## 7.2.3.1 Stable Isotopes of Oxygen and Strontium

*Lauren Walther, Janet Montgomery and Jane A. Evans*

### Introduction

The movement of people and populations in past societies is an abiding theme in both archaeology and bioarchaeology. The migration of peoples to different areas and environments may explain changes in the archaeological record but can arise through many causal factors such as marriage, agriculture, war and cultural differences (Price *et al.*, 2004). Both radiogenic and stable isotope analysis is increasingly used to directly detect migration and diet in past by analysing the skeletons of the people who migrated rather than inferring human mobility from the appearance of new artefacts and cultural practices. The isotope systems most frequently used to detect human migration are those of strontium and oxygen. These provide independent information related to the place of origin of an individual: strontium isotopes in the environment vary geographically with solid and drift geology (Bentley 2006; Evans *et al.*, 2010) and oxygen isotopes vary with climate, altitude and distance from the sea (Longinelli 1984; Darling *et al.* 2003; Daux *et al.* 2008). These two elements are found in the environment and, primarily through the ingestion of food (strontium) and water (oxygen), become incorporated into the human skeleton, linking the person to the place they sourced their food and drink. Strontium and oxygen isotope analysis was, therefore, undertaken on 31 individuals buried at or near Portmahomack to investigate the degree of residential mobility amongst the population by identifying local and non-local origins.

### Materials

Tooth samples for strontium and oxygen isotope analysis were obtained from human permanent dentition (molars and premolars) from 29 individuals from the Tarbat Old Church (St. Colman's Church) site in Portmahomack and two individuals from Balnabruach, near Portmahomack. In addition, two prehistoric individuals were included which were discovered in 1992 during ground preparation for a pump house near Balnabruach. Daphne Home Lorimer conducted the skeletal report on the prehistoric human remains in 1995 (Lormier, 1995). Field Archaeology Specialists Ltd. (FAS) excavated the skeletons at Tarbat Old Church between the 1994 and 2002 field seasons (Carver, 2003) and Sarah E. King (2000) performed the skeletal analysis. Thirty one teeth were selected for strontium and oxygen isotope analysis to determine possible local origins of individuals buried in and near the church. Periods represented within this sample include: Period 0 (prior to 6$^{th}$ Century

AD); Period 1 (AD 550-700); Period 2 (AD 700-830); Period 3 (AD 830-1100); Period 4 (AD 1100-1600); and Period 5 (AD 1600-2000). Two main socio-economic populations were represented:

1. Periods 2 and 3 represented a monastic/post-monastic settlement at Portmahomack during the early medieval period, which was determined from the population demographic of the burials (Carver, 2008). A large number of male burials aged between 17 and 46+ years at death were excavated, whilst few females and non-adults were present (King, 2000; Carver, 2008).
2. Period 4 contains males, females and non-adult burials ranging in age at death and is believed to represent the inhabitants of a medieval settlement (Carver, 1997; King, 2000; Carver, 2008).

The analysis of the 31 enamel samples (one from each individual) was completed on two separate occasions. An initial pilot study of 12 teeth was followed by a larger sample of 19 teeth (Walther 2012). Prior to sampling, a digital photographic record of each tooth was taken from the buccal, lingual, mesial, distal, occlusal and root angles.

**Methods**

Core enamel was used for strontium and oxygen isotope analysis because several studies have shown that it is considerably less susceptible to diagenetic change than bone or dentine and retains lifetime values from the time of tooth formation, i.e. childhood (Budd *et al.*, 2000; Montgomery, 2002; Hoppe *et al.*, 2003). Each tooth forms during a well-constrained period of time in an individual's life and thus contains elemental strontium and oxygen absorbed from the diet during that period. With few exceptions, all the teeth in human permanent dentition complete their crowns between 2.5 and 15 years of age (Table 1). Consequently, the period of life represented by each isotope measurement will depend on the specific tooth selected for analysis (see Table 2 for details of the samples measured in this study).

