British Iron Age Chariot burials of the Arras culture: a multi-isotope approach to investigating mobility levels and subsistence practices

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Abstract

Iron Age Chariot burials in the UK are rare and restricted in their distribution. Historically it has been suggested that their Arras culture affinities with Continental Europe, particularly with the Paris basin in France, may be indicative of migration. The majority of them are found on Chalk and the putative source region is also Chalk. This has meant that a study using only strontium isotopes to identify mobile individuals is problematic. Here we present a range of isotope ratio data (strontium, oxygen, carbon, nitrogen and sulphur) for seven Chariot burials from Wetwang, Garton Station and Kirkburn. The majority of them are men and women who were born and lived locally, although the individual from Kirkburn is likely to have spent his childhood elsewhere. They do, however, differ quite subtly from others in the local population, probably in their relationship to a local land use pattern operating between two distinct biospheres.

Keywords: Chariot; isotope; Yorkshire; Arras culture; Iron Age

Introduction

The Iron Age 'chariot' burials of East Yorkshire (UK) which have been radiocarbon dated fall into the period of the fourth to second centuries BC (Jay et al. 2012; the term chariot is used loosely (Hill 2002)). The first two (not dated, since the skeletal remains are untraced) were excavated between 1815 and 1817 at Arras, providing a type site for the regional Arras culture, and they have been discussed in the context of a possible migration of Iron Age people from northern France, where burials with chariots are also found (Stead 1965; Cunliffe 2005). Only a very small number of the Arras culture burials include vehicles and some of them could date back as far as the late fifth century BC, given La Tène I artefact associations. If a migration occurred as a single population event then it may have occurred at this earlier point (Stead 1991; Cunliffe 2005). Alternatively, if Continental-scale movement were operating over the long-term, on an individual level, then the *idea* of the chariots (if not these particular vehicles) is one of the main cultural imports identified and the people buried with them are candidates for a possible mobile lifestyle, if not single event immigration. Giles (2012) provides a discussion of burial identity and journeying together with further detailed referencing for the archaeology of these burials. Only one of them has been found in Britain outside of Yorkshire, at Newbridge in southern Scotland (Carter, Hunter and Smith 2010; no skeletal material survived here for isotope analysis) and that has radiocarbon dates (on wood from the chariot wheels) for the fifth century BC. All but one of the others known (14 certainly, with a further 7 suggested) are in East and North Yorkshire (Fig. 1), with one (Ferry Fryston) further away in West Yorkshire, located on a different geology (Permian limestone).

This study presents new isotope data from the seven chariot burials located on the Chalk (the geological unit containing the late Cretaceous limestone of southern and eastern England) for which skeletal material can currently be traced, alongside new data from 25 contemporaneous burials and some animal remains (see Supplementary Table 1 for details of individuals). The data obtained are carbon, nitrogen and sulphur isotope ratios ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$) from the organic collagen component of both bone and dentine, and strontium and oxygen isotope ratios ($^{87}Sr/^{86}Sr$ and $\delta^{18}O_{phosphate}$) from the inorganic component of tooth enamel.

The pattern emerging from the isotope data prior to this study was that the Iron Age people from the large cemetery at Wetwang appeared to be remarkably settled in their subsistence routine, living and dying locally (Jay and Richards 2006). The Late Neolithic and Early Bronze Age data from the East Yorkshire Wolds region show a different picture, with lifestyles involving more mobility (possibly between local regions) (Montgomery, Cooper, and Evans 2007; Montgomery, Evans, and Cooper 2007). The Iron Age data set from Ferry Fryston (West Yorkshire) indicated that the chariot burial and contemporaneous people from the site may have been incomers to that area (Jay et al. 2007). The objective of the new research was to compare all of the chariot burials from East Yorkshire for which skeletal remains were currently retrievable with the existing patterns of data from the region. The main aim was to see whether there was mobility indicated for these specific individuals and to put their subsistence practices into the context of the main population at the Wetwang cemetery.

Site and burials

Individual burial details are listed in Supplementary Table 1. The seven chariot burials are from Kirkburn, Wetwang Slack (three individuals), Wetwang Village, Garton Station and Garton Slack.

Wetwang Slack is the largest Middle Iron Age cemetery in Britain, and one of the largest in Continental Europe (Fig. 2). Bayesian analysis dates its main period of use to the 3rd and early 2nd centuries BC, with burial possibly starting before 300 BC, but with the majority of burials taking place within a 150 year core period (Jay et al. 2012). It contains over 450 burials, many of them under barrows surrounded by four-sided ditches ('square' barrows) and some accompanied by La Tène-style artefacts, with three chariot burials located together on the edge of the excavations just outside of the main part of the cemetery (Dent 1984; Dent 1985b; Dent 1985a). The site stretches over a parish boundary, so that the burials also excavated from Garton Slack, including the chariot burial from there, are effectively from the same group (Brewster 1971). The five vehicle burials from Wetwang Slack, Wetwang Village and Garton Slack are within 2.5 km of each other (Dent 1985a; Hill 2002).

The Kirkburn and Garton Station chariot burials are to the east (Fig. 1), approximately 4.5 km away from the Wetwang burials, and are close to each other (Stead 1991). The two-wheeled vehicles included amongst the grave goods of all of the burials analysed had been dismantled with the wheels laid flat, unlike that at Ferry Fryston which was buried intact and upright, as was that at Newbridge in Scotland and some of those off the Chalk in North Yorkshire for which skeletal remains are unavailable for analysis. The upright position is closer to the Continental rite. Two of the burials were of women (Wetwang Village and one of those from Wetwang Slack) who had iron mirrors included amongst their grave goods. The men are often associated with weapons, with two having swords and one a possible shield (Wetwang Slack) and one having an iron chain mail 'coat' (Kirkburn).

Techniques

Detailed explanations of, and primary references for, the background chemistry and the techniques for the different isotope ratio analyses cannot be presented here for reasons of space, but excellent accounts, which provide the detail for the outline summaries below together with further primary references, can be found in Lee Thorp (2008), Hedges (2009), Montgomery, Evans, and Cooper (2007), Bentley (2006), Montgomery (2010) and Nehlich et al. (2011).

Carbon and nitrogen stable isotope analyses are routinely undertaken on skeletal collagen in order to consider dietary inputs, particularly to investigate trophic level, the incorporation of aquatic (marine and freshwater) resources in the diet and the consumption of C_4 plants such as millet, although the latter are not present in prehistoric Britain. Strontium and oxygen isotope ratios from tooth enamel samples are more usually considered as mobility indicators, whilst the use of sulphur isotope ratios from collagen is a more recent technique that is still under development and which is thought to be an indicator of both regional mobility and diet, particularly aquatic diet. Whilst these are the normally accepted uses of individual data sets, all of them are affected by different environmental factors and it is simplistic to suggest that they only reflect one issue, such as diet or mobility. Climate, atmospheric factors, geology, human impact on land use, deforestation, precipitation patterns and many other variables affect one, some or all of the data sets.

The timing of the formation of the tissue being considered will also differ depending on the analysis being undertaken. Strontium and oxygen isotope data in this study are from tooth enamel, since this fraction is better suited to resist diagenetic alteration and contamination during burial and conservation than the inorganic components of bone or dentine. The carbon, nitrogen and sulphur isotope data are from collagen, which has been extracted from both bone and dentine. This organic fraction survives well in the burial environment and there are quality indicators that can be checked for the possibility of post-mortem alterations, so that problematic data can be discarded. Teeth, both the inorganic enamel and the organic fraction of the dentine, form during childhood, the precise age range depending on the tooth chosen. The isotope ratios are largely ‘set’ at that point, with very little remodelling during later life, so that the data obtained from teeth reflect childhood diet. Bone, on the other hand, undergoes biomolecular change during life, with a decreasing rate of turnover as an individual ages. A bone collagen sample from an adult will reflect a life time averaged diet, with a tendency to be weighted towards adolescence in cortical long bone (Hedges et al. 2007). There may also be timing differences between particular bone tissues (e.g., between rib, with a faster turnover period, and long bone cortex which will take longer to remodel: Cox and Sealy 1997). By looking at different tissues, it is possible to track changes between childhood and later life.

