Isotope Analysis Report

Report prepared for: Louise Loe, Oxford Archaeology

Isotopes: Strontium, Oxygen, Carbon, Nitrogen, Sulphur

Skeletal material analysed: Sr: Human tooth enamel
O & C: Human tooth enamel, carbonate fraction
C, N & S: Human bone and dentine collagen

Site: **Worthy Down Camp, North Winchester, Hampshire**

Individuals analysed: 6 late Roman humans

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Note: *The "Non-specialist summary of analyses" section of this report is based on a template adjusted to suit the specifics of this particular project. Much of the wording is therefore reproduced for other projects. The section is therefore suitable for unpublished and general reporting, but may require omission or adjustment for full publication.*

Introduction

Six late Roman (mid to late 4th century) individuals from the Worthy Down Camp in north Winchester, Hampshire, were analysed for strontium, oxygen and carbon isotopes from tooth enamel; carbon, nitrogen and sulphur isotopes were also analysed from both rib and tooth crown dentine. The results are compared with other published human and animal data from the region and are discussed with the purpose of identifying the possibility of mobility in the group, together with an interpretation of their general diet and environment. The oxygen data suggest that at least three of these individuals were non-local, probably from a significantly warmer environment, although the other isotope data are consistent with an origin in Hampshire. All of the data formed a relatively homogenous group, which might suggest that they were all incomers from a location where the range for the oxygen data overlaps the 'warmer' end of the range suggested for Britain and which had coincidentally similar baseline values for the strontium isotope ratios and collagen data.

Non-specialist summary of analyses

Strontium isotope analysis of tooth enamel

Strontium isotope analysis of archaeological humans can provide evidence for geographical origin. Strontium is incorporated from ingested food and water as teeth and bones form. Because the isotope ratios present in these can vary geographically, and on the assumption that ancient people sourced the bulk of their diet locally, these differences can be used to draw conclusions about whether individuals were of local or non-local origin. This report discusses strontium isotope data from tooth enamel, a skeletal tissue which is highly resistant to diagenetic alteration and which represents childhood diet. Most bioavailable strontium originally derives from the underlying geology so that the isotope ratios are usually indicative of the rock present in an individual's home region. In a maritime region such as the UK, the effect of rainwater, which derives from seawater, must be taken into account along with marine salt deposition in coastal areas.

Tooth enamel forms during childhood and the isotope ratio from strontium incorporated during that period does not change during later life. The data obtained therefore mainly reflect the geology of the region where foods were obtained during that childhood formation period. By comparing them with what might be expected for the region of burial it is possible to say whether the childhood signal is consistent with the burial environment,

in which case it may be probable that the individual lived throughout their lives in that location. If the signal does not match the burial environment, then it is likely that they moved away from their original home region during or after childhood, or were transported to the burial site after death.

There are a number of possible confounding factors which must be considered. If an individual moved away after childhood, lived away for many years and then returned to their original home location, this cannot be identified from the enamel signal. Also, if an individual moved between two locations where the geology was very similar, this is unlikely to be identified from these data. The isotope ratios are derived from food and drink, with plants being the dominant dietary source of strontium, so if these were not obtained from the home or burial region, but were brought in from elsewhere, as might be the case if food was being traded or transhumance was being practiced, then this will also have an effect on the interpretation of the data.

Dentine and bone are much more vulnerable to diagenetic alteration in respect of strontium than is the case for enamel. They can be affected by the burial environment, which is why enamel is the preferred analyte. It is, however, useful to analyse some dentine as part of the research because if it is equilibrating towards the local strontium isotope ratios in the soil it may provide at least an indication of the likely direction of alteration for comparison with the values from the enamel samples. In this case, some published cattle dentine samples from Owslebury in Hampshire have been used as comparative data for the site.

Strontium isotope ratios are given as $^{87}Sr/^{86}Sr$ values. Suggested sources for more detailed information about analytical techniques and data interpretation are Montgomery (2010), Evans *et al.* (2010; 2012) and Bentley (2006). The data included in this report were produced at the Durham Geochemistry Centre in the Durham University Earth Sciences.

Oxygen and carbon isotope analysis of tooth enamel

Oxygen isotope ratio data ($\delta^{18}O$ values) from tooth enamel are also generally used for interpreting mobility. They are mainly indicative of the values from ingested water,

particularly drinking water which may be sourced from rain or groundwater. There are a considerable number of variables and error sources which can affect them and, in this respect, they can be more difficult to interpret than some other isotope data sets.

The oxygen isotope composition of precipitation is affected by a number of environmental variables, including latitude, altitude, distance from the coast, levels of precipitation, air temperature and season. In particular, surface air temperature at higher latitudes is a key factor in the variation observed geographically. Variation in the $\delta^{18}O$ values between precipitation and the groundwater sources accessed can be caused by a further range of factors such as evaporation from surface water and recharge from rivers containing water from high altitude precipitation. Drinking water may also be isotopically altered by processing, such as boiling or in the production of alcoholic drinks.

The $\delta^{18}O$ values from human skeletal material are not the same as those from the drinking water, but there is a direct relationship. Ingested water comes from both drinking water and food sources and there is a species-specific relationship for the balance involved, with fractionation incorporated into the system. A range of factors may affect the relationship, including the consumption of milk or blood and physiological factors such as disease or activity level. Traded food and drink, which has been imported from a different region, may also have an effect, as would be the case for all isotope data.

In the past, published original skeletal $\delta^{18}O$ values have often been converted to environmental drinking water values ($\delta^{18}O_{dw}$) using regression equations which are particular to species. This allows comparison of the converted data with environmental water values mapped for the locations being considered as part of a mobility study. In the case of humans there are a number of different regression equations which can be used and significant levels of error can be introduced into the data set by undertaking this conversion. More recent studies of British archaeological material have, therefore, preferred to use the unconverted $\delta^{18}O$ values in the context of empirical data sets available for the relevant regions and time periods under consideration (e.g., Evans *et al.* 2012; Pellegrini *et al.* 2016) and this is the approach taken in this report, although converted drinking water values have been provided for reference purposes.

Enamel oxygen isotope analyses can be undertaken on either the carbonate or the phosphate fraction. In this case carbonate analysis has been undertaken. This allows the carbon isotope ratio from the carbonate to be measured alongside the oxygen and requires a less technically difficult pre-treatment of the sample, making it faster and less expensive. The $\delta^{13}C$ values obtained from the carbonate fraction of the tooth enamel reflects carbon from the whole diet rather than that from the dietary protein alone, while the values obtained from collagen (see below) are usually from protein, with fat and carbohydrate only contributing in circumstances where protein input is a limiting factor. When comparing the data between these two fractions, the formation period of the skeletal material should also be taken into account, with the tooth enamel forming in childhood, cortical long bone collagen reflecting an averaged tissue turnover over a lifetime and rib collagen tending to reflect a period closer to death.

Suggested sources for more detailed information about the analysis and interpretation of $\delta^{18}O$ and $\delta^{13}C_{carbonate}$ data are Evans *et al.* (2012), Lee-Thorp (2008), Lightfoot & O'Connell (2016), Pellegrini *et al*. (2016) and Pollard *et al*. (2011b). The data included in this report were produced at Iso-Analytical Ltd in Crewe following sampling of the enamel in the Archaeology Department isotope laboratory at Durham University.

Carbon and nitrogen isotope analysis of collagen

Carbon and nitrogen stable isotope ratios in skeletal collagen are used to reconstruct dietary patterns (e.g., Sealy 2001; Lee-Thorp 2008; Makarewicz & Sealy 2015 for basic summaries). The carbon and nitrogen in the amino acids which form bone collagen mainly come from the protein element of the consumer's diet. The isotope ratios in collagen therefore bear a direct relationship to those in the protein in the foods which have been eaten, although there is some fractionation in the system (i.e., one of the two isotopes being compared for each element is often taken up in preference to the other). Since the food chain leads back to plants at the base, the data can also be used to consider an individual's connection with the local environment at a particular time and place, often by using data from contemporaneous herbivores to look at the effects of that environment on their plant diets.