Tooth sample preparation followed guidelines outlined by Montgomery (2002). Enamel was removed from the teeth using tungsten carbide burrs and diamond edged dental saws. All surface enamel and adhering dentine were mechanically removed and enamel that was visibly cracked, discoloured or carious was not sampled. In addition, a dentine sample was taken from the crown of four teeth (16, 41, 127 and 140) to monitor diagenetic strontium: dentine has been shown to absorb labile soil strontium and is a useful indicator of local strontium ratios pertaining during the period of burial (Montgomery *et al.* 2007). Cleaned chips of core enamel and dentine were sealed in containers and transferred to the class 100, HEPA-filtered laboratory facility at the NERC Isotope Geosciences Laboratory (NIGL) in Keyworth, UK . Strontium isotope samples were prepared and measured as outlined in Evans *et al.* (2006). The concentrations of $^{87}Sr/^{86}Sr$ were determined by Thermal Ionisation Mass spectrometry (TIMS) using a ThermoTriton thermal ionisation multicollector mass spectrometer. The NBS 987 International $^{87}Sr/^{86}Sr$ standard gave a value of 0.710251±0.00001 (2s, n=18).. Laboratory contamination, monitored by procedural blanks, was negligible (<100 pg).

Oxygen isotope ratios are reported in parts per mil (‰, $^{18}O/^{16}O$) relative to the international standard Standard Mean Ocean Water (SMOW). Oxygen isotopes for the 12 pilot samples were measured by conversion to silver phosphate following the method outlined in Chenery *et al.* 2010. Phosphate oxygen isotope ratios ($\delta^{18}O_p$) were obtained using thermal conversion continuous flow isotope ratio mass spectrometry (TC/EA-CFIRMS) with a ThermoFinnigan thermal conversion elemental analyser gas chromatography (GC) column coupled to a ThermoFinnigan DeltaplusXL via a ConFlo III continuous flow interface. The samples were measured in triplicate, corrected for non-linearity and drift and converted to the VSMOW scale against NBS120C. Estimated analytical precision based on the reproducibility of international and in-house standards is ± 0.16‰ (1SD).

Oxygen isotopes for the second batch of 19 enamel samples were determined by measurement of enamel carbonate using a GV IsoPrime dual inlet mass spectrometer. Carbonate oxygen isotope ratios ($\delta^{18}O_c$) were normalized to v-PDB using an in-house reference material calibrated against NBS19 certified reference material. Analytical precision was estimated as ±0.02‰ (1SD). In order to facilitate comparison between the initial pilot batch and the subsequent 19 samples, $\delta^{18}O_c$ values were reported relative to SMOW using the equation from Coplan (1988) (SMOW=1.03091 x $\delta^{18}O$ PDB +30.91). These ratios were then converted to $\delta^{18}O_p$ using the regression formula published by Chenery *et al.* (2012):

$$(\delta^{18}O_p = 1.0322(\pm 0.008) * \delta^{18}O_c - 9.6849(\pm 0.187))$$

This equation has an associated maximum error of ± 0.013‰, 1SD.

## Results

The isotope results are presented in Table 2. The $^{87}Sr/^{86}Sr$ sample for Skeleton 152 failed and could not be re-measured during the timescale of this project. Strontium isotope ratios for the 30 individuals measured exhibit a wide range of ratios from 0.7097 to 0.7152 with a median value of 0.7112 (Figure 1). The assumption of normality is rejected with 95% confidence (Anderson-Darling, $p = 0.038$). Strontium concentrations range from 57ppm to 200ppm and are consistent with other archaeological individuals from Britain (Evans *et al.* 2012). There is no correlation between $^{87}Sr/^{86}Sr$ and strontium concentrations ($r^2 = 0.16$).

