A REPORT ON THE COMBINED ISOTOPE AND TRACE ELEMENT DATA FOR 20 INDIVIDUALS FROM THE NEW CHURCHYARD (AD 1569-1714), LONDON

Janet Montgomery[1], Ruth Morley[1], Nidia Lisic[2], Julia Beaumont[2], Geoff Nowell[3], Chris Ottley[3], Joanne Peterkin[3]

[1]Department of Archaeology, Durham University, Durham, DH1 3LE

[2]Archaeological Sciences, University of Bradford, Bradford, BD7 1DP

[3]Department of Earth Sciences, Durham University, Durham, DH1 3LE

Prepared for Museum of London Archaeology

December 2016

Contents

1. NON-SPECIALIST SUMMARY

Diet and mobility of twenty individuals, ten from the mass burial pit (the Pit group) and ten single inhumations (the Control group) at the New Churchyard burial ground were investigated using a range of isotopes and trace elements. Nine individuals have a combined strontium and oxygen isotope profile that is inconsistent with childhood residence in London (i.e. Control group: 74, 805, 4307, 7740, group Pit: 8145, 8147, 8204, 8216, 8219) and whilst migrants to London are found in both groups, only one female (4307) from the five investigated is a clear migrant, the majority being males and subadults. A further ten individuals are consistent with origins in southern or northern England and one subadult aged 12-17 years from the Pit group is most likely to have originated outside Britain in a warmer climate. Isotope values are, however, not exclusive to any specific location and there are many other places in Europe and beyond where strontium and oxygen isotopes would be indistinguishable from those of Londoners and migrants from these places would be invisible in the dataset. All the New Churchyard individuals experienced what by modern standards is regarded as a high level of lead exposure during childhood and may have suffered sub-clinical and possibly clinical effects. However, there was no significant difference between lead exposure in the Pit group and the Control group. Several individuals have unusually high strontium concentrations which can arise due to a vegetarian diet, low dietary calcium, fertilization of agricultural soils with seaweed, or residence in arid or coastal regions or unusual geological terrain. Further research needs to be done on the causative factors and the link between high strontium and high lead concentrations in relation to low dietary calcium uptake, nutritional stress and pathologies such as rickets.

Statistical analysis of the data between Pit and Control group and between males and females found few significant differences in origins or diet. However, it appears that whilst there was no difference between childhood diets between the Pit and Control group, in later life the Pit group appear to be consuming a larger proportion of plants and thus less animal protein during later life than the Control group. This may suggest a shift to a poorer, less nutritious diet amongst the individuals in the Pit in the last few years of life. Overall, the dietary isotopes of the New Churchyard population fit within the trend of increasing values from the early Medieval through to the post-Medieval periods which documents the introduction of higher levels of fish, marine and freshwater, to the diet particularly in urban populations such as York and London. Evidence for breastfeeding is limited and suggest that if individuals

were breastfed it was not for a sustained period. A 26-35 year old male from the Pit group (8204) appears to have consumed a very different diet during childhood and his isotope profile suggests he originated in a rural population possibly in northern England. Several individuals show a gradual shift during their lifetime towards a diet typical for urban London which is clearly seen in 8216 the migrant male aged 18-25 years. Two female burials from the Pit group, 8101 and 8223, have almost identical isotope profiles which strongly support shared origins and life-histories.

The data from New Churchyard provide a rich body of evidence for individual life histories during the 16-18th centuries. The results raise new questions both for the period and for what the techniques used can tell us about humans in the past.

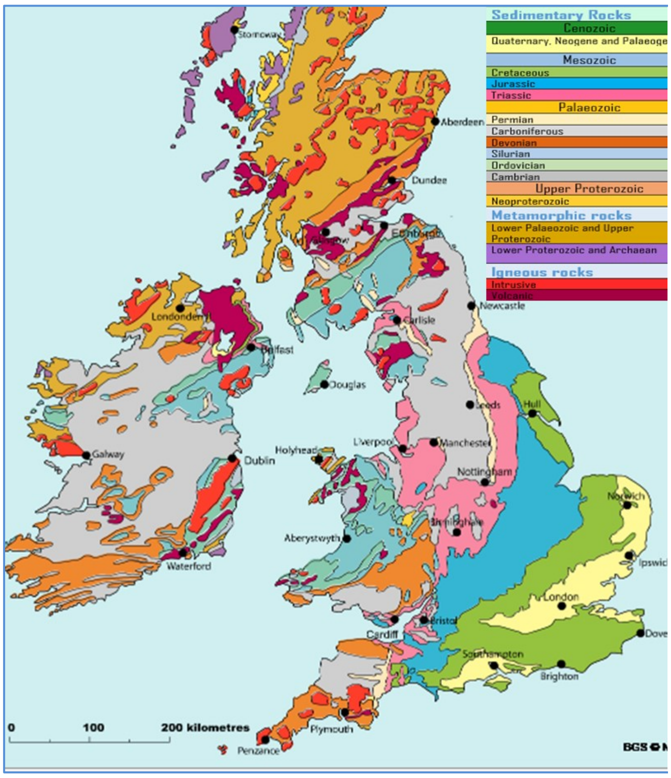
2. INTRODUCTION

The use of isotopes in archaeological studies is based on the principle that humans incorporate into their body tissues chemical elements with isotopic compositions that reflect those of the food, water and pollutants ingested either intentionally or unintentionally during their lifetimes - "You are what you eat and drink". Since the mid-1990s, strontium and oxygen isotopes have been employed in archaeological studies to characterise individuals' places of childhood residence and to identify migrants. The method relies on the assumption that people sourced the bulk of their diet and drinking water locally which in many archaeological periods may be valid. Strontium in skeletal tissues derives primarily from the plants people eat and the isotope ratio of the strontium can be linked back to the place where that food was grown because the strontium comes ultimately from bedrock. Rocks of different type and ages vary in their strontium isotope ratio and because they also vary geographically; if we use tooth enamel which forms in childhood, this provides a mechanism for linking people back to their place of origin (Bentley 2006; Montgomery 2010; Montgomery, Evans, and Cooper 2007). Oxygen isotopes also vary geographically in a known manner as a function of precipitation, altitude, latitude and distance from the sea (Daux et al. 2008; Longinelli 1984; Luz, Kolodny, and Horowitz 1984) and because the oxygen in skeletal tissue derives primarily from rainfall via drinking water, we can measure the oxygen isotopes of tooth enamel to provide a further complementary indication of childhood climatic and hence geographical residential origins (Fricke, O'Neil, and Lynnerup

1995). There are of course complicating factors as geological and environmental peculiarities of a particular region in the form of rainwater, dust, and drift such as glacial deposits, can alter bedrock strontium in the foodchain (Bentley 2006).

Trace element analysis, i.e. how much strontium is present, can provide additional variation as this is also known to vary geographically (Montgomery, Evans, and Cooper 2007) as does the level of lead in human tooth enamel. In Britain from the Roman Period onwards, human lead levels rise above natural prehistoric exposure levels, i.e. >0.5 ppm due to the large scale extraction of lead and its use in cooking utensils, water transport and storage, condiments, medicines, food adulteration, make-up, air pollution and industrial exposure (Montgomery et al. 2010). In the medieval period human lead burdens continue to rise until the 19th century AD when many humans exhibit enamel lead levels of 30 ppm and higher (Millard et al. 2014); this is 10,000 times higher than the lowest levels found in prehistoric humans in Britain and likely to be recording a childhood blood lead level in excess of what is currently considered safe (Montgomery et al. 2010). Lead is a well-known toxin having a deleterious effect on calcium metabolism and the nervous, digestive and reproductive systems (Clarkson 1987; Goyer 1996; Byers and Lord 1943) and high lead exposure is associated with malaria, rickets, gout, Paget's disease and periodontal disease. The toxicity of lead on the neurological development of children is blamed for a range of anti-social and delinquent behaviours and compromised intelligence even at sub-clinical levels (Needleman 2009; Needleman et al. 2002). Enamel lead levels can, therefore, be a useful indicator of the extent of an individual's childhood exposure to lead pollution,

Figure 1. Map showing bedrock geology of Britain and Ireland. © British Geological Survey (2016)



rural versus urban living and possibly throw light on the impact it had on their physical and neurological development.

Dietary isotopes such as carbon and nitrogen have also been found to be extremely useful in reconstructing the childhood diet and physiology of medieval and post-medieval humans showing incidences of dietary change, breastfeeding and periods of trauma, disease and nutritional stress such as famine (Müldner et al. 2009; Müldner and Richards 2006, 2007; Beaumont et al. 2013; Beaumont and Montgomery 2016; Beaumont et al. 2015; Eerkens, Berget, and Bartelink 2011; Richards, Mays, and Fuller 2002; Fuller et al. 2005). In this study, the New Churchyard individuals' dietary profiles will be explored through the use of carbon ($\delta^{13}C$) stable isotopes obtained from tooth enamel carbonate and carbon and nitrogen ($\delta^{15}N$) isotopes from dentine and bone collagen. Bone collagen, because of its slow turnover rate, represents a long-term average of diet which in the cortical femur of mature adults can date back to adolescence but in bones such as the ribs used in this study can represent a much shorter period, e.g. c. the last one to two years of life (Hedges et al. 2007; Beaumont and Montgomery 2016). In contrast, primary dentine is mineralised within 3–4 days of secretion and does not remodel, and thus represents the diet at the time the tooth was growing. The analysis of incremental dentine has allowed researchers to identify short-term changes in the diet of individuals (Eerkens, Berget, and Bartelink 2011; Fuller, Richards, and Mays 2003; Beaumont et al. 2013). Their residential origins will be investigated using strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotopes, and the trace elements of strontium, lead and barium in tooth enamel which like dentine does not remodel and represents a c. 3-4 year time period of childhood (AlQahtani, Hector, and Liversidge 2010). There is little isotope evidence for individuals from this period in either London or the wider UK and thus these data will begin to fill the gap in our knowledge.

3. GEOLOGY AND PREDICTED HUMAN STRONTIUM AND OXYGEN ISOTOPES

The city of London is located in the centre of the London Basin and is bound by an undulating bed of Cretaceous white chalk of the Chiltern Hills and Berkshire Downs to the north and north-west, the North Downs to the south and south-west and extending westwards into the Marlborough Downs of Wiltshire (Figure 1) (British Geological Survey 2001). The Chalk is a pure limestone covered with flint nodules in the upper beds. The chalk extends beneath the entire basin and overlying it are the oldest Palaeogene deposits - the Thanet Sand Formation and the Lambeth Group (Upnor, the Woolwich and the Reading Formations). The Thanet Sand Formation consists of a coarsening-upwards sequence of buff fine-grained glauconitic sand and silts made up of a basal bed of flint cobbles and nodular flints originating from the chalk (Ellison and Zalasiewicz 1996). It reaches a maximum thickness of about 40m in the east of the area but rapidly thinning and overlapped by the Lambeth Group beneath western London. The Lambeth Group is typically composed of clays, gravels, sands and silts. Overlying the Lambeth Group, Eocene sediments of the Thames Group consisting of the Harwich formations and London Clay Formations are found. The Thames group consists of sandy silts, silty clay/mudstone and sandy clayey silts of marine origin. Younger Eocene sediments - the Bracklesham Group (Bagshot, Windlesham and Camberley Sand formations) are also present and are found in south-west London (British Geological Survey 1977, 2001; Ellison and Zalasiewicz 1996; Sumbler 1996).

The average strontium isotope biosphere for regions of London Clay and other regions of yellow on Figure 1, has been estimated by Evans et al. (2010) to lie between 0.7090 and 0.7100 (Figure 2) and it is expected individuals indigenous to London and who source the bulk of their diet from the London Basin would have enamel strontium isotope ratios within, or close to, this range. Regions of Chalk which almost entirely encircle the London Basin (green regions on Figure 1), provide strontium isotope biospheres of 0.7080 to 0.7090. Thus individuals who have originated from the southeast of England should fall within the range of 0.7080 and 0.7100.

