

Spatial Approaches to Assignment

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Spatial Approaches to Assignment

This chapter introduces the spatial approaches which are used to determine the likely geographic origins of humans and animals and which in turn are used to understand mobility and migration. Two approaches are outlined – the first based on the calculation of residuals, and the second based on Bayesian statistics and maximum likelihood estimation. Both approaches compare the observed isotope measurement for an archaeological sample to the expected isotope measurement from baseline data for the area of interest. These approaches are applied to case studies from Annaghmare in Northern Ireland and Duggleby Howe on the Yorkshire Wolds. The case studies highlight the uncertainty implicit within the process of assigning an individual to a geographic region and the importance of using baseline data which adequately accounts for all of the factors that influence the spatial variation of the measured isotope tracer.

Keywords: Isotope tracers, Mobility, Migration, Residuals, Bayesian statistics

Introduction

Two deceptively simple questions are pivotal to definitions of geographic information and, by extension, spatial analysis – what? and where? (Goodchild, 2003). This chapter addresses the second of these questions, focusing on spatial approaches to assignment that can be used to ascertain the likelihood of an archaeological sample originating from a particular geographic region. These approaches are explored with reference to evidence for mobility and migration that can be inferred from isotope tracers from cremated bone and tooth enamel. Questions of geographic origins, however, are equally important with regard to evidence for trade and exchange that can be inferred from the biological or chemical signatures of raw materials. Geochemical analysis of the worked flint from the Gravettian sites at Rhens and Koblenz-Metternich, Germany for example, has identified the use of flint from western Belgium c. 260km away (Moreau et al., 2016). Conversely, wood species identification and strontium isotope analysis has suggested that the wooden artefacts analysed from Pitch Lake, Trinidad were predominantly manufactured from locally sourced materials (Ostapkowicz et al., 2017). In both instances, the distances that raw materials were transported is critical to the understanding of trade and exchange. A degree of caution, however, should be exercised when identifying possible sources of raw material. In the case of Bronze Age copper metals, theoretical frameworks that move

beyond the concept of provenance have been developed that recognise that metal chemistry is the product of a longer life-history of a unit of metal which may reflect re-use and recycling as well as the original source of the ore (Bray et al., 2015; Pollard, 2018). These theoretical frameworks highlight the need to understand the complex range of processes that can contribute to variation in the measurements that are commonly used to determine the possible geographic origins of archaeological samples. The spatial approaches to assignment described below are widely used in bioarchaeology but are equally applicable to other areas of archaeology.

Isotope tracers are used to make inferences about mobility and migration, comparing observed isotope ratios or values for archaeological samples to baseline data to determine whether an individual is local or non-local to a geographic region (e.g. Bentley & Knipper, 2005; Montgomery, Budd, & Evans, 2000; Price, Burton, & Bentley, 2002). For the purposes of determining geographic origins of humans and animals in archaeology, strontium and oxygen isotopes are the most commonly used, with multiple isotope tracers used to narrow down the range of possible locations from where an individual could have originated (Emery, Prowse, Elford, Schwarcz, & Brickley, 2017; Evans, Chenery, & Fitzpatrick, 2006; Laffoon et al., 2017). Traditional approaches to identifying locals and non-locals based on the identification of outliers or extreme values using parametric and non-parametric statistics (Lightfoot & O'Connell, 2016; Wright, 2005) are increasingly being supplemented by spatial approaches based on geographic assignment using isoscapes and Bayesian statistics (Pellegrini, Pouncett, Jay, Parker-Pearson, & Richards, 2016; Schulting et al., 2019; Snoeck et al., 2018; Snoeck, Pouncett, et al., 2016). The key principles underpinning these spatial approaches to determining the geographic origins of individuals are outlined below with reference to case studies from Annaghmare in Northern Ireland and Duggleby Howe on the Yorkshire Wolds.