The $\delta^{18}O_c$ values for the 19 samples range between 24.6‰ and 27.4‰ (± 0.16‰ 1SD), with a mean value of 26.0‰ ±1.6‰ (2SD). As described above, to facilitate comparison with the pilot data these were converted to $\delta^{18}O_p$ using the equation from Chenery *et al.* (2012). The resulting range of $\delta^{18}O_p$ values obtained from the Portmahomack individuals was 15.7‰ to 18.6‰ with a median and mean value of 17.4‰ (±1.6, 2SD, n = 30) (Figure 2). The assumption of normality is accepted with 95% confidence (Anderson-Darling, p = 0.254). There is no correlation between $\delta^{18}O_p$ values and $^{87}Sr/^{86}Sr$ of individuals ($r^2$ = 0.09). An estimated uncertainty to encompass reasonable measurement and conversion errors for $\delta^{18}O_p$ values of ± 0.2‰ (1SD) is shown in Figures 3 and 4; at 1SD there is only a 66% probability that the true value lies within this range and this should be borne in mind when assigning origins. In contrast, there is a 99.9% probability that the true value for $^{87}Sr/^{86}Sr$ lies within the symbols.

The range of strontium isotope ratios that would be expected for human inhabitants of the Devonian Old Red Sandstone of the Tarbat peninsula was estimated from published measurements of mineral waters, stream waters, plants and archaeological dentine from geologically comparable biospheres in Scotland. These provide a range of values from 0.7093 to 0.7116 with a single outlier at 0.7133 and a mean of 0.7098 +/- 0.0010 (1s, n = 29) (Evans *et al.* 2010). The four dentine samples measured from burials at Portmahomack range from 0.7098 to 0.7116 which agrees well with the published data above and suggest the dentine is incorporating strontium with an isotope ratio below 0.710 from the burial soil. These values may reflect the combination of soils derived from the underlying rocks and atmospheric strontium due to the coastal, maritime location of the site: rainwater, marine shell-sands, sea-splash and spray can lower or raise biosphere and human strontium isotope ratios towards 0.7092 which is the value of seawater and marine products (Montgomery *et al.* 2003; Evans *et al*. 2010). Sixteen individuals have a strontium isotope ratio that is consistent with origins on the coastal Old Red Sandstone at Portmahomack (Figure 3). Fourteen individuals from Periods 1 to 4 exhibit strontium isotope ratios which are higher than those expected for individuals originating from the Tarbat Peninsular and indicate origins in regions of older silicate or granitic rocks. These can be found widely in the Highlands of Scotland where biosphere values and a small number of human enamel values exceeding 0.716 have been obtained (Evans *et al.* 2012). No individuals have strontium isotope ratios indicative of origins in regions of basalts, chalks or limestones.

Evans *et al.* (2012) defined the range for $\delta^{18}O_p$ in archaeological human enamel from across Britain to be 16.3-19.1‰ (mean = 17.7‰ ±1.4‰ 2SD, n = 615). Inhabitants of eastern Britain were found to have a mean value of 17.2‰ ± 1.3‰ (2SD, n = 83) and western Britain a mean value of 18.2‰ ± 1‰ (2SD, n =40). Using these estimates, the ranges for eastern and western Britain were calculated at the 1SD level and used in Figures 3 and 4. Only four individuals from Periods 1 and 2 (Burials 129, 152 (not plotted), 153 and 186) fall outside this 1 SD range having lower values; these are discussed further below. To facilitate comparison with geographical variation of mean annual precipitation in Britain which ranges from -4.0‰ in the west to -9.0‰ in the east, measured and calculated $\delta^{18}O_p$ values can be converted to precipitation values; rainwater in Britain has been shown to be the principal source of ground and surface waters, and hence, drinking water (Darling and Talbot 2003; Darling *et al.* 2003). However, there are several published equations to do this and all give slightly different results. Those in Table 2 were calculated using Daux *et al.* (2008) Eq. 6 and range from -5.1‰ to -9.5‰ but the associated error is large (Pollard *et al*. 2011). Based on the published oxygen isotope ratio precipitation map of Darling and Talbot (2003), individuals with $\delta^{18}O_{dw}$ above -7.0‰ are likely to originate in the higher rainfall regions of the western and southwestern seaboard of Britain (and by extension Ireland) or the Western and Northern Isles. Individuals with values below -7.0‰ would be consistent with eastern, central and upland Britain and Ireland. Figure 3 shows that the majority of the early medieval population (Periods 1, 2 and 3) are consistent with origins in eastern or central Britain, whilst only individuals in Period 4 and 5 have $\delta^{18}O_p$ values above 17.9‰, suggesting origins in western Britain or the Northern Isles for a significant proportion of this later medieval sample. There is a statistically significant difference between the early medieval (Periods 2 and 3) and later medieval (Periods 4 and 5) $\delta^{18}O_p$ values (t-Test; $p< 0.004$, n=27). It is possible that some of the higher oxygen isotope ratios in this group may be due to analytical uncertainty, the sampling of first molars with a significant breastfeeding component, or a radically warmer climate in the second millennium AD but none are likely to produce the required ~2‰ shift in $\delta^{18}O_p$ values away from the expected local values at Portmahomack. It is worth noting that the single named individual in the study, William McKenzie in Period 5, is known to have originated in the west of Scotland and has an oxygen isotope ratio consistent with that which would be expected from the western seaboard (Evans *et al.* 2012). These non-local individuals are discussed further below.