Oxygen isotope zones in Britain vary from west to east as a result of the prevailing winds (Darling, Bath, and Talbot 2003; Darling and Talbot 2003). Regions of lower rainfall, such as the east, and lower isotope ratios (Figure 3). London falls within a region with $\delta^{18}O$ values between -7.5‰ and -7.0‰. Individuals from London would, therefore, be expected to have lower oxygen isotope ratios than those originating from the west of Britain or Ireland.

Because oxygen isotopes are also linked to climate, they would also be expected to have lower values than individuals originating from warmer more southerly climates such as the Mediterranean.

Figure 2. Strontium isotope biosphere map for Britain (Evans et al. 2010)

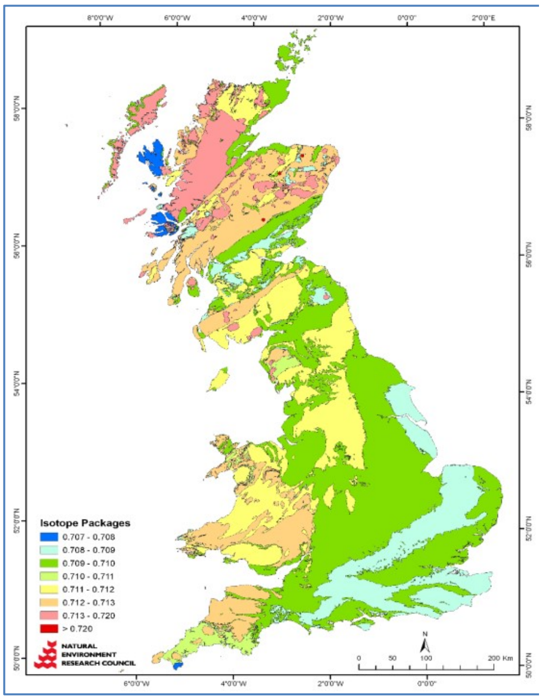
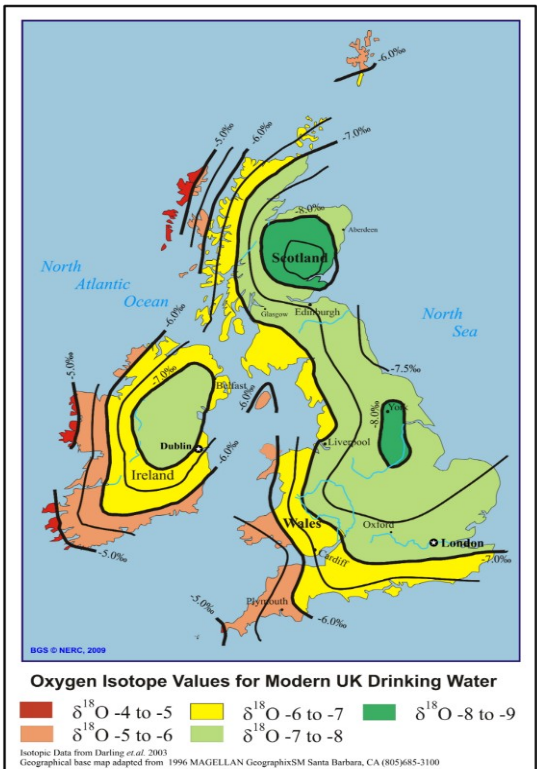


Figure 3. Oxygen isotope values for Modern UK drinking water (Darling, et al., 2003) ©BGS/NERC



4. Materials and Methods

Twenty individuals were sampled for this study (Table 1). From each individual two teeth which formed at different times during childhood were analysed to enable residential and dietary change up to the maximum age of 23 years to be investigated. Ten individuals were selected from mass burial pits (possibly associated with plague epidemics) and ten from individual graves as a control group.

The enamel and dentine samples analysed in this study were obtained from human permanent canines (C1), first (M1), second (M2) and third (M3) molars which form at different times of life. The period of an individual's life represented by the data obtained thus varies between teeth and depending whether the sample is enamel (~birth up to ~15 years of age) or dentine

(~birth up to ~23 years of age). In addition, one deciduous tooth, a second molar, was obtained from burial 8099 a sub-adult aged 6-11 years of age which starts to form in *utero*. The estimated period of life represented by the data for each individual following AlQahtani et al.(2010) are given in Tables 1 and 2.

Detailed sample preparation and analysis protocols are given in Appendix 1.

5. RESULTS

The isotope data are tabulated in Tables 1 and 3 and results summarised below. Statistical data analysis (boxplots, t-tests, ANOVA) can be found in Appendix 2. For the purposes of the data analysis below ?Male and ?Female were grouped with Male and Females respectively. Two teeth were analysed from each individual except 5396 for whom no enamel could be obtained from the M3. $\delta^{13}C$ and $\delta^{15}N$ data for the second tooth is still in process.

5.1 STRONTIUM ISOTOPES AND CONCENTRATIONS

The strontium isotope and concentration data are given in Table 1. The $^{87}Sr/^{86}Sr$ range for all the New Churchyard individuals is 0.70864-0.71091 with a mean of 0.7096± 0.0006 (1σ, n=39). This mean value is very similar to that obtained at other sites in London (Table 2) and the range largely overlaps with individuals from the mass burial pit at East Smithfield (Figure 4).

Site	Mean Sr (ppm)	Mean $^{87}Sr/^{86}Sr$	Mean $\delta^{18}O_p$‰	Study
East Smithfield	112	0.70924	17.9	(Kendall et al. 2013)
Chelsea Old Church	125	0.70924	17.5	(Trickett 2006)
St. Mary Spital	104	0.70954	17.6	(Lakin 2010)
New Churchyard	150	0.70964	17.7	This study

Table 2. Mean Sr and O isotopes and Sr concentrations for comparative London sites

This is a relatively restricted range in strontium isotope terms and falls well within the known range of archaeological individuals excavated in Britain (Evans, Chenery, and Montgomery 2012). It is broadly consistent with values that would be expected for humans inhabiting the sedimentary bedrock and unconsolidated drift that covers the majority of England (Evans et al. 2010). However, whilst it is true that strontium isotope ratios such as these are extremely common in burials from England they are equally common across Europe and beyond and thus do not prove origins in southern England. Nonetheless, almost all of the individuals fall within, or very close to, the estimated biosphere range of the London Clay (Figure 4). Three individuals (8147 and 8216 from the pit and 4307 from the control group) have strontium isotope ratios below 0.7090 and are thus consistent with the Chalk that encircles London (the green areas in Figure 1) or limestones which occur widely over southeastern England; it would not, therefore, be unusual to find individuals with such ratios buried in London. Three adult males from the control group (74, 805 and 7740) and one subadult from the pit (8145) have strontium isotope ratios above 0.7100 that are higher than might be expected for inhabitants of the London Clay although such values are also commonly found in western and northern England, and in Wales and Scotland (Figure 2). Interestingly, in all four of these individuals, as well as for 8147 and 8216 who have lower ratios, both teeth fall outside the range for London implying these individuals moved to London after the formation of their M2/M3, i.e. they were eight years of age or older.

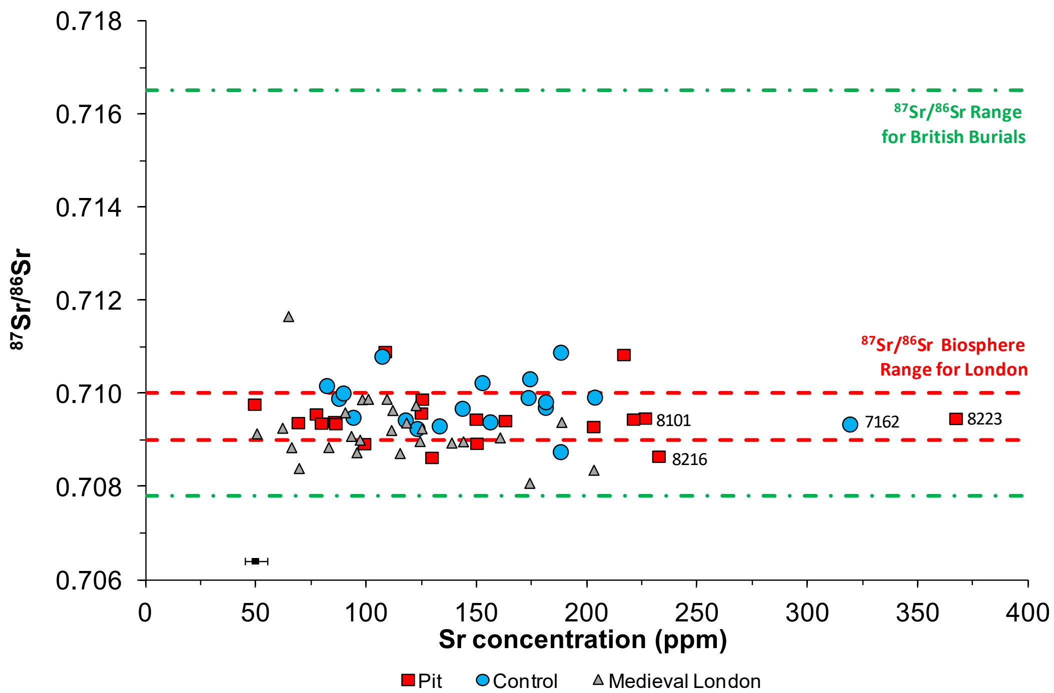


Figure 4. Enamel strontium isotope and concentration data for the New Churchyard individuals. The expected range for indigenous Londoners (red) is estimated from Evans et al. (2010) and the range of values for archaeological humans from Britain (green) is taken from Evans et al. (2012). Comparative data for medieval burials in 14th century London is from Kendall et al.(2013). Analytical uncertainty is shown at 2σ.

A comparison of the Pit and Control groups suggest the mean and median of the Pit group is lower than the Control group and this is significant at the 95% CI (Student t-test, $p = 0.039$ (Appendix 2). This may indicate that more of the Pit group are local to London. However, the overall range is very similar between the two groups, the group sizes are small and the absolute difference in $^{87}Sr/^{86}Sr$ is c. 0.0003, which is not a significant inter-individual difference in the context a group of humans inhabiting the same town (Montgomery 2002, p146). In isolation, therefore, too much weight should not be placed on this finding.

Strontium concentrations range from 49 to 367 ppm, with a mean value of 150 ± 67 ppm (1σ, n=39). All but two of these values, which are identified as statistical outliers (Appendix 2), fall within the range for British populations at the 95% confidence interval (mean 105 ± 138 ppm (2SD, n=614); Evans, et al. 2012, p.755). In a small study of whole teeth of modern individuals in Britain (n=27), Brown et al. (2004) obtained a range of 52 to 262 ppm and suggested a link between high enamel strontium concentration and rickets. Enamel strontium concentrations above 150 ppm are only rarely found in burials from England but this is the mean value at New Churchyard. The mean value is also higher than at other medieval London sites (Table 3). The mean is clearly affected by the two statistical outliers: the female 8223 C1 and the male 7162 M2 have very high strontium concentrations which in Britain have only been found to date on island populations in the Western and Northern Isles of Scotland coupled as they are in these two New Churchyard individuals with a strontium isotope ratio slightly above seawater which has a ratio of ~0.7092 (Montgomery, Evans, and Cooper 2007). The female 8101 and the subadult 8219 also have high strontium concentrations.

