IDENTIFYING COHORTS USING ISOTOPE MASS SPECTROMETRY: THE POTENTIAL OF TEMPORAL RESOLUTION AND DIETARY PROFILES*

JULIA BEAUMONT† iD

University of Bradford, United Kingdom

JELENA BEKVALAC

Centre for Human Bioarchaeology, Museum of London, United Kingdom

SAMUEL HARRIS iD and CATHERINE M. BATT

University of Bradford, United Kingdom

Archaeological skeletal material from most sites represents a cross-sectional, opportunistic sample of the burials. These are influenced by the proportion and area of the site that is excavated, the taphonomic conditions, and survival of tissues. This may not be representative of the population, and in an attritional cemetery may represent a long period of use, during which humans will have differing life courses. Here we describe a commingled skeletal assemblage, the only human remains recovered from the historically significant medieval site of St Stephen's Chapel, Palace of Westminster, London. Using carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope ratios of bulk bone collagen and incremental dentine to investigate dietary life histories from five individuals, we combine the evidence with radiocarbon dating to assign them to two different temporal cohorts.

KEYWORDS: CARBON AND NITROGEN STABLE ISOTOPE RATIOS, LIFEWAYS, COHORT, COMMINGLED REMAINS, RADIOCARBON DATING

INTRODUCTION

During building work in the spaces beneath St Stephen's Chapel, Palace of Westminster, in 1992, human remains were discovered. Within the commingled assemblage, there were the remains of teeth within maxillae and mandibles (upper and lower jawbones) of four individuals, and maxillae from a fifth with complete ante mortem tooth loss (edentulous).

Osteological examination suggests that these were adults and, other than the possible diagnosis of residual rickets in three of the femora and bony reaction to chronic sinusitis in one of the maxillae, there was little pathology. Our hypothesis was that these were the remains of residents of the secular college at the chapel, moved from their original resting places and re-deposited. The archaeological excavation provided no evidence for the dates they had died or been moved, so it was difficult at that stage to glean more about this group, who they were and when they lived.

Excavating the human remains

St Stephen's Chapel, now underneath the larger House of Commons (Fig. 1), was originally part of the Palace of Westminster in London. The building was linked to the quarters of the Plantagenet kings of England, and first mentioned in 1184. In 1292, Edward I began a new
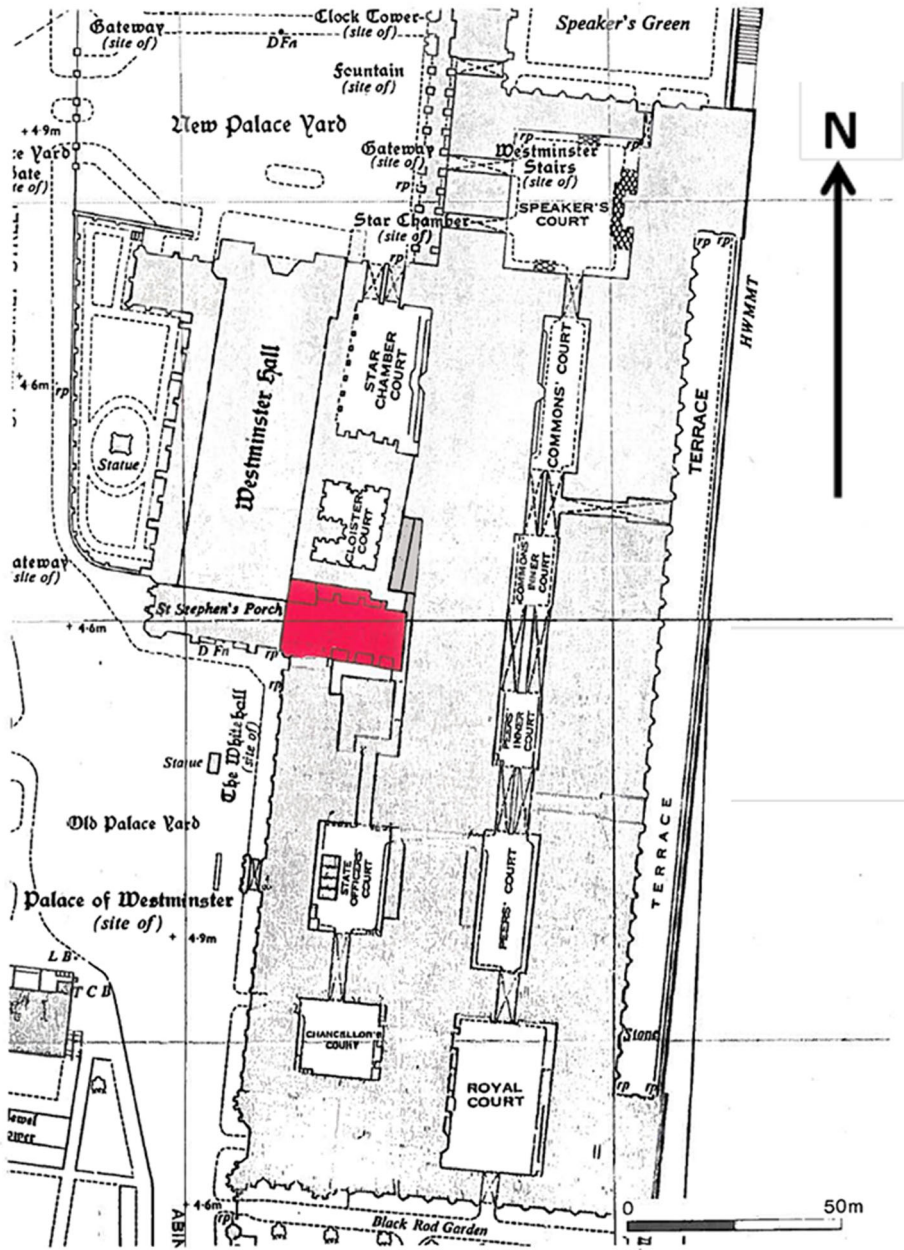

Figure 1   *Plan of the Palace of Westminster, with the position of the site shaded in red (after Thomas 1994, Fig. 2)*

two-storey chapel, which was completed by Edward III when a new college of canons was established in 1348 (Biggs 2016, 7–14).