**Discussion**

Although the population sampled from Portmahomack is small, it nonetheless exhibits a wide range in both strontium and oxygen isotope ratios that are not indicative of a wholly sedentary population. Unfortunately, northern Scotland is not currently a well-characterised region for either oxygen or strontium isotopes of ancient humans due to its heterogeneous and ancient geology, the highland regions, and the shortage of excavated human and animal remains. Until these regions are better characterised for both isotope systems in humans it is difficult to identify all possible places of origin within Britain, let alone beyond its shores. However, it is clear that the range of both strontium and oxygen isotopes obtained from Portmahomack represents a variety of origins for the population in the first and second millennium AD, both within and possibly outside Great Britain.

*Period 0 and Period 1*

There are a total of six samples dating from Period 0 (prior to the 6th Century AD) and Period 1 (AD 550-700). The two Period 0 individuals from Balnabruach are within the local range for both strontium and oxygen isotope ratios (i.e. coastal Old Red Sandstone and east coast precipitation). In contrast, the four individuals dating to Period 1 are isotopically varied. A male skeleton (170) falls within the local isotope range for Portmahomack. The female long cist burial (172) falls in the oxygen isotope range for western, or possibly central, Britain. The other two male long cist burials (186 and 187) have high strontium isotope ratios, indicating they are not of local origin and came to Portmahomack from regions of older or granitic rocks, possibly away from the coast and/or in upland regions. The oxygen isotope ratio of 16.1 ‰ for skeleton 186 is very low and outside the range for eastern Britain at the 1 SD level (i.e. 66% probability) as depicted in Figure 3, but would fall within the range at 95% probability. In contrast, such a value would lie outside the range for Britain as a whole at the 95% probability level (Evans *et al.* 2012). It is, therefore, borderline, and this individual cannot be securely identified as of non-British origin.

*Period 2 and Period 3*

The majority of the burials dating to Periods 2 (AD 700-830) and Period 3 (AD 830-1100) consist of younger to older adult males with one female and no juveniles. Of the 13 individuals from Periods 2 and 3, only four males/probable males (54, 127, 136, 144) fall within the local range for Portmahomack. These four individuals were buried according to the predominant tradition: supine, unaccompanied and unmarked. Only one individual (147) from Period 2 or 3 has an oxygen isotope ratio that could be consistent with origins in the west: although measurement error introduces a margin of uncertainty to this conclusion, it is worth noting that this male individual was also unique with regards to burial style being the only wood-wicker matrix burial. There is evidence of migration from western Scotland when Christians are believed to have visited the Northern Isles as early as the 6th Century (James, 1999) and migrations south from these islands, as well as east, may explain this individual. The remaining eight individuals have either strontium isotopes (111, 130, 140, 156, 158), oxygen isotopes (152), or a combination of strontium and oxygen isotopes (129, 153), that place them outside the range estimated for Portmahomack. Individual 156 was buried as a double burial with individual 136, who seems to be of local origin; these two males have the same oxygen isotope ratios but a slightly different strontium isotope ratio. It is possible that they have the same geographical origins and the difference in strontium isotopes arises through a slightly different access to food resources which can result in a range of ratios amongst a population (Montgomery *et al.* 2007). Nonetheless, in sharp contrast to the local individuals, these eight appear to have been buried either shrouded or with a head support. Monasteries would contain both clerics and lay individuals from a variety of places and it is perhaps not unusual or unexpected to find individuals in a monastic cemetery who originated elsewhere; such a finding was made in a recent isotopic study of the clerics buried at Whithorn Priory in Dumfries and Galloway (Müldner *et al.*, 2009).

