milk for a longer period of time after birth. Alternatively, PL0444, initially via its mother's milk, may have experienced an increase in vegetation $\delta^{13}C$ value during its early life, perhaps

brought about through movement. This may have been within the local area or from further afield. Strontium isotope ratio and concentration values for second molar cuspal enamel from PL0444 suggest a birth place consistent with Pool. However, similar coastal locations, for example on Shetland or the Western Isles of Scotland, cannot be excluded as possible birth places. The appearance of PL0444 in Figure 12.13 as an outlier with respect to third molar crown formation may also support origins elsewhere.

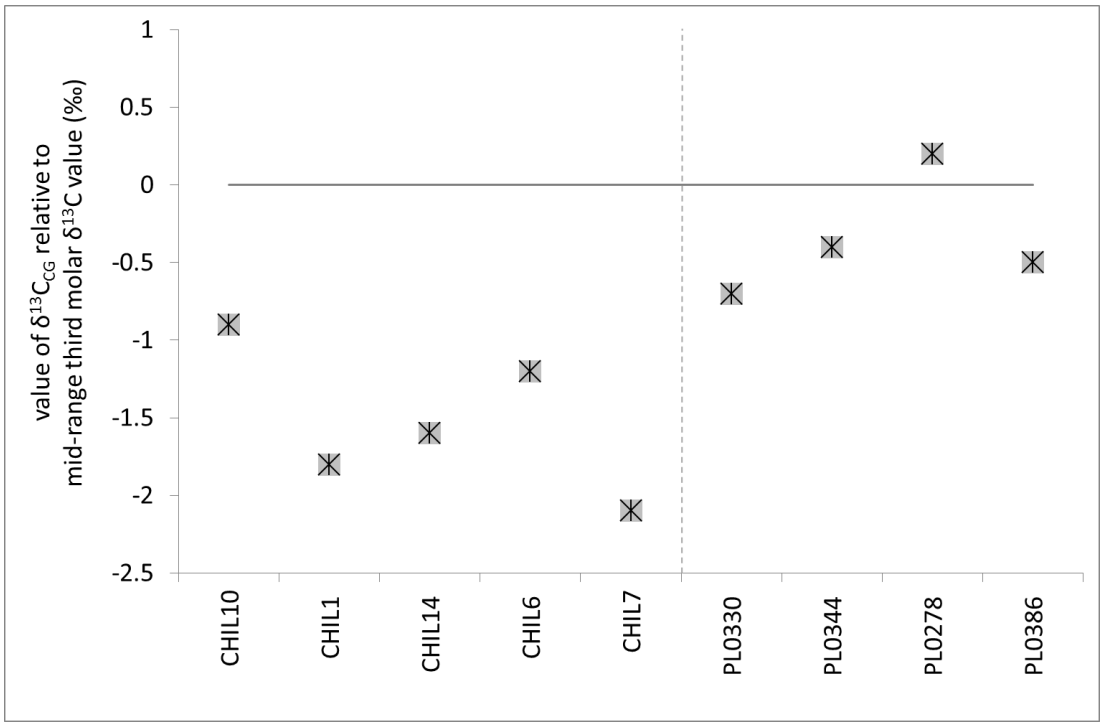


Figure 13.5: Value of $\delta^{13}C_{CG}$ (grey crossed square symbols) relative to the mid-range third molar $\delta^{13}C$ value (horizontal line).

13.1.5 Discussion

Intra-tooth isotope ratio analysis of molar enamel from nine Pool cattle strongly suggests that calving occurred during spring, summer and autumn (Section 13.1.2). The husbandry effort required to achieve calving during at least three seasons of the year would have been considerable according to the reasons proposed in Section 2.1 and would not have been optimally efficient for an economy focussed on the production of meat or storable dairy products (Sections 2.2.1 and 2.2.3). Instead, the likely motivation for this calving pattern was the production of fresh

milk throughout the year (Section 2.2.2). Thus, the information regarding birth seasonality and season of birth obtained through intra-tooth isotope ratio analysis of molar enamel supports the interpretation of a dairy-focussed economy at Pool during the Interface period as suggested by its mortality profile (Serjeantson and Bond 2007a) (Section 6.6), but additionally proposes an emphasis on fresh milk rather than the production of dairy products for long-term storage. Of course, an emphasis on fresh milk would not have excluded the production of storable dairy products or the taking of some animals for meat, which was probably the fate of most of the Pool animals included in the present study. For several of these cattle, it is tentatively proposed that weaning was carried out at an early age through human intervention (Section 13.1.4), which, if true, also supports a dairy-focussed economy. Through early weaning a greater proportion of the milk produced would have been available for human consumption.

Multiple-season calving at Pool during the Interface period implies not only a high level of organisational competence in the detection and mating of oestrous cows, which would have been more difficult during the winter months, but also that food of sufficient quantity and quality was available throughout the year (Section 2.1). The apparent intensification of oat production at Pool during the Interface period suggests that this was possible. Cultivated oats, probably introduced to the Northern Isles during the first few centuries AD, have the advantage that, unlike barley, they do not require much in the way of manuring and can be grown on poor land (Bond 2003). Hence, the production of oats could have been achieved with a relatively modest amount of effort. Oats would have provided a highly nutritious addition to other possible sources of fodder for cattle such as barley stubble and straw, hay and arable weeds (Serjeantson and Bond 2007b). Barley grains may also have been used as fodder. Seaweed was certainly fed to Orcadian cattle in historical times (Fenton 1997 p428). However, intra-tooth enamel $\delta^{13}C$ profiles for the nine Pool cattle included in the present study suggest that seaweed was unlikely to have been a significant dietary component during the Interface period (Section 13.1.3). Further evidence of an adequate supply of food, at least for the human population, derives from faunal remains from Pictish and Norse Orkney, including Pool,

indicating an under-utilisation of wild resources such as birds and shellfish (Bond 1998). Alternatively, an under-utilisation of wild resources may be indicative of a labour-intensive farming system. The case for sufficient winter fodder questions the argument put forward by McCormick (1998) that the high mortality of very young calves at Orcadian sites such as Pool was a result of fodder shortage in the winter rather than a consequence of a dairying economy (Section 6.6).

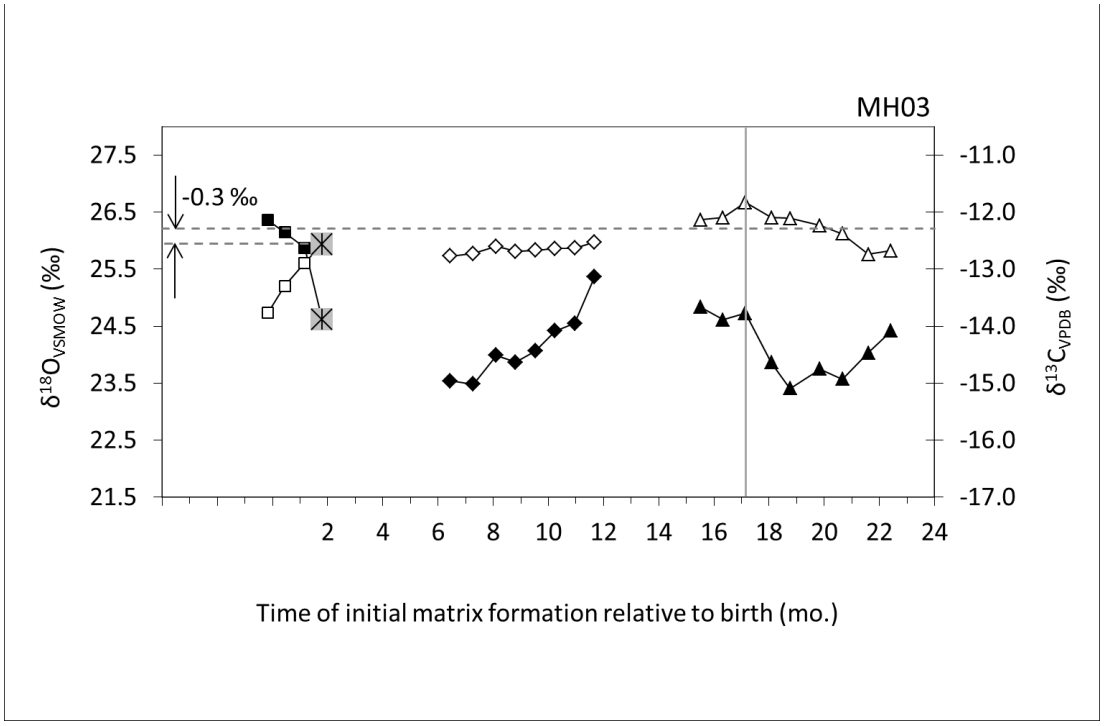
Unfortunately, identification of the various possible C_3 food sources consumed by Pool cattle has not been possible using intra-tooth $\delta^{13}C$ profiles recorded in cattle molar enamel. Distinguishing between grain-rich fodder and grazed vegetation would be particularly useful, given the apparent importance of oats during the Interface period at Pool. In terms of vegetation $\delta^{13}C$ values, black oats and bere barley, traditional crop varieties that may show similar characteristics to those grown during the First Millennium AD, are indistinguishable from Northern Isles unimproved vegetation (Sections 9.1.3). However, it is possible that differences in digestibility and ruminal methane production between grains and grazed pasture may be detectable in enamel $\delta^{13}C$ values (Section 3.3). Controlled diet experiments on modern ruminants would be required to determine the magnitudes involved and whether grain-rich fodder and pasture can ever be differentiated in enamel.

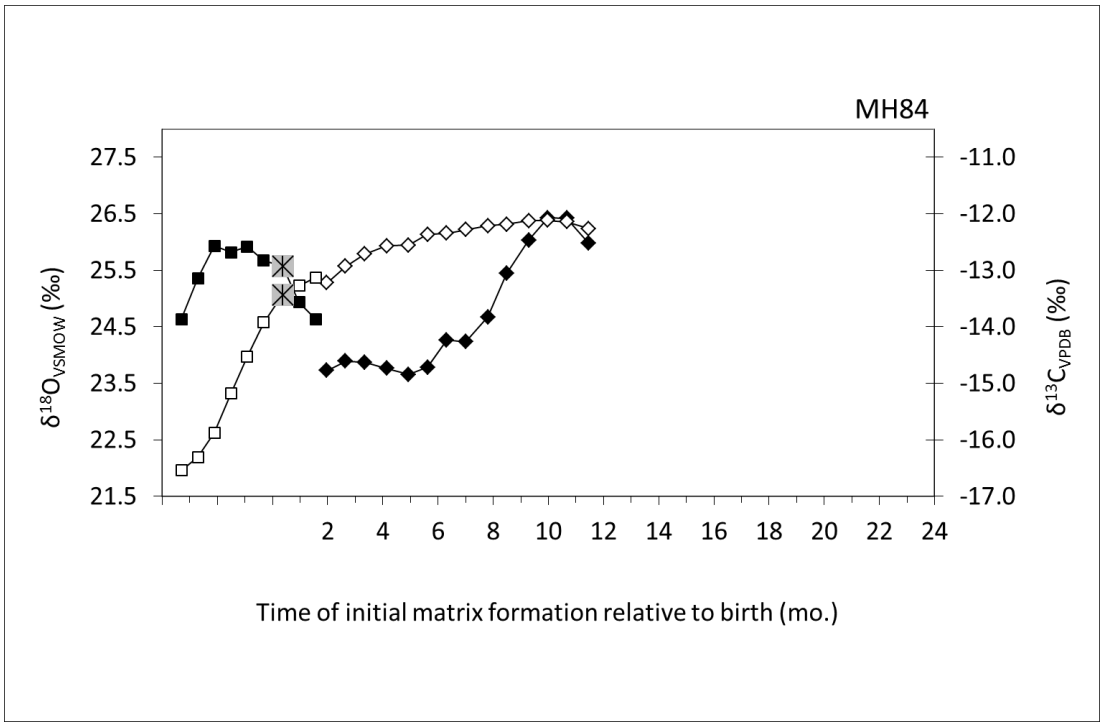
Although identification of particular C_3 food sources has not been possible, examination of intra-tooth $\delta^{13}C$ profiles for Pool cattle has allowed the identification of a recurring pattern for four of the animals (Section 13.1.3). The pattern appears to be related to age rather than time of year, possibly indicating a change in diet through fodder provision or movement between grazing areas. According to the wear stages of their molars (D and E, Halstead 1985), all four animals were slaughtered at a prime age for beef. It is possible that the dietary strategy adopted for these particular cattle was targeted towards meat production and was different to that adopted for milk cows. Thus, it is possible to detect evidence for cattle husbandry strategies in the $\delta^{13}C$ profiles recorded in cattle molar enamel, despite an inability to interpret the profiles in absolute terms.

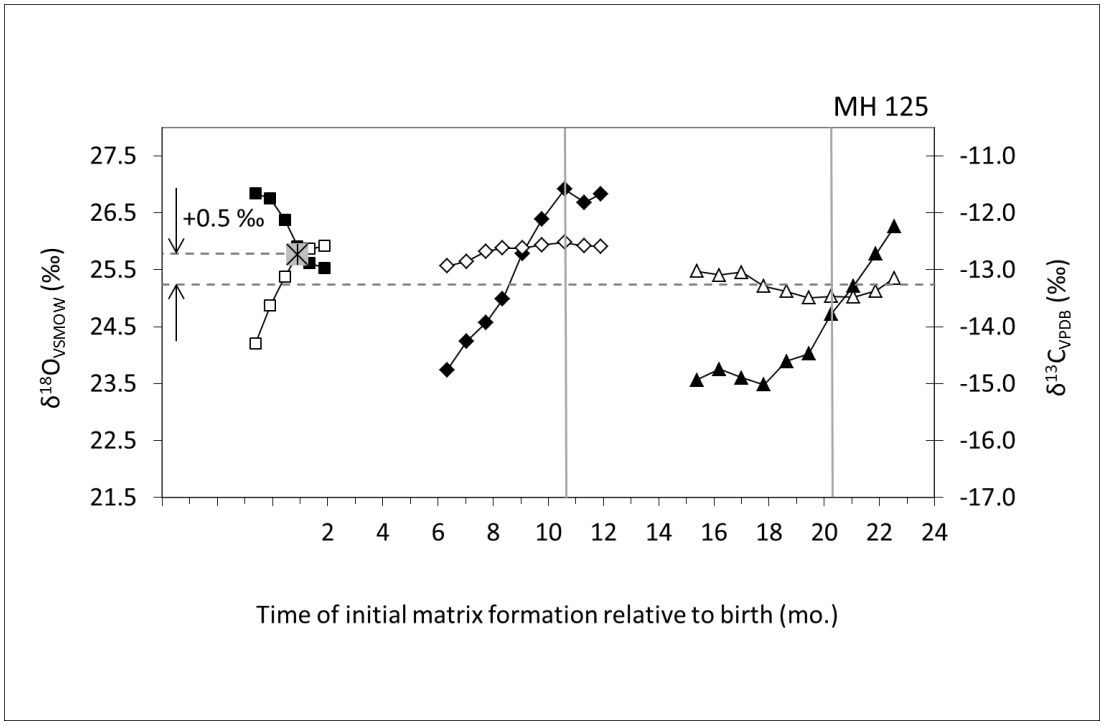
13.2 Mine Howe, Orkney (Mid-Later Iron Age, c. 50 AD – c. 400 AD)

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

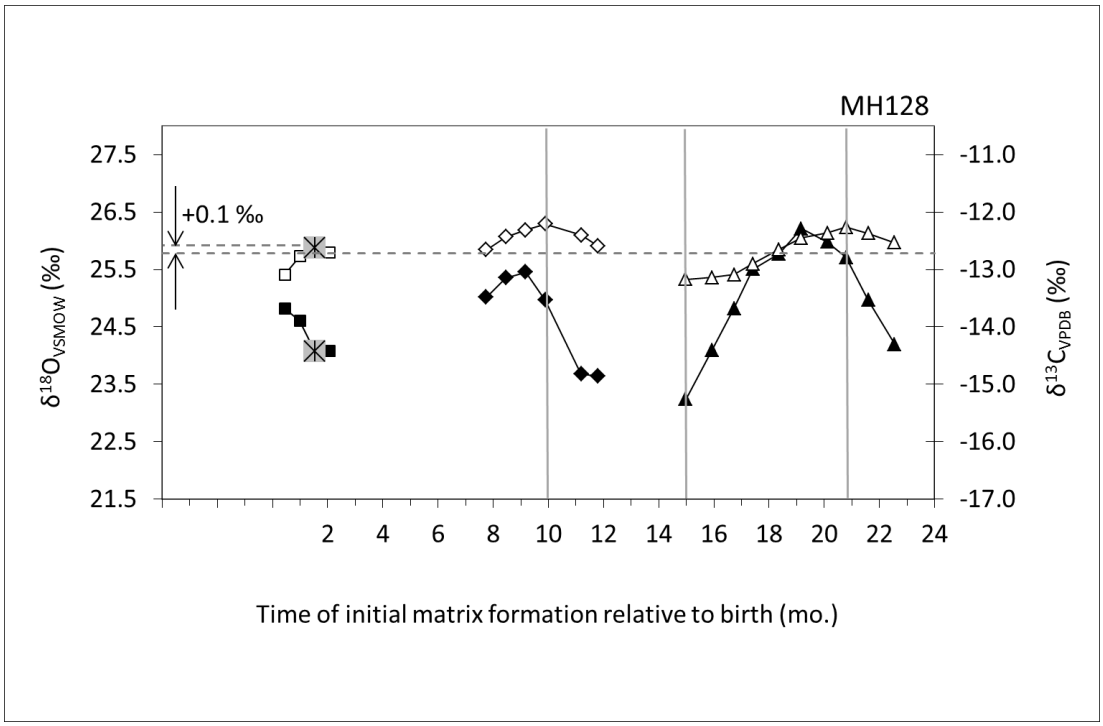
The $\delta^{18}O$ and $\delta^{13}C$ data obtained for all molars from 12 Mine Howe cattle have been plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1 (Figure 13.6).

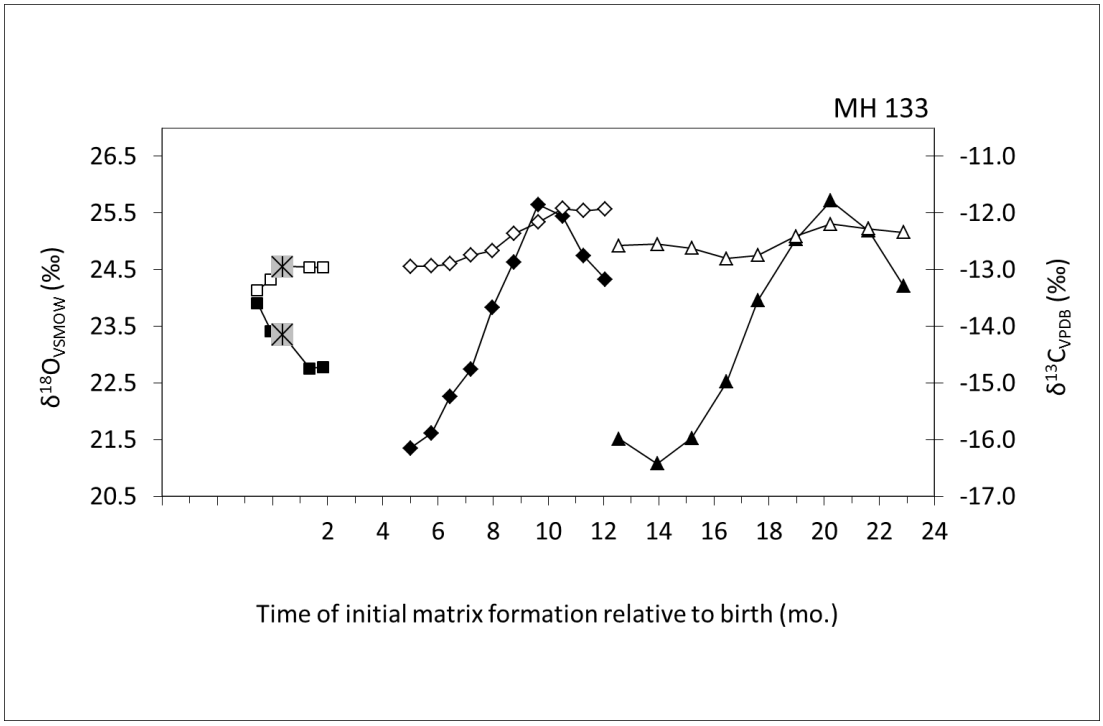




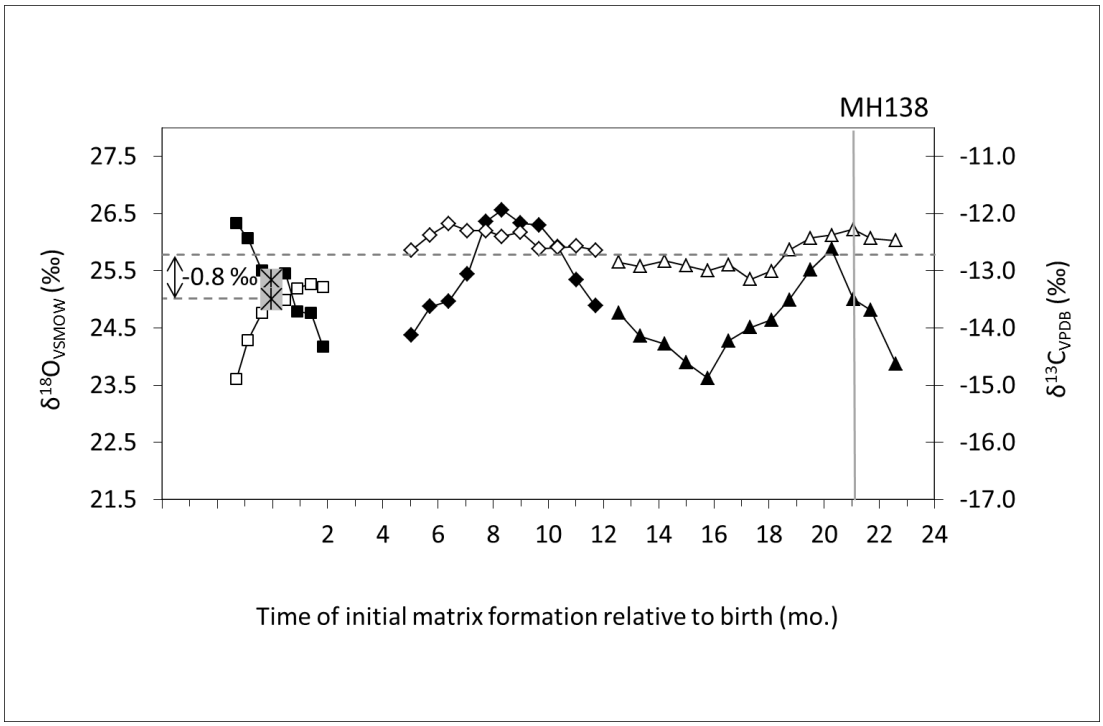


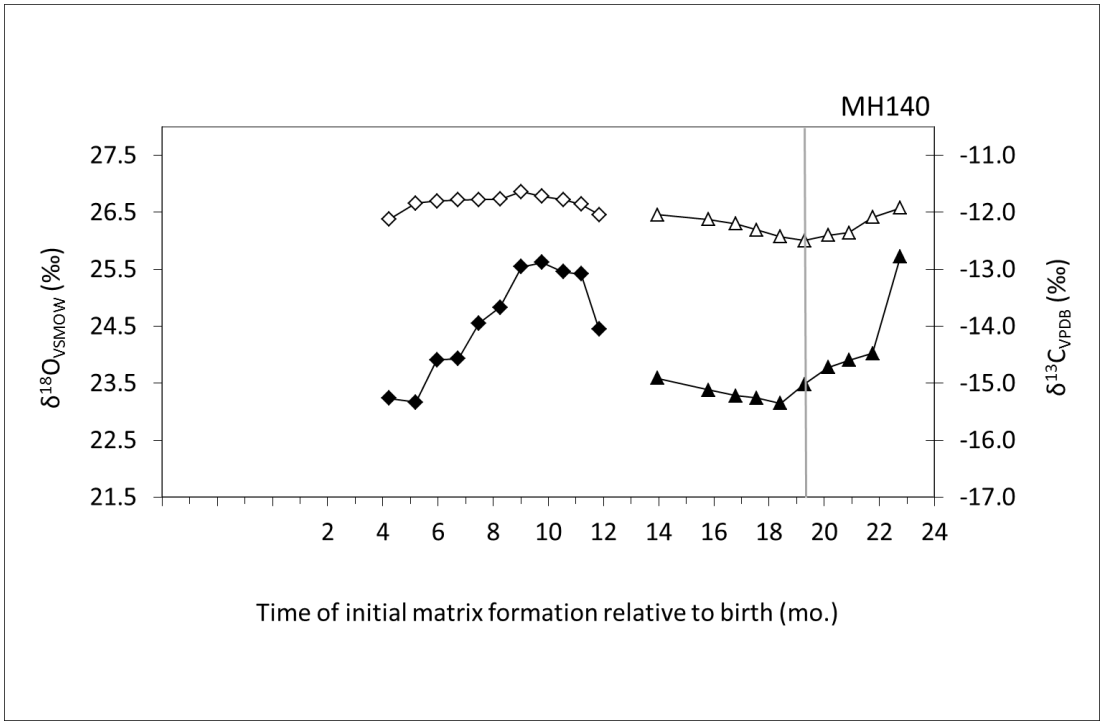
M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon



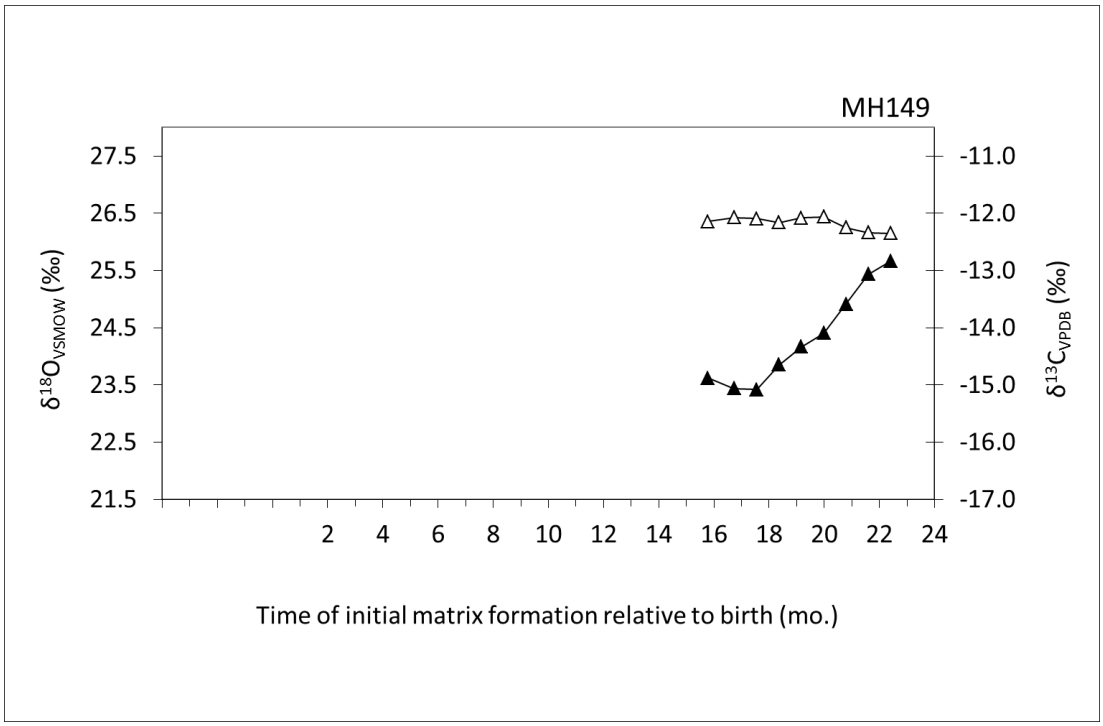


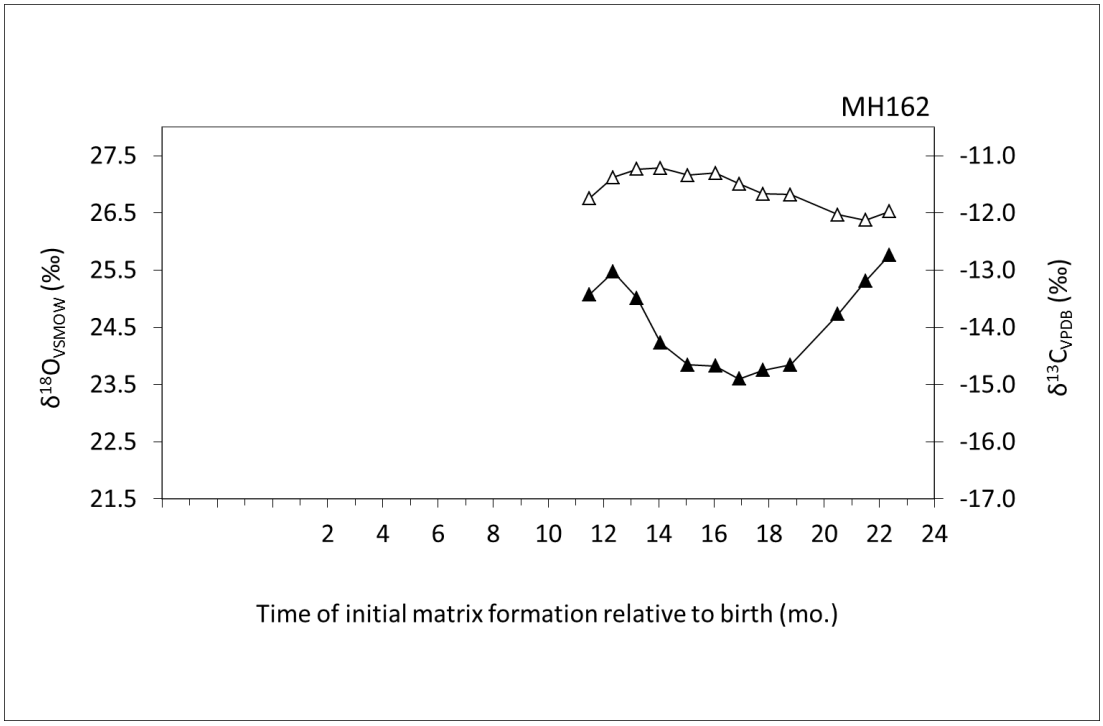
M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon



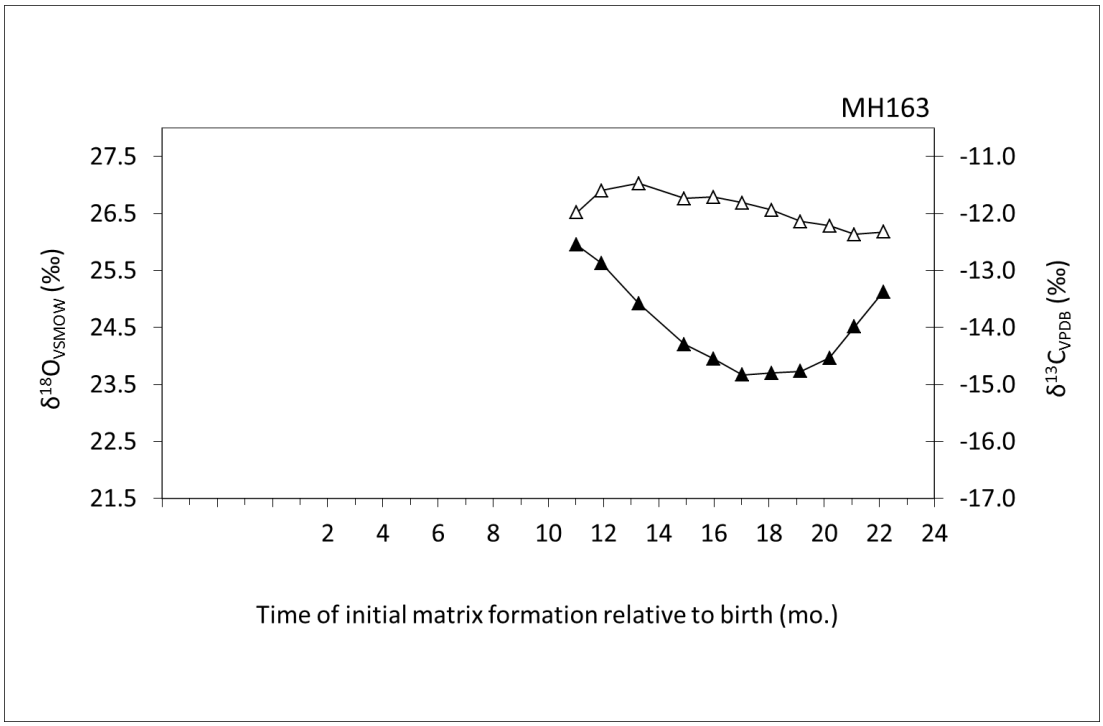


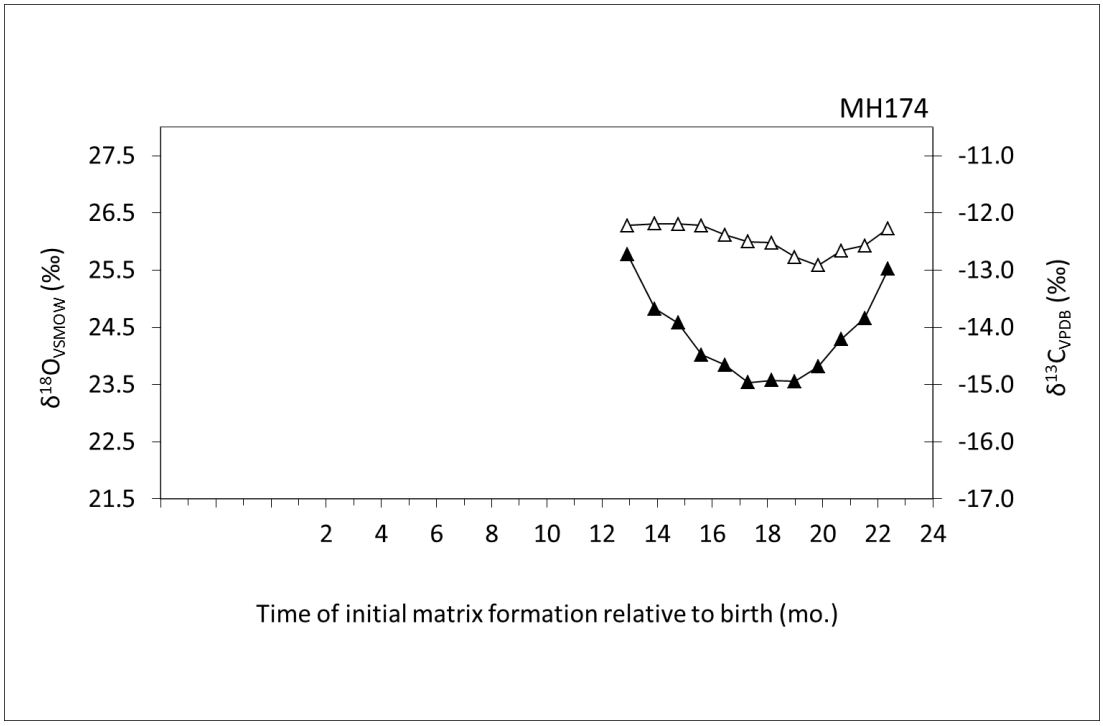
M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon





M3 oxygen M3 carbon





M3 oxygen M3 carbon

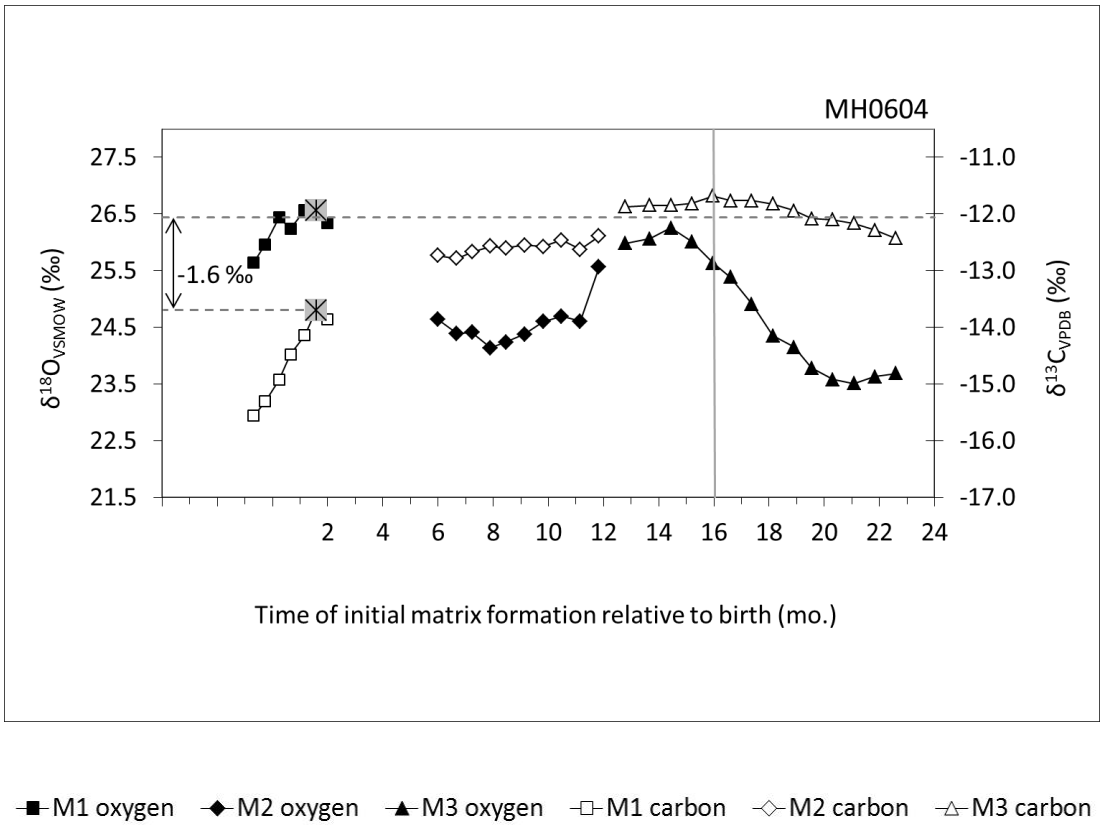


Figure 13.6: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from 12 Mine Howe cattle. The grey crossed square symbols indicate the change in gradient of the first molar $\delta^{13}C$ profile and the equivalent position in the $\delta^{18}O$ profile ($\delta^{13}C_{CG}$ and $\delta^{18}O_{CG}$). For animals with first and third molar data, the dashed lines define the value of $\delta^{13}C_{CG}$ and the mid-range $\delta^{13}C$ value for third molar enamel. The latter was calculated as follows: (maximum M3 $\delta^{13}C$ value + minimum M3 $\delta^{13}C$ value)/2. The solid lines indicate features discussed in the text. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

13.2.2 Estimation of birth seasonality and season of birth

For the Mine Howe profiles displayed in Figure 13.6, the timing of each $\delta^{18}O$ minimum and maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3). All timings are presented in Table 13.4. In addition, values of A_{CG} have been assigned to those animals with first molar data using the procedure outlined in Section 12.3. They are presented in Table 13.5.

