Appendix 3: Isotope Analysis of Individuals from the Ridgeway Hill Mass Grave

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SUMMARY

The multi isotope study of the ribs and femurs from at least 40 individuals and teeth from 31 individuals from the Ridgeway mass grave indicate this was a disparate group in terms of origin, migration and dietary habits. Many, if not all, of the individuals spent most, possibly all, of their lives outside of the British Isles. Isotope evidence suggests they may have lived in places as far afield as Scandinavia, the Baltic States, Belarus and Russia; all of which fall within viking reach. This group also appear to have a wide range of individual diets, which were high in animal protein and primarily based on terrestrial food sources with small to moderate additions of marine and freshwater protein. The circumstances that brought these individuals to the Weymouth area are unknown; however isotope data indicates that at least 38 of them were living outside the British Isles in the few years prior to their deaths.

INTRODUCTION

As part of the assessment phase of work, earlier isotope analysis of tooth enamel from ten of the individuals from the Ridgeway Hill mass grave had shown that this group of men had spent their childhood outside the UK (Chenery *et al*. in press; Boyle 2011). The ten individuals showed a diversity of oxygen and strontium isotope composition which indicated that, although they were not from the UK, they were a disparate group that could have come from across Scandinavia and possibly western Russia. Carbon and Nitrogen isotope analysis of crown dentine from their teeth showed a greater agreement with Scandinavian diets than UK diets of the time.

For this current project, isotope analysis of the Ridgeway Hill assemblage has been extended to measure the strontium and oxygen isotope composition of an additional 21 tooth enamel and carbon and nitrogen isotopes of the associated crown dentine. In addition to this, carbon, nitrogen and oxygen isotope analysis of femur and rib bones, from 45 contexts of infra-cranial remains comprising 23 partially complete skeletons, 17 complete skeletons and 5 isolated limbs, which together represent a minimum number of 40 individuals, has also been undertaken. The aim of this was to compare isotope evidence for climate conditions at place of residence and diet at two stages in the lives of these individuals; the ribs representing a period closer to death and the femurs representing a longer term average (see below).

Isotope Background

Strontium, oxygen and carbon plus nitrogen form three independent isotope systems which reflect local geology, climate and diet respectively. Throughout life bone is constantly remodelling and a number of factors influence the rate of bone turnover such as type of bone tissue, skeletal element, time of life, and nutritional and health status (Sealy *et al*. 1995). A number of authors suggest that any isotopic difference between ribs and femurs is related to dietary difference over time and not to due to metabolic/physiological effects (Jørkov *et al.* 2009; Cox and Sealy 1997; DeNiro and Schoeninger 1983). While the bone turnover rate is not precisely known, Hedges *et al*. (2007) demonstrated that there is a wide envelope of turnover rates for femur collagen that is higher for males under the age of 24 and significantly decreases with age. Their fast and slow turnover models suggest that between 25 and 50% of collagen in a person at 35 years can be expected to have been synthesized prior to the age of 20 and conclude that: '*Human femoral bone collagen isotopically reflects an individual's diet over a much longer time than 10 years, including a substantial portion of collagen synthesized during adolescence*'. Less information in available for ribs, however the general consensus is that the remodelling rate of rib is faster than that of femur with suggested values of 2-5 years (Pollard *et al*. 2012; Jørkov *et al*. 2009; Sealy *et al*. 1995).

Unlike bone, the primary tissues in teeth (bioapatite and collagen) are not remodelled and therefore the isotope values represent an individual's age at

the time of tooth tissue formation (Hillson 1996; Price *et al*. 2002; Hoppe *et al*. 2003). The timing of enamel formation for teeth used in this study (M2 & pM1) is similar and represents the period of between 5.8 and 6.7 years. Primary dentine begins to form at the same time as enamel mineralization begins and develops incrementally from the top of the crown to the root. Crown dentine is complete around 2 years after enamel formation but the root continues to grow for approximately another 5.5-6 years. For this study only bulk crown dentine was sampled for analysis.

Carbon and nitrogen isotopes

Isotope analysis of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in collagen provide evidence for sources of dietary intake – plant carbohydrates (fruits, vegetables and grains) and plant and animal protein (meat, fish and milk products) respectively (Cox 2001). Nitrogen isotopes primarily provide information about trophic level position in the food chain. There is a step-wise increase in $\delta^{15}N$ through each trophic level that entails a fractionation of up to *c* 6‰ from diet to consumer (O'Connell *et al*. 2012). For example, herbivores will be one trophic level above that of the plants on which they graze, and carnivores will be a trophic lever higher than herbivores from the same ecosystem. Extended food chains, involving several carnivorous steps, produce the highest $\delta^{15}N$ values and long food chains are typical of aquatic systems. In general, higher the nitrogen isotope values are generally taken to indicate a greater consumption of animal protein. However a high consumption of grains or plants subjected to manuring can lead to an elevation in $\delta^{15}N$ values (Hedges and Reynard 2007). Additionally, individuals whose diet is high in aquatic food sources will have increased levels of $\delta^{15}N$ values (higher for those consuming marine foods) compared to those with a wholly terrestrial diet (Schoeninger and DeNiro 1984; Richards and Hedges 1999). The most commonly used values for nitrogen is a 3-4‰ shift per trophic level (Hedges and Reynard 2007).

Animal tissues will also reflect the carbon isotope ratios ($\delta^{13}C$) of the plants and animals consumed and can be used to distinguish between marine and terrestrial sources of carbon (Schoeninger and DeNiro 1984). Due to different photosynthetic pathways different plant types can be distinguished by their isotope values. C_4 plants (including grains such as maize or millet, and sugarcane) and marine plants and algae have higher carbon isotope values than C_3 terrestrial plants (almost all other grains, fruits and vegetables) (Schoeninger and DeNiro 1984). However $\delta^{13}C$ values are lower in freshwater plants and aquatic foods sources compared with terrestrial sources (Schoeninger and DeNiro 1984). C_4 cereals and sugar cane were not a food source in northern Europe during the Anglo-Saxon and medieval periods.

As a result of continual bone renewal, carbon and nitrogen isotope values represent periods of time prior to an individual's death based on the turnover rate of the bone in question. Thus comparisons of carbon and nitrogen isotopes measured in primary crown dentine, femur and rib can be used to provide an estimate of dietary change during an individual's life time.

Oxygen isotopes

Oxygen isotopes provide evidence of place of origin and habituation based on the relationship between ingested water and the geographic variation in the isotope value of drinking water sources. Oxygen isotopes ($\delta^{18}O$) in bio-apatite (the mineralized component of teeth and bones) are directly related to body water oxygen which, in turn, is related to the composition of ingested water (Longinelli 1984; Iacumin *et al*. 1996; Luz *et al*. 1994; Koch 1998). Drinking water (and ground water) is ultimately derived from meteoric water and the oxygen

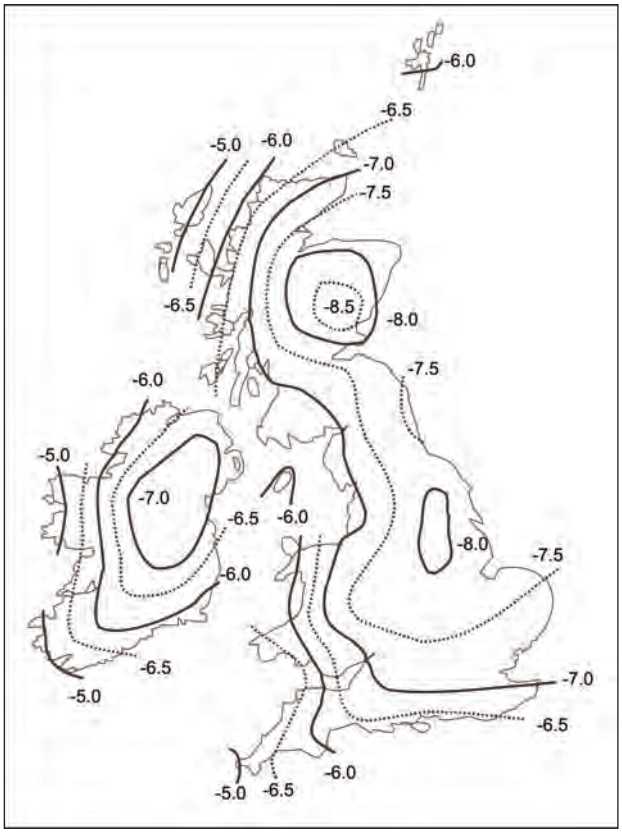

Fig. A3.1 Contour map of $\delta^{18}O$ in recent groundwaters of the British Isles (after Darling et al. 2003, fig 6)

isotope value varies according to geographical and climatic factors and in particular temperature, altitude, and distance to the coast (Dansgaard 1964).

The oxygen isotope values of ground waters are well characterized for the Britain and Ireland and vary systematically across the UK from higher ratios (-4.5‰) on the extreme west coasts to lower in the east (-9.0‰ NE Scotland (Darling *et al*. 2003), see Fig. A3.1)). A similar pattern with more extreme values exists for Western Europe (see Fig. A3.2 and Lecolle 1985; Longinelli and Selmo 2003; IAEA/WMO 2006) and the Eastern Mediterranean follows a similar trend (Lykoudis and Argiriou 2007). In Iceland values for surface and ground waters range from -5.0‰ in the south, to -13.6‰ (for surface waters) and *c*. 15.0‰ (for geothermal waters) (Pope *et al*. 2010). The long term mean values for precipitation (un-weighted) at Reykjavik is around -8.0‰ (IAEA/WMO, 2006) with local bottled water values around -8.7‰ (Bowen *et al*. 2005). The mean expected value for the Weymouth area is -6.5‰ and range for Southern Britain is between -6.0‰ to -7.0‰ (Darling *et al*. 2003).

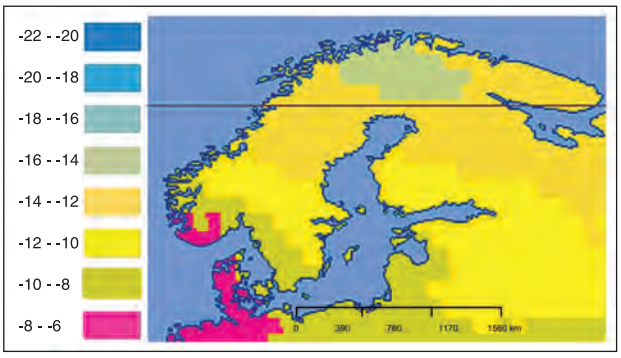

Fig. A3.2 Isotope map of Scandinavia showing long-term average of annual $\delta^{18}O$ in precipitation (after IAEA/WMO 2006; IDW long-term annual average precipitation $\delta^{18}O$ map)

Oxygen (as with other light stable isotopes D/H, C, N) is subject to several stages of metabolic fractionation, from drinking water to body fluids and again from body fluids to bioapatite (bone and tooth enamel). This fractionation is fairly well understood and predictable, thus allowing the calculation of drinking water values to assist in determining an individual's place of origin (Longinelli 1984; Levinson *et al*. 1987; Daux *et al*. 2008). The Levinson *et al*. (1987) equation ($\delta^{18}O_{DW} = (\delta^{18}O_P - 19.4) / 0.46$) will be used to calculate drinking water values, in this report to retain consistency with previous publication from this laboratory, however all the data necessary to calculate using other conversions is provided (see Evans *et al*. 2012 and Chenery *et al*. 2010).

Within mammalian tissues, bioapatite [generalised as $[Ca_{10}(PO_4, CO3)_6(OH, CO3)_2]$ contains two anionic forms of oxygen suitable for isotope analysis: structural carbonate (CO_3^{2-}) and by far the more abundant, phosphate (PO_4^{3-}), see Chenery *et al*. 2012 (Bryant and Froelich 1996; Sonju Clasen 1997; Wilson *et al*. 1999; Munro *et al*. 2008). Oxygen isotopes ratios in CO_3^{2-} and PO_4^{3-} (further referred to as $\delta^{18}O_C$ and $\delta^{18}{}_p$) are cogenetic (formed at the same time) and are directly related by the equation of Chenery *et al*. (2012):

$\delta^{18}O_P = 1.0322 \times \delta^{18}O_C - 9.6849$

(see Chenery *et al*. 2012 for full explanation).

By applying the above equation, $\delta^{18}O_C$ can be converted to $\delta^{18}O_p$ to allow comparison between the anionic types and the calculation of equivalent drinking water values. In this report, $\delta^{18}O_{CP}$ indicates that $\delta^{18}O_C$ has been converted to $\delta^{18}O_p$.

Strontium isotopes

Strontium isotopes ($^{87}Sr/^{86}Sr$) provide evidence for place of origin and habitation based on the relationship between food and water sources that reflect variation in geology. Strontium isotopes in the geosphere relate to the age and type of rock and enters the biosphere through plant and water uptake of strontium derived from the chemical breakdown of rocks and soil. The isotope composition of labile (bioavailable) strontium, is not fractionated by metabolic processes, unlike oxygen, carbon and nitrogen isotopes, and is transmitted unaltered from the geosphere through the biosphere to bioapatite. As strontium isotopes in enamel bioapatite are primarily derived from food, they can be directly related to the labile (soluble) components in the geology of the area where the food was produced (Montgomery *et al*. 2005; Bentley 2006; Evans *et al*. 2006).

The geographic distribution of strontium isotopes in the UK has been characterized by Evans *et al*. (2012), see Fig. A3.3. The Ridgeway Hill site lies on the chalk but is within 7km of Weymouth centre which is situated on London Clay. The map of strontium isotopes in the biosphere of Britain (Evans *et al*. 2010) suggests that individuals raised locally at Ridgeway Hill will have childhood tooth enamel values between 0.708-0.709 (if raised specifically on Chalk), and between 0.709- 0.710 if raised on the nearby London Clay. Hence the best estimate of a local signature is between 0.708 and 0.710 based on these two dominant lithologies. Outside the UK values of between 0.702 and 0.780 can be found in natural mineral waters across Europe (Voerkelius *et al*. 2010). In Denmark the range of bio-available $^{87}Sr/^{86}Sr$ is from approximately 0.7078 to 0.7108 (Frei and Frei 2011; Price *et al*. 2011 and 2012).

Norway and Sweden are composed of old rocks of Palaeozoic and Precambrian age. There is limited strontium biosphere data available from this area. High values (>0.72) are recorded for animals and lake waters in Sweden by Aberg (1995). Samples from 45 rivers plot largely between 0.72 and 0.74 from Sweden and Finland (Aberg and Wickman 1987). However, lower values are also recorded for mineral water in limited coastal areas from Norway (Voerkelius *et al*. 2010). Mineral water $^{87}Sr/^{86}Sr$ for areas of younger geology around the Baltic are expected to have values around 0.708 to 0.711 (Voerkelius *et al*. 2010). Rainwater can also have a muting effect on the geological derived material in coastal areas as is the case in eastern Scotland (Evans *et al*. 2010).

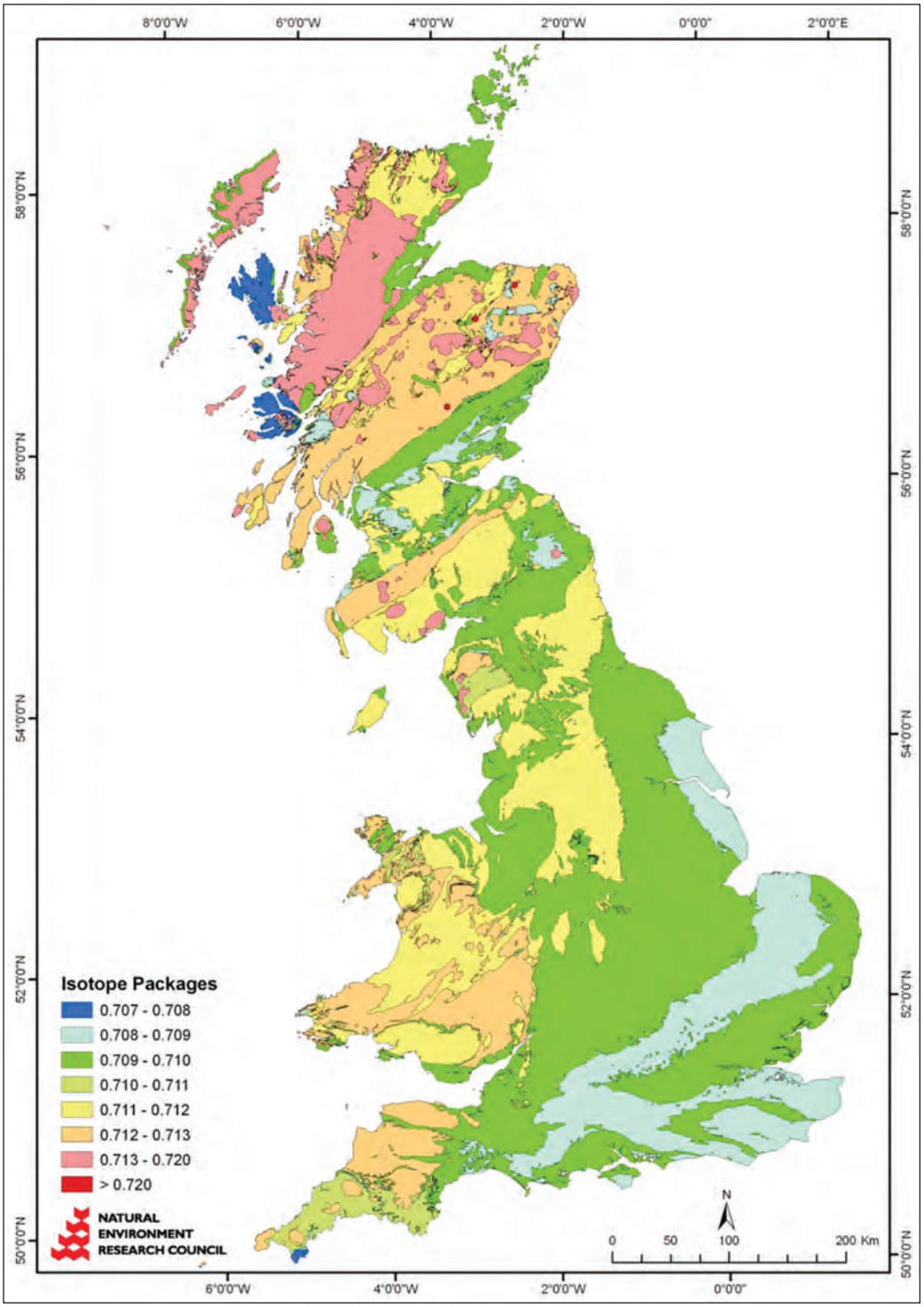

Fig. A3.3 Map of bio-available $^{87}Sr/^{86}Sr$ in the UK (after Evans et al. 2010)

As strontium and oxygen isotopes behave independently of one another, they allow two parameters for investigating an individual's place of origin and migration patterns (Evans *et al*. 2006a).