During the building works in 1992 access to the site in this area of the chapel was extremely restricted, with archaeologists working in a confined space. Descriptions from the site report (Thomas 1994) state that "in Pit S4, a layer of dark grey silty sand was found, containing frequent pieces of disarticulated human bone". The layer was only 0.08 m in depth, with disturbance from a layer of concrete above. There was the tentative suggestion of two *in situ* burials, one aligned east to west and one southeast to northwest. There were two further layers above this, a layer of hard core and a layer of concrete both containing human bone, the majority in the hard core. The relative position of each individual was not recorded and could not assist with dating evidence.

The remains consisted of commingled bones from several individuals, mostly disarticulated and some showing post-mortem damage. Most had been stained by the burial environment, and covered by a deposit that made fine details on the bone and tooth surfaces difficult to identify. However, they had been buried originally in one of the most important royal palaces in England, and in a place that suggested that they were medieval in date, even if disturbed subsequently. Descriptions of the undercroft in the 19th century recorded that it had several layers of medieval flooring which had been cut through in that period for burials (Mackenzie 1844). Although evidence exists for burial requests (Mackenzie 1844), the chances of making any interpretations about these individuals seemed slim, with very little evidence for their original resting place or any accompanying grave goods. However, it is increasingly recognised in both archaeological and forensic research that commingled human remains can yield important information about individuals and the population they represent (Brickley *et al*. 2016; Nikita *et al*. 2019) especially when further scientific analyses are available (Montgomery *et al*. 2013).

OSTEOLOGICAL ANALYSIS

The remains comprised four small containers (approximately 36 x 25 x 13 cm) of disarticulated mixed bones, excavated in 1992 by the then Museum of London Archaeology Services (MoLAS) now Museum of London Archaeology (MoLA) and curated at the Centre for Human Bioarchaeology, Museum of London. The original bone analysis was carried out by the osteologist at the time of the excavation, Janice Conheeney, who concluded that the minimum number of individuals (MNI) represented was nine, based on the number of fragmented femora (Thomas 1994). In a reassessment of the bones prior to isotopic analyses, the same conclusion was reached. No single individual was fully represented, but the nature of the excavation in the small area limited retrieval. As noted above, most of the bones were covered in a concretion, which in most cases obscured much of the detail on the bone surfaces: some of them had a red hue consistent with iron staining from the burial environment.

Because of the fragmentary nature of the skeletal material from post-mortem breaks, it was only possible to reconstruct one tibia, and a right pelvis from an older male. The skeletal material was assessed and recorded macroscopically following standard methods (Connell and Rauxloh 2003; Powers 2012). There was no radiographic or CT scanning. All the skeletal elements present were from adults and, in addition to the reconstructed tibia and right pelvis, also included ribs, a calcaneus, a fifth metatarsal, fragments of a second right pelvis, two sacra, and several cranial fragments including maxillae and mandibles and teeth.

Remodelled lamellar bone was identified on the cortical surfaces of some tibial and femoral shaft fragments. Such periosteal changes on the surface of leg bones are not unusual and are frequently encountered in osteological analyses, particularly so within medieval collections (Weston 2011). Their presence indicates a healed low-grade non-specific infection, caused by abrasions to the overlying soft tissue and the entry of bacteria through the skin. There was little evidence for changes on the joint surfaces with the exception of Grade 1 (slight/intermittent) osteophytic lipping (early arthritic change) at the surface of the knee joint of one femoral fragment, following Sager (1969).

One of the more complete fragments of a femur (right side) and two other smaller long bone shafts had a bowed appearance that could be an indication of residual rickets. The presence of this abnormality is diagnostic for individuals deficient in vitamin D during childhood; the bone that was forming was softer than normal, resulting in the bending of weight-bearing bones, in this case antero-posteriorly (towards the front of the leg). The shape is retained into adulthood as an indicator of living conditions and diet during early life, even when the deficiency has been resolved (Brickley *et al*. 2010).

There were several maxillae and mandibles allowing us to securely identify five different adult individuals from the mixed assemblage, all given unique context numbers (Fig. 2). None showed conclusive evidence for gross bony pathology, trauma, or dental pathology beyond heavy tooth wear consistent with the coarse medieval diet (Dawson and Brown 2013). One individual was edentulous with remodelled alveolar bone: evidence for the loss of all teeth many years before death (Mays 2013).

Figure 2   *The maxillae and mandibles in this study (post sampling) from the St Stephen's assemblage*

CARBON AND NITROGEN STABLE ISOTOPE ANALYSIS

In November 2014, the Palace of Westminster Archivists commissioned stable isotope analysis of this skeletal assemblage. The major components of human diet, both past and present, may be estimated by measuring the carbon and nitrogen isotope ratios ($\delta^{15}N$ and $\delta^{13}C$) of the collagenous proteins in bone and tooth dentine (Schoeninger *et al*. 1983; Wright and Schwarcz 1999). However, the temporal resolution from these two tissues differ substantially: bone collagen records a multiyear average, which can vary depending on the age of the individual and which bone is sampled (Bell *et al*. 2001; Fahy *et al*. 2017), whereas primary dentine records and retains time-bound isotope ratios, which reflect the food and drink ingested during the period of tooth development (Beaumont *et al*. 2013b; Fuller *et al*. 2003). Recent studies have achieved sub-annual temporal sampling resolution by sectioning the dentine along the direction of growth to shed new light on the individual dietary histories of our ancestors, with the potential to identify unexpected radical short-term dietary changes, (Montgomery *et al*. 2013) the duration of breastfeeding, (Beaumont *et al*. 2018; Craig-Atkins *et al*. 2018; Eerkens *et al*. 2011), and migration where dietary change occurs (Beaumont *et al*. 2013a). Several studies have also raised questions regarding factors other than diet that may impact on $\delta^{15}N$ and $\delta^{13}C$ such as dietary or physiological stress (Beaumont and Montgomery 2016; Redfern *et al*. 2019).

