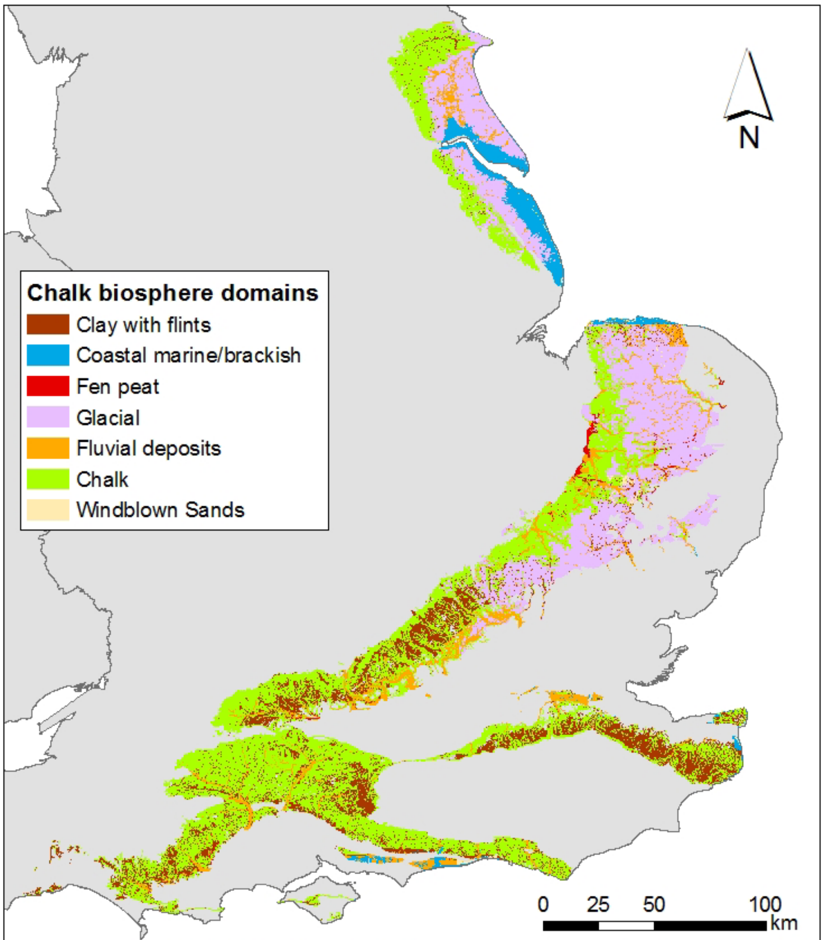
CHAPTER 9

CONCLUSIONS

This research project set out to examine the extent to which patterns of geographic biosphere $^{87}Sr/^{86}Sr$ variation above sedimentary Mesozoic rocks within the lowland zone of England can be spatially resolved. It has been shown that, even in the absence of extreme geological contrasts related geological formations can be grouped into isotopically coherent and topographically distinct biosphere packages. The ranges of values obtained from vegetation and stream waters accord well with archaeological values obtained from domestic livestock (Chapter 7) and with previously published data from the UK (Evans *et al.* 2010). This work has revealed the mosaic-like qualities of biosphere $^{87}Sr/^{86}Sr$ variation within the lowland landscape. This comprises multiple biosphere domains, which are associated with relatively narrow ranges of $^{87}Sr/^{86}Sr$ values. These are not necessarily geographically unique and in some cases overlap with one another, but there are also significant contrasts between some contiguous units.

Important refinements have been made to the current model of biosphere $^{87}Sr/^{87}Sr$ variation above the Cretaceous Chalk outcrops of southern and eastern England (Figure 9.01, overleaf). Although these formations represent a rich source of isotopically well-constrained strontium, the geological $^{87}Sr/^{86}Sr$ range is generally a poor predictor of local biosphere values. Low density data collected above Jurassic and Cretaceous strata show that the interpretive significance of the Chalk as a biosphere package lies in the spatial properties of the exposed outcrops as much as their mineralogical composition. In this context it is important to differentiate between the level of biosphere variation observed above the Chalk *sensu lato* and the Chalk *sensu stricto*. The former, represents an extensive biosphere package defined by the limits of the Chalk outcrop, while the latter refers to those areas where either the Chalk itself or locally-derived chalky drift deposits support the principal soil-resource.

On this basis the biosphere data reported in this thesis, the $^{87}Sr/^{86}Sr$ composition of a population can be understood in terms of the exploitation of multiple geological divisions of the biosphere, possibly with contrasting resource potential. That is, as much as the movement of people and animals between geographically distant locations may influence the range of $^{87}Sr/^{86}Sr$ values found in archaeological skeletal assemblages, so to can patterns of local landscape use. In order to formulate robust and testable archaeological hypotheses, it is vital to understand the character of biosphere $^{87}Sr/^{86}Sr$ variation at an appropriate geographic scale.