Strontium

Strontium is an alkaline earth metal with four naturally occurring isotopes (^{84}Sr , ^{86}Sr , ^{87}Sr and ^{88}Sr) which are formed during primordial nucleogenesis. ^{87}Sr is radiogenic and is formed as a result of the decay of the radioactive alkaline metal rubidium (^{87}Rb). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for bedrock and surface geology are related to both the mineral composition and the age of the geological formation (Faure, 1986). Strontium derived from the weathering of a geological formation will have the same $^{87}\text{Sr}/^{86}\text{Sr}$ ratio as the

parent geology. Consequently, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of soil are related to the geological formations from which they are derived. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for rainwater is related to the mineral composition of the water vapour (evaporated sea- or freshwater) and aerosolised particles in the atmosphere (e.g. Saharan dust) which act as condensation nuclei for excess water vapour. In coastal regions, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of rainfall is equivalent to that of seawater (Hodell, Mueller, McKenzie, & Mead, 1989). Strontium from soil, groundwater and rainwater is absorbed into plants and once it enters the food chain becomes incorporated into the tissues of humans and animals (Capo, Stewart, & Chadwick, 1998).

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel (Montgomery, Evans, & Cooper, 2007; Neil, Evans, Montgomery, & Scarre, 2018) and cremated bone (Snoeck et al., 2018; Snoeck, Pouncett, et al., 2016) reflect the food/drink consumed by an individual and, assuming that the food/drink is locally sourced, can be used to infer the geographic locations where an individual spent specific times of their lives. The time of life for which these inferences can be made is dependent on the tissue (bone, dentine or enamel) analysed which is in turn dependent on the mode of burial. In the case of inhumations, the crystalline structure of tooth enamel preserves the original *in vivo* $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, while bone is often susceptible to diagenesis and through the exchange of calcium for strontium equilibrates with the value of the soil in which it is buried (Budd, Montgomery, Barreiro, & Thomas, 2000; Hoppe, Koch, & Furutani, 2003). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of tooth enamel represent an average of the food/drink consumed during crown formation and depending on the tooth sampled can indicate where an individual spent different stages of their childhood. In the case of cremations, high temperatures cause spalling and loss of tooth enamel, while at the same time resulting in the crystallisation of bone making it resistant to diagenesis such that fully calcined bone retains its original *in vivo* $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Snoeck et al., 2015). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of cremated bone represent an average of the food/drink consumed over the decade or so before death and can indicate where an adult spent the last c.10 years of their life. The time of life represented for non-adults will be shorter given that it reflects the growth stage of the skeleton.

Oxygen

Oxygen is a non-metal with three naturally occurring stable isotopes, a primary isotope (^{16}O) formed during primordial nucleogenesis and two secondary isotopes (^{17}O and ^{18}O) formed during the carbon-nitrogen-oxygen cycle. Spatial and temporal variation in ^{18}O

of rainwater occurs as a result of Rayleigh fractionation or distillation, i.e. the preferential condensation of water with ^{18}O in air masses, depleting the ^{18}O relative to the ^{16}O in the vapour phase (Sharp, 2007). The $\delta^{18}\text{O}$ value of rainwater is dependent on a wide range of variables including latitude, temperature, elevation, amount of rainfall, and distance to surface water (Bowen & Wilkinson, 2002). The $\delta^{18}\text{O}$ value of groundwater is related to that of the local rainfall but may vary due to evaporation of surface water, fractionation within aquifers, and recharge from rivers with water from higher elevations (Gat, 1971). Drinking water and water from food are typically derived from a combination of local groundwater and local rainwater. The $\delta^{18}\text{O}$ values of food/drink consequently will approximate that of these sources. Oxygen from food/drink is incorporated into body water and is in turn incorporated the tissues of humans and animals.