MATERIALS AND METHODS

Materials

Bone

The ribs and femurs from a total of 45 contexts were sampled for isotope analysis. Among these were 17 complete and 23 partially complete skeletons, which represent a total of 40 individuals, as confirmed during osteological analysis. From this group, ribs and femurs were sampled from 31 individuals; just ribs were sampled from 8 individuals and just femurs were sampled from 7 individuals (Table A3.1). In addition, femurs were sampled from five contexts that comprised isolated limbs only. It was not possible to say whether these contexts represent discrete individuals or not and therefore it is possible that they relate to the discrete skeletons already sampled. Throughout the text the isolated femurs are marked with an asterisk (*). Thus, although totalling 45 contexts, the study sample comprised a minimum of 40 individuals.

Teeth

Teeth from the cranial remains of 31 individuals were selected for oxygen and strontium isotope analysis of enamel and carbon and nitrogen isotope analysis of crown dentine. Only one tooth was sampled per individual. The preferred dentition for place of origin studies is the second molar (M2). The first premolar (pM1) is the most appropriate second choice on this occasion, as the timing for enamel and dentine formation is similar to those of M2s. Due to tooth availability M2s were only available for 21 individuals and pM1s were sampled from the remaining ten individuals. Ten second molars were submitted for analysis in the pilot study carried out in 2010 and the remaining 21 submitted for the current (2012) study were either pM1 or M2. As all tooth enamel samples have been analysed for bioapatite carbonate oxygen ($\delta^{18}O_C$), and only the ten from the 2010 study were analysed for bioapatite oxygen ($\delta^{18}O_P$), only the results for the $\delta^{18}O_C$ analysis will presented and discussed in this report. It should be noted that some individuals did not have suitable teeth for analysis. Additionally teeth from 13 individual were not submitted for analysis in order to preserve the entire dental assemblage for future dental morphological examination. If these 13 individuals are related (familiarly or by place of origin) this sampling bias may affect the overall results of the study.

Sample preparation

Tooth sample preparation

A section of crown enamel was abraded from the surface to a depth of >100μm using a tungsten carbide dental bur and the removed material discarded. A thin slice of enamel was then cut from the tooth using a flexible diamond-edged rotary dental saw. Secondary dentine was removed and discarded and the enamel and primary dentine were separated. The primary dentine was reserved for carbon and nitrogen analyses and the enamel was lightly crushed and aliquots were reserved for oxygen and strontium analysis.

Bone sample preparation

Approximately 4cm of rib bone was freezer-milled to a powder and reserved for carbon, nitrogen and oxygen isotope analysis. All femurs were sampled with a diamond coated dental saw. Each sample was taken from the mid-shaft, avoiding areas with either bone pathology, or recent growth such as muscle attachments, and the external and internal surfaces were abraded to remove the periosteum, endosteum and cancellous bone. All cortical femur bone was freezer-milled to a powder and aliquots were reserved for oxygen, carbon and nitrogen isotope analysis. All bone samples were cleaned with distilled water and dried before milling.

Analytical methods

For the stable isotopes (carbon, nitrogen and oxygen), conventional δ notation is used throughout and isotope ratios are expressed in parts per thousand (permil: ‰) relative to a standard:

$$\delta(‰) = ((R_{sample}/R_{standard}) - 1) \times 1000$$

Carbon and Nitrogen analysis ($\delta^{13}C$, $\delta^{15}N$)

The samples were prepared following a modified Longin method (Brown 1988), described briefly below. Approximately 30 - 100mg of powdered femur and dentine and, ~3cm pieces of rib were covered with 8ml of cold 0.5M HCl to demineralise. The remaining solid collagen was rinsed and solubilised in a solution of pH3 HCl at 70°C in a hot block for 48 hours. The solutions were then filtered using an 8μm Ezze filter to remove solids before freeze drying. Three 0.6mg aliquots from each collagen sample were weighed into small tin capsules for analysis. Bone collagen was analysed in

Table A3.1 Carbon and nitrogen isotopes in ribs and femurs

		Femur							
Skeleton No.	*Age category**	$\delta^{13}C‰$	1σ	$\delta^{15}N‰$	1σ	%C	%N	C:N	n
SK3687	Older adult	-20.3	0.1	12.5	0.0	43.3	15.0	3.4	3
SK3688	Adult unspec								
SK3689	Prime adult	-18.8	0.0	13.9	0.0	39.0	13.9	3.3	3
SK3697	Young adult								
SK3700	Young adult								
SK3715	Prime-mature adult	-21.3	0.0	9.4	0.1	33.1	11.6	3.3	3
SK3716	Young adult	-19.8	0.0	10.6	0.0	32.6	11.6	3.3	3
SK3719	Adult unspec	-20.4	0.1	11.7	0.0	35.9	12.6	3.3	3
SK3753	Young adult	-20.8	0.0	11.8	0.1	38.3	11.8	3.3	4
SK3754	Adolescent	-20.4	0.1	10.3	0.1	38.1	13.5	3.3	3
SK3755	Young adult	-20.4	0.1	10.4	0.0	36.9	12.9	3.4	3
SK3756	Adolescent	-18.3	0.1	13.3	0.1	35.5	12.8	3.3	3
SK3762	Prime-mature adult	-20.1	0.0	11.6	0.1	40.8	14.4	3.3	3
SK3763	Young adult	-18.9	0.1	13.7	0.1	32.8	11.4	3.4	2
SK3764	Prime adult	-20.3	0.1	11.8	0.1	42.8	15.0	3.3	3
SK3768	Older adult	-20.0	0.0	11.9	0.1	39.6	13.9	3.3	2
SK3770	Prime adult	-20.1	0.1	12.1	0.0	36.5	12.7	3.4	3
SK3774	Adult unspec	-19.9	0.1	12.3	0.0	39.4	14.0	3.3	3
SK3775	Adolescent	-19.7	0.0	12.3	0.0	35.2	12.6	3.3	3
SK3777	Mature adult	-19.9	0.0	13.1	0.1	34.6	12.4	3.3	3
SK3778	Mature adult	-20.0	0.0	11.7	0.1	27.4	9.4	3.4	3
SK3781	Prime adult	-20.7	0.1	10.6	0.1	31.2	10.8	3.4	4
SK3783	Adult unspec								
SK3784	Adult unspec	-19.6	0.0	13.0	0.1	38.7	13.9	3.3	3
SK3786	Adolescent	-20.0	0.0	12.0	0.0	42.1	14.2	3.5	2
SK3787	Young adult	-19.3	0.1	13.8	0.1	39.8	14.1	3.3	3
SK3788	Prime-older adult								
SK3789	Adolescent								
SK3790	Young adult	-20.4	0.1	12.5	0.1	39.9	14.0	3.3	5
SK3791	Adolescent	-20.2	0.0	13.2	0.1	42.8	14.9	3.4	3
SK3792	Adult unspec	-20.1	0.0	12.7	0.0	43.4	14.7	3.5	2
SK3794	Young-prime adult	-20.3	0.0	12.9	0.2	44.1	14.8	3.5	3
SK3795	Prime adult	-20.1	0.0	12.6	0.1	43.0	14.5	3.5	3
SK3796	Adolescent	-20.1	0.1	12.8	0.0	44.6	15.5	3.4	2
SK3798	Adolescent	-20.2	0.1	12.4	0.1	43.5	14.7	3.5	3
SK3799	Adult unspec								
SK3800	Mature adult	-20.2	0.1	13.3	0.0	44.4	15.2	3.4	3
SK3801	Prime adult	-20.8	0.0	10.6	0.1	44.1	15.1	3.4	3
SK3803	Mature adult	-18.8	0.1	10.4	0.0	43.9	15.0	3.4	2
SK3804	Older adult	-20.7	0.1	10.4	0.1	40.6	14.2	3.3	3
SK3805	Older adult	-19.9	0.1	12.2	0.1	43.0	15.1	3.3	3
SK3806	Mature adult	-20.3	0.0	13.1	0.1	41.7	14.8	3.3	3
SK3809	Young adult	-20.9	0.1	10.9	0.1	44.3	14.9	3.5	3
SK3810	Young adult	-19.6	0.0	13.0	0.1	43.4	14.9	3.4	3
SK3811	Prime adult	-20.1	0.1	13.3	0.1	43.3	14.9	3.4	2

Isotope values presented, by convention, relative to international references materials: vPDB for $\delta^{13}C$ and AIR for $\delta^{15}N$

triplicate. Dentine collagen was analysed in duplicate, because of the small quantity of dentine extracted. Analysis of carbon and nitrogen isotopes was by Continuous Flow Isotope Ratio Mass Spectrometry (CFIRMS). The instrumentation comprises an Elemental analyser (Flash/EA) coupled to a ThermoFinnigan Delta^{Plus}XL isotope ratio mass spectrometer via a ConFlo III interface.

Collagen carbon and nitrogen isotopes ratios ($\delta^{13}C$ and $\delta^{15}N$) are reported in per mil (‰) relative to Vienna Pee Dee Belemnite (vPDB) and Ambient Inhalable Reservoir (AIR) standards respectively. $\delta^{13}C$ and $\delta^{15}N$ ratios were calibrated using an in-house reference material M1360p (powdered gelatine from British Drug Houses) with expected delta values of –20.32‰ (calibrated against CH7, IAEA) and

				Rib					
$\delta^{13}C$‰	1σ	$\delta^{15}N$‰	1σ	%C	%N	C:N	n	$\Delta^{13}C$	$\Delta^{15}N$
-19.5	0.0	14.0	0.1	36.0	12.8	3.3	3	0.8	1.6
-19.4	0.0	14.1	0.0	39.6	14.0	3.3	3		
-19.2	0.0	14.1	0.0	37.0	13.3	3.3	3	-0.3	0.2
-19.0	0.0	14.0	0.1	36.6	13.0	3.3	3		
-20.3	0.1	9.5	0.0	42.1	14.8	3.3	3		
-21.1	0.0	10.0	0.1	39.9	13.9	3.3	3	0.2	0.6
-19.7	0.1	11.8	0.1	38.4	13.5	3.3	3	0.1	1.2
-20.4	0.0	12.6	0.0	40.4	14.3	3.3	3	0.4	0.8
-20.1	0.1	11.1	0.0	36.8	13.0	3.3	3	0.3	0.9
-19.8	0.1	12.2	0.1	31.9	11.2	3.3	3	0.6	1.8
-18.4	0.0	15.3	0.1	38.8	13.7	3.3	3	-0.1	2.0
-19.2	0.0	13.3	0.1	36.0	12.8	3.3	3	0.9	1.7
-17.9	0.0	16.0	0.2	42.0	14.9	3.3	3	1.0	2.4
-19.8	0.1	12.4	0.0	34.0	12.5	3.2	3	0.5	0.6
-19.5	0.0	13.5	0.0	36.1	12.9	3.3	3	0.6	1.4
-19.8	0.1	12.3	0.1	38.4	13.6	3.3	3	-0.1	0.0
-19.7	0.0	13.8	0.1	40.3	14.3	3.3	3	0.2	0.8
-19.9	0.1	12.1	0.1	43.3	15.3	3.3	3	0.1	0.4
-20.1	0.1	12.1	0.0	40.5	14.3	3.3	3	0.6	1.4
-19.9	0.1	13.6	0.1	39.0	13.7	3.3	3		
-19.5	0.0	12.7	0.1	32.2	11.4	3.3	3	0.5	0.7
-19.4	0.0	13.7	0.1	40.8	14.3	3.3	3	-0.1	0.0
-19.6	0.0	13.4	0.1	35.6	12.5	3.3	3		
-18.2	0.0	14.8	0.1	39.9	14.0	3.3	3		
-19.8	0.0	13.0	0.0	33.2	12.5	3.1	3	0.5	0.5
-20.1	0.1	13.6	0.1	29.3	10.3	3.3	3	0.1	0.4
-20.5	0.0	12.8	0.1	33.3	11.7	3.3	3	-0.2	-0.1
-19.8	0.0	13.5	0.0	36.6	13.0	3.3	3	0.3	0.8
-20.0	0.1	13.0	0.1	34.7	12.8	3.1	2	0.1	0.6
-20.1	0.0	12.5	0.1	35.4	12.9	3.2	3		
-19.6	0.0	14.2	0.0	34.1	11.9	3.3	3	0.6	0.9
-19.9	0.0	12.8	0.1	41.1	14.6	3.3	3	-1.0	2.4
-19.1	0.0	14.6	0.1	42.9	15.1	3.3	3	1.6	4.2
-19.7	0.1	12.8	0.1	36.9	13.0	3.3	3	0.1	0.6
-20.1	0.0	13.2	0.1	34.2	12.2	3.3	3	0.2	0.1
-20.3	0.0	11.7	0.0	36.2	13.0	3.3	3	0.6	0.8
-20.8	0.0	10.0	0.1	37.9	13.4	3.3	3	-1.2	-3.0
-19.5	0.0	14.1	0.0	33.8	12.4	3.2	3	0.5	0.8

*Boyle 2011

+8.12‰ (calibrated against N-1 and N-2, IAEA) for C and N respectively. The standard deviation on bone samples analysed in triplicate for carbon and nitrogen isotope analysis in this study was $\delta^{13}C = \pm 0.17$‰ (2σ, n=76 triplicate analyses) and $\delta^{15}N = \pm 0.15$‰ (2σ, n=76 triplicate analyses). The standard deviation on dentine samples analysed in duplicate for was $\delta^{13}C = \pm 0.15$‰ (22σ, n=31 duplicate analyses) and $\delta^{15}N = \pm 0.10$‰ (2σ, n=31 duplicate analyses). The 1 σ reproducibility for mass spectrometry controls in this batch of analysis were $\delta^{15}N = \pm 0.06$‰ and $\delta^{13}C = \pm 0.06$‰ (1σ, n=15). The results for the In-house modern bone standard, SADCOW, analysed in all sample batches for the batch control (external reproducibility of the full chemical procedure) was $\delta^{15}N = \pm 0.10$‰ and $\delta^{13}C = \pm 0.06$‰ (1σ, n=3).

Oxygen Analysis

Bioapatite oxygen isotope analysis ($\delta^{18}OP$)

Powdered bone samples (15-30mg) were treated to solubilise PO_4 anions and precipitated as silver phosphate, using a method adapted from O'Neil *et al*. (1994). The samples were cleaned in concentrated hydrogen peroxide (BDH, AnalaR - NORMAPUR) for 48 hours to remove organic material and subsequently evaporated to dryness; then dissolved in 2M nitric acid (BDH, AnalaR – NORMAPUR) and transferred to clean polypropylene test tubes. Each sample was then treated with 2M potassium hydroxide (MERCK) for neutralization and 2M hydrofluoric acid (ROMIL, France) to remove calcium from the solution by precipitation of calcium fluoride. The samples were then centrifuged and the supernatant added to beakers containing ammoniacal silver nitrate solution and heated gently to precipitate silver phosphate. The silver phosphate was filtered, rinsed, dried and weighed into silver capsules for analysis. Silver phosphate was analysed by Continuous Flow Isotope Ratio Mass Spectrometry (CFIRMS) using the method of Vennemann *et al*. (2002). The instrumentation comprises a TC/EA (high temperature conversion elemental analyser) coupled to a Delta^{Plus}XL isotope ratio mass spectrometer via a ConFlo III interface (Thermo Finnigan, Bremen, Germany). Each sample was analysed in triplicate and the results were corrected against NBS120c (Florida Phosphate Rock; National Institute of Standards, Boulder, Colorado, USA) using a value of 21.7‰. The value of 21.7‰ was derived from a conventional fluorination calibration (see Chenery *et al*. 2010 and 2012 for calibration details). The mean analytical error for $\delta^{18}O_P$ for ribs and femurs (analysed in triplicate) for this study is ±0.12 (1σ, n=76 triplicate analysis) and this compares well with an expected error for $\delta^{18}O_P$ enamel of ±0.13‰ (1σ, n=51; Chenery *et al*. 2012).