These differences, both in the variables which affect the different isotope systems and the timing of the tissue formation, mean that combining the use of different skeletal elements and isotope ratios in a single study will yield more information than can be gained by restricting the study to single chemical elements or skeletal fractions. The study presented here illustrates the value of this wider range of analyses, highlighting quite subtle indications in the combined data.

For all of the isotope systems discussed here, the biomolecular 'building blocks' forming the skeletal tissues are ultimately obtained from ingested food and drink. For collagen analyses (C, N and S), they are mainly derived from protein and the dietary components being reflected are thus often weighted more heavily towards the consumption of animal products where the protein levels are higher. Carbon isotope data mainly reflect atmospheric conditions affecting plants at the base of the food chain, whilst for nitrogen isotopes the soil composition and trophic level of the consumer are both important. Strontium isotopes from enamel are controlled by the local geology, solid and drift, and by atmospheric inputs such as rainfall for which the source is mainly seawater. In contrast to carbon and nitrogen isotopes in collagen, they tend to be weighted towards the consumption of plants rather than animal products. The reasons for this are complex; the majority of strontium in an animal is found in the bones not the edible muscle, and strontium absorption from ingested food is suppressed in the presence of calcium and protein (i.e. meat and milk) and enhanced in the presence of plant fibre and phytate. For oxygen in enamel phosphate, the main origin is drinking water and this is affected by environmental factors such as climate, altitude and distance from the coast. None of these are completely straightforward processes and an understanding of the variables which affect the different systems is essential for interpretation.

The data as presented are ratios of two isotopes and these are stable in the sense that they are not radioactive, so that they do not change over time after the death of the individual. They are compared with the ratios from international standards specific to the element involved and, excepting strontium, are presented as δ values (e.g., $\delta^{13}C$) in ‰ (per mil) units. For strontium, the values are shown as a straightforward ratio ($^{87}Sr/^{86}Sr$). Although the heavier of the two strontium isotopes is radiogenic, formed from the decay of rubidium, the half-life involved is at a geological time scale, so that the ratio effectively provides a stable system for archaeology.

Materials and Methods

Collagen analyses

The new collagen data discussed here ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$) are from both bone and dentine in the majority of cases. The dentine was from the roots of the same teeth that were sampled for enamel for the measurement of strontium and oxygen isotopes. The samples were taken from the enamel dentine junction down to the root apex, so that they reflect later childhood and are not expected to reflect any breastfeeding contribution, particularly bearing in mind that in this population weaning may have been very early indeed (Jay et al 2008). Bone samples were all rib, except for three of the chariot burials (Wetwang Village, Garton Station and Kirkburn) where samples were taken from both rib and humerus, as well as dentine, so that timing differences between the formation periods of the collagen can be obtained (dentine showing a mainly childhood signal, humerus showing long-term averaged lifetime, and rib having a higher turnover rate and possibly indicative of an average more skewed towards the end of an individual's life).

Collagen was extracted in the biomolecular chemistry preparation laboratories at the Max Planck Institute for Evolutionary Anthropology in Leipzig and in the stable isotope facility laboratories of the Archaeology Department at the University of Bradford. Methods employed were the same at both facilities and can be found in the Appendix in Jay (2008) and in Nehlich et al. (2011). Carbon and nitrogen isotope analyses were undertaken at both facilities, whilst all sulphur isotope analyses were undertaken in Leipzig. Two replicates were run for each sample, analysed in separate batches, and the results averaged. Averaged replicates were used where possible for sulphur, but where only one analysis was possible due to limited sample availability, this is indicated by italics in Supplementary Table 2.

The widely accepted quality tests for collagen $\delta^{13}C$ and $\delta^{15}N$ data in terms of atomic C:N ratios and appropriate elemental percentages (DeNiro 1985; Ambrose 1990; van Klinken 1999) were met for all samples referred to in this paper. The quality tests for sulphur suggested by Nehlich and Richards (2009) were also met.

Enamel analyses

Tooth enamel samples were used for $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{phosphate}$ analysis. Methods are detailed in Montgomery, Evans, and Cooper (2007) and Evans, Chenery, and Fitzpatrick (2006). Analyses were undertaken at the NERC Isotope Geosciences Laboratory (NIGL) in Nottingham. Oxygen data are presented as measured phosphate values relative to SMOW, rather than as conversions to drinking water values, in order to avoid the error issues discussed in Pollard, Pellegrini, and Lee-Thorp (2011).

Results and discussion

Supplementary Table 2 lists the $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ data, along with the relevant collagen quality data, and Supplementary Table 3 lists the $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{phosphate}$ data. Table 1 (main text) lists those burials which deviate from the locally expected pattern of isotope ratios and indicates which ratios are unusual for that individual. All of the chariot burials are listed there for completeness, although that from Wetwang Village is not unusual for any of the ratios and is entirely consistent with the local data set. Table 1 also gives information about the ranges which are considered consistent with the local environment, so that it is clear why any particular individual has been identified as exceptional.

Figure 3 shows the $\delta^{13}C$ and $\delta^{15}N$ values from adult bone samples plotted for both the new data presented here and for previously published values from Wetwang Slack (Jay and Richards 2006; Jay et al. 2007). The data set is tightly constrained, other than for the labelled individuals shown on the plot, and reflects a terrestrial diet high in animal protein for a population with an apparently very consistent subsistence base. A full discussion of the previously published data can be found in Jay and Richards (2006), this also covering the suggestion that WWS-14 and 431 might be mobile individuals based on their high $\delta^{15}N$ values. British Iron Age human $\delta^{13}C$ data tend to be constrained within the range here (Jay and Richards 2007), whilst a group containing Continental migrants might be expected to produce a wider range, with data falling towards the more positive end of the scale, partly because millet (a C_4 plant) was included in the food chain outside of Britain at this time (Le Huray and Schutkowski 2005; Schmidl, Jacomet, and Oeggl 2007) and partly due to climate differences (van Klinken, van der Plicht, and Hedges 1994). It is important when looking at the *absolute* range in the literature that data from different laboratories are not compared without a clear understanding of small differences which may occur due to the use of different analytical standards, calibration or data normalization techniques (e.g., Lightfoot et al. 2009; Stevens et al. 2010: $\delta^{13}C$ and $\delta^{15}N$ data here are not directly comparable with this paper). $\delta^{15}N$ values can differ in range for specific locations across very short distances irrespective of dietary components and will be affected by factors affecting the soil, such as salinity or manuring, and also geology, so that the range for Britain generally is much wider than is seen for the majority of this population, even where the diet is interpreted as being very similar (Jay and Richards 2007).

For the new data, WWS-89 also has an unusually high $\delta^{15}N$ value, close to WWS-431. The new chariot burial data appear to group towards the higher end of the $\delta^{13}C$ range and to be slightly enriched in ^{15}N compared to the other samples at this end of the carbon isotope ratio range (see Jay and Richards 2006 for discussion of the apparent trend in mature adult males towards lower $\delta^{15}N$ values combined with enrichment in ^{13}C). However, the Wetwang and Garton Slack vehicle inhumations fit within the general pattern and it is the Garton Station and Kirkburn individuals which fill in this area of the chart. In other words, this difference is not necessarily related to the fact that these individuals were special and had been buried with vehicles, but more likely to be related to them being from other sites, albeit very close to Wetwang (within 5 km).

Figure 4 shows the human bone nitrogen and sulphur isotope data plotted with Iron Age and Romano-British herbivores from Wetwang. The bulk of the non-chariot burials have similar $\delta^{34}S$ values to those of the herbivores, which would be expected for a community who were consuming animal and plant protein from the local area, since there is no significant fractionation between consumer and food. There are, however, distinctions for the chariot burials and for three of the Wetwang non-chariot burials. All but one of the vehicle burials fall below the dotted line on the chart (indicating the local 'baseline' – see Table 1), the one which is more like the general population being Wetwang Village, both rib and humerus plotting above the line. The three non-vehicle burials from Wetwang Slack which fall below the line are WWS-14, 431 and 89, and these appear unusual in terms of δ^{34}S values, as well as for δ^{15}N values as noted for Figure 3. The first two of these are also unusual for their dentine carbon and nitrogen isotope ratios and for their strontium composition (Table 1).