When discussing diet, the data can be used specifically to consider the amount of animal protein that has been consumed (trophic level), the level of aquatic resource consumption (particularly marine resources) and whether plants which use the C_4 photosynthetic pathway have been included in the food chain. Fractionation in the system means that $\delta^{15}N$ values are elevated between trophic levels by around 3 to 5‰ (although this may be flexible, see O'Connell *et al.* 2012), whilst $\delta^{13}C$ values may increase by around 1‰. High levels of marine resources lead to significant enrichments in both the ^{15}N and ^{13}C isotopes. Non-dietary factors, such as nutritional stress, can also affect the values.

C_3 and C_4 plants have different photosynthetic pathways and this results in $\delta^{13}C$ values which are significantly different when they are traced through to the ultimate consumer, with C_4 plants producing $\delta^{13}C$ values which are higher. C_3 plants are those which are usually found in temperate environments and are the main indigenous plant resources available in northern Europe. C_4 plants are more usually found in warmer environments and are not found in significant quantities in early Britain, although small amounts of C_4 halophytes may have been present in salt-marsh environments. They start to appear in the food chain from the Roman period onwards, although at that early point this will generally indicate mobile individuals who have moved from a region where C_4 plants, particularly millet, were present at this time. Millet started to appear in continental European food chains, either in the diet of animals or humans, from the late Neolithic onwards. There are limited finds of broomcorn millet from Roman Britain and it is unlikely to have been grown here. It is also important to bear in mind that, since the bulk of the ^{13}C present in collagen will be from protein consumption, an omnivorous diet will generally produce a signal which is weighted towards the animal part of the diet, so that very small quantities of C_4 plant foods in the diet are unlikely to be visible in the isotope ratios present in the consumer's bone collagen. If such plants are present in the animal diet, such as where millet or C_4 halophytes are being consumed by domesticated herbivores, this may be more clearly visible.

Plants are affected by local environmental conditions, such as climate, salinity and manuring practices. These conditions therefore affect the isotope ratios which are seen in skeletal collagen throughout the food chain. For this reason, the consideration of absolute values for individuals can be problematic, with variation present both through time and

space according to local environments and subsistence practices. It is important, therefore, to have a 'baseline' for the environment when interpreting human data and this is often obtained by analysing animal samples, particularly herbivores, from the same location and time period. Dietary patterns throughout the food chain can then be considered in relative terms. For this report, existing published comparative data have been considered for both humans and animals, rather than animals specifically obtained from these excavations.

Bone collagen is formed over a long period of time, with newly formed molecules replacing older ones throughout an individual's life. The turnover period involved is much longer for adults than it is for infants or growing children. For mature adults it is likely that a significant part of a cortical long bone sample was formed during adolescence and the signal seen is relevant to the averaged diet over many years, but weighted towards that earlier period (Hedges *et al.* 2007; Matsubayashi & Tayasu 2019). Turnover in rib will be faster, so that this fraction will reflect a period of life closer to death (Cox & Sealy 1997).

Where collagen data from bone are used in a multi-isotope study alongside data from tooth enamel, it is important to be aware that there are timing differences between these samples and that the collagen may or may not have had time to equilibrate to a local dietary signal if an immigrant is identified. For crown dentine, the collagen data will reflect the formation period, which in the case of a first premolar extends from around 2 to 6 years, with a second molar going up to around 8 years.

The data included in this report were produced at the Stable Isotope Biogeochemistry Laboratory (SIBL) at Durham University.

Sulphur isotope analysis of collagen

Compared to $\delta^{13}C$ and $\delta^{15}N$ data the use of sulphur isotope ratios are at an earlier stage of the research, with fewer publications available, smaller datasets for comparison and a much less clear understanding of how the data should be interpreted in particular circumstances (e.g. Nehlich *et al.* 2010; Jay *et al.* 2013; Sayle *et al.* 2013; van der Sluis *et al.* 2016). The smaller number of studies has partly been due to the difficulties involved in obtaining the data; collagen contains only small amounts of sulphur, and the analysis of

sulphur isotope ratios from organic remains has been technically relatively difficult when compared to that for carbon or nitrogen, with the analytical error being much larger. These technical issues are being overcome with time so that larger datasets are being produced, allowing a better understanding of the variation that may be caused by environmental variables across space and over time (Privat *et al.* 2007; Nehlich & Richards 2009; Tanz & Schmidt 2010; Nehlich 2015). Analytical error and inter-laboratory comparison continue to be important factors to consider, as does the contentious issue of sample contamination and the requirement for ultrafiltration (Bocherens *et al.* 2011; Nehlich pers. comm.).

These data reflect both diet and environment. The geology of the region of plant growth, and also the proximity of the coastline, where a 'sea spray' effect of marine sulphates can be reflected in dietary resources (Richards *et al.* 2001; 2003; Nehlich 2015), are both important factors. $\delta^{34}S$ values can also help to distinguish dietary consumption of aquatic resources, both marine and freshwater, particularly where multi-isotope studies are being undertaken and $\delta^{15}N$ and $\delta^{13}C$ values are also available (Craig *et al.* 2010; Nehlich *et al.* 2010; Smits *et al.* 2010; Nehlich *et al.* 2011). Again, herbivore and other animal data are invaluable for comparing the 'baseline' signatures for local environments. In this case, however, there is little fractionation seen in the sulphur system, so that there should be no significant trophic level effect in these values (Webb *et al.* 2017; Krajcarz *et al.* 2019). This means that if the $\delta^{34}S$ from human samples differ from those of local animals it may be an indicator of human mobility.

The data included in this report were produced at the Stable Isotope Biogeochemistry Laboratory (SIBL) at Durham University, with replicate tests on three samples undertaken at Iso-Analytical Ltd (Crewe).

Results and discussion

Table 1 provides the sample details, with the isotope data being presented in Tables 2 and 3 and in Figures 1 to 4. The $^{87}Sr/^{86}Sr$ values range from 0.7082 to 0.7087 and the $\delta^{18}O$ values from 27.5‰ to 28.7‰; these values form a relatively homogenous group which might suggest a similar origin for all individuals. A group subsisting on food sourced from a chalk substrate with an input from rainwater, which will have a value similar to seawater, should fall within the $^{87}Sr/^{86}Sr$ range of approximately 0.7075 to approximately

0.7092 (Montgomery *et al.* 2007). The horizontal dotted lines in Figure 1 delimit this range and all of the individuals analysed fall within it. Figure 1 also shows the expected range of $\delta^{18}O$ values for British individuals, with separate and overlapping bands for a generally warmer western and southern region with higher rainfall and a cooler eastern region with lower rainfall. Three of the Worthy Down group fall outside the range suggested for Britain (to 2 sd), falling towards the 'warmer and wetter' end of the spectrum, although the small range of values is suggestive of a cohesive group so that the three extending outside of the British range are not necessarily differentiated significantly from the other three.

Also shown in Figure 1 are the published data from the late Roman cemetery at Lankhills, Winchester (Evans *et al.* 2006; Eckardt *et al.* 2009; Evans *et al.* 2012). Many of these individuals were identified as mobile and those plotting above the Chalk range for $^{87}Sr/^{86}Sr$ values and those to the extreme left of the $\delta^{18}O$ axis, with lower values, will be included in that group. The Worthy Down individuals plot to the right of the chart, with higher $\delta^{18}O$ values, where three of the Lankhills burials are outside the suggested oxygen range for Britain, one of whom also has an $^{87}Sr/^{86}Sr$ value which is outside that expected for the location, but the other two within that range. The Lankhills oxygen data were originally analysed from phosphate samples and the chart in Figure 1 shows these converted to carbonate values for comparison using the equation from Chenery *et al*. (2012). The highest value in the Lankhills group is 28.3‰ as a converted carbonate value and this individual is suggested by Eckardt *et al*. (2009) as possibly originating, within the confines of the Roman Empire, from the Iberian peninsula or the Mediterranean, either on the southern European or North African side. However, they do point out that the value is just within two standard deviations of the Lankhills population mean, so that there is a suggestion that perhaps this person did, after all, fit within the range for the site as a home location and that perhaps the range for Britain might need to be extended for this region.