Bioapatite carbonate oxygen isotope analysis ($\delta^{18}O_C$)

Clean core enamel aliquots for bioapatite carbonate oxygen isotope analysis were crushed to a powder and approximately 3mg was loaded into glass vials and sealed with septa. The vials are transferred to a hot block at 90°C on a GV Multiprep system. The vials are evacuated and 4 drops of anhydrous phosphoric acid are added. The resultant CO_2 is collected cryogenically for 14 minutes and transferred to a GV IsoPrime dual inlet mass spectrometer. The resultant isotope values are reported as per mil (‰ $^{18}O/^{16}O$) normalized to the v-PDB scale using an in-house carbonate reference material (KCM) calibrated against NBS19 certified reference material. $\delta^{18}O_C$ values were then converted to the SMOW scale using the published conversion equation of Coplen, 1988 (SMOW=1.03091 x $\delta^{18}O$ PDB +30.91). The $\delta^{18}O_C$ values have then been converted to equivalent bioapatite oxygen values using the equation of Chenery et al., 2012 (see section 1.1.2) and will henceforth be referred to as $\delta^{18}O_{CP}$.

The 1σ reproducibility of in-house reference material (KCM) for this set of analysis is ± 0.11‰ (n=6) and for samples analysed in duplicate ± 0.15‰ (n=8).

Strontium isotope analysis ($^{87}Sr/^{86}Sr$)

In a clean laboratory, the enamel sample aliquots were washed in acetone and cleaned twice, ultrasonically, in high purity water to remove dust and impurities. They were dried and weighed into precleaned Teflon beakers. Each sample was mixed with ^{84}Sr tracer solution and then dissolved in Teflon distilled 16M $HN0_3$. The sample was then converted to Chloride and taken up in 2.5M HCl. Strontium was collected using conventional, Dowex® resin ion exchange methods.

The Sr isotope composition and concentrations were determined by Thermal Ionisation Mass spectroscopy (TIMS) using a Thermo Triton multicollector mass spectrometer. Samples were run at *c* 5V using single Re filaments loaded using TaF following the method of (Birck, 1986). The international standard for $^{87}Sr/^{86}Sr$, NBS987, gave a value of .710251 ± 0.000007 (1σ, n=26). Strontium procedural blanks provided a negligible contribution.

RESULTS

The results of the isotope analysis for tooth enamel, dentine, rib and femur are reported in separate sections for each isotope, below.

Carbon and nitrogen isotopes in bone and dentine

Dentine, femur and rib, carbon and nitrogen isotope data are presented for cranial and post cranial samples in Tables A3.1 and A3.2 and Figs. A.3.4 and 3.5, statistical parameters are presented in Tables A3.3 and A3.4.

Normal distribution (probability) plots and plots of kernel density estimations (RSC 2006) are used as an aid to identifying groups of related individuals. Kernel density estimation is a non-parametric way to estimate the probability density function of a random variable. The area under the curve of a Kernel density plot is equal to one and allows the distribution of different sized populations to be compared.

Table A3.2 Carbon and nitrogen isotopes in dentine

Skull No.	*Tooth*		$\delta^{13}C$‰	*1σ*	$\delta^{15}N$‰	*1σ*	*%C*	*%N*	*C:N*	*n*
SK3694	LR	M2	-20.0	0.0	8.3	0.0	42.0	14.8	3.3	2
SK3696	UR	M2	-21.0	0.1	12.3	0.0	41.7	14.6	3.3	2
SK3704	LL	M2	-20.3	0.1	13.4	0.1	43.8	15.4	3.3	3
SK3705	LR	pM1	-20.5	0.0	12.1	0.1	42.6	15.2	3.3	2
SK3706	UL	M2	-20.4	0.1	10.4	0.1	43.6	15.3	3.3	3
SK3707	UL	pM1	-19.8	0.0	13.1	0.0	44.2	15.5	3.3	3
SK3710	LR	pM1	-21.0	0.1	11.7	0.1	43.5	15.3	3.3	3
SK3711	UL	pM1	-20.8	0.0	10.3	0.0	45.0	15.8	3.3	3
SK3712	UL	M2	-20.9	0.0	10.0	0.0	42.0	14.9	3.3	2
SK3720	UR	M2	-20.8	0.0	12.6	0.1	46.3	16.3	3.3	2
SK3722	LR	M2	-20.0	0.2	13.3	0.0	41.5	14.6	3.3	2
SK3724	UL	pM1	-21.1	0.1	12.4	0.1	44.9	15.8	3.3	2
SK3725	LL	M2	-19.3	0.0	12.4	0.0	41.9	14.8	3.3	2
SK3726	LR	M2	-21.1	0.1	8.4	0.0	43.6	14.5	3.5	2
SK3729	UR	M2	-19.7	0.1	10.9	0.1	42.0	14.8	3.3	2
SK3730	UL	M2	-20.5	0.0	11.3	0.0	48.3	16.8	3.4	3
SK3733	UR	pM1	-20.8	0.1	11.6	0.0	42.5	15.2	3.3	2
SK3738	UL	M2	-20.5	0.1	12.0	0.2	42.4	14.6	3.4	2
SK3739	UL	pM1	-21.1	0.0	12.0	0.0	44.0	15.5	3.3	3
SK3743	LL	M2	-20.6	0.1	12.6	0.0	42.1	14.9	3.3	2
SK3744	LR	pM1	-19.9	0.1	13.8	0.0	43.8	15.4	3.3	2
SK3746	LL	M2	-20.5	0.1	11.1	0.1	41.9	14.9	3.3	3
SK3747	LL	pM1	-20.9	0.0	9.7	0.1	43.0	15.3	3.3	2
SK3749	LL	M2	-20.4	0.1	13.0	0.2	41.7	14.8	3.3	2
SK3751	UR	M2	-20.7	0.0	11.6	0.1	41.5	14.4	3.4	2
SK3752	LL	M2	-20.6	0.0	12.9	0.2	41.7	14.9	3.3	2
SK3757	UL	M2	-19.8	0.1	11.8	0.1	42.7	14.4	3.5	2
SK3758	LR	pM1	-19.7	0.0	11.8	0.1	42.6	15.0	3.3	3
SK3759	UR	M2	-21.1	0.0	10.7	0.0	41.6	15.0	3.3	2
SK3760	UR	M2	-21.0	0.0	11.7	0.1	42.1	15.0	3.3	2
SK3761	UL	M2	-20.5	0.1	11.2	0.0	44.4	15.5	3.4	3

Isotope values presented, by convention, relative to international references materials: vPDB for $\delta^{13}C$ and AIR for $\delta^{15}N$

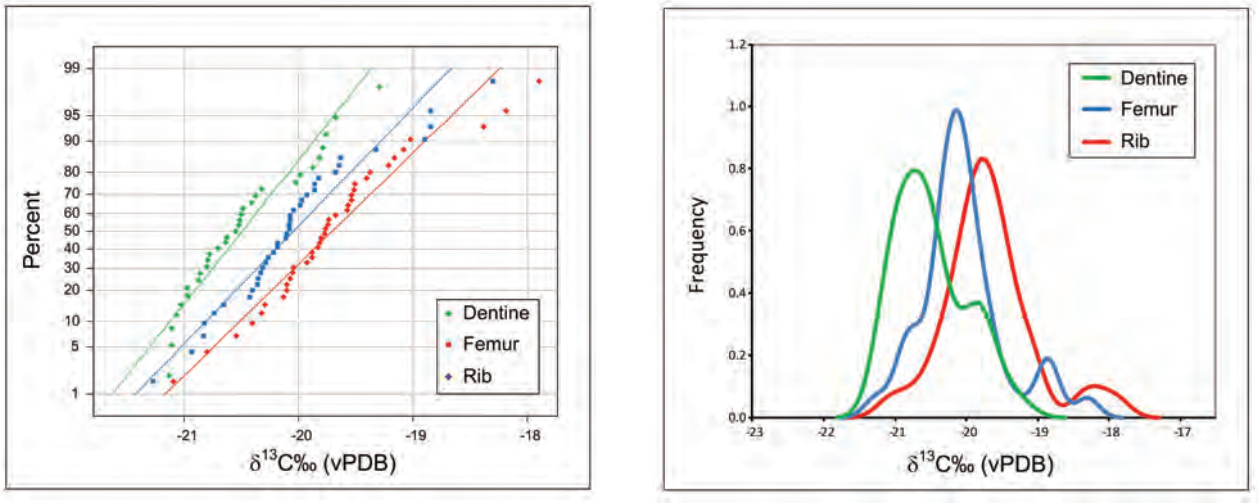

Fig. A3.4 a) Probability and b) Kernel Density plots showing the variation in carbon isotope values of dentine (population 'A'), and femur and rib (population 'B')

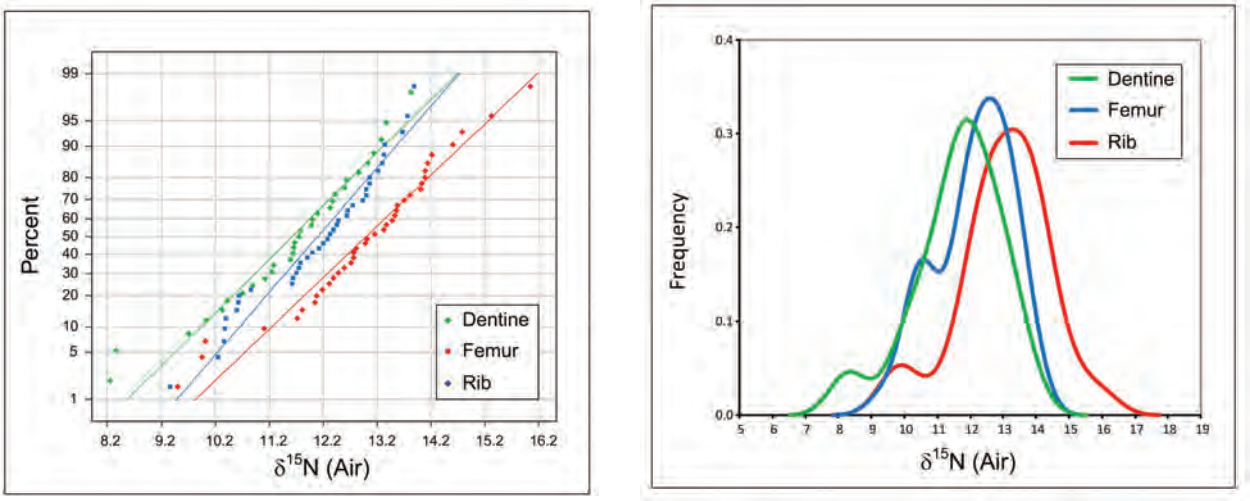

Fig. A3.5 a) Probability and b) Kernel Density plots showing the variation in nitrogen isotope values of enamel (population 'A'), and femur and rib (population 'B')

Carbon isotopes

Dentine

Dentine $\delta^{13}C$ values range from -21.1‰ to -19.3‰ with a mean and median of -20.5 ±0.5‰ (1σ, n=31) and an Anderson-Darling ('AD')[i] goodness of fit of 1.1. Comparing the $\delta^{13}C$ values for pM1s and M2s we find for: pM1a mean of -20.3 ±0.6‰ (1σ, n=9) and a median of -20.5‰ and for M2 a mean of -20.6 ±0.5‰ (1σ, n=22) with a median of -20.7‰. An F-Test for the two sample variables indicated that there was no significant difference between the two types of dentition. Probability and kernel density plots, of the entire dentine set, demonstrate that there is a bi-modal distribution (subsets '1' and '2') with one outlier (Figs A3.4 a and b). Individuals belonging to subset '1' have values ranging from -21.1‰ to -20.3‰ with a median of -20.8 and a mean of -20.7±0.3‰ (1σ, n=23) and a goodness of fit of 0.869. The $\delta^{13}C$ values for individuals in Subset '2' range from -20.0‰ to -19.7‰ with a median of -19.8 and a mean of -19.8 ±0.13‰ (1σ, n=7) and a goodness of fit of 1.65. The single outlying individual (3725) has a $\delta^{13}C$ value of -19.3‰. Subset '1' includes individuals skulls: 3759, 3724, 3726, 3739, 3696, 3710, 3761, 3712, 3747, 3720, 3733, 3711, 3751, 3743, 3752, 3730, 3746, 3738, 3705, 3760, 3706, 3749 and 3704. Subset '2' includes individuals: skulls 3722, 3694, 3744, 3757, 3707, 3758 and 3729.

Infra-cranial elements

Femurs

Femur values for $\delta^{13}C$ range from -21.3‰ to -18.3‰ with a median of -20.1 and a mean of -20.5 ±0.61‰ (1σ, n=38) (Table A3.3) and an 'AD' goodness of fit of 1.4. A probability plot (Fig. A3.4a) and Kernel Density diagram (Fig. A3.4b) of femur $\delta^{13}C$ demonstrates that this is a complex data set. There is a core group of 23 individuals (skeletons 3755, 3790, 3754, 3794, 3687, 3764, 3806, 3791, 3800, 3798, 3792*, 3796, 3811, 3762, 3770, 3795, 3778, 3786, 3768*, 3774*, 3805, 3777, 3716) with $\delta^{13}C$ values ranging from -20.4‰ to -19.8‰, having a normal distribution around a mean of -20.12 ± 0.17‰ (1σ, n=23) and an 'AD' goodness of fit of 0.76. There are two sets of individuals outlying the normal distribution; seven with $\delta^{13}C$ values less than -20.4‰ (3715, 3809, 3801,

Table A3.3 Descriptive statistics for carbon isotopes in dentine, femur and rib

$\delta^{13}C$ *(vPDB)*	*Dentine*			*Femur*		*Rib*	
	All	*pM1*	*M2*	*All*	*pair*	*All*	*pair*
Mean	-20.5	-20.3	-20.6	-20.0	-20.0	-19.7	-19.8
1σ	0.5	0.6	0.5	0.6	0.7	0.6	0.6
Minimum	-21.1	-20.9	-21.1	-21.3	-21.3	-21.1	-21.1
Maximum	-19.3	-19.3	-19.8	-18.3	-18.3	-17.9	-17.9
Median	-20.5	-20.5	-20.7	-20.1	-20.1	-19.8	-19.8
Range	1.8	1.6	1.4	3.0	3.0	3.2	3.2
Count	31	9	22	38	31	38	31

3753, 3781, 3804, 3719*) and eight (3775, 3810, 3784*, 3787, 3763, 3803, 3689, 3756) with values greater than -19.8‰.

Ribs

Rib $\delta^{13}C$ values range from -21.1‰ to -17.9‰ with a median of -19.8‰ and a mean of -19.7 ± 0.64‰ (1σ, n=38) (Table A3.3) and an 'AD' goodness of fit of 1.1. The probability and kernel density plots (Figs. 4 a & b) of rib $\delta^{13}C$ indicate a core data set of 33 individuals whose values range from -20.5‰ to -19.0‰, with a normal distribution around a mean of -19.8 ± 0.38‰ (1σ, n=33) and goodness of fit of 0.48. There are five outlying individuals; three individuals (skeletons 3756, 3789, 3763) with values greater than -19.0‰ and two individuals with values less than -20.7‰. The rib data set has a simpler data distribution than the femurs.

Nitrogen isotopes

Dentine

Dentine $\delta^{15}N$ values range from 8.3‰ to 13.8‰ with a median of 11.8‰ and a mean of 11.6 ± 0.1.3‰ (1σ, n=31) with a goodness of fit of 0.768. While the variance is the same, a t-test suggests they belong to different populations, however given the large difference in sample size; this may not be of great significance. Probability and kernel density plots (Figs A3.5 a and b), for dentine suggests that with the exclusion of two outliers (3694 and 3726 both M2) the remaining samples are normally distributed with a median of 11.8 and a mean of 11.9 ± 0.13‰ (1σ, n=29) with a goodness of fit of 0.51. Comparing the $\delta^{15}N$ values for pM1s and M2s we find for: pM1a mean of +11.6 ±1.0‰ (1σ, n=9) and a median of +12.1‰ and for M2 a mean of 11.5±1.5‰ (1σ, n=22) with a median of +11.7‰. An F-Test for the two sample variables indicated that there was a difference between the two types of dentition. This is also the case when the two M2 outliers are excluded. This difference is not large and may not effect the overall interpretation of the data.