The $\delta^{13}C$ and $\delta^{15}N$ in bone collagen reflect the main sources of protein consumed at the time that new bone is forming (Ambrose and DeNiro 1986; Hedges and Reynard 2007; Sealy *et al*. 1995; van der Merwe and Vogel 1978). Thus, because fractionation gives rise to a trophic level shift, the tissues from a vegan or herbivore will give lower isotope ratios than from an omnivore in the same context; those from a carnivore will be higher still (Richards and Hedges 1999). Marine foods have $\delta^{13}C$, which are distinct from a terrestrial diet, as do some plants such as maize (although these plants were not common foodstuffs in medieval England; Müldner and Hedges 2007; Müldner and Richards 2006). It has also been established that dietary insufficiency can cause rises in the $\delta^{15}N$ caused by the recycling of body proteins, without a rise or even with a fall in the stable carbon isotope compositions from recycled fat stores (Beaumont *et al*. 2013a; Mekota *et al*. 2006). Using both bulk bone and incremental dentine collagen, we can estimate the likely diet of an individual, and changes in diet during life, and thus identify differences between individuals in the same context.

Within a population there may be individual food choices or the application of a social convention of entitlement to certain foods (Sen 1981). In a burial population with a large variation in isotope ratios, this may reflect a wide range of available foodstuffs or individuals present in the cemetery from another place or culture with a different diet. There may be variation in the diet with age or sex and with the different life experiences of individuals (Beaumont 2020). For example, dietary differences between the lay population and religious orders in medieval England have been identified using bone collagen $\delta^{13}C$ and $\delta^{15}N$ (Müldner and Hedges 2007; Müldner and Richards 2005). These differences relate to rules for the exclusion of meat in the diet and fasting, which resulted not only in the consumption of fish as a substitute within religious communities but also an increase in the proportion of marine foods in the diet of the whole population in the later medieval period (Serjeantson and Woolgar 2006). Kancle *et al*. (2018) identified dietary shifts during adolescence in the dentine collagen $\delta^{13}C$ and $\delta^{15}N$ of 10 individuals buried at the sites of two English Late Medieval Carmelite monasteries. These were consistent with dietary changes associated with a lay person joining a religious order in late childhood/early adolescence during that historical period (Kancle *et al*. 2018).

The ability to use temporal profiles from incremental dentine collagen $\delta^{13}C$ and $\delta^{15}N$ to identify short-term changes in diet has also been employed in the investigation of breastfeeding and weaning behaviour. Early studies of modern maternal/infant pairs using sequential keratin samples of hair and fingernail $\delta^{13}C$ and $\delta^{15}N$ (Fogel *et al.* 1989; Fuller *et al.* 2006) showed that there is an apparent trophic level shift in both isotopes in a breastfeeding infant. Breastmilk as the exclusive source of dietary protein reflects maternal values, and after fractionation in the body of the infant, this results in the elevated values in the tissues of the child who are growing at that time. Once supplementary foods are introduced, the infant goes through a period of weaning while the breastmilk is gradually withdrawn and the isotope ratios change as a result of the influence of other protein sources. When breastfeeding ceases, the $\delta^{13}C$ and $\delta^{15}N$ will reflect the weaned diet (likely to be similar to maternal values). A model for the changes expected in the $\delta^{15}N$ was proposed by Millard (2000), and this pattern of rise and fall of the isotope values has been identified in incremental dentine sampled from the teeth of archaeological individuals who are developing in the perinatal period (Beaumont *et al.* 2015; Craig-Atkins *et al.* 2018; Eerkens *et al.* 2011; Fuller *et al.* 2003; Henderson *et al.* 2014) and more recently from the deciduous teeth of modern children (Beaumont 2020). Early studies used bulk bone collagen $\delta^{13}C$ and $\delta^{15}N$ from infants of different ages from the same site in an attempt to identify population-specific weaning behaviour (Jay *et al.* 2008), but given the inherent problems in assigning age at death, and the possible influence of physiological stress on the $\delta^{13}C$ and $\delta^{15}N$ values, these are no longer considered to be as reliable as incremental tissues (Beaumont 2020).

MATERIALS

For this project, bone and permanent teeth were sampled from four of the maxillae and mandibles, and bone from the fifth edentulous maxillae from the assemblage, in order to carry out stable isotope analysis. The collagen produced during this analysis was also used to obtain radiocarbon dates for each of the individuals. Permission for this destructive analysis was granted by the Museum of London Archaeology (MoLA).

The maxillae and mandibles have all suffered post-mortem damage.

PWC92 – [1]– Maxillae (adult). On the left side, where the bone has been damaged post-mortem, there is an indication of possible healed sinusitis, although the presence of surface concretions makes it difficult to be confident of the diagnosis. Tooth sampled: right upper permanent canine (develops between 0.6 and 14.5 years of age ±0.5 years).

PWC92 – [2] – Mandible (adult). The flaring of gonion would suggest sex estimation as male. Tooth sampled: right lower 2nd permanent molar (develops between 2.5 and 15.5 years ±0.5 years).

PWC92 – [3] – Right maxilla fragment (adult). Tooth sampled: right upper1st permanent molar (develops from around birth to 9.5 years ±0.5 years).