Neither WWS-14 nor 431 have any grave goods, the former is male and the latter female, and they are both secondary burials rather than primary and from opposite ends of the cemetery. Overall they are not outstanding archaeologically, although it may be of interest that WWS-14 is located at the extreme eastern end of the cemetery, the other side of a Bronze Age barrow respected by the Iron Age development (Fig. 2). WWS-13, which is the primary burial in the barrow which contains WWS-14, is not unusual for its carbon and nitrogen isotope data, but does have an interesting combination of strontium isotope ratio and concentration (Fig.s 4 and 5). WWS-89 is a primary barrow burial accompanied by an iron brooch and has a strontium isotope ratio that falls within the range expected for material from this location, so it is only the nitrogen and sulphur isotope data which are distinct for this individual.

Figure 4 shows a strong correlation between sulphur and nitrogen isotope ratios (R^2 = 0.6831), with lower δ^{34}S values associating with higher δ^{15}N values, but this is driven by the three individuals below the line and by the chariot burials which fill in the trend. If these are removed, the bulk of the data do not reflect this relationship (R^2 = 0.1177).

If this pattern is related to the types of foods being consumed, then it is not immediately obvious how this might be interpreted. All of the Iron Age people presented here have been interpreted from the carbon and nitrogen isotope data as consuming relatively high levels of animal protein (in addition to C_3 plant foods), and not including significant (isotopically visible) levels of aquatic resources in their diets (Jay and Richards 2006; Jay and Richards 2007). The data relationships do not extend to the $\delta^{13}C$ values, so that minor (currently isotopically invisible) changes in aquatic resource consumption are unlikely to be the driver (see Jay 2008 for an Iron Age aquatic foodweb), although a similar correlation has been seen in British Roman data which has been interpreted in this way (Nehlich et al. 2011). The most extreme values belong to individuals who also have non-local strontium isotope ratios (see below). Whilst this may result from consuming freshwater fish from a water source located on a different type of geology, it is unlikely that such dietary protein would control human strontium isotope ratios unless the humans in question were carnivores (with very low levels of plants in their diet) because plants will have a stronger influence on dietary strontium. The carbon and nitrogen isotope ratios, the osteological evidence for caries and the archaeological evidence for grain consumption all indicate that these people were omnivores.

The coincidence of high $^{87}Sr/^{86}Sr$ values alongside the unusual nitrogen and sulphur isotope ratios might be explained if these people came in from outside the region after childhood (explaining the non-Chalk strontium isotope ratios) and also had a diet which was different to that of the rest of the group. Such a diet might include freshwater fish, which could lead to lower $\delta^{13}C$ values (Jay 2008). There is no indication from the $\delta^{13}C$ values, however, that this is the case, nor do the $\delta^{13}C$ values suggest Continental immigration which would probably lead to higher values caused by climatic influences and millet in the food chain. Excluding immigration is important because Iron Age carbon and nitrogen data from across Britain, including from coastal and riverine sites, do not indicate that either marine or freshwater resources were significant contributors to the diet (Jay and Richards 2007; Jay 2008; Lightfoot et al. 2009; Stevens et al. 2010). If the nitrogen and sulphur isotope ratio relationship here were indicative of the consumption of freshwater protein, then either it is contrary to the trend in British Iron Age people generally, or else such resources were present in the diet elsewhere, but we are fundamentally misunderstanding what we would expect to see from the carbon and nitrogen data in these circumstances. As single individuals, however, it is impossible to completely rule out that these people either had unusual diets, or that they were not from Britain. Larger data sets and more research should improve our understanding of these issues.

Mobility between two locations is believed here to be the most likely governing factor for this correlation, driven by differences in the geological or environmental backgrounds, perhaps involving different water sources, levels of agricultural activity or salinity inputs.

Figure 5 plots $^{87}Sr/^{86}Sr$ against concentration for the tooth enamel samples: the inverse of the concentration is used here as this highlights mixing line relationships and thus high concentrations are on the left and low concentrations on the right. Some dentine values have also been plotted, these being indicative of the trend towards diagenetic change (equilibrating to the burial environment) since the inorganic fraction of bone and dentine is much less resistant than the enamel to such alteration. Cretaceous Chalk is an extremely homogenous, pure rock and has strontium isotope ratios between 0.7075 and 0.7078 (McArthur, Howarth, and Bailey 2001) and in the region of the Wolds there are virtually no overlying drift deposits (British Geological Survey 1977). Measurements of Chalk, Chalk-derived soils and water from Chalk aquifers in England have provided ratios from 0.7075 to 0.7079 and plants grown on Chalk soils range from 0.7077 to 0.7087 (Evans et al. 2010; Montgomery, Evans, and Cooper 2007). The majority of dentine values are consistent with this range, as would be expected if they had been affected by diagenetic change as a result of the burial environment. In addition to the strontium intake directly from the local geology, that from rainwater, introduced indirectly via plant foods and directly via drinking fluids, can be ingested in variable quantities and is a significant source in temperate, high rainfall regions (Montgomery 2002; Montgomery 2010; Evans et al. 2010). According to a simple two-component model, a community subsisting entirely on food sourced from a pure Chalk substrate plus an input from rainwater should, therefore, define a spread of ratios from 0.7075 (as represented by the values for dentine on the chart between 0.7075 and 0.7080) to ~0.7092, the value for rainwater, for which seawater is the main source (Montgomery, Evans, and Cooper 2007). The main population define a diagonal mixing line between two sources of strontium contributing different concentrations and ratios, and conform to a simple two end-member model for sedentary agricultural communities farming on one type of geology with a secondary atmospheric input of rainwater. The majority of the humans from Wetwang fit this simple model and are thus consistent with having lived as children (when the tooth enamel was forming) on the Chalk.

There are exceptions to the pattern. WWS-431 and 14 are above the rainwater line and do not fall within the local mixing line. Two teeth were analysed for WWS-431: 2nd and 3rd molars. Enamel mineralization for these occurs at different times during childhood, the second molar between around 2½ and 8 years, and the 3rd molar between around 7 and 16 years (AlQahtani, Hector, and Liversidge 2010). Both of these teeth plot in a similar area of the chart, suggesting that this individual spent most of her childhood and early adolescence away from the site at which she was buried. WWS-14, which had the most extreme $\delta^{15}N$ value, also has the second highest strontium isotope ratio and this plots alongside a high $^{87}Sr/^{86}Sr$ value for the dentine of the same individual, which has not equilibrated with the local burial environment. The other four individuals which have higher than expected strontium isotope ratios, and do not fit the Chalkland model, are the Kirkburn chariot burial (WWK-37) and three non-chariot burials, WWS-98, 143 and 223. WWS-98, whilst not having a chariot, is unusual in that he was buried with a sword and shield, with WWS-143 being a male without any grave goods from an unremarkable secondary grave in a barrow ditch, and WWS-223 is a female primary barrow burial with an iron brooch (not unusual for this cemetery). WWS-13 (an adolescent male), which was the primary barrow burial contextually related to WWS-14, has a $^{87}Sr/^{86}Sr$ value within the range for Chalk-dwellers, but is separated from the Wetwang population due to an anomalously low strontium concentration. This might suggest that this boy was originally from outside the community, but the factors controlling dietary strontium and consequent levels in tooth enamel are complex and multi-factorial, thus the fact that he died at an early age might have had an effect on, or been affected by, his childhood diet, so that this would be a tentative hypothesis.