Infra-cranial elements

Femurs

Femur $\delta^{15}N$, values range from 9.4‰ to 13.9‰ with a median of 12.3‰ and a mean of 12.1‰ ±1.15‰ (1σn=38) (Table A3.4) with an 'AD' goodness of fit of 1.01. Probability and kernel density plots (Fig. A3.5 a and b) indicate the presence of a core group of 26 individuals approximating a normally distribution between 11.6‰ and 13.4‰ with a mean of 12.5 ±0.56‰ (1σ, n=26) with a goodness of fit of 0.85. The remaining 12 individuals form two groups of outliers; three with values greater than 13.6‰ (skeletons 3763, 3787, 3698) and nine with values less than 10.9‰ (skeletons 3715, 3754, 3803, 3804, 3755, 3801, 3781, 3716, 3809).

Ribs

The rib data range from 9.5‰ to 16.0‰ with a median of 13.1‰ and a mean of 13.0 ±1.39‰ (1σ, n=38) (Table A3.4) with a 'AD' goodness of fit of 0.785. Probability and kernel density plots (Fig. A3.5 a and b) indicate the presence of a core group of 28 individuals approximating a normally distribution between 11.7‰ and 15.3‰ with a mean of 13.3 ±0.90‰ (1σ, n=33) with a goodness of fit of 0.54. Of the remaining five samples are outliers; four individuals (skeleton 3804, 3789, 3756, 3763) with $\delta^{15}N$ values less than 11.7‰ and one individual with a value of 16.0‰ (skeleton 3763).

Oxygen isotopes on tooth enamel and bone

The results of bioapatite oxygen analysis are given in Tables A3.5, A3.6, A3.7, A3.8, and Fig. A3.6. Table A3.4 includes equivalent drinking water values used in the discussion (also see above).

Oxygen isotopes in enamel

Bioapatite carbonate oxygen isotope data is presented in Tables A3.5, A3.7 and A3.8, and Fig. A3.6.

In males, the second molar enamel formation is complete between 6.3 and 6.7 years, and the first

Table A3.4 Descriptive statistics for nitrogen isotopes in dentine, femur and rib

$\delta^{15}N$ (AIR)	*Dentine*			*Femur*		*Rib*	
	All	*pM1*	*M2*	*All*	*pair*	*All*	*pair*
Mean	11.6	11.9	11.5	12.1	12.1	13.0	12.9
1σ	1.3	1.0	1.5	1.2	1.2	1.4	1.5
Minimum	8.3	10.0	8.3	9.4	9.4	9.5	9.5
Maximum	13.8	13.0	13.8	13.9	13.9	16.0	16.0
Median	11.8	12.1	11.7	12.3	12.3	13.1	12.8
Range	5.6	3.0	5.6	4.5	4.5	6.5	6.5
Count	31	9	22	38	31	38	31

Table A3.5 Oxygen, carbon and strontium isotopes in tooth enamel

Skull No.	*Tooth*	$\delta^{18}O_C$‰ (vSMOW)	1σ	$\delta^{18}O_{PC}$‰ (vSMOW)	1σ	$\delta^{18}O_{DW}$‰ (vSMOW)	1σ	$\delta^{13}C_C$‰ (vPDB)	1σ	*Sr ppm*	$^{87}Sr/^{86}Sr$	*1/ppm x 1000*
SK3694	LR M2	+23.50	0.1	14.6	0.1	-13.5	0.1	-15.14	0.03	128	0.70798	7.8
SK3696	UR M2	+24.87	0.2	16.0	0.2	-10.5	0.4	-15.86	0.02	39	0.70974	25.7
SK3704	LL M2	+24.45	0.1	15.6	0.1	-11.4	0.2	-15.94	0.04	70	0.71156	14.2
SK3705	LR pM1	+24.94	0.1	16.1	0.1	-10.3	0.2	-14.63	0.04	59	0.71182	16.9
SK3706	UL M2	+25.21	0.1	16.3	0.1	-9.7	0.2	-15.51	0.04	85	0.71032	11.8
SK3707	UL pM1	+24.63	0.1	15.7	0.1	-11.0	0.2	-14.81	0.08	82	0.71306	12.2
SK3710	LR pM1	+25.10	0.1	16.2	0.1	-9.9	0.2	-15.63	0.04	74	0.71060	13.6
SK3711	UL pM1	+22.95	0.1	14.0	0.1	-14.8	0.2	-15.64	0.04	95	0.71377	10.5
SK3712	UL M2	+23.96	0.2	15.0	0.2	-12.5	0.4	-14.77	0.03	71	0.71588	14.0
SK3720	UR M2	+24.73	0.1	15.8	0.1	-10.8	0.2	-15.39	0.04	117	0.71294	8.5
SK3722	LR M2	+24.57	0.1	15.7	0.1	-11.1	0.2	-14.76	0.04	70	0.71109	14.2
SK3724	UL pM1	+24.76	0.1	15.9	0.1	-10.7	0.2	-15.76	0.04	58	0.72051	17.2
SK3725	LL M2	+26.61	0.1	17.8	0.1	-6.5	0.2	-14.73	0.04	76	0.70945	13.2
SK3726	LR M2	+26.22	0.1	17.4	0.1	-7.4	0.2	-14.54	0.04	62	0.71344	16.2
SK3729	UR M2	+26.78	0.1	18.0	0.1	-6.2	0.3	-13.38	0.03	105	0.71043	9.5
SK3730	UL M2	+24.95	0.1	16.1	0.1	-10.3	0.2	-15.73	0.04	98	0.71013	10.2
SK3733	UR pM1	+25.11	0.1	16.2	0.1	-9.9	0.2	-15.24	0.04	93	0.71105	10.7
SK3738	UL M2	+25.29	0.2	16.4	0.2	-9.5	0.4	-14.93	0.04	98	0.71035	10.2
SK3739	UL pM1	+24.53	0.1	15.6	0.1	-11.2	0.2	-16.37	0.04	61	0.71089	16.3
SK3743	LL M2	+25.00	0.1	16.1	0.1	-10.2	0.2	-15.38	0.04	61	0.71225	16.5
SK3744	LR pM1	+24.73	0.1	15.8	0.1	-10.8	0.2	-14.94	0.04	85	0.71072	11.8
SK3746	LL M2	+24.55	0.1	15.7	0.1	-11.2	0.1	-15.58	0.05	40	0.70960	24.8
SK3747	LL pM1	+24.08	0.1	15.2	0.1	-12.2	0.2	-15.62	0.04	85	0.71184	11.8
SK3749	LL M2	+24.53	0.1	15.6	0.1	-11.2	0.2	-15.69	0.04	103	0.71290	9.7
SK3751	UR M2	+24.26	0.3	15.4	0.3	-11.8	0.6	-15.75	0.00	97	0.71263	10.3
SK3752	LL M2	+25.56	0.1	16.7	0.1	-8.9	0.2	-15.65	0.04	70	0.71681	14.2
SK3757	UL M2	+26.79	0.3	18.0	0.3	-6.2	0.7	-14.81	0.06	161	0.70945	6.2
SK3758	LR pM1	+25.50	0.1	16.6	0.1	-9.1	0.2	-15.40	0.04	113	0.70964	8.9
SK3759	UR M2	+23.38	0.1	14.5	0.1	-13.8	0.2	-15.28	0.04	93	0.71087	10.7
SK3760	UR M2	+24.94	0.1	16.1	0.1	-10.3	0.2	-15.37	0.04	86	0.71567	11.6
SK3761	UL M2	+24.57	0.1	15.7	0.1	-11.1	0.2	-15.01	0.04	84	0.71369	11.8

Phosphate carbonate oxygen data converted to phosphate oxygen using the equation of Chenery *et al.* (2012).
Drinking water values (δ^{18}ODW) were calculated using the equation of Levinson *et al.* 1987.

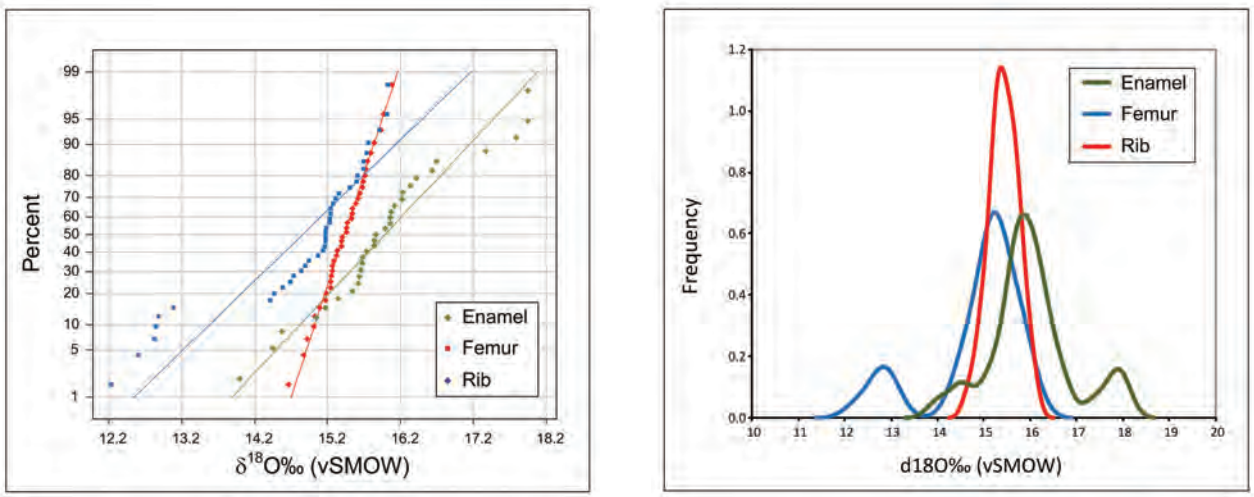

Fig. A3.6 a) Probability and b) Kernel Density plots showing the variation in oxygen isotope values of enamel (population 'A'), and femur and rib (population 'B')

Table A3.6 Oxygen isotopes femur and rib

		Femur					*Rib*					
Skeleton No.	*Age category**	$\delta^{18}O_P$	1σ	$\delta^{18}O_{dw}$	1σ	n	$\delta^{18}O_P$	1σ	$\delta^{18}O_{dw}$	1σ	n	$\Delta^{18}O_P$
SK3687	Older adult	12.2	0.1	-18.6	0.3	2	15.6	0.0	-11.3	0.1	2	-3.38
SK3688	Adult unspecified						15.1	0.1	-12.4	0.2	2	
SK3689	Prime adult	15.2	0.0	-12.1	0.1	2	14.9	0.0	-12.8	0.0	2	0.31
SK3697	Young adult						16.0	0.1	-10.5	0.1	2	
SK3700	Young adult						15.3	0.1	-11.9	0.1	2	
SK3715	Prime-mature adult	15.9	0.1	-10.6	0.3	4	15.9	0.1	-10.6	0.2	2	-0.03
SK3716	Young adult	15.7	0.1	-11.1	0.2	3	15.4	0.0	-11.8	0.0	2	0.30
SK3719	Adult unspecified	15.2	0.1	-12.2	0.1	2						
SK3753	Young adult	15.2	0.1	-12.1	0.2	2	15.6	0.0	-11.3	0.0	2	-0.35
SK3754	Adolescent	15.7	0.1	-11.0	0.2	3	15.8	0.0	-10.8	0.1	2	-0.11
SK3755	Young adult	15.8	0.1	-11.0	0.1	2	15.5	0.1	-11.6	0.2	2	0.30
SK3756	Adolescent	16.0	0.1	-10.4	0.2	2	15.5	0.0	-11.4	0.1	2	0.48
SK3762	Prime-mature adult	15.3	0.1	-11.9	0.3	3	15.3	0.0	-12.0	0.0	2	0.03
SK3763	Young adult	15.5	0.1	-11.5	0.2	3	15.5	0.1	-11.4	0.2	3	-0.03
SK3764	Prime adult	12.9	0.1	-17.2	0.3	3	15.5	0.1	-11.6	0.1	2	-2.59
SK3768	Older adult	15.1	0.1	-12.3	0.2	3						
SK3770	Prime adult	15.1	0.1	-12.5	0.3	3	15.2	0.1	-12.1	0.1	2	-0.18
SK3774	Adult unspecified	15.4	0.0	-11.8	0.0	3						
SK3775	Adolescent	14.6	0.0	-13.5	0.0	2	15.2	0.1	-12.1	0.2	2	-0.64
SK3777	Mature adult	15.2	0.1	-12.2	0.2	3	15.7	0.1	-11.0	0.1	2	-0.54
SK3778	Mature adult	14.8	0.0	-13.0	0.1	2	15.2	0.1	-12.2	0.2	3	-0.34
SK3781	Prime adult	14.7	0.1	-13.3	0.2	3	15.3	0.1	-12.0	0.2	2	-0.58
SK3783	Adult unspecified						15.7	0.1	-11.1	0.2	2	
SK3784	Adult unspecified	15.2	0.1	-12.3	0.3	3						
SK3786	Adolescent	12.6	0.1	-17.8	0.3	2	15.7	0.1	-11.0	0.1	2	-3.13
SK3787	Young adult	15.6	0.1	-11.3	0.2	3	15.8	0.1	-10.9	0.2	3	-0.20
SK3788	Prime-older adult						15.7	0.1	-11.1	0.2	3	
SK3789	Adolescent						16.1	0.0	-10.2	0.1	2	
SK3790	Young adult	15.7	0.1	-11.1	0.1	3	15.2	0.0	-12.2	0.1	2	0.50
SK3791	Adolescent	13.1	0.1	-16.8	0.2	2	15.5	0.1	-11.6	0.2	3	-2.37
SK3792	Adult unspecified	15.3	0.0	-12.1	0.1	2						
SK3794	Young-prime adult	14.5	0.1	-13.8	0.2	2	15.3	0.2	-11.9	0.4	5	-0.86
SK3795	Prime adult	15.3	0.0	-12.0	0.0	2						
SK3796	Adolescent	14.4	0.0	-13.9	0.1	2	15.0	0.1	-12.6	0.3	3	-0.60
SK3798	Adolescent	14.9	0.0	-12.8	0.1	2	15.4	0.0	-11.7	0.0	2	-0.50
SK3799	Adult unspecified						15.8	0.1	-11.0	0.1	5	
SK3800	Mature adult	14.9	0.0	-12.7	0.1	2	15.0	0.1	-12.6	0.2	4	-0.07
SK3801	Prime adult	15.2	0.0	-12.2	0.1	3						
SK3803	Mature adult	16.0	0.1	-10.4	0.1	2	15.6	0.1	-11.2	0.2	2	0.39
SK3804	Older adult	12.8	0.0	-17.3	0.0	2	15.5	0.0	-11.5	0.1	2	-2.70
SK3805	Older adult	15.6	0.0	-11.3	0.0	3	15.3	0.1	-12.0	0.2	3	0.32
SK3806	Mature adult	12.8	0.0	-17.3	0.0	2	14.7	0.1	-13.3	0.3	4	-1.82
SK3809	Young adult	14.7	0.1	-13.2	0.1	3	14.9	0.0	-12.9	0.0	2	-0.14
SK3810	Young adult	15.2	0.0	-12.2	0.1	2	15.3	0.1	-12.0	0.2	3	-0.07
SK3811	Prime adult	15.2	0.1	-12.1	0.2	4	15.4	0.0	-11.8	0.0	2	-0.16

All $\delta^{18}O$ presented relative to vSMOW, $\delta^{18}O$dw values derived suing the equation of Levinson *et al.* 1987. *Boyle 2011

premolar enamel is complete at around 6.3 years, depending on whether it is an upper or lower tooth (Scott and Symons 1982). The exact length of time enamel takes to mineralise is not known, but is believed to occur over a relatively short period of time after the all enamel forming cells are in place. For the purposes of this study, as enamel mineralization is likely to have taken place around the same time of life for both M2s and pM1s, all the teeth will be considered to represent a similar period of time during childhood of ~6.5 years.