**PWC92 – [4]** – Maxillae (adult). Edentulous.

PWC92 – [5] – Right side of mandible (adult). There is some infilling of the tooth sockets post-mortem by the concretions from the burial environment. The flaring of gonion and upright angle of the ramus would suggest sex estimation as male. Tooth sampled: right lower first premolar (develops between 2.5 and 13.5 years ±0.5 years).

METHODS

Radiocarbon dating

Samples of the collagen from each individual were submitted for AMS radiocarbon dating to Beta-Analytic, Miami, Florida. The input of non-terrestrial carbon (e.g. marine fish) into the diet can result in misleadingly older dates, due to the marine reservoir effect (MRE) (Bayliss *et al.* 2004; Meadows *et al.* 2016). Ocean water beneath the surface becomes a reservoir for decaying radiocarbon (contained within the carbonates), which becomes incorporated into marine organisms that can then enter the human food chain (Ascough *et al.* 2012; Stuiver and Braziunas 1993). The carbon in the marine reservoir is thus not comparable to that of the atmospheric/terrestrial reservoir, making the IntCal13 calibration curve unsuitable for calibrating samples with a marine contribution (Reimer *et al.* 2013). Therefore the following radiocarbon ages have also been calibrated using a combination of IntCal13 and Marine13 (Bronk Ramsey 1998) (Fig. 3).

The stable δ^{13}C dietary values for the five individuals were used to estimate the percentage of the diet from marine protein. End-member values of δ^{13}C were taken as −12.5 ‰ for 100% marine diets and −21.0 ‰ for 100% terrestrial diets (Arneborg *et al.* 1999). The regression equation of the linear plot provides the basis from which to ascertain the percentage of the marine input into the diet. The individual marine proportion of the diets varies from 19.7% to 28.9%. This value, along with a 10% error (Hedges *et al.* 2004), was used proportionally to mix the IntCal13 and Marine13 curves (Reimer *et al.* 2013), utilising the Oxcal program (version
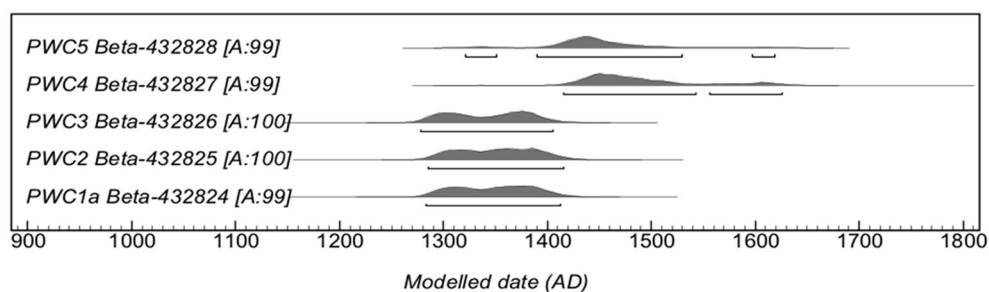
Sample ID.	Lab ID.	14C age	δ13C	% Marine	Calibrated Radiocarbon Dates CE (95.4% unless otherwise stated)	
		(y BP)	(‰)		IntCal13 Curve	Mixed Curves
PWC BONE 1a	Beta-432824	710 ± 30	-19.0	22.90	1255–1385	1280–1415
PWC BONE 2	Beta-432825	690 ± 30	-19.3	19.70	1265–1390	1285–1420
PWC BONE 3	Beta-432826	720 ± 30	-19.3	20.60	1245–1385	1275–1405
PWC BONE 4	Beta-432827	530 ± 30	-18.7	27.00	1315–1440	1410–1540 (81%)
						1550–1625 (14.4%)
PWC BONE 5	Beta-432828	580 ± 30	-18.5	28.90	1295–1420	1320–1350 (2.9%)
						1390–1530 (90.9%)
						1595–1620 (1.6%)

Figure 3   *Radiocarbon dates calibrated with OxCal (Bronk Ramsey 2009), using mixed terrestrial and marine curves as described in the text (Reimer et al. 2013)*

4.2.4; Bronk Ramsey 2009). In accordance with protocol when calibrating samples that are marine or have a marine input, a ΔR value has to be applied in order to account for local geographical deviations from the contemporary global average for the MRE. The regional ΔR value for medieval England is best defined as -29 ± 51 (Russell *et al*. 2010).

Stable isotope analysis

For each of the four dentate individuals, dentine collagen was prepared from the full length of a single root or a full longitudinal root section by demineralisation in a 0.5 M solution of HCl. Bone collagen from all five individuals, including the edentulous individual, was prepared according to the modified Longin method (Brown *et al*. 1988), which included ultra-filtration. The use of cortical bone from maxilla or mandible should provide a long-term average for the diet during life, similar to other cortical bones (Clarke 2008; Fahy *et al*. 2017) and certainly a period of life that is later than the formation of the dentine that was sampled. Previous analysis has demonstrated that unfiltered dentine gives the same analytical data as filtered dentine (Beaumont *et al*. 2013b), allowing the use of small samples without the loss of volume associated with filtration. The isotopic data for all samples are given in Table 1. The demineralised dentine was cut into 1 mm sections (Beaumont *et al*. 2013b) and an approximate age assigned to each segment (Beaumont and Montgomery 2015). This method allows us to investigate isotopic changes over short periods (approximately nine months in permanent teeth), allowing for the averaging and attenuation of the profiles. The approximate ages of development of each tooth are stated in the materials section and on each dentine profile plot (Fig. 4). The demineralised sections were rinsed with de-ionised water and placed in a pH 3 HCl solution at 70° Celsius for 24 hours to denature the collagen. They were then frozen and freeze dried.