The chart also shows some $^{87}Sr/^{86}Sr$ values for late Iron Age and early Roman period cattle dentine samples from Owslebury in Hampshire which is approximately 6 km south east of Winchester and also on chalk bedrock (Minniti *et al.* 2014). The isotope signature from dentine is much less stable than from enamel and is subject to diagenetic alteration in the direction of change indicative of the burial environment. The $^{87}Sr/^{86}Sr$ values from

these dentine samples are therefore likely to reflect the range expected for the local area and they are very similar to all of the Worthy Down data.

Figure 2 shows the $\delta^{13}C$ and $\delta^{15}N$ values from the rib and crown dentine samples in the context of both human and animal data from Iron Age sites at Danebury (approximately 16 km north west of Winchester), Micheldever Wood (approximately 10 km north east of Winchester), Winnall Down (immediately east of Winchester) and Suddern Farm (approximately 4.5 km west of Danebury) (Jay & Richards 2007; Stevens *et al.* 2010; Hamilton *et al.* 2019). All of these sites are close to the two main rivers which flow into Southampton Water (the Rivers Test and Itchen), both rising and flowing through chalk bedrock. The Worthy Down mean averages for the rib $\delta^{13}C$ and $\delta^{15}N$ values are -20.1 ± 0.2‰ and 7.8 ± 0.5‰ respectively and for the dentine they are -19.8 ± 0.2‰ and 8.2 ± 0.6‰. For most of Britain, absolute $\delta^{15}N$ values this low would suggest a human diet which is low in animal protein, but this is not the case in this region where the herbivore values, as evidenced from the Iron Age sites here, are similarly low. This is an example of why it is important to have 'baseline' values when interpreting data, in order to understand them in relative, rather than absolute, terms. This region of Hampshire has generally produced lower 'baseline' $\delta^{15}N$ values than even the similar bedrock chalk of east Yorkshire (Jay & Richards 2007).

The Worthy Down $\delta^{15}N$ values are very similar to the human data from the main groups at Danebury, Micheldever Wood and Winnall Down. Those individuals from these sites which have the higher $\delta^{15}N$ values shown in Figure 2 may well have obtained their dietary resources away from the region, or in some cases have included freshwater fish in their diets. One of the individuals from Winnall Down is a Romano-British child with a high level of marine resources in the diet and this is shown in Figure 2 to give an indication of what this looks like in context.

Figure 3 shows the carbon and nitrogen data from Worthy Down alongside those from Lankhills (Cummings & Hedges 2010). The Lankhills data show a considerable level of variation with the majority of the individuals having higher $\delta^{13}C$ and $\delta^{15}N$ values. These higher values are indicative of individuals originating away from the Hampshire locations which have a low baseline for $\delta^{15}N$, with the higher $\delta^{13}C$, when combined with higher $\delta^{15}N$,

indicating the inclusion of marine resources in the diet and where not combined with higher $\delta^{15}N$ indicating the inclusion of C_4 resources not available in Britain. Neither marine resources nor high levels of C_4 inclusions are indicated for Worthy Down, if the baseline used is that indicated by the Lankhills and Iron Age herbivores shown in Figures 2 and 3. The high level of variation in the Lankhills data set is consistent with that obtained from the strontium and oxygen analyses of the same group (Eckardt *et al.* 2009) and is reflective of variation in the diets and environments of individuals originating from a variety of different places. The three individuals in the Lankhills data set with the highest $\delta^{18}O$ values are labelled on the chart. These individuals were identified as having values above the range expected for Britain and as possibly originating in a warmer environment, such as the Mediterranean or Iberia (Eckardt *et al.* 2009).

The carbon and nitrogen data from Worthy Down support an interpretation as a group of individuals who were consuming animal protein from this region. The bone values are from ribs, which have a relatively high turnover rate, so that these represent the diet towards the end of life (Cox & Sealy 1997; Fahy *et al.* 2017), while the dentine retains the signal from the formation period of the teeth (in this case from around 2 to 6 years for the premolar and 2 to 8 years for the second molars). This suggests that these individuals may have been consuming resources from this region throughout their lives, from childhood through to end of life. This might contradict a suggestion that the three individuals with higher $\delta^{18}O$ values from their tooth enamel were incomers, since there is no significant difference between their childhood values and their later life values.

If at least some of the oxygen data are interpreted to suggest a childhood spent in a warmer region such as the Mediterranean, then it might be expected that the dentine $\delta^{13}C$ and $\delta^{15}N$ values from those individuals would both be higher. Warmer and drier climates tend in this direction for both, while $\delta^{13}C$ values may also increase where C_4 plants are present in the food chain. It is possible that this is the case here, given that the dentine mean values are slightly enriched in both ^{13}C and ^{15}N over the rib values, by 0.3‰ and 0.4‰ respectively. There are, however, different ways to interpret this. It is possible that it is caused by dietary or environmental differences between children and adults; however, the writer believes that there is a small systematic difference which is seen in comparisons of bone and dentine collagen data on a regular basis and is clearer in situations where

there is little long-distance mobility and minimal consumption of aquatic resources (i.e., where some of the variables relevant to interpretation are restricted). It is seen across the entire dataset obtained for the Beaker People project which covers Late Neolithic and Early Bronze Age material from Scotland down to southern England and the writer hypothesizes there that this may be a physiological effect (Jay & Richards 2019). For Worthy Down it could be suggested that it is the product of breastfeeding because crown dentine has been used and it is possible that late breastfeeding is still having an effect after the formation begins at around 2 years. However, this is not true for the material from the Beaker People project, where root dentine from the enamel-dentine junction down was used; the formation period commences much later in that material and breastfeeding there is an unlikely explanation. The writer believes that this is an effect to be expected between dentine and bone when the subsistence environment and general diet are similar between childhood and later life. If this is true, then the small differences seen between bone and dentine in this case are not necessarily reflective of mobility, although it is also possible that both a physiological effect and mobility are in evidence together.

An example of where a clear difference between bone and dentine carbon and nitrogen values supports the suggestion of mobility is sample 1119 from Lankhills who probably spent his childhood in eastern or central Europe and whose rib values were similar to the majority of the other individuals from this site, but whose dentine values were very different (by nearly 1.5‰ for carbon and over 2.0‰ for nitrogen) and probably indicative of the inclusion of millet in the childhood food chain (Eckardt *et al.* 2014).

The sulphur data are plotted with the nitrogen in Figure 4, alongside Iron Age cattle and sheep comparatives from Danebury and Suddern Farm (close to Danebury, approximately 20 km north west of Winchester) (Hamilton *et al.* 2019) and three humans from Winnall Down, of which one is Roman and the other two Iron Age (Jay, unpublished data). There is very little fractionation in sulphur, so that human $\delta^{34}S$ values are expected to be very close to animal values obtained from the region where dietary resources are obtained. The mean $\delta^{34}S$ value for the Danebury and Suddern Farm herbivores is 15.4 ± 4.0‰ (*n* = 49); these compare with the Worthy Down human averages of 13.7 ± 0.6‰ for ribs and 12.6 ± 0.8‰ for dentine. The data from the three humans from Winnall Down are

individuals with low δ^{15}N values similar to that expected for the region, so that they are expected to be locals; the average δ^{34}S for these is 14.7 ± 1.9‰.