Strontium concentrations in enamel can vary with geographical/geological residence but also with calcium intake (low dietary calcium = high metabolised strontium), and trophic level because herbivores have higher concentrations than carnivores in any given food web (Burton and Wright 1995; Montgomery 2010). Unusually high concentrations may therefore indicate a plant-based diet, low dietary calcium, or residence in an island, coastal or arid environment or a region of unusual geology. However, they are clearly multi-factorial and have not yet been well-defined for medieval and post-medieval populations in London.

A comparison between the strontium concentrations of the Pit and Control groups shows no significant differences between the means at the 95% (CI), $p = 0.845$ and there is no significant difference between males and females, $p = 0.388$ (Appendix 2).

5.2 OXYGEN ISOTOPES

Measured carbonate oxygen isotope data and $\delta^{18}O_p$ and $\delta^{18}O_{dw}$ for each sample, calculated using the equation of Chenery et al. (2012) and Daux et al. (2008) Eq. 6, are presented in Table 1.

The $\delta^{18}O_p$ values for the New Churchyard individuals range from 16.2‰ to 19.6‰ (mean 17.7 ± 0.8‰, 1σ) which is almost identical to the mean and standard deviation of archaeological humans excavated in Britain: 17.7 +/- 0.7‰ reported by Evans et al. (2012) and to other medieval and post-medieval populations in London (Table 3). When calibrated to drinking water ($\delta^{18}O_{dw}$) the New Churchyard individuals range from -9.2‰ to -3.3‰ (mean -6.7 ± 1.3‰, 1σ). Unlike the strontium isotope data, there is no clear clustering of $\delta^{18}O_p$ and the data are spread across the range for Britain. Considering the analytical error as well as the large uncertainty error associated with the conversion equations (see Figure 5), all individuals, with the exception of 8219, have $\delta^{18}O_p$ values which fall within the 2σ human phosphate range for eastern England specifically (17.2 +/- 1.3‰ 2SD) and Britain more widely (Evans, Chenery, and Montgomery 2012). The calculated $\delta^{18}O_{dw}$ values (Table 1) also fall within those expected for precipitation in Britain and Ireland (Figure 3) as well as much of Europe with the possible exception of the subadult 8219 from the Pit group ($\delta^{18}O_{dw}$ = -3.3‰). The subadult 8219 falls outside the 2SD for western England (18.2 +/- 1‰ 2SD) and there is, therefore, only a 2.5% probability of origins in Britain. It is possible, if unlikely, that such a value might be obtained in the Western Isles of Scotland or the extreme west coast of Ireland (Figure 3). Comparably high $\delta^{18}O_{dw}$ values are found at lower latitudes, for example in southern Europe and around the Mediterranean.

When the $\delta^{18}O_p$ for the Pit and Control groups are compared there is no significant difference at the 95% CI (student t-test, p = 0.261) and nor is there any significant difference between males, females and subadults (one-way Anova, p =0.465) (Appendix 2). It should be noted, however, that the five females in the dataset cluster more tightly around what could be considered combined local strontium and oxygen isotope ratios and the highest and lowest values belong to males or subadults (Figure 5). This may suggest females are more likely to be of local origin but the dataset is small.

Higher oxygen isotope ratios may indicate origins in the west of Britain or the consumption of milk or heated and brewed liquids such as teas, soups, stews and beer during childhood which can artificially increase the $\delta^{18}O$ of ingested fluids (Brettell, Montgomery, and Evans 2012). Teeth which form prior to the cessation of breastfeeding may thus exhibit raised $\delta^{18}O$ (Wright and Schwarcz 1998), but there is no clear clustering of the M1 teeth towards higher values, indeed the highest value is a M2 whilst four of the five lowest values are M1 teeth, and the only deciduous tooth measured falls at the centre of the dataset (Figure 5).

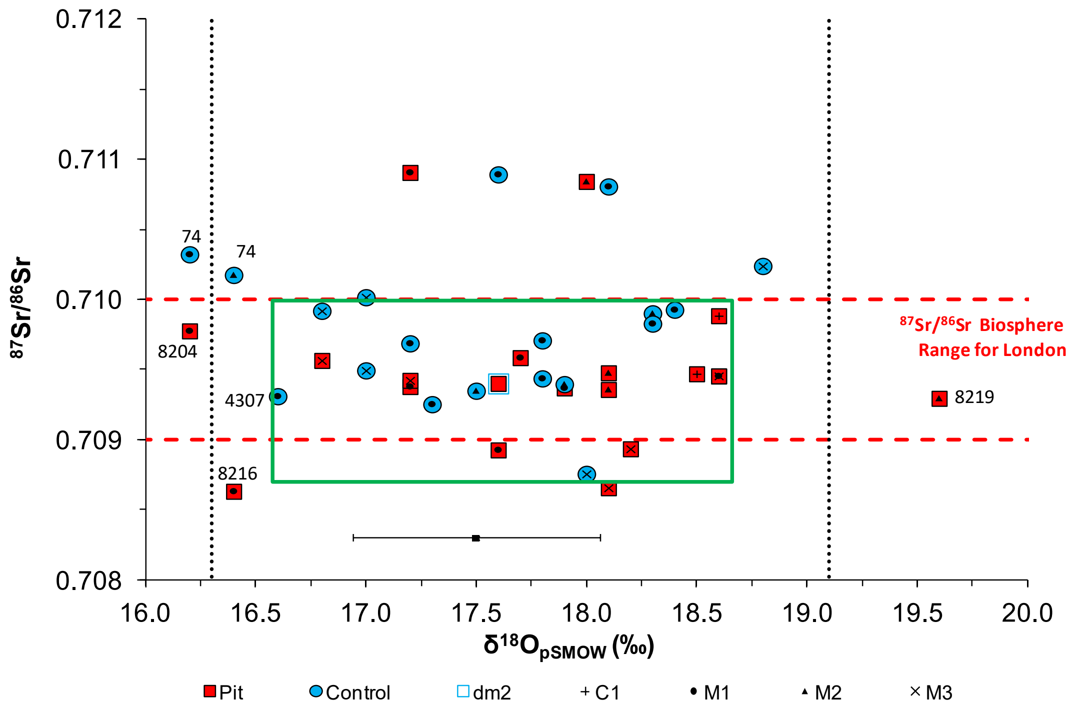


Figure 5. Enamel strontium and phosphate oxygen isotope data for the New Churchyard individuals. The black lines delineate the 2σ range of oxygen isotope ratios for archaeological humans in Britain (Evans et al. 2012). All individuals fall within the oxygen isotope range for Britain within analytical error. No female individuals lie outside the green box. Analytical uncertainty is shown at 2σ.

Three individuals (6085, 7740 and 8099) provide evidence in their carbon and nitrogen isotope profile (Figures 10 and 13) of a possible breastfeeding signal in the M1 but only one of these (8099) has a $\delta^{18}O_p$ above 18.0 ‰. Despite the impression of defined oxygen isotope zones in Figure 3, a spread of 2-3 ‰ is not an uncommon finding in archaeological populations in Britain and may derive from a multiplicity of factors such as a mobile population, analytical uncertainty and environmental and biological variation. Given that London was a cosmopolitan city and there is a significant likelihood that individuals from many different places are present in this time period, it is difficult to define a range unique to

London from this dataset, especially given that the strontium isotope ratios exhibit a very small range which is largely consistent with London Clay and its environs. However, it is very likely that people of different residential origins are present but they mostly cannot be identified by their oxygen isotopes alone. Nonetheless, three individuals of note with large intra-individual shifts are: a middle adult ?male 8204 who has 16.2‰ in the M1 but an increase of c. 2‰ in the M2; and a middle adult female 4307 and a young adult male 8216 who also exhibit a c. 2‰ increase between the M1 and the later forming tooth from c. 16‰ to c. 18‰ (Figure 5). In addition, the young adult male 74 from the control group has non-local strontium isotopes in both teeth plus two of the lowest $\delta^{18}O_p$ values (M1: 16.2‰ and M2: 16.4‰). There are few processes that shift oxygen isotopes to lower values but many that shift them to higher values, e.g. consuming milk, teas, beer, stews (Brettell, Montgomery, and Evans 2012) so the majority of local individuals are likely to have a higher $\delta^{18}O_p$ value than predicted from the map in Figure 3. It is thus unlikely that M1 values below 16.8‰ were obtained whilst resident in London: in Britain they are only consistent with the dark green regions in Figure 3. The data suggest a change in oxygen isotope source sometime after the age of eight for 74, and after the age of four for 8204, 4307 and 8216, possibly for the last three individuals towards London from a region to the northeast or overseas.

5.3 LEAD CONCENTRATIONS

The amount of lead present in the enamel of the New Churchyard individuals varied by an order of magnitude and ranged from 2 to 44 ppm (Figure 6). Prior to the Roman period, inhabitants of Britain had enamel lead levels below ~ 0.5 ppm but the increase in metal extraction and lead compounds and artefact production and use that occurred during the Roman period resulted in an increase in anthropogenic pollution that is reflected in higher enamel lead levels than are found throughout British prehistory (Montgomery et al. 2010). It is suggested that individuals with no exposure to anthropogenic sources will have lead levels below 0.8 ppm (Millard et al. 2014). It is possible, therefore, to use lead levels to provide an indication of rural versus urban residence and exposure to anthropogenic pollutants either voluntarily or unknowingly.

Needleman et al. (2002) suggested a bone lead level of 25 ppm affected cognitive behaviour resulting in an increase in anti-social and delinquent behaviour in juveniles although bone averages lead exposure over a longer period of life than enamel. In a study of modern children at the Broken Hill lead mine, Gulson & Wilson (1994) concluded enamel lead of 2-10 ppm constituted high lead exposure; levels above this are rare in modern humans. Half of the New Churchyard individuals have enamel lead levels between 2-10 ppm (median value 9.9 ppm Appendix 2) and the remainder exceed this. In contrast, the median value for late medieval populations in England was reported as 4.7 ppm by Montgomery et al. (2010) and for post-medieval London 14.0 ppm (Millard et al. 2014). There is little comparative contemporaneous data for London for this period but the New Churchyard data appear to fit into an inexorable rise in human lead exposure throughout the last millennium with a significant proportion of individuals experiencing what today would be classed as high lead exposure (Figures 6 and 7). All individuals at New Churchyard had lead levels consistent with exposure to lead pollutants during childhood and may have suffered sub-clinical and possibly clinical effects.

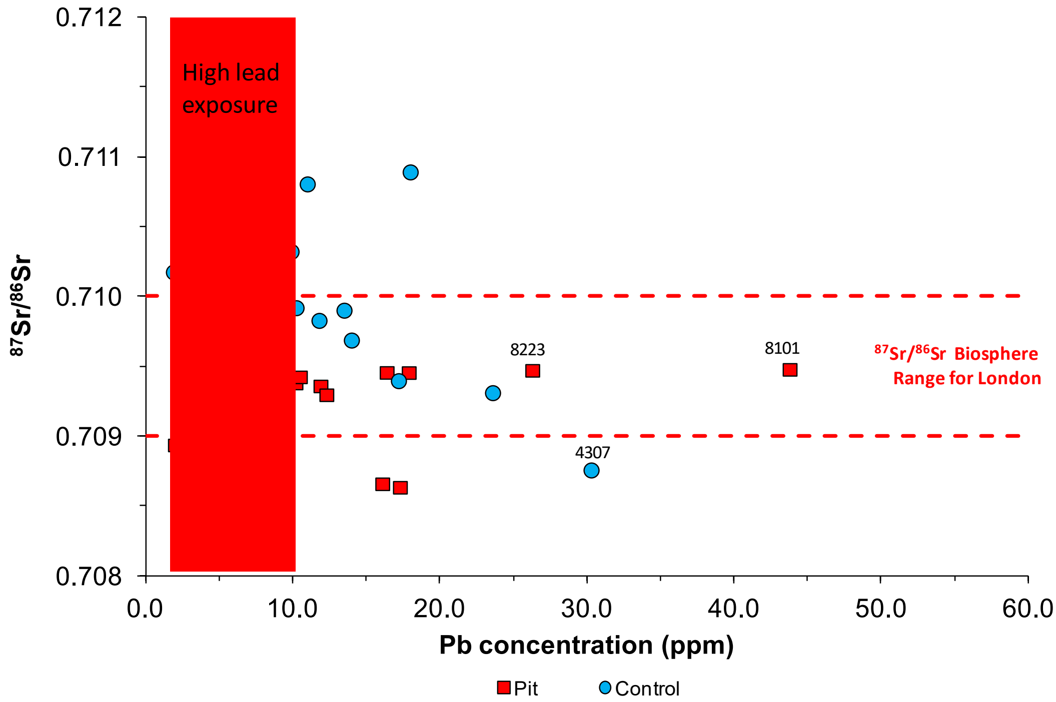


Figure 6. Enamel strontium isotope and lead concentration data for the New Churchyard individuals. The expected $^{87}Sr/^{86}Sr$ range for indigenous Londoners (red) is estimated from Evans et al. (2010) and the range for high lead exposure in modern children from Gulson and Wilson (1994).