   All samples were weighed into tin capsules and ranged from 0.3 to 0.7 mg. These were measured in duplicate by combustion in a Thermo Flash EA 1112 and introduction of separated N_2 and CO_2 to a Finnigan Delta plus XL via a Conflo III interface at the University of Bradford Stable Isotope Laboratory. The collagen samples were interspersed throughout the run with both internal standards (fish gelatine and bovine liver substrate) and international standards (IAEA-N-1, IAEA-N-2, IAEA-CH-3 and IAEA-600). Calibrated against these standards, the analytical error at 1 standard deviation was ±0.2 ‰ or better. The C:N ratios of all the samples fall in the acceptable range suggested by van Klinken (1999) of 3.1–3.5.

RESULTS

Radiocarbon dating

The five radiocarbon determinations obtained are provided in Figure 3. The corrected radiocarbon dates have a larger calibrated date range, which reflects the uncertainties inherent in correcting for reservoir effects. However, there appear to be two distinct groups (Fig. 3): PWC92 [1], [2] and [3] that date from around CE 1280 to CE 1420, and a later group, PWC92 [4] and [5], that date from around CE 1400 to CE 1530. Although there is some overlap, it appears that there are two distinct cohorts, High Medieval (PWC92 [1], [2] and [3]) and Late Medieval (PWC92 [4] and [5]).

Table 1   *Carbon and nitrogen dentine and bone collagen isotope ratio data and quality parameters for individuals from St Stephen's Chapel Westminster*

Tooth sample number	δ15N ‰	δ13C ‰	C/N ratio
PWC92 1–1	11.6	−19.9	3.2
PWC92 1–2	11.7	−19.1	3.1
PWC92 1–3	11.6	−19.3	3.2
PWC92 1–4	12.6	−18.8	3.3
PWC92 1–5	11.7	−19.0	3.1
PWC92 1–6	11.4	−19.2	3.0
PWC92 1–7	12.0	−19.1	3.1
PWC92 1–8	12.4	−18.9	3.1
PWC92 1–9	12.8	−18.8	3.1
PWC92 1–10	12.8	−18.8	3.1
PWC92 1–11	13.1	−18.8	3.0
PWC92 1–12	13.3	−18.7	3.1
PWC92 1–13	13.7	−18.7	3.0
PWC92 2–1	13.0	−19.9	3.0
PWC92 2–2	13.3	−19.7	3.0
PWC92 2–3	13.9	−19.5	3.0
PWC92 2–4	14.0	−19.6	3.0
PWC92 2–5	13.7	−19.5	3.0
PWC92 2–6	12.8	−19.7	3.0
PWC92 2–7	13.0	−19.8	3.1
PWC92 2–8	12.7	−19.5	3.0
PWC92 2–9	12.5	−19.5	3.0
PWC92 2–10	12.5	−19.4	3.1
PWC92 2–11	12.7	−19.6	3.1
PWC92 2–12	13.1	−19.6	3.1
PWC92 2–13	13.4	−19.5	3.0
PWC92 2–14	13.5	−19.5	3.0
PWC92 2–15	13.5	−19.3	3.0
PWC92 3–1	13.8	−19.7	3.0
PWC92 3–2	12.6	−19.9	3.0
PWC92 3–3	11.9	−20.0	3.0
PWC92 3–4	11.6	−19.9	3.0
PWC92 3–5	11.9	−19.7	3.0
PWC92 3–6	11.8	−19.7	3.0
PWC92 3–7	12.1	−19.6	3.0
PWC92 3–8	11.9	−19.7	3.0
PWC92 3–9	12.1	−19.8	3.1
PWC92 3–10	12.1	−19.8	3.0
PWC92 3–11	12.1	−19.7	3.0
PWC92 3–12	12.3	−19.7	3.0
PWC92 3–13	12.9	−19.7	3.1
PWC92 3–14	13.4	−19.4	3.1
PWC92 3–15	13.5	−19.5	3.1
PWC92 3–16	13.6	−19.3	3.0
PWC92 3–17	13.9	−19.3	3.0
PWC92 3–18	14.1	−19.3	3.0
PWC92 5–1	13.3	−19.2	3.0
PWC92 5–2	13.3	−18.9	3.0

(*Continues*)

Table 1　　*(Continued)*

Tooth sample number	δ15N ‰	δ13C ‰	C/N ratio
PWC92 5–3	13.4	−18.8	3.0
PWC92 5–4	13.7	−18.7	3.0
PWC92 5–5	13.7	−18.8	3.0
PWC92 5–6	13.8	−18.7	3.0
PWC92 5–7	13.7	−18.7	3.1
PWC92 5–8	14.0	−18.6	3.1
PWC92 5–9	14.1	−18.7	3.1
PWC92 5–10	14.1	−18.7	3.1
Bone			
PWC92 1	13.5	−18.9	3.1
PWC92 2	13.1	−19.3	3.1
PWC92 3	13.4	−19.2	3.1
PWC92 4	14.5	−18.7	3.1
PWC92 5	14.0	−18.5	3.1
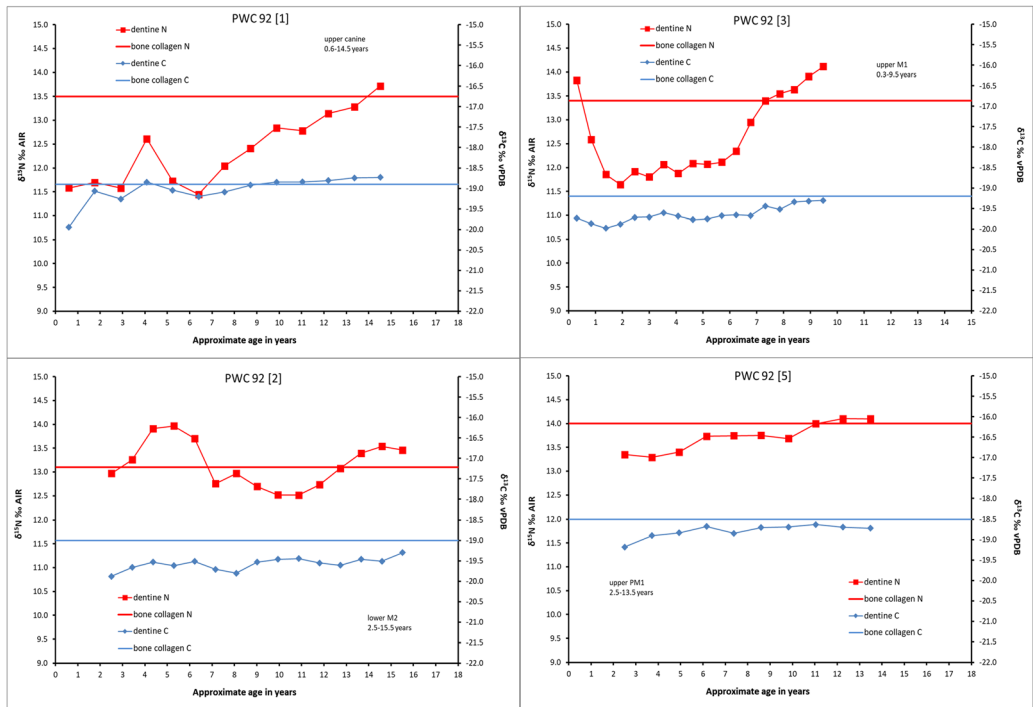
Figure 4　*Plots of carbon and nitrogen isotope ratios: bone collagen and incremental dentine profiles for individuals PWC 1, 2, 3, and 5 from St Stephen's Chapel, Westminster (Table 1)*