When comparing these sulphur values, it is important to be aware that the data were produced in different laboratories at different times; the 2019 published data from Danebury and Suddern Farm was analysed at SUERC, the unpublished data from Winnall Down at Iso-Analytical (Crewe) in 2005 (in the early days of collagen sulphur analysis) and those from Worthy Down at Durham University (with three sample checks obtained at Iso-Analytical, see Table 2). Error in the replication of δ^{34}S values from collagen samples is likely to be an order of magnitude higher than that for carbon and nitrogen (Jay *et al.* 2019), so that data obtained from different laboratories at different times over a 14 year period should probably be compared with the expectation of an error of at least ± 1.0‰, so that the differences between the site data presented here are unlikely to be significant.

The negative correlation between the δ^{34}S and δ^{15}N values suggested by the trendlines shown in Figure 3 has been noted by the writer at a number of sites. They are shown here separately for the rib and dentine because of the differences in δ^{15}N values between the fractions, as discussed above. When seen, this correlation is generally site-specific, so that it does not appear across large, multi-regional studies, but occurs at individual sites where input variables are restricted (e.g., where mobility and marine resource consumption are not in evidence), but it was also seen at the regional level in the Beaker People project (Jay *et al.* 2019). Other examples are from Roman Oxfordshire near the Thames, Iron Age east Yorkshire and herbivores from early Viking Iceland adjacent to a lake (Nehlich *et al.* 2011; Jay *et al.* 2013; Sayle *et al.* 2013).

Nehlich explains the Roman data from Oxfordshire as freshwater influenced resources being consumed from the Thames and its tributaries, probably including fish, birds, crops grown on the floodplain and animal protein from herbivores grazing there (Nehlich *et al.* 2011). Higher levels of animal protein and the consumption of fish will lead to higher δ^{15}N values and the lower δ^{34}S values are a result of these resources having been affected by sulphur in the water which has flowed through regions where highly ^{34}S-depleted sedimentary sulphides are present. The Iron Age Wetwang data have been interpreted as showing short-distance mobility between resource locations, causing a linear relationship

between two endpoints with different environmental 'baselines' for nitrogen and sulphur isotopes, one of which may have been closer to water, such as between the chalk Wolds and the Humber estuary (Jay *et al.* 2013). Sayle suggests that the Icelandic herbivores with higher $\delta^{15}N$ values and the lower $\delta^{34}S$ values were grazing at sites closer to the lake where plants were enriched in ^{15}N by chironomid midges (Sayle *et al.* 2013).

In addition to the Icelandic herbivores, the writer has seen the trend in British herbivores (Jay, unpublished data), so that explaining higher $\delta^{15}N$ values through the consumption of animal protein or fish is unlikely. The effect is more likely driven by the consumption of plants from different environments. If human values were driven entirely by the consumption of freshwater fish with low $\delta^{34}S$ values, then a relationship between the sulphur and carbon data would be expected, such that the lower sulphur values would correlate with lower carbon values. This has not been noted in any of the data sets mentioned and, for pre-Roman material, isotopic studies for Britain suggest that Neolithic through to Iron Age people were not consuming significant levels of either marine or freshwater fish. It is likely, therefore, that the effect seen here reflects varying levels of resource consumption of plants and terrestrial animals sourced from riverine environments, although this explanation only holds if these individuals were from the local environment or if they were mobile, but all originated in the same place.

Carbon isotope data from the enamel carbonate are available for the Worthy Down individuals and these range from -14.3‰ to -13.5‰ (Table 2). These values are generally obtained at the same time as oxygen isotope analysis of enamel carbonate and are not available from published studies where the oxygen analysis was undertaken on the phosphate fraction, which are the majority of those with Roman data currently available for comparison. They are, however, consistent with a terrestrial diet which is mainly based on C_3 resources. They are high enough that they could indicate low amounts of C_4 resources in the food chain, but not at easily identifiable levels.

There are several explanations for the Worthy Down data set as a whole:

- They all originated, and spent their lives in, the local environment and the 'local' $\delta^{18}O$ range for this part of Britain needs to be expanded. The $^{87}Sr/^{86}Sr$ values are consistent with this hypothesis, as are the carbon and nitrogen data, including the

fact that the rib and dentine samples produced very similar values. Militating against this explanation are the $\delta^{34}S$ values for the dentine, which are all slightly lower than the rib, and the highest two of the $\delta^{18}O$ values, at 28.6‰ and 28.7‰, which are considerably higher than anything which has been accepted as British to date.

- They all originated, and spent their lives in, the local environment, but the $\delta^{18}O$ values have been affected by the consumption of processed water and foods in childhood through cultural practices (e.g., wine, boiling, fermenting; Brettell *et al.* 2012). This is a possible explanation for the high $\delta^{18}O$ values as an isolated data set, but it appears unlikely that such high values would be obtained specifically from these individuals when they are not also present in the Lankhills data set. Similarly the higher $\delta^{18}O$ values could have been affected by breastfeeding, but the majority of samples are second molars, for which the enamel starts formation after the age of two years and finishes at around seven or eight years, which would mean that breastfeeding was occurring at a very late age given that the enamel analysed was from bulk samples. This is an unlikely scenario and is also not seen at Lankhills.

- They all originated outside of Britain in a region which is coincidentally similar to this part of Hampshire in terms of strontium, carbon and nitrogen isotopic baselines. Such places do exist (e.g., the carbon and nitrogen data from Roman Velia on the south west coast of Italy look quite similar without having a marine component to the diet (Craig *et al.* 2009) and this west coast is likely to have high $\delta^{18}O$ values and conceivably similar $^{87}Sr/^{86}Sr$ values (Emery *et al.* 2018), although this location is mentioned here as an example and not as a definitive origin identification). While the carbon and nitrogen data are very similar to the regional Iron Age sites at Danebury, Winnall Down and Micheldever Wood, compared to the late Roman Lankhills data set all of the Worthy Down data are at the low end of the ranges. Assuming that the Lankhills data are a much better comparison in terms of dietary constituents, and given that the sites are very close, this may indicate different origins with the lower $\delta^{13}C$ and $\delta^{15}N$ being coincidentally similar to those expected for Hampshire. It might also be true that the data sets are not completely

comparable, since they were obtained from different laboratories at different times, or that the diets of those buried at Worthy Down and Lankhills were slightly different for some reason.

Examples of other high $\delta^{18}O$ values from Roman Britain which have been interpreted as immigrants include a 2nd century AD individual from Kent (Pollard *et al.* 2011a) who has quite similar isotope data for strontium, carbon and nitrogen as are available from Worthy Down and who was suggested as having an oxygen value (28.2‰) outside the British range. At the other extreme, a Roman individual from Driffield Terrace in York has been interpreted on the basis of DNA evidence and a much higher $\delta^{18}O$ value (31.6‰) as being from the Middle East (Martiniano *et al.* 2016), although in that case not only is the $\delta^{18}O$ value very high, but the $\delta^{15}N$, at 14.3‰ for the dentine, is much more like a value to be expected from a hot, dry environment. Another individual from the same site, who had been decapitated, had a value of 28.6‰ (phosphate 19.8‰) and was identified as probably from a warmer climate than Britain (Müldner *et al.* 2011) as was one from Trentholme Drive in York, a Roman of mixed ancestry with a $\delta^{18}O$ value of 28.5‰ (phosphate 19.7‰), (Leach *et al.* 2009). At the London site of Lant Street almost 50% of the group analysed had values above 28.0‰, ranging up to 29.7‰ (phosphate 19.2 to 21.0‰) and a conservative five out of nine of these were interpreted as having originated outside of Britain (Redfern *et al.* 2016). An individual from Scorton (North Yorkshire) has a value very similar to those from Worthy Down at around 28.6‰ (phosphate 19.9‰), but in that case the analysis was of an early forming first molar and the value interpreted as probably due to breastfeeding (Eckardt *et al.* 2015).