A linear relationship has been demonstrated between the $\delta^{18}\text{O}$ values of phosphate from the bioapatite fraction of teeth and bones ($\delta^{18}\text{O}_\text{p}$) and the mean annual $\delta^{18}\text{O}$ values of rainwater ($\delta^{18}\text{O}_\text{w}$) from the region where an individual lived (Longinelli, 1984; Luz, Kolodny, & Horowitz, 1984). $\delta^{18}\text{O}_\text{p}$ values from tooth enamel represent an average of the food/drink consumed during crown formation and depending on the tooth sampled can be used to infer the regions where an individual spent different stages of their childhood (Evans et al., 2006). A number of issues have been raised regarding the utility of oxygen as an isotope tracer (Lightfoot & O'Connell, 2016; Pouncett, 2019). This is because $\delta^{18}\text{O}$ values may be affected by a number of factors, including: variation in ^{18}O due to changes in climate conditions (Daux et al., 2008); fractionation of ^{18}O as a result of the preparation of food/drink (Brettell, Montgomery, & Evans, 2012); physiological variation between individuals (White, Spence, Longstaffe, & Law, 2004); and enrichment of ^{18}O due to weaning and/or the consumption of milk (Lin, Rau, Chen, Chou, & Fu, 2003). Unlike strontium, oxygen cannot be used to infer the geographic origins of individuals who were cremated, since cremation alters the $\delta^{18}\text{O}$ values of bone and teeth, reflecting pyre characteristics such as temperature and ventilation rather than diet and mobility (Snoeck, Schulting, Lee-Thorp, Lebon, & Zazzo, 2016).

Local or Non-Local?

The geographic origins of an individual can be inferred by comparing observed values of one or more isotope ratios to the expected values from baseline data for the area of interest

– typically biologically available strontium (BASr) from modern plants or animals in the case of strontium, and modern groundwater or rainwater in the case of oxygen. If the isotope ratio from an archaeological sample has a value that is similar to that for the baseline data for a given geographic region the individual could have been local to that region, i.e. spent part of their childhood (tooth enamel) or the last decade or so of their adult life (cremated bone) there. Conversely, if the isotope ratio from an archaeological sample has a value that differs from that for the baseline data for a given geographic region the individual is unlikely to have been local to that region, i.e. did not spend part of their childhood (tooth enamel) or the last decade or so of their life (cremated bone) there. The ability to identify whether an individual is local or non-local to a geographic location is dependent upon a number of factors, most significantly in this context: analytical errors associated with the isotope ratios for the archaeological samples; sampling errors associated with the generation of the isotopic baseline data; equifinality with the same values of isotope ratios found in multiple geographic regions; and the scale of analysis/spatial extent of the ‘local’ signal. The uncertainty introduced as result of these factors is integral to the methods of geographic assignment described below and applied to the case studies for this chapter.

Methodology

Two principal methods have been used to determine the geographic origins of humans and animals. The first method, based on the calculation of residuals between the expected isotope measurement from the baseline data for the area of interest and the observed isotope measurement for an archaeological sample, is applied to a case study from Annaghmare in Northern Ireland using a single isotope tracer. The second method, based on the use of Bayesian statistics to determine the likelihood that an individual came from a particular location given the observed isotope measurement, is applied to a case study from Duggleby Howe on the Yorkshire Wolds using two isotope tracers.

Calculation of Residuals

The simplest method of determining the geographic origins of humans and animals is to calculate the residuals between the expected isotope measurement for a location and the observed measurement for an individual (Pellegrini et al., 2016; Snoeck et al., 2018):

$$e_i = \delta_{s,i} - \delta_s \quad (1)$$

Where:

e_i = the residual between the expected and observed isotope measurements.

$\delta_{s,i}$ = the expected isotope measurement for location i .

δ_s = the observed isotope measurement for the individual.

The expected isotope measurement for a location can be estimated from the baseline data for the area of interest. A threshold can be applied to the residuals to identify locations from which an individual could have originated (cf. Laffoon et al., 2017). Typically, the threshold used to identify the locations from which an individual could have originated will be based on the sum of the sampling error for the baseline data and the analytical error for the measured isotope. For example, in the case of the fragments of cremated bone analysed from Aubrey Hole 7 at Stonehenge, Wiltshire locations with residuals less than ± 0.0005 (equivalent to the sum of the sampling error for the BASr baseline and the analytical error for the strontium measurements) were identified as possible geographic origins for the cremated individuals (Snoeck et al., 2018).

Bayesian Statistics

Bayesian statistics have been widely employed by biologists and archaeologists for the purposes of determining the geographic origins of humans and animals (Bowen, Liu, Vander Zanden, Zhao, & Takahashi, 2014; Laffoon et al., 2017; Wunder, Kester, Knopf, & Rye, 2005). The likelihood that an individual came from a particular location given the observed isotope measurement can be calculated using Bayes' theorem which can be expressed as:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum P(B|A_i)P(A_i)} \quad (2)$$

Where:

$P(A_i|B)$ = the **posterior probability distribution** of individual A originating from location i , given observed isotope measurement B .