The Kirkburn individual, in addition to having grave goods which included the vehicle accoutrements, was buried with an iron mail tunic. The only other such Iron Age mail from Yorkshire comes from the Stanwick hoard, although there are other finds from further south in England, but these are generally later in date (Stead 1991). He was, therefore, buried with an unusual item at a date earlier than would be expected. The strontium isotope data indicate that he did not spend his childhood on the Yorkshire Wolds Chalk, whilst the rest of the data suggest that he may have lived there for some years in later life (before he died aged 25-35 years) and was equilibrating a signal similar to his local peers. It is unfortunate that we do not have carbon and nitrogen isotope data from the dentine for this individual (the sample was limited and was used to obtain one analysis of $\delta^{34}S$), but the difference between rib and humerus values is within statistical error, so that post-childhood collagen values are similar. It is highly unlikely that he would have moved from the Paris Basin region of France, suggested in the past as a source area for the chariot burial rite. This is because the geology in that area is also predominantly Chalk, such that the strontium signal would be expected to be similar to the local signal seen for the rest of this group. In addition, the $\delta^{18}O$ value is similar to all of the other chariot burials (Fig. 6) and falls well within the range for Britain, as does the dentine $\delta^{13}C$ value, which might be expected to be higher for a Continental migrant (van Klinken, van der Plicht, and Hedges 1994). It is likely, therefore, that the location would have been in Britain and there are geological terrains not far distant to the north and west as well as further afield that could provide such biosphere values (Evans, Chenery, and Montgomery 2012).

In addition to unusual strontium isotope ratios, WWS-98 has a significant difference between the bone and dentine $\delta^{13}C$ values, WWS-143 has a similar difference between the bone and dentine $\delta^{15}N$ values and WWS-223 has an interesting combination of dentine nitrogen and sulphur isotope ratios (Fig. 5). Differences between the bone and dentine values are important because of the timing of the tissue formation. If the values differ significantly, then there is a likelihood that either *in situ* dietary components changed after childhood, or else there was mobility. The coincidence between the unusual values for strontium and the other indicators, alongside the fact that the diet for the Wetwang group as a whole (excluding these unusual individuals) was consistent across age ranges (Jay and Richards 2006) would suggest that in these cases the driver is mobility, although it is not impossible that the strontium isotope data indicate mobility, whilst the collagen isotope data indicate coincidental or associated changes in dietary component or source.

Other than Kirkburn, the chariot burials fit well on the local strontium mixing line. Bearing in mind that the strontium data are from childhood tooth enamel, the tissue formation timing is closer to the dentine rather than the bone, so that Figure 6, showing dentine $\delta^{34}S$ and $\delta^{15}N$ data, better reflects early diet than Figure 4. Whilst the general trend of higher nitrogen isotope ratios plotting with lower sulphur isotope ratios is once again present, most of the chariot burials sit above the 'baseline' for the dentine, with only WWS-14, 223 and 431 showing at the other extreme, and the chariot burial WWS-454 somewhat adrift from expectations. The Kirkburn chariot burial is not shown on this chart because no $\delta^{15}N$ value is available for the dentine, but the $\delta^{34}S$ value is 12.4‰ so that it would be just below the line. In general, therefore, the idea that the childhood values match the local environment for the chariot burial group is true for both strontium and sulphur, although Kirkburn has a disparate strontium isotope ratio and WWS-454 is outside the sulphur isotope range.

The $\delta^{18}O$ data are plotted on Figure 7 with strontium isotope ratios. The ranges shown for Britain are taken from the NIGL archaeological data archives and the mean for Britain of 17.7 ± 0.7‰ is from a normally distributed data set of 615 individuals (Evans, Chenery, and Montgomery 2012). The chariot burials are all very close to that value. All of the data fall within the British range, with a tendency towards the eastern side of the chart, which is consistent with the site locations in East Yorkshire (Fig. 1).

Conclusions

The majority of the Wetwang individuals show an isotope ratio pattern which supports a settled community living and dying on the Chalk. This makes them highly valuable as a 'baseline' template for a community which lives in this way. For this majority, the strontium data define a two end-member mixing line and indicate a group of individuals consuming locally sourced foods. This pattern is expected in theory, but is unusually seen because 'noise' from mobility and a number of different dietary resources will make it invisible for most groups. Very few individuals fall outside of this, or produce data which would indicate mobility, but one of the chariot burials (Kirkburn) is clearly different.

The sulphur and nitrogen isotope data correlate, suggesting again the presence of two end-members. The chariot burials tend to fill in an area of the chart along the trendline between the main group and a small number of outliers for bone, but not for dentine, indicating that their subsistence pattern has been slightly different to that of the main group during their adult lives, but that they lived similarly as children. This may be related to the fact that Garton Station and Kirkburn are at different sites, since they are further along the trend than the Wetwang burials, but Wetwang Village is the only one which is above the local sulphur 'baseline' value. The other two sites are some kilometres to the east of Wetwang, on lower ground, and closer to currently permanent water sources that run into the River Hull. It may be that the data structure is showing a link between the use of resources between these two parts of the local landscape for a small number of individuals after childhood.

Some of the strontium isotope outliers are certainly indicative of movement outside of the Chalkland (e.g., WWS-14 and 431) and these continue to fit on the extreme of the sulphur and nitrogen correlation trendlines for both childhood dentine and adult bone, such that they may have spent a large part of their early childhood off the Yorkshire Wolds. This might mean that whilst the majority of the population rarely left the main site, a few either travelled backwards and forwards between two locations during their lifetime, or else lived most of their lives at the other location and were buried at the Wolds sites. There are no particular archaeological indicators attaching to those involved, since they range from a chariot burial through to an individual with no grave goods buried in a barrow ditch and they are a mix of males and females.

Strontium and oxygen isotope analysis of the chariot burials alone would not have answered the question of whether they originated in the putative source region of the Paris Basin because the geology is the same as that of the Yorkshire Wolds and the oxygen isotope ratio may not have differed substantially. It is the combination of data here, together with the context of the pattern of isotope data produced by the main part of the Wetwang population, which has allowed us to state that the majority of them did not originate on the Continent and probably did not move far from their burial sites for long periods during their lives. Kirkburn may have come to the Wolds after childhood, but this move is unlikely to have been from outside Britain.

The patterns being picked up here are quite subtle and are only visible because the data set comprises different skeletal tissues, the analyses cover different isotope systems and the main population is settled and restricted to the local environment, with an apparently consistent diet. These factors together have produced data which will continue to yield interesting interpretations as we build further on investigating the hypotheses presented here.

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Figures

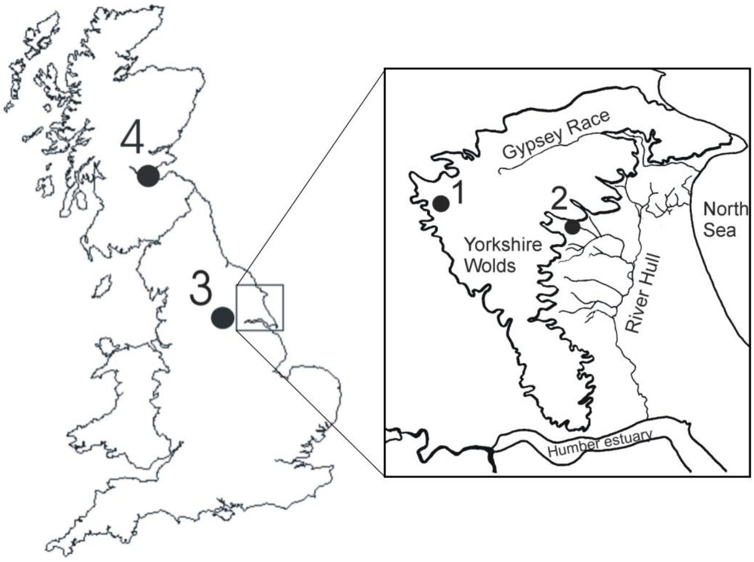

Figure 1. Map showing the East Yorkshire Wolds area (heavy black outline is the 60m contour), with drainage to the east into the River Hull, on lower ground between the chalk Wolds and the North Sea coast. The Humber estuary is to the south of the Wolds and the seasonal watercourse of the Gypsey Race is in the northern high ground. The sites mentioned in the text are marked as: (1) Wetwang and Garton Slacks, and Wetwang Village; (2) Garton Station and Kirkburn; (3) Ferry Fryston; (4) Newbridge.