Figure 13.7 is a plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Mine Howe cattle. As in a similar plot for Pool cattle, second molar minima timings are also shown as a horizontal line of data-points running along the bottom of the plot which includes one individual for which there is no measured value of A_{CG}. The timings of all data-points lie between 2.6 months for MH128 and 8.0 months for MH0604 producing an overall distribution of births of 5.4 months (method 2). Alternatively, the distribution of births, calculated from values of A_{CG} is (134/360) x 12 = 4.5 months (method 3). Thus, the results from method 2 as applied to second molar $\delta^{18}O$ minima timings are in reasonable agreement with those from method 3, suggesting a distribution of ~5 months. Figure 13.8 is a plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Mine Howe cattle. Again, minima timings are also shown as a horizontal line of data-points running along the bottom of the plot. The plot shows that timings from additional third molars fall in the centre of the group and do not call into question the distribution calculated above. According to Figure 12.13, crown formation for Mine Howe third molars is much more variable than for Grimes Graves third molars and the bulk of Pool third molars. This variability is reflected by the increased spread of data-points in Figure 13.8, third molar timings producing a distribution of births of 7.8 months.

Table 13.4: $\delta^{18}O$ minima and maxima timings for Mine Howe second and third molars.

	Predicted time after birth (months)			
Animal	**M2 $\delta^{18}O$ minimum (min 1)**	**$\delta^{18}O$ maximum (max 1)**	**M3 $\delta^{18}O$ minimum (min 2)**	**$\delta^{18}O$ maximum (max 2)**
MH03	6.3	13.7	19.5	
MH84	4.4	10.3		
MH125	5.4	11.2	17.4	
MH128	2.6	8.8	13.4	19.3
MH133	5.2	10.2	13.9	20.4
MH138	3.4	8.9	15.4	20.1
MH140	3.7	9.9	17.5	
MH149			16.9	
MH162			17.0	
MH163			18.0	
MH174			18.1	
MH0604	8.0	14.0	21.2	

Table 13.5: Angular positions (A_{CG}) of $\delta^{18}O_{CG}$ on the $\delta^{18}O$ profile for the Mine Howe cattle. * $\delta^{13}C_{CG}$ not present in profile. Datapoint closest to cervix used ($\delta^{13}C_{CG}$ falls earlier than a time of 2 months on the x-axis for all cases included in this study). † $\delta^{18}O_{CG}$ falls ~1.1 month (33°) before $\delta^{18}O_{min}$. ‡ value of neighbouring maximum used.

Animal	$\delta^{18}O_{max}$ (‰)	$\delta^{18}O_{min}$ (‰)	$\delta^{18}O_{CG}$ (‰)	Position of $\delta^{18}O_{CG}$ on sinusoidal curve	Angle A_{CG} (°)
MH03	26.32	23.56	24.6 *	falling slope	103
MH84	25.97	23.68	25.6	falling slope	49
MH125	26.85	23.70	25.9	falling slope	66
MH128		† see note		falling slope	147
MH133	25.50 ‡	20.99	23.4	falling slope	87
MH138	26.60 ‡	24.12	25.3	falling slope	91
MH0604	26.52	24.22	26.5	falling slope	13

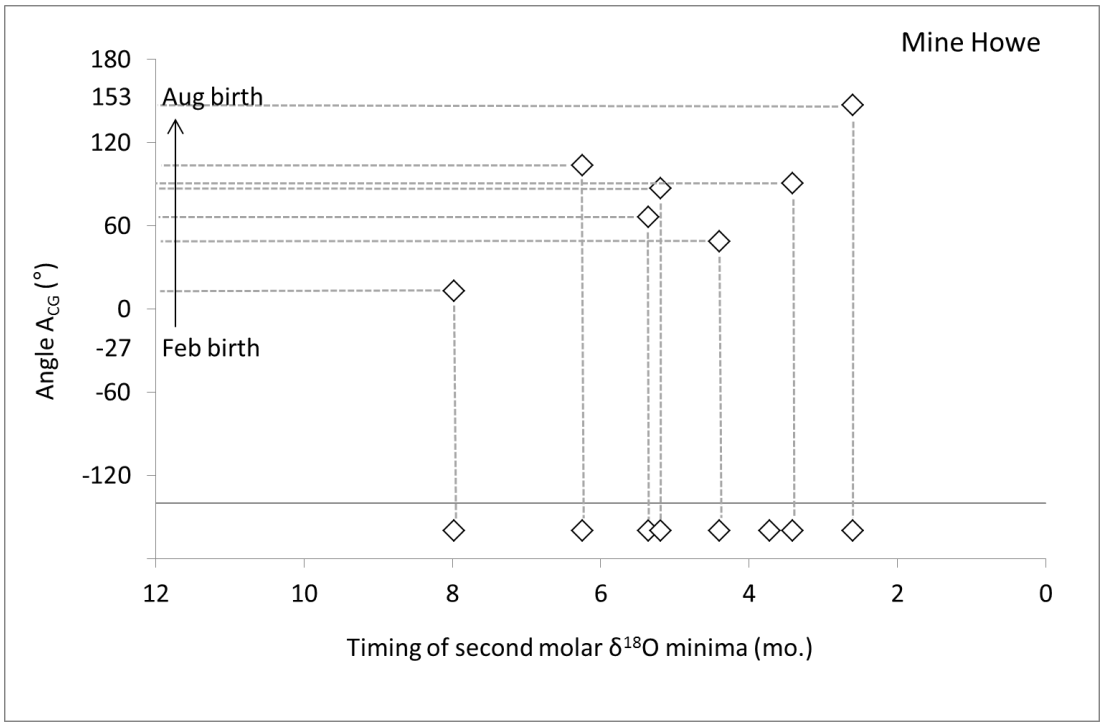


Figure 13.7: Plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Mine Howe cattle.

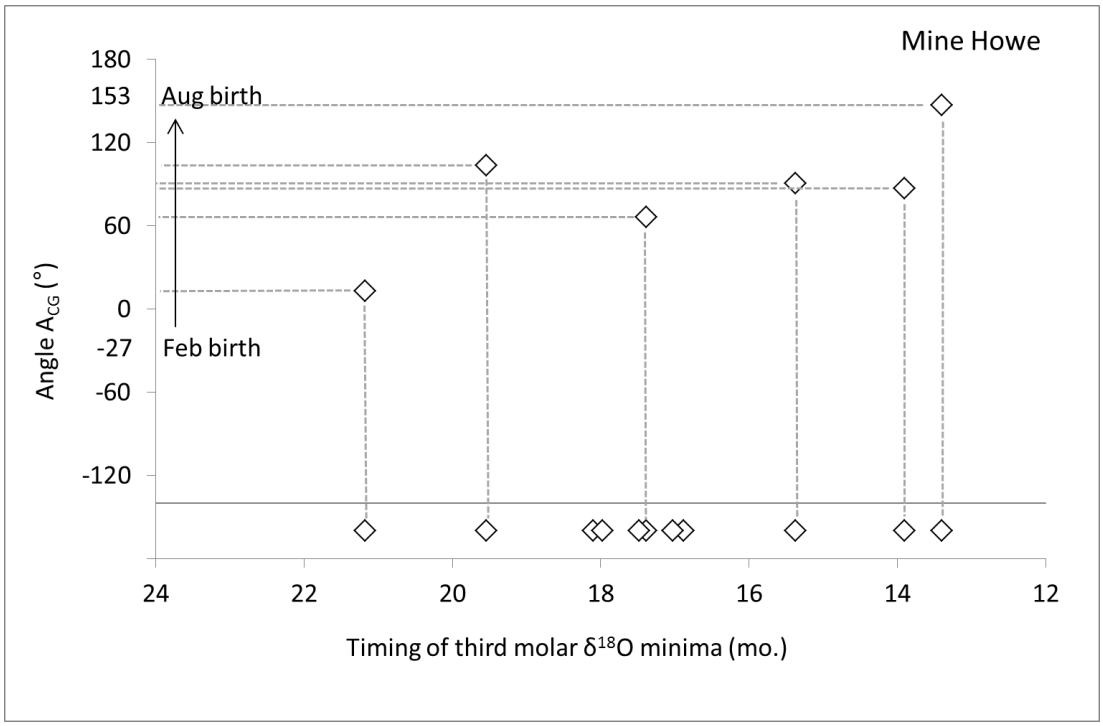


Figure 13.8: Plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Mine Howe cattle.

The month and season of birth for each Mine Howe animal with an assigned value of A_{CG} are estimated using the procedure outlined in Section 13.1.2 for the Pool cattle. Results are displayed in Table 13.6 and show that these seven Mine Howe cattle appear to have been born during two seasons of the year: spring and summer. Figures 13.7 and 13.8 suggest that all 12 cattle included in this study were born during these two seasons.

Table 13.6: Estimated season of birth for each Mine Howe animal.

Animal	Angle A_{CG} (°)	Difference in angle A_{CG} between Mine Howe animal and the Dexter (A_{CG} = -27°) (°)	Approximate month of birth	Season of birth
MH03	103	+130	June	summer
MH84	49	+76	April	spring
MH125	66	+93	May	spring
MH128	147	+174	August	summer
MH133	87	+114	June	summer
MH138	91	+118	June	summer
MH0604	13	+40	March	spring

13.2.3 Diet and environment

The plot of third molar enamel $\delta^{13}C$ data in Figure 13.4 and the summary in Table 9.3 show that the mid-range $\delta^{13}C$ value for all Mine Howe third molars is identical to that of Earl's Bu and 0.5 ‰ lower than that of Pool. As proposed in Section 13.1.4, this may be related to the properties of the local soil. The soil around Pool on the small island of Sanday was probably drier and more saline than the soils around Mine Howe on Mainland Orkney, which would have elevated the $\delta^{13}C$ values of Pool vegetation. Moreover, it is thought that much of the land around Mine Howe in the Iron Age was boggy or wet (Section 6.2), which is likely to have lowered the $\delta^{13}C$ values of the local vegetation. However, the environment in the vicinity of Mine Howe may not be the dominant influence on cattle enamel $\delta^{13}C$ values. Because the overall range of third molar enamel $\delta^{13}C$ values is larger for Mine Howe cattle than for Pool and Earl's Bu cattle (Figure 13.4, Table 9.3), it is possible that the cattle excavated at Mine Howe were raised at various locations around Orkney. Certainly, one of the Mine Howe cattle, MH133, appears not to have been born in Orkney, according to strontium concentration and oxygen isotope ratios of its molar enamel (Sections 9.2 and 9.3.1). However, it was probably living on Orkney by the age of around two years. The relatively large range of third molar enamel $\delta^{13}C$ values for Mine Howe cattle may also reflect long term changes in dietary regime, since the contexts from which the cattle remains were excavated span approximately 350 years.

An examination of the Mine Howe third molar enamel profiles in Figure 13.6 reveals a feature common to six of the 12 cattle (MH03, MH125, MH128, MH138, MH140 and MH0604): the $\delta^{13}C$ 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 solid lines in the relevant plots. The pattern is similar for MH128 and MH0604, animals born approximately five months apart according to the analysis in Section 13.2.2. Therefore, it appears to be related to season rather than age. $\delta^{13}C$ maxima in $\delta^{13}C$ profiles following this pattern resemble the profiles of modern sheep from Rousay, Orkney (Balasse et al 2009)

(Figure 5.3) and may represent grazing outside during the summer months. Tracing the profiles of MH128 back in time, the form of the $\delta^{13}C$ profile appears to be seasonal throughout with a minimum approximately six months before the maximum and an earlier maximum approximately six months before the minimum (indicated by solid lines on the plot in Figure 13.6). This may indicate grazing outside all year round. However, it is not possible to distinguish this from grazing during the summer months and the consumption of fodder with lower $\delta^{13}C$ values during the winter months as illustrated in Figure 13.9. Both recorded profiles show the same sinusoidal-like form. Only the amplitudes are different.

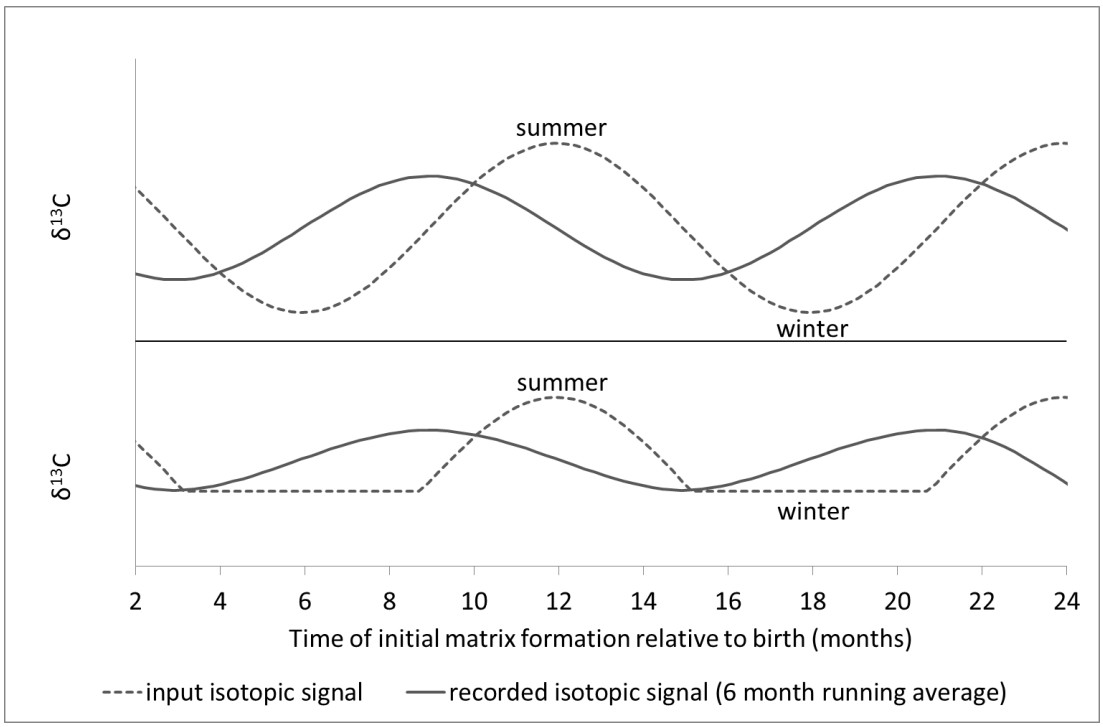


Figure 13.9: Simple model of $\delta^{13}C$ signals recorded in enamel assuming that cattle molar enamel takes approximately six months to fully mineralize, as determined by Balasse (2002) for second molars. The upper profiles represent grazing outside all year round. Those below represent grazing outside during the summer months and the consumption of fodder with lower $\delta^{13}C$ values during the winter months.

Other cattle show different patterns in earlier forming enamel, perhaps indicating different husbandry regimes. For example, the $\delta^{13}C$ profile of MH125 shows a maximum approximately nine or ten months before the third molar minimum (indicated by a solid line on the relevant plot in Figure 13.6), while that of MH03 is

very flat in later forming second molar enamel. Two animals, MH162 and MH163, show $\delta^{13}C$ profiles that are comparable in shape and magnitude to the profiles of a number of Pool cattle (PL0278, PL0330, PL0344 and PL0386) discussed in Section 13.1.3 above. Perhaps they were also raised in a coastal environment using a similar husbandry regime. The $\delta^{13}C$ profiles of the Mine Howe cattle suggest that seaweed was not a significant dietary component, unlike the $\delta^{13}C$ profile of an Iron Age sheep from Mine Howe which does show evidence for seaweed consumption (Balasse et al 2009).

Interestingly, the $\delta^{13}C$ profile of MH133 shows no obvious sign of movement despite strontium concentration and oxygen isotope ratio measurements strongly suggesting origins outside Orkney. $\delta^{13}C$ values in the second and third molars of this animal are similar in shape and magnitude. Equally, any internal movement within Orkney by other Mine Howe cattle may not be apparent in their $\delta^{13}C$ profiles.

13.2.4 Exploring weaning strategy

In order to investigate weaning for Mine Howe, the offset between $\delta^{13}C_{CG}$ and the mid-range third molar $\delta^{13}C$ value has been calculated for each animal with first and third molar data. Figure 13.10 displays the offset values calculated for Mine Howe together with those for the Pool and Chillingham cattle. Comparison between the three datasets indicates that the offsets for three of the Mine Howe cattle are similar in magnitude to those of the Pool cattle, perhaps suggesting that they may have been actively weaned at a young age through human intervention, while the offset of one animal (MH0604) falls within the range of Chillingham values. This animal may have been weaned naturally by its mother or, at least, had access to its mother's milk for a significant period of time after birth. The offset of the fifth Mine Howe animal (MH138) suggests an intermediate weaning period. One animal from Mine Howe not included in this particular analysis is MH133, which, according to strontium concentration results, appears to have originated outside Orkney. It is likely that this animal's first molar isotopic values relate to its place of origin whereas third molar values reflect its life in Orkney. Therefore, a measure of the

offset between $\delta^{13}C_{CG}$ and the mid-range third molar $\delta^{13}C$ value may be misleading in terms of weaning.

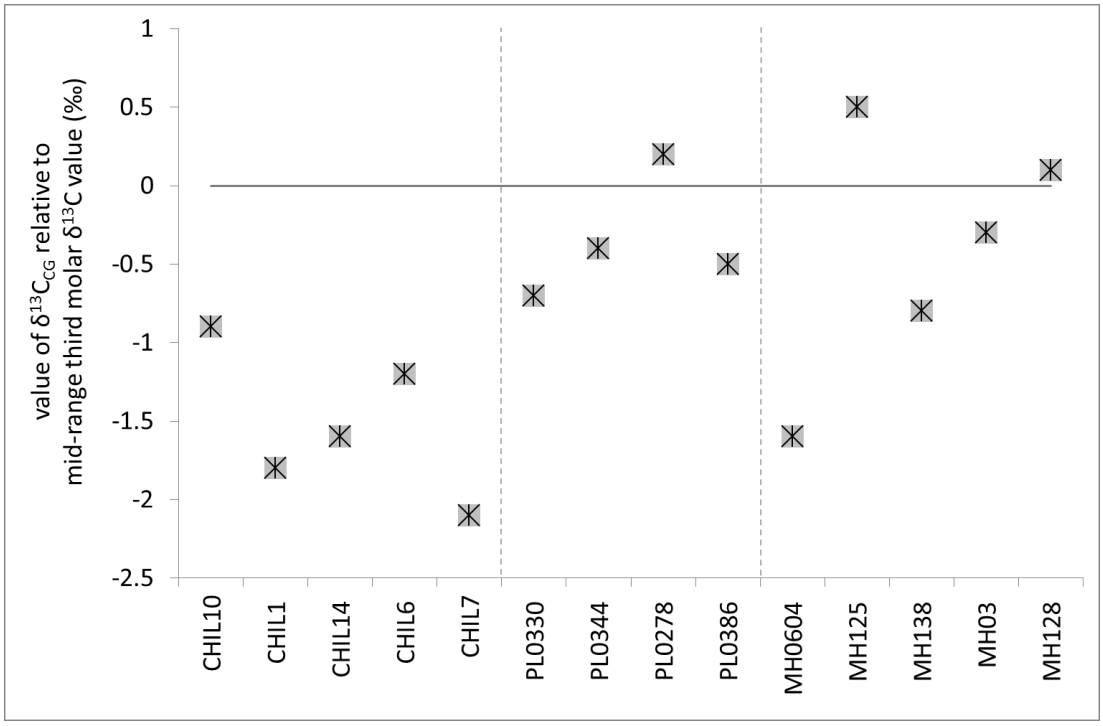


Figure 13.10: Value of $\delta^{13}C_{CG}$ (grey crossed square symbols) relative to the mid-range third molar $\delta^{13}C$ value (horizontal line).

13.2.5 Discussion

Intra-tooth isotope ratio analysis of molar enamel from 12 Mine Howe cattle suggests that the calving period was approximately five months and that calves were born during spring and summer (Section 13.2.2). For a prehistoric settlement, spring calving would have been the most efficient calving strategy for economies focussed on the production of meat or storable dairy products (Sections 2.2.1 and 2.2.3). If calving was synchronized to the growing season, milk yield was maximised. In a meat-focussed economy this would have resulted in maximum calf growth for minimal effort. In an economy based on the production of storable dairy products, a greater quantity of milk would have generated a greater quantity of dairy products. Increased calf mortality may have been a consequence of calving too early, due to poor weather and the lack of new growth in late winter and early spring, or from calving too late, when the reduced nutrient content of vegetation in late summer

would have resulted in some calves being insufficiently large and healthy to survive their first winter. For these reasons, it is likely that communities with meat-focussed economies in particular would have strived for a short calving period of around 3 months that synchronised with maximum vegetation growth. This would have required an equally short period of successful mating during the summer which may not always have been easy to achieve. Some cows may have required an extended period of time after the previous winter to restore their body reserves to a level sufficient for oestrous cycling, particularly if they were lactating and suckling (Section 2.1.3). Thus, a calving period of five months may reflect what could be achieved in reality rather than what might be regarded as ideal for an economy focussed on the production of meat or storable dairy products. It is likely to have been too short to provide year-round fresh milk, particularly during the leanest time of year during late winter before the new spring growth.

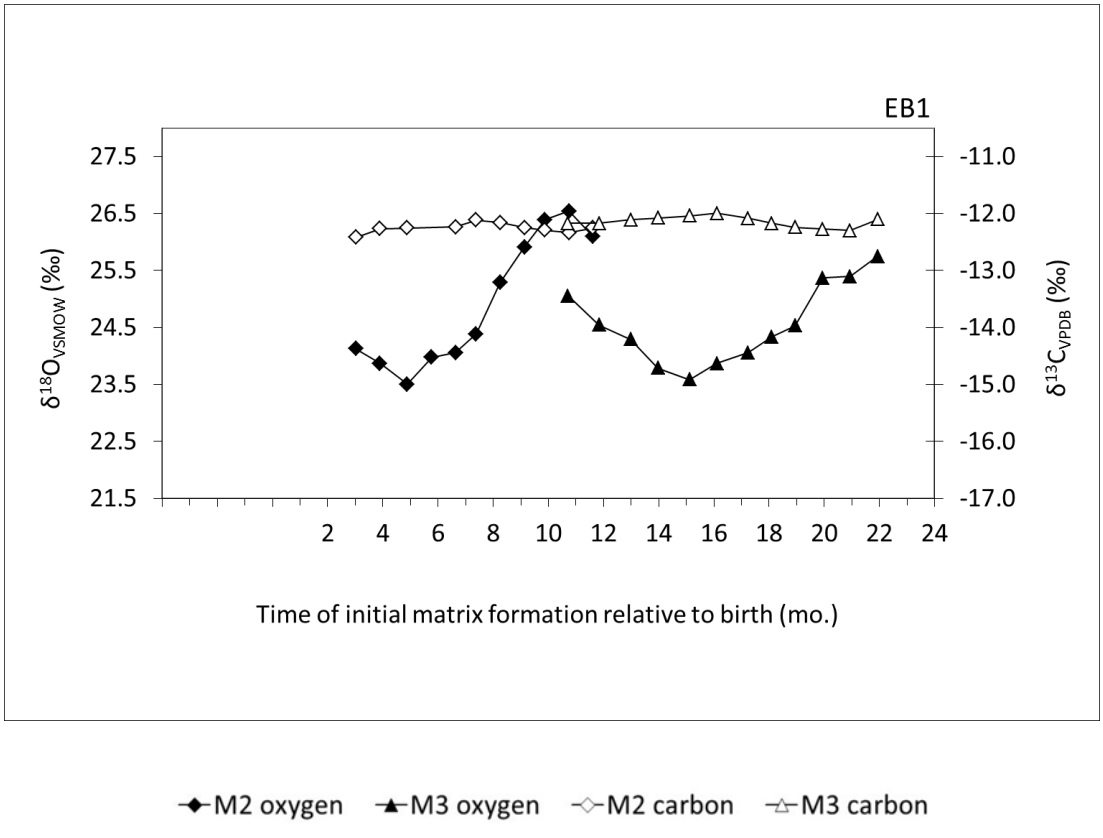
If Mine Howe was a settlement site, then a five month calving period during spring and summer might be indicative of an economy focussed on the production of meat or storable dairy products. The mortality profile for Mine Howe during the Mid-Later Iron Age includes elements suggestive of both a dairy- and a meat-based economy (Davis 2010 p425) (Section 6.6). However, Mine Howe has been interpreted as having religious significance (Harrison 2005 pp18) and the form of the mortality profile may reflect ritual slaughter of particular age groups. Therefore, the cattle remains discovered at Mine Howe are not necessarily representative of a local herd structure, i.e. the cattle analysed in this study may have been raised at a number of settlements with diverse economic goals, possibly across a broad time period. This idea is perhaps supported by the isotopic data: the overall range of third molar enamel $\delta^{13}C$ values is larger for the Mine Howe cattle than for the Pool and Earl's Bu cattle (Figure 13.4). A more detailed examination of their intra-tooth enamel $\delta^{13}C$ profiles has revealed a variety of patterns that may indicate different husbandry regimes based upon C_3 vegetation (Section 13.2.3). There is no evidence to suggest significant consumption of seaweed. Weaning strategy may have been variable also, suggesting both meat- and dairy-focussed husbandry (Section 13.2.4). In addition, Mine Howe third molar crown formation appears to be significantly

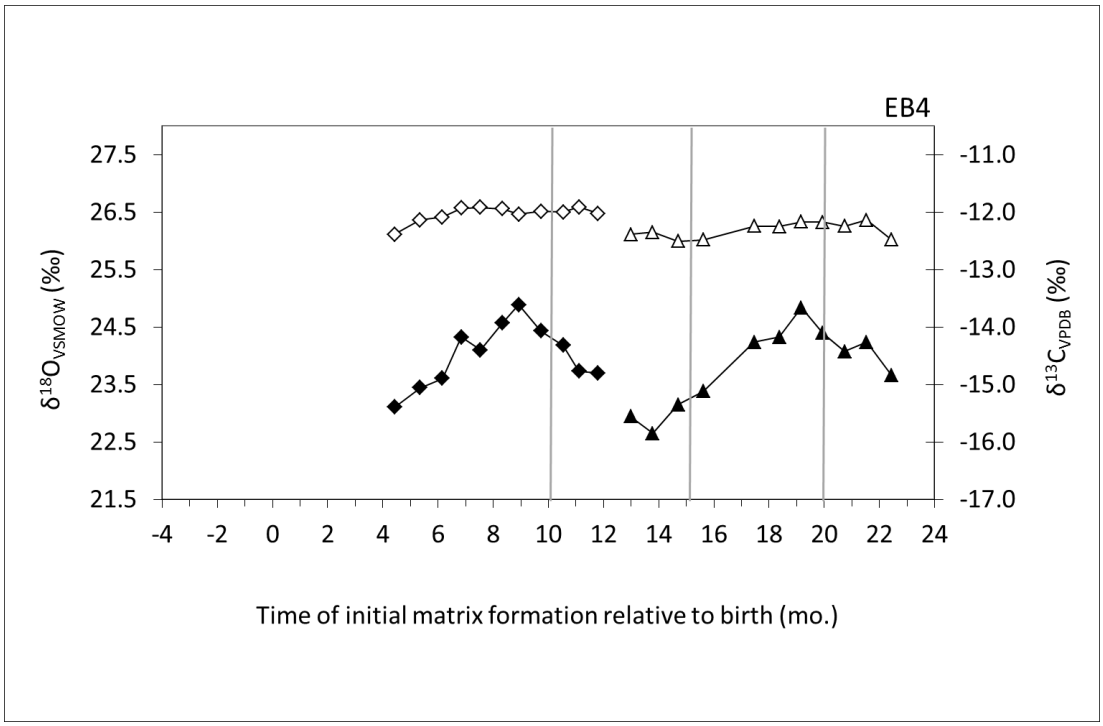
more variable than for Pool, Earl's Bu and Grimes Graves (Figure 12.13). One possible factor affecting third molar crown formation is genetic make-up (Hillson 2005 pp210). Thus, the observed variation might reflect the introduction of cattle from locations external to Orkney. Strontium and oxygen isotope data for the Mine Howe cattle included in this study indicate that one of these animals originated outside the Orkney archipelago at a non-coastal location with a cooler climate on average and more seasonally variable water sources (Sections 9.2 and 9.3.1), suggesting that cattle trading networks, possibly long-distance and certainly with a maritime element, were in operation during the Mid-Later Iron Age.

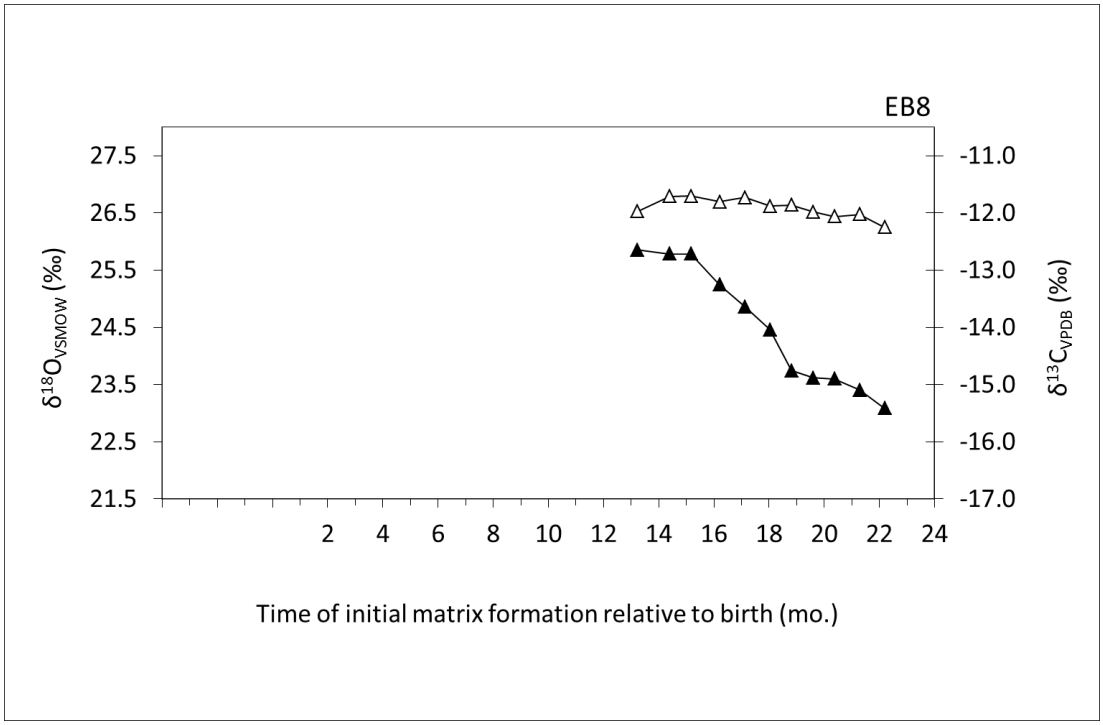
13.3 Earl's Bu, Orkney (Viking period, c. 800 AD – c. 1050 AD)

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

The $\delta^{18}O$ and $\delta^{13}C$ data obtained for all molars from nine Earl's Bu cattle have been plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1 (Figure 13.11).