The $\delta^{18}O_{cp}$ values obtained from tooth enamel have a very broad distribution and range from +14‰ to +18.0‰ with a median of 15.9‰ and a mean of +16.0 ± 0.92‰ (1σ, n=31) (Table A3.7). The calculated drinking water values range from

Table A3.7 Descriptive statistics for oxygen isotopes in enamel, femur and rib

$\delta^{18}O_P$ (vSMOW)	*Enamel*	*Femur*		*Rib*	
		All	*Pair*	*All*	*Pair*
Mean	16.0	14.9	14.8	15.4	15.4
1σ	0.9	1.0	1.1	0.3	0.3
Minimum	14.0	12.2	12.2	14.7	14.7
Maximum	18.0	16.0	16.0	16.1	15.9
Median	15.9	15.2	15.2	15.4	15.4
Range	4.0	3.8	3.8	1.4	1.3
Count	31	38	31	38	31

Table A3.8 Descriptive statistics for calculated drinking water in enamel, femur and rib

$\delta^{18}O_{DW}$ (vSMOW)	*Enamel*	*Femur*		*Rib*	
		All	*Pair*	*All*	*Pair*
Mean	-10.5	-12.9	-13.1	-11.7	-11.8
1σ	2.0	2.2	2.4	0.7	0.6
Minimum	-14.8	-18.6	-18.6	-13.3	-13.3
Maximum	-6.2	-10.4	-10.4	-10.2	-10.6
Median	-10.7	-12.2	-12.2	-11.7	-11.8
Range	8.6	8.3	8.3	3.1	2.8
Count	31.0	37	31	38	31

-14.8‰ to -6.2‰ with a median of -10.7 and a mean of -10.46 ±2.0‰ (1σ, n=31) (Table A3.8). Henceforth the teeth will be treated as one population. Only the $\delta^{18}O_{cp}$ will be described as the $\delta^{18}O_{DW}$ follows the same trends.

Probability and Kernel Density plots (Fig. A3.6 a and b) of the enamel $\delta^{18}O_{cp}$ data show non-normal distribution centring on a mean of 16.0 ± 0.9‰ (1σ, n=31) and a goodness of fit of 1.146. The enamel results can be split into three main groups: three (14.7%) low $\delta^{18}O_{cp}$ outliers (3711, 3759, 3694) with values less than 14.6‰; four (17.1%) high $\delta^{18}O_{cp}$ outliers (3726, 3725, 3729, 3757) with values greater than 17.3‰; a normally distributed core group of the remaining 24 individuals. The core group represents 77.4% of the set and has a range 15.0‰ to 16.7‰ with a median of 15.9‰ and is distributed around a mean of 16.0 ± 0.4‰ (1σ, n=24) with a goodness of fit of 0.629.

Oxygen isotopes in femurs and ribs

Rib and femur oxygen data is presented in Table A3.6 and Fig. A3.6; statistical parameters are presented in Tables A3.7 and A3.8.

As the tissue turnover in ribs is considerably faster (2-5 years) than that of femurs (>10 years) we have analysed both ribs and femurs to look for evidence of changes in place of habitation during an individual's lifetime.

$\delta^{18}O_P$ values for all femurs and ribs range from 12.2‰ to 16.1‰ (n=76). Femur values range from 12.2‰ to 14.7‰ and ribs range from 14.7‰ to 16.1‰. All of the rib or femur $\delta^{18}O$ values fall outside the expected range for native Britains (Evans *et al.* 2012). The difference in $\delta^{18}O$ distribution between femurs and ribs, which cannot be accounted for by sampling constraints, will be highlighted below.

Femur

The $\delta^{18}O_P$ of femurs, which represent a greater than 10 year average of oxygen isotopes from ingested fluids prior to death, range from 12.2‰ to 16.0‰ with a median of 15.2‰ and a mean of 14.9 ± 1.01‰, 1σ, n = 38 (Table A3.7). Probability and kernel density plots (Fig. A3.6 a and b) of the data indicate the distribution of $\delta^{18}O$ values is non-normal with a goodness of fit of 3.139. Six individuals have been identified as outliers (3687, 3786, 3804, 3806, 3763, 3791) with a $\delta^{18}O_P$ values less than 13.1‰. The remainder of samples approximate a normal distribution around a mean of 15.3 ± 0.43‰ (1σ, n=32) with a median of 15.2‰.

Rib

The oxygen isotope values of rib bio-apatite relates to average intake of dietary oxygen (derived primarily from ingested liquids) over approximately two to five years before death. The $\delta^{18}O_P$ of all the ribs range from 14.7‰ to 16.1‰ with a median of 15.4‰ and a normal distribution around a mean of 15.4 ± 0.32‰, 1σ, n=38 (Table A3.7) with a goodness of fit of 0.397 (see Fig. A3.6 a and b).

Overall, ribs tend to have higher $\delta^{18}O_P$ values than femurs and a narrower range of only 1.4‰ compared to 3.8‰ for femurs. The broader distribution of femur $\delta^{18}O$ values is due largely to six outliers. Excluding the femur outliers, the femur and rib $\delta^{18}O$ values are statistically the same (t-Test) with femurs having slightly lower mean and median values.

Femur – rib comparisons for carbon, nitrogen and oxygen from 31 individuals with both femur and rib analysis

Data for both rib and femur are available for 31 individuals. Similar data ranges were obtained for both $\delta^{13}C$ and $\delta^{15}N$ for the 31 femur paired to rib samples, which indicate that the 31 are representative of the whole population (see Tables A3.3 and A3.4). The results presented below make use of the difference in isotope value between rib and femur ($\Delta^{13}C_{(r\text{-}f)} = \delta^{13}C_{rib}$ minus $\delta^{13}C_{femur}$ and $\delta\Delta^{15}N_{(r\text{-}f)}$)

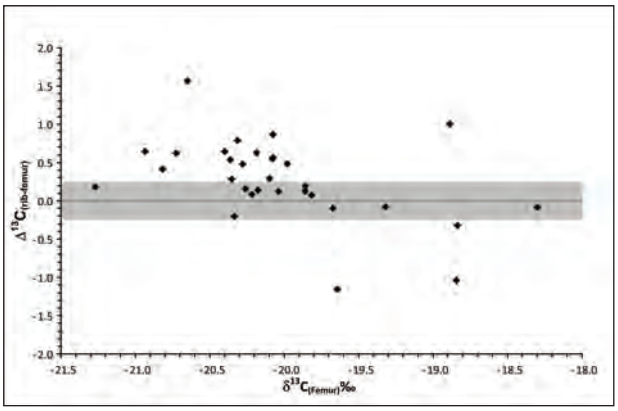

Fig. A3.7 Plot of femur $D^{13}C_{(r-f)}$ (the difference between rib and femur $\delta^{13}C$) against $\delta^{13}C$ for the 31 individuals analysed for both rib and femur. Grey band represents ±3s of the analytical error and represents the value range for individuals unlikely to have had a significant change in carbohydrate intake during the last 10 + years of life

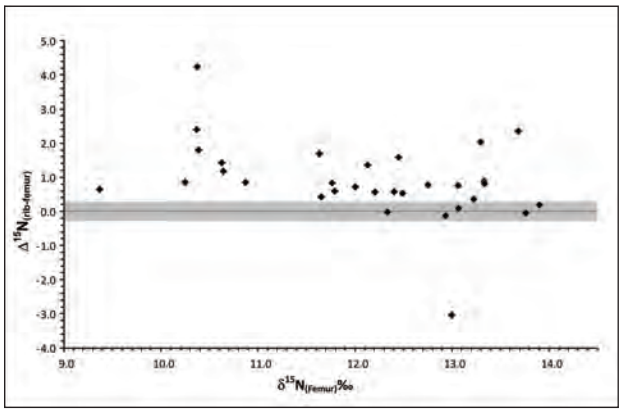

Fig. A3.8 Plot of femur $\Delta^{15}N_{(r-f)}$ (the difference between rib and femur $\delta^{15}N$) against $\delta^{15}N$ for the 31 individuals analysed for both rib and femur. Grey band represents ±3s of the analytical error and represents the value range for individuals unlikely to have had a significant change in protein intake during the last 10 + years of life

= $\delta^{15}N_{rib}$ minus $\delta^{15}N_{femur}$). The isotope values of ribs represent an individual's most recent diet and femurs represent a long term average, >10 years, of their diet. Therefore we can use the differences between rib and femur for single individuals to evaluate dietary change over time. The larger the value of Δ the greater and more significant the change, with positive values indicating an increase over time and negative values a decrease over time.

Few studies have compared rib and femur stable isotopes in the same individual and as a result there is paucity of information in the literature of data defining the expected response in collagen $\delta^{13}C$ and $\delta^{15}N$ with change in diet over time. In the following results section we have chosen Δ significance values based on ± 3σ of the analytical error for $\delta^{13}C$ and $\delta^{15}N$ analysis in collagen (see methods) to identify individuals who had no significant change their isotope values over time. The choice of these criteria is supported by data presented in the work of Jørkov *et al*. 2009. In their paper they present rib and femur carbon and nitrogen isotope data for 58 individuals from a single static community in Holbæk, Denmark. The difference between rib and femur in this population is statistically insignificant showing that, although considerable variation can be found within a population, an individual remaining in one place will, with no change of diet, will record the same value within analytical error between rib and femur.

Carbon isotopes

The $\Delta^{13}C_{(r-f)}$ values range from -1.2‰ to +1.6‰ with a median of 0.3‰ and a mean of 0.3 ± 0.53‰ (1σ, n=31). For the majority (77%) of individuals rib $\delta^{13}C$ is elevated in relation to femur $\delta^{13}C$, Fig. A3.7. Based on the criteria above, twelve individuals (3794, 3775, 3756, 3787, 3716, 3791, 3778, 3805, 3798, 3806, 3715, 3777) show no significant difference between femur and rib $\delta^{13}C$ ($\Delta^{13}C_{(r-f)}$ <± 0.25‰). Four outliers have been identified; two individuals (3810, 3803) with $\Delta^{13}C_{(r-f)}$ values <-1.0‰ and two (3763, 3804) with values >+1.0‰ and these individuals have experienced a significant change, although not a complete trophic level shift, over time, based on the criteria defined above. The $\Delta^{13}C_{(r-f)}$ values for remainder of the group fall between 0.28‰ and 0.87‰, which may represent small changes in diet.

Nitrogen isotopes

The $\Delta^{15}N_{(r-f)}$ values are highly variable ranging from -3.0‰ to +4.2‰ with a median of 0.8‰ and a mean of 0.9 ± 1.15‰ (1σ, n=31). The majority of individuals (87%) rib $\delta^{15}N$ is elevated in relation to femur $\delta^{15}N$, Fig. A3.8). Using the criteria above, five individuals (3794, 3787, 3775, 3806, 3689) have no significant difference between their rib and femur values ($\Delta^{15}N_{(r-f)}$ <± 0.23‰). The remainder of the individuals the difference in $\delta^{15}N$ between ribs and femurs may be significant to some degree. Ten individuals (3716, 3770, 3781, 3687, 3762, 3755, 3756, 3763, 3803, 3804) have $\Delta^{15}N_{(r-f)}$ greater than 1.0‰. Two individuals stand out as have very large differences in their rib and femur values; 3804 with a difference of +4.2‰ and 3810 with a difference of -3.0‰ that suggest a serious change in diet and/or food source in the years prior to their death. Only these last two individuals' are likely to have a

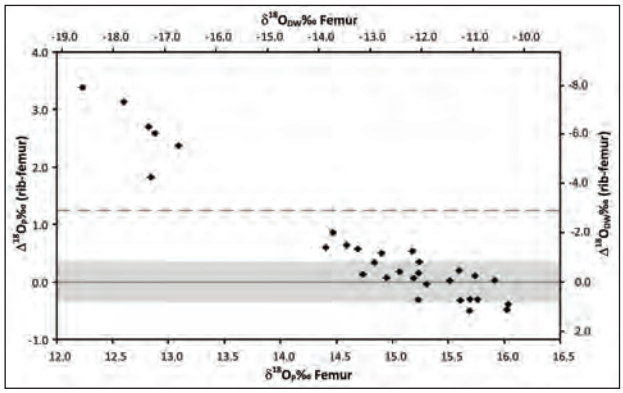

Fig. A3.9 Plot of femur $\Delta^{18}O_{(r\text{-}f)}$ (the difference between rib and femur $\delta^{18}O$) against $\delta^{18}O$ for the 31 individuals analysed for both rib and femur. Grey band represents ±3s of the analytical error and represents the value range for individuals unlikely to have had a significant change in drinking water intake during the last 10 + years of life. Individuals with drinking water $\Delta^{18}O_{DW(r\text{-}f)} > 2.9‰$ (dashed line) are highly likely to have lived in different locations in the last 2 to 5 years of life than during the previous 10+ years

dietary shift of one trophic level, based on the generally accepted difference of 3‰ to 4‰ per trophic level (Hedges and Reynard 2007).

Bioapatite Oxygen isotopes

Initial data observations (Table A3.6), indicate that the six outliers (3687, 3786, 3804, 3806, 3763, 3791), from the group of 31 rib-femur pairs, correspond to the six 'outliers' with low femur $\delta^{18}O_P$ values from the entire set of femurs. The remaining 25 individuals approximate a normal distribution around a mean of 15.3 ±0.47‰ (1σ, n=25) with a median of 15.2‰ and a goodness of fit of 0.726 (see Fig. A3.6).

As in the case of carbon and nitrogen isotopes, few studies have compared rib and femur stable isotopes in the same individual and as a result there is paucity of information in the literature of data defining the expected response in bio-apatite $\delta^{18}O$ with change in drinking water $\delta^{18}O$ over time. To more clearly understand if an individual had lived in more than one place during his lifetime, we have calculated the difference in oxygen isotope values between rib and femur bio-apatite ($\Delta^{18}O_{(r\text{-}f)}$) to be used in the statistical treatment of the data. A positive $\Delta^{18}O_{(r\text{-}f)}$ suggests a possible change in residence from a cold/high altitude to a less cold environment, while a negative value suggests a move towards a colder environment. In the absence of published criteria, a Δ cut-off values has been chosen, based on ± 3σ of the analytical error for $\delta^{18}O_P$ (± 0.36‰, see methods), to identify individuals who have no significant difference in their $\delta^{18}O$ values (ie change in habitation location over time).

Individual $\Delta^{18}O_{(r\text{-}f)}$ values range between -0.5‰ and +3.4‰ (median = 0.2‰; mean = 0.6 ±1.1‰ 1σ, n=31) (Table A3.6). A group of six outliers (3687, 3786, 3804, 3806, 3763, 3791) with low femur $\delta^{18}O_P$ have $\Delta^{18}O_{(r\text{-}f)} > 1.8‰$ suggesting a dramatic change in their water sources (see Fig. 9). The $\Delta^{18}O_{(r\text{-}f)}$ of the remaining 25 individuals approximates a normal distribution around a mean of 0.1 ± 0.37‰ (1σ, n=25). A conservative interpretation would suggest that these 25 individuals did not experience a significant change in their drinking water source during their lives. However, within this group a number of individuals lie outside the $\Delta^{18}O_{(r\text{-}f)}$ ±0.36‰ cut-off points. Three individuals (3803, 3756, 3790) have negative $\Delta^{18}O_{(r\text{-}f)}$ values a little lower than -0.36‰, which might suggest a possible migration to areas with lower $\delta^{18}O_{DW}$ during their later years. Six individuals from the core group have $\Delta^{18}O_{(r\text{-}f)}$ values between 0.5 and 0.9‰ that suggests the possibility that they may have moved to areas with higher $\delta^{18}O_{DW}$ during the last years of their lives. This subgroup includes individuals 3798, 3777, 3781, 3796, 3775 and 3794. All of the outliers have $\Delta^{18}O_{(r\text{-}f)}$ values greater than 1.8‰ suggesting a significant change in drinking source, i.e. moving to areas with higher $\delta^{18}O_{DW}$ values during the later years of their lives.

Strontium isotopes ($^{87}Sr/^{86}Sr$)

Strontium isotopes ($^{87}Sr/^{86}Sr$) represent dietary intake (solid and liquid) and is related to the geology of the areas where an individual lived during their life (see above). Strontium concentration reflects the amount of available Sr in the biosphere and this may reflect soil and drinking water concentrations and/or the types of foods consumed (see Evans *et al*. 2012). Strontium concentrations are not expected to correlate to strontium isotope ratios. All tooth enamel $^{87}Sr/^{86}Sr$ results will be treated as one population, as above.