$P(B|A_i)$ = the **sampling probability distribution** of observing isotope measurement B , given all locations i from which individual A could have originated.

$P(A_i)$ = the **prior probability distribution** of individual A originating from location i , given assumptions or knowledge prior to observing isotope measurement B .

If there are no prior assumptions or knowledge of the likely geographic origin of an individual, it is assumed that all locations are equally possible and a **non-informative prior** is used as the prior probability distribution – typically, this will be a **uniform distribution** (a,b) with probability density function:

$$f(x) = \frac{1}{b-a} \quad (3)$$

Where:

a = the minimum isotope measurement for all locations i .

b = the maximum isotope measurement for all locations i .

If there are prior assumptions or knowledge of the likely origin of an individual, the probability density function which best describes the prior assumptions or knowledge should be used as the prior probability distribution. For example, in a test of geographic assignment of mountain plover chicks (*Charadrius montanus*) using isotope tracers in feathers, it was assumed that the chick feathers were exclusively of known geographic origin and the sample sizes per location were used to estimate the prior probability density (Wunder et al., 2005).

It is generally assumed that the observed isotope measurement for a sample is an outcome of a random process and that the sampling probability distribution can consequently be estimated using the probability density function for a **normal distribution** (μ, σ) with location μ and scale σ .

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \quad (4)$$

The parameters of the normal distribution are commonly estimated using the observed isotope value or ratio for the individual, the total of the sampling error for location i and the analytical error for the observed isotope measurement:

$$\mu = \delta_s \quad (5)$$

$$\sigma = \sigma_{s,i} + \sigma_\epsilon \quad (6)$$

Where:

δ_s = the observed isotope measurement for the individual.

$\sigma_{s,i}$ = the sampling error for location i estimated from the baseline data.

σ_ε = the analytical error for the observed isotope measurement.

If a uniform distribution is used as a non-informative prior and a normal distribution is used as the sampling probability function, equation 2 can be rewritten as:

$$P(A_i|\delta_s) = \frac{\left(\frac{1}{(\sigma_{s,i}+\sigma_\varepsilon)\sqrt{2\pi}}e^{-(\delta_{s,i}-\delta_s)^2/2(\sigma_{s,i}^2+\sigma_\varepsilon^2)}\right)\left(\frac{1}{\delta_{s,i_{max}}-\delta_{s,i_{min}}}\right)}{\sum_1^i\left(\frac{1}{(\sigma_{s,i}+\sigma_\varepsilon)\sqrt{2\pi}}e^{-(\delta_{s,i}-\delta_s)^2/2(\sigma_{s,i}^2+\sigma_\varepsilon^2)}\right)\left(\frac{1}{\delta_{s,i_{max}}-\delta_{s,i_{min}}}\right)} \quad (7)$$

Which can be simplified to:

$$P(A_i|\delta_s) = \frac{\frac{1}{(\sigma_{s,i}+\sigma_\varepsilon)\sqrt{2\pi}}e^{-(\delta_{s,i}-\delta_s)^2/2(\sigma_{s,i}^2+\sigma_\varepsilon^2)}}{\sum_1^i\frac{1}{(\sigma_{s,i}+\sigma_\varepsilon)\sqrt{2\pi}}e^{-(\delta_{s,i}-\delta_s)^2/2(\sigma_{s,i}^2+\sigma_\varepsilon^2)}} \quad (8)$$

The posterior probability distributions are commonly rescaled by the largest observed density, with the resultant probability densities ranging between 0 and 1 (cf. Wunder, 2010). Where multiple isotope tracers are used to determine the geographic origin of an individual, Bayes' theorem can be applied iteratively with the posterior probability density from the iteration for one isotope tracer used as the prior probability density for the iteration for the next isotope tracer.

Maximum likelihood estimation is commonly used to determine the geographic origin of an individual, with the individual assigned to the location with the highest probability density. Ultimately, the validity of this assignment is dependent on the robustness of the baseline data used to determine the geographic origin of an individual. If the baseline does not adequately account for all of the factors that influence spatial variation in the ratios or values of the isotope tracer within the area of interest (see above), the location to which an individual is assigned may not be valid and the process by which it was derived will not be robust.