One avenue of interest, given the link with high lead exposure and anti-social and delinquent behaviours and compromised intelligence even at sub-clinical levels (Needleman 2009;

Needleman et al. 2002) was whether individuals in the mass burial pit had higher childhood lead exposure than the control population. The four teeth with lead levels over 20 ppm belonged to three adult females (4307, 8223, 8101) but there is no visible clustering of the data between Pit and Control groups (Figure 6) and the lead levels in the individuals from the Pit were not higher than the Control group at the 95% CI (p = 0.389) (Appendix 2). Despite the highest lead levels being found in adult females suggesting they were exposed to higher lead pollution as children, there is no statistical difference at the 95% confidence interval (p = 0.059) between males and females (Appendix 2). However, the number of actual individuals is small (M = 11, F = 5) and given the wider range and higher mean in the smaller female group this avenue may be worth exploring further.

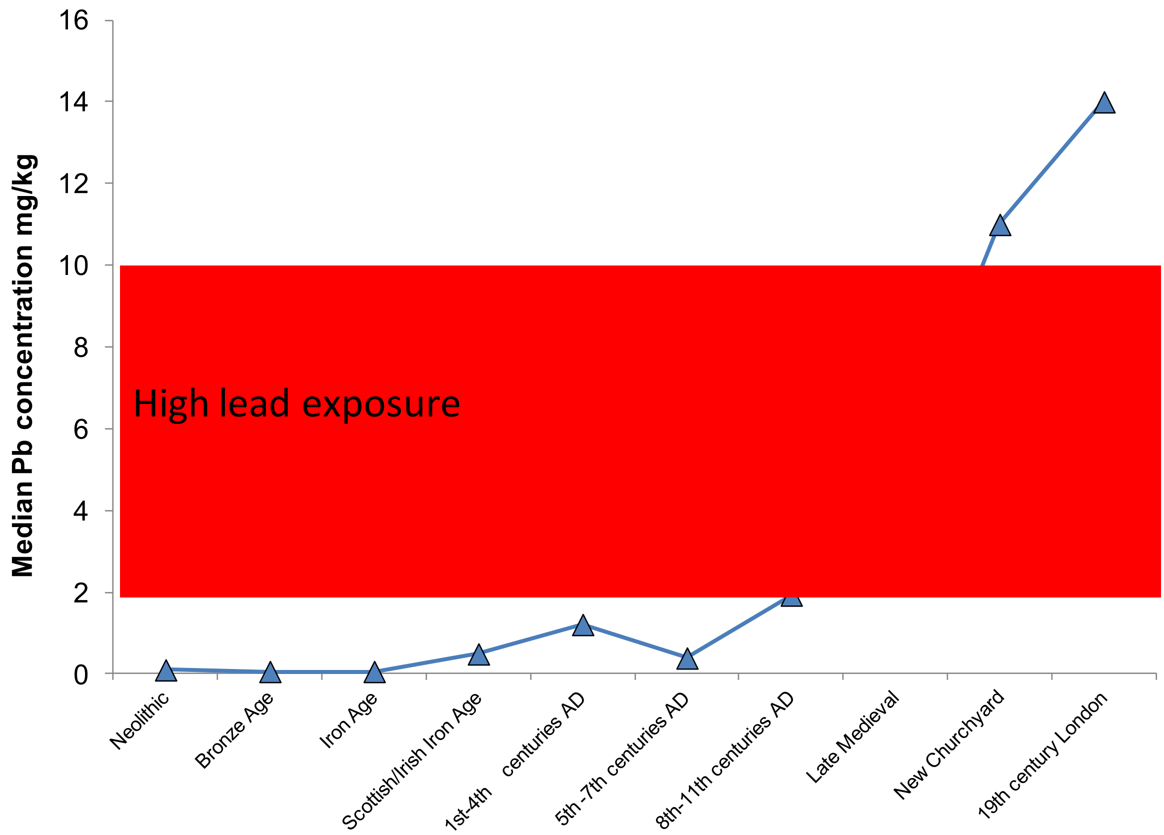


Figure 7. Human enamel lead concentrations from the Neolithic to the 19th century in Britain. Data from Montgomery et al. (2010) and Millard et al. (2014). Range for high lead exposure in children taken from Gulson & Wilson (1994).

5.4 CARBON AND NITROGEN ISOTOPES

The $\delta^{13}C_{carbonate}$ data for enamel are presented in Table 1 and the $\delta^{13}C$ and $\delta^{15}N$ data for bone and dentine collagen in Table 3.

5.4.1 ENAMEL CARBONATE

The $\delta^{13}C_{carbonate}$ values for the New Churchyard individuals range from -14.5‰ to -12.7‰ (Table 1) with a mean value of -13.8 ± 0.5‰ (1σ). This is a range of less than 2‰ and the data fall within the typical spectrum of a predominantly terrestrial diet in north-western Europe characterised by consumption of C_3 plants such as wheat, barley, rye, root vegetables, as well as animals feeding on C_3 flora and a limited amount of marine or freshwater fish (Jay and Richards 2007; Müldner and Richards 2007). Box and whisker plots show there is no difference between the Pit and Control groups nor between males and females (Appendix 2).

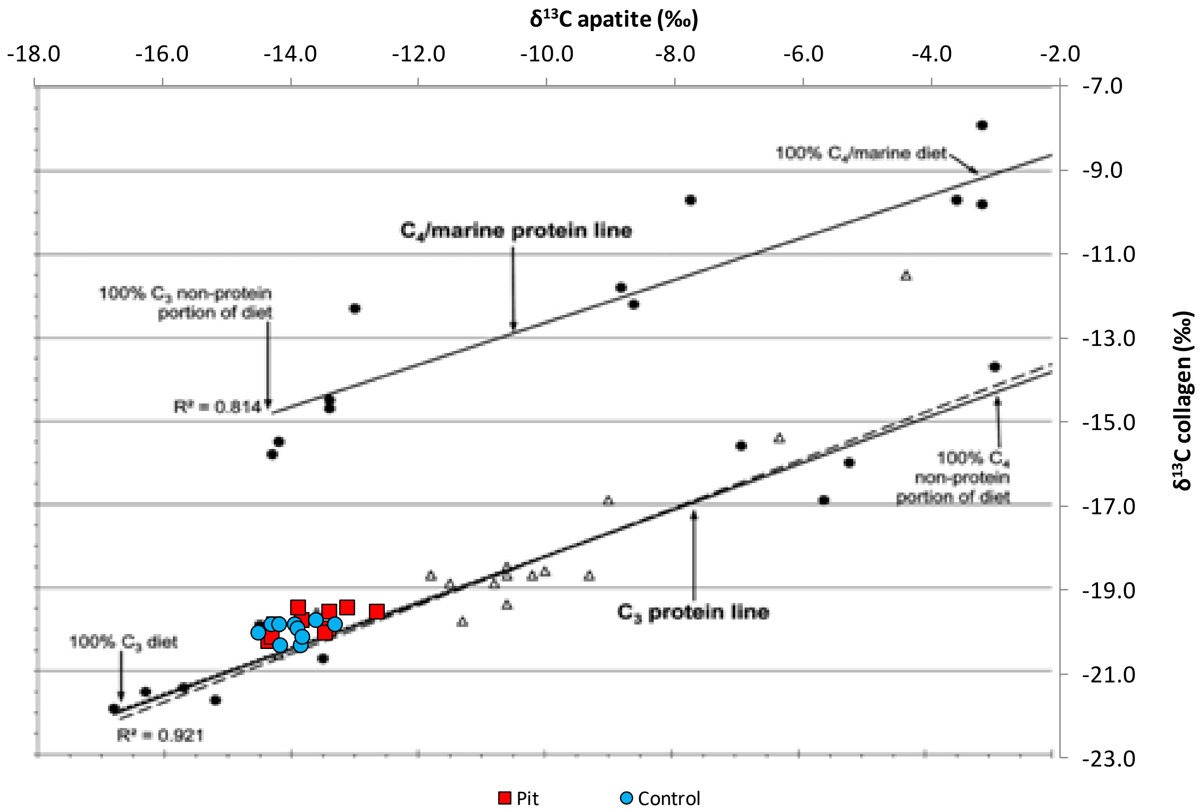


Figure 8. Enamel carbonate (apatite) versus co-genetic mean crown dentine collagen carbon isotope ratios for the New Churchyard individuals. The data are plotted against the regression equations of Froehle et al. (2010).

The $\delta^{13}C$ value of enamel carbonate reflects the whole diet (protein, carbohydrate and fats) as opposed to collagen which is routed primarily from consumed protein (Krueger and Sullivan 1984; Lee-Thorp, Sealy, and Van der Merwe 1989; Froehle, Kellner, and Schoeninger 2010). Figure 8 combines the enamel $\delta^{13}C_{carbonate}$ data with the mean of the $\delta^{13}C_{collagen}$ values obtained from the co-genetic crown dentine and presents it relative to Froehle et al.'s (2010) experimentally derived regression lines distinguishing between C_3 and C_4/marine diets; the $\delta^{13}C_{collagen}$ data have an even smaller range than the $\delta^{13}C_{carbonate}$ data (Table 3) suggesting even less variation in protein sources than in whole diet. Both the Pit and Control groups cluster tightly in the bottom left of the plot where predominantly terrestrial C_3 diets fall suggesting there was no significant difference in childhood diet - either whole diet or protein source - between the two groups.

5.4.2 DENTINE AND BONE COLLAGEN

Collagen isotope data are summarised in Table 3 with minimum, maximum and mean values for each tooth and ages assigned to each increment (Beaumont and Montgomery 2015). Data for bone and mean dentine are presented in Figure 9 along with comparative Medieval human data as no animal samples were measured from New Churchyard to establish the faunal baseline for this period. Data from only one tooth per individual is presented in Figures 10-13 so the period of life represented varies between individuals. A fuller comparative picture of the dietary life histories of the New Churchyard individuals will be available once data for the second tooth is received.

The bone and mean dentine $\delta^{13}C$ and $\delta^{15}N$ values are plotted in Figure 9 and compared to means for earlier and later populations in northern England and London. The results show the New Churchyard individuals sit within expected values for humans in England from the High Medieval when a shift to higher values occurred relative to the preceding early Medieval populations as a result of the increased dietary breadth and particularly the consumption of marine and freshwater fish; this trend to higher $\delta^{13}C$ and $\delta^{15}N$ continued through to the Post-Medieval period (Müldner and Richards 2006, 2007).