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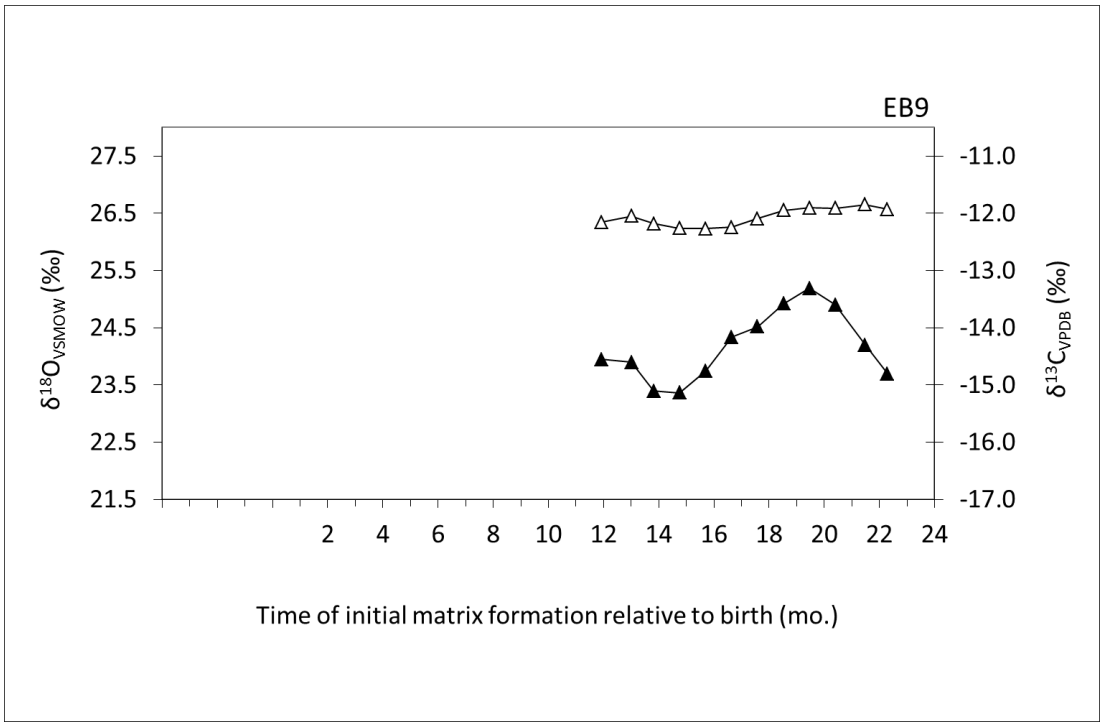
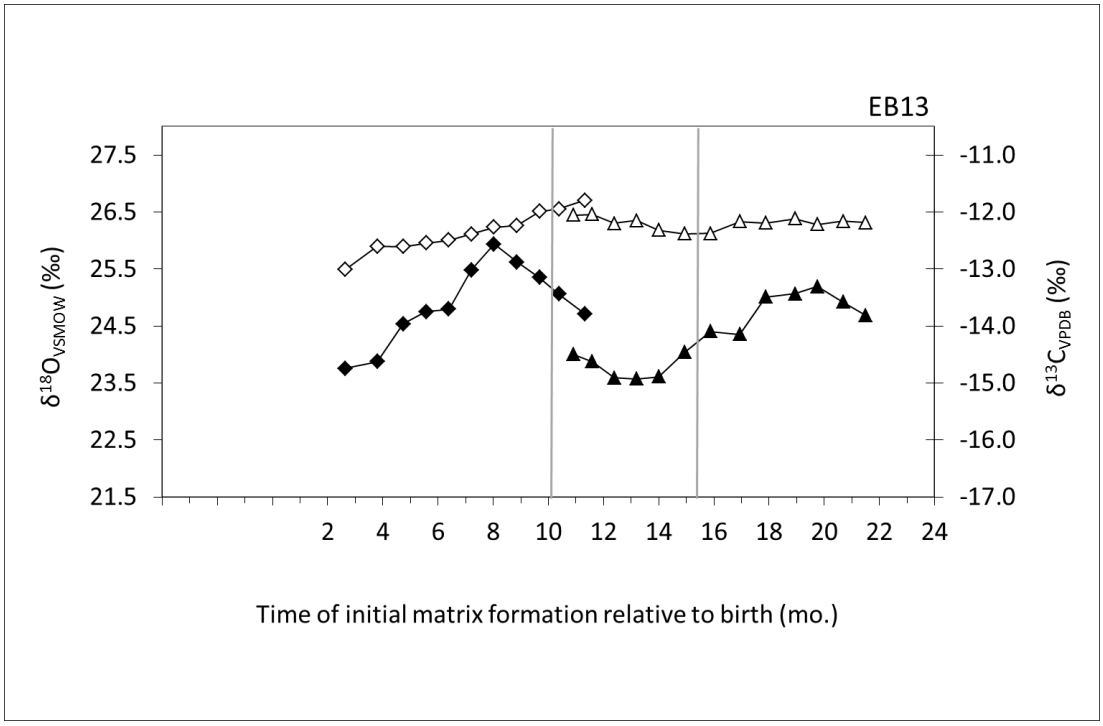
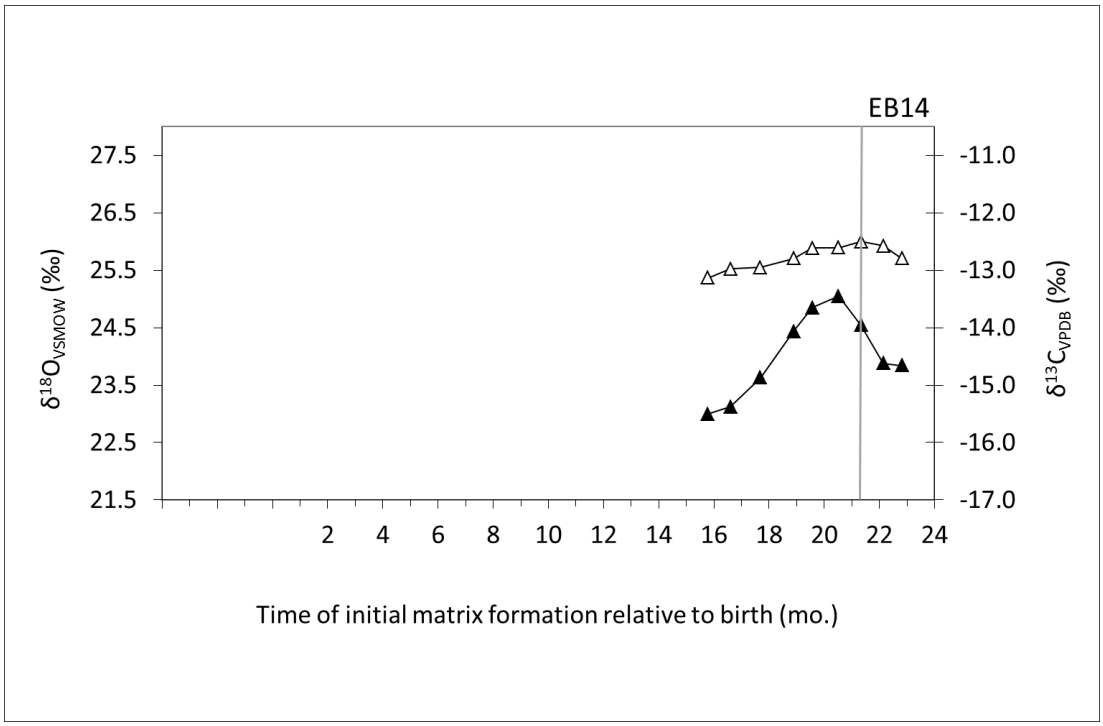
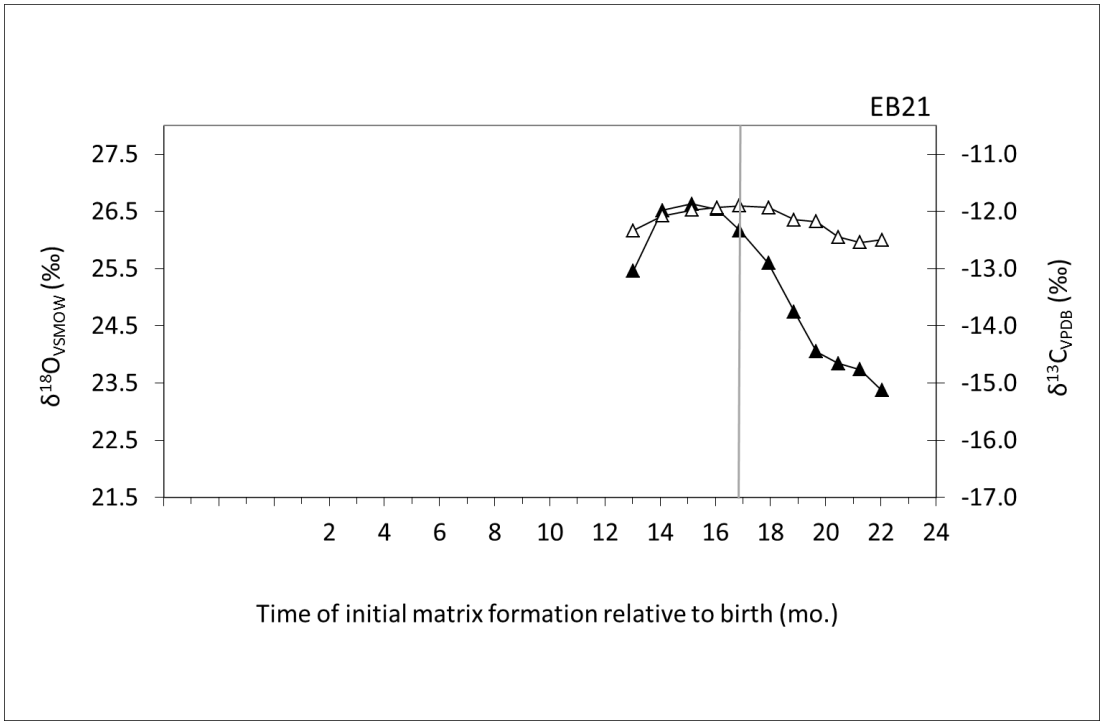




M2 oxygen M3 oxygen M2 carbon M3 carbon





M3 oxygen M3 carbon

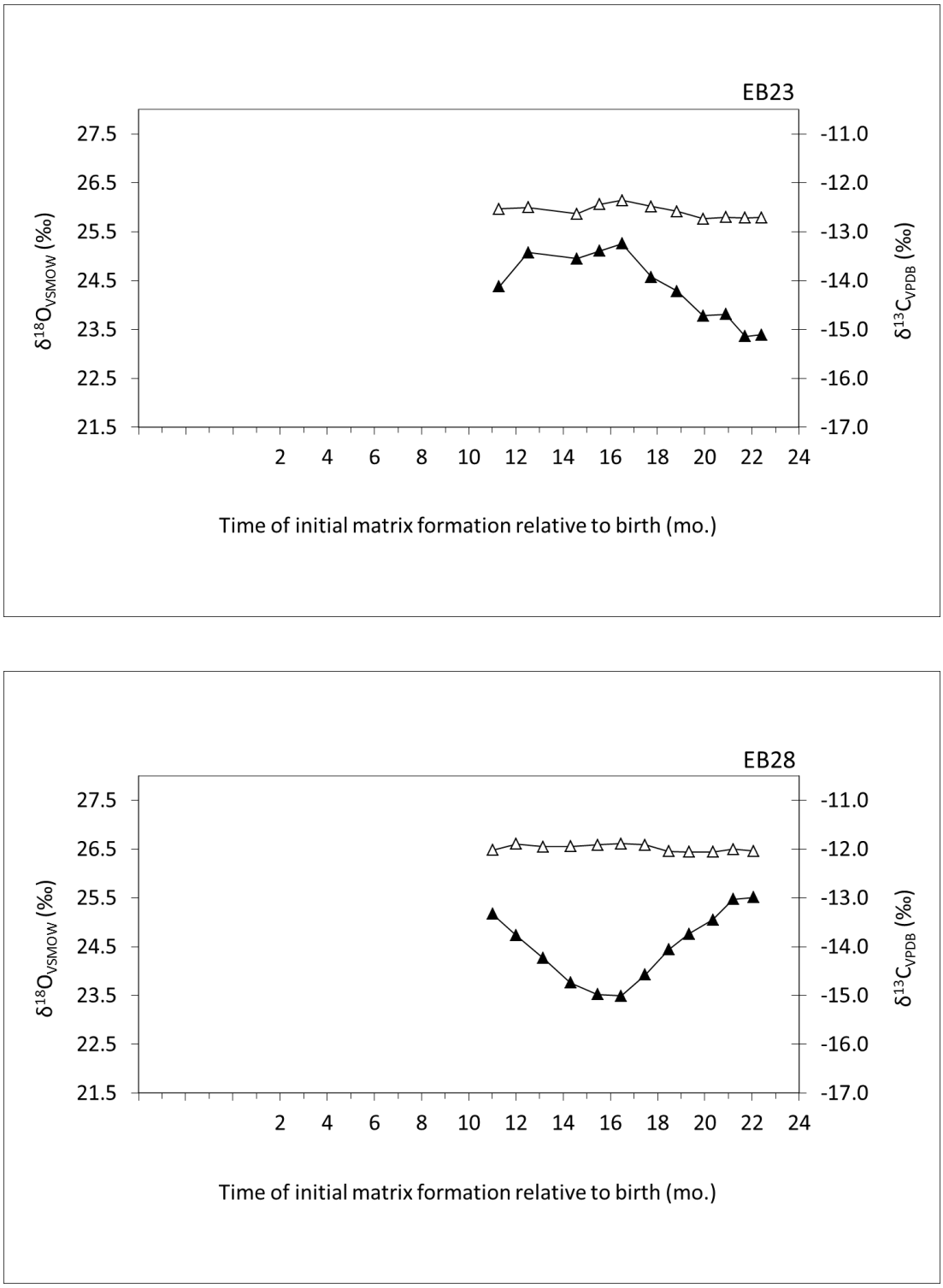


Figure 13.11: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from nine Earl's Bu cattle. The solid lines indicate features discussed in the text. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

13.3.2 Estimation of birth seasonality and season of birth

For the Earl's Bu profiles displayed in Figure 13.11, the timing of each $\delta^{18}O$ minimum and maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3). All timings are presented in Table 13.7. Unfortunately, only three of the analysed teeth were second molars and there were no first molars. Therefore, it has not been possible to estimate the distribution of births using methods 2 or 3 as has been carried out for Pool and Mine Howe cattle.

Figure 13.12 displays graphically the timings of third molar $\delta^{18}O$ minima. Four of the nine $\delta^{18}O$ profiles comprise third molar $\delta^{18}O$ maxima only and minima timings were calculated from the maxima timings assuming a separation of 6 months. Although it is not advisable to estimate the distribution of births from the timings in Figure 13.12 because of the greater degree of uncertainty associated with third molar crown formation (Section 12.4), some information regarding season of birth might be obtained through comparison with the equivalent Pool data in Figure 13.3. In Section 12.4, it was suggested that variation in third molar crown formation may be reduced for cattle from a restricted time period and geographical area. The cattle from Earl's Bu and Pool are dated to the same period (c. 800 AD – c. 1000 AD) and the two sites are in the same archipelago. Timing differences between second and third molar $\delta^{18}O$ minima, [min2 – min1], and between second and third molar $\delta^{18}O$ maxima, [max2 – max1] are displayed for both sites in Figure 12.13. These parameters can be regarded as a measure of the variability of third molar crown formation provided that second molar crown formation is significantly less variable, which appears to be true according to the analysis in Section 12.4. Because the four Earl's Bu values lie within the range of the bulk of Pool values, it is assumed here that the timing of molar crown formation for Earl's Bu cattle was similar to that of most Pool cattle and comparison will be made between Earl's Bu and Pool third molar $\delta^{18}O$ minima timings.

Table 13.7: $\delta^{18}O$ minima and maxima timings for Earl's Bu second and third molars.

	Predicted time after birth (months)			
Animal	**M2 $\delta^{18}O$ minimum (min 1)**	**$\delta^{18}O$ maximum (max 1)**	**M3 $\delta^{18}O$ minimum (min2)**	**$\delta^{18}O$ maximum (max 2)**
EB1	4.8	10.5	15.3	21.9
EB4		8.8	13.9	19.3
EB8				13.8
EB9			14.5	19.4
EB13		8.5	13.1	19.4
EB14				20.2
EB21				15.5
EB23				14.8
EB28			15.7	

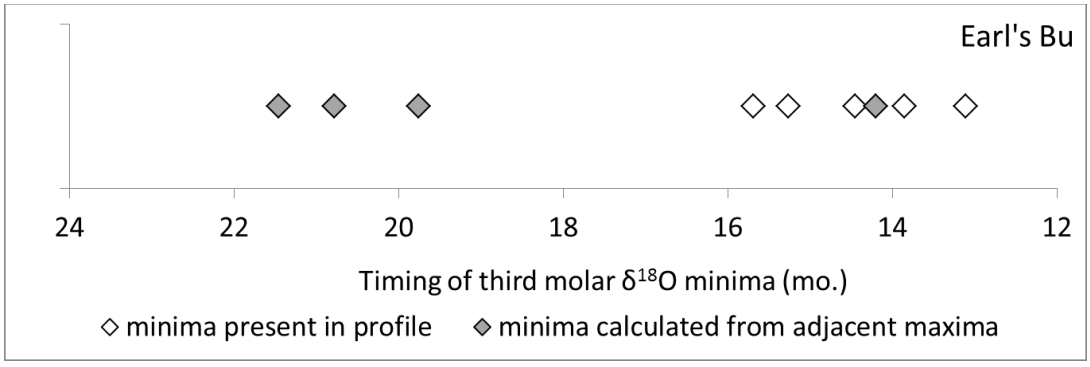


Figure 13.12: The timing of third molar $\delta^{18}O$ minima for Earl's Bu cattle. A six month separation is assumed for minima calculated from adjacent maxima.

Figure 13.12 shows that there is a cluster of six $\delta^{18}O$ minima with timings between 13 and 16 months, of which the mean value is 14.4 months. Following a cautious approach, if the error associated with each of the $\delta^{18}O$ minima values is assumed to be ± 2.0 months (Section 12.6), despite Figure 12.13 suggesting the possibility of a smaller degree of uncertainty, then the error associated with the mean value (the standard error) is only ± 2.0/√n = ± 0.8 months for n = 6 (Drennan 2004 pp107). Thus, comparison with the Pool data in Figure 13.3 suggests a calving period in the summer. Similarly, there is a second cluster of three $\delta^{18}O$ minima with timings between 19 and 21 months, for which the mean value is 20.7 ± 1.2 months. This would put the calving period in the winter. Although the data appear to show two calving seasons approximately six months apart, such a conclusion must be

regarded as speculative due to the small sample size and degree of uncertainty associated with each of the $\delta^{18}O$ minima timings and with the two cluster mean values.

13.3.3 Diet and environment

The plot of third molar enamel $\delta^{13}C$ data in Figure 13.4 and the summary in Table 9.3 show that the mid-range $\delta^{13}C$ value for all Earl's Bu third molars is 0.5 ‰ lower than that of Pool. As proposed in Section 13.1.3, this may be related to the properties of the local soil. The soil around Pool on the small island of Sanday was probably more saline and possibly drier than the soils around Earl's Bu on Mainland Orkney (Sections 6.1 and 6.3). Both factors would have acted to elevate the $\delta^{13}C$ values of Pool vegetation. Whereas Pool is located on the west coast of a peninsula only ~1-2 km wide, Earl's Bu is situated on the south coast of Mainland, Orkney, a much larger island. As a result, the land around Earl's Bu was probably less affected by sea-spray, particularly to the north, set back from the coast itself. The "canopy effect" (Section 3.3) is unlikely to have been a significant factor in Orkney since trees are thought to have been largely absent since the Neolithic period, apart from small pockets of woodland in stream gullies (Berry 2000 pp52). Figure 13.4 and Table 9.3 also indicate that the overall range of third molar enamel $\delta^{13}C$ values is smaller for Earl's Bu cattle than for Pool and Mine Howe cattle. 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. Therefore, it is possible that the Earl's Bu cattle were raised within a similarly restricted geographical area, probably local to Earl's Bu, under a common husbandry regime.

Upon closer examination, the enamel $\delta^{13}C$ profiles in Figure 13.11 show little internal variation, which is the factor most influencing the overall range of third molar enamel $\delta^{13}C$ values discussed above. This is particularly apparent for the profiles of EB1 and EB28. Thus, the difference in overall range between Earl's Bu and Pool $\delta^{13}C$ values is probably due more to husbandry and dietary regime than being restricted geographically, since the condition of geographical restriction

would have been applicable to the cattle of Pool. The profiles of EB4, EB13, EB14 and EB21 appear to show a common pattern: the $\delta^{13}C$ and $\delta^{18}O$ profiles co-vary, but with a temporal shift of ~1-3 months between the two, as indicated by the solid lines on the plots. Since EB21 was probably born at a different time of year to EB4, EB13 and EB14 according to the analysis in Section 13.3.2, the patterning in the $\delta^{13}C$ profiles appears to be related to season rather than age. Such patterning resembles the profiles of modern sheep from Rousay, Orkney, that grazed outside all year round (Balasse et al 2009) (Figure 5.3). However, the variation in the Earl's Bu $\delta^{13}C$ profiles is much reduced. The $\delta^{13}C$ maxima may represent grazing outside during the summer months. However, the $\delta^{13}C$ minima are more likely to represent fodder provision during the winter months rather than grazing outside, although the level of variation expected for year-round grazing outside at Earl's Bu is not known. It is possible that the consumption of winter fodder with higher $\delta^{13}C$ values than winter grazing, perhaps hay, straw or grains harvested during the summer, might act to reduce the amount of variation in a $\delta^{13}C$ profile. Similarly, winter consumption of seaweed in small quantities cannot be ruled out.

13.3.4 Discussion

Due to the lack of first and second molars, intra-tooth isotope ratio analysis of molar enamel from nine Earl's Bu cattle has produced somewhat speculative predictions regarding seasonality and season of birth. There is the possibility that there were two calving seasons approximately six months apart (Section 13.3.2). If this were the case, such a bimodal distribution would have enabled the production of fresh milk all year round. In contrast, the mortality profile for Earl's Bu resembles Payne's (1973) meat model (Davis 2010 p450) (Section 6.6). However, the cattle remains at Earl's Bu were probably food waste from a high-status building and not necessarily representative of a local herd structure.

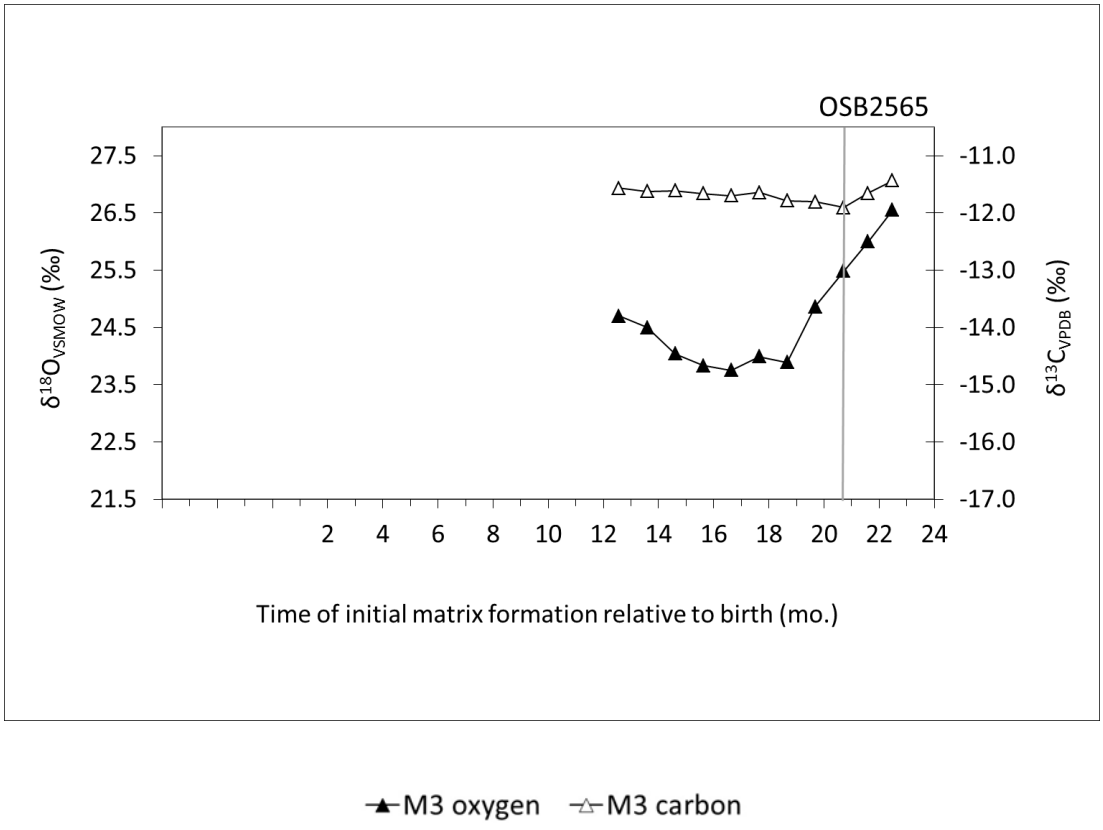
The overall range of third molar enamel $\delta^{13}C$ values is smaller for Earl's Bu cattle than for Pool and Mine Howe cattle and more detailed examination of their intra-tooth enamel $\delta^{13}C$ profiles has revealed little internal variation (Section 13.3.3). The

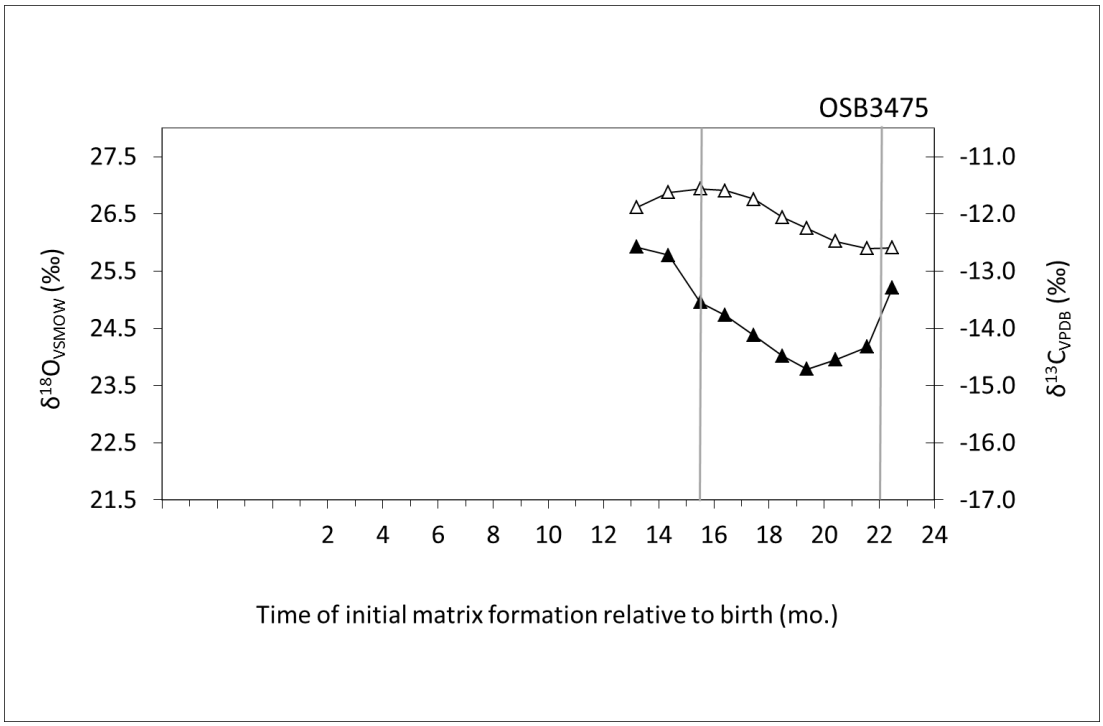
low level of variation may indicate the provision of winter fodder but identification of particular food sources is not possible as discussed for the Pool results in Section 13.1.5.These observations suggest that the Earl's Bu cattle included in this study may have been raised within a restricted geographical area, probably local to Earl's Bu, under the same husbandry regime. It is possible one or more of the local farms supplied both beef and a year-round supply of fresh milk for the occupants of the high-status building at Earl's Bu.

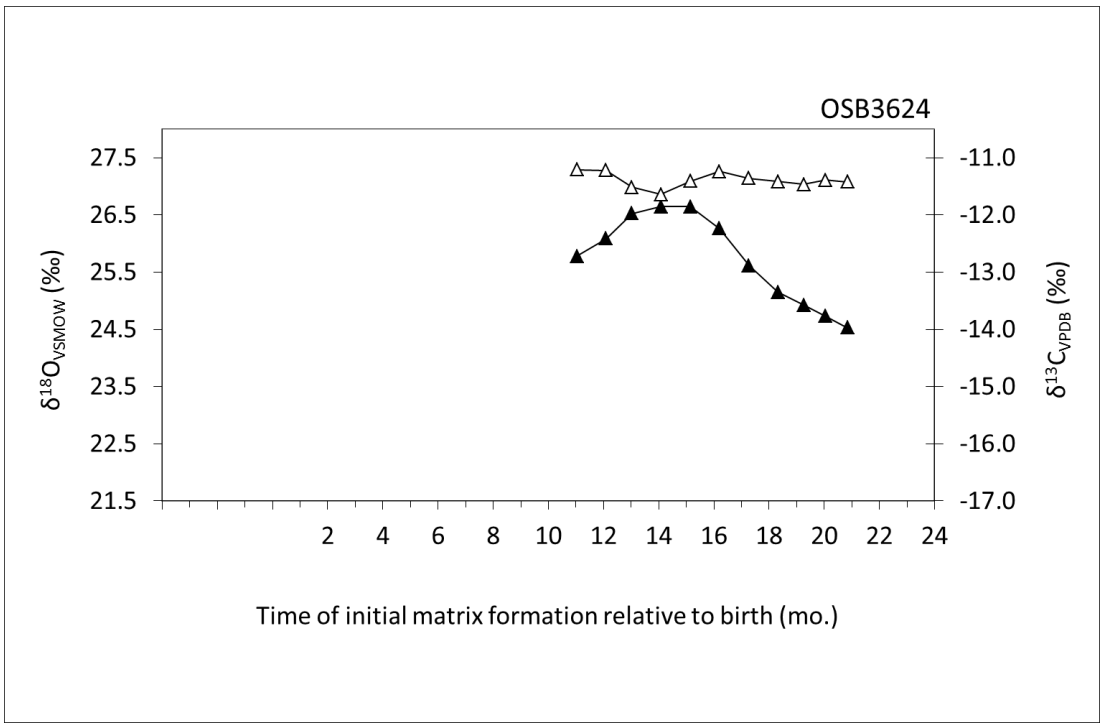
13.4 Old Scatness, Shetland (c. 200 BC – c. 400 AD)

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

The $\delta^{18}O$ and $\delta^{13}C$ data obtained for all molars from ten Old Scatness cattle have been plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1 (Figure 13.13).







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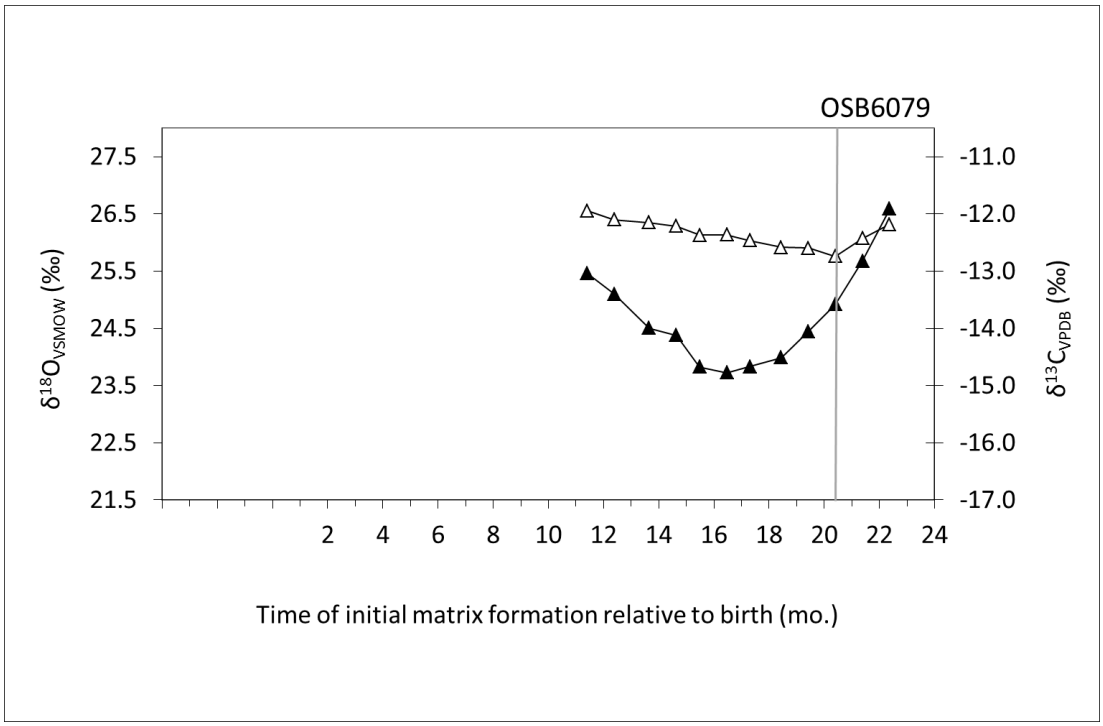

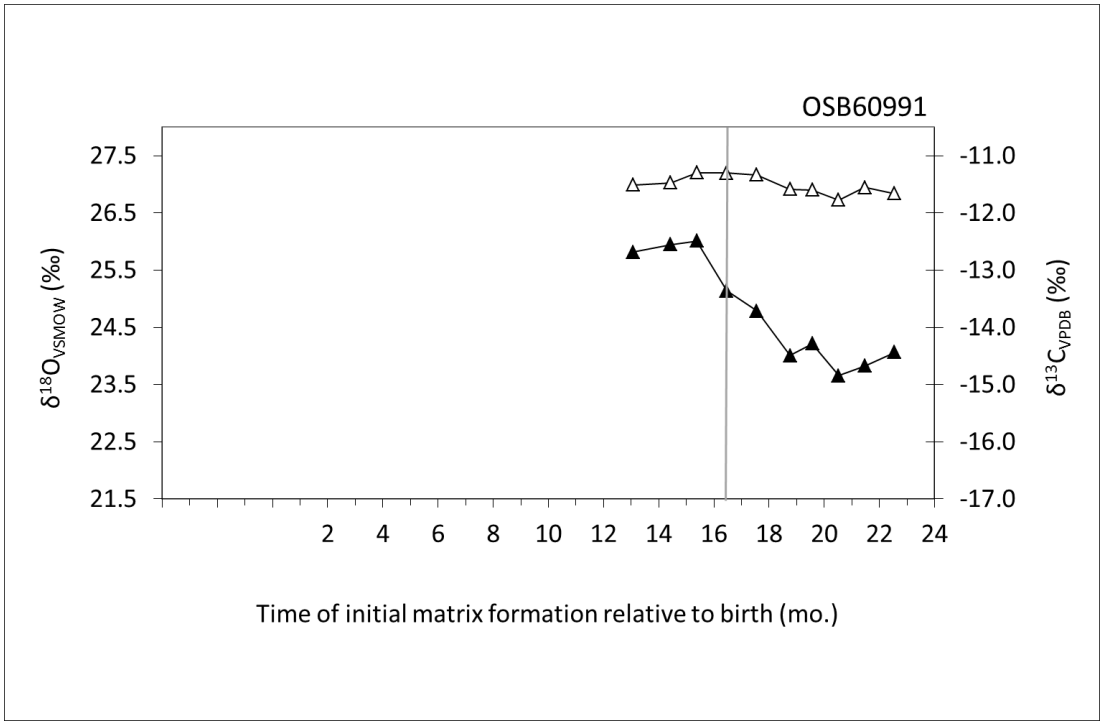

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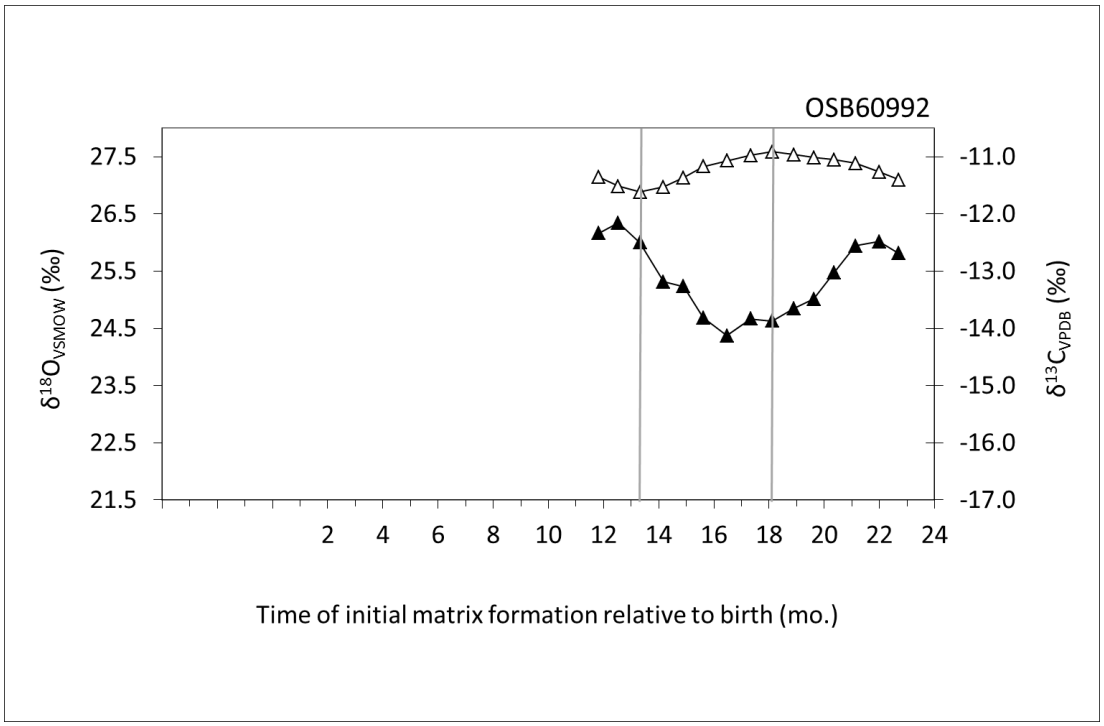