Overall, values which are just above 28.0‰ are difficult to interpret, but in the case of Worthy Down, they go up to 28.7‰ and the group is relatively consistent, with a range of only 1.2‰, which is not seen in the other data sets mentioned here.

If they all originated outside of Britain, then the small differences seen between the rib and dentine collagen data sets (carbon, nitrogen and sulphur) may be due to childhoods spent in a location with slightly different baselines, rather than the

physiological explanation for the carbon and nitrogen differences mentioned above, although both effects may be combined.

The explanation that they all originated outside of Britain from the same region which had a similar baseline for strontium, carbon and nitrogen to that seen for Hampshire seems the most likely for this group of individuals.

- Those with oxygen values within the British range originated in Hampshire, whilst the other three originated elsewhere, but in a region which is coincidentally similar to this part of Hampshire in terms of all of the isotope systems except oxygen. This is probably the most unlikely explanation.

Conclusions

The strontium and oxygen data are relatively closely grouped for these six individuals. For three of them the $\delta^{18}O$ values are higher than expected for a British origin, although all of the strontium isotope ratios are consistent with the burial location. The carbon, nitrogen and sulphur data are consistent with Hampshire and a terrestrial diet mainly consisting of C_3 resources. There is a contradiction between the higher oxygen values and the general consistency of the other data with the location. Given that the oxygen values also fall into a relatively small range, the most likely explanation may be that all of these individuals originated outside of Britain, in a region with a warmer climate, and that the baselines for the other isotope data are coincidentally similar to those for the Hampshire region.

Recommendations for possible future work

While enamel carbonate is generally a stable fraction for the analysis of oxygen isotopes, there are no quality indicators available to identify diagenesis. It is possible that the reason for the close grouping of high $\delta^{18}O$ values relates to a problem in this respect. One way to check for this is to analyse the phosphate fraction of one or more of the same teeth and to compare the data (Lee-Thorp 2008).

Since there is some apparent contradiction in the data from this group, lead analysis of the enamel might help to confirm whether a non-British origin is indicated. Data can be obtained from tooth enamel for a number of lead isotope ratios (of ^{204}Pb, ^{206}Pb, ^{207}Pb and

^{208}Pb) alongside the lead concentration. For the Roman period lead ingestion can reflect cultural habits and artefact use rather than the local geological sources. It was, for instance, used in pipes, tableware, cooking pots, cosmetics and as a food and drink additive. If the lead concentration from the analysed sample is high enough to indicate this anthropogenic 'pollution' (over approximately 0.5 ppm), then the isotope ratios can be compared with the field of values expected based on lead obtained from Britain generally (Montgomery *et al.* 2010). If the ratios fall outside this field, it is likely that the pollutant lead was obtained from sources outside of Britain. Such analysis will not definitively identify immigrants, but the data may provide further evidence to add to the interpretation.

Analytical methods

Collagen extraction was undertaken at Durham University in the Archaeology department isotope preparation laboratories and was based on a modified Longin's method (Longin 1971). Samples were demineralized in 0.5 M HCl at 4°C. The remaining collagen was denatured in pH 3 aqueous solution at 70°C for 48 hours. The solution was filtered using Ezee filters® and then freeze-dried. The resultant collagen product was weighed to tin capsules and the samples combusted to N_2 and CO_2 and analysed at the Stable Isotope Biogeochemistry Laboratory (SIBL) at Durham. Samples of approximately 0.4 mg were weighed into tin capsules and measured in duplicate using a Costech Elemental Analyser (ECS 4010) connected to a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer. Carbon isotope ratios are corrected for ^{17}O contribution and reported in standard delta (δ) notation in per mil (‰) relative to Vienna Pee Dee Belemnite (VPDB). Isotopic accuracy is monitored through routine analyses of in-house standards, which were stringently calibrated against international standards (e.g., USGS 40, USGS 24, IAEA 600, IAEA CH3, IAEA CH7, IAEA N1, IAEA N2): this provides a total linear range in δ^{13}C between -46‰ and +3‰, and between -4.5‰ and +20.4‰ for δ^{15}N. Analytical uncertainty in δ^{13}C and δ^{15}N is typically ±0.1‰ or better for replicate analyses of the international standards and <0.2‰ for replicate sample analysis. The charts show an error bar at 0.2‰. Total organic carbon and nitrogen was obtained as part of the isotopic analysis using an internal standard (glutamic acid, C = 40.82%, N = 9.52%).

For δ^{34}S analysis, the same equipment was used. Collagen samples of 9-12 mg were weighed into tin capsules and approximately the same weight of vanadium pentoxide

(V_2O_5) was added to aid in the combustion process to release sulphur. Sulphur samples in this report were run as duplicate analyses, except for the dentine from SK 7032 and 7039, for which there was insufficient sample for duplication. Isotopic accuracy was monitored using the following barium sulphate international standards: IAEA-SO-5, IAEA-SO-6 and NBS-127. Analytical uncertainty is typically <0.2‰ for replicate analyses of the international standards and samples. The charts show an error bar at 0.4‰ for 2 sd. Total sulphur was obtained as part of the isotopic analysis using the OEA organic analytical standard sulphanilamide (S = 18.62%).

For sulphur analysis, analytical precision based on a single collagen extraction from a sample is typically better than the replication error likely to be obtained from analysing different extractions from the same sample or analyzing the same extraction at two different laboratories. Error at that level is likely to be closer to ± 1.0‰ at 1 sd.

For three samples, including two of those with higher S% values, the remaining collagen from the same extraction was sent for repeat analysis at Iso-Analytical Ltd, Crewe, where the $\delta^{34}S$ values obtained were very similar to the originals (see Table 2), but the S% values were lower, so that all of the $\delta^{34}S$ values obtained from Durham are considered to be acceptable for interpretation despite some of the original S% values being slightly higher than the generally accepted range.

For oxygen isotope analysis, the enamel surface of each tooth sample was sampled at Durham University in the Archaeology department isotope preparation laboratories. The enamel was removed using a diamond dental burr which was then discarded. Samples of powdered enamel (~ 5-15 mg) were produced for oxygen and carbon isotope analysis of the carbonate fractions. Analysis was undertaken at Iso-Analytical Ltd in Crewe. Samples were weighed into clean Exetainer™ tubes and then flushed with 99.995 % helium. After flushing, phosphoric acid was added to the samples and they were allowed to react in the acid overnight to allow complete conversion of carbonate to CO_2. Reference and control materials were prepared in the same way. The CO_2 gas liberated from samples was then analysed by Continuous Flow-Isotope Ratio Mass Spectrometry (CF-IRMS). Carbon dioxide was sampled from the Exetainer™ tubes into a continuously flowing He stream using a double holed needle. The CO_2 was resolved on a packed column gas chromatograph and the resultant chromatographic peak carried forward into the ion