The first five (111, 130, 140, 156, 158), have oxygen isotopes which could indicate origins in eastern Britain or Ireland rather than their western or southern seaboards. However, of particular note are the three male individuals from Period 2 (129, 152 and 153), whose oxygen isotope ratios of 15.7‰, 16.2‰ and 15.8‰ respectively are exceedingly low for either Great Britain or Ireland. . Whilst statistically, these are not sufficiently low to feature as outliers amongst the Portmahomack population (Figure 2) such values fall outside the 2 SD $\delta^{18}O_p$ range (16.3‰ to 19.1‰) but within the 3 SD range for Britain (15.6‰ – 19.8‰). This gives only a 2.5% probability based on oxygen that these individuals are of British or (by extension as a result of comparable $\delta^{18}O$ precipitation values) Irish origin (Evans *et al.* 2012). Such low oxygen isotope ratios are indicative of origins at higher altitude or in colder, more northerly or more continental regions. Scandinavia, central Europe or mountainous regions of Scotland may thus all be suitable regions of origin. The strontium isotope ratios for 129 and 153 (the sample for 152 failed) would also support origins on old rocks which are found in Scandinavia and the Scottish Highlands. It is worth noting here that individual 152 had three severe, and possibly fatal, blade wounds.

*Period 4 and 5*

The medieval burial assemblage from Period 4 (AD 1100-1600) is very different from that of Periods 2 and 3 and includes males, female, and non-adults ranging in age from approximately six to 46+ years. As was found in Periods 2 and 3, there is considerable variability in strontium isotope ratios amongst this group: they range from 0.7099 to 0.7151 (Figure 1) and in isolation, this may simply reflect the heterogeneous and ancient geology of northeastern Scotland beyond the Tarbat peninsula. However, of the eleven individuals in Period 4, only two adult males (30 and 117) fall within the strontium *and* oxygen isotope range estimated for Portmahomack (Figure 3). One other individual, an older adult female (62) has an oxygen isotope ratio consistent with eastern Scotland but her strontium isotope ratio suggests origins away from the coast on ancient Palaeozoic rocks. The most striking characteristic of the individuals in Period 4 is that, whilst possessing a range of strontium isotopes that suggests they do not share a single common geographic origin, the remaining eight have high oxygen isotopes ratios (i.e. 18.0‰ or above) that are unlikely to be consistent with origins in eastern or central Britain or Ireland. This non-local group is not restricted to male individuals but includes a female (88) and all the juveniles (16, 86, 110, 119) measured in the study (Figure 3). As the first molars measured for these four individuals complete crown formation by the age of five, they must have arrived in Portmahomack during childhood between the ages of five and death at, variously, 6.5 to 14.5 years of age. It is possible therefore that their time at Portmahomack was short as at least two of these children (16 and 86) appear to have died within two years of arriving. In addition, the non-local group includes the three Period 4 individuals in this strontium/oxygen study (Skeletons 16, 35 and 88) who were found to have consumed a diet high in marine protein (Curtis and Montgomery D4.3), one of which is a juvenile (16). The clustering of the strontium, oxygen, carbon and nitrogen isotope data thus suggest a group of immigrant consumers of marine protein, possibly from the western seaboard or Northern Isles, is present in the later medieval period. It is also possible such migrant individuals may be involved in, or connected with, the medieval fishing trade which may underpin the high level of mobility in this population (Barrett *et al.* 2004).

