CHAPTER 7

AN EVALUATION OF THE POTENTIAL OF BIOSPHERE MAPPING IN THE CONTEXT OF FAUNAL DATA FROM ARCHAEOLOGICAL SITES

In southern England sheep and cattle remains are ubiquitous finds on later prehistoric sites that provide evidence of habitation (Hambleton 2008). Whilst it may be desirable to use archaeological material to generate site-specific, local $^{87}Sr/^{86}Sr$ biosphere estimates as a baseline for human studies (e.g. Bentley *et al.* 2004), faunal data may also reveal differences in the management of livestock resources (Evans *et al.* 2007), evidence of seasonal transhumance (Bentley and Knipper 2005), and the transport of animals over significant distances for special purposes (Towers *et al.* 2010; Viner *et al.* 2010).

Although mammalian tooth development follows a gross directional axis, from the cusp tip to the root apex, the formation of the enamel crown is a complex process comprising a number of stages, from initial secretion of an organic matrix, to enamel maturation (Mann 1997). This should not be confused with incremental growth (Montgomery 2002: 54–56). Nonetheless, it may still be possible to detect a smoothed, time-related record of dietary variation in the crowns of animals bearing hypsodont dentition (high-crowned teeth), such as sheep and cattle (Montgomery *et al.* 2010). Thus, modern biosphere data (Chapters 4 and 5) suggest that livestock movements, even within less than 10 km of a given site – a scale commensurate with locally managed grazing and fodder production – could give rise to significant variations in enamel $^{87}Sr/^{86}Sr$ composition.

The study reported in this chapter uses macroscopic sampling techniques to recover time-resolved sequences of $^{87}Sr/^{86}Sr$ variation from the posterior dentition of the two principal domestic taxa of Iron Age economies: cattle and sheep/goat. The selected specimens were recovered from archaeological sites with a close affinity to those geological divisions of the biosphere characterised previously in Chapters 4 and 5. The aim of this work is to assess the accuracy of biosphere $^{87}Sr/^{86}Sr$ estimates based on modern environmental samples. This ‘ground truthing’ exercise for the available biosphere $^{87}Sr/^{86}Sr$ mapping data addresses three iterative questions:

- Is there any evidence of significant intra-tooth $^{87}Sr/^{86}Sr$ variation in the teeth?
- Is the range of $^{87}Sr/^{86}Sr$ values obtained from individual animals coincident with the range of expected values obtained from modern biosphere samples?
- Is there any evidence of differences in $^{87}Sr/^{86}Sr$ variation between archaeological sites, which might be anticipated on the basis of data provided by modern biosphere samples?

7.1 The identification of suitable archaeological faunal assemblages: opportunities and constraints

Samples of stream water (Water) and vegetation (Wood) have provided a broad $^{87}Sr/^{86}Sr$ biosphere transect, which runs from the Chalk escarpment of the Chilterns (Buckinghamshire) to the NE limit of the Cotswolds region (Oxfordshire) (Chapter 4). Relatively narrow ranges of $^{87}Sr/^{86}Sr$ values were obtained from specific, geologically defined divisions of the biosphere. The geographic distances involved suggest that, both humans and their domestic livestock are likely to have incorporated more than one such geological domain within their local home-range. It is therefore necessary to assess whether or not archaeological data provide any indication that the landscape functioned in this way, using material that is likely to be of local origin.

Large faunal assemblages associated with ritual monuments may not reliably provide local animals (Towers *et al.* 2010 ; Viner *et al.* 2010). Conversely, the assumptions necessary for studies such as those suggested by Bentley *et al.* (2004) – who propose using prehistoric fauna to provide local $^{87}Sr/^{86}Sr$ biosphere ranges – are likely to break down less frequently at rural settlements associated sedentary occupation and primary production. This represents a significant constraint on the applicability of this approach to biosphere $^{87}Sr/^{86}Sr$ characterisation. That is, whilst settlements make a significant contribution to our understanding of British Iron Age archaeology, the record of earlier periods includes a high proportion of non-settlement sites, such as burial mounds, causewayed enclosures and henge monuments (Mills 1985).

Historically, Iron Age research has emphasised the importance of boundaries and the creation of cultural landscapes, both in terms of the subdivision and enclosure of the landscape and the formal delineation of settlement areas (Haselgrove *et al.* 2001). Iron Age agricultural intensification may also have increased the biosphere $^{87}Sr/^{86}Sr$ range associated with local production; for example, by the extension of land use to include the heavy clay soils as well as the light calcareous soils thought to have been initially exploited by earlier agricultural communities (Clay 2007). By using archaeological material, which can potentially be linked to other sources of evidence for landscape use, the British Iron Age may represent a good target period for the assessment of biosphere $^{87}Sr/^{86}Sr$ ranges. However, excavation biases limit the extent to which it is possible to compare contemporary assemblages located above different geological formations within the same in the same region.

Kidd (2009) reports that Milton Keynes and the Thames Valley represent the most intensively studied areas of Buckinghamshire. In contrast, only a scattering of sites on the Chiltern dipslope have been investigated, and largely as a part of the activities of antiquarians in the 19th and early 20th centuries (Holgate 1995). In the adjacent county of Oxfordshire, as in other areas of lowland Britain (Fulford and Nichols 1992), aggregate extraction has historically provided a major impetus for archaeological research (Lambrick 2010). Thus, regional knowledge of the rural settlement types and distributions within Oxfordshire and Buckinghamshire is heavily biased towards the terraces of the upper Ouse (Green 1974) and the river gravels of the middle and upper Thames (Booth *et al.* 2007 ; Lambrick *et al.* 2009). However, extensive alluvial systems are likely to homogenise material from an upstream catchment, muting otherwise potentially distinctive $^{87}Sr/^{86}Sr$ biosphere end-member characteristics (Chapter 4).

Hambleton (2008) provides a gazetteer of middle Bronze Age to late Iron Age sites in southern England, from which substantial faunal assemblages were recovered. In an area that relates closely to the mapping exercise detailed in Chapter 4, the author (*ibid.*) identifies three published sites that are located to the south of the glacial till and beyond the river terraces of the upper Thames (Figure 7.01, overleaf): Ivinghoe Beacon, (Cotton and Frere 1968 ; Brown 2001); Bierton Vicarage Garden, (Allen 1988); and Bicester Fields Farm (Cromarty *et al.* 1999). Due to the small amount of stratified material available within the finds archive for Ivinghoe Beacon, a late Iron Age site known as Ward's Coombe has also been identified to provide supplementary material, potentially associated with a Chalk-influenced grazing environment (Dunnett 1972).

For reference purposes Table 7.01 (overleaf) provides a broad chronological scheme for the sites identified and, in the following sections (7.1.1–7.1.3), a brief description of the sites is given, together with their geographic setting. Existing interpretations emphasise the distinctive range of agricultural and pastoral activities thought to be associated with each site. These are located within three distinctive divisions of the biosphere:

- **Chalk sensu lato**

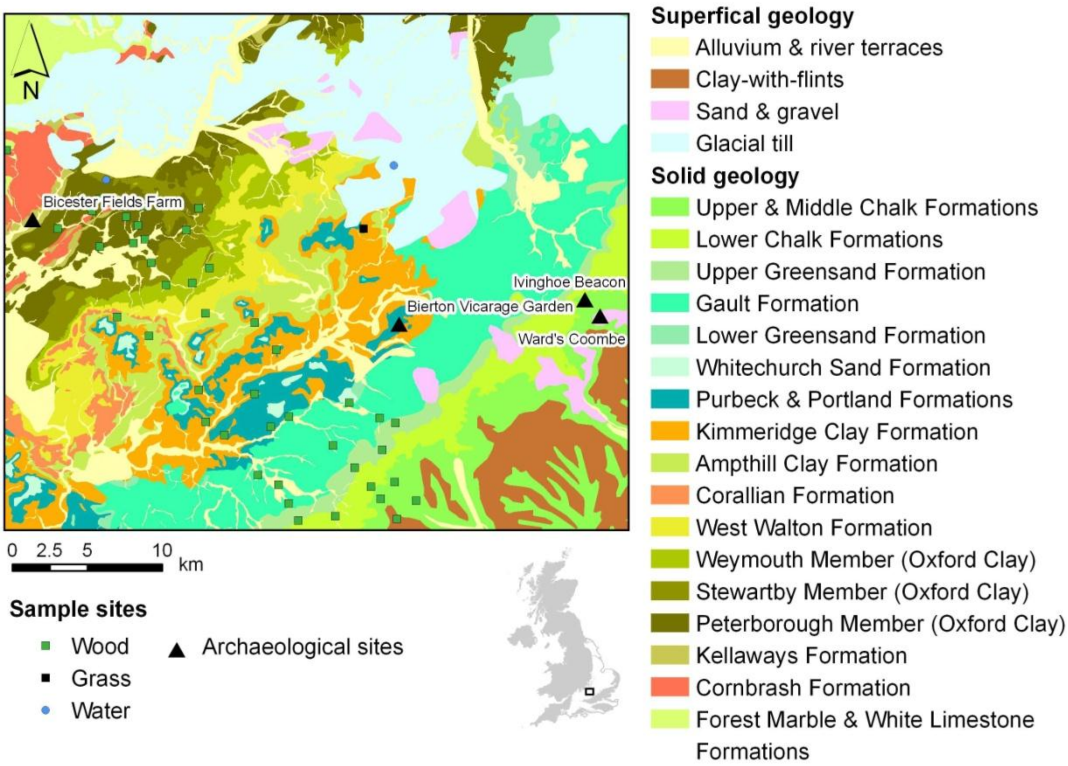
  Early Iron Age occupation activity in the Ivinghoe Hills has been interpreted in relation to the large scale land divisions that are present above the Upper Chalk, focused on pastoral agriculture (Brown 2001).

- **Upper Jurassic mid-vale ridge**

  During the Late Iron Age Bierton Vicarage Garden may have specialised in the cultivation of heavy clay soils (Kimmeridge Clay) and provides a faunal assemblage dominated by older sheep that suggests investment in winter pasture (Allen 1988).

- **Oxford Clay and Great Oolite Group**

  The location of Bicester Fields Farm provides immediate access to both heavy clay soils (Peterborough member of the Oxford Clay formation) and free draining soils (Cornbrash formation) that could have supported a mixed agricultural economy (Cromarty *et al.* 1999).