87Sr/86Sr	Biosphere domains	Area (sq km)	Area (%)
0.7094 - 0.7098	Clay with flints	2903	14.9
0.7091 - 0.7099	Coastal marine/brackish	812	4.2
0.7085 - 0.7092	Fen peat	96	0.5
0.7083 - 0.7099	Glacial	5071	26.1
0.7078 - 0.7085	Fluvial deposits	1718	8.8
0.7075 - 0.7088	Chalk	8761	45.1
n/a	Wind-blown sands	78	0.4
	Total	*19439*	

Figure 9.01: Map showing a generalised scheme of $^{87}Sr/^{86}Sr$ variation within the Chalk biosphere package *sensu lato.*

9.1 Findings summarised with reference to original aims

Aim 1: **To identify the most appropriate sampling and analytical techniques for biosphere $^{87}Sr/^{86}Sr$ characterisation and mapping.**

- Within the range of biosphere $^{87}Sr/^{86}Sr$ values reported in this thesis replicate analysis of NIST Standard Reference Material 1515 (Apple leaves), indicates that well homogenised vegetation samples can be analysed with sufficient precision to resolve site-by-site differences in $^{87}Sr/^{86}Sr$ composition of approximately 0.0001 (Chapter 3).
- Under appropriate conditions, vegetation and stream water can be used interoperably to characterise biosphere $^{87}Sr/^{86}Sr$ values (Chapter 4).
- The outer surfaces of plant foliage are exposed directly to the effects of atmospheric deposition, but the comparison of wood and unwashed leaf material indicates that no method-bias is introduced by measuring wood alone (Chapter 6).
- The methods designed to assess the bioavailability of trace-elements in soils can produce internally consistent, but procedurally-defined ranges of $^{87}Sr/^{86}Sr$ values. These may be numerically off-set from stream water and vegetation (Chapter 4). Thus, soil samples should be avoided for general biosphere mapping and characterisation.
- Serial analysis of the enamel of the high-crowned teeth of archaeological domestic livestock may help elucidate the range of biosphere $^{87}Sr/^{86}Sr$ variation within the pastoral landscape used by past populations, but the bulk samples may be misleading with respect to ‘average’ biosphere values (Chapter 7).

Aim 2: **To assess the benefits of using high-density and low density sampling methods to characterise geographic biosphere $^{87}Sr/^{86}Sr$ variation.**

- Within the lowland zone of England, low density sample collection allows accurate but imprecise generalised regional biosphere $^{87}Sr/^{86}Sr$ ranges to be estimated across large geographic areas of the UK, but does not allow local detail to be resolved (Chapter 4).
- Regional ranges of biosphere $^{87}Sr/^{86}Sr$ values, predicted on the basis of underlying geology can be resolved into smaller sub-

domains, mapped in relation to underlying geology registered at a scale of 1:50000 (Chapter 3).

- There is no evidence that biosphere $^{87}Sr/^{86}Sr$ variation above the Chalk *sensu stricto* is scale-dependent (Chapter 5).

Aim 3: **To evaluate the influence of weathering, erosion, and sediment transport mechanisms on patterns of biosphere $^{87}Sr/^{86}Sr$ variation related to underlying geology.**

- The complex tributaries of the upper Thames integrate sediments derived from a range of geological end-members, leading to a muting of otherwise potentially distinctive biosphere $^{87}Sr/^{86}Sr$ characteristics associated with underlying solid geology (Chapter 3); thus, large river valley systems and alluvial plains should be treated as distinct biosphere domains.
- There is no evidence that glacial transport has resulted in a range of radiogenic biosphere $^{87}Sr/^{86}Sr$ values that can be distinguished from those associated with regionally important Mesozoic sedimentary strata (Chapter 4).
- Intensive, *in situ* periglacial weathering has resulted in the formation of a distinctive, but discontinuous biosphere domain, superimposed above the Chalk, in the form of the Clay-with-flints (Chapter 4).
- Extensive post-glacial fluvial and marine sedimentation in the Fenland Basin of eastern England has disconnected this region from the direct influence of underlying geology (Chapter 4).