Table A3.9 descriptive statistics for strontium isotopes in enamel

Strontium	*Sr ppm*	*$^{87}Sr/^{86}Sr$*
Mean	85	0.7120
1σ	25	0.0026
Minimum	39	0.7080
Maximum	161	0.7205
Median	85	0.7111
Range	122	0.0125
Count	31	31

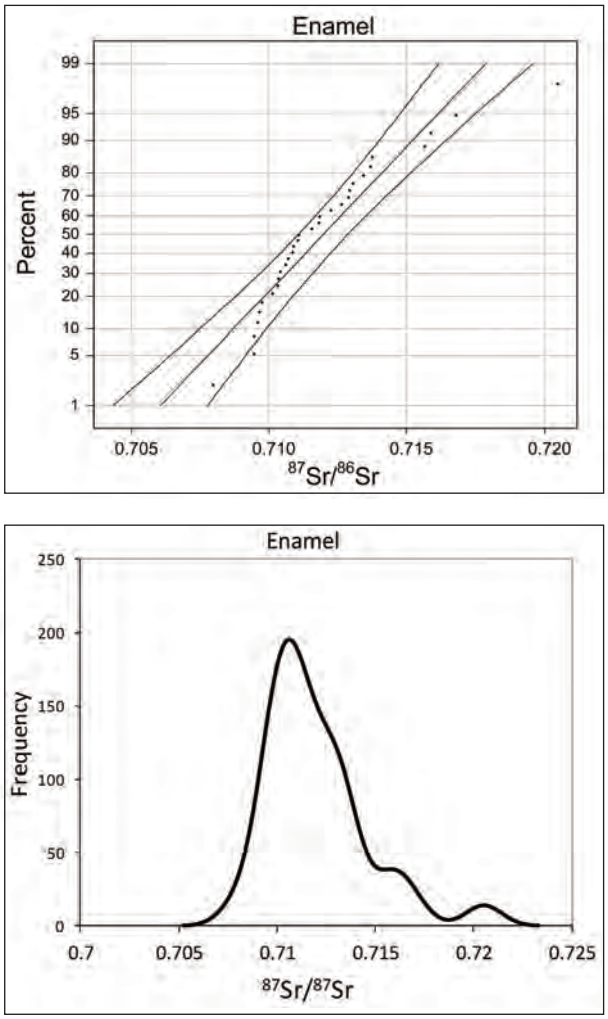

Fig. A3.10 a) Probability and b) Kernel Density plots showing the variation in strontium isotope values in tooth enamel from population 'A'

Enamel $^{87}Sr/^{86}Sr$ values have a broad distribution, ranging from 0.7080 to 0.7205 having a median of 0.7111 and a mean of 0.7120 ±0.0026, 1σ, n=31 (Table A3.9). The kernel density and probability plots of the $^{87}Sr/^{86}Sr$ data (Fig. A3.10 a and b) show that the distribution of all enamel values is not normal, with a mean of 0.7119 ±0.0025 (1σ, n=31) and a goodness of fit of 1.388. This data can be split into three groups: three outliers (9.7%) with $^{87}Sr/^{86}Sr$ values less than 0.7095 (skulls 3694, 3725, 3757); four (10.8%) outliers with values greater than 0.7138 (skulls 3760, 3712, 3752, 3724), and a core group of the remaining 24 individuals. The core group represents 77.4% of the set and has a range of 0.7096 to 0.7138 with a median of 0.7111 and approximates a normal distribution around a mean of 0.7115 ±0.0013 (1σ, n=24)‰ with a goodness of fit of 0.981.

Strontium concentrations in the entire enamel data set range from 39ppm to 161ppm with a median 85ppm and a mean of 85 ±25ppm (1σ, n=31). Two individuals (skulls 3696, 3746) have concentration values that would be considered to be low, and one individual (skull 3757) has a value that would be considered high, compared with a median value of 84ppm for UK archaeological populations (Evans *et al*. 2012). Otherwise the remainder have unremarkable Sr concentrations.

DISCUSSION

The results of the combined oxygen, strontium, carbon and nitrogen isotope analyses indicate that the group of individuals excavated from the Ridgeway mass grave are diverse in their place of origin, migration history and dietary habits. As there are no positive osteological matches between cranial and post-cranial elements, these need to be treated as separate populations: Population A represented by the cranial elements (teeth) and Population B, represented post-cranial elements (femurs and ribs). The order of discussion will be split between place of origin for Population A, migration patterns for Population B and diets for populations 'A' and 'B' combined. The reader should note that oxygen isotopes will be largely discussed in terms of calculated drinking water values, which have been derived using the Levinson *et al*. (1987) bioapatite oxygen to drinking water equation (see Chenery *et al*. 2010 and above).

Place of Origin

Population 'A', childhood place of origin

Although the age at death suggested for the Ridgeway individuals ranges from early adolescent to over 50 years, the teeth selected for analysis represent the individuals at ages between 6.3 and 6.7 years (mean = 6.5 years). It is therefore necessary to consider the results, for population 'A', as representing the individuals' childhood place of residence and diet.

As shown above, there is a wide range of oxygen and strontium isotope values in this population (see Fig. A3.11).

To constrain an individual's likely place of residence, the first stage is to determine who is 'local' to the burial area and who is not. This is done by comparing the $\delta^{18}O_{DW}$ (calculated drinking water $\delta^{18}O$) and $^{87}Sr/^{86}Sr$ values of enamel to the expected local mean drinking water $\delta^{18}O_w$ and $^{87}Sr/^{86}Sr$ ranges. This is achieved by using $\delta^{18}O_w$ data and maps of UK surface and groundwater produced by Darling *et al*. (2003) and UK $^{87}Sr/^{86}Sr$ data and maps produced by Evans *et al*. (2010 and 2012) and Montgomery *et al*. (2006). To establish the constraints on the place of residence of 'non-locals'

the $\delta^{18}O_{DW}$ values are compared to the various maps and data sources indicated above, to identify likely climatic regions. The individual's $^{87}Sr/^{86}Sr$ values are then applied to locate likely geologic terrains within the identified climatic regions.

It is important to remember that ranges in $\delta^{18}O_w$ and $^{87}Sr/^{86}Sr$ values associated with a particular region do not exclude the possibility of other regions and where identifiable alternative regions will be offered as places of origin or residence.

Individuals likely to have origins outside the British Isles

Oxygen isotope values are used as the main criteria for discriminating between 'British' and 'non-British' place of origin (i.e. $\delta^{18}O_{DW}$ values of less than -9.0‰ are considered to be 'non-British'). Oxygen isotope values, for surface, ground and meteoric waters ($\delta^{18}O_W$), less than -9.0‰ can be found throughout Scandinavia (excluding Denmark), the Baltic States, northern Germany and Poland, and throughout Belarus and Russia. Geologic maps and literature resources are then used to identify compatible $^{87}Sr/^{86}Sr$ terrains.

Twenty six of the individuals whose teeth were analysed had $\delta^{18}O_{DW}$ values that place their origins outside the British Isles. Based on $\delta^{18}O_{DW}$ values, the 'non British' individuals can be split between: individuals with $\delta^{18}O_{DW}$ values <12.0‰ who are likely to come from Arctic regions or very cold climates such as Northern Scandinavia; and, individuals with values between -12.0‰ and -9.0‰ who are likely to come from moderately cold climates such as southern Scandinavia. This represents a geographical division between the northern regions of Scandinavia and northern continental Europe including southern Sweden and Norway, discussed separately below (Fig. A3.2).

Individuals from very cold regions outside Britain

Five individuals (skulls 3747, 3712, 3694, 3759, 3711), having $\delta^{18}O_{DW}$ values less than -12.0‰, are identified as having been raised in very cold environments (see Fig. A3.11); however values such as these do not rule out extremely high altitudes in other areas of Europe. As these individuals do not fit into distinct isotope groupings, they will be considered singly.

Individual 3711 has the lowest $\delta^{18}O_{DW}$ value (-14.8‰) and a relatively high $^{87}Sr/^{86}Sr$ value (0.7138) and these combined values are compatible with origins in Arctic Norway. Individual 3712 also has a high $^{87}Sr/^{86}Sr$ value (0.7159) and a $\delta^{18}O_{DW}$ value of -12.5‰ that is indicative of origins in sub Arctic regions of northern Scandinavia.

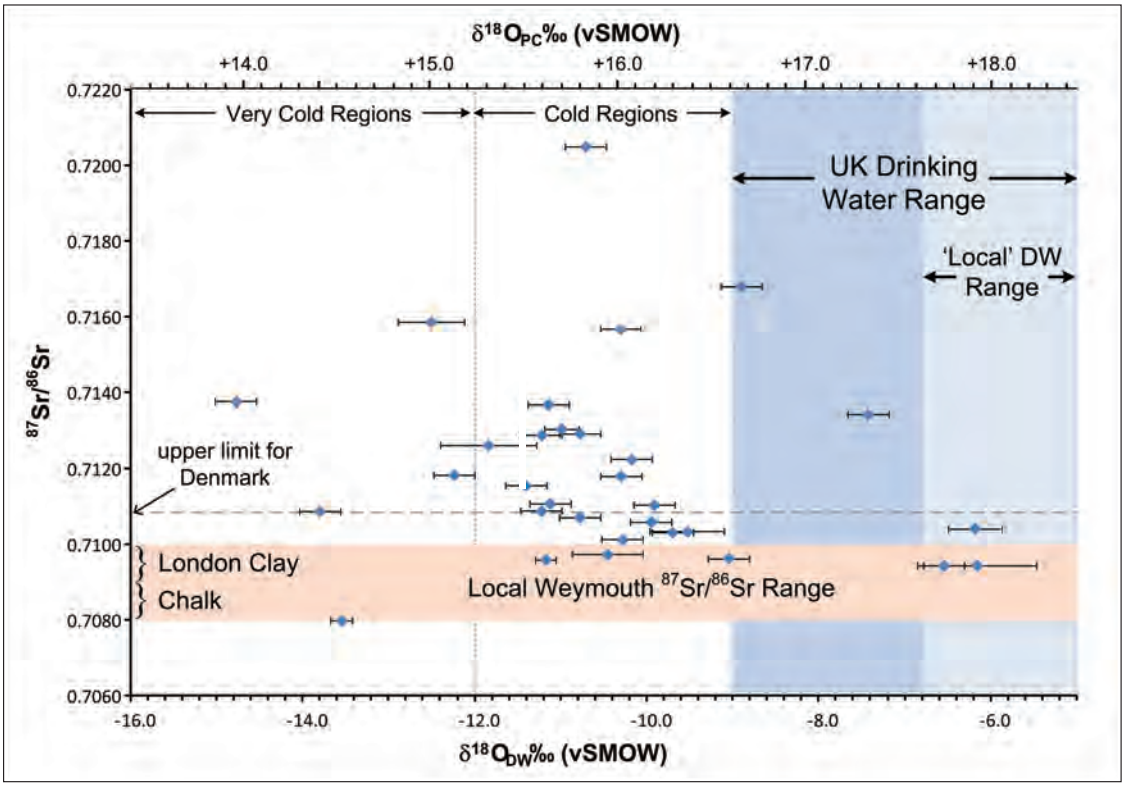

Fig. A3.11 Plot of mean $\delta^{18}OP$ (±1s) and $^{87}Sr/^{86}Sr$ for enamel (population 'A') against the expected $^{87}Sr/^{86}Sr$ range values for 'local' Weymouth and upper limit for Denmark, and $\delta^{18}O$ drinking water ranges for 'local' Weymouth area, UK, cold and very cold climate regions

Although individual 3759 has a $\delta^{18}O_{DW}$ value of -13.8‰, compatible with sub Arctic Scandinavia, but a relatively low $^{87}Sr/^{86}Sr$ value (0.7108) the geology of this region. His combined oxygen and strontium isotope values suggest origins Cainozoic terrains south of the Baltic Sea or western Russia. Alternatively his $^{87}Sr/^{86}Sr$ value could represent origins in coastal regions of northern Scandinavia, where strontium isotope values are mediated by rain and sea splash (Evans *et al*. 2010). Individual 3747 has the highest $\delta^{18}O_{DW}$ value of this group (-12.2‰) and also a relatively low $^{87}Sr/^{86}Sr$ value (0.7118) and could have been raised in sub Arctic Scandinavia. However, his values are also compatible with the geologic terrains and $\delta^{18}O$ precipitation values within the Viking catchment of the Ukraine or Russia.

Individual 3694 has the lowest $^{87}Sr/^{86}Sr$ value (0.708) of all the individuals investigated in this project. His low $\delta^{18}O_{DW}$ value (-13.5‰) is indicative of cold climate origins in northern Scandinavia or northern Iceland where compatible $\delta^{18}O_w$ values have been reported by Atas 2006. Strontium isotope values this low are normally associated with young igneous (eg Tertiary basalts) and young limestone terrains. However, there is no evidence of strontium isotope ratios this low in northern Scandinavia, even in coastal areas. The young volcanic terrains of Iceland and young limestone terrains in Russia do have compatible $^{87}Sr/^{86}Sr$ values and therefore provide possible locations for his place of origin.

Individuals from cold regions outside Britain

Twenty one individuals are likely to have come from cold regions outside northern Scandinavia. Their $\delta^{18}O_{DW}$ values fall between -12.0‰ and -9.0‰ and $^{87}Sr/^{86}Sr$ values between 0.709 and 0.721. These individuals can be roughly grouped based on their strontium isotope values into those coming from old radiogenic terrains that are typical of the Baltic Shield of Norway, Sweden and Finland ($^{87}Sr/^{86}Sr$ >0.711) and those coming from younger Cenozoic terrains found in Denmark and south of the Baltic Sea ($^{87}Sr/^{86}Sr$ 0.709 to 0.711), These individuals are discussed below, largely in terms of the geologic terrains where they may have lived.

Individuals from younger geologic terrains

Eleven individuals are likely to have been raised on Cenozoic terrains of northern Europe, with $\delta^{18}O_{DW}$ values in the range of -9‰ to -12‰ and having $^{87}Sr/^{86}Sr$ values in the range of 0.709 to 0.711 they are likely to come from a broad area including countries bordering the southern Baltic Sea, eastern Russia, Belarus and coastal north eastern Denmark. These individuals include: skulls 3739, 3746, 3722, 3744, 3696, 3730, 3710, 3733, 3706, 3738 and 3758 (in order of increasing $\delta^{18}O_{DW}$).

Potential places of origin can be further constrained for the above individuals. Individuals 3710, 3733, 3706, 3738 and 3758 have $\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values that are compatible with eastern coastal regions of Denmark, southern most Sweden and western Baltic. There is a paucity of $\delta^{18}O_w$ data for Denmark, however geographic position and limited data (Fricke *et al*. 1995; IAEA/WMO 2006) suggests that oxygen values in the range of -4.0‰ (on western coasts) to -9.7‰ (in the east; Copenhagen mean rainfall 1966 to 1971) are to be expected. Six individuals (3739, 3746, 3722, 3744, 3696, 3730) have lower $\delta^{18}O_{DW}$ values (<-10.0‰) suggesting origins in Baltic areas east of the river Vistula (Poland).

Individuals from older geologic terrains

Ten individuals have $^{87}Sr/^{86}Sr$ values that are compatible with coming from Palaeozoic and Precambrian terrains and cold climates and their $\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values vary within the range of -11.8‰ to -10.2‰ and 0.712 to 0.721 respectively. This group includes individuals 3704, 3705, 3743, 3751, 3749, 3720, 3707, 3761, 3760 and 3724. Within this group two sets of individuals are likely to come from the similar locations: 3705 and 3743 with a mean $\delta^{18}O_{DW}$ of -10.2 ± 0.1‰ (1σ and $^{87}Sr/^{86}Sr$ of 0.712 ± 0.0003 (1σ) and, 3720, 3707 and 3749 with a means $\delta^{18}O_{DW}$ of -11.0 ± 0.2‰ (1σ) and $^{87}Sr/^{86}Sr$ of 0.713 ± 0.0001 (1σ). Two individuals stand out by having significantly higher $^{87}Sr/^{86}Sr$ values: 3724 with the highest value or 0.721 ($\delta^{18}O_{DW}$ = -10.7‰.), and 3760 with a value of 0.716 ($\delta^{18}O_{DW}$ = -10.3). All of these individuals are likely to have come from mid latitude regions of Scandinavia. However, It should be noted, that areas in eastern Germany, and Czechoslovakia also have old geologic terrains, and compatible $^{87}Sr/^{86}Sr$ and $\delta^{18}O_W$ values (IAEA/WMO 2006; Fricke *et al*. 1995), therefore we cannot rule out these locations based on either oxygen or strontium isotope values.

Individuals that cannot be excluded from the British Isles

Individuals consistent with the Weymouth area and other parts of Europe

Five individuals (3752, 3726, 3725, 3729, 3757), representing 16% of the population, have $\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values that fall within the expected ranges for Britain (-4.5‰ to -9.0‰ and 0.704 to 0.720 respectively) and may have UK origins. Within this group only two individuals (3725, 3757) have

$\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values compatible with being 'local' to the area.

Their $^{87}Sr/^{86}Sr$ values (0.7095) suggest that if 'local' they were raised on London Clay rather than the chalk. However, their combined $\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values are also compatible with of Danish origins, as are their $\delta^{13}C$ and $\delta^{15}N$, based on data from Price *et al*. (2012), the IAEA isotope map of Scandinavia (see above, Fig. A3.2) and Jørkov *et al*. 2009.

Individuals consistent with 'British' and European origins outside the Weymouth area.

Three of the five individuals, listed above (3729, 3726, 3752), have combined isotope values that are compatible with UK regions outside the Weymouth area. Although individual 3729's oxygen isotope value (-6.2‰) is compatible with southern England, his $^{87}Sr/^{86}Sr$ signature (0.7103) indicates that any British origins are restricted to areas in south west England (Devon and Cornwall and the west coast of the Lake District (as defined in Evans *et al*. 2012). As with individuals 3725 and 3757 (see above), Denmark cannot be ruled out as a likely place of origin for individual 3729. The final potentially 'British' individual (3752), has a $\delta^{18}O_{DW}$ value (-8.9‰) close to the lower limit for Britain and a high $^{87}Sr/^{86}Sr$ value (0.71681) that are compatible with the coldest and geologically oldest areas of north east Scotland. However, he is also may have origins in southern Norway, as his combined $\delta^{18}O_{DW}$ and $^{87}Sr/^{86}Sr$ values are only compatible with 1% of the area of the UK (see Evans *et al*. 2012). Interestingly both of these individuals have elevated $\delta^{13}C$ and $\delta^{15}N$ values that suggest a mixed terrestrial and marine diet that is atypical of the British Isles and more closely resemble Scandinavian diet (see below).