The analysis of human skeletal remains from Portmahomack by King (2000) revealed the general health of people in Period 4 was poor in comparison to contemporaneous sites within the region. They are slightly shorter in stature and this is particularly apparent amongst females. Stress indicators such as linear enamel hypoplasia and cribra orbitalia were recorded and this combination may evidence a population under environmental stress and possible malnutrition (King, 2000) which could have been a migratory push factor if these conditions were indicative of their putative homeland in the west.

Combined strontium and oxygen isotope data is only available for a few geographically and temporally comparable populations: on the east coast of northern Britain from 7th-17th Century Auldhame in East Lothian (Lamb *et al.*, 2012) and Bamburgh in Northumberland (Groves *et al.* 2013); from the 13th-14th Century cemetery at St Thomas' Kirk in Orkney (Toolis, 2008); and burials of various date from the west coast of Britain (Evans *et al.* 2012). As expected, the data from Orkney and the west coast cluster in the range for western Britain and have strontium isotopes dominated by marine strontium ($^{87}Sr/^{86}Sr$ = 0.7092) (Figure 4). The individuals from Auldhame and Bamburgh exhibit wide ranges in oxygen isotopes across the full range for Britain (Auldhame) and beyond (Bamburgh). Several individuals from Auldhame have $^{87}Sr/^{86}Sr$ below 0.7092 which is indicative of the Carboniferous limestone which occurs extensively in southern Scotland, and only one individual has $^{87}Sr/^{86}Sr$ above 0.712 which points to origins on the older and granitic rocks of northern Scotland. Lamb *et al.* (2012) concluded that very little migration to Auldhame was visible in the individuals analysed which contrasts with the situation at Portmahomack where migrants appear to predominate amongst the study sample.

Environmental and dietary stress is unlikely to explain the presence at Portmahomack of the single individual in Period 5 (AD 1600-2000). Burial 017 was buried in a coffin and has been identified as William Mackenzie (Cecily Spall, email communication, 2012). According to Carver (2008), William Mackenzie was a parish minister of Tarbat from AD 1638 until his death in AD 1642. His strontium and oxygen isotope ratios are entirely consistent with origins in the Western Isles (Figure 4). Based on age at death and the first premolar selected for analysis, William Mackenzie travelled to Portmahomack from the western part of Scotland after the minimum age ranges of 4.25-7 years of age.

**Conclusion**

Migration to Portmahomack from various regions within and outside of Great Britain was detected during the monastic phases of Periods 2 and 3 (AD 550-1100) and the medieval Period 4 (AD 1100-1600). However, in Periods 2 and 3 the majority of the migrants appear to be from the eastern part of mainland Great Britain or Ireland and there are suggestions that origins may be linked to burial rite. Two, possibly three, burials within this phase have such low oxygen isotope ratios that there is only a 2.5% probability that they originate from Great Britain and Ireland. Such values would be found at higher altitude, and in colder, more continental or more northerly regions such as Scandinavia or central Europe.

In the medieval Period 4, the majority of individuals investigated appear to originate from the western or southern seaboard of Britain or Ireland, or the Northern Isles. This non-local group includes males, females and juveniles and implies the medieval population at Portmahomack were highly mobile. Given the evidence that they were marine protein consumers and the osteological evidence for nutritional stress, this may be linked to the fishing trade or to migration due to economic factors. The lack of comparative sites in the north-eastern part of Scotland makes it difficult to compare Portmahomack to similarly sited, contemporaneous sites, and further isotopic studies of humans excavated from Scotland are recommended to elucidate and interpret Scotland's past more clearly.

**References**

Anderson, D.L., Thompson, G.W, Popovich, F. 1976. Age of attainment of mineralization stages of the permanent dentition. Journal of Forensic Sciences 21: 191-200.

Barrett, J.H., Locker, A.M., Roberts, C.M. 2004. "Dark Age Economics" revisited: The English fish bone evidence AD 600-1600. Antiquity 18: 618-636.

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

Budd, P., Montgomery, J., Barreiro, B., Thomas, R.G. 2000. Differential diagenesis of strontium in archaeological human dental tissues. Applied Geochemistry 15: 687-694.

Carver, M. 1997. Bulletin of the Tarbat Discovery Programme Number 3. York, United Kingdom: University of York.