Aim 4: **To evaluate the potential influence of atmospheric transport on patterns of biosphere $^{87}Sr/^{86}Sr$ variation.**

- Under normal conditions dried down salts and other atmospherically deposited aerosols inadvertently consumed with plant material are unlikely to make an isotopically distinctive contribution to dietary inputs of strontium (Chapter 6).
- Atmospheric deposits become rapidly de-focused from a seawater $^{87}Sr/^{86}Sr$ signature as air-masses move inland, potentially under different regional terrestrial influences (Chapter 6).
- In inland areas, although the $^{87}Sr/^{86}Sr$ composition of atmospheric inputs may be stable in the short term (i.e. weeks), over the course of a year the precipitation may be at least as variable month-by-month as any one geological division of the biosphere (Chapter 6).

- It is not appropriate to attribute a blanket marine signature to atmospheric inputs across the UK, making it difficult to define distinctive atmospheric end-member in low-rainfall areas that are not exposed directly to westerly, Atlantic weather systems and affected by orographic precipitation (Chapter 6).

Aim 5: **To understand the implications of modern patterns of biosphere $^{87}Sr/^{86}Sr$ variation for the interpretation of archaeological human and faunal data.**

- Due to the mosaic-like quality of biosphere variation within lowland England, time-related change in the $^{87}Sr/^{86}Sr$ composition of the enamel of the high-crowned teeth individual archaeological sheep and cattle can potentially be interpreted in terms of local livestock management regimes (Chapter 7).
- It is proposed that a significant component of the variation in a local human population is influenced by the averaging of multiple, independent biosphere distributions (Chapter 8).
- It is legitimate to attempt to estimate a local $^{87}Sr/^{86}Sr$ range for a given archaeological skeletal assemblage, but only on the basis of explicit assumptions regarding the character and geographical extent of the local resource base (Chapter 8).
- The Clay-with-flints deposits extend the range of local values associated with subsistence above the Chalk. Individuals providing $^{87}Sr/^{86}Sr$ values that fall well within the range of values detected above the Chalk *sensu stricto*, may indicate the exploitation of a geographically restricted resource-base, focused on the areas that are free of de-calcified Pleistocene deposits, or areas where there is active physical erosion of the Chalk, such as the escarpment zone (Chapter 5).

9.2 Limitations

Within this thesis the research aims have been addressed (see Section 9.2), using sample media that can be collected routinely as part of a systematic environmental survey, using protocols designed to avoid the direct influence of anthropogenic inputs, such as fertilizers and industrial waste, primarily by careful site selection. In this way, the influence of these factors has been minimised, but not necessarily eliminated. Although it is unlikely that the patterns of systematic biosphere $^{87}Sr/^{86}Sr$ variation reported within this thesis are driven by differences in exogenous inputs, the influence of agricultural practices on biosphere $^{87}Sr/^{86}Sr$ variation certainly warrants further investigation.

It has been found that in a mature, temperate lowland terrain, stream water samples collected from small simple catchment systems resemble vegetation $^{87}Sr/^{86}Sr$ ranges very closely (Chapter 4). Within the current research, vegetation and stream water have been used interoperably as biosphere proxies. However, it has also been shown that in the lowland zone, wet deposits may represent a regional homogenizing influence on biosphere $^{87}Sr/^{86}Sr$ values, rather than a distinctive biosphere end-member. Accordingly, under contrasting environmental conditions – for example, upland areas where high rainfall, and low levels of water-rock interaction lead to a pronounced dilution effect in stream waters (e.g. Shand *et al.* 2007) – this pattern may need to be reassessed.

It has not been possible to compare a large number of faunal samples for the selected archaeological sites reported in Chapter 7, but the ranges of values are consistent with those obtained from modern sample media and can potentially be interpreted in terms of locally managed seasonal livestock movement. However, it was not possible to compare contemporary archaeological human and faunal assemblages from the same region, but potentially such a study could be required to confirm the relationship between humans and their livestock.

9.3 Recommendations for techniques of biosphere mapping

Ultimately, biosphere survey is the only way to attach geographic meaning to the ranges of $^{87}Sr/^{86}Sr$ values obtained from any given archaeological skeletal assemblage. Ideally, some form of characterisation study should be built into any project seeking to understand the origin of archaeological $^{87}Sr/^{86}Sr$ values, as an integral part of that work. However, the detail with which it is necessary to characterise biosphere $^{87}Sr/^{86}Sr$ variation will depend substantially on the aims and objectives of the research being undertaken and the nature of the hypotheses that are to be tested using isotope analysis. Demanding high spatial and isotopic precision from a broad, small-scale map would be costly and unproductive. Likewise, low-resolution survey is unlikely ever to provide relevant detail in respect of local variation. Accordingly, it is unrealistic to dictate that sampling should be undertaken always at a specific density.