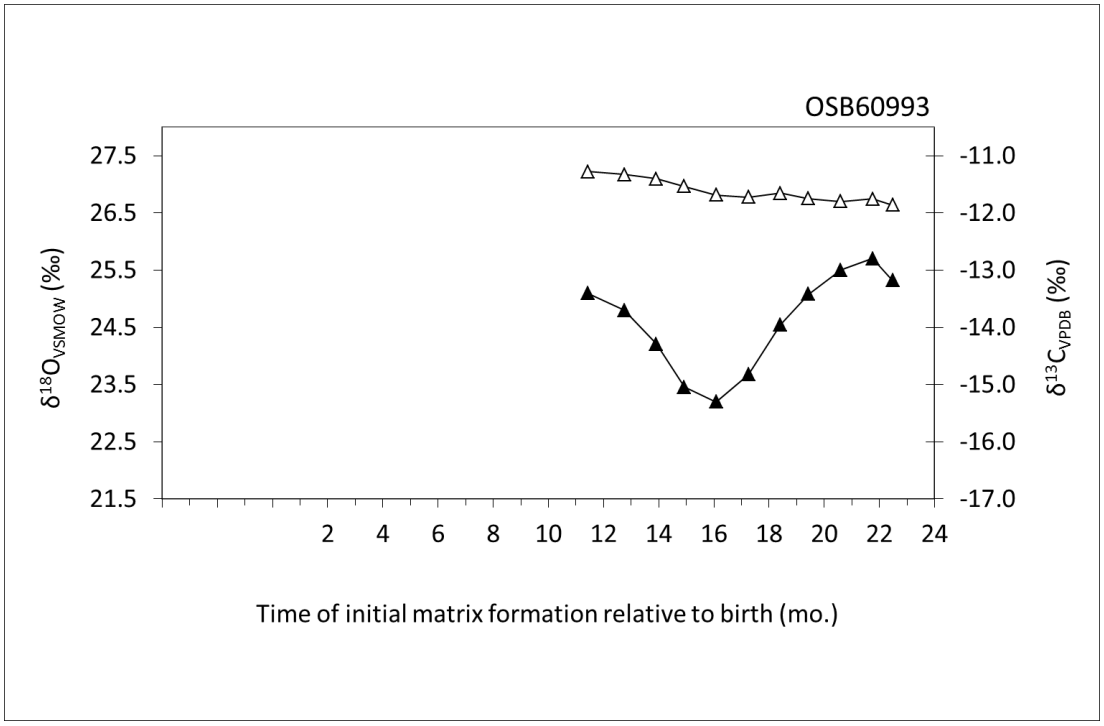

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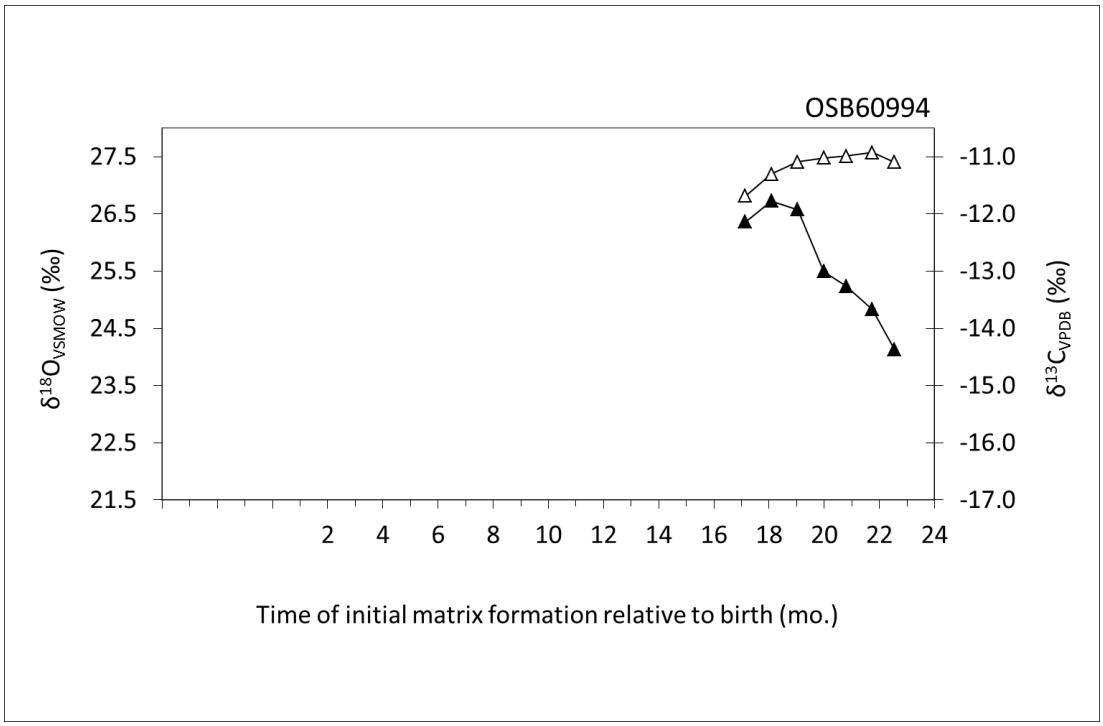
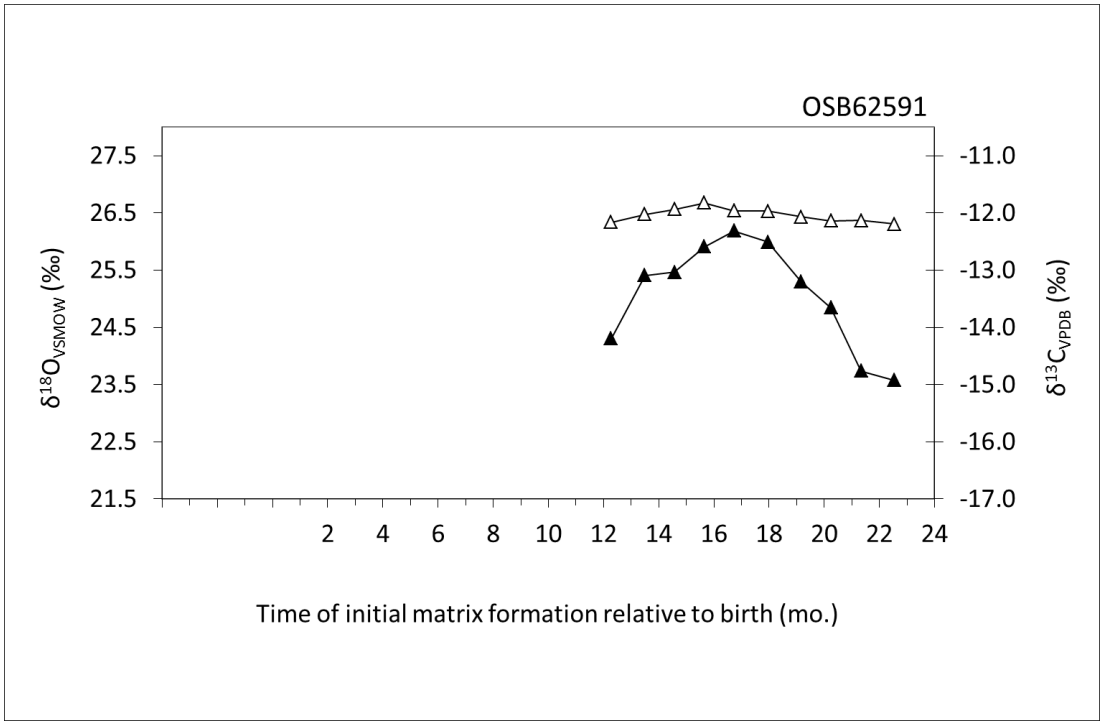




M3 oxygen M3 carbon

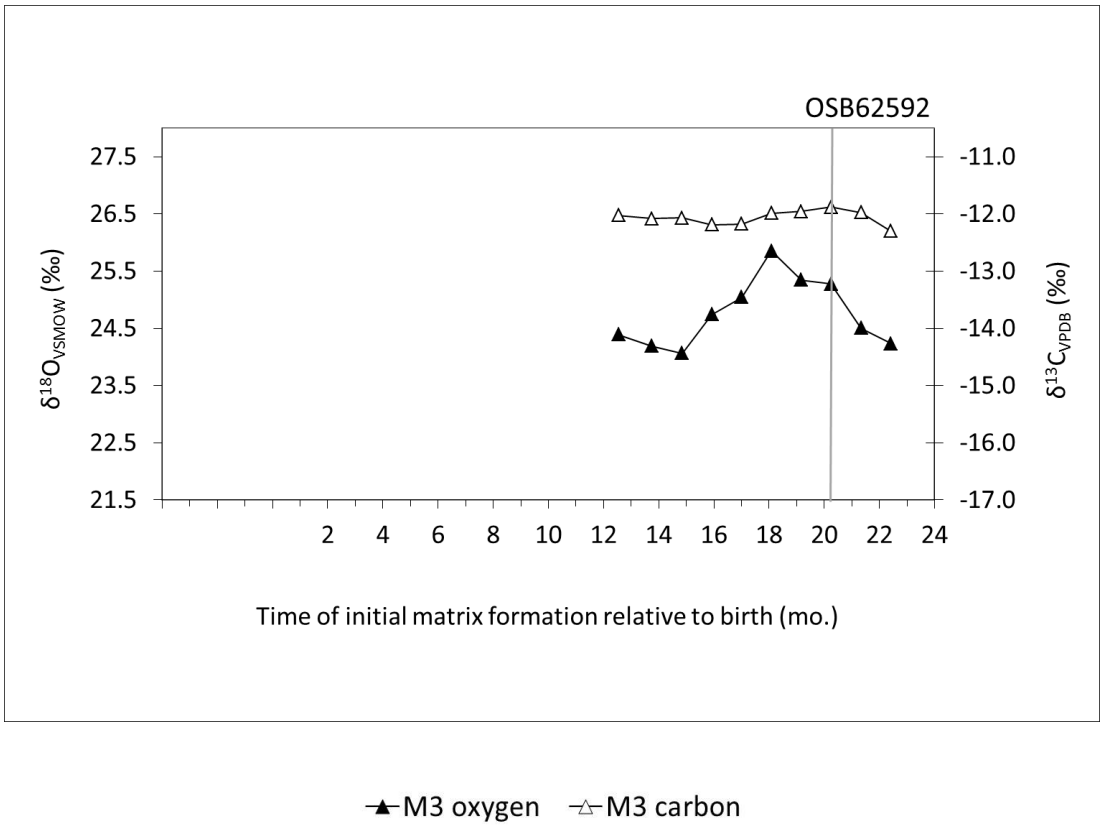


Figure 13.13: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from ten Old Scatness cattle. The solid lines indicate features discussed in the text. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

13.4.2 Estimation of birth seasonality and season of birth

For the Old Scatness profiles displayed in Figure 13.13, the timing of each $\delta^{18}O$ minimum and maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3). All timings are presented in Table 13.8. Unfortunately, it has not been possible to estimate the distribution of births using methods 2 or 3, as has been carried out for Pool and Mine Howe cattle (Sections 13.1.2 and 13.2.2), because only third molars were analysed. Figure 13.14 displays graphically the timings of third molar $\delta^{18}O$ minima. Three of the ten $\delta^{18}O$ profiles comprise third molar $\delta^{18}O$ maxima only and minima timings were calculated from the maxima timings assuming a separation of six months.

Timing differences between second and third molar $\delta^{18}O$ minima and maxima are not available due to the lack of second molars. Therefore, Old Scatness does not feature in Figure 12.13 and it is not known how the degree of variability in third molar formation compares to that of the other archaeological sites. It is assumed here that the error associated with each of the $\delta^{18}O$ minima values in Figure 13.14 is ± 2.0 months. The plot shows two clusters, one of four data-points with a mean value of 16.6 ± 1.0 months and the other of three data-points with a mean value of 20.3 ± 1.2 months, the errors calculated using the formula for standard error (Section 13.3.2). However, it is possible that these two clusters are artefacts of the error associated with the $\delta^{18}O$ minima values and that the seven data-points represent a single period of calving, probably spring/summer. Even the three outliers may belong to the same period, given the possible magnitude of the associated error. Unfortunately, conclusions regarding seasonality and season of birth for Old Scatness cannot be drawn with any degree of confidence.

Table 13.8: $\delta^{18}O$ minima and maxima timings for Old Scatness third molars.

	Predicted time after birth (months)		
Animal	**$\delta^{18}O$ maximum**	**M3 $\delta^{18}O$ minimum**	**$\delta^{18}O$ maximum**
OSB2565		16.5	
OSB3475		19.7	
OSB3624	14.3		
OSB6079		16.7	
OSB60991	14.2	20.9	
OSB60992	12.4	17.2	21.8
OSB60993		16.0	21.3
OSB60994			18.2
OSB62591			16.8
OSB62592		14.0	18.5

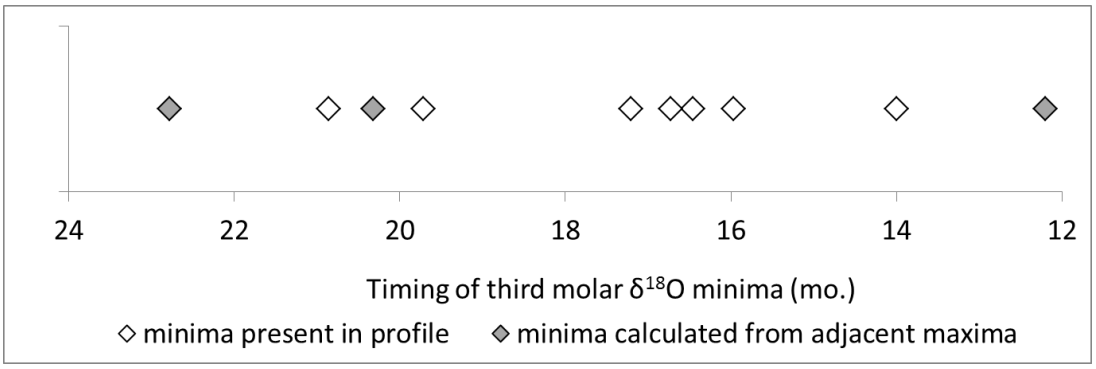


Figure 13.14: The timing of third molar $\delta^{18}O$ minima for Old Scatness cattle. A six month separation is assumed for minima calculated from adjacent maxima.

13.4.3 Diet and environment

The plot of third molar enamel $\delta^{13}C$ data in Figure 13.4 and the summary in Table 9.3 show that the mid-range $\delta^{13}C$ value for all Old Scatness third molars is similar to that of Pool and 0.6 ‰ higher than the equivalent values for Earl's Bu and Mine Howe. The similarity between Old Scatness and Pool mid-range $\delta^{13}C$ values may be due to comparable soil conditions. The soil in the vicinity of both sites is sandy which would have resulted in relatively good drainage and drier growing conditions (Section 6.4). In addition, Old Scatness, like Pool, is situated on a narrow peninsula ~1 km wide. As a result, soil salinity levels would have been high due to sea-spray. Good drainage and high salinity are likely to have raised vegetation $\delta^{13}C$ values at Old Scatness relative to those at Earl's Bu. Nevertheless, as for Pool, enamel $\delta^{13}C$ values are consistent with a terrestrial C_3 diet although the consumption of seaweed in small quantities cannot be ruled out.

Upon closer examination, the third molar enamel $\delta^{13}C$ profiles in Figure 13.13 show a variety of patterns, which are likely to reflect different husbandry regimes. Solid lines on the plots indicate various features that are discussed below. For example, the $\delta^{13}C$ profiles of OSB2565 and OSB6079 descend gradually moving from the cusp towards the cervix but rise again close to the cervix at approximately the same position relative to the $\delta^{18}O$ curve, possibly indicating a change in diet at a certain time of year. The profile of OSB60993 is similar in that there is a gradual descent from cusp to cervix but, in this case, there is no rise close to the cervix. The gradual

downward trend continues for at least one cycle of the $\delta^{18}O$ profile, i.e. there is no obvious seasonal variation. In contrast, the $\delta^{13}C$ profile of OSB3475 is more cyclic in form, co-varying with the $\delta^{18}O$ profile but with a temporal shift of ~2-3 months between the two. This pattern is thought to be consistent with grazing outside all year round or grazing outside during the summer months and consuming fodder with a more negative $\delta^{13}C$ signature during the winter months (Figure 13.9), as discussed for MH128 in Section 13.2.3 above. Cattle OSB60991 and OSB62592 show similar $\delta^{13}C$ maxima, suggesting summer grazing. However, seasonal variation is much suppressed compared to the $\delta^{13}C$ profile of OSB3475, which may indicate the consumption of fodder during the winter months with a more positive $\delta^{13}C$ signature than that for OSB3475. The $\delta^{13}C$ profile of OSB60992 takes this idea one stage further. In this case the $\delta^{13}C$ and $\delta^{18}O$ profiles are almost anti-phase suggesting the provision of fodder during the winter months with a more positive $\delta^{13}C$ signature than summer grazing. Seaweed may have been a component of this winter fodder but only in small quantities otherwise $\delta^{13}C$ values would be much higher.

13.4.4 Discussion

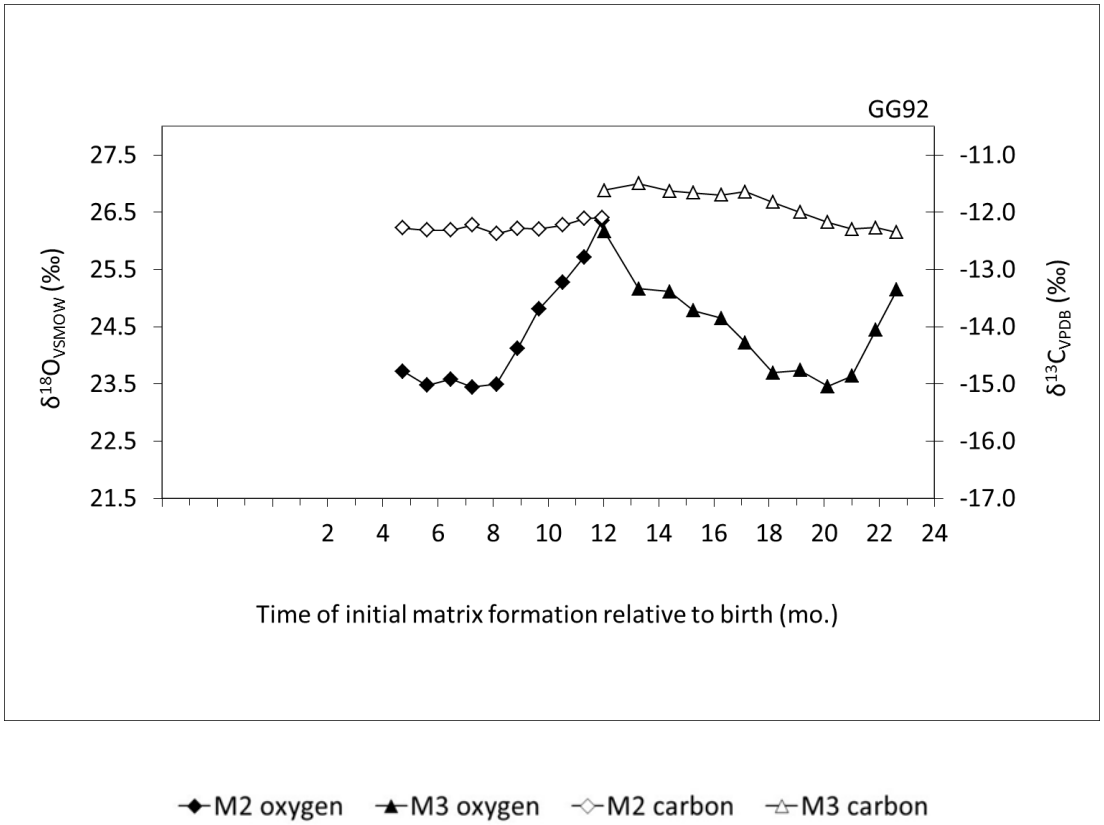
Unfortunately, due to the lack of first and second molars, intra-tooth isotope ratio analysis of molar enamel from ten Old Scatness cattle has produced inconclusive predictions regarding seasonality and season of birth (Section 13.4.2). Superficially, the third molar isotopic data for Old Scatness indicates a distribution of births spanning the whole year, which would suggest an economy focussed on the year-round provision of fresh milk and support the interpretation of a dairy-based economy at Old Scatness during the Middle Iron Age as suggested by its mortality profile (Bond et al, in press) (Section 6.6). Alternatively, the uncertainty associated with the data may mean that the distribution of births is, in reality, much narrower, in which case an economy with an emphasis on the production of meat or storable dairy products may be more likely. An emphasis on storable dairy products would not conflict with the interpretation derived from the mortality profile.

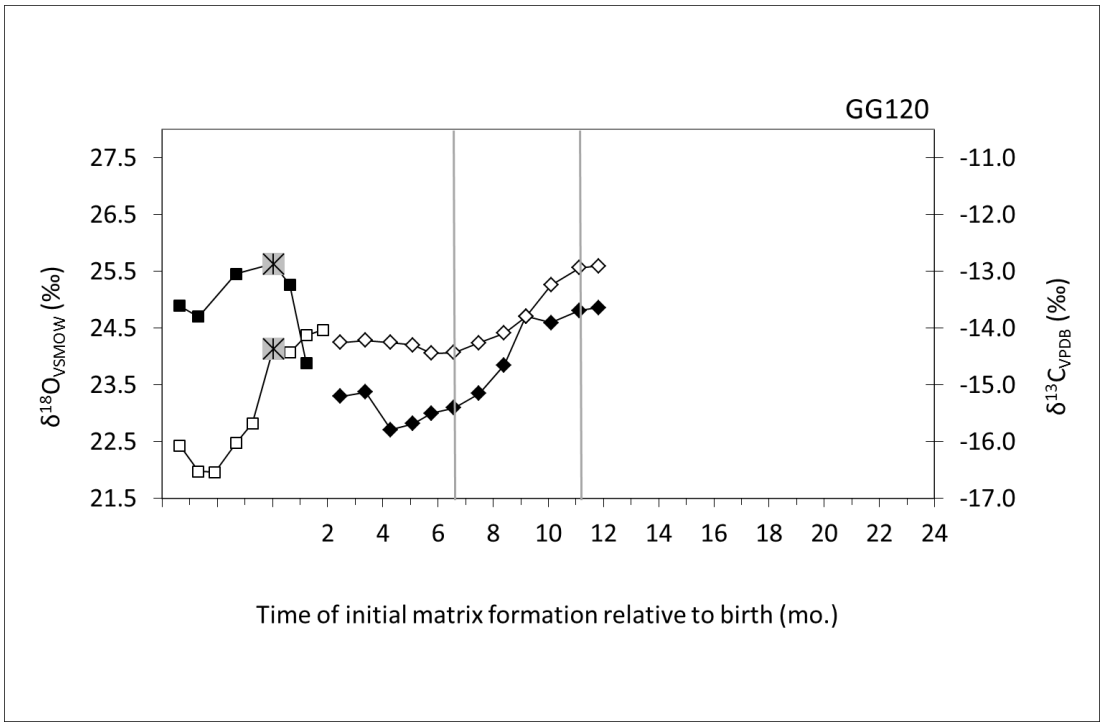
Upon closer examination, the third molar enamel $\delta^{13}C$ profiles show a variety of patterns, which are likely to reflect different husbandry regimes. Several may indicate the provision of winter fodder in one form or another. Enamel $\delta^{13}C$ values are consistent with a terrestrial C_3 diet although the consumption of seaweed in small quantities cannot be ruled out.

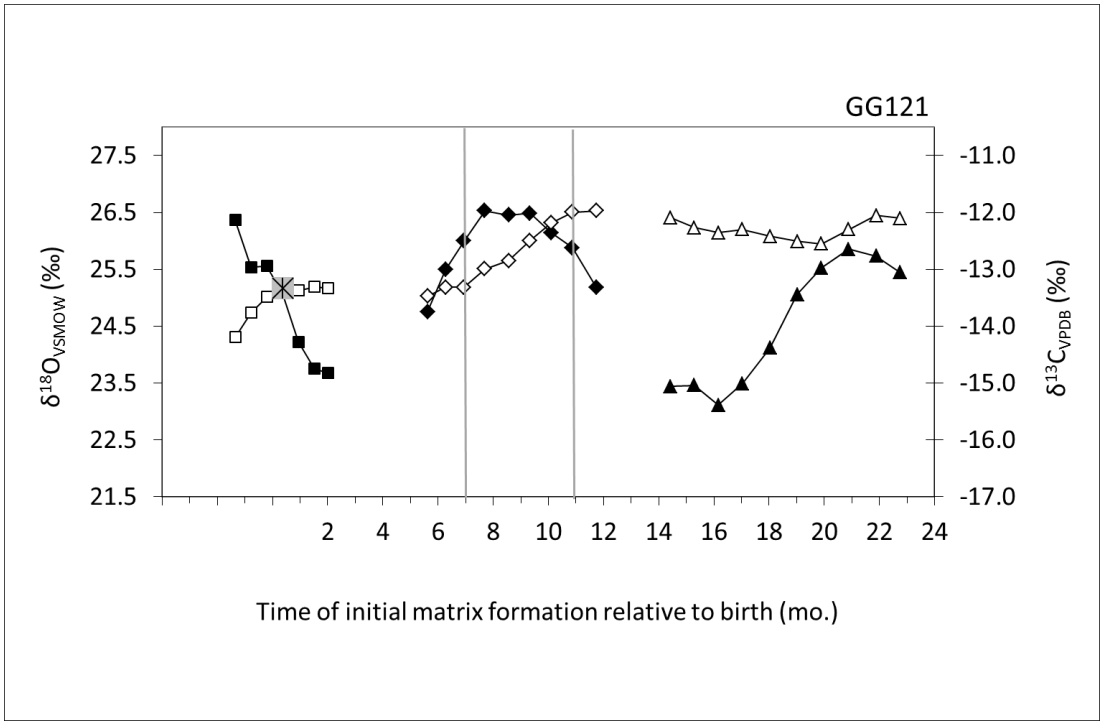
13.5 Grimes Graves, Norfolk (c. 1400 BC – c. 850 BC)

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

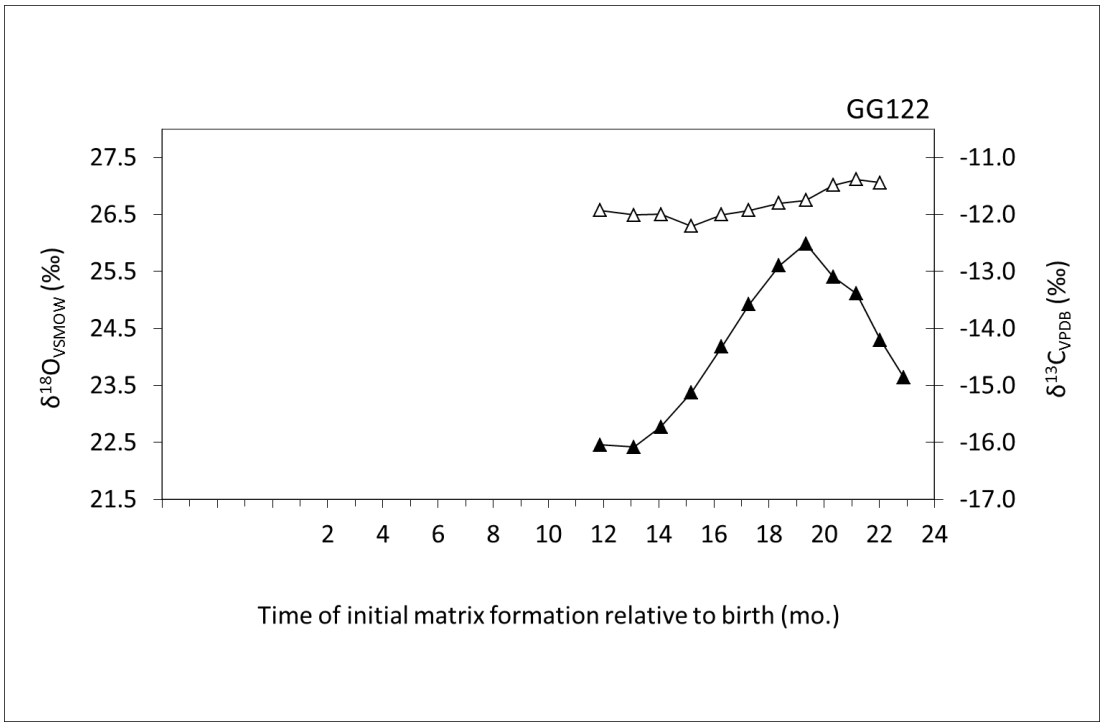
The $\delta^{18}O$ and $\delta^{13}C$ data obtained for all molars from 13 Grimes Graves cattle have been plotted versus time rather than distance from the cervix using the procedure outlined in Section 10.1 (Figure 13.15).

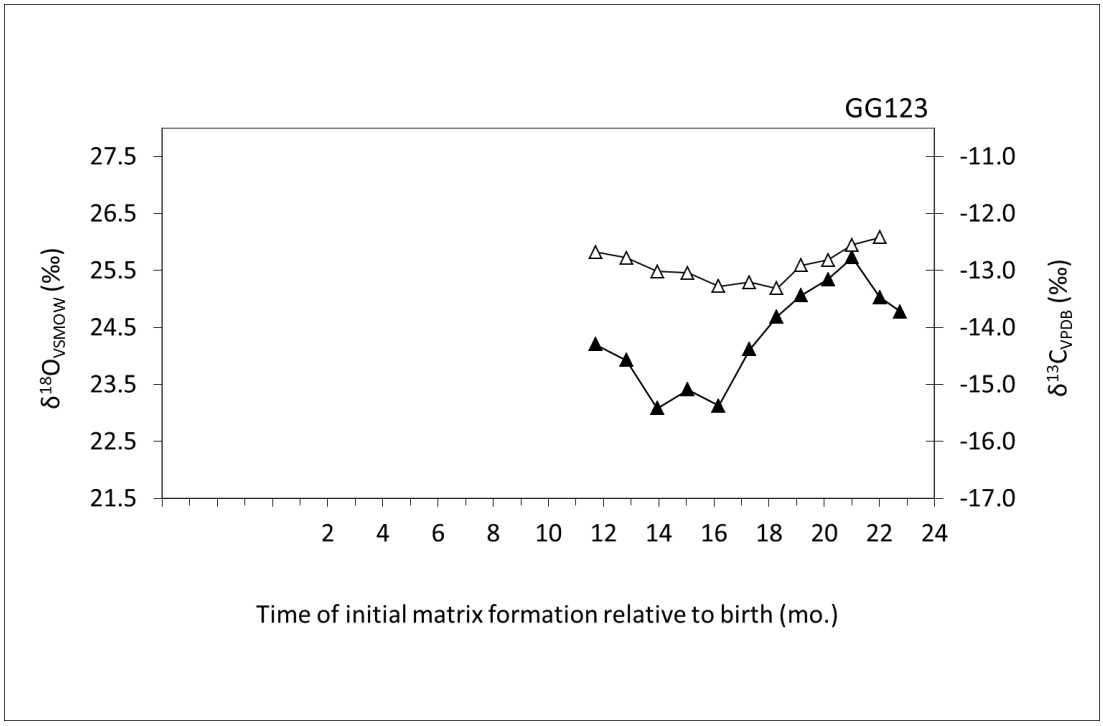






M1 oxygen M2 oxygen M3 oxygen M1 carbon M2 carbon M3 carbon





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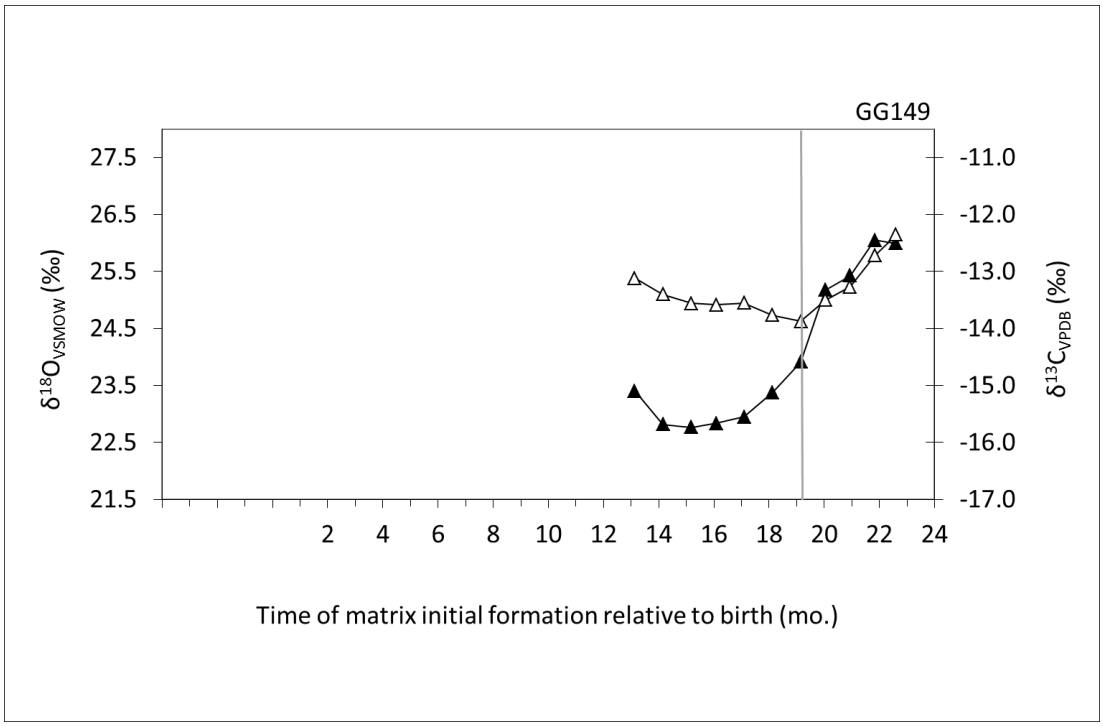