A few individuals from New Churchyard appear to be slightly anomalous: a male burial 8204 from the Pit group has low $\delta^{15}N$ values in childhood (dentine) which may indicate a reduced proportion of animal protein or, given the other indicators for his residential origins being outside London (Figure 5), it may indicate this individual spent his childhood in a food web less enriched in ^{15}N and thus lower overall $\delta^{15}N$ values such as the rural Wharram Percy

(Fuller, Richards, and Mays 2003). Individuals can be observed with what appear to be high $\delta^{15}N$ values, such as the bone value for 7162 an adult male from the Control group, two dentine values for females from the Pit group (8101 and 8223) and 8219 a juvenile with an anomalously high $\delta^{18}O$ value from the Pit group. Raised $\delta^{15}N$ with no corresponding increase in $\delta^{13}C$ can result from the consumption of freshwater fish (Müldner and Richards 2007; Müldner and Richards 2005), breastfeeding (Jay et al. 2008; Richards, Mays, and Fuller 2002) or, because the $\delta^{13}C$ and $\delta^{15}N$ values of body tissues also change when dietary intake is insufficient for the individual's energy requirements, a period of nutritional stress or wasting (Fuller et al. 2005). In the latter instance, a corresponding fall in $\delta^{13}C$ may also be observed (Neuberger et al. 2013; Beaumont and Montgomery 2016). There is no evidence for breastfeeding in the dentine profiles of 8101, 8219 or 8223 (Figures 12 and 13). For 7162 the shift to higher bone $\delta^{15}N$ occurred after the tooth had completed mineralising and it is not possible to distinguish freshwater fish consumption or stress for this individual. The two females 8101 and 8223 have two periods of stress visible in their dentine profiles (Figure 12 and discussion below) whereas the subadult 8219 has high $\delta^{15}N$ throughout the root of the M2 which is incompatible with the bone value and requires further investigation when the evidence for the M1 is obtained (Figure 13). It is worth noting that all four of these individuals have high strontium concentrations, i.e. > 200 ppm which could be indicative of a vegetarian diet but that is unlikely to be the case here unless it was the consumption of plants grown on a heavily fertilized or arid/saline soils. Alternatively, a combination of high $\delta^{15}N$ and high strontium ppm may document dietary stress such as recycling of proteins coupled with a low calcium intake which may be linked to insufficient and/or low-nutrient foods and/or disease, given the synergistic link between disease and nutrition (Webb et al. 2015).

There is remarkable consistency and no difference (Appendix 2) between the bone $\delta^{13}C$ and the mean $\delta^{13}C$ values for each tooth: means range from -19.6‰ to -19.8‰. However, behind this apparent similarity from birth to death there is more, but still limited, variation indicated in juvenile diets within individual teeth: $\delta^{13}C$ values exhibit a c. 2‰ range from -20.7‰ to -18.8‰ (mean = -19.7 ± 0.3‰, 1σ, n=179). There were no statistical differences in $\delta^{13}C$ values between childhood (dentine) and later life (bone) or between the Pit and Control groups for bone or dentine. Nitrogen isotopes also exhibit similar means between the bone $\delta^{15}N$ and the mean $\delta^{15}N$ values for each tooth: means range from 11.9‰ to 12.4‰ with the highest value being the mean bone value of the subadults which average a shorter time period than adult bone (Hedges et al. 2007). A greater range of over 6‰ is also found in $\delta^{15}N$ within individual teeth: dentine increment $\delta^{15}N$ values range from 9.1‰ to 15.4‰ (mean 12.2 ±1.3‰, 1σ, n=179). Whilst there was no difference found between childhood (dentine) and later life (bone), nor between Pit and Control groups during childhood (dentine), the $\delta^{15}N$ values of the Pit group were significantly lower than those of the Control group at the 95% CI ($p = 0.036$). This suggests that the individuals in the Pit group were consuming a larger proportion of plants and thus less animal protein during later life than the Control group. It appears that both groups ate at a similar trophic level during childhood (no statistical difference, $p = 0.788$) but in later life the Control group's $\delta^{15}N$ increases slightly whilst that of the Pit group decreases (Appendix 2). Again the number of individuals is not large but this finding warrants further investigation as it may be documenting a shift to a poorer, less nutritious diet amongst the individuals in the Pit group in the last few years of life.

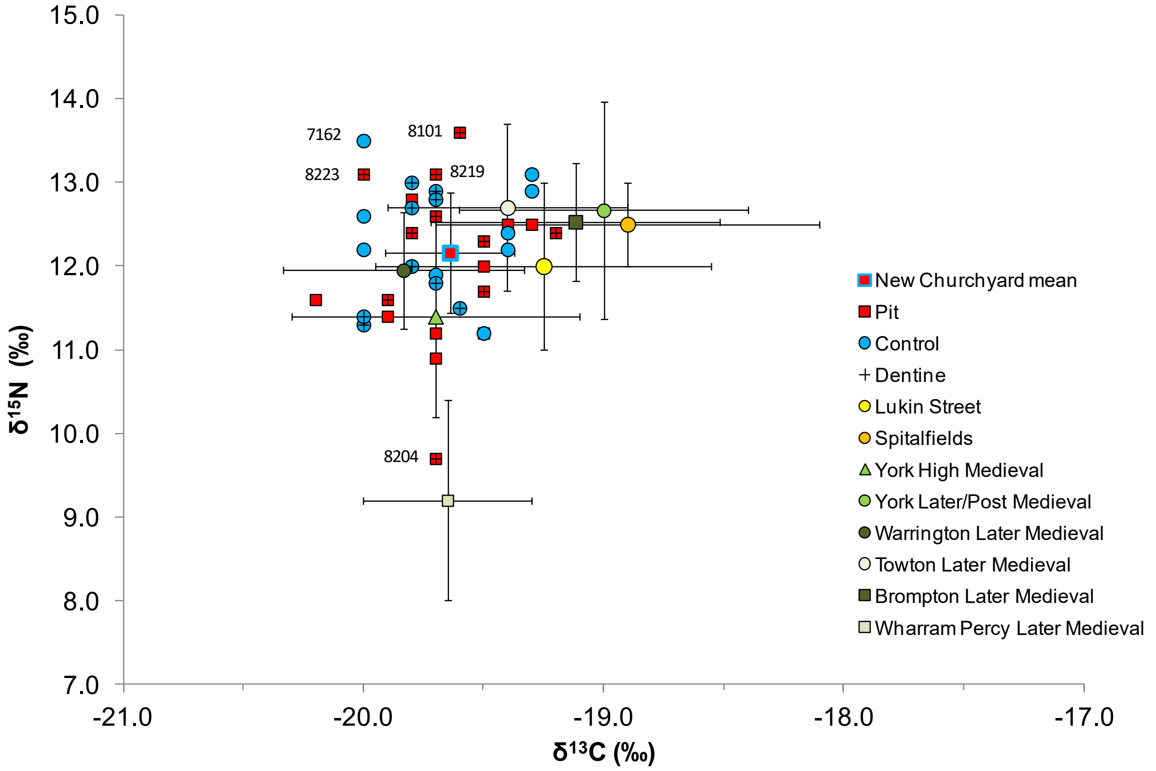


Figure 9. Bone and mean dentine $\delta^{13}C$ and $\delta^{15}N$ values for the New Churchyard individuals against comparative bone data (mean and 1sd) from post-medieval London (O'Connell and Hedges 1999; Beaumont 2013) and medieval and post-medieval northern England (Fuller, Richards, and Mays 2003; Müldner and Richards 2007; Müldner and Richards 2005).

Carbon and nitrogen isotope profiles were produced for each individual over the life course represented by the teeth submitted for analysis and all the data for each increment and individual are plotted using the same axis scales along with the bone values representing the last few years of life in the following figures:

Figure 10 - M1 teeth for male burials from the Control group

Figure 11 - M2 and M3 teeth for male burials from the Control and Pit groups

Figure 12 - M2 and M3 teeth for female burials from the Control and Pit groups

Figure 13 - M1and M2 teeth for subadult burials from the Control and Pit groups.

For the majority of individuals childhood diets are close to or span the later life diet indicated by the bone values, e.g. 4307, 5396, 5586, 7740, or the final dentine values converge within analytical uncertainty on the bone values, e.g. 74, 4695, 8204 and 8216. For some individuals, the majority in the Pit group, there is a significant difference between childhood diet and later life diet for either $\delta^{13}C$ or $\delta^{15}N$ which may be simply explained by a change in diet after the tooth has formed. This is likely to be the case for 8193 and 7162 who survived into middle age and for 8101, 8147, 8223 who survived for several years after the tooth stopped recording diet. For the 18-25 years old male 8198 (Figure 10), and the subadult 8219 (Figure 13) who died whilst the tooth was still forming, it is difficult to explain - for both individuals $\delta^{15}N$ is 1-2‰ higher in the tooth than in the bone throughout the profile and thus cannot be explained by analytical uncertainty at 2SD. It does, however, tie in with the statistically significant shift to lower bone $\delta^{15}N$ in the Pit group compared to the Control group (Appendix 2) discussed above. It is possible 8198 lived long enough, i.e. 2-3 years after the M3 completed to record a higher $\delta^{15}N$ in the rib bone but for 8219 the tooth was still forming at death. The profiles of two other subadults, 5695 and 8099, record diet up to death and in both these cases there is the expected convergence of the final dentine and bone values (Figure 13). In this case it may be worth re-measuring the bone $\delta^{15}N$ value of 8219 to confirm the result but it is worth noting that 8219 has an anomalously high $\delta^{18}O$ value in the M2 (Figure 5).

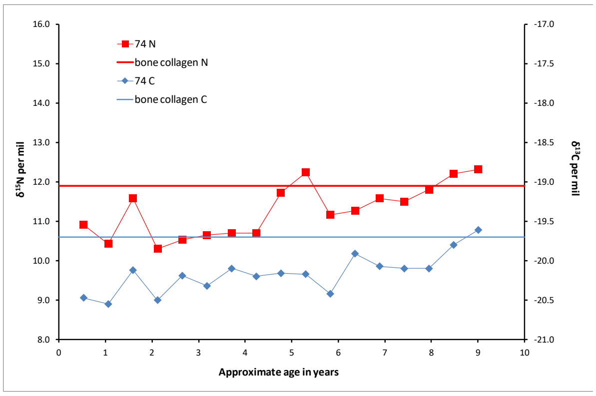
The six M1 profiles (c. birth to 9.5 years of age) for the five males (Figure 10) and one female (Figure 12) in the Control group show a good agreement between the bone and dentine values for both $\delta^{13}C$ and $\delta^{15}N$, low variation and a comparable range of values. All the males appear to show a rising $\delta^{15}N$ profile in the M1 around eight to nine years of age. There is no conclusive evidence for breastfeeding in any of these early forming teeth nor in the C1 teeth of 8193 and 8223, two females in the Pit group (Figure 12). Subadult 8099 in the

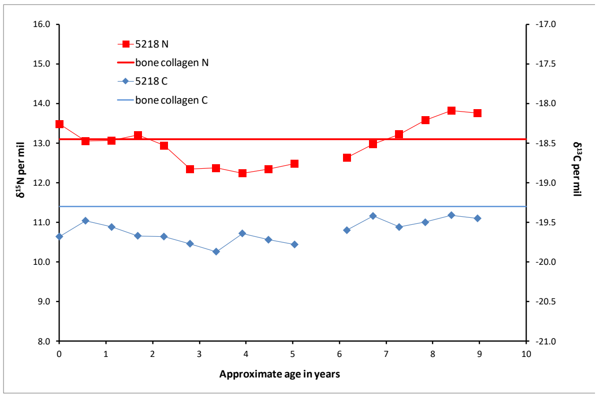
Pit group has the highest $\delta^{15}N$ values in this study at c. 1 year of age at the start of the M1 profile (Figure 13) which may indicate breastfeeding although the $\delta^{13}C$ values do not rise sufficiently to confirm this conclusively and thus the high $\delta^{15}N$ may be recording a period of pre or postnatal stress (Beaumont et al. 2015). The profile of the deciduous m2 tooth should assist with this interpretation. A prolonged period of breastfeeding may be indicated for the subadult 6085 from the Control group where both the $\delta^{13}C$ and $\delta^{15}N$ profiles are falling at the start of the profile and indicate a dietary change in trophic level (Figure 13) and again, the M1 profile should be able to confirm this.