An extensive, systematic approach to biosphere $^{87}Sr/^{86}Sr$ characterisation is by definition un-targeted. Such data may be amenable to *post hoc* analysis, concerned with finding patterns of variation that would otherwise remain undetected. Such methods may be applicable to the characterisation of ambient variation within an apparently geologically homogeneous biosphere domain, or to the production of much generalised, small-scale maps of biosphere variation suitable for viewing at a national or sub-continental scale. In contrast, an intensive, targeted approach to biosphere survey may be more flexible, and can be used to examine specific patterns of variation derived from basic assumptions regarding the origin of geographic $^{87}Sr/^{86}Sr$ variation. In general terms surveys that are designed to evaluate a proposed model of biosphere $^{87}Sr/^{86}Sr$ variation may be more productive than an extensive, systematic approach that depends on achieving an un-biased sample distribution across a wide area.

When attempting to characterise $^{87}Sr/^{86}Sr$ variation in a ‘new’ study area appropriate consideration must be given to the presence of superficial deposits and their likely origins, as well as to interconnected bio-geographic factors influenced by underlying geology; these include landscape characteristics, such as topography, drainage conditions, and direction of sediment transport. These are crucial in constructing biosphere packages that it may be appropriate to treat as cohesive domains. In any ‘new’ study area, consideration should be given to the collection of a sufficient number of samples to characterise the domain under investigation, informed by the degree of scatter shown in data-sets from comparable regions. Nonetheless, multiple samples are required from different locations in order to understand the character of variation above any given sub-division of the biosphere. A number of choices can be made in respect of the selection of sample media, informed by the findings of this thesis:

Soil sampling

- The $^{87}Sr/^{86}Sr$ composition of the strontium that it is possible to extract from soils is influenced by methods of collection and sample processing, as well as the leaching method used.
- Although internally consistent ranges of $^{87}Sr/^{86}Sr$ values can be generated using soils, these may be offset in respect of the scale of variation and range of values associated with other biosphere proxies.
- Biosphere mapping and characterisation studies should focus on sample media that it is legitimate to subject to bulk analysis rather than procedurally defined values.

Vegetation sampling

- As well as supplying most of the strontium consumed by domestic livestock, plant-based foodstuffs may provide the majority of the strontium in the human diet (Wasserman *et al.* 1977; IAEA 2008).
- Strontium concentrations in foliage are generally higher than in other plant tissues, and under temperate conditions there is no evidence that surface deposits on plant leaves have significant influence on their bulk $^{87}Sr/^{86}Sr$ composition.
- Plant foliage can be collected without specialist training. It can be collected in bulk and requires less protracted preparation than, for example, wood. This potentially allows large, representative composite samples to be prepared from individual sample sites.
- Specific decisions regarding the appropriate type of plant foliage to collect should be made based on prevailing environmental conditions. However, grasses occupy a wide range of ecological niches, are effectively ubiquitous and make a significant contribution to the diet of archaeologically important domestic taxa. On this basis, grasses may represent a useful starting point for the design of future sampling programs.

Water sampling

- In mature, temperate lowland terrain, stream water can be used interoperably with vegetation to characterise biosphere $^{87}Sr/^{86}Sr$ variation.
- It is possible to characterise specific geological formations using small simple stream catchments, but larger and more complex systems have the capacity to integrate a wider range of geological end-members. Thus, special attention should be paid to large river-valley systems and alluvial plains that may encompass variable end members within their sub-catchments.
- Unlike vegetation, the laboratory methods for the preparation of stream water for analysis are very simple. However, a significant investment in staff training and field equipment are needed to maintain high standards of quality control
- The collection of stream waters is subject to methodological constraints with respect to drainage density, which may be affected by underlying geology. This potential source of bias may not be significant in lower-density surveys that operate at a regional or national scale.
- In some regions, it is possible that water and vegetation may represent isotopically distinctive dietary components (cf. Section 9.2). As both surface waters and vegetation feed into the food chain, it is conceivable that in some regions it may be advisable to collect both sample media.

9.4 Implications for future research

It is usually assumed that a given population will achieve a $^{87}Sr/^{86}Sr$ distribution that is characteristic of the geological formations that support its resource-base. However, it is unlikely that the available dietary resources within a given territory will be distributed randomly across that area. Accordingly, even if the local resource-base was constrained within strict geographic limits, there may not be a one-to-one relationship between the area occupied by any one geological domain, and the proportion of strontium supplied to the diet from that area. Moreover, the population $^{87}Sr/^{86}Sr$ distribution will reflect the extent to which any one individual is able to sample all of the available resources in a representative manner, under a given dietary regime. Therefore, depending on the character of geographic variation within any given area, changes in resource exploitation and dietary regime could result in changes the population $^{87}Sr/^{86}Sr$ distribution.