Based upon DiGMapGB-250 and Based upon DiGMapGB-50, with the permission of the British Geological Survey.

Figure 7.01: Map showing the location of selected Iron Age archaeological sites in Oxfordshire and Buckinghamshire, shown in relation to distribution of superficial (glacial till, river terraces and alluvium) and bedrock geology.

Table 7.01: Simplified Iron Age chronological scheme for lowland Britain based on Cunliffe (2005: 22, Figure 2.2) and indicative date-ranges associated with the selected sites used within this study.

	LBA/EIA 800 BC–600 BC 2750–2550 cal BP	**EIA** 600 BC–300 BC 2550–2250 cal BP	**MIA** 300 BC–100 BC 2550–2050 cal BP	**LIA** 100 BC–AD 43 2050–1907 cal BP
Ivinghoe Beacon				
Wards Coombe				
Bierton Vicarage Garden				
Bicester Fields Farm				

LBA = Late Bronze Ag; EIA = Early Iron Age; MIA = Middle Iron Age; LIA = Late Iron Age

7.1.1 *Ivinghoe Beacon and Ward's Coombe: two sites above the Chalk sensu lato*

- **Ivinghoe Beacon**

Ivinghoe Beacon (228 m OD, NGR 496040, 216850) is thought to be an Early Iron Age hillfort. It occupies the top of a prominent V-shaped spur of the Chalk escarpment of the Chilterns (Beacon Hill), which extends to the East above the low lying clay vale below. The excavated site (Cotton and Frere 1968) represents a defensive enclosure, the construction of which is cited as an example of a timber strengthened box-constructed rampart (Cunliffe 2005: 351). The site marks the terminus of the Ridgeway National Trail, which traces part of the Icknield Way; this ancient track-way skirts the Chalk escarpment from Avebury, to the Brecklands of East Anglia. Although some doubt has been cast on the antiquity of the route (Harrison 2003), Ivinghoe Beacon is located within a distinctive Chalk escarpment zone which stretches for some considerable distance from SE–NW and provides relatively uniform agricultural potential along its length.

Cunliffe (2005: 97) argues that the ceramic evidence from Ivinghoe Beacon represents part of a native tradition centred on the Chilterns, and on this basis a tentative date of around 700 BC is indicated for its earliest initial occupation. However, an earthwork survey undertaken by English Heritage (Brown 2001) shows that a pre-existing Bronze Age settlement may have been present. Although the available radiocarbon dates cover a wide period in the earlier first millennium BC (Green 1981), Kidd (2009) suggests that three of the recalibrated analyses are consistent with a late Bronze Age or early Iron Age date. Accordingly, the rampart can be interpreted as an early Iron Age addition to an un-enclosed settlement.

The faunal remains that were recovered during the excavations of the 1960's (Cotton and Frere 1968) represent one of the larger assemblages available from the Chalk landscape in this area (Hambleton 2008). However, there is some ambiguity regarding the stratigraphic security the material retained within the finds archive. This problem was encountered by Green (1981), when a radiocarbon dating program was attempted using material which had, according to Cotton and Frere (1968), accumulated behind the northern rampart. The secure context (A VII 11) identified by Green (1981) lies at the bottom of a sequence sealed by the collapse of the rampart. On Page 37 of the original site notebook – "*IVINGHOE BEACON 1963, SITE A (NORTHERN PART)"* (marked on the front cover as "IB, 63, iii-v, viii-ix") – these layers are recorded as part of a series of banked deposits. On page 37 of the notebook, the description of "A VII 11" as an *"Old 'turf line' below 10A, large quantities of bone, broken pottery etc. – blacker towards S. although greyish brown above top of nat VIII 12."* also suggests some form of midden material, rather than a 'natural' *in situ* soil.

On inspection of the finds archive, context "A VII 11" provided a limited quantity of material suitable for analysis: one fragmented sheep mandible and one fragmented cattle mandible, each retaining a second and third molar (Appendix B). Cotton and Frere (1968) suggest that this material is associated with the occupation of the fortified site, possibly relating to an early occupation phase, either post-dating or contemporary with the construction of the rampart. However, it is possible that it may be redeposited, residual material associated with an earlier phase of occupation. This has implications for its likely local origin. Considerable debate surrounds the function of early hillforts within Iron Age society (for example Hill 1995 ; James 2007). If the site is not associated with primary production centred on the Chiltern Hills, the faunal material may have been procured from a much wider area, beyond the influence of Chalk.

- **Ward's Coombe**

The enclosure recorded at Ward's Coombe (179 m OD, NGR 497050, 215760) is one of a limited number of Iron Age features that have been subject to some form of intervention in the area of the Chalk escarpment (Holgate 1995 ; Kidd 2009). Within the current study it was selected to complement the coverage of the Chalk biosphere package provided by faunal material obtained from Ivinghoe Beacon (which lies approximately 1.5 km to the NW). Ward's Coombe is located on National Trust land within 'Meads Plantation'. In the 1970's, land clearance in advance of the reestablishment the woodland plantation exposed a penannular bank, open on its SE side and forming a distorted 'C' shape around 35 m in diameter. This was subject to a limited program of trial excavation (Dunnett 1972) which revealed an internal ditch up to 1.5 m deep and 2 m wide. However, excavation was not extensive enough to determine the original function of the site.

The published site report (Dunnett 1972: 145) indicates that several sherds of *"…hand-made pottery dating from the Iron Age…"* were recovered from the primary fills of the enclosure ditch. No Belgic or Romano British pottery was recovered from these contexts. However, as Belgic pottery and later Romanised ceramics (including Romano British roof tile) were recovered from the upper fills, it is unclear whether the finds from the early deposits relate to the initial use-life of the feature, or whether they represent residual material from an earlier period. Bryant (2007) cites Ward's Coombe amongst 20 late Iron Age sites that occupy the Clay-with-flints dip-slope, in the hills surrounding the Bulbourne valley; although these do not include any settlements, seven iron-working sites are identified as well a number of extensive of track-ways and enclosure systems.

Investigation of the finds archive yielded a limited quantity of fragmented faunal material recovered from the primary ditch fill (Appendix B). Due to the limited availability of archaeological faunal remains from this landscape zone, permission was obtained to sample this material, which consisted of a fragment of cattle mandible retaining a first and second molar and a fragmented sheep mandible which retained the posterior dentition. If this site had some function relating to livestock management – such as a pinfold enclosure – as an external bank might imply, then it is possible that the faunal material contained by lower fills represent locally grazed animals.

7.1.2 *Bierton Vicarage Garden: a site located above the Upper Jurassic mid-vale ridge*

The modern-day village of Bierton occupies an area to the NE of Aylesbury, underlain by the limestones, clays and sands of the Portland Beds. These formations overlie the Kimmeridge Clay, which forms the larger part of the Vale of Aylesbury below. The excavation of Bierton Vicarage Garden (89 m OD, NGR 483650, 215230) took place 1979, in advance the development of the site for housing. The initial trial excavations, undertaken in 1975 by Buckinghamshire County Museum service, provided evidence for late Iron Age occupation. The more comprehensive investigation which followed, confirmed the presence of a large Iron Age settlement and the continuity of intensive occupation into the Roman, Medieval and Post-Medieval periods. The published text (Allen 1988) reports that the earliest features were truncated by later activity; hence, no Iron Age occupation layers were detected.

The exposed Iron Age features included four substantial enclosure ditches up to 2.5 m wide and as deep as 1.5 m, and a series of earlier shallow curvilinear and linear features associated with the continued re-organisation of the site (Allen 1988). In addition to numerous discrete pits and post holes, other features included two proposed beam slots, and putative evidence for a number of round houses in the form of the fragmentary segments of circular drip-gullies. Allen (1988) indicates that the ceramic assemblage recovered from the site suggests a first century AD, pre-conquest date for all of the Iron Age phases of activity, with no evidence for typological variation.

The Iron Age faunal assemblage recovered at Bierton is unusual locally, in that it is dominated by the remains of sheep/goat rather than cattle (cf. Holmes and Reilley 1994 ; Hambleton 1999). However, this bias is more typical of the national pattern (Albarella 2007). It is also reported that the assemblage contained only a small number of young lambs, suggesting that a significant proportion of the animals may have been kept beyond their second winter. This management strategy may have provided more wool and a larger carcass, but would have required greater investment in winter pasturage than if surplus sheep had been culled (Payne 1973). In addition, the plant macrofossil assemblage recovered from Bierton Vicarage Garden is cited by Cunliffe (2005: 410) as an example of the early use of bread wheat during the Iron Age. This may indicate an intensification of grain production, and possible specialisation in the cultivation of the surrounding Kimmeridge Clay (Allen 1988).

Allen (1988) divides the Iron Age features into four phases of activity, based largely on the stratigraphy of the site; the larger enclosure ditches fall into the final phase. However, the relationship between only one major ditch and the preceding phase was resolved during excavation. Approximately 44 % (based on the number of identifiable specimens) of the Iron Age faunal assemblage was recovered from this feature (context numbers 0460, 0510, 0610), which cut an earlier alignment of shallow gullies and was itself cut by later Roman features. On inspection, the assemblage retained from this feature provided six fragmented sheep mandibles from separate animals, bearing both second and third molars, and two fragmented cattle mandibles (Appendix B). The cattle mandibles also retained the posterior dentition, but in a very advanced stage of wear.

Both of the selected cattle mandibles and three of the sheep mandibles were recovered from the same excavated section of the ditch (0610). In order to avoid duplication, only the two left sheep mandibles were selected for analysis. The environmental evidence from the site suggests some division of production within the surrounding landscape and possibly some level of specialisation (wheat and sheep/wool). Importantly, the plant macrofossil remains are used to suggest that the Kimmeridgian mudrocks surrounding the site were well drained enough to be agriculturally productive. Depending on how a grazing regime was managed, animals may have been excluded from cultivated areas at different times.