Carver, M. 2003. Bulletin of the Tarbat Discovery Programme Number 7. http://www.york.ac.uk/archaeology/staff/sites/tarbat/bulletins/bulletin7/contents.html.

Carver, M. 2008. Portmahomack: Monastery of the Picts. Edinburgh: Edinburgh University Press.

Chenery, C., Müldner, G., Evans, J., Eckardt, H., Lewis, M. 2010. Strontium and stable isotope evidence for diet and mobility in Roman Gloucester, UK. Journal Archaeological Science 37: 150-163.

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

Coplan, T.B. 1988. Normalization of oxygen and hydrogen isotope data. Chemical Geology (Isotope Geoscience Section) 12: 293-297.

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

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

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

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

Evans, J., Stoodley, N., Chenery, C. 2006. A strontium and oxygen isotope assessment of a possible fourth century immigrant population in a Hampshire cemetery, southern England. Journal of Archaeological Science 33: 265-272.

Groves, S.E., Roberts, C.A., Lucy, S., Pearson, G., Gröcke, D.R., Nowell, G., Macpherson, C.G., Young, G. 2013. Mobility histories of 7th-9th century AD people buried at early medieval Bamburgh, Northumberland, England. American Journal of Physical Anthropology 151: 462-476.

Gustafson, G., Koch, G. 1974. Age estimation up to 16 years of age based on dental development. Odontologisk Revy 25: 297-306.

Hoppe, K.A., Koch, P.L., Furutani, T.T. 2003. Assessing the Preservation of Biogenic Strontium in Fossil Bones and Tooth Enamel. International Journal of Osteoarchaeology 13: 20-28.

James, H.G. 1999. Excavation of a medieval cemetery at Skaill House, and a cist in the Bay of Skaill, Sandwick, Orkney. Proceedings of the Society of Antiquaries of Scotland 129: 753-777.

King, S. 2000. Part 2: The Human Remains from Tarbat Old Church, Portmahomack: The Specialist Report. In Bulletin of the Tarbat Discovery Programme Number 6, Carver M (Ed). (http://www.york.ac.uk/depts/arch/staff/sites/tarbat) 86 pages.

Lamb, A.L., Melikian, M., Ives, R., Evans, J. 2012. Multi-isotope analysis of the population of the lost medieval village of Auldhame, East Lothian, Scotland. Journal of Analytical Atomic Spectrometry 27: 765-777.

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

Lorimer, D.H. 1995. Report on the human bones found at the Portmahomack Drainage Site, Archaeological Section, Highland Region. http://www.tarbatdiscovery.co.uk/Balnabruach%20Man/Report%20on%20the%20human%20bones%20found%20at%20the%20Portmahomack%20Drainage%20Site.pdf.

Montgomery, J. 2002, Lead and strontium isotope compositions of human dental tissues as an indicator of ancient exposure and population dynamics, Unpublished PhD Thesis, Department of Archaeological Sciences, University of Bradford, UK.

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

Montgomery, J., Evans, J.A., Neighbour, T. 2003. Sr isotope evidence for population movement within the Hebridean Norse community of NW Scotland. Journal of the Geological Society 160: 649-653.

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

Pollard, A.M., Pellegrini, M., Lee-Thorp, J.A. 2011. Technical note: Some observations on the conversion of dental enamel $\delta^{18}O_p$ values to $\delta^{18}O_w$ to determine human mobility. American Journal of Physical Anthropology 145: 499-504.

Price, T.D., Knipper, C., Grupe, G., Smrcka, V. 2004. Strontium isotopes and prehistoric human migration: the Bell Beaker Period in central Europe. European Journal of Archaeology 7: 9-40.

Toolis, R. 2008. Excavation of medieval graves at St Thomas' Kirk, Hall of Rendall, Orkney. Proceedings of the Society of Antiquaries of Scotland 138: 239-266.

Walther, L. 2012 Strontium and Oxygen Isotope Analysis of Burials Recovered from an Early Christian site at the Tarbat Old Church in Portmahomack, Scotland. Unpublished MSc thesis, Department of Archaeology, Durham University, UK.