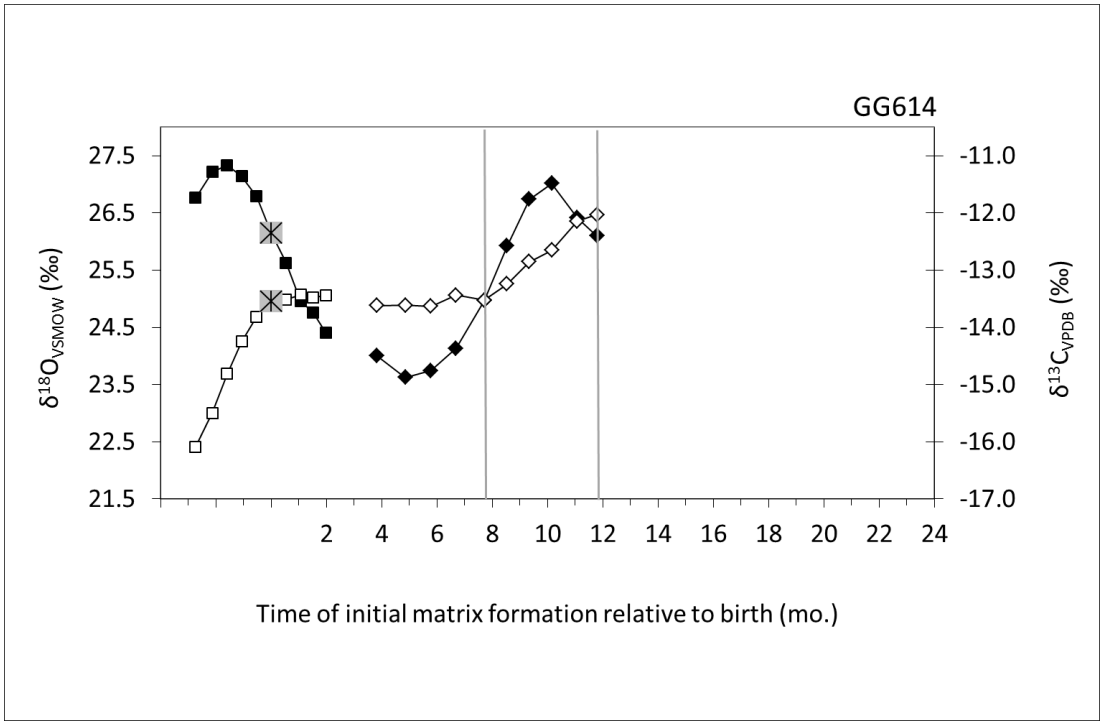

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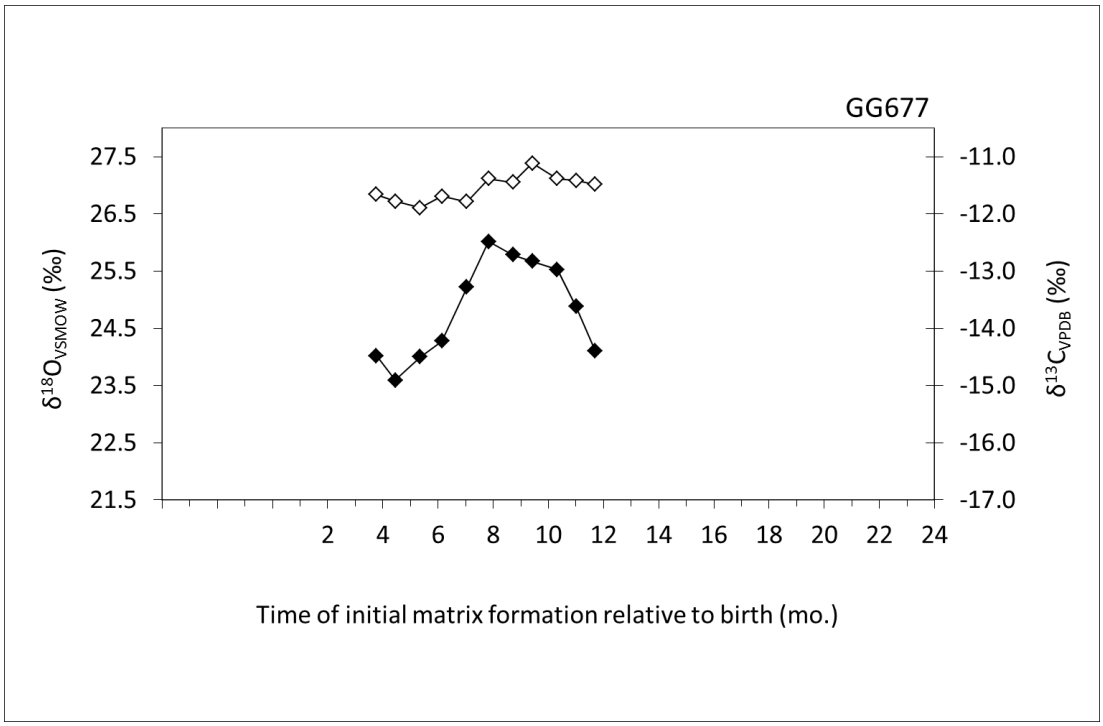
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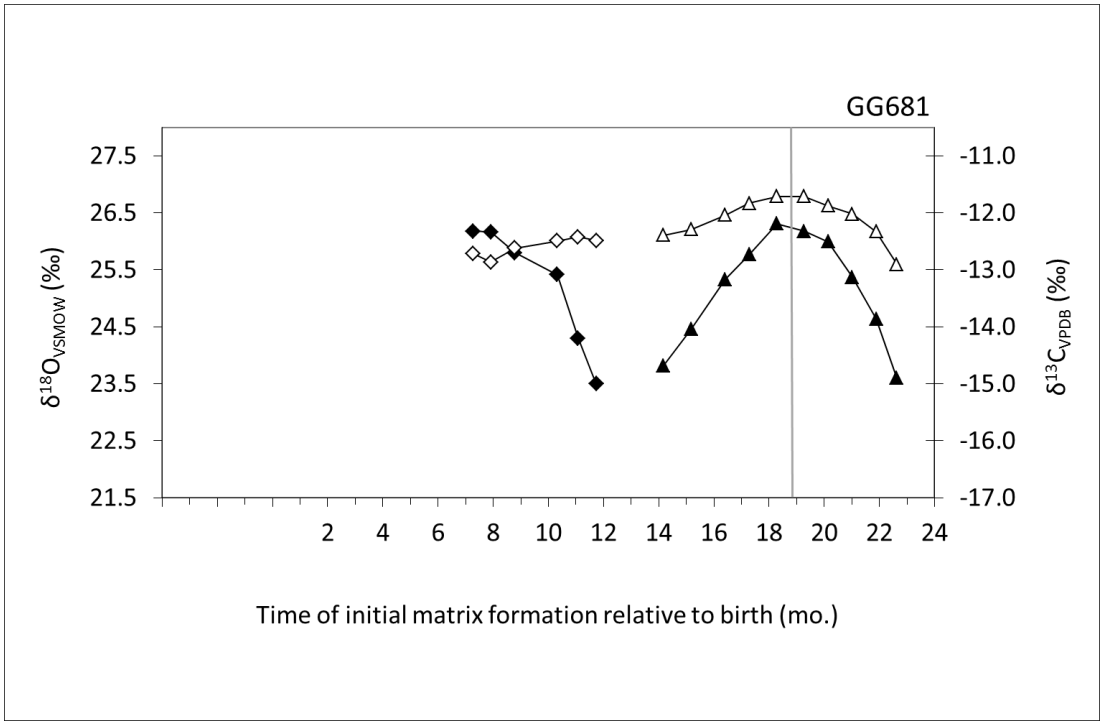
24.5
23.5
22.5
21.5
-11.0
-12.0
-13.0
-14.0
-15.0
-16.0
-17.0
2 4 6 8 10 12 14 16 18 20 22 24
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)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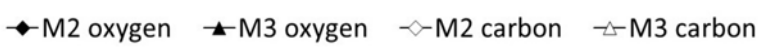
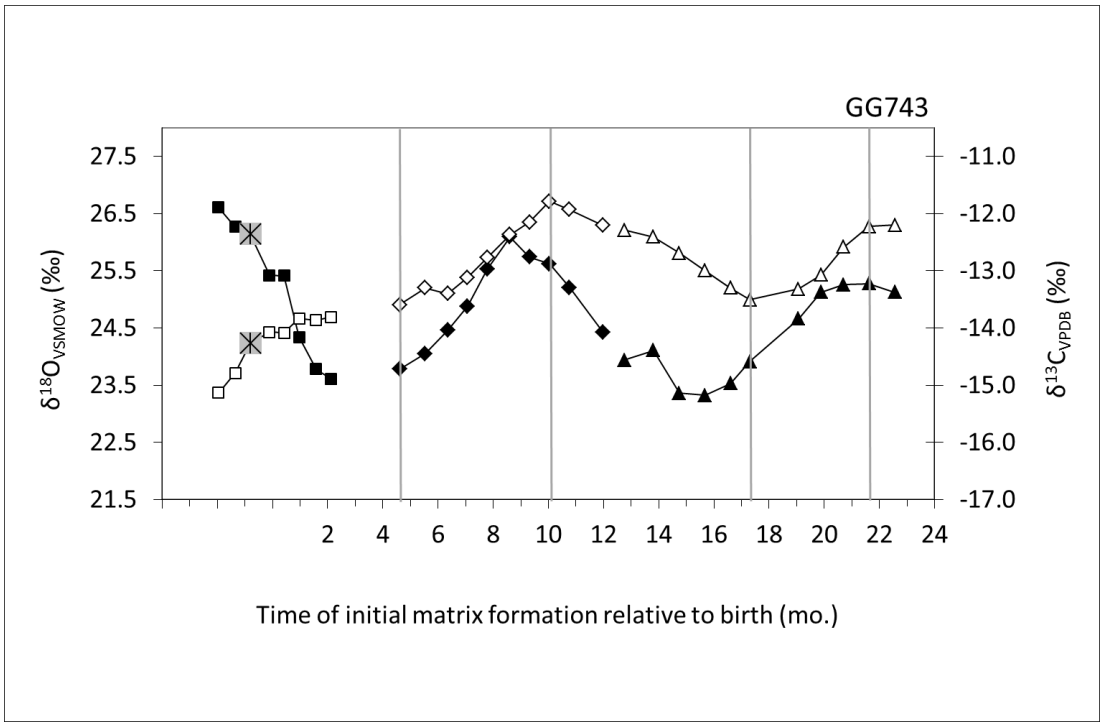
2 4 6 8 10 12 14 16 18 20 22 24
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)


M2 oxygen
M3 oxygen
M2 carbon
M3 carbon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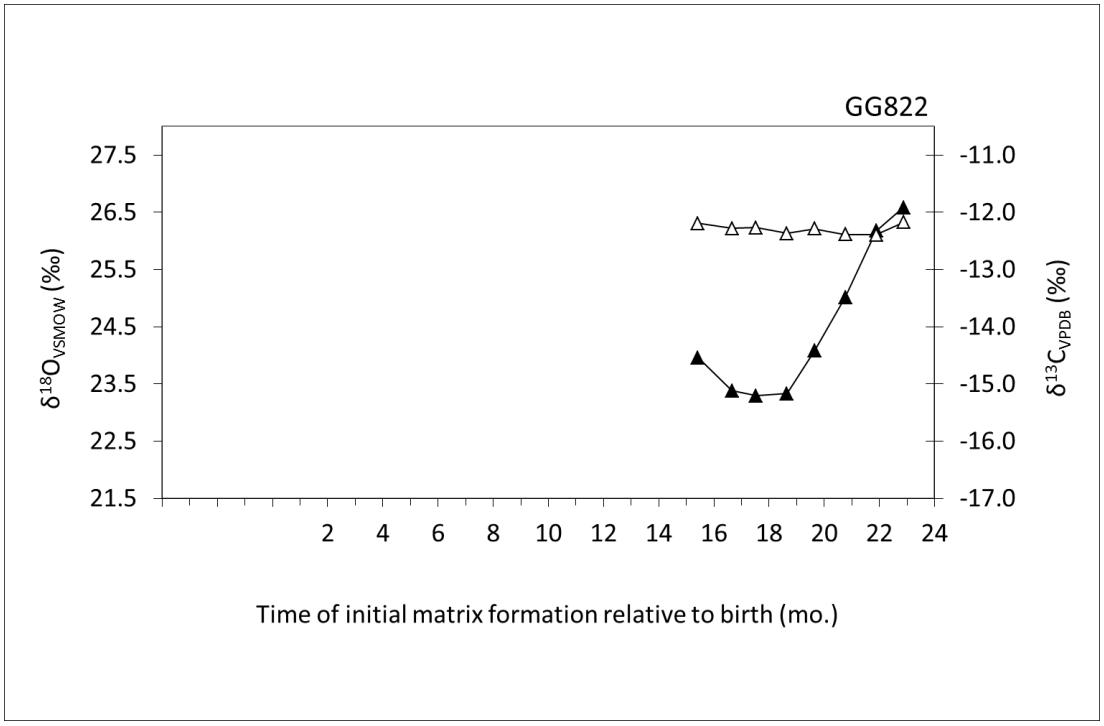
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)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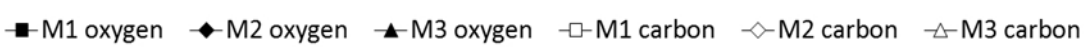
2 4 6 8 10 12 14 16 18 20 22 24
δ18OVSMOW (‰)
δ13CVPDB (‰)
Time of initial matrix formation relative to birth (mo.)


M1 oxygen
M2 oxygen
M3 oxygen
M1 carbon
M2 carbon
M3 carbon

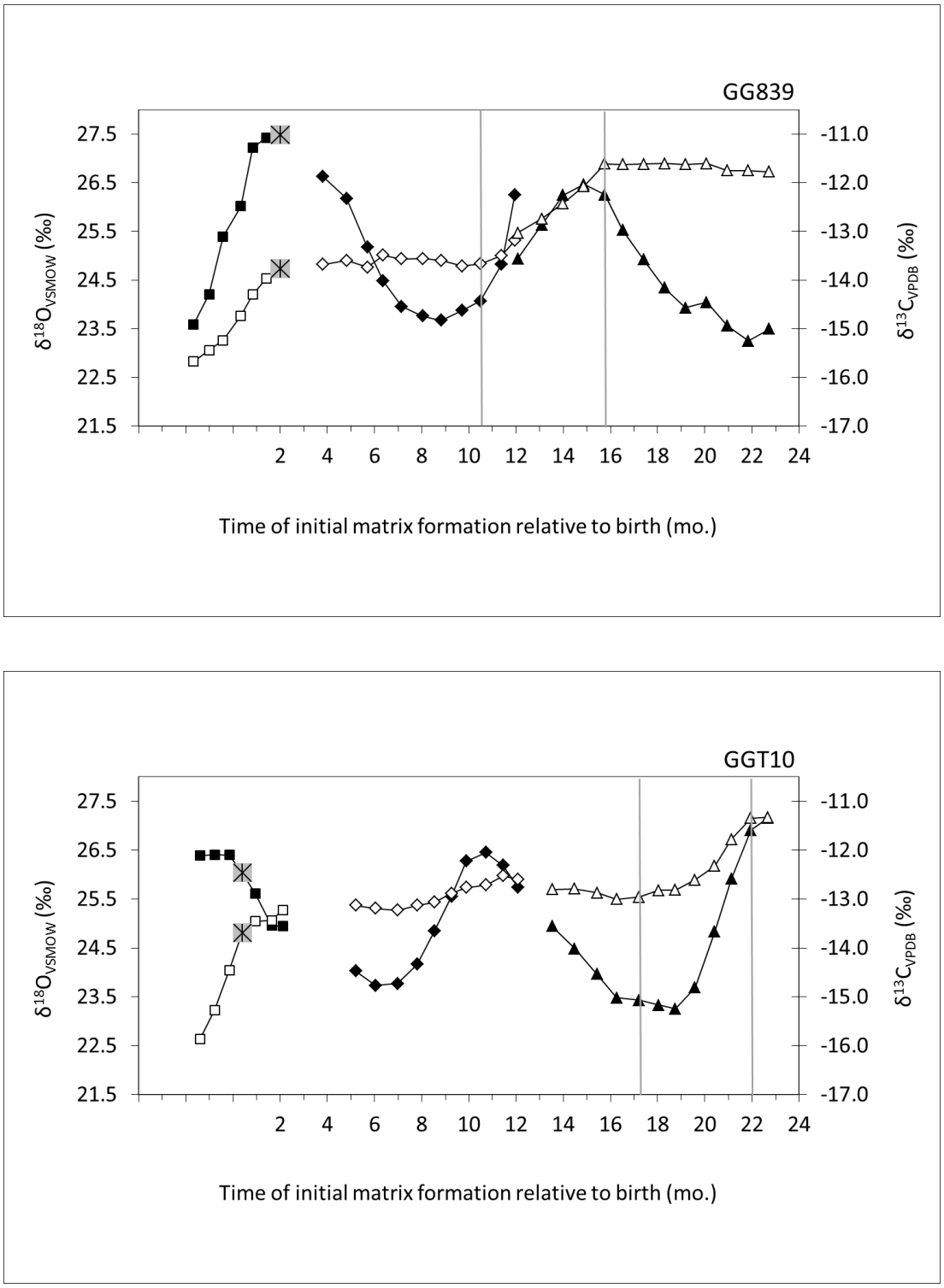


Figure 13.15: Combined $\delta^{18}O$ and $\delta^{13}C$ profiles for first, second and third cattle molar enamel from 13 Grimes Graves cattle. The grey crossed square symbols indicate the change in gradient of the first molar $\delta^{13}C$ profile and the equivalent position in the $\delta^{18}O$ profile ($\delta^{13}C_{CG}$ and $\delta^{18}O_{CG}$). The solid lines indicate features discussed in the text. Analytical error is ± 0.1 ‰ for $\delta^{13}C_{VPDB}$ and ± 0.2 ‰ for $\delta^{18}O_{VSMOW}$.

13.5.2 Estimation of birth seasonality and season of birth

For the Grimes Graves profiles displayed in Figure 13.15, the timing of each $\delta^{18}O$ minimum and maximum relative to birth has been calculated by differentiation of a second order polynomial fitted to the surrounding data points (Appendix 3). All timings are presented in Table 13.9. In addition, values of A_{CG} have been assigned to those animals with first molar data using the procedure outlined in Section 12.3. They are presented in Table 13.10.

Figure 13.16 is a plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Grimes Graves cattle. As in similar plots for Pool and Mine Howe cattle, second molar minima timings are also shown as a horizontal line of data-points running along the bottom of the plot which includes two individuals for which there are no measured values of A_{CG}. The timings of all data-points lie between 3.1 months for GG121 and 8.6 months for GG839 producing an overall distribution of births of 5.5 months (method 2). Alternatively, the distribution of births, calculated from values of A_{CG} is (97/360) x 12 = 3.2 months (method 3). Although not proved at present, method 3 is potentially more accurate than method 2 (Section 12.4) and a narrow distribution of perhaps three or four months is possible. Figure 13.17 is a plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Mine Howe cattle. Again, minima timings are also shown as a horizontal line of data-points running along the bottom of the plot. The plot shows that timings from four additional third molars fall within or just outside the group of data-points with assigned A_{CG} values, but the timings from two further third molars lie approximately two months beyond the main group indicating that these cattle may have been born later in the year.

Table 13.9: $\delta^{18}O$ minima and maxima timings for Grimes Graves second and third molars.

	Predicted time after birth (months)			
Animal	**M2 $\delta^{18}O$ minimum (min 1)**	**$\delta^{18}O$ maximum (max 1)**	**M3 $\delta^{18}O$ minimum (min 2)**	**$\delta^{18}O$ maximum (max 2)**
GG92	6.5	12.2	19.5	
GG120	4.9	11.1		
GG121	3.1	8.7	15.8	21.2
GG122			12.5	19.3
GG123			15.0	20.6
GG149			15.6	22.3
GG614	5.1	10.2		
GG677	4.7	8.7		
GG681			13.0	18.8
GG743	3.4	9.0	15.4	21.3
GG822			17.5	
GG839	8.6	14.8	21.9	
GGT10	5.6	10.7	17.8	22.9

Table 13.10: Angular positions (A_{CG}) of $\delta^{18}O_{CG}$ on the $\delta^{18}O$ profile for the Grimes Graves cattle. * value of neighbouring maximum used. † visual estimate used.

Animal	**$\delta^{18}O_{max}$ (‰)**	**$\delta^{18}O_{min}$ (‰)**	**$\delta^{18}O_{CG}$ (‰)**	**Position of $\delta^{18}O_{CG}$ on sinusoidal curve**	**Angle A_{CG} (^{o})**
GG120	25.66	22.89	25.6	falling slope	12
GG121	26.52 *	23.38	25.1	falling slope	84
GG614	27.32	23.63	26.2	falling slope	68
GG743	26.80 †	23.50	26.1	falling slope	53
GG839	27.53	23.50 †	27.5	rising slope	-13
GGT10	26.46	23.76	26.0	falling slope	47

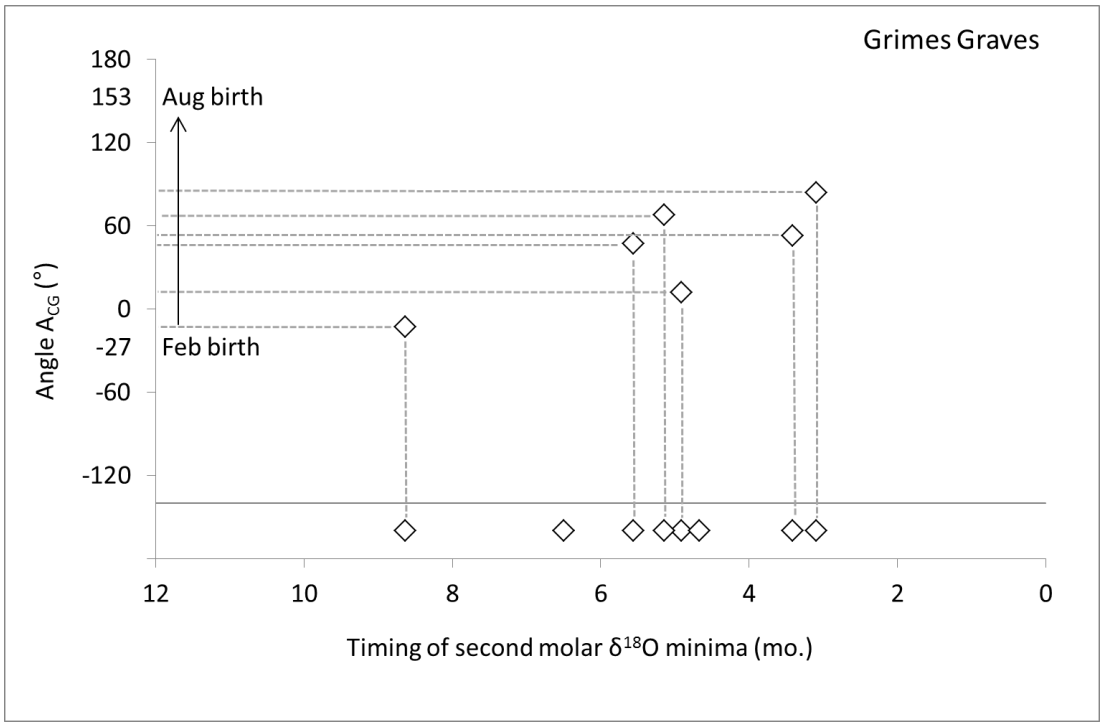


Figure 13.16: Plot of angle A_{CG} versus the timing of second molar $\delta^{18}O$ minima for Grimes Graves cattle.

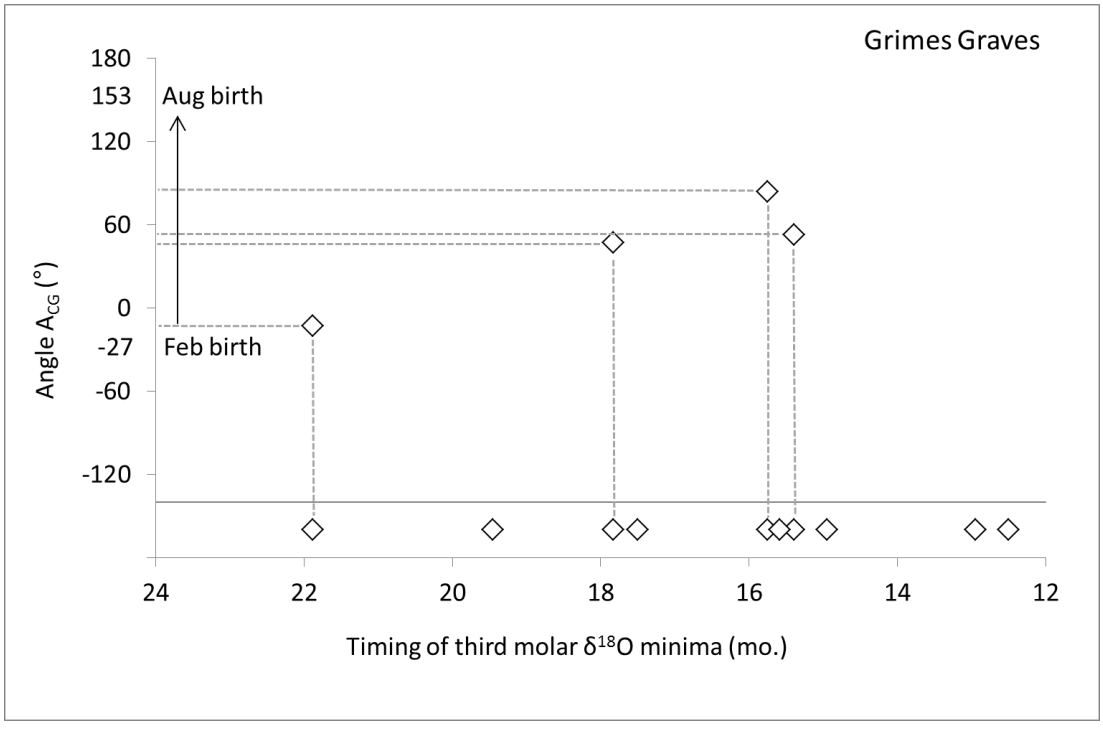


Figure 13.17: Plot of angle A_{CG} versus the timing of third molar $\delta^{18}O$ minima for Mine Howe cattle.

The month and season of birth for each Grimes Graves animal with an assigned value of A_{CG} are estimated using the procedure outlined in Section 13.1.2 for the Pool cattle. Results are displayed in Table 13.11 and show that five of these six Grimes Graves cattle appear to have been born during spring with the seventh animal perhaps during late winter. Although Figure 12.13 suggests that the uncertainty associated with each of the third molar $\delta^{18}O$ minima values may be < ± 2 months, assigning a particular month to the birth of each individual falling outside the main group in Figure 13.17 is not possible. However, it is likely that they were born sometime during the summer. Thus, of the 13 cattle included in this study, ten appear to have been born during the spring, one may have been born during late winter and two during the summer. Of course, calibration by a single example (the modern Dexter) means that any season of birth prediction for the Grimes Graves cattle is approximate and it is possible that the "late winter" calving actually took place after the onset of vegetation growth in spring.

Table 13.11: Estimated season of birth for each Grimes Graves animal.

Animal	Angle A_{CG} (°)	Difference in angle A_{CG} between Grimes Graves animal and the Dexter (A_{CG} = -27°) (°)	Approximate month of birth	Season of birth
GG120	12	+39	March	spring
GG121	84	+111	May	spring
GG614	68	+95	May	spring
GG743	53	+80	April	spring
GG839	-13	+14	February	winter
GGT10	47	+74	April	spring

13.5.3 Diet and environment

In Section 9.3.2, the summary in Table 9.3 and the plot of third molar enamel $\delta^{13}C$ data in Figure 9.11 indicate that the overall range of third molar enamel $\delta^{13}C$ values for Grimes Graves is larger than for any of the Northern Isles sites, for which there are several possible contributing factors. Firstly, the cattle molars analysed in this study were excavated from contexts spanning approximately 550 years. Therefore, the range of third molar enamel $\delta^{13}C$ values may have been influenced by long term changes in dietary regime. Secondly, strontium isotope ratio measurements suggest

that, of those that were analysed, half of the Grimes Graves cattle originated from outside the region of chalk geology in which Grimes Graves is located (Section 9.2, Figure 9.8). As a result, the number of habitats, growing conditions and husbandry practices experienced by this group of animals was likely to have been greater than experienced by a herd in which all the animals were born and raised in the same location. In addition, bone collagen $\delta^{13}C$ results for Grimes Graves cattle show two groups of $\delta^{13}C$ values, a tight group between -22.3 and -22.0 ‰ and a more dispersed group between -21.6 and -21.0 ‰ (Section 9.5, Figure 9.13). The two groups of data are not related to different time periods. Neither are they related to the origins of the cattle; cattle suspected of having non-local origins are present in both groups. One possibility is that they represent different habitats in the local area. According to Legge (1981), there are three main soil groupings within the vicinity of Grimes Graves: calcareous slope soils which are easily worked and suitable for cereal production; dry valley and upland soils which are acidic and unsuitable for cereal production but suitable for grazing; and wet valley soils suitable for pasture (Section 6.5, Figure 6.2). Again, this variety of habitats and growing conditions may have acted to increase the range of third molar enamel $\delta^{13}C$ values. Such an explanation was proposed by Stevens et al (2013) for bone collagen isotopic data measured for domestic animals from Danebury Iron Age hillfort and several other Iron Age sites close by (Section 5.3). These sites were also situated in an area of chalk geology with similar ecological zones to those in the vicinity of Grimes Graves.

Upon closer examination, eight of the 13 $\delta^{13}C$ profiles in Figure 13.15 show noticeable shifts in $\delta^{13}C$, indicated by solid lines parallel to the y-axis in each of the relevant plots. One clear example occurs in the profile for GG839. The strontium isotope ratio measured for this animal is consistent with a birth place local to Grimes Graves (Section 9.2) yet its $\delta^{13}C$ profile shows two distinct levels at -13.6 ‰ and -11.6 ‰ and a slope between the two covering a period of approximately six months. This pattern suggests two distinct food sources with an abrupt change from one to the other that may have involved relocation from one local habitat to another. The translation of an abrupt change in food $\delta^{13}C$ value to a slope recorded

in enamel is caused by the enamel mineralization process and is modelled in Figure 13.18. The schematic diagram in Figure 13.18 shows the $\delta^{18}O$ and $\delta^{13}C$ input signals along with a simplistic prediction of the isotopic profiles recorded in the enamel. The process of mineralization is modelled using a six month running average (the figure of six months is approximately the time taken for cattle molar enamel to fully mineralize as determined by Balasse (2002) for second molars). The position at which the slope meets the high $\delta^{13}C$ level in the recorded $\delta^{13}C$ profile is aligned with the recorded $\delta^{18}O$ profile just after a maximum of the sinusoidal curve, indicated by the grey bar in Figure 13.18. This alignment is evident in the plot for GG839 in Figure 13.15. The grey bar in Figure 13.18 also shows that the abrupt change in input $\delta^{13}C$ signal aligns with the upward slope of the input $\delta^{18}O$ sinusoidal profile suggesting that the change in food source experienced by GG839 occurred during the late spring, in which case it was probably brought about by movement locally.

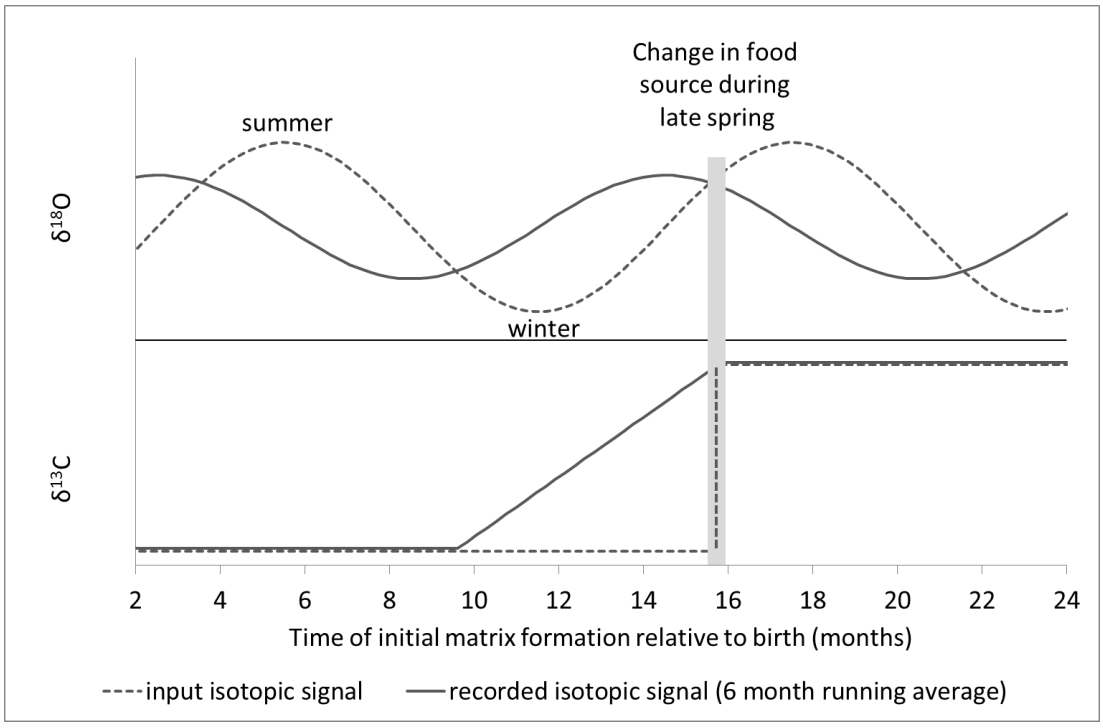


Figure 13.18: Simple model of $\delta^{18}O$ and $\delta^{13}C$ signals recorded in enamel for an animal experiencing an abrupt change in food source. The model assumes that cattle molar enamel takes approximately six months to fully mineralize, as determined by Balasse (2002) for second molars.

If the low and high $\delta^{13}C$ levels recorded in the profile of GG839 are due to movement in the vicinity of Grimes Graves, they probably result from differences in certain environmental factors such as water availability or tree cover (Section 3.3). It is possible that water availability was a key factor at Grimes Graves and that the low and high $\delta^{13}C$ levels represent the aforementioned wet valley and dry valley/upland environments respectively. However, it is worth remembering that wherever the cattle did graze, they would have needed access to an open water source being obligate drinkers. Carbon isotope ratio analysis of vegetation collected from these types of chalk environment has not been carried out for this study but would be a useful exercise in the future to determine the validity of the above explanation suggested for the $\delta^{13}C$ profile of GG839.

Three other cattle with plots in Figure 13.15, GG92, GG677 and GG681, also produced strontium isotope ratios consistent with origins local to Grimes Graves (Section 9.2). However, their $\delta^{13}C$ profiles do not show the same patterning as the profile for GG839. Those of GG92 and GG677 show relatively little variation, that of GG92 perhaps reflecting the seasonal variation in vegetation $\delta^{13}C$ values, co-varying with the $\delta^{18}O$ but with a small temporal offset. Whether or not winter fodder was provided cannot be determined as discussed in Section 13.2.3 for Mine Howe profiles (Figure 13.9). The $\delta^{13}C$ profile of GG681 is a little different in that $\delta^{13}C$ values gradually fall in the cervical half of the third molar crown. This may reflect a change in food source, perhaps brought about by relocation between local habitats. The maximum $\delta^{13}C$ value of GG681 is similar in magnitude to the $\delta^{13}C$ values of GG92 and GG677 and the higher $\delta^{13}C$ level of GG839, perhaps reflecting the same food source or habitat.

Five of the cattle with plots in Figure 13.15, GG120, GG121, GG614, GG743 and GGT10, originated outside the region of chalk geology in which Grimes Graves is located, according to strontium isotope ratio measurements (Section 9.2). GG120 and GG614 are thought to have been born in western or northern Britain, at least 150 km from Grimes Graves. Their $\delta^{13}C$ profiles in Figure 13.15 are similar, each showing a level section in the first molar cervical enamel and second molar cuspal

enamel followed by a sloping section in the second molar cervical enamel (indicated on the plots by solid lines). Animals GG121, GG743 and GGT10 are thought to have originated from an area of Jurassic geology, closer to Grimes Graves than the birth places of GG120 and GG614 (Section 9.2). The second molar $\delta^{13}C$ profiles of GG121 and GG743 are similar to those of GG120 and GG614 in that they exhibit a substantial rise in value. It is possible that the $\delta^{13}C$ slope in each of these four cases represents the seasonal variation in local vegetation $\delta^{13}C$ values. Seasonal changes of similar magnitude were observed in the $\delta^{13}C$ profiles of modern sheep from Rousay, Orkney (Balasse et al 2009) (Figure 5.3). However, the $\delta^{13}C$ profiles recorded in Chillingham cattle molar enamel showed a smaller degree of variation compared to the slopes in the profiles of GG120, GG121, GG614 and GG743, although the influence of winter hay consumption by the Chillingham animals is not known (Figure 11.6).The $\delta^{13}C$ profile of GGT10 is different in form, showing a much reduced level of variation apart from a prominent increase in the cervical third molar enamel. The $\delta^{13}C$ profiles of local cattle GG92 and GG677 do not vary a great deal either, and both the low and high $\delta^{13}C$ levels before and after the sloping section of GG839 are remarkably constant in value. If this level of variation reflects the seasonal variation in vegetation $\delta^{13}C$ values, then the comparatively large slopes recorded in the second molar enamel of GG120, GG121, GG614 and GG743 and the third molar of GGT10 are more likely to reflect a change in food source, perhaps brought about through movement.