7.1.3 *Bicester Fields Farm: a site between the Middle Jurassic Oxford Clay and the Great Oolite*

Bicester Fields Farm (68 m OD, NGR 459200, 222200) was excavated in 1998 by the Oxford Archaeology Unit and is reported on by Cromarty *et al.* (1999). The site is located on the SE outskirts of Bicester, above a narrow (< 600 m wide) outcrop of the Kellaways beds. This formation lies between the considerably more extensive outcrops of the Peterborough member of the Oxford Clay and the Cornbrash formation of the Great Oolite Group. The site is positioned in the angle between alluvial deposits that flank the NW–SE course of an unnamed stream and it's confluence with Langford Brook, which runs NE–SW along the top of outcrop of the Kellaways Clay. Cromarty *et al.* (1999) characterise the site as a pastoral farmstead and suggest that it may have been abandoned as a settlement prior to, or shortly after the Roman conquest.

The site is represented principally by a mid to late Iron Age enclosure, which comprises two phases of construction and probably sits within a larger complex of boundary ditches. Cromarty (1999) indicates that many of the features – away from the settlement enclosure – lacked any datable ceramic evidence; the majority of the pottery that was recovered is attributed to the late Iron Age. Although the dating of the site relies chiefly on the ceramic evidence, the chronology is supplemented by one radiocarbon date, provided by bone recovered from the discrete cattle burial. The upper range of the 95 % CI of the calibrated date (334–326 cal. BC to 200 cal. BC–cal. AD 66) is consistent with the active use-life of the enclosure during the mid–late Iron Age (Cromarty *et al.* 1999).

Bicester Fields Farm is located at around 68 m OD between the Cornbrash limestone and the heavy clay soils of Peterborough member Oxford Clay. Most of the heavy clay soils in this area are subject to seasonal waterlogging, and lie around 65 m OD, just over 0.5 km to the SE of the site (Thompson 1983). Thus, Bicester Fields Farm is located in an intermediate landscape zone, above the floodplain but with immediate access to fertile seasonal pastures to the SE and light, well drained and calcareous soils to the NW. If the site was positioned to make efficient use of the surrounding landscape resources, and managed, seasonal livestock movements took place, the dental enamel of sheep and cattle may record a substantial oscillation in the $^{87}Sr/^{86}Sr$ composition of the diet.

Excluding the highly fragmented remains recovered from the dated cattle burial, the second phase of the mid-late Iron Age enclosure supplied over 60 % of the hand-collected bone detailed in the site archive (Cromarty *et al.* 1999). This fraction of the assemblage provided three cattle and nine sheep/goat mandible fragments that retained both an erupted second and third molar. However, one cattle third molar displayed a gross, circumferential hypoplasic band rendering it unsuitable for analysis. On the basis of the condition of the enamel, two sheep mandibles were selected from the five that showed signs of wear on the third molar, suggesting that the crown would be likely to be fully mineralised (Appendix B).

7.2 Characterisation of the age-related bias in the selected faunal material

The faunal material selected for analysis was obtained from skeletal assemblages made up of the commingled, disarticulated remains of a number of individuals. Thus, only complete hemi-mandibles or mandibular fragments bearing a significant proportion of each posterior tooth row were sampled. This allowed an estimate of the age at death of each individual to be made using standard tooth-wear scoring methods. Under the system devised Grant (1982), numerical values were attributed each permanent molar and added together to calculate a molar wear score (MWS); these data are fully documented in Appendix B. The estimated age stages for the selected mandibles are shown in Table 7.02 (overleaf). Although the timing of the eruption of teeth allows the age at death of young animals to be reasonably well constrained, the age ranges become increasingly broad and generalised as dental wear progresses (Hillson 2005: 207–256).

Table 7.02: Age stage of selected cattle and sheep/goat mandibles estimated following the recommendations of Hambleton (1999) using mandible wear score allocated following Grant (1982).

	Archaeological site	Mandible ID	Age stage‡	Estimated age at death
Cattle	Ivinghoe Beacon	IB_01	G	Adult
	Ward's Coombe	WC_01	F	Young adult*
	Bierton Vicarage Garden	BIE_01	I	Senile
		BIE_02	G	Adult
	Bicester Fields Farm	BIFF_01	G	Adult
		BIFF_04	E	30–36 months
Sheep/Goat	Ivinghoe Beacon	IB_02	F	3–4 years
	Ward's Coombe	WC_02	F	3–4 years
	Bierton Vicarage Garden	BIE_06	G	4–6 years
		BIE_08	F	3–4 years
	Bicester Fields Farm	BIFF_02	F	3–4 years
		BIFF_05	G	4–6 years

‡Halstead/Payne age stage estimated using mandible wear score (MWS) following the recommendations of Hambleton (1999): record is fully documented in Appendix B. Age stages commonly used for the evaluation of age at death in cattle and sheep/goat are based on the assessment of tooth wear, defined by Halstead (1985) following Payne (1973).
*Grigson (1982) suggests that in cattle, slight wear is usually visible on the M_3 after at least three years of age and that the distal third cusp (or post) of the crown comes into wear at around five years; this suggests a level of M_3 wear equivalent to Grant's wear stage 'e' and greater conferring, on the basis of the patterns observed by Grant (1982), a MWS ≥ 37 and membership of the 'young adult' age stage 'F'.

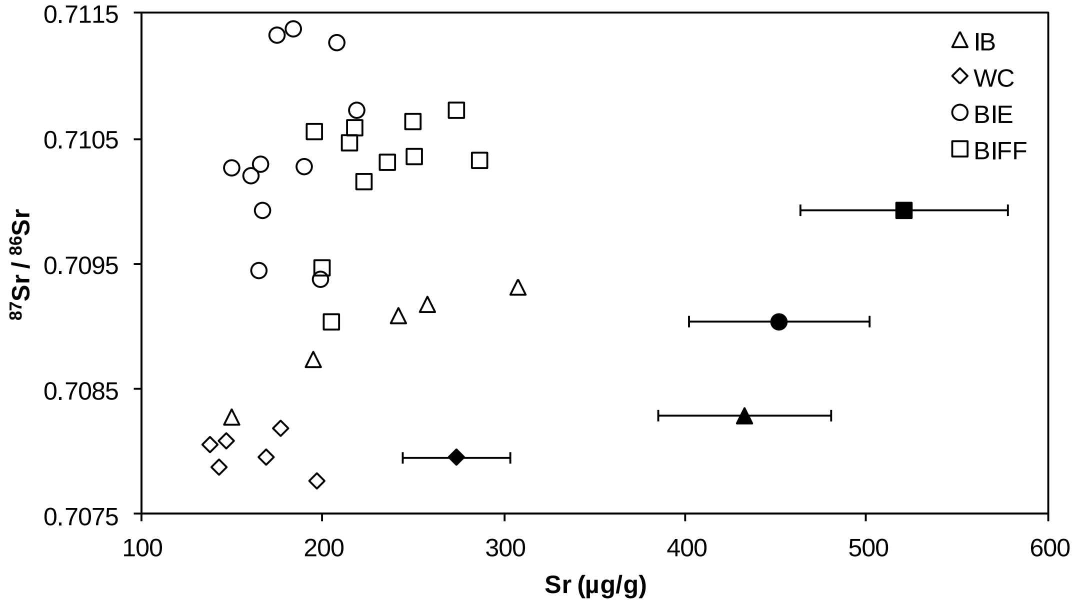
The majority of sheep/goat mandibles were obtained from individuals of between 3–4 years of age (Table 7.02). Assuming that a flock is used to provide multiple products including meat, Payne (1973) suggests that slaughter at 2–3 years will maximise the size and condition of the resulting carcass. It is also suggested that in most instances males will not be retained beyond this age, except for breeding purposes, or wool production as wethers (castrated males). The suggested survivorship profiles indicate a rapid increase in the rate of mortality at around six years, as productivity begins to decline (Payne 1973). Most of the selected cattle cattle (Table 7.02) also exceed the optimal age of slaughter for meat production, as growth rates slow considerably after 30–36 months (e.g. Halstead 1985). Only the individual identified as BIFF_04 falls within this age-range. The advanced age stages of most of the cattle suggest that these animals were maintained into later life for purposes other than meat production: principally for breeding purposes, milk production and traction.

In the case of the senescent cattle specimen obtained from Bierton Vicarage Garden (BIE_01), the use of this individual for traction is perhaps the most convincing explanation for retention into old age. These observations raise an interesting question regarding the variability of the isotope composition within the selected individuals pertaining to the level of forward-planning involved in livestock management; that is, whether animals maintained into adult age are likely to have been managed in the same way during the lifetime of enamel mineralisation as those slaughtered at an earlier age. This study is undertaken in full cognisance that the resulting interpretations relate to individuals belonging to specific age classes. However, if it is assumed that animals were managed on a herd basis and were subject to consistent controlled seasonal movement, $^{87}Sr/^{86}Sr$ variation in individual specimens may be representative of a larger population.

7.3. Assessment of diagenesis

Dentine has an established role as a diagenetic control for archaeological dental enamel, based on the assumption that the two cogentic tissues are likely to display similar initial strontium concentrations and $^{87}Sr/^{86}Sr$ compositions (eg. Montgomery 2002; Evans *et al.* 2007; Viner *et al.* 2010). Unlike enamel, dentine is poorly crystalline and porous, making it susceptible to alteration (Koch *et al.* 1997). For example, Kohn *et al.* (1999) found concentrations of secondary minerals in the dentine of fossil teeth of around 5 % w/w, whilst the concentrations in enamel were an order of magnitude lower. However, leaching experiments suggest that strontium diagenesis may involve ionic exchange and remineralisation, as well as the deposition of secondary minerals within pore spaces (Trickett *et al.* 2003). Thus, in archaeological teeth, Budd *et al.* (2000) found that 15–100 % of dentine strontium was of diagenetic origin.

In the current study, sheep/goat dentine was analysed from for each site (data documented in Appendix C). Sheep/goat teeth are smaller than those of cattle and thus present a greater surface area to the burial environment per unit-volume. On this basis, it can be assumed that sheep/goat dentine may progress further along a given diagenetic trajectory than cattle dentine. As anticipated, the dentine contained high concentrations of strontium with respect to the enamel from each site (Figure 7.02). Only the dentine from Wards Coombe shows any overlap with enamel concentrations. However, at this Chalk site, the concentration of strontium in the enamel of both species (cattle and sheep/goat) is also low, suggesting that this apparent off-set may reflect a low initial strontium concentration.