Stable isotope analysis

The results of the $\delta^{13}C$ and $\delta^{15}N$ analysis are shown in Table 1. Plots of incremental dentine data can be seen in Figure 4 and all bone collagen data in Figure 5. The $\delta^{13}C$ ranges from -20.0 ‰ to -18.5 ‰, and $\delta^{15}N$ from 11.4 ‰ to 14.5 ‰. There is an upwards shift between the mean dentine $\delta^{13}C$ and the bulk bone in all cases, and in the $\delta^{15}N$ of PWC92 [1], [2] and [3]. The bulk bone $\delta^{13}C$ and $\delta^{15}N$ from PWC92 [4] and mean dentine and bulk bone $\delta^{13}C$ and $\delta^{15}N$ from PWC92 [5] are the three highest values from the samples.

Incremental dentine analysis

The dentine profile for PWC92 [5] shows the least variability in $\delta^{13}C$, which rises gradually by 0.6 ‰ and $\delta^{15}N$ by 0.8 ‰ during the age of tooth formation (approximately 2.5 to 13.5 years). By comparison, PWC92 [1] has a $\delta^{15}N$ range of 3.1 ‰, with a peak at approximately five years of age and a second rise from 11.4 to 14.5 ‰ from about 6.5 years until the end of tooth formation. The $\delta^{13}C$ profile covaries with the $\delta^{15}N$ until approximately nine years of age, but then remains around -18.8 ‰ until the end of the tooth.

The $\delta^{13}C$ profile for PWC92 [2] remains relatively stable around -19.5 ‰, with a range of 0.6 ‰ and does not covary with $\delta^{15}N$, which has two peaks at the age of 4–5 years and 14–15 years, with a range of 4.1 ‰.
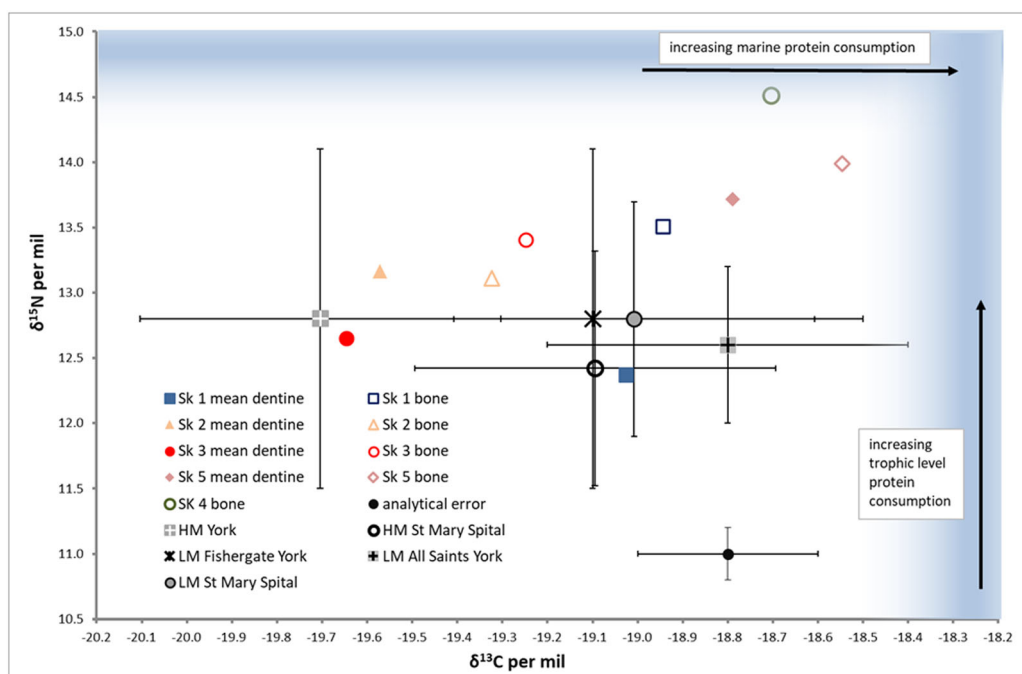

Figure 5   *Plot of carbon and nitrogen isotope ratios for bone collagen and mean dentine collagen from individuals from St Stephen's Chapel, Westminster (Sk 1,2,3,4 and 5), and mean bone collagen isotope ratios for High Medieval (HM) and Late Medieval (LM) populations from York (Müldner and Richards 2007: Müldner and Hedges 2007) and from London (Walter et al. 2020a; Walter et al. 2020b) with error bars denoting 1sdNote: Determination of marine protein and trophic level are discussed in the text.*

PWC92 [3] has a gradually rising profile for $\delta^{13}C$, rising across the age of tooth development by 0.7 ‰. $\delta^{15}N$ is high at birth, falling rapidly from 13.8‰ to a minimum of 11.6 ‰ at age 2 years. The $\delta^{15}N$ profile is then stable until about the age of six years, when it climbs steadily to reach 14.1 ‰ at the end of the tooth (approximately 9.5 years of age).