It is instructive to consider the $\delta^{13}C$ profile recorded in the enamel of GG743 which is particularly variable and shows three sloping sections, each with a slightly different form (Figure 13.15). Figure 13.19 shows a simulation of this profile produced by modelling the process of enamel mineralization using the 6 month running average. The same simplistic model was previously applied in Figures 12.14, 13.9 and 13.18. Figure 13.19 also shows the $\delta^{13}C$ input signal that produces the simulated enamel $\delta^{13}C$ profile using the model. Although the $\delta^{13}C$ input signal is unlikely to be entirely accurate in form given the simplistic nature of the model, it does suggest a seasonal pattern involving several food sources or locations. The $\delta^{18}O$ profile of GG743 and the $\delta^{18}O$ input signal producing such a profile are also

represented. The grey bars in Figure 13.19 labelled “a” and “c” indicate an increase in the $\delta^{13}C$ input signal during late spring or summer (according to where the grey bars cross the $\delta^{18}O$ input signal), while those labelled “b” and “d” indicate a decrease in the $\delta^{13}C$ input signal, perhaps back to the original value, during autumn or early winter. Changes in food source at these times of year are likely have involved movement. Figure 13.19 also shows that the form of the $\delta^{13}C$ slope recorded in enamel depends on the length of time spent at each location. Similarly large shifts in the $\delta^{13}C$ profiles of GG120, GG121, GG614 and GGT10 also suggest movement during the spring or summer, as does that of GG149, the birth place of which, local or remote, is unknown. It is not possible to determine the age at which GG120, GG121, GG614, GG743 and GGT10 relocated to Grimes Graves from their $\delta^{13}C$ profiles (nor from their $\delta^{18}O$ profiles). Movement between regions does not necessarily produce a noticeable change in enamel $\delta^{13}C$ value, as observed for the non-local Mine Howe animal MH133 (Section 13.2.3). In addition, movement to Grimes Graves may have occurred after the completion of enamel mineralization.

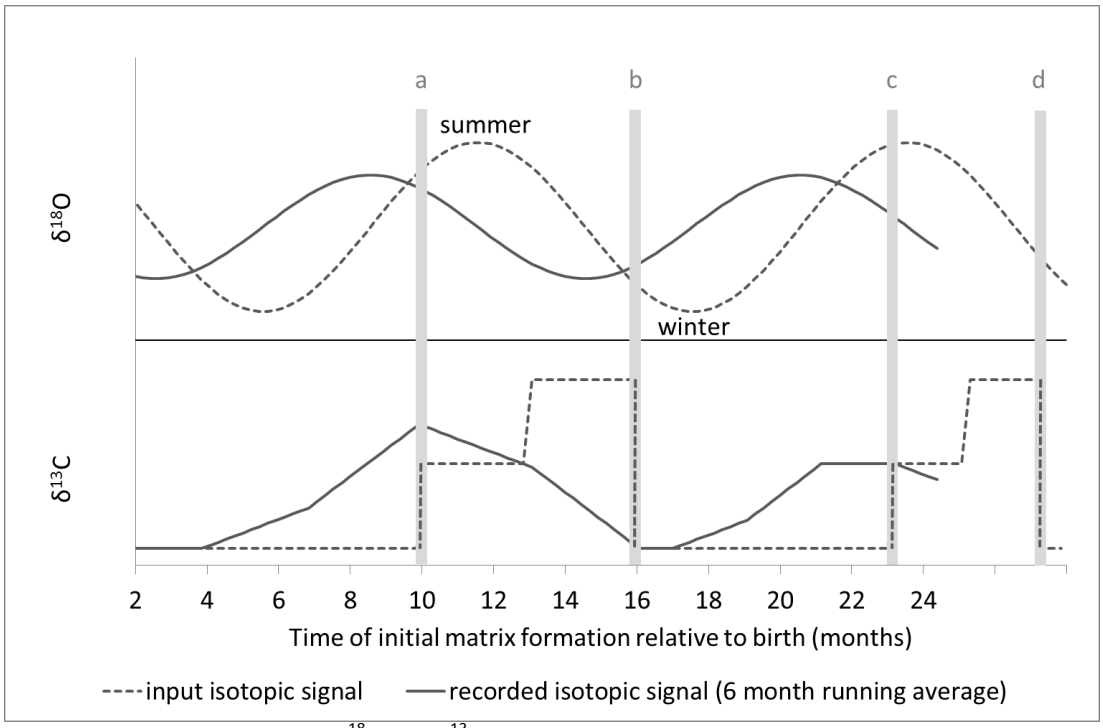


Figure 13.19: Simple model of $\delta^{18}O$ and $\delta^{13}C$ signals recorded in enamel simulating the patterning exhibited in the enamel of animal GG743. The model assumes that cattle molar enamel takes approximately six months to fully mineralize, as determined by Balasse (2002) for second molars. The grey bars a-d are referred to in the text.

13.5.4 Exploring weaning strategy

Because many of the Grimes Graves $\delta^{13}C$ profiles in Figure 13.15 appear to show evidence of movement in the form of large shifts in $\delta^{13}C$ value, it is not possible to investigate weaning using the method proposed in Section 11.2 that calculates the offset between the mid-range $\delta^{13}C$ value for third molar enamel and the value of $\delta^{13}C_{CG}$. Any large change in the $\delta^{13}C$ value of an animal's food source during the mineralization of its second or third molar will affect the calculated value of such an offset. The $\delta^{13}C$ profiles for GG120, GG121, GG614, GG839 and GGT10 show a very flat section for several months after the occurrence of $\delta^{13}C_{CG}$. If weaning can influence the shape of an enamel $\delta^{13}C$ profile as proposed in Section 11.2, then, ostensibly, the flat sections for these five Grimes Graves cattle suggest that they were actively weaned through human intervention at an early age, close to the time when the rumen becomes fully functional at 6-10 weeks. The $\delta^{13}C$ profile of GG743 is a little different in that it continues to rise after the occurrence of $\delta^{13}C_{CG}$ inferring that the animal had less restricted access to its mother's milk and weaning was a more gradual process. Alternatively, it is possible that the form of these $\delta^{13}C$ profiles might be produced by two opposing influences acting during the same period: on the one hand, increasing amounts of ^{13}C-enriched CO_2 produced in the rumen and incorporated into enamel as the animal is gradually weaned, and on the other, a significant decrease in the $\delta^{13}C$ value of its vegetation-based food. More research, through modelling and, ideally, through controlled feeding experiments, would be required to investigate this possibility.

13.5.5 Discussion

Intra-tooth isotope ratio analysis of molar enamel from 13 Grimes Graves cattle suggests that the majority of these animals were born during the spring with one being born during late winter and two during the summer (Section 13.5.2). As stated above, any season of birth prediction for the Grimes Graves cattle is approximate. It is possible that the "late winter" calving actually took place after the onset of vegetation growth in spring. For cattle born into a single herd, calving focussed on the spring and summer might be indicative of an economy with an

emphasis on the production of meat or storable dairy products for the reasons outlined in Section 13.2.5 for the Mine Howe cattle. However, the Grimes Graves cattle included in this study appear to have been born across a broad time period and at diverse locations: strontium isotope analysis suggests that five of the 13 animals with intra-tooth enamel $\delta^{18}O$ and $\delta^{13}C$ profiles originated from outside the region of chalk geology in which Grimes Graves is located and four were born locally (Section 9.2, Figure 9.8). The remaining four were not measured for strontium isotope ratios. The distribution of births for the four local cattle is approximately the same as exhibited by all 13 cattle. Thus, it is possible that the distribution of births for all 13 cattle is representative of the calving strategy practised at the Grimes Graves settlement during the Mid-Late Bronze Age. If true, it may indicate that plentiful provision of fresh milk all year round was not a major concern. Interpretation of the mortality profile for Grimes Graves has suggested a dairy-based economy (Legge 1981) (Section 6.6). An economy focussed on storable dairy products would satisfy the interpretations from both approaches.

Of the 13 intra-tooth enamel $\delta^{13}C$ profiles obtained by this study for Grimes Graves cattle, eight show noticeable shifts in $\delta^{13}C$, which are likely to reflect a change in food source, perhaps brought about through movement (Section 13.5.3). For animals born and raised locally, the observed shifts in $\delta^{13}C$ may reflect movement between different habitats in the vicinity of Grimes Graves, for example wet valley and dry valley/upland environments. For animals originating outside the region of chalk geology in which Grimes Graves is located, the $\delta^{13}C$ shifts may reflect movement between habitats in the vicinity of their birth places or movement between regions. The five cattle included in this study that were interpreted as having been born elsewhere according to strontium isotope ratio analysis were slaughtered at various ages (wear stages C-G, Halstead 1985). It is not possible to surmise why these animals were brought to Grimes Graves: whether they were intended for meat or for milk production or calf rearing. Whatever the reasons, the presence of these cattle at Grimes Graves suggests that long-distance cattle trading networks were in operation during the Mid-Late Bronze Age. The long distance movement of cattle has also been inferred from similar analyses for the Late

Neolithic (Viner et al 2010) and Early Bronze Age (Towers et al 2010) (Section 5.4). The implication is that prehistoric people recognized the importance of fresh bloodlines to their livestock.

14 Conclusions and further research

The conclusions of this thesis are summarised in this chapter and discussed with respect to the aims outlined in Chapter 1 (Introduction). Ideas for future research are also presented.

14.1 Summary of conclusions with reference to the original aims and research questions

14.1.1 Did prehistoric farmers manipulate cattle birth seasonality?

The first aim of this research, addressed in Chapter 2, was to investigate the likelihood that prehistoric farmers manipulated cattle birth seasonality to suit economic focus such that calving strategies for milk and meat production were distinct. The findings from a comprehensive review of modern, scientific, ethnographical and historical literature and interviews with farmers in Orkney and Shetland suggest that, for the production of meat or storable dairy products, both today and in the past, efficiency appears to be the principal motivation behind the choice of calving strategy: maximising production while minimising effort. Research into feral cattle has shown that, if food is seasonally limited, these animals tend to calve in spring when vegetation growth and nutrient content are greatest. The breeding behaviour of feral cattle reverts to the most efficient system in which milk yield is maximised. Thus, by adopting a spring calving strategy, prehistoric cattle farmers would have been able to maximise milk yield, translating into increased calf growth for a meat-focussed economy, or greater volumes of cheese and/or butter. There are further efficiency related advantages to spring calving. Calves raised for meat are at least six months old by winter and better able to withstand the harsher weather conditions. Hence, the number of surviving calves is maximised. Also, since spring calving requires mating during the summer, a bull can live outside amongst the cows during that period, alleviating the need for human effort in the detection of oestrous cows. Of course, such a short period of successful mating may not always have been easy to achieve. For example, some cows may have required an extended period of time after the previous winter to restore their body reserves to

a level sufficient for oestrous cycling, particularly if they were lactating and suckling. In that case, a spring calving period may have extended into the summer.

Only the provision of fresh milk during the winter would have necessitated calving outside of the spring/summer period. Research into the lactation period of domestic cows past and present suggests that autumn calving would have been required for winter milk. For fresh milk all year round, two calving seasons, in spring and autumn, or an extended period through spring, summer and autumn would have been necessary. Since food energy is prioritised for an animal's survival rather than its reproduction, a high degree of effort and management would have been required to provide food of sufficient quantity and quality throughout the year and, perhaps, shelter during winter. In addition, human detection of oestrous cows may have been necessary at certain times of year. A bull also had to be organised to ensure mating at the appropriate times for the calving strategy being practised.

To summarise, it is highly likely that prehistoric farmers would have attempted to manipulate cattle birth seasonality to suit their economic focus. However, calving strategies for milk and meat production may only have been distinct if the provision of fresh milk during the winter months was important. With respect to cattle birth seasonality and arguing from the perspective of efficiency, a dairying economy focussed on the production of storable dairy products is likely to be indistinguishable from a meat-focussed economy, both favouring a short calving period centred around spring.

14.1.2 The interpretation of intra-tooth carbon isotope ratio data

The second aim of this research, addressed in Chapter 11, was to increase understanding of intra-tooth carbon isotope ratio data recorded in cattle enamel, i.e. possible interpretation in terms of physiological changes in early life, diet and environment. Comparison between intra-tooth enamel and dentine collagen $\delta^{13}C$ profiles from three modern cattle (two Chillingham animals and the Dexter bull) has proved very informative regarding the interpretation of the $\delta^{13}C$ profile recorded in

first molar enamel, which shows a distinctive rise towards the cervix followed by a noticeable reduction in gradient. This patterning appears to be heavily influenced by methanogenesis resulting from ruminal digestion. The rise in $\delta^{13}C$ values is thought to represent the transition between purely non-ruminant digestion immediately after birth (relatively low $\delta^{13}C$ values) and the utilisation of a fully formed rumen (relatively high $\delta^{13}C$ values) several weeks later. It has been proposed in this thesis that the reduction in gradient indicates the completion of rumen functionality at the age of ~6-10 weeks and is, therefore, an indirect indication of birth. As such, it has been used as the basis of a possible new method to estimate cattle birth seasonality (Section 14.1.3).

Comparison between the intra-tooth enamel and dentine collagen $\delta^{13}C$ profiles of the two Chillingham cattle also revealed that the $\delta^{13}C$ values of third molar enamel are elevated compared to the value at which the first molar enamel $\delta^{13}C$ value reduces in gradient. Because there is no equivalent difference in the dentine collagen data, it has been suggested in this thesis that the offset in the enamel data may be related to the process of natural weaning whereby the proportion of milk in the diet gradually decreases and the proportion of vegetation increases, resulting in an increasing contribution of enriched CO_2 in the bloodstream from methanogenetic fermentation in the rumen. If this explanation is correct, then enamel $\delta^{13}C$ profiles from cattle fully weaned at an early age through human intervention would be expected to show smaller offsets than the naturally weaned Chillingham cattle. Thus, investigation of weaning strategy for archaeological cattle may be possible through the measurement of such offsets. Knowledge of weaning strategy would aid interpretation regarding economic goal since calves raised for meat might be expected to suckle their mothers for a longer period of time than the calves of milk cows. Much more research is required to assess the validity of this approach.

Unfortunately, interpretation of diet and environment from the post-weaning enamel of the modern Chillingham cattle has been very limited because the molars are generally well worn and the animals' diet is not well defined, particularly in

winter. Obtaining more suitable material would have been very difficult, requiring a carefully planned, long-term biological study using experimental animals, which was beyond the scope of this thesis. Nevertheless, some interpretation has been possible: comparison between intra-tooth $\delta^{13}C$ data from Chillingham cattle molars and $\delta^{13}C$ data from Chillingham Park vegetation suggests that if co-varying sinusoidal $\delta^{13}C$ and $\delta^{18}O$ profiles are recorded in post weaning enamel, the $\delta^{13}C$ profiles may be reflecting the $\delta^{13}C$ values of pasture, which have been shown to vary seasonally. However, this is unlikely to be the only explanation for a sinusoidal-like $\delta^{13}C$ profile recorded in enamel. It is possible that interpretation of an animal's diet and environment may be enhanced through intra-tooth isotope ratio analysis of dentine collagen samples extracted from molar roots. The dentine collagen $\delta^{13}C$ profile for the first molar root of the modern Dexter bull appears to show higher temporal resolution than profiles recorded in coronal dentine or enamel. Again, more research is required to confirm this suggestion.

To summarise, there is now a greater understanding of the relationship between intra-tooth carbon isotope ratio data recorded in enamel and the physiological changes related to digestion in early life. However, interpretation of diet and environment remains limited. To gain the maximum amount of information from the enamel of a prehistoric animal, first, second and third molars are required.

14.1.3 Can intra-tooth isotope ratio data be used to estimate cattle birth seasonality?

The third aim of this research, addressed in Chapter 12, was to determine whether intra-tooth isotope ratio data recorded in cattle enamel can be used to estimate birth seasonality with a degree of accuracy that will enable the investigation of different economic goals. The degree of accuracy is defined here as an ability to discriminate between one-, two-, three- and four-season calving. Three methods to estimate cattle birth seasonality were identified by this thesis and evaluated using a common dataset produced from the molar enamel of 13 archaeological cattle. Methods 1 and 2 are based upon the positioning along the crown of the sinusoidal-

like $\delta^{18}O$ profile recorded in second and third molar enamel. Birth seasonality for a particular assemblage is estimated by comparing the $\delta^{18}O$ profile positions of several cattle in that assemblage. Method 1 uses plots of intra-tooth $\delta^{18}O$ data versus distance from the cervix and applies a procedure to correct for inter-animal variability in molar growth rate through normalisation to period, as suggested by Balasse et al (2012a, 2012b). For method 2, the intra-tooth $\delta^{18}O$ data is plotted versus time rather than distance from the cervix using a common chronology for molar crown development. In contrast, method 3, newly proposed in this thesis, utilises the shape of the $\delta^{13}C$ profile recorded in first molar enamel, particularly the noticeable reduction in $\delta^{13}C$ gradient which is thought to be an indirect indication of birth (Section 14.1.2). Birth seasonality for a particular assemblage is estimated by comparing how this reduction in $\delta^{13}C$ gradient relates to the sinusoidal-like $\delta^{18}O$ profile for several cattle in that assemblage.

An attempt was made to identify and quantify theoretically the principal sources of uncertainty associated with the timing of an animal's birth for each of the three methods. For methods 1 and 2, uncertainties related to the chronology of crown formation were identified as contributing factors. However, because method 3 is based upon the direct comparison of $\delta^{13}C$ and $\delta^{18}O$ profiles recorded in enamel, which are equally affected by variability in the timing and rate of crown formation, the influence of this source of uncertainty on estimates of birth seasonality is removed. A comparison between all three methods concluded that method 3 is likely, though not proven, to be the most accurate of the three methods for estimating cattle birth seasonality and should be able to discriminate between one-, two-, three- and four-season calving. However, this statement cannot be accepted with a high level of confidence until the molars of more cattle have been analysed, particularly from modern animals with known histories, and the associated uncertainties investigated and evaluated thoroughly. Comparison between the three methods also suggested that variability in the timing of crown formation appears to be more pronounced for third molars than for second molars. As a result, discrimination between one-, two-, three- and four-season calving is unlikely to be achievable by applying either method 1 or method 2 to third molars.

Therefore, the use of third molars to estimate cattle birth seasonality is not recommended, which is unfortunate as loose third molars are often the most common component in archaeozoological dental collections because they are easy to identify. In addition, at least for the particular dataset used in this study, the normalisation approach of method 1 appears to produce less accurate estimates of birth seasonality than method 2. The only method that may lead to the same interpretation regarding economic focus as method 3 in many cases is method 2 as applied to second molars. However, it is unclear just how well this method would be able to discriminate between one-, two-, three- and four-season calving.

To summarise, a possible new approach to determine cattle birth seasonality has been identified that utilises both carbon and oxygen intra-tooth isotope ratio measurements of first molar enamel. Second molar carbon and oxygen isotope ratio measurements are also required for this method. Although the method requires verification through more extensive testing, particularly of modern material, initial results suggest that it has the potential to estimate cattle birth seasonality with a degree of accuracy that will enable the investigation of different economic goals.

14.1.4 Predicting season of birth

The fourth aim of this research, addressed in Chapter 12, was to devise a method to predict the actual season of birth of an animal from its intra-tooth isotope ratio data. It has been possible to devise a method to predict the actual season of birth of an animal. The method uses intra-tooth enamel $\delta^{13}C$ and $\delta^{18}O$ profiles from the first molar of the modern Dexter bull, Karst, the only animal included in this study with a known date of birth. The profiles exhibit the necessary features to allow the calculation of angle A_{CG}, the basis of the proposed new method to estimate cattle birth seasonality (method 3, Section 14.1.3). This means that it is possible to predict the season of birth of any other animal with an assigned value of A_{CG} by calculating the difference in birth date between the animal in question and that of the Dexter (360° being equivalent to 12 months). Because the isotope data of only one modern

animal could be used for this purpose, season of birth predictions made in this thesis should be regarded as approximate.

14.1.5 Estimating cattle birth seasonality for archaeological assemblages

The fifth aim of this research, addressed in Chapter 13, was to determine whether the economic focus of an archaeological site inferred from an estimate of cattle birth seasonality concurs with the interpretation of its mortality profile. The findings for each archaeological site included in this study are summarised below:

Interface period Pool: Intra-tooth isotope ratio analysis of molar enamel strongly indicates that calving occurred during spring, summer and autumn. According to the arguments summarised in Section 14.1.1, the likely motivation for this calving pattern would have been the production of fresh milk throughout the year. The mortality profile suggests a dairy-focussed economy during the Interface period. Both approaches lead to the same conclusion – a dairy-based economy – but the interpretation derived from the calving seasonality prediction additionally proposes an emphasis on fresh milk rather than the production of dairy products for long-term storage.

Mid-Later Iron Age Mine Howe: Intra-tooth isotope ratio analysis of molar enamel suggests that the calving period was approximately five months during spring and summer. Such a calving period is unlikely to have provided year-round fresh milk, particularly during the leanest time of year during late winter before the new spring growth. Instead, the interpretation is for an economy focussed on the production of meat or storable dairy products. The mortality profile for Mine Howe during the Mid-Later Iron Age includes elements suggestive of both a dairy- and a meat-based economy, which is not incompatible with the interpretation derived from birth seasonality. However, Mine Howe has been interpreted as having religious significance. Therefore, the cattle remains discovered there may not be representative of a local herd structure; they may have been raised at a number of settlements with diverse economic goals, possibly across a broad time period.

Viking Earl's Bu: Intra-tooth isotope ratio analysis of molar enamel has produced a somewhat speculative interpretation that there were two calving seasons approximately six months apart, possibly in summer and winter, which would have enabled the production of fresh milk all year round. The mortality profile for Earl's Bu suggests a meat-focussed economy during the Viking period. The two approaches lead to different conclusions. However, it is likely that Earl's Bu was a consumer site and the cattle remains are not representative of a local herd structure.

Middle Iron Age Old Scatness: Intra-tooth isotope ratio analysis of molar enamel has produced inconclusive predictions regarding cattle birth seasonality. This is because only third molars were available for analysis (Section 14.1.3). Thus, the results could not be interpreted with respect to economic focus and compared with the interpretation from the mortality profile of a dairy-focussed economy during the Middle Iron Age.

Mid-Late Bronze Age Grimes Graves: Intra-tooth isotope ratio analysis of molar enamel suggests that the majority of these animals were born during the spring with one being born during late winter and two during the summer. These predictions are approximate (Section 14.1.4). Such a calving period with its strong bias towards the spring appears to indicate an economy focussed on the production of meat or storable dairy products. The mortality profile for Grimes Graves suggests a dairy-based economy. Both approaches lead to the same conclusion if the calving pattern is interpreted as representing an economy with an emphasis on storable dairy products rather meat. However, according to strontium isotope ratio results, several of the cattle used to estimate birth seasonality were not born locally to Grimes Graves. In addition, they appear to have been born across a broad time period. Thus, the group as a whole is unlikely to represent the local herd structure.

The above summaries indicate that most of the archaeological sites selected for this study, for various reasons, have not proved ideal choices to pursue this particular aim. If the economic interpretations derived from a site's cattle mortality profile and birth seasonality estimate are to be compared meaningfully, the site should ideally be a self-sufficient or producer settlement. For two of the sites, this may not be true: Earl's Bu is likely to be a consumer site, while Mine Howe is thought to have religious significance. Grimes Graves and Old Scatness are not ideal sites for different reasons. For Grimes Graves, the estimate of birth seasonality may not be representative of the local herd due to the presence of cattle born elsewhere, while, for Old Scatness, an estimate of birth seasonality of sufficient accuracy could not be obtained from third molars, the only teeth available for isotopic analysis.

Nevertheless, carrying out this exercise has demonstrated the potential benefit of taking a multi-proxy approach when investigating the economic role of prehistoric cattle. In particular, it has highlighted the possibility of discriminating between different dairying strategies – fresh milk provision throughout the year or an emphasis on storable dairy products – both of which may have been practised in prehistoric Britain but result in indistinguishable mortality profiles (Table 14.1). This thesis has also proposed a possible new method to investigate weaning strategy which might also be employed as part of a multi-proxy approach.

Thus, with respect to the first research question presented in Chapter 1 (Introduction), it may be concluded provisionally that intra-tooth isotope ratio data recorded in enamel can be used to investigate prehistoric cattle dairying. More research is required to confirm this conclusion (Section 14.2).

Table 14.1: Detecting the different economic roles of prehistoric cattle through a multi-proxy approach.

Interpretation of economic focus from mortality profile	Distribution of births	Age when weaned	Multi-proxy interpretation of economic focus
meat	narrow	late	meat
milk	narrow	early	storable dairy products
milk	wide	early	year-round fresh milk

14.1.6 Investigating the diet and environment of prehistoric cattle

The sixth aim of this research, addressed in Chapter 13, was to determine whether intra-tooth carbon isotope ratio data recorded in cattle enamel can provide useful information about the diet and environment of the archaeological cattle included in this study. The findings for each archaeological site included in this study are summarised below:

Interface period Pool: Intra-tooth carbon isotope ratio analysis of molar enamel suggests that seaweed was unlikely to have been a significant dietary component during the Interface period. Mid-range third molar $\delta^{13}C$ values are slightly elevated compared to those of Earl's Bu and Mine Howe, interpreted as reflecting different local growing conditions. The soils at Pool are expected to have had relatively high salinity and better drainage. Closer examination of intra-tooth $\delta^{13}C$ profiles for Pool cattle has allowed the identification of a recurring pattern for several animals which appears to be related to age rather than time of year, possibly indicating a change in diet through fodder provision or movement between grazing areas.

Mid-Later Iron Age Mine Howe: Intra-tooth carbon isotope ratio analysis of molar enamel has revealed a variety of $\delta^{13}C$ profiles that may indicate different husbandry regimes based upon C_3 vegetation. This suggestion supports the idea that the cattle at Mine Howe may have been raised at a number of different settlements.

Viking Earl's Bu: Intra-tooth carbon isotope ratio analysis of molar enamel has revealed $\delta^{13}C$ profiles that are similar in value. They also show little internal

variation, which may indicate the provision of winter fodder. These observations suggest that the Earl's Bu cattle included in this study may have been raised within a restricted geographical area, probably local to Earl's Bu, under the same husbandry regime.

Middle Iron Age Old Scatness: Intra-tooth carbon isotope ratio analysis of molar enamel has produced a variety of $\delta^{13}C$ profiles, which are likely to reflect different husbandry regimes with several perhaps indicating the provision of winter fodder in one form or another. Enamel $\delta^{13}C$ values are consistent with a terrestrial C_3 diet although the consumption of seaweed in small quantities cannot be ruled out. Mid-range third molar $\delta^{13}C$ values are similar to those of Pool and are thought to reflect comparable growing conditions, i.e. relatively high salinity and good drainage.

Mid-Late Bronze Age Grimes Graves: Intra-tooth carbon isotope ratio analysis of molar enamel has revealed shifts in $\delta^{13}C$ that are evident in the profiles of the majority of cattle included in this study. These are likely to reflect a change in food source, perhaps brought about through movement. For animals born and raised locally, the shifts in $\delta^{13}C$ may reflect movement between different habitats in the vicinity of Grimes Graves. For animals originating elsewhere, they may reflect movement between habitats in the vicinity of their birth places or movement between regions.

The above summaries indicate that intra-tooth carbon isotope ratio analysis of molar enamel does not permit the identification of specific C_3 food sources. Seaweed consumption of any significance by cattle should be detectable but is not evident in this study. Equifinality is expected to further limit the investigation of C_3-based husbandry, whereby a number of different dietary regimes result in identical $\delta^{13}C$ profiles. Despite such limitations, intra-tooth carbon isotope ratio analysis of molar enamel does enable some cattle husbandry-related information to be gained through the identification of recurring patterns in the $\delta^{13}C$ profiles and interpretation with respect to the accompanying $\delta^{18}O$ profiles. For example, an age-

related change in diet was observed for some of the Pool cattle, while movement between habitats, often in spring or summer, was inferred for many of the Grimes Graves cattle. Such detailed information cannot be extracted from bulk collagen $\delta^{13}C$ measurements of bone and can only be speculated upon if isotopic data are unavailable.

Thus, with respect to the second research question presented in Chapter 1 (Introduction), it may be concluded that intra-tooth isotope ratio data recorded in enamel can provide useful information regarding sub-annual variation in the diet and environment of prehistoric cattle, although it is not possible to identify particular C_3 food sources.

14.2 Potential for further research

Several areas of future research have been proposed throughout this thesis. Intra-tooth isotope ratio analysis of both enamel and dentine collagen from the molars of modern cattle with known birth dates and closely controlled dietary and drinking water sources would be particularly beneficial and would enable:

1) Verification of the proposed new method to estimate cattle birth seasonality (method 3): its theoretical basis, associated uncertainties and accuracy compared to the alternative methods described in this thesis.
2) More confident predictions of season of birth.
3) Further exploration of the proposed new method to investigate weaning strategy based on the offset between first and third molar $\delta^{13}C$ values. Verification of the basis of the proposed method and the determination of its efficacy might be facilitated through comparison between intra-tooth $\delta^{13}C$ and $\delta^{15}N$ profiles recorded in molar enamel and dentine collagen respectively. Because $\delta^{15}N$ values increase with trophic level, and a suckling mammal is one trophic level above its mother (Fogel et al 1989), intra-tooth $\delta^{15}N$ profiles recorded in molar dentine collagen during the early life of an animal should reflect the process of weaning as a reduction in $\delta^{15}N$ values to

the trophic level of its mother. Previous studies have demonstrated this patterning in the dentine of modern and archaeological cattle dentine (Balasse et al 2001, Balasse and Tresset 2002). A reliable method to interpret weaning strategy would help to discriminate between economies focussed on meat and those focussed on storable dairy products (Section 14.1.5).

4) Investigation of whether grain-rich fodder and pasture can be differentiated in enamel $\delta^{13}C$ values due to differences in digestibility and ruminal methane production between grains and pasture.

Increasing the dataset and the number of archaeological sites included is also recommended to test further the proposal that intra-tooth isotope ratio data recorded in enamel can be used to investigate prehistoric cattle dairying through the estimation of cattle birth seasonality and weaning strategy. In addition, comparison between a larger number of sites may eventually enable a more nuanced interpretation of $\delta^{13}C$ data with respect to diet and environment. Inter- and intra-site variability in third molar crown formation might also be explored with respect to the possible influences of genetic make-up, sex and plane of nutrition.

Of the archaeological sites investigated for this study, the results from Grimes Graves are particularly intriguing with respect to the movement of cattle in the Bronze Age, both long-distance and locally. More focussed strontium isotope ratio analysis of cattle molar enamel together with carbon isotope ratio analysis of vegetation collected from different chalk-based habitats would improve interpretation.

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Personal communications

Personal communication from Mr Cyril Annal, owner of the Swona cattle herd, Orkney. The communication was received during a telephone interview on January 24th 2011 about the Swona cattle.

Personal communication from Dr Julie Bond, senior lecturer in archaeology at the University of Bradford. The communication was received during a postgraduate monthly meeting on March 14th 2013.

Personal communication from Mr Jim Chalmers, lecturer at Orkney College, UHI. The communication was received during an interview on July 15th 2010 about cattle farming in Orkney.

Personal communication from Mr Ronnie Eunson, cattle farmer, Uradale Farm, East Voe, Scalloway, Shetland. The communication was received during an interview on August 6th 2011 about cattle farming in Shetland.

Personal communication from Mr James Foubister, cattle farmer, West Burnside, Tankerness, Orkney. The communication was received during a telephone interview on July 18th 2010 about cattle farming in Orkney.

Personal communication from Louisa Gidney, owner of the Dexter Bull Karst. The communication was received during an interview on May 25th 2011 about the Dexter.

Personal communication from Mr Tommy Isbister and Mrs Mary Isbister, cattle farmers, Burland Croft, Trondra, Shetland. The communication was received during an interview on August 5th 2011 about cattle farming in Shetland.

Personal communication from Mr Chris Leyland, Park Manager, Chillingham Park, Northumberland. The communication was received during an interview on October 10th 2009 about the Chillingham Wild White Cattle herd.

Personal communication from Mr John Mainland, farmer, Rousay, Orkney. The communication was received during an interview on July 18th 2010 about cattle farming in Orkney.

Personal communication from Mr Kenny Meason, cattle farmer, Shapinsay, Orkney. The communication was received during an interview on July 18th 2010 about cattle farming in Orkney.

Personal communication from Mrs Rona Towrie, tour guide, Sanday, Orkney. The communication was received during a tour of Sanday on August 17th 2011.

Appendix 1

Table A.1: Molar terminology.

Cervix	'neck' of a molar where the crown meets the root
Cusp	pointed projection on the occlusal surface of a molar
Lobe	Buttress-like structure on lingual or buccal side of the crown
Mesial	closest to the front of the mouth
Distal	closest to the rear of the mouth
Lingual	closest to the tongue
Buccal	closest to the cheek
Occlusal surface	grinding surface of a molar

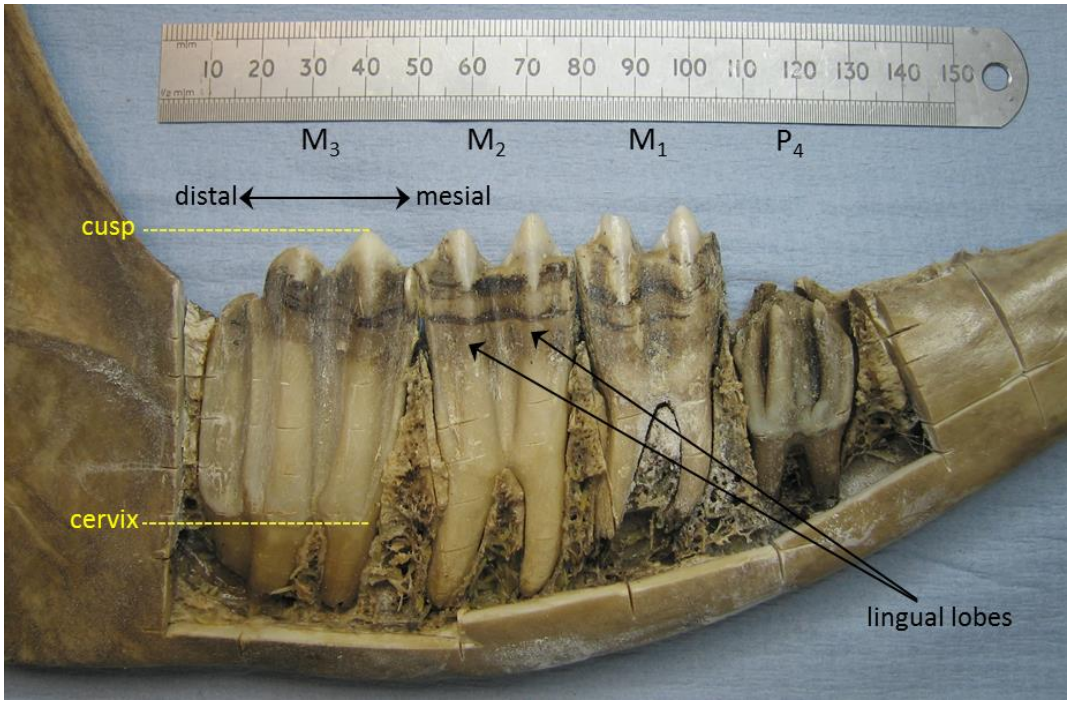

Figure A.1: Left mandible of animal CHIL1 showing the positions of the first, second and third mandibular molars (M_1, M_2 and M_3).

Table A.2: Details of Pool mandibles and loose teeth. 1st, 2nd and 3rd mandibular molars are designated M_1, M_2 and M_3. Wear stages after Grant (1982).