IB = Ivinghoe Beacon; WC = Ward's Coombe; BIE = Bierton Vicarage Garden; BIFF = Bicester Fields Farm. Open symbols = enamel; closed symbols = dentine. Estimated error (2σ) of each $^{87}Sr/^{86}Sr$ measurement falls within the area of each symbol; 2 RSD associated with Sr (µg/g) has been estimated as ± 11 % (Chapter 3). Error-bars have been fitted to only the dentine data. Data are documented in Appendix C.

Figure 7.02: Scatter plot of $^{87}Sr/^{86}Sr$ versus Sr (µg/g), comparing sheep/goat dentine (closed symbols) with sheep/goat enamel (open symbols).

In a model of digenesis that invokes only mineral deposition, the concentration of strontium in dentine will reach a plateau as it approaches that of the diagenetic component. Based on the data shown in Figure 7.02, some form of saturation may be reached at a concentration of around 400–600 µg/g. This is similar to the concentration of strontium in Chalk rock (Bailey *et al.* 2000) and other marine carbonates (Turekian and Wedepohl 1961), and is also consistent with the highest concentrations seen in surface soils above the Chalk *sensu stricto* (Figure 5.06). Assuming an initial dentine $^{87}Sr/^{86}Sr$ composition of 0.7105 – consistent with the biosphere range associated with the Peterborough member of the Oxford Clay (Chapter 4) – and a low initial strontium concentration, it is possible to illustrate the changes that might accompany the alteration of dentine within a Chalk burial environment (Figure 7.03); this indicative model suggests that although measureable isotopic alteration would accompany the deposition of secondary minerals representing less than 5 % w/w of the sample mass, there would not be a significant change strontium concentration.

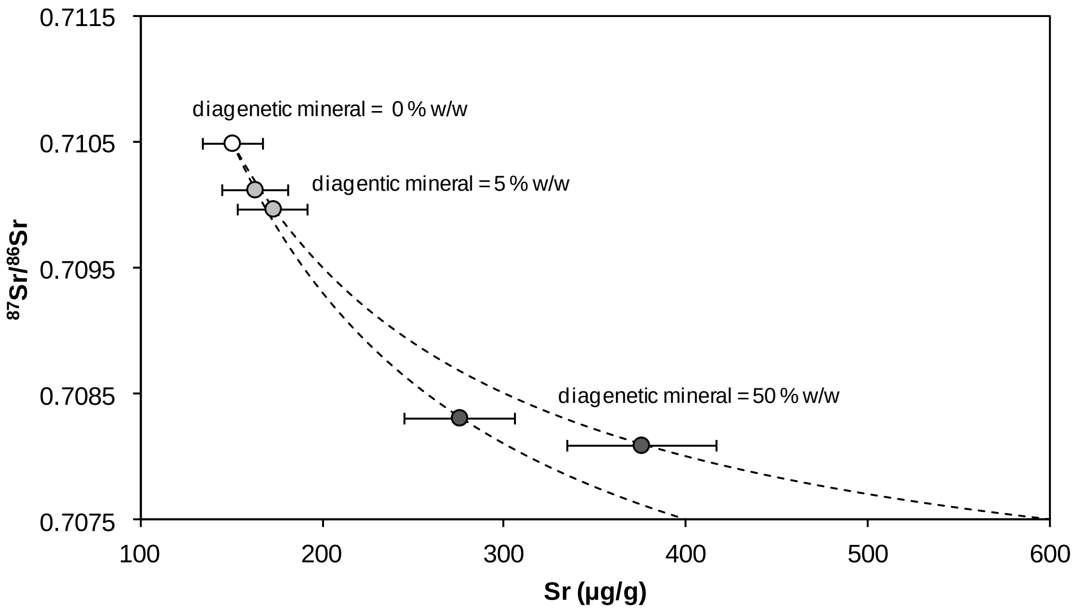


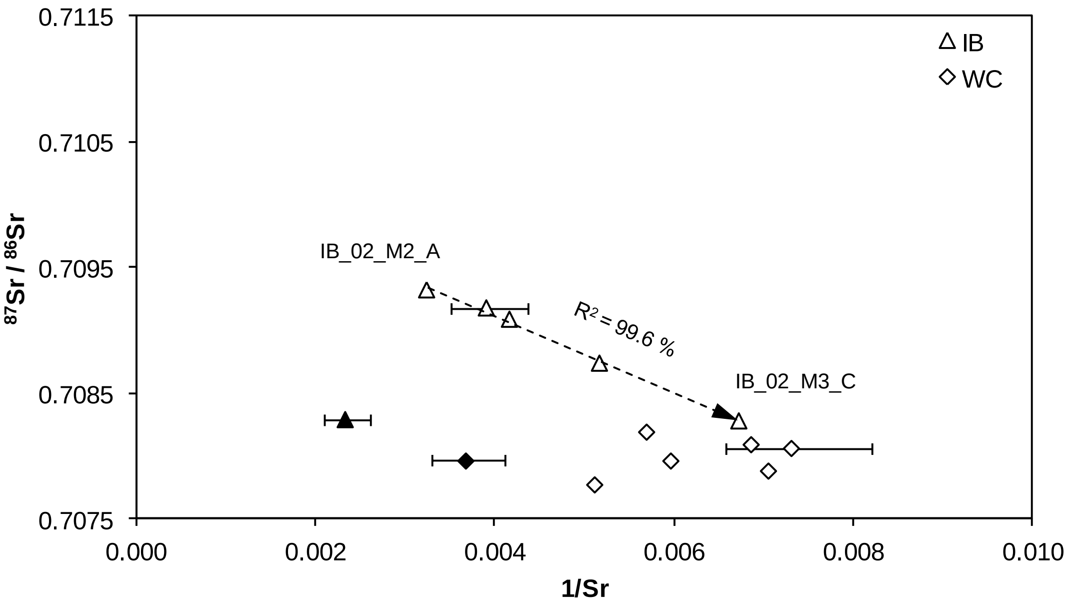
Figure illustrates the effect of adding a digenetic mineral component with a $^{87}Sr/^{86}Sr$ composition of 0.7075 and Sr concentration of 400 µg/g (lower mixing line) or 600 µg/g (upper mixing line) to a dentine sample with an initial $^{87}Sr/^{86}Sr$ composition of 0.7105 and Sr concentration of 150 µg/g. Symbols show the position on each mixing line where the digenetic mineral component represents 0 % w/w, 5 % w/w, and 50 % w/w of the sample mass. Estimated error (2σ) of each $^{87}Sr/^{86}Sr$ value falls within the area of each symbol; 2 RSD associated with Sr (µg/g) has been estimated as ± 11 % (Chapter 3).

Figure 7.03: Hypothetical mixing lines illustrating the possible magnitude of strontium diagenesis on dentine within a Chalk burial environment, allowing only for the deposition of secondary minerals with a $^{87}Sr/^{86}Sr$ composition of 0.7075.

The concentrations of strontium in archaeological dentine (Figure 7.02) are consistent with the accumulation of secondary minerals from the burial environment, at a level three orders of magnitude greater than observed within fossilised dental enamel (Kohn *et al.* 1999). Thus, although dentine may provide an indicative range of diagenetic $^{87}Sr/^{86}Sr$ values, which enamel may tend towards if it is structurally compromised, it does not provide an appropriate model for enamel diagenesis *per se*. The effect of any diagenetic influence on enamel would be reflected in a marginal reduction in inter- and intra-individual variation in $^{87}Sr/^{86}Sr$ composition, but a significant shift in strontium concentrations should not be expected. Given the level of biosphere variation reported in Chapter 4, it is unlikely that such a small bias would significantly influence the interpretative value of a given measurement.

The current study represents an attempt to monitor changes in the composition of the dental enamel of individuals, as part of a developmental sequence. To achieve this, a series of samples were taken from each tooth and, where available, more than one tooth was analysed from each individual. As reported below (Section 7.4), significant variations were found in $^{87}Sr/^{86}Sr$ composition and strontium concentration within most teeth. However, developmentally proximal samples, taken from different anatomical positions on different teeth all provide internally consistent, $^{87}Sr/^{86}Sr$ values and strontium concentrations (7.03 and 7.04, pages 181 and 182). Thus, serial sampling provides an internal control for diagenesis. The clearest example of this is illustrated in figure 7.04 (overleaf).

Figure 7.04 is intended to provide an indication of the potential significance of any differences in concentration in relation to a binary mixing model (Faure 1977: 97–106). This highlights an apparent mixing line within the samples from sheep/goat mandible WC_02. Although this is the only example of such a pattern in the current study, similar arrays have been noted by Evans *et al.* (2007), Montgomery *et al.* (2010), and Towers *et al.* (2010) in the teeth of cattle and are also present within the data-sets presented by Viner *et al* (2010). In general, such patterns occur when a suite of samples contain varying mixtures of strontium derived from just two sources that posses different $^{87}Sr/^{86}Sr$ ratios and distinctive strontium concentrations. In the case of WC_02, although the trajectory of the apparent mixing line (from cusp to cervix) tends towards the dentine $^{87}Sr/^{86}Sr$ values, this is associated with significant decrease in strontium concentration across both teeth (M_2 and M_3). This is not consistent with the diagenetic process as it is currently understood, and suggests that the pattern is endogenous.



IB = Ivinghoe Beacon; WC = Ward's Coombe. Open symbol = enamel; closed symbol = dentine. Estimated error (2σ) of each $^{87}Sr/^{86}Sr$ measurement falls within the area of each symbol; 2 RSD associated with 1/Sr has been estimated on the basis of a ± 11 % error in Sr (µg/g) (Chapter 3). Error bars have been fitted to only the dentine-enamel pair. A possible mixing line has been fitted by OLS regression to the enamel samples obtained from mandible IB_02, which is consistent with the direction of growth indicated by the arrow-head. Data are documented in Appendix C.

Figure 7.04: Scatter plot of Sheep/goat data from Chalk burial environments (Ward's Coombe and Ivinghoe Beacon) shown as $^{87}Sr/^{86}Sr$ versus 1/Sr, highlighting a possible mixing line within the enamel data obtained from one individual (IB_02) recovered from the site of Ivinghoe Beacon.