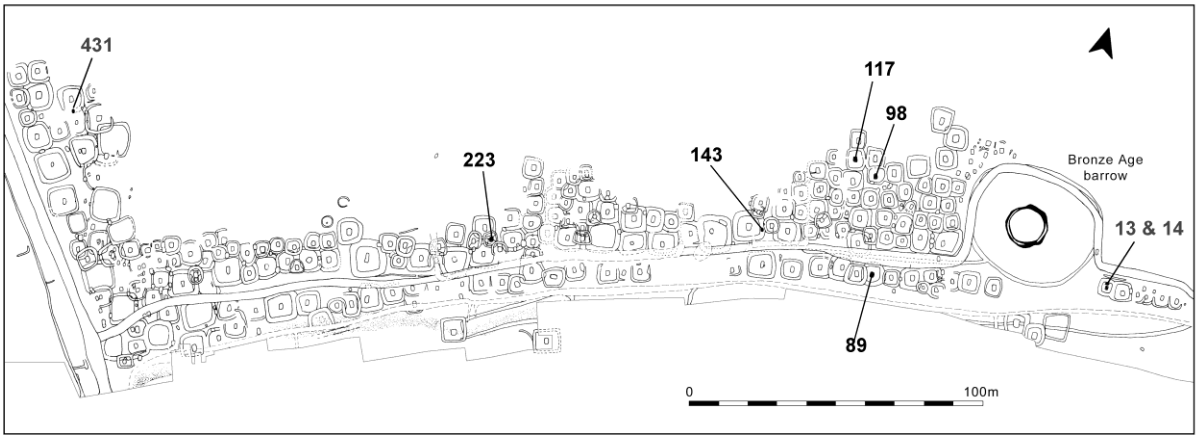

Figure 2. Plan of the Iron Age cemetery at Wetwang Slack, showing positions of those non-chariot burials which are mentioned in the text. The three Wetwang Slack chariot burials are slightly outside of the plan, to the south west. Original plan is courtesy of John Dent.

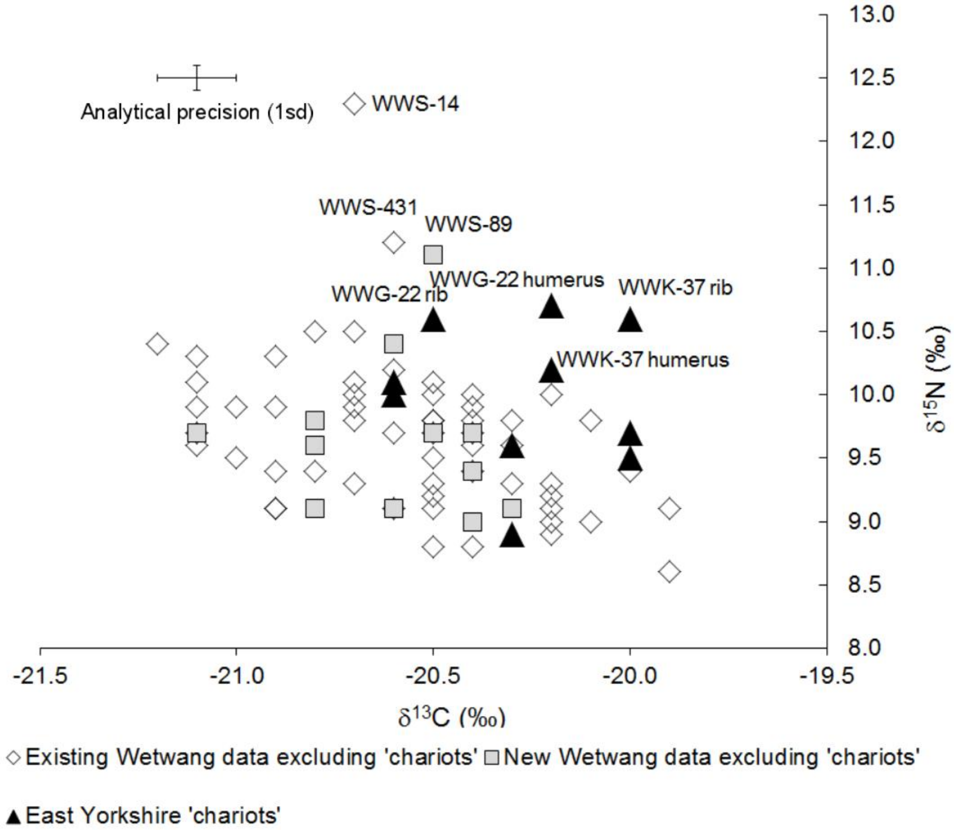

Figure 3. Carbon and nitrogen isotope ratios from bone plotted for Iron Age Wetwang (both previously published and new data), with chariot burials plotted separately and individuals of particular interest marked. Three of the chariot burials (Garton Station, Kirkburn and Wetwang Village) show values plotted for both humerus and rib analyses. WWS = Wetwang Slack; WWG = Garton Station; WWK = Kirkburn. For previously published data, see Jay and Richards 2006 (Wetwang).

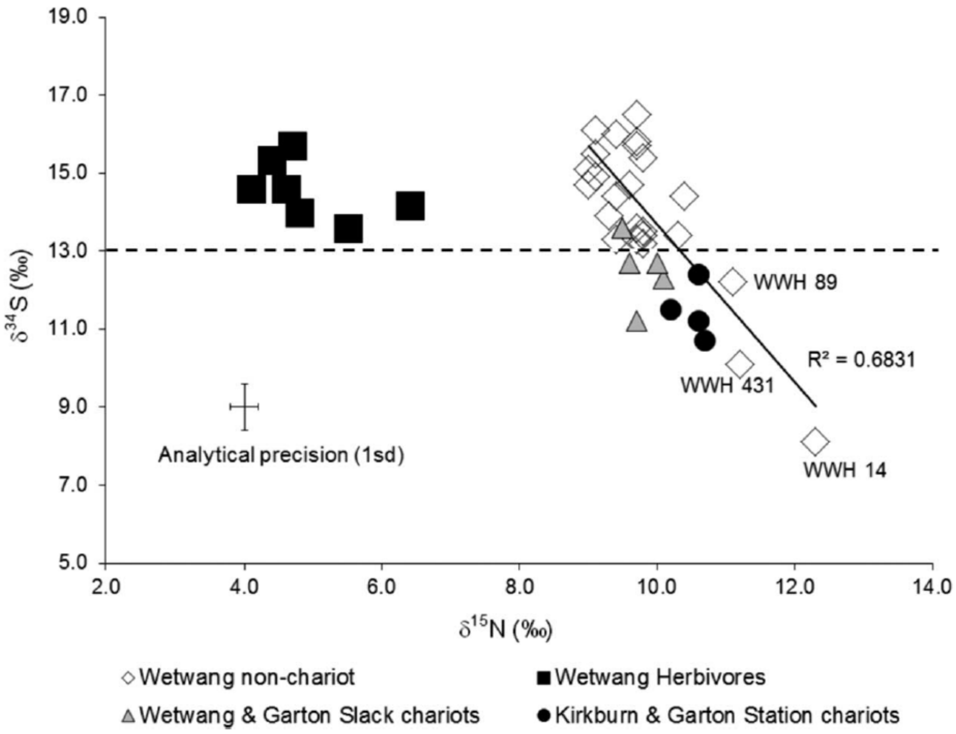

Figure 4. δ^{15}N and δ^{34}S data plotted for bone from the East Yorkshire Wolds humans and herbivores (sheep (*n* = 4); red deer (*n* = 2); cattle (*n* = 1)), showing a strong correlation for the humans. The dotted line indicates a possible cut-off point above which the main group of humans is equivalent in δ^{34}S values to the herbivores. Three of the chariot burials (Garton Station, Kirkburn and Wetwang Village) show values plotted for both humerus and rib analyses, with both of the values above the line being from Wetwang Village.