Animal ID	Phase	Context	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)		
PL0025	PL83A/Ph7.2	0025	M	R			M_3 (a/b)
PL0278	-/Ph7.2	0278	M	L	M_1 (j)	M_2 (e/f)	M_3 (a)
PL0302	-/Ph7.1	0302	LT	R			M_3 (k)
PL0330	-/Ph7.2	0330	M	R	M_1 (g)	M_2 (?)	M_3 (a/b)
PL0339	-/Ph7.2	0339	M	L	M_1 (h)	M_2 (f)	
PL0344	-/Ph7.2	0344	M	R	M_1 (g)	M_2 (f)	M_3 (b)
PL0364	PL84/Ph7.2	0364	LT	L			M_3 (c)
PL0386	PL84/Ph7.2	0386	M	R	M_1 (g)	M_2 (f)	M_3 (a/b)
PL0444	-/Ph7.1	0444	M	L	M_1 (j)	M_2 (f)	M_3 (b)

Table A.3: Details of Mine Howe mandibles and loose teeth. 1st, 2nd and 3rd mandibular molars are designated M_1, M_2 and M_3. Wear stages after Grant (1982).

Animal ID	Phase	Trench	Context	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)		
MH03	D10	00/E?B	87/1956	M	L	M_1 (l/k)	M_2 (k)	M_3 (g)
MH84	D10	00/C	85/2218	M	R	M_1 (g)	M_2 (c)	
MH125	D10	00/E?C	85/2218	M	R	M_1 (k)	M_2 (k)	M_3 (g)
MH128	D10	00/E?C	85/2218	M	L	M_1 (l)	M_2 (k)	M_3 (g)
MH133	D10	00/B	85/2215	M	R	M_1 (?)	M_2 (j)	M_3 (d)
MH138	D10	-	85/2217	M	R	M_1 (k)	M_2 (k)	M_3 (f)
MH140	D9	00/B	89/1983	M	R		M_2 (j)	M_3 (f)
MH149	D10	03/G	1034/6366	LT	R			M_3 (h)
MH162	D10	00/B	85/2217	LT	L			M_3 (d)
MH163	D10	00/?	86/1946	LT	L			M_3 (b)
MH174	D10	03/G	1034/6367	LT	L			M_3 (f)
MH0604	D11	03/G	1003/4903	M	R	M_1 (k)	M_2 (j)	M_3 (f)

Table A.4: Details of Earl's Bu mandibles and loose teeth. 2nd and 3rd mandibular molars are designated M_2 and M_3. Wear stages after Grant (1982).

Animal ID	Year	Phase	Context	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)	
EB1	EB88	M	377/367	LT	R	M_2 (f)	M_3 (a)
EB4	EB90F	M	556/379	M	R	M_2 (g)	M_3 (f)
EB8	EB90	M	551/362	LT	R		M_3 (f)
EB9	EB90	M	DA tray 11	LT	R		M_3 (d)
EB13	EB90	M	560-2/603	LT	R	M_2 (f)	M_3 (a/b)
EB14	EB90	M	OD tray 17	M	L		M_3 (j)
EB21	EB88	M	ODT3	LT	R		M_3 (f)
EB23	EB88	M	OOT3	LT	L		M_3 (d)
EB28	EB88	M	382/368	LT	L		M_3 (a)

Table A.5: Details of Old Scatness loose teeth. 3rd mandibular molars are designated M_3. Wear stages after Grant (1982).

Animal ID	Year	Period	Area/Context	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)
OSB2565	OSB00	Fills	C/2565	LT	L	M_3 (e)
OSB3475	OSB04	Ph6	B/3475	LT	L	M_3 (f)
OSB3624	OSB02	Ph5	C/3624	LT	R	M_3 (b)
OSB6079	OSB04	Ph6	B/6079	LT	R	M_3 (a)
OSB60991	OSB05	Ph6	B/6099	LT	R	M_3 (g)
OSB60992	OSB05	Ph6	B/6099	LT	L	M_3 (b)
OSB60993	OSB05	Ph6	B/6099	LT	R	M_3 (g)
OSB60994	OSB05	Ph6	B/6099	LT	L	M_3 (j)
OSB62591	OSB06	Ph6	B/6259	LT	L	M_3 (g)
OSB62592	OSB06	Ph6	B/6259	LT	R	M_3 (g)

Table A.6: Details of Grimes Graves mandibles and loose teeth. 1st, 2nd and 3rd mandibular molars are designated M_1, M_2 and M_3. Wear stages after Grant (1982).

Animal ID	Area	Context	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)		
GG92	1972 Shaft	Gps 1-3 midden	M	L		M_2 (g)	M_3 (c)
GG120	1972 Shaft	Gps 1-3 midden	M	R	M_1 (f)	M_2 (a/b)	
GG121	1972 Shaft	Gps 1-3 midden	M	R	M_1 (k/l)	M_2 (j)	M_3 (g)
GG122	1972 Shaft	Gps 1-3 midden	LT	R			M_3 (d)
GG123	1972 Shaft	Gps 1-3 midden	LT	L			M_3 (c/d)
GG149	1972 Shaft	Gps 1-3 midden	M	L			M_3 (e/f)
GG614	1972 Shaft	Gps 1-3 midden	M	L	M_1 (j/h)	M_2 (f)	
GG621	1972 Shaft	Gps 1-3 midden	M	R		M_2 (f)	
GG661	1972 Shaft	Gps 1-3 midden	M	R	M_1 (f)		
GG677	1972 Shaft	Gps 1-3 midden	M	L		M_2 (f)	
GG681	1972 Shaft	Gps 1-3 midden	M	L		M_2 (j)	M_3 (g)
GG722	1973 Shaft	Gps 1-3 midden	M	R	only bone analysed		
GG743	1972 Shaft	Gps 1-3 midden	M	L	M_1 (k/l)	M_2 (g)	M_3 (e/f)
GG822	1972 Shaft	Gps 1-3 midden	M	L			M_3 (g)
GG839	1972 Shaft	Gps 1-3 midden	M	R	M_1 (k)	M_2 (g)	M_3 (d)
GGT10	1972 trench 10 (812)	Sq 62 Layer 13 Gp 3	M	L	M_1 (k/l)	M_2 (g)	M_3 (f)

Table A.7: Details of mandibles and loose teeth from Chillingham cattle and the modern Dexter bull (Karst). 1st, 2nd and 3rd mandibular molars are designated M_1, M_2 and M_3. 4th mandibular deciduous premolars are designated dP_4. Wear stages after Grant (1982).

Animal ID	Mandible or loose teeth (M or LT)	Left or right (L or R)	Teeth analysed (+ wear stage)			
CHIL1	M	L	dP_4 (m)	M_1 (h)	M_2 (g)	M_3 (f)
CHIL5						
CHIL6	M	R		M_1 (l)	M_2 (l)	M_3 (k)
CHIL7	M	L		M_1 (l)	M_2 (k)	M_3 (j)
CHIL8	M	L				M_3 (l)
CHIL9						
CHIL10	M	R		M_1 (l)	M_2 (k)	M_3 (j)
CHIL14	M	R		M_1 (k)	M_2 (k)	M_3 (h)
KAR	M	L	dP_4 (j)	M_1 (g)	M_2 (b/c)	

Table A.8: Sampling undertaken for this study.

Animal ID	Mandible or loose teeth (M or LT)	Left or right (L or R)	Sampled material			
			enamel for $\delta^{18}O$, $\delta^{13}C$	enamel for $^{87}Sr/^{86}Sr$, Sr conc	dentine for $\delta^{13}C$, ($\delta^{15}N$)	bone for $\delta^{13}C$, ($\delta^{15}N$)
Pool						
PL0025	M	R	√			
PL0278	M	L	√			
PL0302	LT	R	√			
PL0330	M	R	√			
PL0339	M	L	√			
PL0344	M	R	√			
PL0364	LT	L	√			
PL0386	M	R	√			
PL0444	M	L	√	√		
Mine Howe						
MH03	M	L	√	√		
MH84	M	R	√	√		
MH125	M	R	√	√		
MH128	M	L	√	√		
MH133	M	R	√	√		
MH138	M	R	√	√		
MH140	M	R	√	√		
MH149	LT	R	√			
MH162	LT	L	√			
MH163	LT	L	√			
MH174	LT	L	√			
MH0604	M	R	√	√		
Earl's Bu						
EB1	LT	R	√			
EB4	M	R	√			
EB8	LT	R	√			
EB9	LT	R	√			
EB13	LT	R	√			

EB14	M	L	√			
EB21	LT	R	√			
EB23	LT	L	√			
EB28	LT	L	√			
Old Scatness						
OSB2565	LT	L	√			
OSB3475	LT	L	√			
OSB3624	LT	R	√			
OSB6079	LT	R	√			
OSB60991	LT	R	√			
OSB60992	LT	L	√			
OSB60993	LT	R	√			
OSB60994	LT	L	√			
OSB62591	LT	L	√			
OSB62592	LT	R	√			
Grimes Graves						
GG92	M	L	√	√		√
GG120	M	R	√	√		√
GG121	M	R	√	√		√
GG122	LT	R	√			
GG123	LT	L	√			
GG149	M	L	√			√
GG614	M	L	√	√		√
GG621	M	R		√		√
GG661	M	R	√			√
GG677	M	L	√	√		√
GG681	M	L	√	√		√
GG722	M	R				√
GG743	M	L	√	√		√
GG822	M	L	√			√
GG839	M	R	√	√		√
GGT10	M	L	√	√		√
Chillingham						
CHIL1	M	L	√	√	√	
CHIL5	M	L		√		
CHIL6	M	R	√	√		
CHIL7	M	L	√	√		
CHIL8	M	L		√		
CHIL9	M	R		√		
CHIL10	M	R	√	√		
CHIL14	M	R	√	√	√	
Modern Dexter						
KAR	M	L	√		√	

Table A.9: Chillingham vegetation $\delta^{13}C$ results. $\delta^{15}N$ results are included but are not discussed in this thesis. Each result is the mean of two replicates.

Vegetation sample	Grid reference	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)
		May (10/05/2010)		August (09/08/2010)	
CHW_01	NU07122632	-30.6	3.9	-30.4	1.3
CHW_02	NU07182625	-30.4	2.8	-29.5	-0.9
CHW_03	NU07302622	-29.5	-0.2	-30.1	-1.5
CHW_04	NU07182615	-30.0	1.3	-30.1	-0.2
CHW_05	NU06992596	-30.4	0.4	-29.9	-0.8
CHW_06	NU07052589	-29.6	-0.4	-30.1	-1.1
CHW_07	NU06902584	-29.6	-0.1	-30.0	0.4
CHW_08	NU06802570	-29.5	2.0	-29.9	-0.2
CHW_09	NU06722556	-30.3	2.5	-29.7	1.1
CHW_10	NU06862555	-30.1	2.1	-30.4	0.1
CHW_11	NU07052551	-29.9	2.3	-30.3	1.9
CHW_12	NU07182550	-29.8	2.0	-30.4	-0.8
CHW_13	NU07122566	-29.7	1.1	-30.0	-1.1
CHW_14	NU07302577	-29.9	0.9	-29.8	-0.9
CHW_15	NU07202591	-29.5	0.0	-29.8	-0.5
CHE_01	NU07282547	-30.0	1.3	-30.1	-1.1
CHE_02	NU07272537	-30.0	0.7	-29.4	0.1
CHE_03	NU07522541	-30.2	-1.0	-28.7	-2.2
CHE_04	NU07612546	-29.3	1.4	-29.2	-1.0
CHE_05	NU07702544	-30.0	1.7	-29.3	-0.9
CHE_06	NU07712538	-30.2	1.4	-29.4	-0.9
CHE_07	NU07722567	-30.1	2.4	-29.8	1.5
CHE_08	NU07842578	-30.0	2.1	-29.8	0.7
CHE_09	NU07772590	-30.0	1.0	-29.5	-2.4
CHE_10	NU07722597	-30.0	0.5	-29.4	0.9
CHE_11	NU07702605	-29.9	0.1	-30.1	-0.9
CHE_12	NU07532608	-29.7	1.6	-30.0	-0.6
CHE_13	NU07492599	-30.1	0.4	-29.2	-1.2
		November (15/11/2010)		February (07/02/2011)	
CHW_01	NU07122632	-31.0	1.2	-31.4	2.1
CHW_02	NU07182625	-31.0	2.0	-30.6	-0.2
CHW_03	NU07302622	-30.4	-0.2	-30.7	0.7
CHW_04	NU07182615	-31.0	0.6	-30.6	0.3
CHW_05	NU06992596	-31.1	1.4	-30.6	0.9
CHW_06	NU07052589	-31.0	-0.2	-31.0	-0.1
CHW_07	NU06902584	-30.6	-0.5	-31.1	1.3
CHW_08	NU06802570	-30.2	0.6	-30.4	0.2
CHW_09	NU06722556	-30.8	1.4	-30.9	1.6
CHW_10	NU06862555	-31.3	1.9	-31.1	1.2
CHW_11	NU07052551	-31.0	5.5	-31.2	4.0
CHW_12	NU07182550	-30.7	1.7	-31.2	1.5
CHW_13	NU07122566	-30.8	0.1	-30.2	-1.1
CHW_14	NU07302577	-30.6	0.5	-31.3	1.4
CHW_15	NU07202591	-30.8	0.8	-30.3	1.8
CHE_01	NU07282547	-31.1	1.0	-31.0	1.4
CHE_02	NU07272537	-30.5	-0.4	-29.6	-0.4
CHE_03	NU07522541	-30.1	-0.6	-30.1	-1.2
CHE_04	NU07612546	-30.8	0.3	-29.8	-0.1
CHE_05	NU07702544	-31.1	0.6	-31.3	-0.6
CHE_06	NU07712538	-29.9	-2.3	-29.8	0.8

CHE_07	NU07722567	-30.9	0.8	-30.3	-0.7
CHE_08	NU07842578	-29.6	-1.2	-30.6	-0.3
CHE_09	NU07772590	-29.9	-2.3	-31.1	-4.0
CHE_10	NU07722597	-31.1	0.0	-29.7	0.5
CHE_11	NU07702605	-30.7	-0.5	-31.1	-2.8
CHE_12	NU07532608	-29.9	0.3	-30.7	0.1
CHE_13	NU07492599	-30.8	-0.1	-29.7	-0.4

Table A.10: $\delta^{13}C$ values for the dietary components of the modern Dexter bull (Karst). $\delta^{15}N$ values are also included but are not discussed in this thesis. Each result is the mean of two replicates.

Location	Grid reference		vegetation sample	Date collected	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)
barn (where Dexter born), High Stoop	NZ104401	Darlington hay	DARLINGTON_01	25/05/2011	-29.7	4.9
			DARLINGTON_02		-28.4	4.7
			DARLINGTON_03		-30.0	5.8
		sugar beet pellets	SBP		-28.0	5.6
field (F274), High Stoop	NZ105400	vegetation	F274_01	25/05/2011	-30.9	5.6
			F274_02		-30.6	5.0
			F274_03		-30.6	4.5
			F274_04		-30.0	5.2
field, Snowsfield Farm, Stanhope	NY981387	vegetation	STAN_01	25/05/2011	-29.5	0.7
			STAN_02		-29.2	1.0
			STAN_03		-28.7	2.9
			STAN_04		-29.8	4.2
			STAN_05		-29.3	2.1
barn, Dapple Farm	NZ103391	bedding	BEDDING_01	25/05/2011	-28.5	0.3
		straw	BEDDING_02		-28.2	-1.7
		barley feed	BFEED_01	25/05/2011	-27.8	3.4
			BFEED_02		-27.9	3.6
			BFEED_03		-27.6	3.5
		haylage	HAYLAGE_01	25/05/2011	-29.5	2.1
			HAYLAGE_02		-29.7	2.2
			HAYLAGE_03		-29.2	2.1

Table A.11: $\delta^{13}C$ values for unimproved, indigenous vegetation collected from various locations in Orkney. $\delta^{15}N$ values are included but are not discussed in this thesis. Each result is the mean of two replicates. * may include introduced species.

Location	Grid reference	Vegetation sample	Date collected	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)
Birsay Bay	HY246270	BIRSB_01	16/08/2011	-28.6	0.0
Birsay Bay	HY246271	BIRSB_02	16/08/2011	-27.1	4.2
Birsay Moor	HY342242	BIRSM_01	16/08/2011	-29.8	-6.0
Birsay Moor	HY342242	BIRSM_02	16/08/2011	-26.6	-1.8
Brodgar *	HY297130	BROD_01	16/08/2011	-29.4	1.2
Cottascarth	HY368198	COTT_01	16/08/2011	-30.3	1.1
Cottascarth	HY367198	COTT_02	16/08/2011	-28.2	-1.0
Durkadale	HY296249	DURK_01	16/08/2011	-29.7	0.5

Durkadale	HY300248	DURK_02	16/08/2011	-28.9	4.5
Evie Bay	HY374262	EVIE_01	16/08/2011	-29.0	6.2
The Fidge	HY351047	FIDGE_01	18/08/2011	-30.2	2.4
The Fidge	HY351048	FIDGE_02	18/08/2011	-30.0	7.4
The Loons	HY253245	LOONS_01	16/08/2011	-28.3	2.8
The Loons	HY253245	LOONS_02	16/08/2011	-27.8	1.0
Wideford Hill	HY412116	WID_01	12/08/2011	-28.3	-3.8
Saville, Sanday	HY683443	SAND_01	17/08/2011	-24.8	2.3
Scuthvie Bay, Sanday	HY769439	SAND_02	17/08/2011	-28.1	-0.4
Churchyard, Sanday *	HY677399	SAND_03	17/08/2011	-29.3	3.8

Table A.12: $\delta^{13}C$ values for unimproved, indigenous vegetation collected from various locations in southern Shetland. $\delta^{15}N$ values are included but are not discussed in this thesis. Each result is the mean of two replicates. * may include introduced species.

Location	Grid reference	Vegetation sample	Date collected	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)
Uradale	HU412380	URA_01	06/08/2011	-29.2	0.9
Uradale	HU416380	URA_02	06/08/2011	-29.7	-5.7
Uradale	HU418378	URA_03	06/08/2011	-28.3	0.9
Burland Croft, Tondra	HU393364	BURL_01	05/08/2011	-29.6	0.5
Burland Croft, Tondra	HU392370	BURL_02	05/08/2011	-30.6	0.6
Lang Lochs	HU430382	SHET_01	06/08/2011	-29.6	0.4
Gord	HU440294	SHET_02	09/08/2011	-28.9	0.2
Taing of Helliness *	HU461281	SHET_03	09/08/2011	-29.3	7.5
Helli Ness *	HU455284	SHET_04	09/08/2011	-28.2	-1.2
Gord	HU440294	SHET_05	09/08/2011	-30.5	0.8

Table A.13: $\delta^{13}C$ values for barley and oats from Orkney and Shetland. $\delta^{15}N$ values are included but are not discussed in this thesis. Each result is the mean of two replicates. The modern oat variety is "Belinda".

Location	Grid reference	Crop details	Crop sample	Date collected	$\delta^{13}C_{VPDB}$ normalised (‰)	$\delta^{15}N_{AIR}$ normalised (‰)
Agronomy Institute, Orkney College UHI	HY458114	2011 bere grains	ORKBB_01	12/08/2011	-27.2	6.9
	HY458114	2011 black oat grains	ORKBO_01	12/08/2011	-27.8	11.6
	HY458115	2011 modern oat grains	BEL_01	12/08/2011	-27.4	10.9
	HY458114	2011 bere stems	ORKBB_02	12/08/2011	-28.1	4.7
	HY458114	2011 black oat stems	ORKBO_02	12/08/2011	-28.9	10.2
	HY458115	2011 modern oat stems	BEL_02	12/08/2011	-29.0	7.4
Burland Croft, Trondra, Shetland	HU393369	2010 bere grains	SHETBB_01	05/08/2011	-28.2	3.2
	HU393369	2010 black oat grains	SHETBO_01	05/08/2011	-30.0	5.6

Table A.14: Water $\delta^{18}O$ results.

Chillingham, Northumberland			Rousay, Orkney	
Collection date	$\delta^{18}O_{VSMOW}$ stream water (NU06932593) (‰)	$\delta^{18}O_{VSMOW}$ spring water (NU07462598) (‰)	Collection date	$\delta^{18}O_{VSMOW}$ stream water (HY397278) (‰)
10/05/2010	-8.06	-8.30	02/10/2010	-6.26
10/06/2010	-8.04	-8.26	13/11/2010	-6.67
08/07/2010	-8.04	-8.23	31/12/2010	-6.76
09/08/2010	-8.16	-8.23	26/02/2011	-6.46
28/09/2010	-7.93	-8.19	26/03/2011	-6.33
01/11/2010	-7.82	-7.73	08/05/2011	-6.31
15/11/2020	-7.74	-7.92	05/06/2011	-6.17
15/12/2010	-8.07	-8.19	10/08/2011	-6.18
07/02/2011	-8.54	-8.30	08/10/2011	-6.03
18/04/2011	-8.11	-8.23		

Table A.15: Strontium isotope ratios and concentrations from Mine Howe, Pool, Grimes Graves and Chillingham cattle molar enamel. Mandibular 2nd and 3rd molars are designated M_2 and M_3.

Animal ID	Tooth	Position on tooth lobe	$^{87}Sr/^{86}Sr$ normalised	Sr concentration (ppm)
MH03	M_2	cusp	0.710452	467
MH84	M_2	cusp	0.710038	381
MH125	M_2	cusp	0.709947	555
MH128	M_2	cusp	0.710505	400
MH133	M_2	cusp	0.710082	129
MH133	M_3	cervix	0.710130	383
MH138	M_2	cusp	0.709893	384
MH140	M_2	cusp	0.709731	400
MH0604	M_2	cusp	0.710365	362
PL0444	M_2	cusp	0.709352	943
GG92	M_2	cusp	0.708945	107
GG120	M_2	cusp	0.711993	333
GG121	M_2	cusp	0.709190	284
GG614	M_2	cusp	0.710962	192
GG621	M_2	cusp	0.708909	169
GG677	M_2	cusp	0.708415	113
GG681	M_2	cusp	0.708745	161
GG743	M_2	cusp	0.709588	287
GG839	M_2	cusp	0.708517	155
GGT10	M_3	cusp	0.709833	162
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

Table A.16: Intra-tooth oxygen and carbon isotope ratios of enamel from Pool cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal, LC = lingual central. 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 (‰)**
PL0025 (M_3), LM, wear stage a/b cusp to cervix 48.5 mm				PL0278 (M_3), LM, wear stage a cusp to cervix 49.0 mm			
1	45.0	26.3	-12.2	1	45.0	25.1	-11.3
2	41.5	26.0	-12.2	2	41.0	24.7	-11.5
3	38.0	25.4	-12.2	3	37.0	24.2	-11.7
4	34.0	24.9	-12.2	4	33.0	23.9	-11.8
5	31.0	24.6	-12.1	5	29.5	24.1	-11.8
6	27.0	24.5	-12.0	6	25.5	24.5	-11.9
7	24.0	24.3	-12.0	7	22.0	24.6	-12.0
8	20.5	24.5	-12.1	8	19.0	25.0	-12.0
9	17.0	24.8	-12.2	9	16.0	25.6	-12.0
10	13.5	24.8	-12.3	10	13.0	25.9	-11.9
11	10.0	25.0	-12.3	11	10.0	26.3	-11.6
12	6.5	25.1	-12.4				
13	3.5	25.7	-12.3				
PL0302 (M_3), LM, wear stage k cusp to cervix 24.5 mm				PL0330 (M_3), LC, wear stage a/b cusp to cervix 51.0 mm			
1	21.0	23.2	-11.9	1	45.0	25.1	-11.3
2	17.5	24.0	-12.0	2	39.5	24.4	-11.3
3	14.5	24.9	-11.7	3	33.5	24.2	-11.4
4	11.5	25.3	-11.8	4	28.0	24.1	-11.6
5	8.5	25.3	-11.7	5	22.0	24.3	-11.9
6	6.0	25.1	-11.5	6	16.5	25.3	-12.2
7	2.5	25.1	-11.4	7	11.0	26.0	-12.3
				8	6.0	26.0	-12.0
PL0344 (M_3), LC, wear stage b cusp to cervix 48.0 mm				PL0364 (M_3), LM, wear stage c cusp to cervix 47.5 mm			
1	46.5	25.7	-12.0	1	45.0	25.7	-12.3
2	43.5	25.5	-12.0	2	41.5	25.1	-12.2
3	40.5	25.4	-11.8	3	38.0	24.6	-12.3
4	37.0	24.8	-11.7	4	35.0	24.7	-12.4
5	34.0	24.6	-11.7	5	31.5	24.3	-12.5
6	31.0	24.4	-11.8	6	28.0	24.4	-12.4
7	28.0	24.1	-11.9	7	24.5	24.1	-12.5
8	25.0	24.0	-12.0	8	20.5	24.2	-12.5
9	22.0	23.7	-12.1	9	16.5	24.4	-12.6
10	19.0	23.4	-12.1	10	13.0	24.7	-12.6
11	16.5	23.6	-12.3	11	10.0	25.1	-12.6
12	13.5	23.8	-12.4	12	6.0	25.7	-12.4
13	10.5	24.1	-12.5	13	3.0	26.0	-12.3
14	7.5	24.6	-12.4				
15	4.0	25.1	-12.1				
PL0386 (M_3), LM, wear stage a/b cusp to cervix 57.5 mm				PL0444 (M_3), LM, wear stage b cusp to cervix 47.0 mm			
1	55.0	25.3	-11.1	1	44.0	24.1	-12.7
2	52.0	24.6	-11.2	2	41.0	24.6	-12.6

3	49.0	24.3	-11.0	3	38.0	25.1	-12.3
4	46.5	24.1	-11.2	4	34.0	25.3	-12.4
5	43.5	23.7	-11.3	5	31.5	26.0	-12.4
6	40.0	24.0	-11.4	6	28.0	26.3	-12.3
7	36.5	24.1	-11.6	7	24.5	26.6	-12.1
8	33.0	24.1	-11.7	8	21.0	26.8	-11.9
9	29.0	24.7	-11.8	9	17.0	26.5	-11.6
10	25.5	25.2	-11.9	10	13.5	26.1	-11.5
11	22.5	25.5	-12.0	11	6.5	25.3	-11.6
12	19.5	25.7	-12.0	12	2.5	24.1	-11.5
13	16.5	25.6	-12.0				
14	13.5	25.6	-11.9				
15	10.5	25.2	-11.8				
16	7.0	25.2	-11.6				
17	3.5	25.1	-11.6				

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 (‰)
PL0278 (M_2), LM, wear stage e/f cusp to cervix 43.0 mm				PL0330 (M_2), LD, wear stage ? cusp damaged			
1	39.0	23.8	-11.4	1	34.0	23.7	-11.8
2	35.0	23.8	-11.2	2	28.0	24.0	-11.9
3	31.0	24.0	-11.1	3	24.5	24.6	-11.9
4	27.5	24.1	-11.2	4	21.0	25.1	-11.8
5	24.0	24.4	-11.2	5	17.5	25.5	-11.9
6	20.5	25.3	-11.3	6	13.5	25.5	-12.1
7	16.5	25.8	-11.5	7	10.0	26.0	-12.0
8	12.5	26.3	-11.5	8	6.5	26.3	-11.8
9	8.5	26.0	-11.5	9	3.0	25.6	-11.5
10	4.5	25.1	-11.3				
PL0339 (M_2), LM, wear stage f cusp to cervix 44.0 mm				PL0344 (M_2), LD, wear stage f cusp to cervix 44.0 mm			
1	36.0	26.8	-12.0	1	41.0	24.9	-12.6
2	31.5	26.8	-11.8	2	38.0	24.5	-12.3
3	27.0	26.0	-11.7	3	35.0	24.1	-12.3
4	22.5	24.9	-11.9	4	32.0	23.9	-12.4
5	18.0	24.5	-11.9	5	29.0	23.9	-12.5
6	14.0	24.0	-12.2	6	26.0	23.7	-12.4
7	9.5	24.1	-12.3	7	23.0	23.5	-12.4
8	6.0	23.9	-12.5	8	20.5	23.3	-12.2
9	2.5	24.5	-12.6	9	17.0	23.3	-12.2
				10	13.5	24.1	-12.2
				11	10.5	24.5	-12.2
				12	7.5	24.9	-12.2
				13	4.0	26.0	-12.2
PL0386 (M_2), LM, wear stage f cusp to cervix 51.5 mm				PL0444 (M_2), LM, wear stage f cusp to cervix 41.0 mm			
1	49.5	23.9	-11.9	1	38.0	26.7	-14.0
2	47.0	23.8	-11.7	2	35.5	26.7	-13.4
3	44.0	23.8	-11.6	3	32.5	26.3	-13.1
4	41.0	24.2	-11.5	4	29.0	25.9	-12.8

5	38.0	24.5	-11.6	5	26.0	26.2	-12.4
6	34.5	25.1	-11.5	6	23.0	25.5	-12.4
7	31.0	26.1	-11.6	7	19.5	25.0	-12.4
8	28.0	26.6	-11.7	8	16.0	24.2	-12.7
9	25.5	26.7	-11.8	9	12.5	24.2	-12.8
10	22.0	26.9	-11.7	10	9.0	24.1	-12.8
11	19.0	26.8	-11.6	11	5.5	24.3	-12.8
12	16.0	26.3	-11.5	12	2.5	23.9	-12.7
13	13.5	25.7	-11.5				
14	10.5	25.3	-11.4				
15	7.5	24.7	-11.3				
16	4.5	24.5	-11.2				

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 (‰)
PL0278 (M_1), LM, wear stage j cusp to cervix 31.5 mm				PL0330 (M_1), LM, wear stage g cusp to cervix 35.5 mm			
1	28.5	26.4	-14.5	1	33.0	24.5	-13.6
2	24.5	26.2	-14.0	2	28.5	25.5	-13.6
3	21.0	26.4	-13.6	3	24.5	26.1	-13.4
4	17.0	26.5	-12.9	4	21.5	26.4	-13.1
5	13.5	25.8	-12.4	5	15.5	26.5	-12.5
6	9.5	25.3	-11.9	6	12.0	27.0	-12.4
7	5.5	25.1	-11.6	7	9.0	26.5	-12.4
8	2.5	24.7	-11.4	8	6.0	26.1	-12.1
				9	2.5	25.4	-12.1
PL0339 (M_1), LM, wear stage h cusp to cervix 33.5 mm				PL0344 (M_1), LD, wear stage g cusp to cervix 35.0 mm			
1	27.0	23.5	-14.5	1	30.0	24.1	-14.7
2	23.0	23.8	-13.7	2	26.0	25.0	-14.5
3	18.5	24.2	-13.3	3	22.5	25.7	-14.4
4	14.5	24.7	-13.0	4	18.5	26.3	-14.4
5	11.0	25.6	-13.1	5	15.0	27.4	-13.9
6	6.5	26.5	-13.0	6	11.5	27.3	-13.2
7	3.5	27.1	-12.8	7	6.5	26.8	-12.5
				8	3.0	26.4	-12.4
PL0386 (M_1), LM, wear stage g cusp to cervix 39.0 mm				PL0444 (M_1), LD, wear stage j cusp to cervix 33.5 mm			
1	36.0	26.3	-15.3	1	30.0	23.9	-16.2
2	32.5	26.3	-15.0	2	26.5	24.2	-16.1
3	29.5	26.6	-14.6	3	23.5	23.9	-16.0
4	26.0	26.4	-14.3	4	20.0	24.0	-15.7
5	22.5	26.0	-13.8	5	16.5	24.8	-15.5
6	19.0	25.8	-13.3	6	12.5	25.1	-15.4
7	15.5	25.3	-13.0	7	9.0	25.7	-15.2
8	12.5	24.5	-12.7	8	6.0	26.2	-15.0
9	9.0	23.9	-12.3	9	3.0	26.3	-14.8
10	6.0	23.6	-12.0				
11	3.0	23.5	-11.9				

Table A.17: Intra-tooth oxygen and carbon isotope ratios of enamel from Mine Howe 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 (‰)**
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	9	7.0	24.0	-12.1
10	15.5	25.5	-12.4	10	3.0	25.7	-11.9
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				MH162 (M_3), LM, wear stage d cusp to cervix 43.5 mm			
1	28.5	23.6	-12.1	1	42.0	25.1	-11.7

2	25.0	23.4	-12.1	2	39.0	25.5	-11.4
3	22.0	23.4	-12.1	3	36.0	25.0	-11.2
4	19.0	23.9	-12.2	4	33.0	24.2	-11.2
5	16.0	24.2	-12.1	5	29.5	23.8	-11.3
6	13.0	24.4	-12.1	6	26.0	23.8	-11.3
7	10.0	24.9	-12.2	7	23.0	23.6	-11.5
8	7.0	25.4	-12.3	8	20.0	23.8	-11.7
9	4.0	25.7	-12.3	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
MH163 (M_3), LM, wear stage b cusp to cervix 44.0 mm				MH174 (M_3), LM, wear stage f cusp to cervix 40.0 mm			
1	41.5	25.9	-12.0	1	37.5	25.8	-12.2
2	38.5	25.6	-11.6	2	34.0	24.8	-12.2
3	34.0	24.9	-11.5	3	31.0	24.6	-12.2
4	28.5	24.2	-11.7	4	28.0	24.0	-12.2
5	25.0	24.0	-11.7	5	25.0	23.8	-12.4
6	21.5	23.7	-11.8	6	22.0	23.5	-12.5
7	18.0	23.7	-11.9	7	19.0	23.6	-12.5
8	14.5	23.7	-12.1	8	16.0	23.6	-12.8
9	11.0	24.0	-12.2	9	13.0	23.8	-12.9
10	8.0	24.5	-12.4	10	10.0	24.3	-12.7
11	4.5	25.1	-12.3	11	7.0	24.7	-12.6
				12	4.0	25.5	-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				
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 A.18: Intra-tooth oxygen and carbon isotope ratios of enamel from Earl's Bu cattle mandibular molars. Sampled lobe: LM = lingual mesial, LD = lingual distal, LC = lingual central. 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				EB23 (M_3), LC, wear stage d			

cusp to cervix 43.0 mm				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 A.19: Intra-tooth oxygen and carbon isotope ratios of enamel from Old Scatness cattle mandibular molars. Sampled lobe: LM = lingual mesial. 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 (‰)**
OSB2565 (M_3), LM, wear stage e cusp to cervix 47.5 mm				OSB3475 (M_3), LM, wear stage f cusp to cervix 44.5 mm			
1	43.0	24.7	-11.6	1	40.0	25.9	-11.9
2	39.0	24.5	-11.6	2	35.5	25.8	-11.6
3	35.0	24.0	-11.6	3	31.0	25.0	-11.6
4	31.0	23.8	-11.7	4	27.5	24.7	-11.6
5	27.0	23.8	-11.7	5	23.5	24.4	-11.7
6	23.0	24.0	-11.6	6	19.5	24.0	-12.1
7	19.0	23.9	-11.8	7	16.0	23.8	-12.3
8	15.0	24.9	-11.8	8	12.0	23.9	-12.5
9	11.0	25.5	-11.9	9	7.5	24.2	-12.6
10	7.5	26.0	-11.7	10	4.0	25.2	-12.6
11	4.0	26.6	-11.4				
OSB3624 (M_3), LM, wear stage b cusp to cervix 50.0 mm				OSB6079 (M_3), LM, wear stage a cusp to cervix 48.0 mm			
1	47.0	25.8	-11.2	1	43.0	25.5	-11.9
2	43.0	26.1	-11.2	2	39.5	25.1	-12.1
3	39.5	26.5	-11.5	3	35.0	24.5	-12.1
4	35.5	26.6	-11.6	4	31.5	24.4	-12.2
5	31.5	26.6	-11.4	5	28.5	23.8	-12.4
6	27.5	26.3	-11.2	6	25.0	23.7	-12.4
7	23.5	25.6	-11.4	7	22.0	23.8	-12.5
8	19.5	25.1	-11.4	8	18.0	24.0	-12.6
9	16.0	24.9	-11.5	9	14.5	24.4	-12.6
10	13.0	24.7	-11.4	10	11.0	24.9	-12.7
11	10.0	24.5	-11.4	11	7.5	25.7	-12.4
				12	4.0	26.6	-12.2
OSB60991 (M_3), LM, wear stage g cusp to cervix 41.0 mm				OSB60992 (M_3), LM, wear stage b cusp to cervix 50.5 mm			
1	38.5	25.8	-11.5	1	44.5	26.2	-11.4
2	33.5	25.9	-11.5	2	41.5	26.3	-11.5
3	30.0	26.0	-11.3	3	38.5	26.0	-11.6
4	26.0	25.1	-11.3	4	35.5	25.3	-11.5
5	22.0	24.8	-11.3	5	32.5	25.2	-11.4
6	17.5	24.0	-11.6	6	30.0	24.7	-11.2
7	14.5	24.2	-11.6	7	26.5	24.4	-11.1
8	11.0	23.7	-11.8	8	23.5	24.7	-11.0
9	7.5	23.8	-11.6	9	20.5	24.6	-10.9

10	3.5	24.1	-11.7	10	17.5	24.9	-11.0
				11	14.5	25.0	-11.0
				12	12.0	25.5	-11.1
				13	9.0	25.9	-11.1
				14	5.5	26.0	-11.3
				15	3.0	25.8	-11.4
OSB60993 (M_3), LM, wear stage g cusp to cervix 45.0 mm				OSB60994 (M_3), LM, wear stage j cusp to cervix 27.0 mm			
1	41.5	25.1	-11.3	1	23.5	26.4	-11.7
2	37.0	24.8	-11.3	2	20.0	26.7	-11.3
3	33.0	24.2	-11.4	3	16.5	26.6	-11.1
4	29.5	23.5	-11.5	4	13.0	25.5	-11.0
5	25.5	23.2	-11.7	5	10.0	25.2	-11.0
6	21.5	23.7	-11.7	6	6.5	24.8	-10.9
7	17.5	24.5	-11.7	7	3.5	24.1	-11.1
8	14.0	25.1	-11.7				
9	10.0	25.5	-11.8				
10	6.0	25.7	-11.8				
11	3.5	25.3	-11.9				
OSB62591 (M_3), LM, wear stage g cusp to cervix 45.5 mm				OSB62592 (M_3), LM, wear stage g cusp to cervix 43.5 mm			
1	41.5	24.3	-12.2	1	40.5	24.4	-12.0
2	37.0	25.4	-12.0	2	36.0	24.2	-12.1
3	33.0	25.5	-11.9	3	32.0	24.1	-12.1
4	29.0	25.9	-11.8	4	28.0	24.7	-12.2
5	25.0	26.2	-12.0	5	24.0	25.0	-12.2
6	20.5	26.0	-12.0	6	20.0	25.9	-12.0
7	16.0	25.3	-12.1	7	16.0	25.3	-12.0
8	12.0	24.8	-12.1	8	12.0	25.3	-11.9
9	8.0	23.7	-12.1	9	8.0	24.5	-12.0
10	3.5	23.6	-12.2	10	4.0	24.2	-12.3

Table A.20: 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).