7.4 Results

Serial samples of faunal enamel (documented in Appendix B) were prepared and analysed following the methods outlined in Chapter 3. The results are reported in Tables 7.03 (overleaf) and 7.04 (page 182), and documented Appendix C. The $^{87}Sr/^{86}Sr$ values obtained from each crown are presented in developmental order, together with the estimated time of enamel formation (Time), which is based on the distance of each sample from the cervix of the crown (Chapter 3). Duplicate samples suggest that – within the limitations of the sampling method – differences between samples from the same crown that exceed an interval of ± 0.0001 are significant (Chapter 3). Average $^{87}Sr/^{86}Sr$ values are expressed as concentration-weighted means, and the average strontium concentrations of the same samples are calculated as a simple arithmetic mean.

The strontium concentrations reported in Tables 7.03 and 7.04 are substantially higher than those found in archaeological human samples recovered from sites within the British Isles, which are often less than 150 µg/g (Evans *et al.* 2012). However, the data are consistent with those for Bronze Age cattle reported by Viner *et al.* (2010), which vary between 69–305 µg/g, with a median of 151 µg/g (n = 55). A trophic level effect – between herbivores and omnivorous – should be anticipated, due to the bio-purification of calcium that through the food chain, but there are also likely to be physiological differences between humans and ungulates, which could drive such an off-set (Burton and Wright 1995).

Table 7.03: Results of serial ^{87}Sr/^{86}Sr analysis of cattle molars.

	Second molars (M_2)				**Third molars (M_3)**			
	Sample ID	**Time‡**	**Sr (µg/g)**	**^{87}Sr/^{86}Sr**	**Sample ID**	**Time‡**	**Sr (µg/g)**	**^{87}Sr/^{86}Sr**
Ivinghoe Beacon	IB_01_M2_A	7	117	0.71055	IB_01_M3_A	15	116	0.71032
	IB_01_M2_B	12	124	0.71035	IB_01_M3_B	22.5	123	0.71049
	Mean enamel*	**9.5**	**121**	**0.7104**	**Mean enamel***	**19**	**120**	**0.7104**
Ward's Coombe	WC_01_M2_A	4	114	0.70796	—	—	—	—
	WC_01_M2_B	7.5	105	0.70794				
	WC_01_M2_C	11.5	89.8	0.70811				
	Mean enamel*	**7.5**	**103**	**0.7080**				
Bierton VicarageGarden	BIE_01_M2_A	10	153	0.71028	BIE _01_M3_A	20.5	146	0.71028
	BIE _01_M2_B	12	142	0.71021	BIE _01_M3_B	22.5	128	0.71014
	Mean enamel*	**11**	**148**	**0.7102**	**Mean enamel***	**21.5**	**137**	**0.7102**
	BIE _02_M2_A	7	198	0.71021	BIE _02_M3_A	15	157	0.71045
	BIE _02_M2_B	12	161	0.71042	BIE _02_M3_B	22.5	154	0.71044
	Mean enamel*	**9.5**	**180**	**0.7103**	**Mean enamel***	**19**	**156**	**0.7104**
Bicester Fields Farm	BIFF_01_M2_A	4.5	112	0.70964	BIFF_01_M3_A	12.5	158	0.71031
	BIFF_01_M2_B	8.0	167	0.70987	BIFF_01_M3_B	17.0	161	0.71037
	BIFF_01_M2_C	12	159	0.71037	BIFF_01_M3_C	22.0	154	0.71036
	Mean enamel*	**8.0**	**146**	**0.7100**	**Mean enamel***	**17.0**	**158**	**0.7103**
	BIFF_04_M2_A	3.5	209	0.70982	—	—	—	—
	BIFF_04_M2_A2	3.5	242	0.70996				
	BIFF_04_M2_B	7.5	266	0.71017	BIFF_04_M3_A	10.5	258	0.71007
	BIFF_04_M2_C	12	231	0.70960	BIFF_04_M3_B	16.5	185	0.70962
	BIFF_04_M2_C2	12	224	0.70951	BIFF_04_M3_C	23.0	190	0.71045
	Mean enamel*	**7.5**	**235**	**0.7099**	**Mean enamel***	**16.5**	**211**	**0.7101**

Samples are fully documented in Appendix B and results in appendix C
‡Central vertical position of each sample along growth axis (measured from cervical margin) scaled to mineralisation time (months) appropriate to each tooth and rounded to the nearest 0.5 months (see Section 7.2.3b).
*Mean enamel values exclude replicate and bulk samples; mean ^{87}Sr/^{86}Sr is weighted for Sr concentration of each contributing sample.

Table 7.04: Results of serial $^{87}Sr/^{86}Sr$ analysis of sheep/goat molars.

	Second molars (M_2)				Third molars (M_3)			
	Sample ID	Time‡	Sr (µg/g)	$^{87}Sr/^{86}Sr$	Sample ID	Time‡	Sr (µg/g)	$^{87}Sr/^{86}Sr$
Ivinghoe Beacon	—	—	—	—	IB_02_M3_A	13.5	241	0.70909
	IB_02_M2_A	7.5	308	0.70932	IB_02_M3_B	17	194	0.70874
	IB_02_M2_B	11.0	257	0.70918	IB_02_M3_C	20	149	0.70828
	Mean enamel*	**9.5**	**283**	**0.7093**	**Mean enamel***	**17**	**195**	**0.7088**
Ward's Coombe	WC_02_M2_A	5	176	0.70819	WC_02_M3_A	13.5	146	0.70809
	WC_02_M2_B	8	196	0.70777	WC_02_M3_B	17	168	0.70796
	WC_02_M2_C	11	137	0.70806	WC_02_M3_C	20	142	0.70788
	Mean enamel*	**8**	**170**	**0.7080**	**Mean enamel***	**17**	**152**	**0.7080**
Bierton Vicarage Garden	—	—	—	—	BIE_06_M3_A	15	183	0.71138
	BIE_06_M2_A	7.5	207	0.71127	BIE_06_M3_B	17.5	218	0.71073
	BIE_06_M2_B	11	174	0.71133	BIE_06_M3_C	20	198	0.70938
	Mean enamel*	**9**	**191**	**0.7113**	**Mean enamel***	**17.5**	**200**	**0.7105**
	BIE_08_M2_A	5	164	0.70945	BIE_08_M3_A	12.5	189	0.71028
	BIE_08_M2_B	8	166	0.70993	BIE_08_M3_B	16.5	160	0.71020
	BIE_08_M2_C	11	166	0.71029	BIE_08_M3_C	20	149	0.71027
	Mean enamel*	**8**	**165**	**0.7099**	**Mean enamel***	**16.5**	**166**	**0.7103**
Bicester Fields Farm	BIFF_02_M2_A	6	204	0.70904	BIFF_02_M3_A	14.5	195	0.71055
	BIFF_02_M2_B	8.5	199	0.70947	BIFF_02_M3_B	17	250	0.71036
	BIFF_02_M2_C	10.5	214	0.71047	BIFF_02_M3_C	20	249	0.71064
	Mean enamel*	**8.5**	**206**	**0.7097**	**Mean enamel***	**17**	**231**	**0.7105**
	—	—	—	—	BIFF_05_M3_A	15	236	0.71031
	BIFF_05_M2_A	8.0	222	0.71016	BIFF_05_M3_B	17.5	286	0.71032
	BIFF_05_M2_B	11.0	272	0.71073	BIFF_05_M3_C	20	218	0.71058
	Mean enamel*	**9.5**	**247**	**0.7105**	**Mean enamel***	**17.5**	**247**	**0.7104**

Samples are fully documented in Appendix B and results in appendix C.
‡Central vertical position of each sample along growth axis (measured from cervical margin) scaled to mineralisation time (months) appropriate to each tooth (see Section 7.2.3b).
*Mean enamel values exclude replicate and bulk samples and dentine; mean $^{87}Sr/^{86}Sr$ is weighted for Sr concentration of each contributing sample.

Figure 7.05 (overleaf) compares the concentration of strontium in various biosphere sample media, with those found in cattle and sheep/goat enamel. There is a substantial difference between the concentrations found in stream waters and vegetation, of at least an order of magnitude, and the difference between the concentrations in vegetation and enamel is around another order of magnitude greater than that. Likewise, the concentration of leachable strontium in surface soils is around two orders of magnitude lower than their bulk strontium concentration. Thus, although under some grazing conditions, sheep and cattle may consume prodigious quantities of soil

(Thornton and Abrahams 1983), the high strontium content of dental enamel is testament to the integration of substantial dietary inputs of bone-forming cations from a variety of dietary sources.