The variation in $^{87}Sr/^{86}Sr$ composition seen in archaeological skeletal assemblages may be driven by the exploitation of a variable landscape, comprising multiple, independent biosphere domains. However, there are many unanswered questions concerning the fundamentals of strontium uptake, from dietary intake to its deposition in mineralising enamel. Under the pattern of variation shown within this thesis, this becomes an extremely important area of research, as the distribution of $^{87}Sr/^{86}Sr$ values in a human population could be biased by use of a dominant geological domain within the wider landscape. For example, if only plant-based food-stuffs substantially influence human $^{87}Sr/^{86}Sr$ compositions, this may restrict the scale of local variation in a sedentary agricultural population. If domestic livestock are grazed and provided with fodder from areas that are not used for crop production, this may also limit the extent to which aggregated faunal data can provide a proxy for human $^{87}Sr/^{86}Sr$ values.

However, the faunal data presented in Chapter 7, derived from serial enamel samples, suggest that an integrated archaeological approach to biosphere characterisation may be possible, based on the integration of isotopic and palaeo-economic, environmental data. Faunal material recovered from occupation sites and/or sites associated with livestock management may help to constrain $^{87}Sr/^{86}Sr$ biosphere variation on a scale commensurate with past landscape use. This level of control may prove crucial to the accurate interpretation of data from sites that represent a major focal point, or ‘central place’ within a landscape, from burial mounds and henge monuments to Iron Age hillforts and oppida, and even early urban centres.

Strontium isotope analysis has been used very successful to identify occasional, non-local individuals within human skeletal assemblages. However, unless only individuals originating within certain geological provinces were mobile, the isotopically local component of a given population is likely to also contain both geographically and geologically non-local individuals. Together with previously published data, the biosphere $^{87}Sr/^{86}Sr$ values reported within this thesis proved a high degree of control on the lower limits of variation in lowland England. In contrast, there is very poor control on the upper limits of biosphere $^{87}Sr/^{86}Sr$ variation, and indeed the patterns of geographic variation in areas underlain by the igneous and metamorphic rocks thought to be responsible for the occurrence of radiogenic values in humans and animals.

Archaeological studies within which $^{87}Sr/^{86}Sr$ analysis can be applied have lead, and are likely to continue to lead, to a focus on areas where preservation conditions mean that skeletal tissue – both human and faunal – can be recovered in quantity and in good condition. On this basis, it is unlikely that archaeological investigations will drive the characterisation of biosphere $^{87}Sr/^{86}Sr$ variation in areas were bone preservation is poor and/or excavation activity is infrequent. However, the advantages offered by isotope methods in general, centre on an ability to place individuals and populations in a bio-geographic context that extends beyond the limits of specific archaeological sites. Thus, without understanding biosphere $^{87}Sr/^{86}Sr$ variation in areas where bone-preservation conditions are poor and excavated archaeological sites are scarce, it is difficult to know how geographically specific radiogenic ranges of biosphere values might be.

An understanding of the processes that lead to local and regional variations in areas of radiogenic terrain is vital to the accurate interpretation of the isotopic characteristics of skeletal assemblages from other areas. This necessarily develops from the use of $^{87}Sr/^{86}Sr$ analysis as an 'exclusive' method. That is, how likely it is that individuals originating in areas underlain by ancient granites and gneisses will be associated with a similar range of $^{87}Sr/^{86}Sr$ values to those individuals from areas underlain by more recent sedimentary formations, especially under the influence of high rainfall conditions and low levels of water-rock interaction. Are radiogenic biosphere

$^{87}Sr/^{86}Sr$ values unusual only regionally, with respect to areas underlain by recent sediments and low Rb/Sr volcanics, nationally, or at an even wider continental scale? There is a pressing need for low-density survey data capable of rendering generalised maps of wider national and continental areas, as well as the reflexive, process-lead localised studies that are necessary to understand local and regional variation.

To date, $^{87}Sr/^{86}Sr$ analysis has generally been applied to test archaeological hypotheses that operate at an inter-regional, national or sub-continental scale. Such studies assume that the resource catchments of individual populations operate at a local or regional scale. That is, large-scale patterns of geographic biosphere variation are used in an attempt to understand distributions thought to result – **by definition** – from the influence of local patterns of biosphere $^{87}Sr/^{86}Sr$ variation. Thus, the spatial scales at which geographic variations in biosphere composition operate are critical to all interpretations of archaeological $^{87}Sr/^{86}Sr$ data. This study has shown the importance of carrying out biosphere measurements if archaeological studies are to achieve their full potential.