Individual 3726 has oxygen and strontium values (-7.4‰, 0.7134 respectively) that are compatible with mainland areas in north-west Scotland but equally his origins may have been in south-western Norway.

Place of habitation and migration patterns (Population 'B')

Population 'B' is composed of ribs and/or femurs from 45 of the individuals found at the Ridgeway site. Oxygen isotope analyses were undertaken on rib and femur pairs for 31 individuals and on separate rib or femur samples from another 14 individuals (7 ribs and 7 femurs).

As there are different turnover rates for bone, oxygen isotope values for ribs and femurs can provide information on the climatic environments where these individuals may have spent their time during different periods of their life, thus revealing general patterns of migration within the population.

Likely areas of habitation up to fifteen years prior to death

As seen above, there is a considerable spread in $\delta^{18}O_P$ values for the 38 femurs analysed (12.2‰ to 16.0‰), which represents a $\delta^{18}O_{DW}$ range of -18.6‰ to -10.4‰. This is a strong indication that none of population 'B' spent a substantial portion of the last 10+ years of their lives in the British Isles. Twenty-six individuals have $\delta^{18}O_{DW}$ values less than -12.0‰. The $\delta^{18}O_{DW}$ values for femurs, suggest that the majority of these individuals spent a significant portion of the last 10+ years of their lives in regions with very cold climates. This includes individuals: 3687, 3786, 3804, 3806, 3763, 3791, 3796, 3794, 3775, 3781, 3809, 3778, 3798, 3800, 3768*, 3764, 3784*, 3801, 3716, 3777, 3810, 3689, 3811, 3719*, 3792* and 3795. Areas with compatible $\delta^{18}O_W$ values are to be found in the northern regions of Scandinavia, northern and eastern Russia. Six of these individuals (3687, 3786, 3804, 3806, 3763, 3791) stand out as having exceptionally low $\delta^{18}O_{DW}$ values (< -16.5‰) and two of these (3786, 3791) are under 18 years of age (see below). This group with exceptionally low $\delta^{18}O_{DW}$ values are very likely to lived in extremely cold, high mountain terrains or Arctic regions within the navigable ranges of the Viking period.

The remaining twelve individuals have femur $\delta^{18}O_{DW}$ values between -12.0‰ and -10.0‰ that are compatible with a more restricted area in south Scandinavia (excluding the southern-most regions of Norway, Sweden and all of Denmark) Belarus and Eastern Russia (see Fig. A3.2).

There is no systematic relation between the mean of the probable age range ('mean age' henceforth in this discussion) assigned to these individuals and their $\delta^{18}O_{DW}$ values. Individuals specified as 'adolescents', with a 'mean age' of less than 18 years, are highly likely to have $\delta^{18}O_{DW}$ values that represent their place of origin or, at least, where they spent most of their childhood and early adolescent years. In population 'B' seven individuals have been designated as 'adolescent': SK3791, 3796, 3754, 3798, 3756, 3786 and 3775). Individuals 3786 and 3791 have exceptionally low $\delta^{18}O_{DW}$ values (<-16.7‰) and are likely to have come from extremely cold Arctic or mountain environments (see above). 'Adolescent' individuals 3796, 3775 and 3798 have $\delta^{18}O_{DW}$ values between -14‰ and -12‰ that are compatible with living northern Scandinavian regions, excluding Arctic areas. The remaining two 'adolescents' (3754, 3756), with $\delta^{18}O_{DW}$ values of -10.8 and -11.49 respectively), are most likely to have spent their childhood years

anywhere in the terrain covering southern Scandinavia (excluding southernmost Norway and most of Denmark), countries bordering the Baltic Sea, Belarus, or western Russia.

Interestingly, three of the nine adults with 'mean ages' greater than 40 years (3687, 3804, 3806) have $\delta^{18}O_{DW}$ values ≤-17.3‰ and may have spent much of the later 10+ years of their lives in Arctic regions (see discussion above).

Likely areas of habitation within two to five years prior to death

The range of $\delta^{18}O_P$ values for ribs is considerably narrower than for femurs (14.7‰ to 16.1‰ see above), which represents a $\delta^{18}O_{DW}$ range of -13.3 to -10.2‰. The reason for this is that fewer individuals have $\delta^{18}O_{DW}$ values that are compatible with spending the last two to five years of their lives in the colder regions of Scandinavia with no individuals spending this time in arctic regions or within the British Isles. Only thirteen individuals have ribs $\delta^{18}O_{DW}$ values < -12.0‰ and are likely to have spent their last years in sub-Arctic regions of northern Scandinavia. These individuals are: 3806, 3809, 3689, 3796, 3800, 3688, 3778, 3790, 3775, 3770, 3810, 3781 and 3762. The remaining twenty five individuals have rib $\delta^{18}O_{DW}$ values between -12.0‰ and -10.0‰ and are likely to have spent a significant amount of the their last years in areas compatible with a more restricted area in south Scandinavia (excluding the southernmost regions of Norway, Sweden and all of Denmark); Belarus, western Russia, northern Iceland (see Fig. A3.2).

Migration

As documented in historical accounts, and indeed as it is today, it is not uncommon for individuals to move about and establish residence in geographically different locations at different times in their lives. Evidence already discussed above, suggests that none of the individuals in population 'B' resided in the British Isles at any time within 10+ years of their violent death on the Ridgeway. Oxygen isotope analysis was carried out on rib and femur pairs from a subset of population 'B' (n= 31 individuals) for the express purpose of establishing whether this was a static or migratory population. As shown in the result section (3.5.3) a number of this subset have significantly different $\delta^{18}O$ values between their ribs and femurs ($\Delta^{18}O_{(r\text{-}f)}$) to indicate that they spent the last few years of their lives in a different place to where they lived earlier. A significant difference in terms of bioapatite oxygen values for $\Delta^{18}O_{(r\text{-}f)}$ should be values outside 0.0 ± 0.36‰ see above). However there are additional errors incurred in converting $\delta^{18}O_P$ to $\delta^{18}O_{DW}$ and a more appropriate cut-off value for drinking water $\Delta^{18}O_{(r\text{-}f)}$ is 0.0 ± 2.9‰ (the 3σ error incurred from the analysis of $\delta^{18}O_P$ and the errors associated with Levinson *et al*. 1987 drinking water equation).

By plotting $\Delta^{18}O_{(r\text{-}f)}$ against femur $\delta^{18}O_{DW}$ (Fig. A3.9) we get a sense of movement for individuals in the last 2 to 5 years of life during previous 10+ years. A positive $\Delta^{18}O_{(r\text{-}f)}$ values indicates a change in location, from colder to warmer locations.

Individuals likely to have migrated prior to their arrival at Weymouth

Individuals who have migrated (moved to and lived in a different climate and geological environment) at least once during the 10+ years of their lives prior to their arrival at Weymouth are expected to have calculated drinking water $\Delta^{18}O_{(r\text{-}f)}$ values > 0.0 ± 2.9 (Fig. A3.9). Only six individuals (3806, 3791, 3764, 3804, 3786, 3687) meet this criteria with $\Delta^{18}O_{(r\text{-}f)}$ values between +4.0 and +7.4. These are the same six individuals that have extremely low femur $\delta^{18}O_{DW}$ values and were likely to have come from very cold/high altitude regions. Individual 3687, a prime adult (26-35 yrs), appears to have moved from a very cold to a less cold location probably sub-Arctic areas of northern Scandinavia. The remaining 5 individuals (3791, 3786, 3764, 3806, 3804), with roughly similar femur $\delta^{18}O_{DW}$ values, appear to have moved to similar and significantly warmer locations during the last two to five years of life. While it in not possible to pinpoint the location the most compatible areas can be found in south Scandinavia (excluding the southernmost regions of Norway, Sweden and all of Denmark); Belarus, western Russia and northern Iceland (see Fig. A3.2). It is worth noting that this group is composed of two adolescents (13-17 yrs), two prime adults (25-35 yrs); one mature adult (36-45 yrs) and one older adult (45+ yrs), which leads to question of whether they come from a similar area and/or were related?

Few oxygen isotope studies have been carried out on Scandinavian or Viking Age individuals. However Pollard *et al*. (2012) investigated a mass burial of similar age (AD 893 to AD 978) discovered at St John's College, Oxford UK. The burial, apart from decapitations, was similar to the Ridgeway mass grave in that the individuals were male (n=35), appeared to have suffered severe perimortem trauma and were dumped on top of one another with no grave goods or personal artefacts. The age range for these individuals was assessed as being between 16 and 45 yrs and many had healed wounds. Strontium isotope analysis carried out on six individuals and gave values higher than would be expected for the Oxford area and lowland

Britain. Oxygen isotope analysis on 14 individuals fall within the $\delta^{18}O_P$ range for tooth enamel of the Ridgeway individuals. Pollard *et al*. (2012) concluded that they were to most likely to be the result of a mass execution of a captured raiding party with Scandinavian origins.

Individuals unlikely to have migrated prior their arrival at Weymouth

The remaining individuals in population 'B' have $\Delta^{18}O_{(r\text{-}f)}$ values < 0.0 ± 2.9 making it unlikely that they migrated to significantly different climate locations during the last years of their lives. However some of the $\Delta^{18}O_{(r\text{-}f)}$ values are marginal in terms of the criteria used to assess migration, therefore the possibility that these individuals lived in different places at different periods of life cannot be wholly ruled out.

Diet

The investigation of diet through the combined use of carbon and nitrogen isotope analysis is a well established technique and a large body of data exists for Britain, Ireland, Denmark, Sweden, Iceland and various areas in Europe. Many diet studies begin with the assumption that both the human and faunal populations are local. In such studies, researchers rely on the isotope values of the fauna to estimate the type and quantities of local food consumed. In this study the assumption is that none of the Ridgeway population is likely to be local. Thus in the absence of appropriate faunal data, only a 'broad brush' approach can applied to diet interpretation. This will be done by comparing results from the Ridgeway population with a range of published human data from other diet studies, based mainly on British, Scandinavian, Icelandic and other European populations (see Figs. A3.12 and A3.13 for references).

The individuals in population 'A' and 'B' have a considerable range of carbon and nitrogen isotope values that suggest a wide range of plant carbohydrate and animal protein sources.

Dietary trends over time

If we consider the Ridgeway burials as being a single group of individuals, then it is highly likely that significant numbers of individuals in population 'A' are a subset of population 'B'. Bearing this in mind, a comparison of the $\delta^{13}C$ and $\delta^{15}N$ data for dentine, femurs and ribs can provide an insight into dietary trends over time for the entire population. Taking a 'broad brush' approach, the overall dietary trend for this population is one of increased protein consumption over time. The increase in $\delta^{13}C$ as well as $\delta^{15}N$ values suggests that they may have consumed greater proportions of marine foods during the last few years of life. The reasons for this trend may relate to change in status or food preference with age, or a consequence of migration resulting in a change in the type of available foods or isotope value of basic foods in different locations.

Childhood Diet (population 'A')

The childhood diets for population 'A' were very diverse, which is not surprising given the diversity in their places of origin. There is insufficient faunal carbon and nitrogen isotope data in the literature to cover all the likely places of origin for these individuals and only broad assumptions can be made in regards to diet.

Comparisons of our data with data from British, Scandinavian and Belgian sites enable us to speculate as to the type of foods the population 'A' consumed (Fig. A3.12 and A3.13). Most of these individuals appeared to have consumed greater proportions of animal protein (including dairy and marine products) than inland adult British 5th–10th century populations. In general the childhood diet of the majority of population 'A' most closely resembles adult Scandinavian 4th–11th century diets of the population at Björned N. Sweden (Linderholm *et al*. 2008b) than diets for other Scandinavian, (including Icelandic) or British 8th to 15th century populations (see Figs. A3.12 and A3.13 for references and Pollard *et al*. 2012 for other British and Scandinavian examples). Individuals from the Björned are described as having a diet '*mainly based on terrestrial resources, with a small contribution of protein from marine sources and in some cases a diet consisting of freshwater fish, providing elevated nitrogen values.*' (Linderholm *et al*. 2008b, 183), and this is likely to be the case with the majority of Ridgeway Hill individuals. Within population 'A' five individuals with lower than average $\delta^{15}N$ (<11.0‰) are thought to come from very cold climates (3759, 3711, 3712, 3747, 3694) and may have consumed less or different animal protein during their childhoods.

One individual (3726), with $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values compatible with either north western Scotland or southern Norway has comparatively low $\delta^{13}C$ and $\delta^{15}N$ values which represent a typical terrestrial diet. Individual 3752, who may have origins in northeast Scotland, has the relatively high $\delta^{15}N$ and moderately low $\delta^{13}C$ values expected for a mixed terrestrial and freshwater diet.

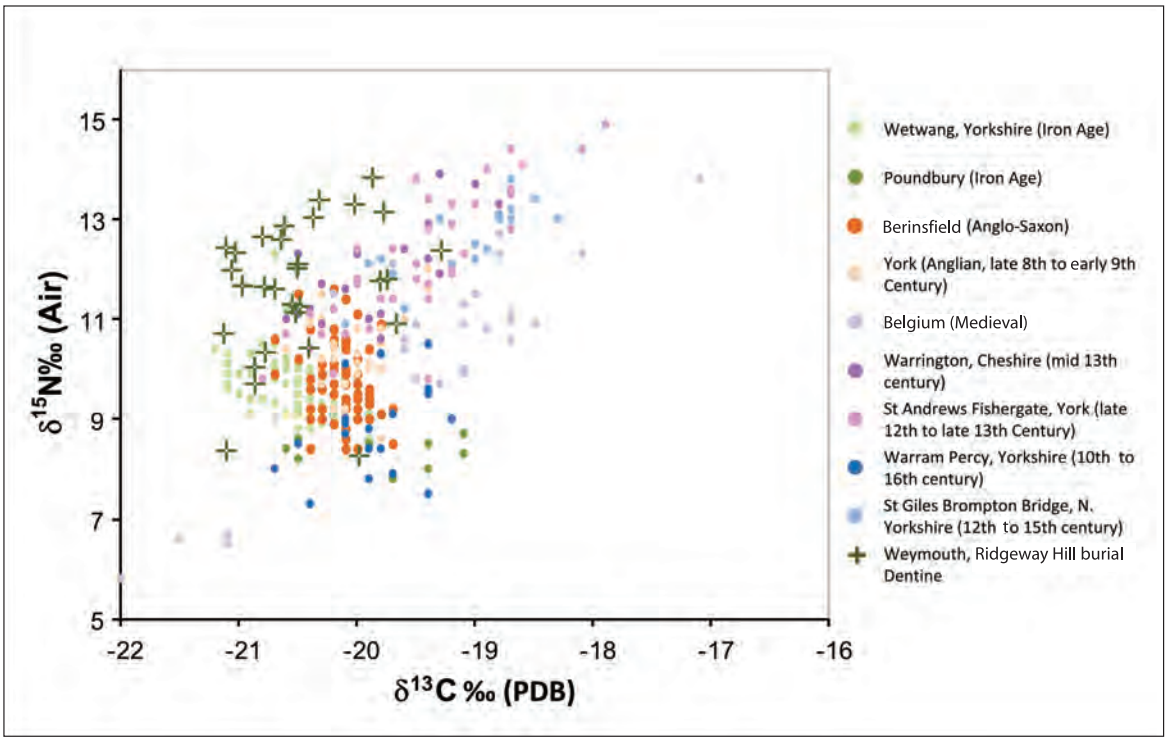

Fig. A3.12 A comparison of carbon and nitrogen isotope composition of dentine from individuals in population 'A' with UK and Belgian data. Data taken from; 1) Jay and Richards 2006; 2) Richards et al. 1998; 3) Privat et al. 2002; 4) Müldner and Richards 2007; 5) Polet and Katzenberg 2003; 6) Müldner and Richards 2005; 7) Müldner and Richards 2007; 8) Fuller et al. 2003; 9) Müldner and Richards 2005; 10) Fischer et al. 2007