<div align="center">DISCUSSION</div>

Life histories

The following interpretations of life histories have been made for PWC92 [1], [2], [3], [4] and [5] from the stable isotope analyses of the bone and dentine collagen.

PWC92 [1]

There is no evidence for breastfeeding or weaning in this dentine profile: the permanent canine starts to develop at about six months of age and each 1 mm section represents approximately nine months of life, thus missing variations in $\delta^{15}N$ and $\delta^{13}C$ visible in teeth which form earlier in life (Fig. 4). Initially the diet appears $\delta^{15}N$ and $\delta^{13}C$ to be of a low-trophic level, possibly very terrestrial, with a short period of higher trophic-level input at about four years of age. After this, the trophic level of the diet and thus the $\delta^{15}N$ and $\delta^{13}C$ appear to rise gradually from the age of seven years to match the bone level (the solid red and blue lines) by the end of the tooth growth, at about 14 years of age. The final $\delta^{15}N$ and $\delta^{13}C$ indicate potential for some marine input to the diet. Many factors could explain changing life circumstances in childhood but might include their education. If this person was a member of the clerical community at St Stephen's, the higher trophic levels in later life, reflected in the bone values, may be the result of a career in the service of the church and/or the king; in the medieval period high trophic level foods were generally consumed by higher status individuals (Müldner and Hedges 2007; Müldner and Richards 2006).

PWC92 [2]

This individual has a range (1.5 ‰) of perturbations in $\delta^{15}N$, with very little corresponding change in $\delta^{13}C$, which implies that this is not the result of trophic level dietary change. This could be due to periods of nutritional or health-related stress in the early and late periods of tooth formation or that may relate to periods of rapid growth around the age of five years and puberty, and the reduction of nitrogen deficit between (Henderson *et al.* 2014). This may also be linked to the sort of evidence seen for residual rickets in some of the long bones. Where such opposing covariance of $\delta^{15}N$ and $\delta^{13}C$ has been observed in this and other archaeological individuals, they appear to be of a long duration. It should be clarified that, because of the sampling technique, there will be averaging of the tissue sampled, causing not only an extension of the affected period but also smoothing and attenuation of the signal (Tsutaya 2020). It is probable that the period of physiological stress affecting the individual was shorter and produced an even greater change in the $\delta^{15}N$. The teeth of this individual did not have any visible markers for stress. There is $\delta^{15}N$ and $\delta^{13}C$ evidence for a high trophic level diet but without a high proportion of marine input.

PWC92 [3]

This individual shows a wider range (4.5 ‰) of $\delta^{15}N$ over the period of tooth formation, again with a relatively flat $\delta^{13}C$ profile. After very high $\delta^{15}N$ values in infancy (possible

trophic-level effect seen during breastfeeding), weaning appears to have occurred at the age of about two years. This is consistent with evidence from bone collagen measurements of other English medieval populations (Haydock *et al.* 2013; Mays *et al.* 2002; Nitsch *et al.* 2011). The low, stable period at the age of two to six years is at the same age as PWC92 [1] implying they had a similar life history with an upward shift in dietary trophic level between childhood and adolescence. Neither shows evidence of high levels of marine consumption, but they may have been eating freshwater fish, or eels, which move between freshwater and marine environments during their life cycle, and thus can result in either terrestrial or marine $\delta^{13}C$ values (Fuller *et al.* 2012).

PWC92 [4]

No teeth were present, but the bone collagen $\delta^{15}N$ and $\delta^{13}C$ suggest a significant marine input in the averaged adult diet.

PWC92 [5]

Throughout the dentine profile both $\delta^{13}C$ and $\delta^{15}N$ are relatively constant, with co-varying rises of 0.8 ‰ in $\delta^{15}N$ and 0.6 ‰ in $\delta^{13}C$. The later adolescent values match well with the adult bone collagen values. These suggest that when the tooth was forming, the person was eating a stable diet very similar to the adult diet seen in the bone sample. The values for both tissues suggest a high input of marine fish in the diet throughout life.

Contemporaneous English $\delta^{13}C$ and $\delta^{15}N$ data

As there is little published faunal data from London during this period, these data have been divided into High Medieval (PWC92 1, 2 and 3) and Late Medieval individuals (PWC92 4 and 5) for comparison with human bulk bone $\delta^{13}C$ and $\delta^{15}N$ from contemporary sites from York, England (Müldner and Hedges 2007; Müldner and Richards 2007) and well-dated individuals from medieval St Mary Spital, London, England (Walter *et al.* 2020a; Walter *et al.* 2020b). The data from this study are shown with the published bulk bone collagen means for the High Medieval and Late Medieval populations from York and London (Fig. 5). The $\delta^{13}C$ and $\delta^{15}N$ for the individuals from this study are consistent with the wider range of values obtained from contemporary York and London sites, and show the same overall shift towards a more marine life-long diet in the later medieval period. Walter *et al.* (2020a) observed a shift toward higher $\delta^{15}N$ from sub-adults to adults in the London populations. Three of the individuals from St Stephen's demonstrate this shift between the dentine formed in their childhood and adolescence and the later-forming bone, suggesting that there was a common difference between the diet of juveniles and adults during these periods or that the physiological effect of growth is affecting the recorded $\delta^{13}C$ and $\delta^{15}N$ in the collagen. The combination of dentine and bone from the same individuals avoids any risk that the observed difference was due to some factor that caused the early death of those juveniles with lower $\delta^{15}N$. The fourth, PWC92 [5] shows the least variation in the dentine profile data and the least dietary change from childhood to adult life, with a shift upwards in $\delta^{13}C$ between mean dentine and bone.