source of a Europa Scientific 20-20 IRMS where it is ionized and accelerated. Gas species of different mass are separated in a magnetic field then simultaneously measured using a Faraday cup collector array to measure the isotopomers of CO_2 at m/z 44, 45, and 46. The phosphoric acid used for digestion had been prepared for isotopic analysis in accordance with Coplen *et al.* (1983), was injected through the septum into the vials. The reference material used during analysis was IA-R022 (Iso-Analytical working standard calcium carbonate, $\delta^{13}C_{V\text{-}PDB}$ = -28.63 ‰ and $\delta^{18}O_{V\text{-}PDB}$ = -22.69 ‰). IA-R022, NBS-18 (carbonatite, $\delta^{13}C_{V\text{-}PDB}$ = -5.01 ‰ and $\delta^{18}O_{V\text{-}PDB}$ = -23.20 ‰) and IA-R066 (chalk, $\delta^{13}C_{V\text{-}PDB}$ = +2.33 ‰ and $\delta^{18}O_{V\text{-}PDB}$ = -1.52 ‰) were run as quality control check samples during analysis of the samples. Acid preparations of samples and controls are measured directly against acid preparations of working calcium carbonate standard. This procedure removes the need to apply separate corrections for temperature dependent isotope fractionation. The results obtained for the NBS18 and IA-R066 controls are used to check and correct the data as required. IA-R022 has been calibrated against and is traceable to NBS-18 and NBS-19 (limestone, $\delta^{13}C_{V\text{-}PDB}$ = +1.95 ‰ and $\delta^{18}O_{V\text{-}PDB}$ = -2.2 ‰). IA-R066 has been calibrated against and is traceable to NBS-18 and IAEA-CO-1 (carrara marble, $\delta^{13}C_{V\text{-}PDB}$ = +2.5 ‰ and $\delta^{18}O_{V\text{-}PDB}$ = -2.4 ‰). NBS-18, NBS-19 and IAEA-CO-1 are inter-laboratory comparison standard materials distributed by the International Atomic Energy Agency (IAEA). The equivalent calcium carbonate content values (%) were derived by comparing the total ion beam data for the samples against the pure calcium carbonate references.

Following surface abrasion to a depth of >100μm, a chip of ~20 mg of core enamel, free from adhering dentine, was removed from each tooth with a diamond tipped rotary dental saw for strontium isotope analysis following the procedure of Montgomery (2002). From three teeth, a sample of similar size for dentine was also taken. The samples were sealed in microtubes and transferred to the clean laboratory facility in the Durham Geochemistry Centre at Durham University Earth Sciences Department. The enamel samples were prepared for strontium isotope analysis using column chemistry methods as outlined in Charlier *et al.* 2006. Samples were heated on a hot plate for 20 minutes in 75 µl of 16M HNO_3; the solution was then diluted with 325 µl of MQ H_2O to make 3M HNO_3 and heated overnight. The samples were loaded onto cleaned and preconditioned columns containing 60 µl of Eichrom strontium-specific resin. 2x250 µl 3M HNO_3 was eluted to remove the bulk of the matrix followed by 2x200 µl MQ H_2O to elute the strontium, which was

collected. The Sr fraction was acidified with 17.5µl 16M HNO_3 to prepare the samples for analysis. Following Sr purification, the size of the ^{86}Sr beam was tested for each sample to derive a dilution factor so that each sample yielded a beam size of approximately 20V ^{88}Sr to match the intensity of the isotopic reference material, NBS987. Samples were aspirated using an ESI PFA-50 nebuliser coupled with a glass expansion cinnabar micro-cyclonic spraychamber. Sr isotopes were measured using a static multi-collection routine with each measurement representing a single block of 50 cycles with each cycle being a 4 second integration (total analysis time ~3.5mins). Instrumental mass bias was corrected for using a $^{88}Sr/^{86}Sr$ ratio of 8.375209 (the reciprocal of the $^{86}Sr/^{88}Sr$ ratio of 0.1194) and an exponential law. Corrections for interferences from Rb and Kr on ^{87}Sr and ^{86}Sr were performed using ^{85}Rb and ^{83}Kr as the monitor masses but in all cases the intensity of monitor mass was <0.1mV and therefore insignificant. The average $^{87}Sr/^{86}Sr$ ratio and reproducibility for the international isotope reference material NBS987 during this study was 0.710239 ± 0.000009 (2σ; n=10) for three samples and 0.710249 ± 0.000011 (2σ; n=9) for the other three. Maximum error based on analytical reproducibility of the data is considered to be 0.000023 (2σ).

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Table 1: Sample information

Sample ID	Laboratory codes (rib; crown dentine; enamel; strontium laboratory)	Samples	Sex	Age	Further information
SK 7003	5220; 5226; 5186; A169.21	Rib; Mandibular left M2, crown dentine & enamel	M	26-25	Grave 7001; NW-SE; supine; mixed ancestry
SK 7010	5221; 5227; 5187; A169.22	Rib; Mandibular right PM1, crown dentine & enamel	F?	Adult	Grave 7008; NW-SE; supine; decapitated with head placed at feet
SK 7032	5222; 5228; 5188; A169.23	Rib; Maxillary left M2, crown dentine & enamel	F	36-45	Grave 7031; WNW-ESE; on left side; hobnails
SK 7039	5223; 5229; 5189; A169.24	Rib; Mandibular left M2, crown dentine & enamel	M	26-25	Grave 7037; NW-SE; supine; coffin
SK 7047	5224; 5230; 5190; A169.25	Rib; Mandibular right M2, crown dentine & enamel	?	40-44	Grave 7046; NW-SE; supine
SK 7051	5225; 5231; 5191; A169.26	Rib; Maxillary left M2, crown dentine & enamel	F	35-39	Grave 7049; NW-SE; supine

Table 2: Enamel isotope data

Sample ID	Strontium Lab code	$^{87}Sr/^{86}Sr$ (enamel)	$^{87}Sr/^{86}Sr$ 2 SE	$\delta^{13}C_{carb}$ (‰)	$\delta^{18}O_{carb\_SMOW}$ (‰)	Calculated $\delta^{18}O_{phos}$ (‰)[1]	Calculated $\delta^{18}O_{dw}$ (‰)[2]
SK 7003	A169.21	0.708343	0.000007	-14.3	27.9	19.2	-4.2
SK 7010	A169.22	0.708293	0.000007	-13.7	28.6	19.9	-3.1
SK 7032	A169.23	0.708520	0.000009	-13.7	27.5	18.7	-4.9
SK 7039	A169.24	0.708690	0.000009	-13.5	27.6	18.8	-4.7
SK 7047	A169.25	0.708358	0.000009	-14.3	28.3	19.5	-3.7
SK 7051	A169.26	0.708234	0.000010	-13.6	28.7	19.9	-3.0

Notes:

1. The calculated $\delta^{18}O_{phosphate}$ values use the equation from Chenery *et al*. 2012 to convert from the measured carbonate values. These data are provided for the purpose of comparison with other published data sets.
2. The calculated $\delta^{18}O_{dw}$ values use equation 6 from Chenery *et al*. 2012 (based on Daux *et al*. 2008) to convert from the measured carbonate values. These data are provided for the purpose of comparison with other published data sets, but care should be taken in using them with environmental water value maps (Pollard *et al*. 2011).

Table 3: Bulk collagen isotope data from bone and dentine

Sample ID	$\delta^{13}C$ (‰)[1]	$\delta^{15}N$ (‰)[1]	$\delta^{34}S$ (‰)[1]	C:N (atomic)[2]	C:S (atomic)[2]	C%	N%	S%[2]
SK 7003: rib	-20.0	8.1	13.0	3.2	320	43.8	15.7	0.37
Repeat, Iso-Analytical			13.6					0.24
SK 7010: rib	-20.2	8.2	13.0	3.2	410	42.3	15.4	0.28
Repeat, Iso-Analytical			13.1					0.23
SK 7032: rib	-20.3	8.0	14.3	3.3	324	42.2	15.1	0.35
SK 7039: rib	-20.0	7.6	13.9	3.2	306	42.0	15.2	0.37
SK 7047: rib	-19.7	7.8	13.6	3.3	305	42.8	15.2	0.37
SK 7051: rib	-20.1	6.9	14.2	3.2	313	42.2	15.4	0.36
Repeat, Iso-Analytical			14.6					0.23
SK 7003: dentine	-20.0	8.6	11.4	3.2	336	41.6	15.3	0.33
SK 7010: dentine	-19.8	7.2	13.5	3.2	322	41.6	15.3	0.35
SK 7032: dentine	-20.0	7.9	13.0	3.2	441	41.5	15.1	0.25
SK 7039: dentine	-19.7	8.2	13.3	3.2	413	42.3	15.4	0.27
SK 7047: dentine	-19.5	8.6	11.9	3.2	485	42.0	15.3	0.23
SK 7051: dentine	-20.0	8.9	12.6	3.2	361	42.0	15.5	0.31