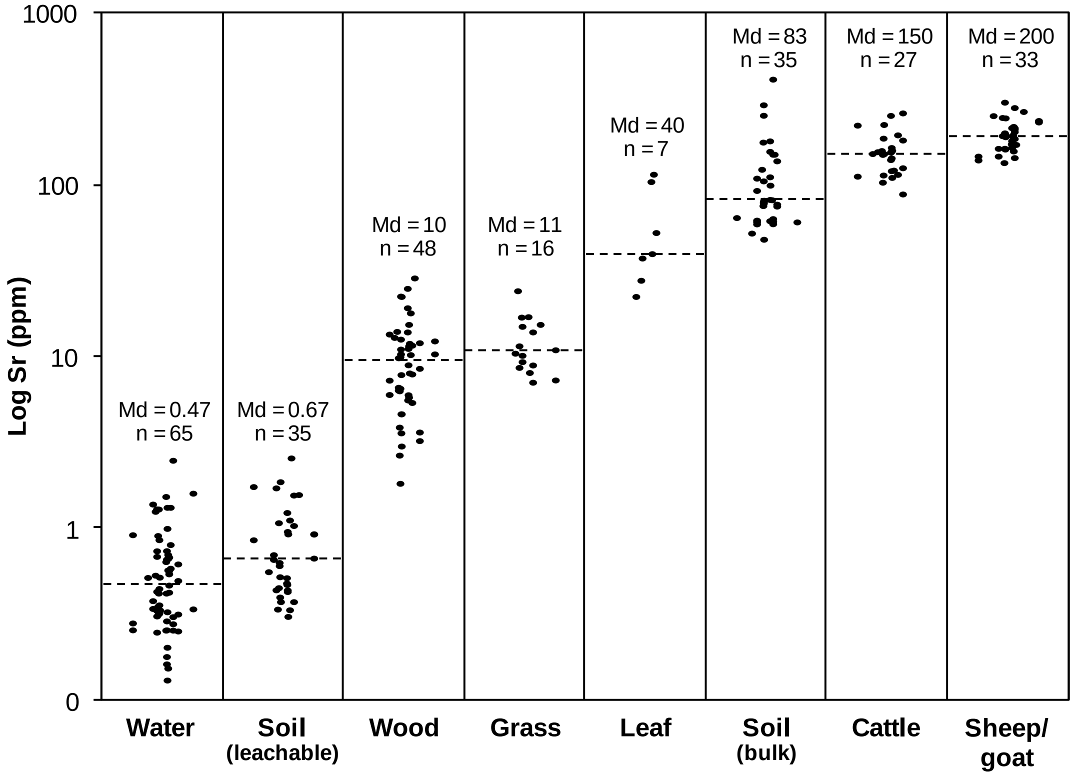


Figure shows the median (Md) concentration of strontium (2 s.f.) found in various sample media documented in Appendix C (dashed lines), and the number of samples within each class (n): Water = mg/l (Table C 02); Soil = mg/kg (leachable) (Table C 03); Wood = mg/kg (Tables C 01 and C 05); Grass = mg/kg (Tables C 04 and C 06); Leaf = mg/kg (Table C 01); Cattle = µg/g (Table C 09): Sheep/goat = µg/g (Table C 09). Where multiple biosphere samples are available from the same location (i.e. field duplicates) the mean value has been used, as has the mean for replicate analyses (i.e. replicates A and B). Mean concentration has also been used for all duplicate samples of cattle enamel, but bulk samples of enamel (cattle and sheep/goat) are excluded. For clarity, data have been jittered and are shown on a Log scale.

Figure 7.05: Individual value plot comparing the concentration of strontium in modern sample media – Water < Soil (leachable) << Wood < Grass < Leaf << Soil (leachable) – with that in archaeological cattle and sheep/goat dental enamel.

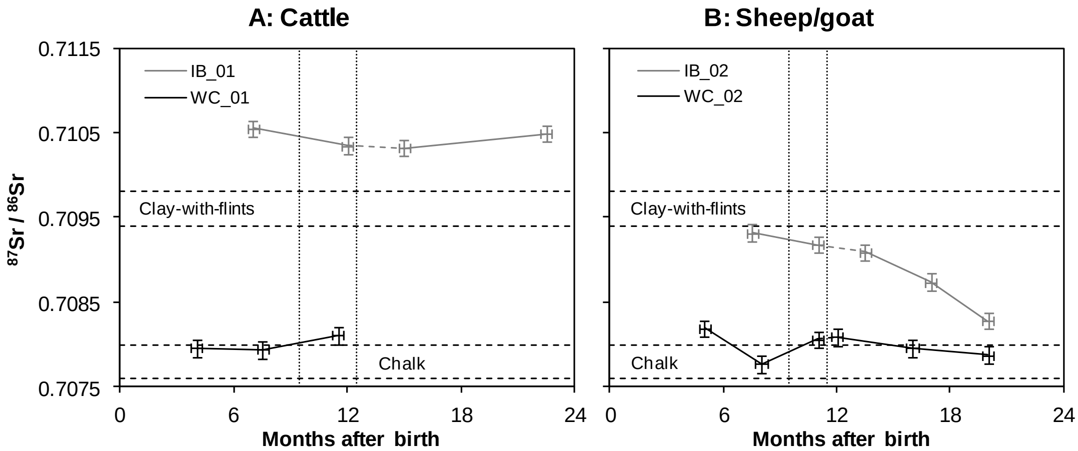
The relationship between ambient biosphere strontium concentrations, the bulk strontium content of the diet of an individual animal, and the strontium concentrations seen in dental enamel are poorly understood. As observed by Montgomery *et al.* (2007), the transfer of strontium through the food-chain is affected by *"…complex synergisms and antagonisms with other dietary components such as Ca, fibre and protein…"* (Montgomery *et al*. 2007: 1509). For example, even at the base of the food-chain, the uptake of strontium by plants may be inhibited by high levels of calcium and magnesium (Kabata-Pendias and Pendias 2001: 126–128). Accordingly, at present it is not clear whether the changes in concentrations seen in high crowned teeth relate to changes in the strontium content of the diet, the Sr/Ca composition of the diet, fundamental changes in the composition of the diet related to the grazing regime, or physiological changes due to growth and development (Montgomery 2010). However, the $^{87}Sr/^{86}Sr$ composition of dental enamel relates to the geographic provenance of dietary strontium, and can be interpreted in relation to biosphere survey data.

Figures 7.06–7.08 (Sections 7.4.1–7.4.3), show the serial enamel data from each site (Tables 7.03 and 7.04) plotted on a consistent time-related axis. Each point displays an error of ± 0.3 months, equivalent to the ≈ 2 mm height of each sample (Chapter 3). However, the apparent time of formation represents a gross approximation undertaken as a scaling exercise, and does not necessarily reflect the time taken for the enamel to form (Chapter 3). Horizontal reference lines relate to the range of $^{87}Sr/^{86}Sr$ values provided by biosphere survey data (vegetation) reported in Chapter 4, appropriate to the location of each archaeological site. Vertical reference lines indicate the degree of overlap between the second and third molar crowns. Thses data from the basis of the discussion which follows (Section 7.5)

7.4.1 Ivinghoe Beacon and Ward's Coombe

In the escarpment zone to the SW of both sites, vegetation samples collected above the Chalk *sensu stricto* have returned $^{87}Sr/^{86}Sr$ values of 0.7076–0.7080, and those influenced by the Clay-with-flints 0.7094–0.7098 (Chapter 4). Faunal $^{87}Sr/^{86}Sr$ data associated with the exploitation of the Chalk plateau can be expected to reflect dietary inputs from each of these two principal soil-forming environments. At a wider geographic scale vegetation samples collected above the Chalk *sensu stricto* (Table 5.06) provide $^{87}Sr/^{86}Sr$ values of 0.7075–0.7088, with a mean of 0.7080 (n = 14); samples collected above the Upper Greensand and Gault, below the Chalk escarpment, provide an overlapping $^{87}Sr/^{86}Sr$ biosphere range (0.7079–0.7084), suggesting that the adjacent geological division of the biosphere may be isotopically indistinguishable from the Chalk biosphere domain *sensu stricto* (Chapter 4).

The cattle enamel from Ivinghoe Beacon (IB_01) ranges in $^{87}Sr/^{86}Sr$ composition from 0.7103–0.7106 (Figure 7.06). However, the sheep/goat enamel (IB_02) from the same site is significantly less radiogenic and shows a distinctive gradual decline in $^{87}Sr/^{86}Sr$ composition from 0.7093–0.7083 in the direction of crown growth (Figure 7.03). Moreover, the linear relationship between $^{87}Sr/^{86}Sr$ and 1/Sr suggests that this pattern may be controlled by a long-term dilution or averaging process (Montgomery *et al.* 2010). The $^{87}Sr/^{86}Sr$ composition of the latest forming enamel from IB_02 is similar to the range of sheep/goat values from Ward's Coombe, both in terms of strontium concentration and $^{87}Sr/^{86}Sr$ composition (Tables 7.03 and 7.04). The mean $^{87}Sr/^{86}Sr$ composition of each cattle and sheep/goat crown from Ward's Coombe is 0.7080: these are the lowest reported averages.



Vertical reference lines indicate the degree of overlap between the record provided by the earlier forming second molar and the later forming third molar; horizontal reference lines represent the range of $^{87}Sr/^{86}Sr$ values measured in vegetation (Wood) collected above Chalk (0.7076–0.7080) and the Clay-with-flints (0.7094–0.7098) in the Chalk escarpment zone, reported in Chapters 4 and 5. Error bars in the x-axis represent the equivalent of the ≈ 2 mm height of each sample; y-axis error bars represent the ± 0.014 % sampling error estimated using duplicate samples (Chapter 3).

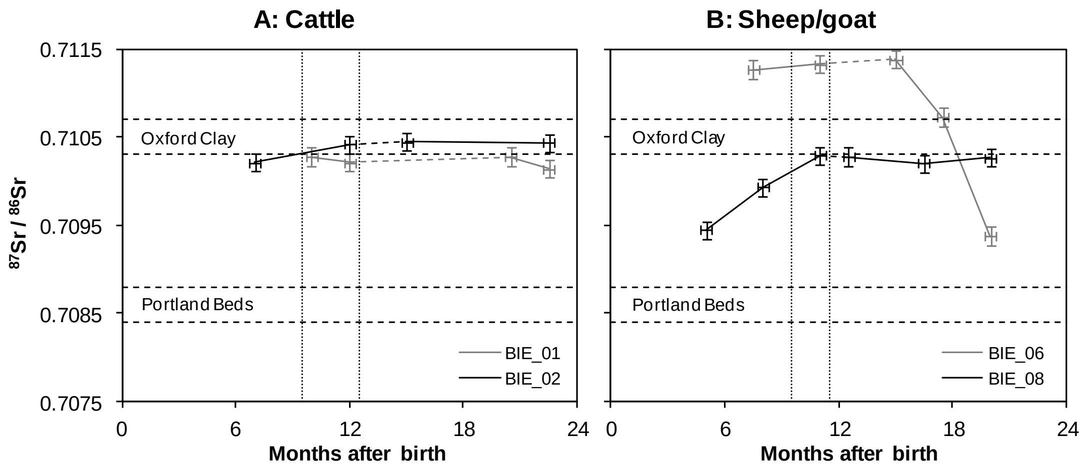
Figure 7.06: Line charts showing $^{87}Sr/^{86}Sr$ composition of serial enamel samples from (A) cattle, and (B) sheep/goat teeth obtained from Ivinghoe Beacon and Ward's Coombe, plotted on common developmental timeline.