All the St Stephen's individuals were found to have higher bone $\delta^{15}N$ than any of the York or London population mean $\delta^{15}N$. Müldner and Hedges *et al.* (2007) interpreted high bone collagen $\delta^{15}N$ as a marker for high status diet, particularly supported by documentary evidence for diet in the Late Medieval population of the Gilbertine Priory at Fishergate, York. Given that the St

Stephen's individuals were excavated from a high status site, their bone collagen δ^{15}N is consistent with a diet rich in high trophic level proteins, relative to contemporaneous populations in lower status St Mary Spital London (Walter *et al.* 2020a) or York.

Using the assumption (as per the marine consumption adjustments for the radiocarbon date) that the δ^{13}C for a 100% human terrestrial diet is -21.0‰ (Arneborg *et al.* 1999), it is possible to put forward a potential minimum δ^{13}C and δ^{15}N combination for high marine consumption. Allowing for a 2‰ trophic level shift from baseline terrestrial faunal consumption for δ^{13}C (Bocherens *et al.* 2005), a 5‰ shift for δ^{15}N and analytical error of 0.2‰ as a robust threshold, then the stable isotope ratios of some of the samples measured for this study show strong evidence for marine input to the diet. It is assumed that a δ^{13}C measurement of the bone or dentine collagen of -18.8 ‰ or higher combined with a δ^{15}N above 12.1 ‰ is evidence that marine protein consumption has taken place during tissue formation. The higher δ^{13}C in the dentine and bone collagen of PWC92 [5] and bone collagen of PWC92 [4] could also be considered as evidence for a greater proportion of marine foods in their diet and is consistent with the δ^{13}C at the high status Late Medieval All Saints Gilbertine priory in York (Müldner and Richards 2007).

Figure 5 demonstrates that the bone collagen δ^{15}N and δ^{13}C can be divided into two probable dietary groups, which match with their different radiocarbon dates and with the populations from London and York. Figure 5 shows that all individuals from St Stephen's can be interpreted as consumers of a higher trophic level diet, with more marine input, than the mean of the contemporaneous populations and thus had higher status in terms of their diet as adults.

<center>CONCLUSIONS</center>

The individuals buried in the area beneath St Stephen's Chapel, five of whom were represented by maxillae or mandibles, had been moved from their original burial position by the many stages of renovation and reconstruction in the undercroft. The initial examination of these bones was unpromising in terms of gleaning any information about the lives of the owners. However, using detailed osteological re-analysis, and scientific methods of radiocarbon dating and δ^{13}C and δ^{15}N analysis, it has been possible to reconstruct some of the life history of these people. The dentine profiles represent the dietary history of the individuals during the formation of the sampled teeth (Beaumont and Montgomery 2015), and the bone represents an adult dietary average (Fahy *et al.* 2017; Hedges *et al.* 2007); thus, we can compare diet as a child with that in adulthood.

PWC92 [1] and [3] appear to have had relatively similar dietary life histories with low trophic-level foods in their childhoods, and a rise to a higher status diet at the age of about seven years. This could be related to their education or training for a clerical career and is consistent with a study of individuals at two friaries in northern England who show similar dietary shifts (Kancle *et al.* 2018) although lower status burials at St Mary Spital show the same trend for higher trophic level foods in adulthood (Walter *et al.* 2020a). According to the radiocarbon dates, the two individuals lived at the same period and could have experienced very similar lifeways. PWC92 [2] dates to the same period as PWC92 [1] and [3] but appears to have had a more varied childhood diet with suggestions of physiological stresses as a younger child.

PWC92 [4], an edentulous adult, appears to have lived to an older age, possibly with access to dental treatment (there is no sign of retained, damaged or decayed roots in the edentulous maxillae), with an adult diet rich in marine foods. PWC92 [5] appears to have had a stable diet throughout life, with similar high marine input both in childhood and adulthood and was probably a contemporary of PWC92 [4]. According to the radiocarbon dating evidence both probably

lived later than PWC92 [1], [2], and [3]. The childhood δ^{13}C and δ^{15}N of PWC92 [5] is consistent with the more marine-based dietary regimes identified in the bone collagen isotope ratios of the Late Medieval contemporaneous general populations in England: those who lived in religious orders show consistently higher proportions of marine fish in their adult diet (Müldner and Hedges 2007), and the δ^{15}N and δ^{13}C of all 5 St Stephen's burials are consistent with the higher trophic level individuals in contemporaneous populations in York and London.

These data and the possible interpretations are consistent with individuals working in the palace in a religious role after the time of the rebuilding of St Stephen's Chapel in 1292 ([1], [2] and [3]), and in the following century ([4] and [5]). The five individuals whose bones were found in the excavations of 1992 underneath the former site of St Stephen's Chapel (especially those who demonstrate a change from lower to higher trophic level diets at the age of approximately seven years) can be most obviously associated with the secular college active at the chapel from 1,348 to 1,548 (Biggs 2020). The project illustrates how the application of new scientific analyses to an unpromising assemblage of poorly preserved human remains from such an important historic location can allow the reconstruction of detailed dietary histories and possible life histories, for these individuals who died, were buried, disturbed, and reburied. In addition it has enabled us to match individuals with similar dietary profiles as a possible cohort. The combination of radiocarbon dating and dietary isotopic profiles could potentially add to, and in some cases refine, dating evidence by allowing us to identify individuals in the same burial context as a group who have lived through historical events such as famine or followed well-documented lifeways such as those who join a religious order during childhood.

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