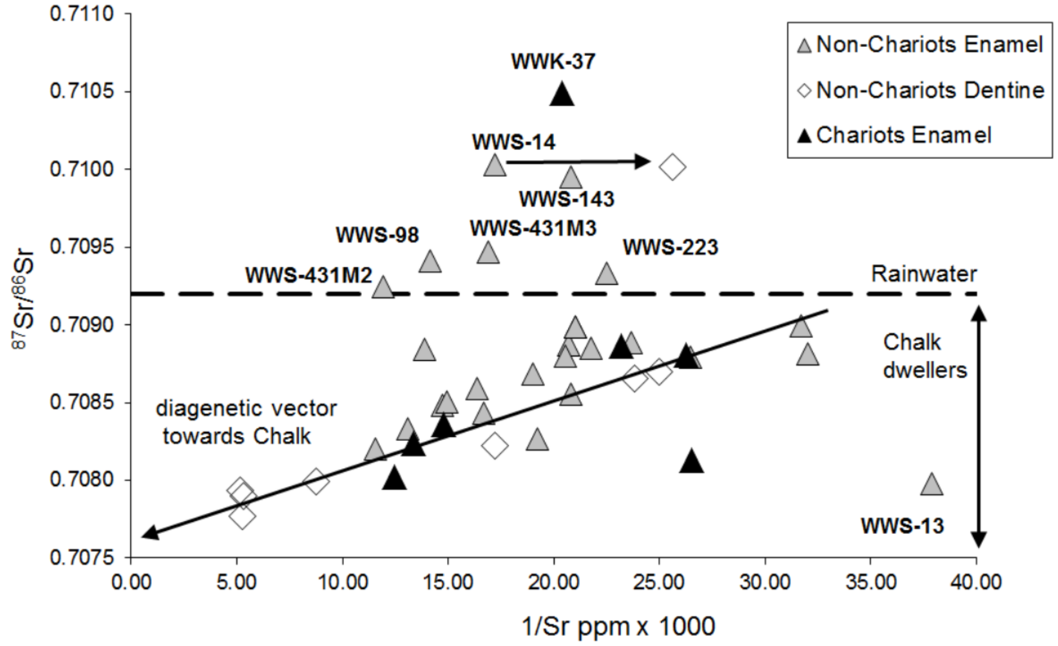

Figure 5. $^{87}Sr/^{86}Sr$ data plotted against strontium concentration for enamel and dentine. The band below the dotted line reflects the expected enamel range for a childhood diet sourced from the local chalk geology. The dentine is liable to diagenetic alteration and expected to equilibrate with the local burial environment, so that the more extreme values for this fraction represent the location. Those samples which plot above the dotted line are suggestive of some level of mobility and are labelled. Only one of these is a chariot burial (Kirkburn). 2sd errors are within symbol.

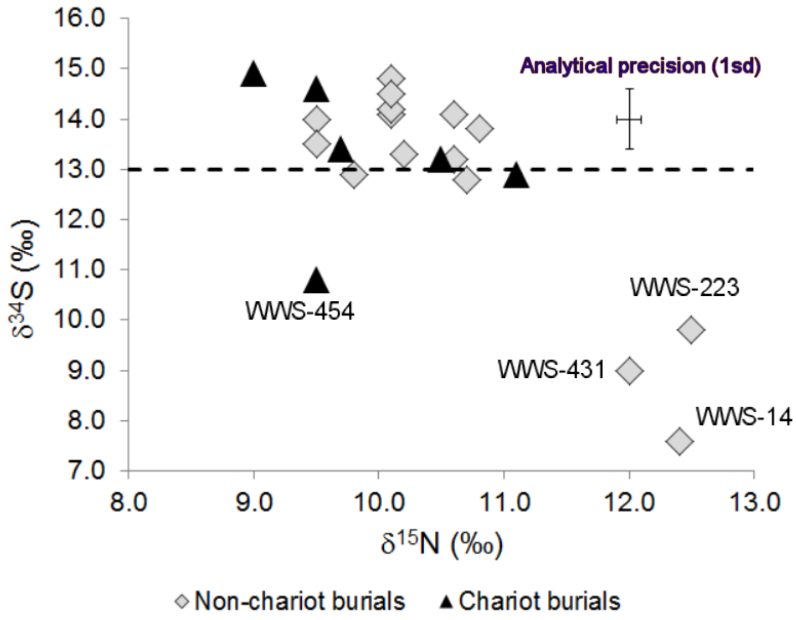

Figure 6. Nitrogen and sulphur isotope ratios from dentine, with chariot burials plotted separately and individuals of particular interest marked. The dotted line represents the $\delta^{34}S$ value 'baseline' for the herbivores, as shown in Figure 4.

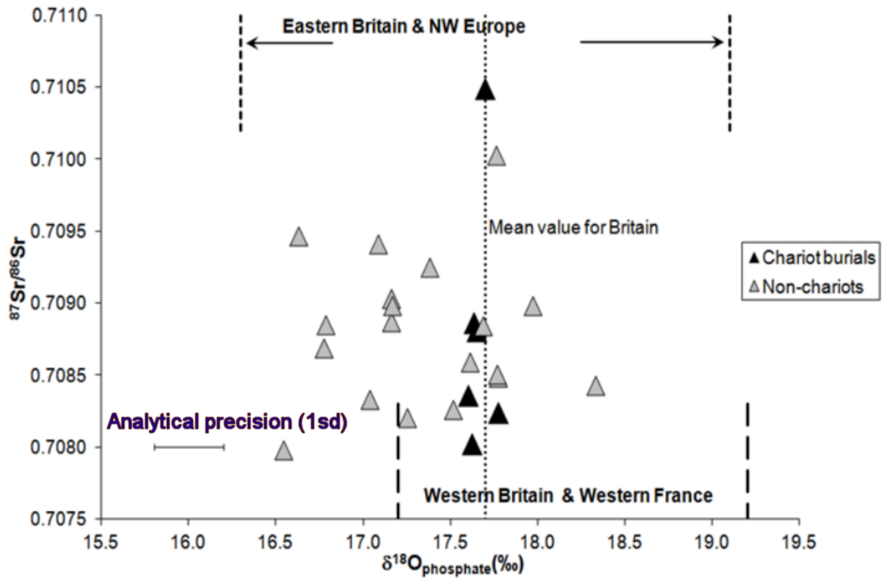

Figure 7. $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ data from enamel. 2sd errors are within symbol for $^{87}Sr/^{86}Sr$. The ranges of $\delta^{18}O$ values shown for eastern and western Britain and the mean value for Britain (17.7 ± 0.7‰) are taken from Evans, Chenery, and Montgomery (2012).

Tables

Table 1. Individuals with notable isotope ratios highlighted (Yes = notable; No = 'normal'; nd = no data). Those not included in the table have no value of particular interest, but data are provided in Supplementary Table 2. The definitions of expected ranges are given below.