Notes:

1. Bone collagen samples were analysed as duplicates for carbon and nitrogen and the data presented here are the mean values. Sulphur data were also duplicated, except for the dentine analyses of SK 7032 and 7039.
2. All C:N ratios fall into the acceptable quality indicator range of 3.0 to 3.4 and the elemental percentages also fall into the generally accepted ranges. All C:S ratios fall into the acceptable range of 600 ± 300, with S% falling into the acceptable range of 0.15 to 0.35% for all but the rib analyses for SK 7003, 7039, 7047 and 7051 which are slightly higher. For three samples, including two of these with higher S% values, remaining collagen from the same extraction was sent for repeat analysis at Iso-Analytical Ltd, Crewe, where the $\delta^{34}S$ values obtained were very similar to the originals, but the S% values were lower, so that the $\delta^{34}S$ values are considered to be acceptable for interpretation.

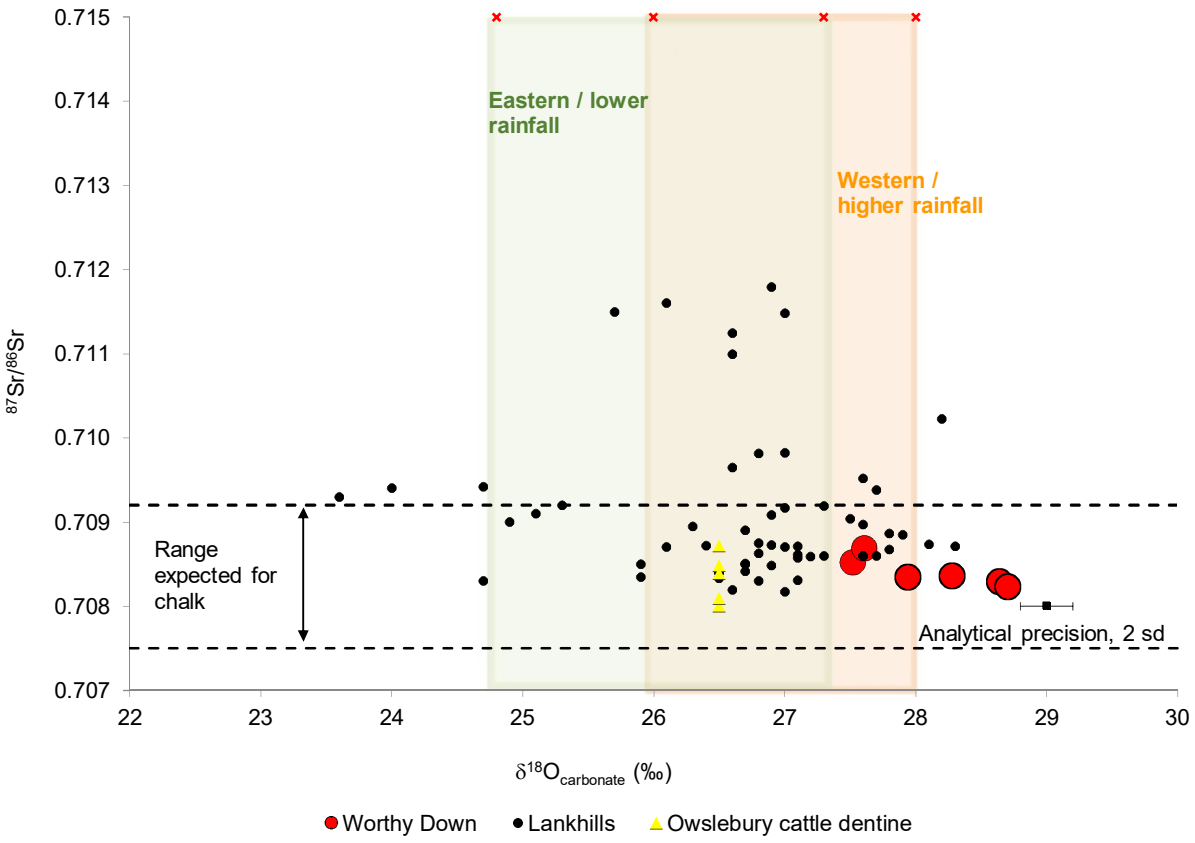

Figure 1: Strontium and oxygen isotope data for Worthy Down in the context of the late Roman comparatives from Lankhills (Eckardt *et al.* 2009; Evans *et al.* 2006; 2012) and some late Iron Age and Early Roman cattle dentine from Owslebury (Minniti *et al.* 2014) for which only the strontium isotope ratios are available (oxygen position plotted centrally). The cattle dentine values provide evidence to support the local baseline, since dentine will be affected by diagenesis in the burial environment, while the more stable enamel samples will not. The dotted lines indicate the range of strontium isotope ratios expected for chalk. The vertical coloured fields indicate the range of oxygen isotope ratios expected generally for Britain, with a 'cooler / lower rainfall' range to the left and a 'warmer / higher rainfall' range to the right, and some area of overlap. These ranges are plotted to 2 sd and taken from Evans *et al*. 2012. Analytical error for the strontium isotope ratios is within symbol.

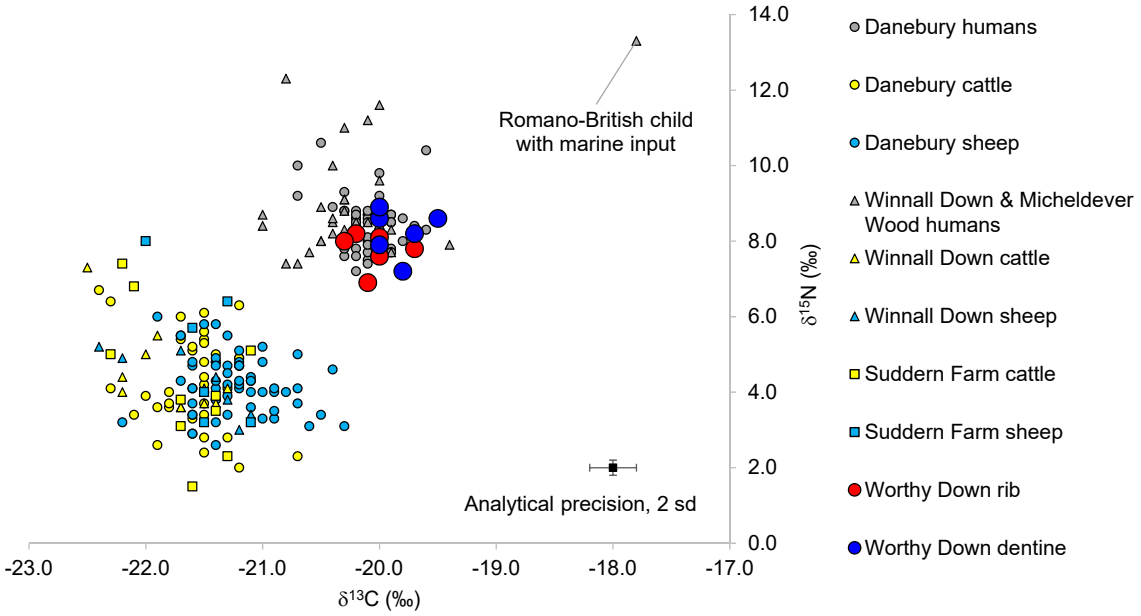

Figure 2: Carbon and nitrogen isotope data from Worthy Down rib and dentine collagen alongside comparative data from other sites in Hampshire (Jay & Richards 2007; Stevens *et al*. 2010; Hamilton *et al*. 2019)