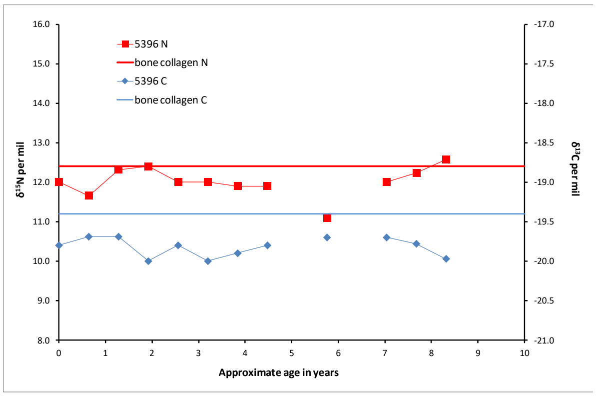
Some individuals such as the male burial 8147 from the Pit group have relatively flat dietary profiles suggesting a physiologically steady state between the age of 8 and 23 (Figure 11) despite suffering possible tuberculosis, and this is coupled with low lead exposure and residence outside London up to 14 years of age. Overall, however, the M2 (c. 2.5 to 15.5 years of age) and M3 (c. 8.5 to 23 years of age) profiles for the males from the Control and Pit groups (Figure 11) contrast with the M1s and suggest a more variable dietary experience. Three individuals have notable changes in $\delta^{15}N$:

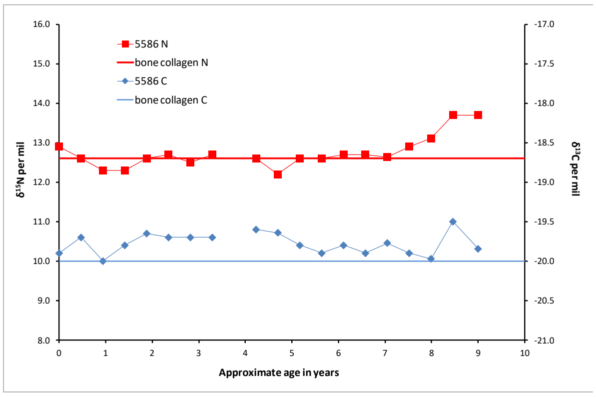
1. 7162 - who is consistent with origins in London - has >3‰ increase in $\delta^{15}N$ from early childhood to the last years of life. This does not appear to be a result of increased consumption of marine resources because there is no concomitant increase in $\delta^{13}C$ which stays within the range of terrestrial values and rises by only 0.5‰. The $\delta^{15}N$ may therefore be recording either increased stress or an increase in the proportion of terrestrial protein, for example freshwater fish (Müldner and Richards 2007).

2. The male burial 8216 aged 18-25 years from the Pit group shows a significant jump in $\delta^{15}N$ c. 14 years of age that is accompanied by a small rise in $\delta^{13}C$ and thus may be documenting an increase in animal protein consumption, either marine or terrestrial meat of freshwater fish and/or a prolonged period of stress (Figure 11). It is of note that 8216 also has a c. 2‰ increase in $\delta^{18}O$ between the M1 and the M3 enamel that may indicate that a change in residence at some time between the ages of four and fourteen could explain the dietary shift. Nonetheless, both teeth have strontium isotopes indicative of residence in a region of chalk or limestone and are not consistent with the London Clay.









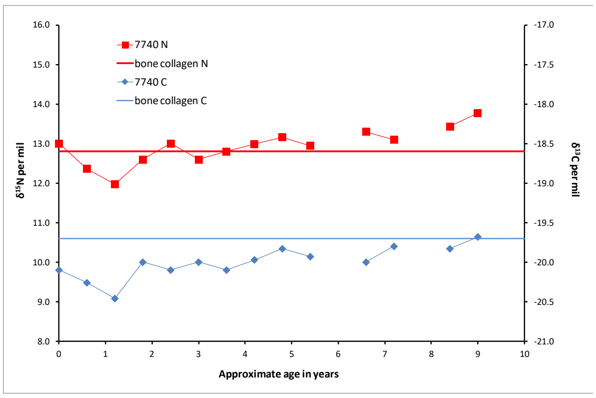


Figure 10. Five M1 $\delta^{13}C$ and $\delta^{15}N$ profiles for male burials from the Control group.

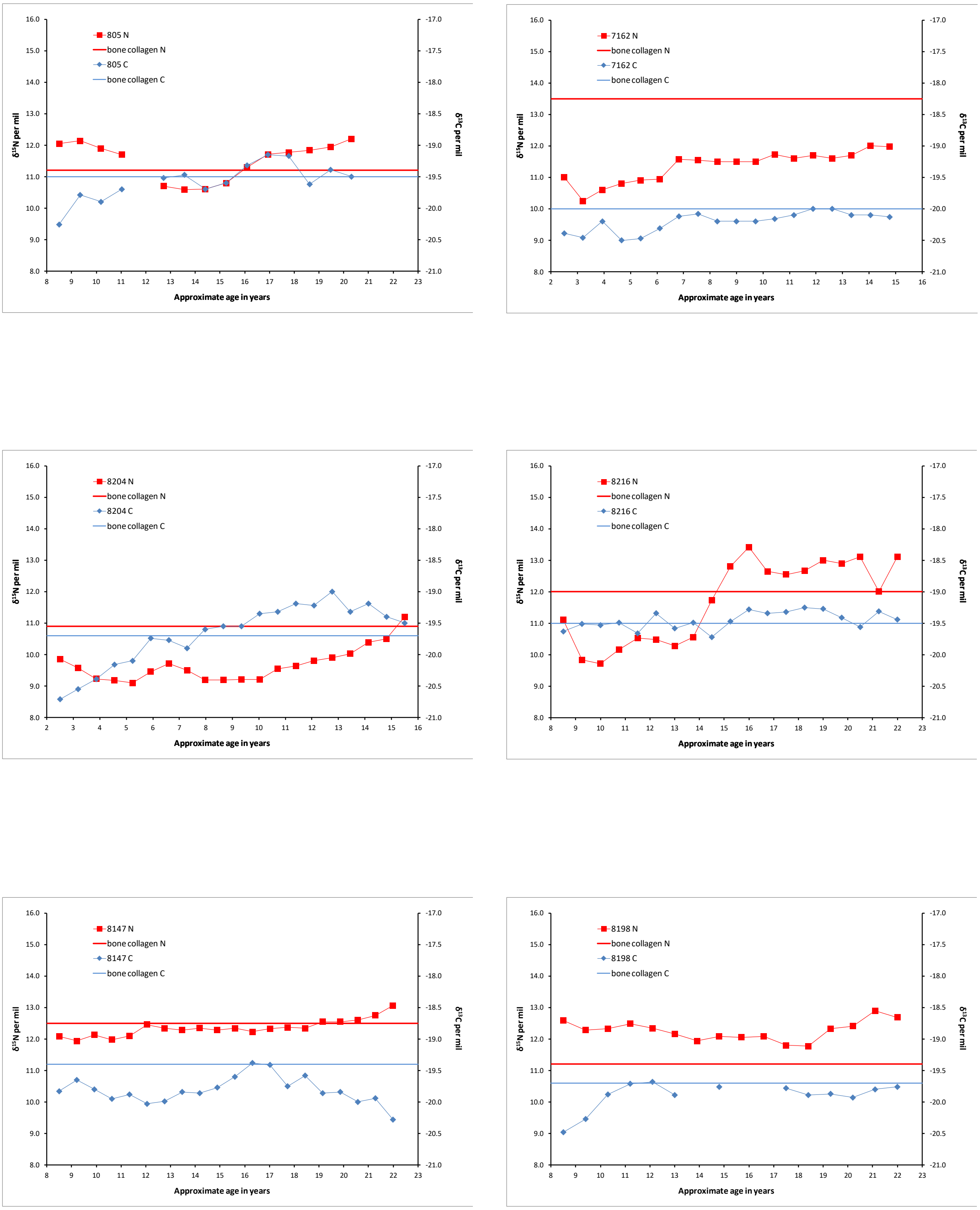
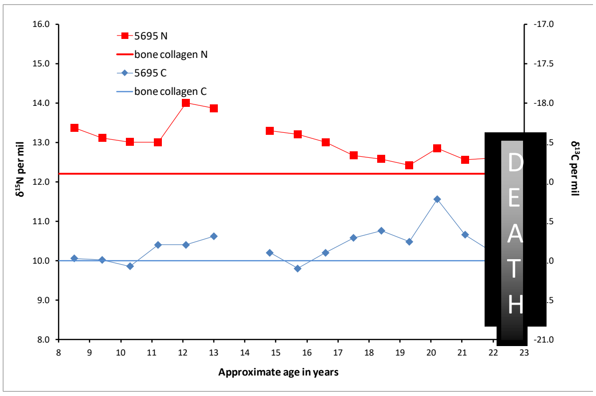
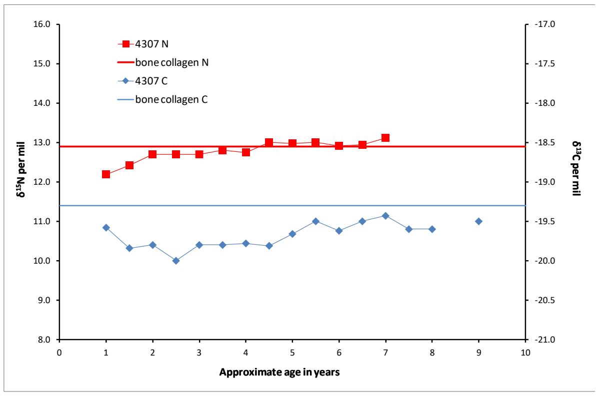
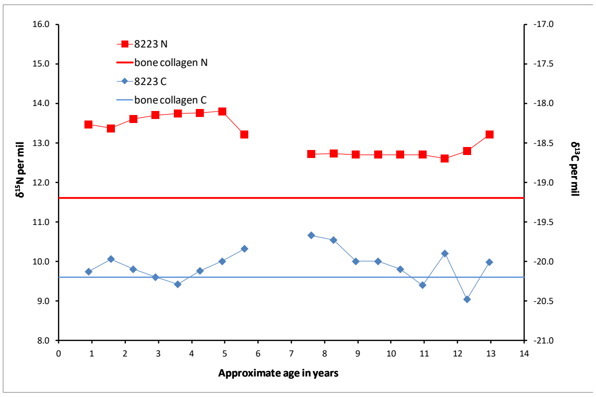
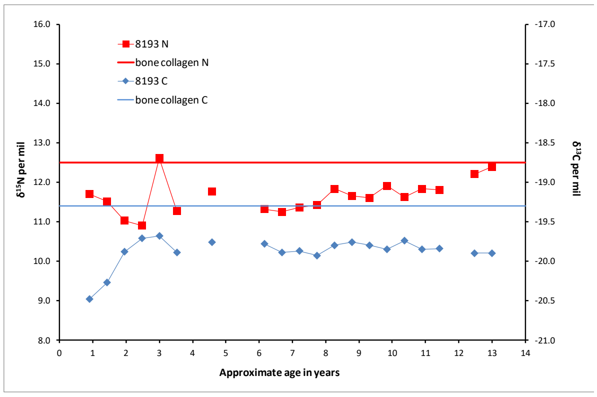


Figure 11. Six M2 and M3 $\delta^{13}C$ and $\delta^{15}N$ profiles for male burials from the Control group (top two) and the Pit group.