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 (‰)**
GG92 (M_3), LM, wear stage c cusp to cervix 52.0 mm				GG121 (M_3), LM, wear stage g 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				
GG122 (M_3), LM, wear stage d cusp to cervix 51.5 mm				GG123 (M_3), LM, wear stage c/d cusp to cervix 51.5 mm			
1	47.5	22.5	-11.9	1	47.5	24.2	-12.7
2	42.5	22.4	-12.0	2	43.0	23.9	-12.8
3	38.5	22.8	-12.0	3	38.5	23.1	-13.0
4	34.0	23.4	-12.2	4	34.0	23.4	-13.0
5	29.5	24.2	-12.0	5	29.5	23.1	-13.3
6	25.5	24.9	-11.9	6	25.0	24.1	-13.2
7	21.0	25.6	-11.8	7	21.0	24.7	-13.3
8	17.0	26.0	-11.7	8	17.5	25.1	-12.9
9	13.0	25.4	-11.5	9	13.5	25.3	-12.8
10	9.5	25.1	-11.4	10	10.0	25.7	-12.6
11	6.0	24.3	-11.4	11	6.0	25.0	-12.4
12	2.5	23.6	-11.7	12	3.0	24.8	-12.4
GG149 (M_3), LM, wear stage e/f cusp to cervix 46.0 mm				GG681 (M_3), LM, wear stage g cusp to cervix 42.5 mm			
1	40.5	23.4	-13.1	1	37.5	23.8	-12.4
2	36.5	22.8	-13.4	2	33.5	24.5	-12.3
3	32.5	22.8	-13.6	3	28.5	25.3	-12.0
4	29.0	22.8	-13.6	4	25.0	25.8	-11.8
5	25.0	22.9	-13.6	5	21.0	26.3	-11.7
6	21.0	23.4	-13.8	6	17.0	26.2	-11.7
7	17.0	23.9	-13.9	7	13.5	26.0	-11.9
8	13.5	25.2	-13.5	8	10.0	25.4	-12.0
9	10.0	25.4	-13.3	9	6.5	24.6	-12.3
10	6.5	26.1	-12.7	10	3.5	23.6	-12.9
11	3.5	26.0	-12.4				
GG743 (M_3), LM, wear stage e/f cusp to cervix 51.0 mm				GG822 (M_3), LM, wear stage g cusp to cervix 36.5 mm			
1	46.0	23.9	-12.3	1	32.5	24.0	-12.2
2	41.5	24.1	-12.4	2	27.5	23.4	-12.3
3	37.5	23.4	-12.7	3	24.0	23.3	-12.3
4	33.5	23.3	-13.0	4	19.5	23.3	-12.4
5	29.5	23.5	-13.3	5	15.5	24.1	-12.3
6	26.5	23.9	-13.5	6	11.0	25.0	-12.4
7	19.0	24.7	-13.3	7	6.5	26.2	-12.4
8	15.5	25.1	-13.1	8	2.5	26.6	-12.2
9	12.0	25.3	-12.6				
10	8.0	25.3	-12.2				
11	4.0	25.1	-12.2				
GG839 (M_3), LM, wear stage d cusp to cervix 49.5 mm				GGT10 (M_3), LM, wear stage f cusp to cervix 49.0 mm			
1	45.0	24.9	-13.0	1	42.0	24.9	-12.8
2	41.0	25.6	-12.7	2	38.0	24.5	-12.8
3	37.5	26.2	-12.4	3	34.0	24.0	-12.9
4	34.0	26.5	-12.1	4	30.5	23.5	-13.0
5	30.5	26.3	-11.6	5	26.5	23.4	-13.0
6	27.5	25.5	-11.6	6	23.0	23.3	-12.8
7	24.0	24.9	-11.6	7	20.0	23.3	-12.8
8	20.5	24.3	-11.6	8	16.5	23.7	-12.6
9	17.0	23.9	-11.6	9	13.0	24.8	-12.3
10	13.5	24.0	-11.6	10	10.0	25.9	-11.8

11	10.0	23.6	-11.8	11	6.5	26.9	-11.3
12	6.5	23.2	-11.8	12	3.5	27.2	-11.3
13	3.0	23.5	-11.8				

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 (‰)
GG92 (M_2), LM, wear stage g cusp to cervix 43.0 mm				GG120 (M_2), LM, wear stage a/b cusp to cervix 50.0 mm			
1	35.5	23.7	-12.3	1	44.0	23.3	-14.2
2	31.5	23.5	-12.3	2	40.0	23.4	-14.2
3	27.5	23.6	-12.3	3	36.0	22.7	-14.3
4	24.0	23.4	-12.2	4	32.5	22.8	-14.3
5	20.0	23.5	-12.4	5	29.5	23.0	-14.4
6	16.5	24.1	-12.3	6	26.0	23.1	-14.4
7	13.0	24.8	-12.3	7	22.0	23.4	-14.3
8	9.0	25.3	-12.2	8	18.0	23.9	-14.1
9	5.5	25.7	-12.1	9	14.5	24.7	-13.8
10	2.5	26.4	-12.1	10	10.5	24.6	-13.2
				11	6.0	24.8	-12.9
				12	3.0	24.9	-12.9
GG121 (M_2), LM, wear stage j cusp to cervix 41.0 mm				GG614 (M_2), LM, wear stage f cusp to cervix 48.5 mm			
1	31.5	24.8	-13.5	1	42.5	24.0	-13.6
2	28.5	25.5	-13.3	2	37.5	23.6	-13.6
3	25.5	26.0	-13.3	3	33.0	23.7	-13.6
4	22.0	26.5	-13.0	4	28.5	24.1	-13.4
5	18.0	26.5	-12.8	5	23.5	25.0	-13.5
6	14.5	26.5	-12.5	6	19.5	25.9	-13.2
7	11.0	26.1	-12.2	7	15.5	26.7	-12.9
8	7.5	25.9	-12.0	8	11.5	27.0	-12.7
9	3.5	25.2	-12.0	9	7.0	26.4	-12.1
				10	3.5	26.1	-12.0
GG677 (M_2), LM, wear stage f cusp to cervix 50.0 mm				GG681 (M_2), LM, wear stage j cusp to cervix 31.5 mm			
1	44.0	24.0	-11.7	1	24.0	26.2	-12.7
2	40.5	23.6	-11.8	2	21.0	26.2	-12.9
3	36.0	24.0	-11.9	3	17.0	25.8	-12.6
4	32.0	24.3	-11.7	4	10.0	25.4	-12.5
5	27.5	25.2	-11.8	5	6.5	24.3	-12.4
6	23.5	26.0	-11.4	6	3.5	23.5	-12.5
7	19.0	25.8	-11.4				
8	15.5	25.7	-11.1				
9	11.0	25.5	-11.4				
10	7.5	24.9	-11.4				
11	4.0	24.1	-11.5				
GG743 (M_2), LM, wear stage g cusp to cervix 45.5 mm				GG839 (M_2), LM, wear stage g cusp to cervix 44.5 mm			
1	38.5	23.8	-13.6	1	39.0	26.6	-13.7

2	34.0	24.0	-13.3	2	34.5	26.2	-13.6
3	30.0	24.5	-13.4	3	30.5	25.2	-13.7
4	26.5	24.9	-13.1	4	27.5	24.5	-13.5
5	23.0	25.5	-12.8	5	24.0	24.0	-13.6
6	19.0	26.1	-12.4	6	20.0	23.8	-13.6
7	15.5	25.7	-12.1	7	16.5	23.7	-13.6
8	12.0	25.6	-11.8	8	12.5	23.9	-13.7
9	8.5	25.2	-11.9	9	9.0	24.1	-13.7
10	2.5	24.4	-12.2	10	5.0	24.8	-13.5
				11	2.5	26.2	-13.2
GGT10 (M_2), LM, wear stage g cusp to cervix 41.0 mm							
1	35.0	24.0	-13.1				
2	31.0	23.7	-13.2				
3	26.5	23.8	-13.2				
4	22.5	24.2	-13.1				
5	19.0	24.8	-13.1				
6	15.5	25.6	-12.9				
7	12.5	26.3	-12.8				
8	8.5	26.5	-12.7				
9	5.0	26.2	-12.5				
10	2.0	25.7	-12.6				

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 (‰)**
GG120 (M_1), LM, wear stage f cusp to cervix 39.5 mm				GG121 (M_1), LM, wear stage k/l cusp to cervix 30.5 mm			
1	34.5	24.9	-16.1	1	23.5	26.4	-14.2
2	30.5	24.7	-16.5	2	20.0	25.5	-13.8
3	27.0		-16.5	3	16.5	25.6	-13.5
4	22.5	25.5	-16.0	4	13.0	25.1	-13.3
5	19.0		-15.7	5	9.5	24.2	-13.4
6	14.5	25.6	-14.4	6	6.0	23.8	-13.3
7	11.0	25.3	-14.4	7	3.0	23.7	-13.3
8	7.5	23.9	-14.1				
9	4.0	22.5	-14.0				
GG614 (M_1), LM, wear stage j/h cusp to cervix 37.0 mm				GG661 (M_1), LM, wear stage f cusp to cervix 39.5 mm			
1	34.5	26.8	-16.1	1	34.0	25.7	-14.4
2	30.5	27.2	-15.5	2	30.0	26.1	-14.8
3	27.0	27.3	-14.8	3	25.5	26.2	-14.7
4	23.5	27.1	-14.2	4	22.0	26.6	-14.0
5	20.0	26.8	-13.8	5	17.5	26.0	-13.3
6	16.5	26.2	-13.5	6	13.5	25.8	-12.8
7	13.0	25.6	-13.5	7	10.0	24.8	-12.8
8	9.5	25.0	-13.4	8	3.5	23.8	-12.6
9	6.5	24.8	-13.5				
10	3.5	24.4	-13.4				
GG743 (M_1), LM, wear stage k/l				GG839 (M_1), LM, wear stage k			

cusp to cervix 32.5 mm				cusp to cervix 29.0 mm			
1	29.0	26.6	-15.1	1	25.0	23.6	-15.7
2	25.0	26.3	-14.8	2	21.0	24.2	-15.4
3	21.5	26.1	-14.3	3	17.5	25.4	-15.2
4	17.0	25.4	-14.1	4	13.0	26.0	-14.7
5	13.5	25.4	-14.1	5	10.0	27.2	-14.3
6	10.0	24.3	-13.8	6	6.5	27.4	-14.0
7	6.0	23.8	-13.9	7	3.0	27.5	-13.8
8	2.5	23.6	-13.8				
GGT10 (M_1), LM, wear stage k/l cusp to cervix 28.5 mm							
1	25.0	26.4	-15.9				
2	21.0	26.4	-15.3				
3	17.0	26.4	-14.5				
4	13.5	26.0	-13.7				
5	10.0	25.6	-13.5				
6	5.5	25.0	-13.4				
7	2.5	24.9	-13.2				

Table A.21: Intra-tooth oxygen and carbon isotope ratios of enamel from the mandibular molars of Chillingham cattle and the modern Dexter bull (Karst). Sampled lobe: LM = lingual mesial, LD = lingual distal, LC = lingual central, BM = buccal mesial. 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 (‰)**
CHIL1 (M_3), BM, wear stage f cusp to cervix 45.5 mm				CHIL6 (M_3), LM, wear stage k 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				CHIL10 (M_3), LM, wear stage j cusp to cervix 30.5 mm			
1	31.5	23.6	-14.7	1	28.5	22.8	-15.2
2	28.5	24.1	-14.5	2	26.0	22.8	-15.1
3	25.5	24.4	-14.4	3	23.0	22.9	-15.1
4	22.5	24.2	-14.2	4	20.0	23.0	-15.0
5	20.0	23.9	-14.2	5	17.0	23.2	-14.9
6	17.0	23.5	-14.3	6	14.0	23.5	-14.7
7	14.0	23.2	-14.4	7	12.0	24.0	-14.6
8	10.5	22.5	-14.4	8	9.5	24.5	-14.6

9	7.0	22.1	-14.6	9	7.0	24.6	-14.5
10	3.5	22.0	-14.7	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

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 (‰)**
CHIL1 (M_2), BM, wear stage g cusp to cervix 39.0 mm				CHIL6 (M_2), LM, wear stage l cusp to cervix 16.0 mm			
1	37.0	23.1	-16.1	1	15.0	24.2	-14.3
2	33.5	23.1	-16.0	2	13.0	24.4	-14.3
3	30.5	23.3	-15.9	3	10.5	24.2	-14.4
4	27.5	23.6	-15.6	4	8.5	23.8	-14.3
5	24.0	23.9	-15.3	5	6.0	23.8	-14.4
6	20.5	24.2	-15.1	6	3.0	23.5	-14.7
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				
CHIL7 (M_2), BM, wear stage k cusp to cervix 27.5 mm				CHIL10 (M_2), LD, wear stage k cusp to cervix 25.5 mm			
1	25.5	24.8	-14.9	1	24.0	22.0	-15.4
2	22.0	24.2	-14.9	2	20.5	22.2	-15.3
3	18.5	23.8	-14.9	3	15.0	22.8	-15.1
4	15.0	23.5	-14.9	4	12.0	23.3	-14.9
5	11.5	22.8	-14.9	5	9.0	23.5	-14.8
6	8.5	22.7	-14.8	6	6.5	23.6	-14.6
7	6.0	22.3	-14.9	7	3.5	24.1	-14.6
8	3.0	22.4	-14.8				
CHIL14 (M_2), LM, wear stage k cusp to cervix 33.5 mm				KAR (M_2), LM, wear stage b/c cusp to cervix 50.5 mm			
1	30.0	22.1	-15.4	1	47.0	24.4	-16.4
2	26.0	22.2	-15.2	2	43.5	24.1	-15.9
3	22.5	22.7	-15.1	3	40.0	23.6	-15.6
4	19.0	23.3	-15.1	4	36.5	23.3	-15.3

5	15.5	23.5	-15.0	5	32.5	22.9	-14.7
6	12.0	24.0	-15.1	6	29.0	22.8	-14.5
7	9.0	24.2	-15.0	7	26.0	22.7	-14.3
8	5.5	24.2	-14.8	8	22.5	22.3	-14.2
9	2.0	23.9	-14.9	9	19.0	22.7	-13.8
				10	16.0	22.5	-13.8
				11	13.0	22.6	-13.5
				12	9.5	22.8	-13.4
				13	6.5	23.0	-13.3
				14	3.5	22.8	-13.2

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 (‰)
CHIL1 (M_1), BM, wear stage h cusp to cervix 30.5 mm				CHIL6 (M_1), LM, wear stage l cusp to cervix 15.0 mm			
1	28.5	25.9	-18.1	1	14.5	24.2	-16.1
2	25.0	26.0	-17.5	2	12.5	23.5	-15.8
3	22.0	25.8	-17.2	3	10.5	23.7	-15.7
4	19.0	25.6	-17.0	4	8.0	23.3	-15.7
5	15.5	25.0	-17.1	5	6.0	23.3	-15.8
6	12.0	24.5	-16.9	6	3.5	22.7	-15.7
7	8.5	24.0	-17.0				
8	4.5	23.5	-16.9				
CHIL7 (M_1), BM, wear stage l cusp to cervix 19.5 mm				CHIL10 (M_1), LD, wear stage l cusp to cervix 16.0 mm			
1	16.0	23.3	-17.5	1	14.5	25.5	-16.0
2	13.5	22.9	-17.3	2	12.5	25.1	-15.8
3	11.0	23.0	-17.0	3	10.0	25.5	-15.7
4	8.5	22.9	-16.7	4	7.5	25.2	-15.8
5	6.0	23.1	-16.5	5	5.5	25.0	-15.7
6	3.5	23.1	-16.5	6	3.0	24.8	-15.8
CHIL14 (M_1), LM, wear stage k cusp to cervix 22.5 mm				CHIL1 (dP_4), LC cusp to cervix 10.0 mm			
1	19.5	23.8	-17.5	1	8.5	22.3	-16.0
2	16.0	24.8	-17.2	2	6	22.6	-16.4
3	12.5	24.9	-16.9	3	3.5	23.1	-16.4
4	9.0	24.9	-16.5				
5	6.0	24.4	-16.3				
6	2.5	24.0	-16.3				
KAR (M_1), LM, wear stage g cusp to cervix 38.5 mm				KAR (dP_4), LC, wear stage j cusp to cervix 14.0 mm			
1	34.5	21.4	-17.7	1	11.5	20.8	-15.6
2	31.0	21.6	-18.0	2	8.0	20.6	-15.6
3	27.5	22.4	-18.1	3	4.5	20.8	-16.0
4	24.0	23.0	-18.0	4	2.0	20.7	-16.1
5	21.0	23.2	-17.8				
6	17.5	23.7	-17.5				
7	14.0	24.8	-17.0				

8	10.5	24.7	-16.6				
9	7.0	25.0	-16.5				
10	3.0	25.0	-16.3				

Table A.22: Intra-tooth dentine collagen $\delta^{13}C$ results from the mandibular molars of Chillingham cattle and the modern Dexter bull (Karst). $\delta^{15}N$ results are also included but are not discussed in this thesis. Lingual mesial lobes were sampled. Distance from cervix is shown as a negative value for root samples. Each result is the mean of two replicates.

Second molars								
Sample No.	**Distance from root tip (mm)**	**Distance from cervix (mm)**	**$\delta^{13}C_{VPDB}$ normalised (‰)**	**$\delta^{15}N_{AIR}$ normalised (‰)**	**C(%)**	**N(%)**	**C:N**	**Collagen yield (%)**
CHIL1 M_2 root dentine								
1	19.75	-0.75	-24.9	6.9	40.1	14.7	3.2	17.8
2	17.75	-2.75	-24.9	6.8	44.1	16.2	3.2	17.9
3	15.75	-4.75	-25.0	6.8	43.9	16.0	3.2	18.6
4	13.50	-7.00	-25.0	6.8	43.9	16.1	3.2	19.0
5	11.25	-9.25	-24.9	6.6	44.4	16.2	3.2	19.5
6	9.25	-11.25	-24.8	6.4	44.4	16.3	3.2	19.5
7	7.50	-13.00	-24.9	6.2	44.3	15.9	3.2	20.1
8	5.50	-15.00	-24.8	6.2	44.1	16.3	3.2	20.3
9	2.25	-18.25	-24.9	6.1	44.3	16.4	3.2	17.5
CHIL14 M_2 root dentine								
1	25.50	-1.00	-24.6	6.3	43.8	16.2	3.2	17.8
2	23.25	-3.25	-24.5	6.2	43.9	16.2	3.2	17.5
3	21.25	-5.25	-24.5	6.1	43.8	16.2	3.2	18.8
4	19.00	-7.50	-24.5	6.0	44.0	16.2	3.2	18.5
5	16.75	-9.75	-24.4	6.0	44.9	16.7	3.1	18.7
6	14.75	-11.75	-24.4	5.7	44.3	16.1	3.2	18.4
7	13.00	-13.50	-24.4	5.8	44.0	16.4	3.1	18.3
8	11.00	-15.50	-24.4	5.7	44.2	16.4	3.2	19.0
9	8.75	-17.75	-24.5	5.9	44.3	16.3	3.2	19.4
10	7.00	-19.50	-24.8	5.9	44.4	16.1	3.2	20.3
11	5.25	-21.25	-24.9	5.9	44.4	16.3	3.2	20.4
12	2.25	-24.25	-25.0	6.0	44.5	16.4	3.2	20.1
KAR M_2 root dentine								
1	8.75	-3.25	-23.0	4.6	43.5	16.1	3.1	22.2
2	5.75	-6.25	-23.0	4.7	43.7	16.2	3.1	22.6
3	2.25	-9.75	-23.1	5.1	43.9	16.2	3.2	24.4

First molars								
Sample No.	**Distance from root tip (mm)**	**Distance from cervix (mm)**	**$\delta^{13}C_{VPDB}$ normalised (‰)**	**$\delta^{15}N_{AIR}$ normalised (‰)**	**C(%)**	**N(%)**	**C:N**	**Collagen yield (%)**
CHIL1 M_1 crown and root dentine								
1	50.50	28.50	-24.6	7.5	42.1	15.3	3.2	14.4

2	48.25	26.25	-24.6	7.4	42.0	15.4	3.2	14.3
3	46.00	24.00	-24.6	7.4	42.2	15.5	3.2	14.6
4	43.75	21.75	-24.6	7.6	42.3	15.5	3.2	14.9
5	41.50	19.50	-24.6	7.6	42.1	15.5	3.2	14.8
6	38.75	16.75	-24.7	7.7	42.0	15.4	3.2	13.6
7	36.50	14.50	-24.7	7.8	41.8	15.3	3.2	11.9
8	34.50	12.50	-24.7	7.6	42.1	15.5	3.2	14.0
9	32.00	10.00	-24.9	7.4	42.0	15.4	3.2	14.0
10	29.50	7.50	-25.0	7.4	42.1	15.5	3.2	14.8
11	27.25	5.25	-24.9	7.3	42.0	15.4	3.2	14.8
12	25.25	3.25	-25.0	7.2	42.1	15.5	3.2	15.3
13	23.25	1.25	-25.1	7.0	42.1	15.4	3.2	16.0
14	20.75	-1.25	-25.1	7.1	42.3	15.5	3.2	19.6
15	18.50	-3.50	-25.1	7.1	42.6	15.7	3.2	19.8
16	16.50	-5.50	-25.0	7.0	42.3	15.5	3.2	20.0
17	14.25	-7.75	-25.0	6.8	42.4	15.6	3.2	20.7
18	11.75	-10.25	-24.8	6.8	42.3	15.5	3.2	20.6
19	9.25	-12.75	-24.8	6.5	42.5	15.7	3.2	20.7
20	6.75	-15.25	-24.7	6.4	42.6	15.6	3.2	21.1
21	2.75	-19.25	-24.9	6.4	42.9	15.8	3.2	21.7
CHIL14 M_1 crown and root dentine								
1	48.75	22.25	-24.7	7.3	41.6	15.3	3.2	11.9
2	46.25	19.75	-24.7	7.5	41.9	15.5	3.2	11.3
3	43.75	17.25	-24.8	7.4	42.1	15.6	3.2	13.7
4	41.25	14.75	-24.7	7.4	41.8	15.5	3.1	12.4
5	39.00	12.50	-24.8	7.4	41.6	15.5	3.1	13.3
6	37.00	10.50	-24.7	7.4	40.1	14.8	3.2	6.9
7	34.75	8.25	-24.9	7.1	41.9	15.5	3.2	13.5
8	32.50	6.00	-24.8	7.0	41.7	15.5	3.1	15.2
9	30.75	4.25	-24.7	6.9	42.0	15.7	3.1	14.9
10	28.25	1.75	-24.9	6.9	41.9	15.6	3.1	15.8
11	25.75	-0.75	-24.8	6.9	41.8	15.6	3.1	17.1
12	23.75	-2.75	-24.7	7.0	42.5	15.9	3.1	18.6
13	21.50	-5.00	-24.6	7.0	42.1	15.7	3.1	19.2
14	18.75	-7.75	-24.6	6.8	42.4	15.7	3.1	19.0
15	16.50	-10.00	-24.5	6.5	42.4	15.8	3.1	19.4
16	14.75	-11.75	-24.5	6.4	42.2	15.7	3.1	19.9
17	12.25	-14.25	-24.4	6.2	42.2	15.8	3.1	20.3
18	9.50	-17.00	-24.5	6.2	42.0	15.7	3.1	20.3
19	7.00	-19.50	-24.6	6.1	42.2	15.6	3.2	20.0
KAR M_1 crown and root dentine								
1	56.25	37.25	-24.6	8.4	42.4	15.4	3.2	16.0
2	54.25	35.25	-24.5	8.4	43.2	15.8	3.2	17.2
3	52.25	33.25	-24.3	8.2	42.8	15.8	3.2	16.5
4	50.00	31.00	-24.3	8.1	43.5	16.1	3.2	16.5
5	47.75	28.75	-24.2	8.2	43.3	16.1	3.1	16.9
6	45.50	26.50	-24.3	8.4	43.2	16.0	3.1	16.5
7	43.25	24.25	-24.3	8.5	43.6	16.1	3.2	17.4
8	41.00	22.00	-24.3	8.5	43.1	15.9	3.2	16.1
9	38.75	19.75	-24.2	8.3	43.2	16.0	3.1	16.0
10	36.75	17.75	-24.2	8.2	43.2	16.0	3.1	16.6
11	34.50	15.50	-24.3	8.2	43.4	16.1	3.1	16.3
12	32.00	13.00	-24.2	7.9	43.3	16.1	3.1	16.8
13	29.75	10.75	-24.2	7.9	43.5	16.0	3.2	17.0
14	27.75	8.75	-24.2	7.7	43.2	16.1	3.1	16.1
15	25.50	6.50	-24.1	7.6	43.0	15.9	3.1	17.4
16	23.25	4.25	-23.9	7.0	43.2	15.9	3.2	20.9

17	21.00	2.00	-23.9	6.6	43.6	16.1	3.1	19.6
18	18.75	-0.25	-23.7	6.6	44.2	16.3	3.2	20.2
19	16.50	-2.50	-23.7	6.5	43.7	16.2	3.2	19.9
20	14.00	-5.00	-23.7	6.4	43.5	16.3	3.1	20.4
21	12.00	-7.00	-23.7	6.5	43.8	16.3	3.1	20.3
22	10.25	-8.75	-23.7	6.3	43.7	16.1	3.2	21.0
23	8.00	-11.00	-23.2	5.6	43.1	16.0	3.1	21.1
24	5.25	-13.75	-23.1	4.8	43.1	15.9	3.2	21.9

Table A.23: Bone collagen $\delta^{13}C$ results for Grimes Graves cattle mandibles. $\delta^{15}N$ are also included but are not discussed in this thesis. Each result is the mean of two replicates.

Sample	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{VPDB}$ (‰)	C:N	N(%)	C(%)	Collagen yield (%)
GG92	4.4	-21.6	3.2	14.6	40.7	1.5
GG120	4.3	-22.3	3.3	14.2	40.4	0.7
GG121	5.2	-22.0	3.3	14.1	40.5	0.2
GG149	5.6	-22.2	3.3	14.6	41.2	0.6
GG614	4.8	-22.3	3.3	14.4	41.2	0.3
GG621	5.9	-22.2	3.3	14.5	40.7	0.6
GG661	4.5	-21.5	3.2	14.8	40.8	3.0
GG677	4.1	-21.1	3.3	14.6	41.2	0.5
GG681	5.1	-22.2	3.3	13.7	38.7	0.5
GG722	5.3	-22.1	3.3	14.5	41.1	0.5
GG743	5.4	-22.1	3.3	14.4	40.6	0.5
GG822	4.9	-22.2	3.3	14.2	40.6	0.3
GG839	3.6	-21.0	3.3	14.4	40.7	0.6
GGT10	4.4	-21.4	3.3	14.4	41.0	0.3

Appendix 2

In order to correct for any variation in instrument performance between different instrument runs, data are normalised relative to three standards. Normalisation is performed for each batch of data (corresponding to each instrument run) by plotting the expected values of the three standards against the mean measured values for the batch and fitting a straight line. Figure A.2 shows an example of such a plot for the standards used to normalise enamel carbonate $\delta^{13}C$ data (NBS-19, Merck Suprapur $CaCO_3$, and OES1). The equation of the straight line for this particular batch of data is:

$$y = 0.9966x + 0.2628$$

It is used to calculate normalised data values for the enamel samples as follows:

$$\delta^{13}C_{normalised} = (0.9966 \times \delta^{13}C_{measured}) + 0.2628$$

Normalisation is performed in exactly the same way for collagen and vegetation samples using different sets of standards (Table A.24).

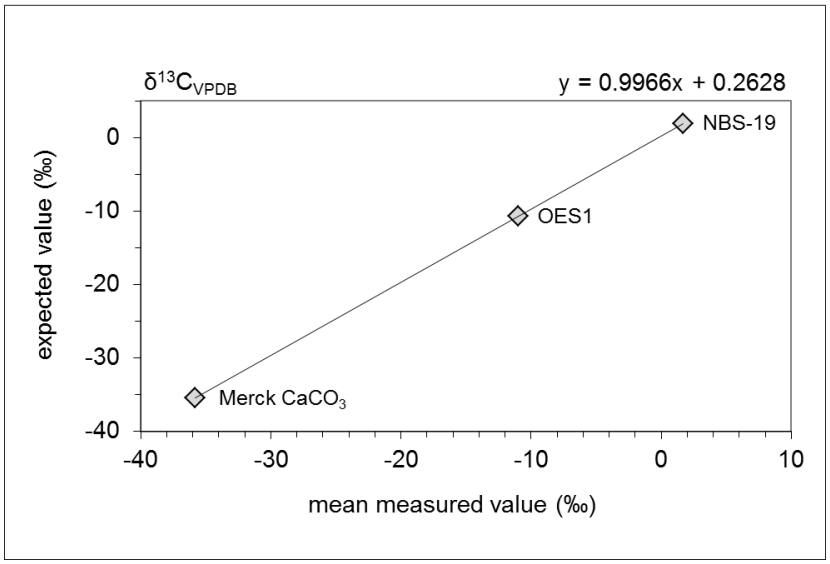

Figure A.2: Generation of normalisation equation for the standards run with enamel carbonate samples.

Table A.24: Standards used for normalisation of isotope ratio data.

Analysis of enamel carbonate	**$\delta^{18}O_{VSMOW}$**	**$\delta^{13}C_{VPDB}$**
NBS-19	+28.65	+1.95
Merck Suprapur $CaCO_3$	+13.35	-35.45
OES1	+25.53	-10.70
Analysis of collagen	**$\delta^{15}N_{AIR}$**	**$\delta^{13}C_{VPDB}$**
IAEA-600	+1.0	-27.77
BLS (bovine liver standard)	+7.65	-21.59
Fish gelatine	+14.45	-15.52
Analysis of vegetation	**$\delta^{15}N_{AIR}$**	**$\delta^{13}C_{VPDB}$**
IAEA-600	+1.0	-27.77
Wheat flour (B2157)	+2.85	-27.21
Fish gelatine	+14.45	-15.52

Appendix 3

The timing and magnitude of each minimum and maximum in a $\delta^{18}O$ profile may be calculated by differentiation of a second order polynomial fitted to the surrounding data points, as shown in Figure A.3 for animal MH0604. The equation of each second order polynomial has the form:

$$y = ax^2 + bx + c$$

The gradient dy/dx is calculated by differentiation:

$$dy/dx = 2ax + b$$

<u>To determine the timing (x) of a minimum or maximum</u>

At a minimum or maximum, gradient dy/dx = 0

When dy/dx = 0, x = -b/(2a)

Take, as an example, the later of the two peaks in Figure A.3. The equation for this peak is $y = - 0.1345x^2 + 3.7677x - 0.1990$

When dy/dx = 0, x = -b/(2a) = -3.7677/(-0.2690) = 14.0

i.e. the timing of the peak is 14.0 months.

<u>To determine the magnitude (y) of a minimum or maximum</u>

Calculate y for x = -b/(2a).

Again, taking the later of the two peaks in Figure A.3 as an example:

when x = -b/(2a) = 14.0, $y = -0.1345(14.0^2) + 3.7677(14.0) - 0.1990 = 26.2$

i.e. the magnitude of the peak is 26.2 ‰.

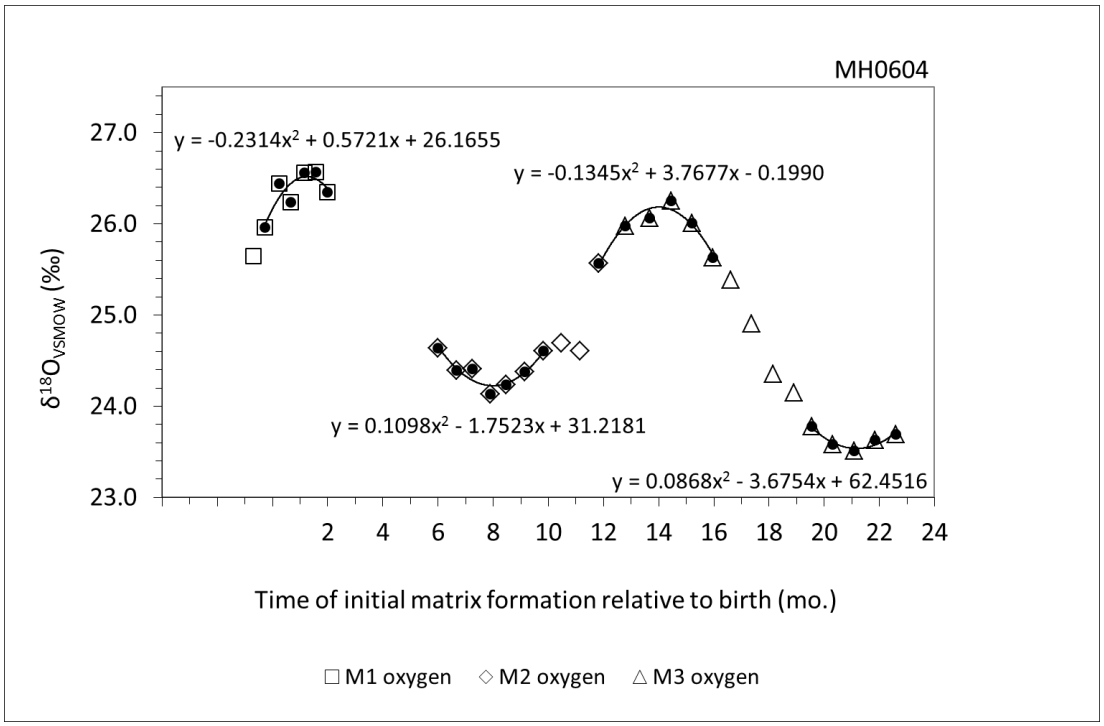

Figure A.3: Fitting second order polynomials to an intra-tooth enamel $\delta^{18}O$ profile.