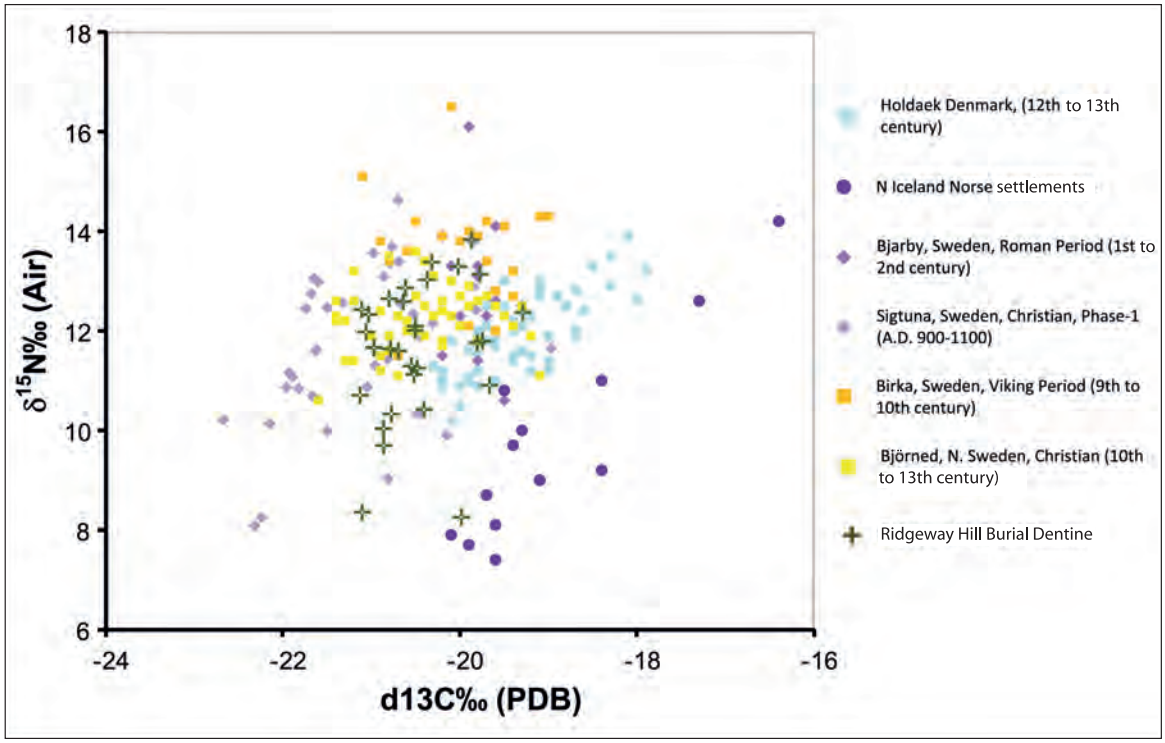

Fig. A3.13 A comparison of carbon and nitrogen isotope composition of dentine from individuals in population 'A' with Scandinavian and Icelandic populations. Data taken from 1) Jørkov et al. 2009; 2)Ascough et al. 2012; 3) Eriksson et al. 2008 (M2 data only); 4) Kjellstroma et al. 2009; 5) Linderholm et al. 2008a; 6) Linderholm et al. 2008b

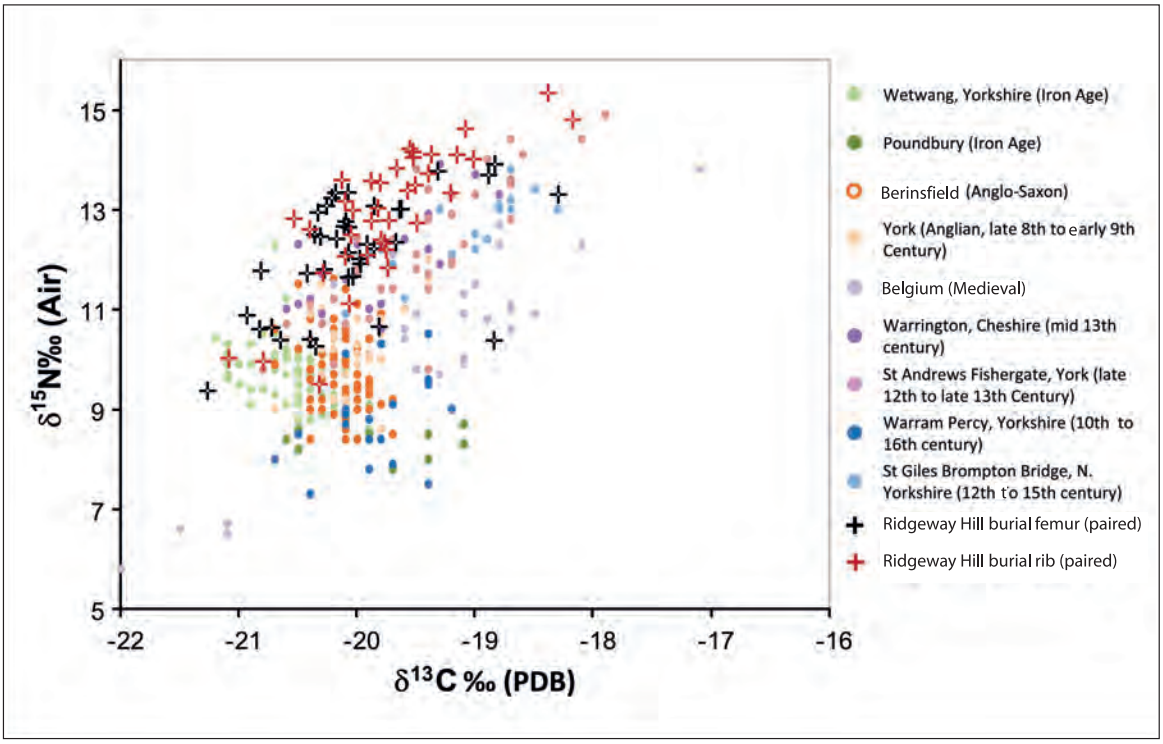

Fig. A3.14 A comparison of carbon and nitrogen isotope composition of femurs and ribs from individuals in population 'B' with UK and Belgian data. Data taken from; 1) Jay and Richards 2006; 2) Richards et al. 1998; 3) Privat et al. 2002; 4) Müldner and Richards 2007; 5) Polet and Katzenberg 2003; 6) Müldner and Richards 2005; 7) Müldner and Richards 2007; 8) Fuller et al. 2003; 9) Müldner and Richards 2005; 10) Fischer et al. 2007

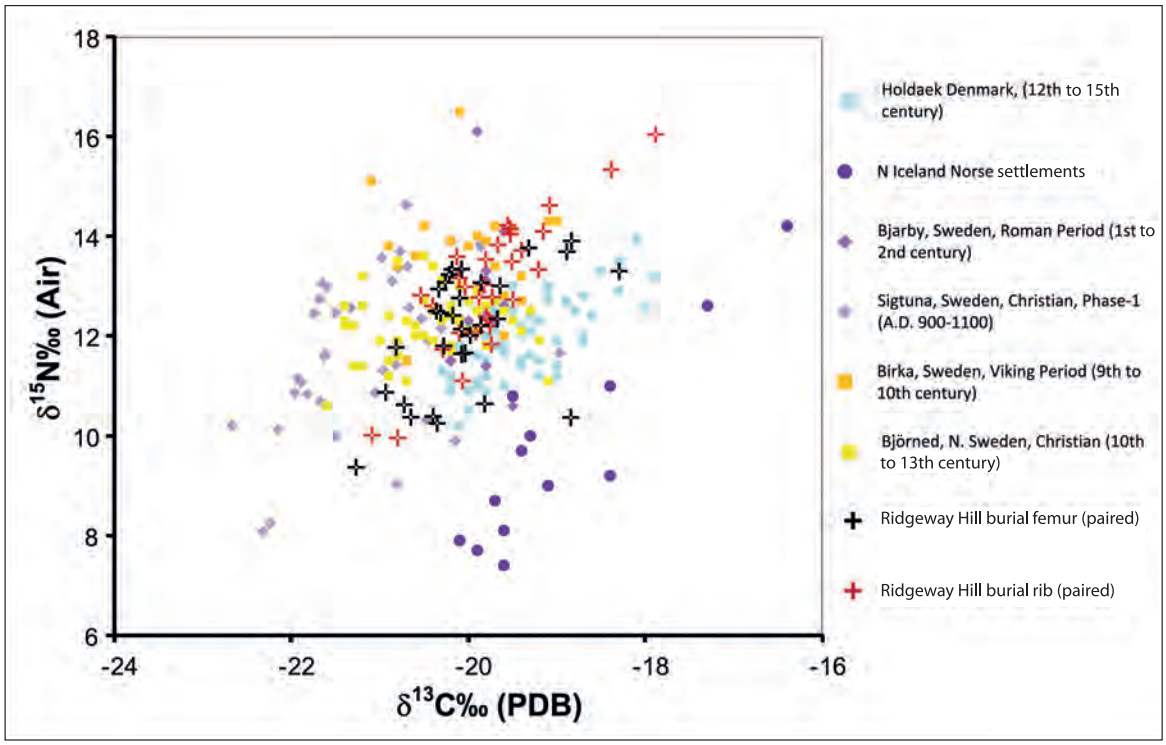

Fig. A3.15 A comparison of carbon and nitrogen isotope composition of femurs and ribs from individuals in population 'B' with Scandinavian and Icelandic populations.Data taken from 1) Jørkov et al. 2009; 2) Ascough et al. 2012; 3) Eriksson et al. 2008 (M2 data only); 4) Kjellstroma et al. 2009; 5) Linderholm et al. 2008a; 6) Linderholm et al. 2008b

Diet in later life (population 'B')

In considering the entire data set for population 'B', the majority of individuals have $\delta^{13}C$ and $\delta^{15}N$ femur values that are very similar to the 10th–13th century population at Björned, Sweden where marine sources made a small contribution to diet (Linderholm *et al*. 2008b) and they fall outside British populations of comparable age, see Figs A3.14 and A3.15. By contrast in the most recent years of their lives the majority of the population appears to have a greater marine component in their diets as reflected in the overall higher values for both $\delta^{13}C$ and $\delta^{15}N$. A number of individuals have relatively low $\delta^{13}C$ values but $\delta^{15}N$ values higher than expected for a wholly terrestrial diet suggesting that freshwater fish was a component of their diets.

By examining the difference in femur and rib $\delta^{13}C$ and $\delta^{15}N$ values it is possible to trace changes in diet for 31 of the individuals in population 'B'. As seen in the results (see above and Figs A3.7 and A3.8) a number of individuals experienced a change in either $\delta^{13}C$ or $\delta^{15}N$ during their last years of life. By comparing $\delta^{13}C$ to $\delta^{15}N$ (Fig. A3.16) a clearer picture of dietary change emerges. A few individuals (3794, 3775, 3791, 3778, 3805) appear to have had little or no changes in their diet. Individual 3791 was one of the youngest individuals of the population and his diet appears to be a mix of terrestrial and freshwater protein. Lack of change in his diet is unusual for someone who has apparently migrated from an exceptionally cold region to an area in central Scandinavia and his young age may explain to his dietary behaviour. The majority of individuals experienced minor to moderate changes in diet and this is most likely attributed to increased consumption of marine sourced food.

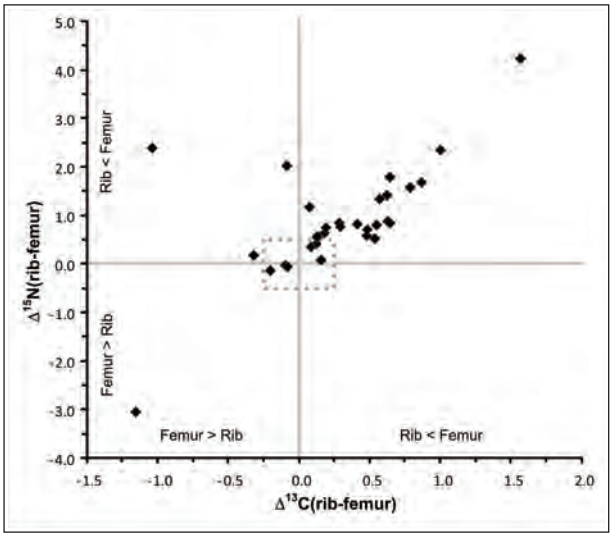

Fig. A3.16 Plot of the difference in $\delta^{13}C$ between rib and femur ($\Delta^{13}C$(rib-femur) against the difference in $d^{15}N$ between rib and femur ($\Delta^{15}N$(rib-femur) for the 31 individuals from population 'B' with rib and femur pairs. Grey dotted box outlines the individuals unlikely to have had a significant change in carbohydrate intake during the last 10 + years of life

A number of individuals have experienced more significant changes in their diets. Two individual (3804, 3763), who had similar migration patterns to 3791 (above), display dietary patterns that stand out amongst the rest of population 'B'. Individual 3804 appears to have switched from a primarily terrestrial based diet to one with a significant marine component, while individual 3763 appears to have significantly increased his marine protein consumption. Individual 3803 is unusual in that his $\delta^{13}C$ has decreased and $\delta^{15}N$ has increased over time. While falling outside the criteria for migration, 3803 may have moved to a colder location in the last years of his life and in the process exchanged marine protein for freshwater protein in his diet. Individual 3810, who died as a young adult, does not appear to have migrated during his life; however his diet has changed significantly during this time. Prior to death he appears to be eating a largely terrestrial based diet but during his adolescent years he had a moderate amount of marine foods in his diet.

Comparative studies of $\delta^{13}C$ and $\delta^{15}N$ on ribs and femurs in the same individuals have been recently reported in several publications. Data from a large study of a static population from the medieval cemetery (AD 1200–1573) at Holbæk, Denmark (Jørkov *et al*. 2009) show insignificant dietary difference between earlier and later periods of life. British 18th century sailors buried at Gosport, UK (Roberts *et al*. 2012) show varied dietary change, with ~20% consuming less animal protein and ~30% consuming more animal protein during the later part of their lives. Data from Pollard *et al*. (2012) for Viking Age individuals from a mass burial at St John's College, Oxford, UK, show similar dietary changes to the Ridgeway Hill group, in that those with a significant change appear to have consumed more animal protein in the two to five years prior to their deaths.

SUMMARY AND CONCLUSIONS

This multi isotope study of the ribs and femurs of at least 40 individuals and teeth of 31 individuals from the Ridgeway Hill mass grave indicate this was a disparate group in terms of origin, migration and dietary habits. Many, if not all, of the individuals spent most, possibly all, of their lives outside of the British Isles. Isotope evidence suggests they may have lived in places as far afield as Scandinavia, the Baltic States, Belarus and Russia all of which fall

within viking reach. This group also appear to have a wide range of individual diets, which were high in animal protein and primarily based on terrestrial food sources with small to moderate additions of marine and freshwater protein. The circumstances that brought these individuals to the Weymouth area are unknown; however isotope data indicates that for at least 38 of them were living outside the British Isles in the two to five years prior to their deaths.

The key points derived from this study are:

1) The oxygen isotope composition of tooth enamel, representing the childhood place of origin of 31 individuals, is beyond the range of UK values for most individuals and consistent with an origin in a colder climate or a high altitude region.
   a. The calculated drinking water oxygen isotope composition is consistent with childhood origins, for 26 individuals, in areas including Arctic and sub-Arctic areas of Scandinavia, northern Iceland, the Baltic States, Belarus and Russia.
   b. Five individuals are compatible with origins or spending their childhoods exceptionally cold locations either north of the Arctic Circle or central Russia.
   c. Five individuals have oxygen isotope values that are consistent with origins either in the UK, Denmark or southern Norway.
2) The strontium isotope composition of tooth enamel of 29 individuals supports the 'non local' origin, insofar as none were raised on the local Chalk (on the Ridgeway) or London Clay in Weymouth, Britain.
   a. Two individuals have strontium isotope values compatible with origins on the local London Clay around Weymouth however their values are also compatible with geologic terrains in Denmark and the Baltic states.
3) The range of both strontium and oxygen isotope values shows that this is a group of people that do not have a common geographic origin.
4) The oxygen isotope composition of ribs and femurs for 17 complete skeletons, 23 partial skeletons and 5 isolated limbs and extremities, representing at least 40 individuals, falls outside the expected range of the UK. Their calculated drinking water values suggest they spent the 10+ years before their deaths in colder areas that are compatible with documented ground and/or surface water values for a wide range of locations including: Scandinavia, northern Iceland, the Baltic States, Belarus, Russia and Arctic regions.
5) The migration history for 31 individuals, derived from oxygen isotope data for their ribs and femurs, indicates that:
   a. The majority of individuals are unlikely to have relocated during the 10+ years prior to their deaths.
   b. Six individuals are highly likely to have migrated from an exceptionally cold region to significantly less cold locations. Five of these individuals, including two adolescents, have a similar migration pattern and appear to have spent time together in both locations.
6) The carbon and nitrogen isotope data for the majority of individuals is most similar to a population of 10th–13th century Christians buried at Björned, N Sweden, which is typical for a mixed high protein diet, based on terrestrial and marine sources.
7) Variations in carbon and nitrogen for dentine, femur and rib suggest that on the whole, the protein content, and in particularly marine protein, of their diets increased over time.
8) The isotope data for the individuals from the mass grave on Ridgeway Hill are consistent with being a mixed group of people who originated and/or migrated through the areas known to have been occupied by Viking settlements between AD 970 and AD 1025.

NOTE

The Anderson-Darling (AD*) statistic associated with each distribution plot gives a measure of 'goodness of fit' or how far the data points fall from the fitted line of probability (ie. 'normality'); the lower the value the better the fit.