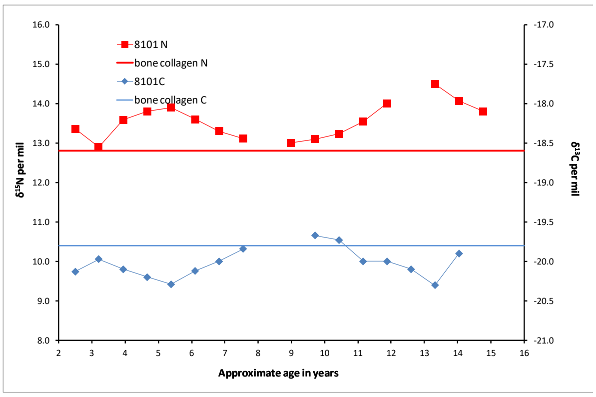


Figure 12. Five C1, M1, M2 and M3 $\delta^{13}C$ and $\delta^{15}N$ profiles for two adult females from the Control group (top two) and three from the Pit group. For one individual the tooth root was incompletely formed at the time of death.

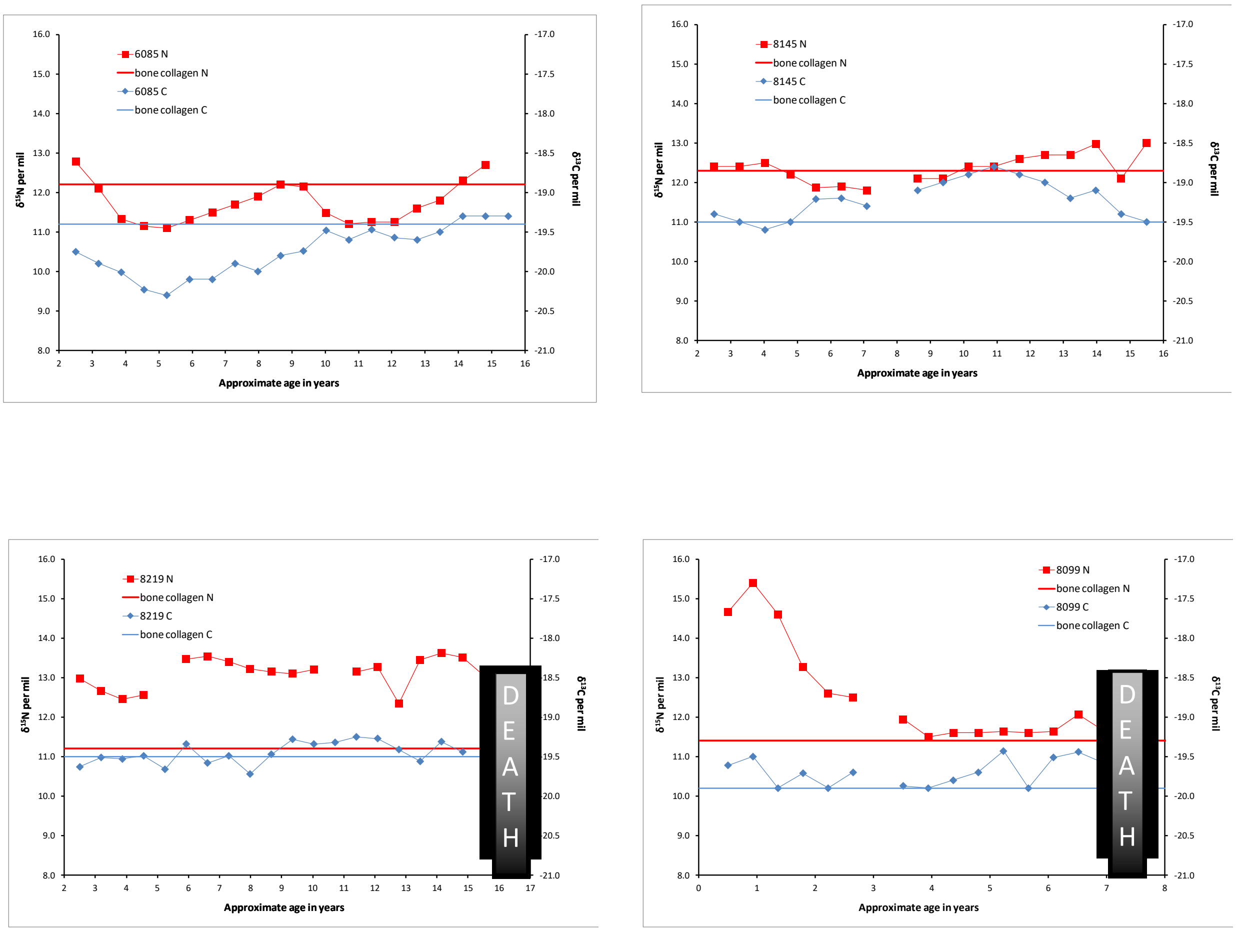


Figure 13. Four M1 and M2 $\delta^{13}C$ and $\delta^{15}N$ profiles for three subadults from the Pit group and one from the Control group (top left). For two individuals the tooth root was incompletely formed at the time of death.

3. The male burial 8204 aged 26-35 years from the Pit group shows a gradual increase in $\delta^{13}C$ and $\delta^{15}N$ from wholly terrestrial protein at two years of age which appears incompatible with high, late or post medieval urban diets in England (Figure 9) to a mixed terrestrial/marine protein in adolescence (Figure 11). Similarly to 8216 above, there is a concomitant and significant 3‰ increase in $\delta^{18}O$ after the age of four but also a large increase in lead exposure between the M1 and M2 teeth which together suggests a change in residence, e.g. relocating from an inland relatively unpolluted rural place in northeastern England, e.g. similar to Wharram Percy (Figure 9) to an urban centre such as London.

Of particular interest are the dietary profiles for two of the female burials aged 18-25 years from the Pit group. The $\delta^{13}C$ and $\delta^{15}N$ profiles for 8101 and 8223 (Figure 12) are almost identical in absolute values and shape and appear to define two stress episodes between two and seven years of age and a second between 12 and 14 years of age where the $\delta^{13}C$ falls as the $\delta^{15}N$ rises (Beaumont and Montgomery 2016). Their strontium isotopes are indicative of London Clay in both teeth from each individual and they have some of the highest enamel strontium (Figure 4) and lead (Figure 6) concentrations obtained in this study which together may indicate low dietary calcium (Brown et al. 2004). The two appear to be good candidates for indigenous Londoners. Several other females also show a rising $\delta^{15}N$ profile around the ages of 12 to 14 years of age which contrasts with that seen earlier at c. eight to nine years in the M1 teeth of the male Control group (Figure 10). Consistent patterns such as these may be documenting a physiological developmental milestone rather than a dietary change but more comparative data are needed and the data from New Churchyard are thus a significant addition to the study and interpretation of stable isotope dietary profiles.

6. DISCUSSION AND CONCLUSION

Diet and mobility of twenty individuals, ten from the mass burial pit (the Pit group) and ten single inhumations (the Control group) at the New Churchyard burial ground were investigated using a range of isotopes and trace elements. The results are summarised in Table 4. Nine individuals have a combined strontium and oxygen isotope profile that is inconsistent with childhood residence in London (i.e. Control group: 74, 805, 4307, 7740, group Pit: 8145, 8147, 8204, 8216, 8219) and whilst migrants to London are found in both groups, only one female (4307) from the five investigated is a clear, and multiple, migrant. All the outlying values for strontium and oxygen are males and subadults (Figure 5) and this may suggest females are more likely to be of local origin but the dataset is small. There is only one individual for whom British origins are problematic: the subadult 8219 has a high oxygen isotope ratio which is incompatible with eastern England and also falls outside the 2SD for western England and there is, therefore, at most only a 2.5% probability of origins in Britain. It is possible, if unlikely, that such a value might be obtained in the Western Isles of Scotland or the extreme west coast of Ireland (Figure 3). Comparably high $\delta^{18}O_{dw}$ values are also found at lower latitudes, for example in southern Europe and around the Mediterranean.

There are of course many other places in Europe and beyond where strontium and oxygen isotopes would be indistinguishable from those of Londoners and migrants from these places would be invisible in the dataset.

The trace element data show a high childhood lead burden in all individuals evidencing exposure to anthropogenic sources in both the Control and the Pit groups with the highest levels being found in three females but this is not statistically significant due to the low number of individuals. Nonetheless, all individuals at New Churchyard had lead levels consistent with exposure to lead pollutants during childhood and may have suffered sub-clinical and possibly clinical effects. Several individuals have high strontium concentrations which are unusual for archaeological populations in England although there is little comparative data for London specifically at this time. High strontium concentrations can be evidence for a vegetarian diet, low dietary calcium, fertilization of soils with seaweed, or residence in arid or coastal regions or unusual geological terrains such as strontianite. Further research is required on the causative factors and the link between high strontium and high lead concentrations in relation to low dietary calcium uptake, nutritional stress and pathologies such as rickets. However, the high strontium concentrations are found in migrant individuals, e.g. 8219 as well as those identified as of local origin and the cause may be multi-factorial.

Statistical analysis of the data between Pit and Control group and between males and females found few significant differences. One of particular note was the finding that whilst there was no difference between childhood diets (dentine) between the Pit and Control group, in later life the Control group's bone $\delta^{15}N$ increases slightly whilst that of the Pit group decreases (Appendix 2). This suggests that the individuals in the Pit group were consuming a larger proportion of plants and thus less animal protein during later life than the Control group. Again the number of individuals is not large but this finding warrants further investigation as it may be documenting a shift to a poorer, less nutritious diet amongst the individuals in the Pit in the last few years of life. Overall, the $\delta^{13}C$ and $\delta^{15}N$ values of the New Churchyard population fit within the trend of increasing values from the early Medieval through to the post-Medieval periods (Figure 9) which documents the introduction of higher levels of fish, marine and freshwater, to the diet particularly in urban populations such as York and London. One individual 8204 falls outside this field of data and exhibits lower $\delta^{15}N$ values during childhood which are consistent with rural populations and match the evidence from other isotopes that this individual originated in northern England. The dentine incremental profiles show a range of life experiences. Evidence for breastfeeding is limited even in the M1s suggesting that if individuals were breastfed it was not for a sustained period. Several individuals show a gradual shift in diet during tooth formation or from tooth to bone from lower values to the higher ones typical for urban London. This is perhaps most abrupt for the male migrant individual 8219 around the age of 14 years and it is possible the raised $\delta^{15}N$ values also document increased stress levels. Raised $\delta^{15}N$ values coupled with lower $\delta^{13}C$ values may document episodic stress and this is evident for the two female burials from the Pit group, 8101 and 8223, who have almost identical dietary profiles which record two probable stress episodes at the same period of life. In addition, these two have strontium and oxygen isotopes consistent with London, the highest levels of lead, and strontium over 200ppm. The data strongly support shared origins and life-histories for these two females but the high strontium concentrations coupled with high $\delta^{15}N$ also seen in (8219 and 7162) are interesting and would suggest that the high strontium concentrations in this case are unlikely to be documenting a plant-based diet^{15}N values unless the plants are grown on heavily fertilized or arid ground. The latter is a possibility for 8219 who has high $\delta^{18}O$ value. Alternatively, as discussed above, the $\delta^{15}N$ may be documenting nutritional stress and the high strontium concentrations a calcium deficiency.

The data from New Churchyard provide a rich body of evidence for individual life histories during the 16-18th centuries. The results raise new questions both for the period and for what the techniques used can tell us about humans in the past.