	Bone collagen			Dentine collagen			Enamel	
Sample	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{34}S$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{34}S$**	**$\delta^{18}O$**	**$^{87}Sr/^{86}Sr$**
Chariot Burials								
WWK-37 (Male)	Yes*	Yes*	Yes	nd	nd	No	No	Yes
WWG-22 (Male)	Yes*	Yes*	Yes	No	No	No	No	No
WWE-01 (Female)	No	No	No	No	No	No	No	No
WWG-825 (Male)	No	No	Yes	No	No	No	No	No
WWS-453 (Male)	No	No	Yes	Yes	No	No	No	No
WWS-454 (Female)	No	No	Yes	No	No	Yes	No	No
WWS-455 (Male)	No	No	Yes	No	No	No	No	No
Non-chariot Burials								
WWS-431 (Female)	No	Yes	Yes	No	Yes	Yes	No	Yes
WWS-14 (Male)	No	Yes	Yes	No	Yes	Yes	No	Yes
WWS-89 (Male)	No	Yes	Yes	No	No	No	No	No
WWS-117 (Male)	No	No	No	Yes	No	No	No	No
WWS-223 (Female)	No	No	No	No	Yes	Yes	No	Yes
WWS-143 (Male)	No	No	No	No	Yes	No	No	Yes
WWS-98 (Male; sword & shield)	No	No	No	Yes	No	No	No	Yes
WWS-13 (Probable male)	No	No	No	No	No	No	No	Yes

Local data range definitions:

Bone collagen:	
$\delta^{13}C$	In absolute terms, the range for Britain and this site in particular for Iron Age individuals with a terrestrial, C_3 diet, is -19.9 to -21.4‰ (see Jay & Richards 2007). Where two of the chariot burials are highlighted as unusual, this is *in combination* with the $\delta^{15}N$ data. They are not outside the absolute range.
$\delta^{15}N$	For this particular site and time period, the mean value is 9.6 ± 0.5‰ (*n*=62, including WWS-431, but excluding WWS-14). At 95%, anything out of the range 8.6 to 10.6‰ is considered unusual here (Jay & Richards 2006). Whilst two of the chariot burials fall just within that range, at 10.6‰, they are considered unusual *in combination* with the $\delta^{13}C$ data for those samples.
$\delta^{34}S$	The main cluster of Wetwang individuals, together with the animals from the site, range from 13.0 to 16.5‰ (see Fig. 3). Anything below 13.0‰ is considered unusual here.
Dentine collagen:	
$\delta^{13}C$	For prehistoric, terrestrial C_3 diets, a shift between bone and dentine $\delta^{13}C$ and $\delta^{15}N$ is indicated over large data sets from Britain (including over 350 individuals analysed for the Beaker People project, unpublished, in prep.), which may be physiological. $\Delta^{13}C_{bone\text{-}dentine}$ is estimated at -0.2 ± 0.3‰ for carbon based on unpublished data, such that the 95% range for absolute dentine values here is given as -21.4 to -19.1‰. Based on that, no individual is unusual, but the table highlights two individuals who have $\Delta^{13}C_{bone\text{-}dentine}$ values outside the 95% range.
$\delta^{15}N$	As above, with the $\Delta^{15}N_{bone\text{-}dentine}$ shift estimated at 0.2 ± 0.5‰, such that the range for dentine here is given as 8.6 to 11.8‰. Three individuals fall outside that range (WWS-431, 14 and 223), whilst two also have $\Delta^{15}N_{bone\text{-}dentine}$ values outside the 95% range (WWS-223 and 143).
$\delta^{34}S$	The shift noted above is not apparent for sulphur data. The range for dentine data is therefore the same as for bone above.

Enamel	
$^{87}Sr/^{86}Sr$	The expected range for the chalk geology on the Yorkshire Wolds is estimated at 0.7077 (as represented by the lowest equilibrated dentine value obtained) to 0.7092 (as represented by seawater/rainwater). Highlighted individuals have values above this, except for WWS-13, which is highlighted because of the lower value *in combination* with a strontium concentration which falls away from the main trendline illustrated in Fig. 4.
$\delta^{18}O_{phosphate}$	The range for archaeological samples from Britain is taken from Evans *et al.* 2012 as 17.2 ± 1.3‰ (2sd) for eastern Britain and 18.2 ± 1‰ (2sd) for western Britain, so that the 95% ranges are 15.9 to 18.5‰ and 17.2 to 19.2‰ respectively. No individuals fall outside the range for Britain.

Notes:

*These carbon and nitrogen ratios are unusual in combination, rather than in isolation.

nd = no data. The Kirkburn chariot burial dentine did not yield sufficient collagen to run carbon and nitrogen analyses, although one replicate for $\delta^{34}S$ was obtaine

Supplementary Table 2: δ^{13}C, δ^{15}N and δ^{34}S data for bone and dentine collagen.

Sample no.	Skeletal fraction	δ^{13}C (‰)	δ^{15}N (‰)	δ^{34}S (‰)	C:N	C:S	N:S	C (%)	N (%)	S (%)
Chariot Burials										
WWK-37	Humerus	-20.2	10.2	11.5	3.3	550	170	44.6	16.1	0.222
WWK-37	Rib	-20.0	10.6	11.2	3.2	522	163	43.7	15.9	0.217
WWK-37	Dentine	nd	nd	*12.4*	nd	nd	nd	nd	nd	0.275
WWG-22	Humerus	-20.2	10.7	10.7	3.2	495	154	44.0	16.0	0.237
WWG-22	Rib	-20.5	10.6	*12.4*	3.3	471	144	43.1	15.4	0.244
WWG-22	Dentine	-19.9	11.0	*12.9*	3.2	433	134	41.5	15.0	0.256
WWE-01	Humerus	-20.0	9.5	*13.6*	3.2	463	146	42.4	15.6	0.241
WWE-01	Rib	-20.2	9.5	13.6	3.2	506	158	44.3	16.2	0.238
WWE-01	Dentine	-19.8	9.0	14.9	3.2	436	136	41.2	15.0	0.253
WWS-453	Rib	-20.0	9.7	**11.2**	3.2	**636**	**198**	42.6	15.6	**0.179**
WWS-453	Dentine	-19.4	9.7	*13.4*	3.2	424	131	40.9	14.8	0.258
WWS-454	Rib	-20.6	10.0	12.7	3.4	532	161	43.0	15.2	0.216
WWS-454	Dentine	-20.2	9.5	10.8	3.2	427	133	42.7	15.5	0.267
WWS-455	Rib	-20.3	9.6	*12.7*	3.3	513	154	44.3	15.5	0.230
WWS-455	Dentine	-20.1	9.5	14.6	3.2	433	136	41.2	15.5	0.260
WWG-825	Rib	-20.6	10.1	*12.3*	3.3	509	153	42.5	14.9	0.223
WWG-825	Dentine	-19.8	10.5	13.2	3.2	420	131	41.4	15.0	0.263
Non-Chariot Burials										
WWS-13	Rib	-20.1	9.0	14.7	3.3	464	140	44.4	15.5	0.256
WWS-13	Dentine	-19.8	10.1	*14.5*	3.2	415	128	42.0	15.1	0.270
WWS-14	Rib	-20.7	12.3	*8.1*	3.3	458	140	44.5	15.9	0.223
WWS-14	Dentine	-20.1	12.4	*7.6*	3.3	418	129	42.4	15.2	0.271
WWS-89	Rib	-20.5	11.1	12.2	3.3	475	147	45.3	16.3	0.256
WWS-89	Dentine	-20.1	10.6	13.2	3.2	403	124	41.4	14.9	0.275
WWS-98	Rib	-21.1	9.7	15.7	3.3	458	138	45.9	16.2	0.268
WWS-98	Dentine	-20.0	10.1	14.1	3.2	414	128	40.9	14.8	0.245
WWS-117	Rib	-20.9	10.3	*13.4*	3.3	479	144	42.6	15.0	0.238
WWS-117	Dentine	-20.0	10.1	14.2	3.2	419	131	41.2	15.0	0.263
WWS-121	Rib ext 1	-20.5	9.8	nd	3.3	nd	nd	44.5	15.7	nd
WWS-121	Rib ext 2	-20.3	9.7	*13.2*	3.3	458	138	42.7	15.3	0.259
WWS-121	Dentine	-19.7	9.5	14.0	3.2	406	127	41.3	15.1	0.273
WWS-143	Rib	-20.4	9.0	15.1	3.2	461	143	44.8	16.3	0.260
WWS-143	Dentine	-19.9	10.7	12.8	3.3	390	121	44.1	14.8	0.283
WWS-152	Rib	-20.8	9.8	15.4	3.3	495	152	43.1	15.5	0.236
WWS-160	Rib	-20.8	9.1	14.9	3.3	436	132	45.9	16.3	0.298
WWS-161	Rib ext 1	-20.5	9.3	nd	3.4	nd	nd	43.9	15.4	nd
WWS-161	Rib ext 1	nd	nd	13.9	nd	440	132	nd	nd	0.266
WWS-173	Rib	-20.0	9.4	*13.3*	3.3	423	135	42.2	15.3	0.194
WWS-173	Dentine	-20.2	10.1	14.8	3.2	414	131	40.7	15.0	0.264
WWS-209	Rib	-20.5	9.7	15.8	3.3	450	133	43.7	15.4	0.260
WWS-223	Rib	-20.4	10.4	14.4	3.2	504	156	46.7	16.9	0.249
WWS-223	Dentine	-20.6	12.5	9.8	3.2	399	123	43.1	15.5	0.289
WWS-249	Rib	-20.4	9.4	16.0	3.3	480	144	45.7	16.4	0.255
WWS-268	Rib	-20.6	9.1	16.1	3.3	446	137	44.0	15.8	0.263
WWS-274	Rib	-20.8	9.6	***14.7***	3.4	**346**	**101**	44.0	15.0	**0.339**
WWS-275	Rib	-20.7	9.8	13.4	3.2	454	141	45.6	16.2	0.207
WWS-275	Dentine	-19.9	10.6	14.1	3.2	453	142	42.6	15.4	0.246
WWS-301	Rib	-21.1	9.7	*13.6*	3.4	454	134	44.3	15.2	0.260
WWS-301	Dentine	-20.4	9.8	*12.9*	3.2	495	154	37.2	13.6	0.201
WWS-336	Rib	-20.4	9.7	16.5	3.2	483	151	44.8	16.3	0.248
WWS-336	Dentine	-20.8	10.2	*13.3*	3.3	416	127	41.8	14.9	0.268
WWS-348	Rib	-20.4	9.8	13.5	3.4	541	166	42.1	15.0	0.225
WWS-351	Rib	-20.4	9.7	*13.3*	3.4	506	151	43.1	15.1	0.228
WWS-351	Dentine	-20.1	10.8	*13.8*	3.3	433	132	42.1	15.0	0.259
WWS-388	Rib ext 1	-20.9	9.4	nd	3.4	nd	nd	43.4	14.8	nd