7.4.2 *Bierton Vicarage Garden*

The settlement at Bierton is located on an island-like outcrop of the Portland and Purbeck formations; vegetation samples collected above these calcareous strata have provided $^{87}Sr/^{86}Sr$ values of 0.7084–0.7088 (Chapters 4 and 5). Locally, these rocks are preceded in the geological column by an extensive outcrop of the Kimmeridge Clay. The accepted interpretation of economic activity at the site emphasises the exploitation of heavy soils developed in these organic-rich mudrocks (Cunliffe 2005: 431). However, the available biosphere data associated with Kimmeridgian strata (Chapter 4) were obtained to the SE of Bierton, amongst some of the largest outcrops of the Portland Beds in England; the $^{87}Sr/^{86}Sr$ composition of vegetation ranges from 0.7087–0.7091. Potentially, locally grazed livestock could provide a more accurate indication of the $^{87}Sr/^{86}Sr$ biosphere range associated with the local mudrocks than these data, which may be disproportionately influenced by carbonate weathering from the superior calcareous rock formations.

Sheep/goat BIE_06 provides the greatest range of $^{87}Sr/^{86}Sr$ values associated with any one individual (Tables 7.03 and 7.04). In developmental order, the first three samples – across the second and the third molar crowns – are similar to one another and provide a mean $^{87}Sr/^{86}Sr$ value of 0.7113; the final two samples from the second molar crown record a steep drop in composition from 0.7107–0.7094 (Figure 7.07, overleaf). The composition of the latest forming sample is much closer to that of the earliest forming enamel from sheep/goat BIE_08. However, BIE_08 increases steeply in composition from the cusp (0.7095) to the cervix (0.7103) of the second molar crown, so that the final four samples appear to stabilise around a mean $^{87}Sr/^{86}Sr$ value 0.7103. There is no consistent relationship between $^{87}Sr/^{86}Sr$ and strontium concentration in the enamel from either sheep/goat.

The recovery of similar time-related data from the cattle from Bierton Vicarage Garden was hampered by dental attrition. Overall, BIE_01 and BIE_02 show very little variation in $^{87}Sr/^{86}Sr$ composition. The majority of the samples from BIE_02 are of a slightly higher $^{87}Sr/^{86}Sr$ composition than those from BIE_01, and this is reflected in the average $^{87}Sr/^{86}Sr$ composition of each tooth (Table 7.04). However, due to the advanced state of wear presented by BIE_01, it may not be appropriate to make a direct comparison on this basis. Nonetheless, the data suggest a range of typical local values for this site of between 0.7102–0.7104. Although this is not sufficient to explain the level of variation observed in sheep/goat enamel, the plateau-like sequence four samples from BIE_08 fall within a similar range (Figure 7.07).



Vertical reference lines indicate the degree of overlap between the record provided by the earlier forming second molar and the later forming third molar; horizontal reference lines represent the range of $^{87}Sr/^{86}Sr$ values measured in vegetation (Wood) collected above the Portland and Purbeck beds (0.7084–0.7088) and the Peterborough member of the Oxford Clay (0.7103–0.7107), reported in Chapter 4. Error bars in the x-axis represent the equivalent of the ≈ 2 mm height of each sample; y-axis error bars represent the ± 0.014 % sampling error estimated using duplicate samples (Chapter 3).

Figure 7.07: Line charts showing $^{87}Sr/^{86}Sr$ composition of serial enamel samples from (A) cattle, and (B) sheep/goat teeth obtained from Bierton Vicarage Garden, plotted on common developmental timeline.

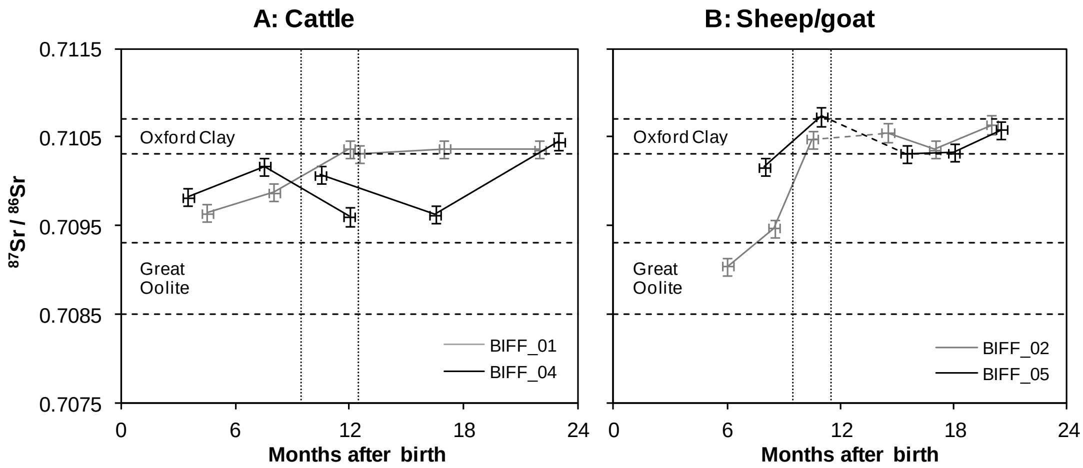
7.4.3 Bicester Fields Farm

Bicester Fields Farm is located above a narrow outcrop of a mudrocks (Kellaways Beds), which lie between the limestone Cornbrash formation of the Great Oolite Group to NW and the Peterborough member of the Oxford Clay to the SE. This position provides immediate access to well drained, though droughty calcareous soils (above the limestones) and fertile pasture, subject to seasonal waterlogging (above the Oxford Clay). Within Chapter 4 a significant contrast was detected between the range of $^{87}Sr/^{86}Sr$ values associated with vegetation collected above the Great Oolite group (0.7085–

0.7093) and those samples from high in the catchments supported by the Peterborough member of the Oxford Clay (0.7103–0.7107). Samples collected at locations lower in the catchments (Chapter 4) returned intermediate values (0.7092–0.7101), presumably reflecting the integration of material weathered from the wider area, incorporating the Great Oolite and calcareous members of the Oxford Clay.

The $^{87}Sr/^{86}Sr$ composition of the teeth provided by the two cattle, – BIFF_01 and BIFF_02 – both vary within a comparable range of $^{87}Sr/^{86}Sr$ values (Figure 7.08, overleaf), consistent with the anticipated local biosphere range. The pattern of variation across BIFF_01 is relatively simple: there is a consistent, upward trend in $^{87}Sr/^{86}Sr$ composition throughout the crown of the second molar to a value that is indistinguishable from the measured bulk composition of the third molar crown (Table 7.04). There is no evidence of significant variation in the third molar. In contrast, the weighted means of the second (0.7099) and third molar (0.7101) of BIFF_02 are very similar to one another, but result from a distinctive sinusoidal pattern of variation, which takes place across both crowns.

The teeth provided by sheep/goat BIFF_02 and BIFF_05 both show a complex pattern of $^{87}Sr/^{86}Sr$ variation (Figure 7.08). Due to the earlier age at death of BIFF_02 (Table 7.02), the second and third molar crowns from this individual provide a slightly longer record of the lifetime of enamel formation. Accordingly, although the weighted means of the two second molars are different from one another (Table 7.04) it is not possible to determine whether or not this is a result of the loss of enamel in the older animal (BIFF_05) through dental attrition. In comparison, the weighted mean $^{87}Sr/^{86}Sr$ compositions of both sheep/goat third molars are very similar to one another – 0.7105 and 0.7104, respectively – and resemble the highest values achieved in the cattle enamel from the same archaeological site.



Vertical reference lines indicate the degree of overlap between the record provided by the earlier forming second molar and the later forming third molar; horizontal reference lines represent the range of $^{87}Sr/^{86}Sr$ values measured in vegetation samples (Wood) collected above the limestones of the Great Oolite group (0.7085–0.7093) and the Peterborough member of the Oxford Clay (0.7103–0.7107), reported in Chapter 4. Error bars in the x-axis represent the equivalent of the ≈ 2 mm height of each sample; y-axis error bars represent the ± 0.014 % sampling error estimated using duplicate samples (Chapter 3).

Figure 7.08: Line charts showing $^{87}Sr/^{86}Sr$ composition of serial enamel samples from (A) cattle, and (B) sheep/goat teeth from Bicester Fields Farm, plotted on common developmental timeline.

7.5 Discussion

Recent work indicates that gross developmental patterns do not accurately represent the progress of mineralisation within the enamel crowns of hypsodont teeth (Montgomery *et al.* 2010). As strontium is incorporated during a protracted period of enamel maturation, it may be more accurate to treat each sample as an artificial subdivision of a smoothed record of continuous isotopic variation; that is, a moving average rather than a discrete time-slice. Accordingly, excursions between geological subdivisions of the biosphere may only be detectable if sufficient time passed for an animal to begin to equilibrate with a sufficiently contrasting $^{87}Sr/^{86}Sr$ biosphere range. Nonetheless, if livestock movements were strictly controlled, systematic management of grazing and fodder production could potentially result in significant shifts in the $^{87}Sr/^{86}Sr$ composition dietary inputs.

At present there is no experimental data available to illustrate how an abrupt change in the dietary strontium isotope composition is manifested in the composition of a given crown. However, a model of variation in sheep/goat enamel presented by Meiggs (2007) suggests that any given measurement is likely to represent a mixture of: 1) dietary inputs obtained during crown formation; 2) strontium buffered within the animals own somatic pool. Thus, even if the maxima and minima within a time-series represent the highest and the lowest $^{87}Sr/^{86}Sr$ compositions achieved in the labile pool available to the developing tooth, they may not directly represent the composition of the diet at a given time. Accordingly, only the plateau-like portions of a developmental sequence have the potential to provide a reliable indication of average dietary input.

- **Do plateau-like series provide an accurate indication of the average composition of a diet?**

Most of the enamel series contain measurable differences in $^{87}Sr/^{86}Sr$ composition between at least two data-points, even when a sampling error of ± 0.014 % is applied (Chapter 3). Whilst substantial variations are likely to represent the influence of at least two distinctive biosphere end-members, even subtle shifts could represent an excursion between contrasting biosphere domains. Equally, it is not possible to be sure whether the apparent stability in some records results from the exploitation of one homogeneous resource, the homogenisation of varied inputs at the dietary level, or smoothing brought about by sampling enamel that matured over an extended period.

Accordingly, the difference between the plateau-like series provided by the cattle third molar of BIFF_01 and the sinusoidal pattern provided by sheep/goat BIFF_05 (Figure 7.08) may not be as distinctive as it first appears. All three, average crown compositions (Tables 7.03 and 7.04) fall into a range that could be attributed to the Peterborough member of the Oxford Clay, which lies immediately adjacent to the site from which this material was recovered (Figure 7.01). Alternatively, both patterns may represent the effect of mixing resources from divergent biosphere domains associated with contrasting bioavailable $^{87}Sr/^{86}Sr$ values. Any interpretation of these data, in terms of landscape use, rests on assumptions regarding the likely local origin of the animals.