7. BIBLIOGRAPHY

AlQahtani, S.J.; M.P. Hector; and H.M. Liversidge. 2010. Brief communication: The London atlas of human tooth development and eruption. *American Journal of Physical Anthropology* **142:481-490**.

Beaumont, J. 2013. *An isotopic and historical study of diet and migration during the Great Irish Potato Famine (1845-1852).* Unpublished PhD thesis, University of Bradford, UK.

Beaumont, J.; J. Geber; N. Powers; A.S. Wilson; J. Lee-Thorp; and J. Montgomery. 2013. Victims and survivors: stable isotopes used to identify migrants from the Great Irish Famine to 19th Century London. *American Journal of Physical Anthropology* **150:87-98**.

Beaumont, J. and J. Montgomery. 2015. Oral Histories: assigning chronological age to isotopic values from human dentine collagen. *Annals of Human Biology* **42:407-414**.

Beaumont, J. and J. Montgomery. 2016. The Great Irish Famine: identifying starvation in the tissues of victims using stable isotope analysis of bone and incremental dentine collagen. *PLoS ONE* **11:e0160065**.

Beaumont, J.; J. Montgomery; J. Buckberry; and A. Jay. 2015. Infant mortality and isotopic complexity: new approaches to stress, maternal health and weaning. *American Journal of Physical Anthropology***:441-457**.

Bentley, R.A. 2006. Strontium isotopes from the earth to the archaeological skeleton: A review. *Journal of Archaeological Method and Theory* **13:135-187**.

Brettell, R.; J. Montgomery; and J. Evans. 2012. Brewing and stewing: the effect of culturally mediated behaviour on the oxygen isotope composition of ingested fluids and implications for human provenance studies. *Journal of Analytical Atomic Spectrometry* **27:778-785**.

British Geological Survey. 1977. Quaternary map of the United Kingdom South. Southampton: Ordnance Survey/NERC.

———. 2001. Solid Geology Map UK South Sheet. Southampton: Ordnance Survey/NERC.

Brown, C.J.; S.R.N. Chenery; B. Smith; C. Mason; A. Tomkins; G.J. Roberts; L. Sserunjogi; and J.V. Tiberindwa. 2004. Environmental influences on the trace element content of teeth--implications for disease and nutritional status. *Archives of Oral Biology* **49:705-717**.

Burton, J.H. and L.E. Wright. 1995. Nonlinearity in the relationship between bone Sr/Ca and diet: paleodietary implications. *American Journal of Physical Anthropology* **96:273-282**.

Byers, R.K. and E.E. Lord. 1943. Late effects of lead poisoning on mental development. *American Journal of Diseases in Children* **66:471-483**.

Chenery, C.; V. Pashley; A. Lamb; H. Sloane; and J. Evans. 2012. The oxygen isotope relationship between the phosphate and structural carbonate fractions of human bioapatite. *Rapid Communications in Mass Spectrometry* **26:309-319**.

Clarkson, T.W. 1987. Metal toxicity in the central nervous system. *Environmental Health Perspectives* **75:59-64**.

Darling, W.G.; A.H. Bath; and J.C. Talbot. 2003. The O & H stable isotopic composition of fresh waters in the British Isles: 2, Surface waters and groundwater. *Hydrology and Earth System Sciences* **7:183-195**.

Darling, W.G. and J.C. Talbot. 2003. The O and H stable isotopic composition of fresh waters in the British Isles. 1. Rainfall. *Hydrology and Earth System Sciences* **7:163-181**.

Daux, V.; C. Lécuyer; M.-A. Héran; R. Amiot; L. Simon; F. Fourel; F. Martineau; N. Lynnerup; H. Reychler; and G. Escarguel. 2008. Oxygen isotope fractionation between human phosphate and water revisited. *Journal of Human Evolution* **55:1138-1147**.

Eerkens, J.W.; A.G. Berget; and E.J. Bartelink. 2011. Estimating weaning and early childhood diet from serial micro-samples of dentin collagen. *Journal of Archaeological Science* **38:3101-3111**.

Ellison, R.A. and J.A. Zalasiewicz. 1996. Palaeogene and Neogene. In *British Regional geology: London and the Thames Valley*, ed. M.G. Sumbler, 92-109. London: Her Majesty's Stationary Office for the British Geological Survey.

Evans, J.; C.A. Chenery; and J. Montgomery. 2012. A summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain. *Journal of Analytical Atomic Spectroscopy* **27:754-764**.

Evans, J.A.; J. Montgomery; G. Wildman; and N. Boulton. 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. *Journal of the Geological Society* **167:1-4**.

Fricke, H.C.; J.R. O'Neil; and N. Lynnerup. 1995. Oxygen isotope composition of human tooth enamel from Medieval Greenland: linking climate and society. *Geology* **23:869-872**.

Froehle, A.W.; C.M. Kellner; and M.J. Schoeninger. 2010. FOCUS: effect of diet and protein source on carbon stable isotope ratios in collagen: follow up to Warinner and Tuross (2009). *Journal of Archaeological Science* **37:2662-2670**.

Fuller, B.T.; J.L. Fuller; N.E. Sage; D.A. Harris; T.C. O'Connell; and R.E. Hedges. 2005. Nitrogen balance and $\delta^{15}N$: why you're not what you eat during nutritional stress. *American Journal of Physical Anthropology* **19:2497-2506**.

Fuller, B.T.; M.P. Richards; and S.A. Mays. 2003. Stable carbon and nitrogen isotope variations in tooth dentine serial sections from Wharram Percy. *Journal of Archaeological Science* **30:1673-1684**.

Goyer, R.A. 1996. Toxic Effects of Metals. In *Casarett & Doull's Toxicology: The Basic Science of Poisons*, ed. C.D. Klaassen; M.O. Amdur; and J. Doull, 691-736. New York: McGraw-Hill.

Gulson, B.L. and D. Wilson. 1994. History of lead exposure in children revealed from isotopic analyses of teeth. *Archives of Environmental Health* **49:279-283**.

Hedges, R.E.M.; J.G. Clement; C.D.L. Thomas; and T.C. O'Connell. 2007. Collagen turnover in the adult femoral mid-shaft: Modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology* **133:808-816**.

Jay, M.; B.T. Fuller; M.P. Richards; C.J. Knusel; and S.S. King. 2008. Iron Age breastfeeding practices in Britain: isotopic evidence from Wetwang Slack, East Yorkshire. *American Journal of Physical Anthropology* **136:327-337**.

Jay, M. and M.P. Richards. 2007. British Iron Age diet: stable isotopes and other evidence. *Proceedings of the Prehistoric Society* **73:169-190**.

Kendall, E.; J. Montgomery; J. Evans; C. Stantis; and V. Mueller. 2013. Mobility, Mortality, and the Middle Ages: Identification of Migrant Individuals in a 14th Century Black Death Cemetery Population. *American Journal of Physical Anthropology* **150:210-222**.

Krueger, H.W. and C.H. Sullivan. 1984. Models for carbon isotope fractionation between diet and bone. Acs Symposium Series , 258, 205-220. *ACS Symposium Series* **258:205-220**.

Lakin, K.E. 2010. *Mobility, mortality and the Middle Ages: Identification of migrant individuals in a 14th century Black Death cemetery population.* Unpublished PhD thesis. University of Reading, UK.

Lee-Thorp, J.; J.C. Sealy; and N.J. Van der Merwe. 1989. Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *Journal of Archaeological Science* **16:585-599**.

Longinelli, A. 1984. Oxygen isotopes in mammal bone phosphate: a new tool for paleohydrological and paleoclimatological research? *Geochimica Et Cosmochimica Acta* **48:385-390**.

Luz, B.; Y. Kolodny; and M. Horowitz. 1984. Fractionation of Oxygen Isotopes between Mammalian Bone-phosphate and Environmental Drinking Water. *Geochimica Et Cosmochimica Acta* **48:1689-1693**.

Millard, A.; J. Montgomery; M. Trickett; J. Beaumont; J. Evans; and S. Chenery. 2014. Childhood lead exposure in the British Isles during the Industrial Revolution. In *Modern Environments and Human Health: Revisiting the Second Epidemiological Transition.* , ed. M. Zuckerman, 279-300. Columbia, SC.: Wiley Blackwell.

Montgomery, J. 2010. Passports from the past: Investigating human dispersals using strontium isotope analysis of tooth enamel. *Annals of Human Biology* **37:325-346**.

Montgomery, J.; J. Evans; and R. Cooper. 2007. Resolving archaeological populations with Sr-isotope mixing models. *Applied Geochemistry* **22:1502-1514**.

Montgomery, J.; J.A. Evans; S.R. Chenery; V. Pashley; and K. Killgrove. 2010. "Gleaming, white and deadly": the use of lead to track human exposure and geographic origins in the Roman period in Britain. In *Roman diasporas: archaeological approaches to mobility and diversity in the Roman Empire*, ed. H. Eckardt, 199-226. Portsmouth: Rhode Island: JRA.

Müldner, G.; J. Montgomery; G. Cook; R. Ellam; A. Gledhill; and C. Lowe. 2009. Isotopes and individuals: diet and mobility among the medieval Bishops of Whithorn. *Antiquity* **83:1119-1133**.

Müldner, G. and M.P. Richards. 2005. Fast or feast: reconstructing diet in later Medieval England by stable isotope analysis. *Journal of Archaeological Science* **32:39-48**.

Müldner, G. and M.P. Richards. 2006. Diet in medieval England: the evidence from stable isotopes. In *Food in medieval England: history and archaeology*, ed. C. Woolgar; D. Serjeantson; and T. Waldron, 228-238. Oxford: Oxford University Press.

———. 2007. Stable isotope evidence for 1500 years of human diet at the City of York, U.K. *American Journal of Physical Anthropology* **133:682-697**.

Needleman, H. 2009. Low Level Lead Exposure: History and Discovery. *Annals of Epidemiology* **19:235-238**.

Needleman, H.; C. McFarland; R. Ness; S. Fienberg; and M. Tobin. 2002. Bone lead levels in adjudicated delinquents. A case control study. *Neurotoxicology and Teratology* **24:711-717**.

Neuberger, F.M.; E. Jopp; M. Graw; K. Püschel; and G. Grupe. 2013. Signs of malnutrition and starvation—Reconstruction of nutritional life histories by serial isotopic analyses of hair. *Forensic Science International* **226:22–32**.

O'Connell, T.C. and R.E.M. Hedges. 1999. Isotopic Comparison of Hair and Bone: Archaeological Analyses. *Journal of Archaeological Science* **26:661-665**.

Richards, M.P.; S. Mays; and B.T. Fuller. 2002. Stable carbon and nitrogen isotope values of bone and teeth reflect weaning age at the medieval Wharram Percy site, Yorkshire, UK. *American Journal of Physical Anthropology* **119**.

Sumbler, M.G. 1996. British Regional Geology: London and the Thames Valley. London: Her Majesty's Stationary Office for the British Geological Survey.

Trickett, M. 2006. *A Tale of Two Cities: Diet, Health and Migration in Post-Medieval Coventry and Chelsea through Biographical Reconstruction, Osteoarchaeology and Isotope Biogeochemistry*. Unpublished PhD thesis, Durham University, UK.

Webb, E.; C. White; S. Van Uum; and F. Longstaffe. 2015. Integrating cortisol and isotopic analyses of archeological hair: reconstructing individual experiences of health and stress. *American Journal of Physical Anthropology* **156:577-593**.

Wright, L.E. and H.P. Schwarcz. 1998. Stable carbon and oxygen isotopes in human tooth enamel: Identifying breastfeeding and weaning in Prehistory. *American Journal of Physical Anthropology* **106:1-18**.