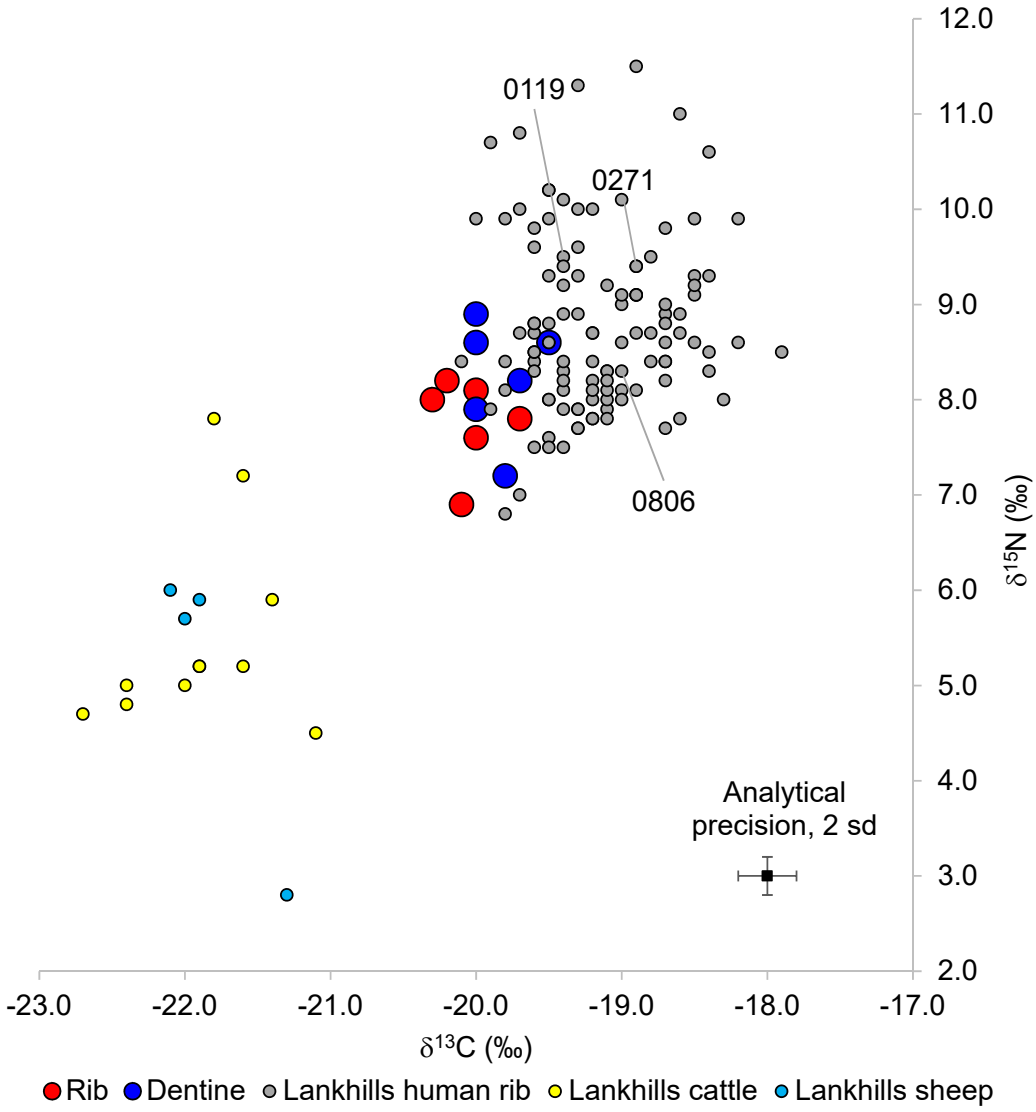

Figure 3: Carbon and nitrogen isotope data with comparatives from Lankhills (Cummings & Hedges 2010). The three labelled individuals from the Lankhills data set have the three highest oxygen isotope ratio values and are suggested as likely immigrants into Britain.

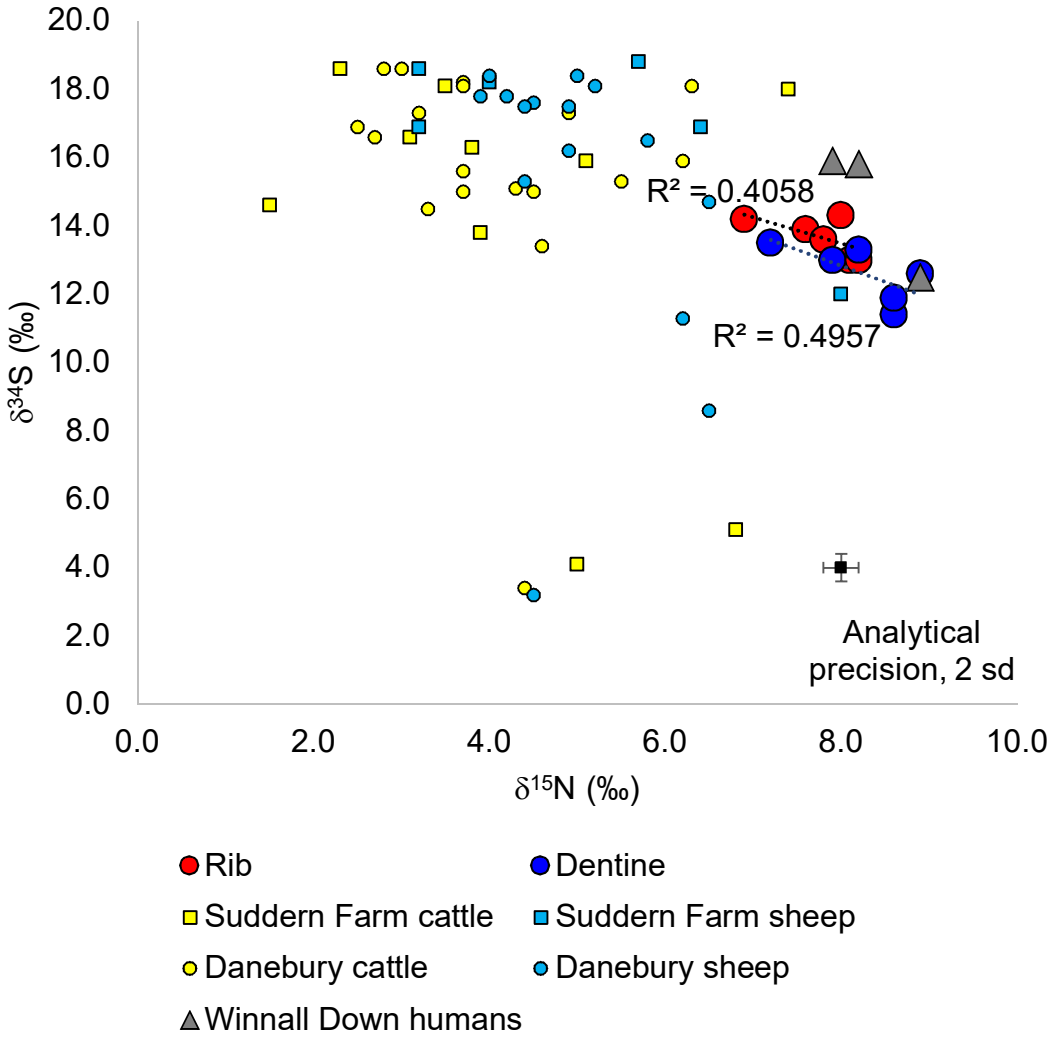

Figure 4: Sulphur and nitrogen isotope data with comparatives from Suddern Farm, Danebury hillfort and Winnall Down (Hamilton *et al*. 2019; Jay unpublished data).