The data provided by cattle enamel from Ivinghoe Beacon (IB_01) contrast with the likely local sources (Figure 7.06). The data from Ward's Coombe (WC_01 and WC_02) provide examples of what might be predicted; the crowns show some degree of variation, but the highest values are only moderately elevated above the $^{87}Sr/^{86}Sr$ range indicated by vegetation collected above the Chalk of the escarpment zone (Figure 7.06). Considering the trend shown by sheep/goat mandible IB_02, these data could be explained by grazing regimes that shifted, between the Clay-with-flints and the Chalk *sensu stricto.* Nonetheless, the scale of landscape use, or the trade and exchange networks required to encompass areas beyond the Chalk capable of achieving higher biosphere $^{87}Sr/^{86}Sr$ values consistent with those reported for IB_01 or IB_02, are relatively modest.

The $^{87}Sr/^{86}Sr$ compositions of the cattle from Ivinghoe Beacon (Figure 7.06) are similar to a substantial proportion of the faunal data from Bicester Fields Farm (Figure 7.07) and Bierton Vicarage Garden (7.08). This highlights a significant issue regarding the definition of local $^{87}Sr/^{86}Sr$ ranges and the extent to which they are likely to be geographically unique. That is, values obtained from vegetation collected from the Peterborough member of the Oxford Clay near Bicester may be applicable to the whole outcrop (Chapter 4), but different formations comprising similar facies might also be capable of providing similar biosphere $^{87}Sr/^{86}Sr$ values. It is cannot be assumed that the biosphere range associated with the Peterborough member of the Oxford Clay is unique.

- **Do outlying values indicate the exclusive influence of a distinctive division of local biosphere or large scale geographic movement?**

Although the similarity between the cattle from Bierton Vicarage Garden and the plateau-like portion of the record from the sheep/goat mandible BIE_08 (Figure 7.07) suggests the influence of a biosphere end-member capable of providing strontium with a $^{87}Sr/^{86}Sr$ composition ≥ 0.7104, it is not necessarily legitimate to attribute these values solely to influence of the Oxford Clay. They may indicate the presence of a similar local source with a significant contrast to the expected range associated with the calcareous strata of the Portland and Purbeck Beds (possibly the Kimmeridge Clay vale surrounding Aylesbury). Although sheep/goat BIE_06 indicates the influence of a distinctive, radiogenic biosphere end-member, the $^{87}Sr/^{86}Sr$ values appear to be too high for a local origin to be likely.

Compared to all other animals within this study, and biosphere data reported in Chapters 4 and 5, the $^{87}Sr/^{86}Sr$ values of around 0.7113 provided by sheep/goat BIE_06 are exceptional. The nearest regions of the British Isles to consistently return biosphere $^{87}Sr/^{86}Sr$ values in this range are those areas of the West Midlands underlain by the Carboniferous Coal Measures (Evans *et al.* 2010a); further afield, similar biosphere values have been reported in Devon, Somerset, the Malvern Hills, Derbyshire, Cheshire, Wales, the Lake District and some parts of Scotland. These are all areas underlain either by evolved granitic rocks and gneisses, or siliceous mudstones and sandstones derived from parent materials of considerable geological age.

In central England, bulk enamel $^{87}Sr/^{86}Sr$ values have been reported from Anglo-Saxon sheep/goat and cattle teeth of 0.7112 and 0.7113 respectively (Evans and Tatham 2004). These individuals are thought to represent part of 'local' rural herds grazed within the clay/carbonate terrain of central England. However, there is no independent environmental evidence that biosphere $^{87}Sr/^{86}Sr$ values substantially in excess of 0.7110 are closely associated with recent Mesozoic sediments (Evans *et al.* 2010b). Where serial data are available from one cattle tooth recovered in the same region (Evans *et al.* 2007), the data show a steep decline in strontium concentration and $^{87}Sr/^{86}Sr$ (from 0.7115–0.7106) in the direction of growth; this could be consistent with the import of an animal from a more radiogenic terrain.

The second molar from sheep/goat mandible BIE_06 records a dramatic decline in $^{87}Sr/^{86}Sr$ composition, into a range that could be accommodated locally (Figure 7.06). The timing of this change suggests that a dramatic shift in the composition of dietary inputs took place at some point soon after the animal's first year of independent life. The timing of this change is not consistent with other sheep/goat crowns within this study, which provide $^{87}Sr/^{86}Sr$ compositions consistent with the highest biosphere values obtained from Jurassic mudrocks (Chapter 5). These animals show an increasing trend in $^{87}Sr/^{86}Sr$ composition throughout the earlier forming crown of second molar.

- **To what extent do time-related directional trends provide evidence of the influence of distinctive domains?**

Due to a relatively early age at death, BIFF_04 provides the longest continuous record for any one animal in this study (Table 7.03). The data suggest that a change in dietary inputs can result in substantial, cyclic variation in a single crown with an apparent frequency of ≤ 1 year (Figure 7.08). There is no clear relationship with strontium concentration, and the overlap between the two teeth indicates that this is not a diagenetic artefact. However, although the latest forming enamel excised from the cervix of the third molar crown has a $^{87}Sr/^{86}Sr$ composition (0.7105) that falls within range of the vegetation samples from the Peterborough member of the Oxford Clay, the lowest values are significantly in higher than the highest biosphere values associated locally with the Great Oolite group (Chapter 4).

On a case-by-case basis, it is not clear that any one of the measurements from any animal from Bicester Fields Farm relates to the influence of a single $^{87}Sr/^{86}Sr$ biosphere domain. Each value could represent a mixture of strontium derived from at least two different sources. Nonetheless, the pronounced sinusoidal pattern across BIFF_04 is very different to that provided by BIFF_01 (Figure 7.08). The differences in the patterns could indicate the use of the two animals for different purposes. On the basis of tooth-wear, BIFF_01 falls into the 'Adult' cattle age category whereas BIFF_04 may have been slaughtered at an age optimised for meat yield (Table 7.02). If this is the case, the data suggest that livestock management decisions were made before the end of the first year of life of each individual, and more than a year in advance of slaughter.

If it is legitimate to treat all of the animals from Bicester Fields Farm as a coherent local group, the data may be consistent with livestock movement between the same two geological domains, possibly as a result of seasonal changes in grazing regime and/or fodder procurement. Each animal provides evidence of an increase in $^{87}Sr/^{86}Sr$ composition within the first molar, which might suggest that – early in the first year of independent life – the focus changed from a free-draining, carbonate terrain to the low lying mudrocks. Possibly, if animals were born early spring, this may represent a need to avoid poorly-draining mudrocks during the wettest times of year. Alternatively, if lambs and calves were kept closer to the settlement site during the first weeks or months of life, this could have the same effect.

The record of variation within sheep/goat BIE_08, from Bierton Vicarage Garden also shows an increase in $^{87}Sr/^{86}Sr$ composition through the first year of enamel formation until a level is reached, similar to that provided by cattle teeth from the same site (Figure 7.07). If this general observation is accurate as regards the management of animals within this region, it could support an argument that BIE_06 represents an imported animal. Although the latest forming enamel sample from the third molar (BIE_06_M3_C) does not fall within range of vegetation collected above the Portland Beds (Chapter 4), the composition of dietary inputs must have been ≤ 0.7094. This animal may have been brought to Bierton after its first year of life and then grazed close to the settlement rather than with the livestock of local origin. Although the estimated age at death of this individual is only 4–6 years (Table 7.02), this makes it one of the oldest animals included in the current study. Accordingly, the pattern may still be consistent with that of a male animal imported as breeding stock.

7.6 Conclusions

The low resolution, macroscopic sampling methods used in this study provide more reliable local environmental data than bulk crown samples. Although patterns of individual $^{87}Sr/^{86}Sr$ variation have the potential to elucidate local biosphere values, bulk crown compositions are misleading. Bulk values will decrease the range of apparent variation associated with an faunal assemblage but, depending on the characteristics of the local biosphere and livestock management strategies, dental wear and tooth loss could bias averages towards higher or lower $^{87}Sr/^{86}Sr$ values, and either increase or decrease the degree of scatter in a data-set. It is not acceptable that individual age-at-death should be allowed to have such a profound influence on baseline data-sets.

While plateau-like enamel series may give an indication of average dietary inputs, longer-term directional trends provide evidence of the influence of more than one isotopically distinctive division of the biosphere. These may even have functioned as discrete end-members, providing average dietary values equal to or lower than the minimum values measured in dental enamel and *vice versa.* Unusual patterns of variation may indicate either that an individual animal was managed in a specific manner, or that it may have originated within a different geological terrain to other specimens from the same site or region. Biosphere surveys of the modern environment allow these data to be plotted on an appropriate scale and will be indispensible in understating the potential geographic significance of such patterns. Where unusual patterns are associated with extreme $^{87}Sr/^{86}Sr$ values these can be legitimately excluded from baseline data-sets. There is no evidence that the long-term processes involved in the formation of dental enamel (Montgomery *et al.* 2010) and dietary temporal averaging (Price *et al.* 2002), obviate the need for high-density biosphere $^{87}Sr/^{86}Sr$ survey data.

In this study the first three samples out of five from the teeth obtained from one sheep/goat mandible (BIE_06) returned $^{87}Sr/^{86}Sr$ values 0.7113–

0.7114, which are substantially in excess of the anticipated local biosphere range. The remaining $^{87}Sr/^{86}Sr$ values in sheep/goat teeth ranged from 0.7078–0.7107 and from 0.7079–0.7106 in those of cattle. The lowest average values were obtained from mandibles recovered from the Cretaceous Chalk escarpment zone, and the highest from those sites located in positions adjacent to Jurassic mudrocks. Although these biosphere $^{87}Sr/^{86}Sr$ values are not unique to the study area, they accord well with the regional biosphere characteristics indicated by modern vegetation and stream water samples (Chapter 4). The high crowned teeth of domestic livestock show considerable potential to provide information regarding the scale and variety of the landscape zones used by the groups that managed them.