WWS-388	Rib ext 2	*-20.8*	*9.9*	*14.4*	3.4	423	124	44.3	15.5	0.273
WWS-431	Rib ext 1	-20.6	11.2	nd	3.3	nd	nd	42.5	15.5	nd
WWS-431	Rib ext 2	-20.8	11.2	10.1	3.3	489	150	45.4	16.3	0.249
WWS-431	Dentine	-20.6	12.0	9.0	3.2	410	128	42.7	15.5	0.278
WWS-451	Rib	-20.3	9.1	15.5	3.3	494	152	46.0	16.5	0.248
WWS-451	Dentine	-19.9	9.5	*13.5*	3.3	502	154	39.5	14.2	0.210
Herbivores										
WWA-10	Sheep humerus	-21.0	4.6	*14.6*	3.3	568	177	41.7	15.2	0.196
WWA-12	Red deer mandible	-20.9	4.7	*15.7*	3.4	552	168	41.8	14.8	0.202
WWA-15	Sheep rib	-21.8	4.8	*14.0*	3.3	558	171	42.5	15.2	0.204
WWA-27	Cattle long bone	-20.8	4.4	*15.3*	3.3	539	166	41.2	14.8	0.204
WWA-39	Red deer tibia	-21.6	6.4	*14.2*	3.3	526	162	42.1	15.2	0.214
WWA-50	Sheep tibia	-21.8	4.1	*14.6*	3.2	507	158	41.1	14.9	0.216
WWA-57	Sheep rib	-22.8	5.5	*13.6*	3.3	574	177	42.3	15.2	0.197

Notes:

1. Isotope ratio data shown in italics are from only one sample run. All others have been duplicated.
2. Sulphur data in bold suggest a cautious concern over sample quality, although they are not outside the absolute limits of the quality criteria suggested by Nehlich & Richards, 2009.
3. nd = no data; ext 1/2 = collagen extraction & analysis 1/2 (1 = Bradford; 2 = Leipzig).
4. Where carbon and nitrogen data have been previously published (Jay & Richards, 2006; 2007) for 17 of the human samples and all of the animals, they are presented here again for ease of access of sample quality data for the sulphur analyses. All of the sulphur data are new.
5. All samples were processed and analysed either in the University of Bradford or the Leipzig Max Planck Institute laboratories. For bone, inter-laboratory comparisons have been done and no significant differences are noted, such that the data are comparable. The processing was undertaken by Jay personally in both laboratories and the analysis overseen by her. She has a number of years' experience working in both laboratories and has regularly compared collagen samples, international standards and laboratory standards between the two locations. For dentine, all samples were processed and analysed in the Bradford University laboratories and were run after the 2006 change in the internationally recognised value for the standard for carbon, IAEA CH-7, had been instituted at that laboratory. For this reason, the $\delta^{13}C$ values for the dentine have been adjusted to be comparable to the bone data in this respect.

Supplementary Table 3: $^{87}Sr/^{86}Sr$ (enamel and dentine) and $\delta^{18}O_{phosphate}$ (enamel) data.

Sample no.	Tooth	$^{87}Sr/^{86}Sr$	Sr ppm	1/Sr x 1000	$\delta^{18}O_{phosphate}$ (‰)
WWK-37	P_2L Enamel	0.710492	49	20.40	17.8
WWG-22	P_2R Enamel	0.708240	75	13.33	17.6
WWE-01	M^2L Enamel	0.708360	68	14.76	17.7
WWS-453	M_2L Enamel	0.708022	80	12.48	17.7
WWS-454	M^1R Enamel	0.708807	38	26.28	17.6
WWS-455	M_2R Enamel	0.708129	38	26.53	nd
WWG-825	M^2R Enamel	0.708866	43	23.19	17.6
WWS-13	P_2L Enamel	0.707980	26	37.89	17.3
WWS-14	P_1L Enamel	0.710028	58	17.24	17.9
WWS-14	P_1L Dentine	0.710019	39	25.64	
WWS-89	M_2L Enamel	0.708997	32	31.71	17.2
WWS-98	M^2R Enamel	0.709411	71	14.15	16.8
WWS-117	M^2R Enamel	0.708985	48	21.03	17.2
WWS-121	M^2L Enamel	0.708430	60	16.67	17.3
WWS-121	M^2L Dentine	0.708226	58	17.24	
WWS-143	M^2R Enamel	0.709952	48	20.80	17.0
WWS-152	P^2L Enamel	0.708202	86	11.56	17.8
WWS-160	M_2L Enamel	0.708792	38	26.46	17.1
WWS-161	P_2L Enamel	0.708484	68	14.71	17.2
WWS-161	P_2L Dentine	0.707933	193	5.18	
WWS-173	P_1R Enamel	0.708505	67	14.93	18.3
WWS-173	P_1R Dentine	0.707989	114	8.77	
WWS-186	M^2R Enamel	0.708330	76	13.11	17.8
WWS-209	M^2L Enamel	0.708886	42	23.68	16.8
WWS-223	M^3L Enamel	0.709332	44	22.48	16.6
WWS-249	M^1L Enamel	0.708685	53	19.00	17.6
WWS-268	C_1(L?) Enamel	0.708554	48	20.81	17.4
WWS-274	M^1L Enamel	0.708812	31	32.03	18.0
WWS-275	M_2R Enamel	0.708847	46	21.74	17.5
WWS-275	M_2R Dentine	0.708700	40	25.00	
WWS-301	M^2R Enamel	nd	nd	nd	17.5
WWS-336	M^2L Enamel	0.708800	49	20.55	16.5
WWS-348	M_2L Enamel	0.708969	52	19.19	17.1
WWS-348	M_2L Dentine	0.708657	42	23.81	
WWS-351	P_1L Enamel	0.708593	61	16.39	18.2
WWS-351	P_1L Dentine	0.707771	189	5.29	
WWS-388	M_2R Enamel	0.708845	72	13.89	17.3
WWS-388	M_2R Dentine	0.707900	188	5.32	
WWS-431(1)	M^3R Enamel	0.709466	59	16.91	17.7
WWS-431(2)	M^2R Enamel	0.709247	84	11.93	17.2
WWS-451	M^2R Enamel	0.708263	52	19.21	18.3

Note: nd = no data