Case Study 1: Annaghmare, Northern Ireland

The Neolithic court tomb at Annaghmare, known locally as *The Black Castle*, is located

c.1km to the north of Crossmaglen in Co. Armagh, close to the Republic of Ireland border. The tomb, excavated between 1963 and 1964, is comprised of a trapezoidal cairn with an open forecourt, burial gallery and two lateral chambers (Waterman & Morton, 1965). It is defined by orthostatic and dry-stone walls constructed from local Silurian rocks. The burial gallery has three chambers (Chambers 1 to 3). Fragments of cremated bone were present in all three chambers. A child mandible and an adult femur, both of which were unburnt, were also found in Chamber 2. The mortuary deposits from Annaghmare can be dated to the second half of the 4th millennium BC (Schulting, Murphy, Jones, & Warren, 2012; Snoeck, Pouncett, et al., 2016), with the unburnt child mandible from Chamber 2 dated to 3485-3105 cal. BC (UB-6741: 4556 ± 35 BP) and cremated cranial fragment A2 dated to 3370-3116 cal. BC (OxA-32110: 4572 ± 28 BP; OxA-30188: 4532 ± 36 BP). These dates agree with a date that had previously been obtained for a charcoal sample sealed by the primary blocking of the forecourt, which was dated to 3330-2900 cal. BC (UB-241: 4935 ± 55 BP) (Smith, Pilcher, & Pearson, 1971).

⁸⁷Sr/⁸⁶Sr ratios have been obtained for two of the fragments of cremated bone (A1: 0.71055 ± 0.00001; A2: 0.70900 ± 0.00001) from Annaghmare (Snoeck, Pouncett, et al., 2016). The magnitude of the difference between the ⁸⁷Sr/⁸⁶Sr ratios (0.00155) is larger than the variation between duplicate samples from the same individual (maximum 0.000160) from Bronze Age urns in Northern Ireland (Snoeck, Pouncett, et al., 2016), suggesting that the two fragments of cremated bone come from different individuals. Comparison of the observed isotope ratios for the two individuals to baseline data from modern plants suggests that while Individual A1 could have been spent the last decade or so of their life in the immediate vicinity of the site, Individual A2 could not. If Individual A2 did not spend the last decade or so of their life in the immediate vicinity of the site, this raises the obvious question - where did they come from?

A BASr baseline suitable for geographic assignment at a national or regional scale has recently been produced for Ireland (Snoeck et al., 2019). This baseline is based on published ⁸⁷Sr/⁸⁶Sr measurements for modern plants (Ryan, Snoeck, Crowley, & Babechuk, 2018; Snoeck, Pouncett, et al., 2016; Snoeck et al., 2019; Wilson & Standish, 2016) and Geological Survey of Ireland (GSI) Bedrock Geology 500k Series data (<https://data.gov.ie/dataset/gsi-bedrock-geology-500k-series>). Strontium isotope ratios for the plant samples were aggregated in order of preference by outcrop (single part polygons for individual outcrops of bedrock), formation (multi-part polygons for each

geological formation) and type/age (multi-part polygons for formations of similar type/age), with a range of descriptive statistics calculated for the polygons corresponding to each outcrop/formation. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the modern plants are not normally distributed (Shapiro-Wilk test: $W=0.949$, $df=228$, $p=0.000$) and the median and median absolute deviation (MAD) are consequently used to describe the spatial variation in biologically available strontium rather than the mean and standard deviation.

<FIGURE 1 HERE>

The expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the outcrops of Silurian sandstone, greywacke and shale (Formation 49, Snoeck, Pouncett, et al., 2016) in the immediate vicinity (<5km) of Annaghmare based on the BASr baseline for Ireland is 0.71081 ± 0.00049^1 (Figure 1). The observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Individual A2 falls more than 3 MAD below the median for the Silurian sandstone, greywacke and shale (Figure 2), consistent with the interpretation of this individual as a non-local. Marked variation, however, can be seen in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the modern plants from the Silurian sandstone, greywacke and shale ($n=24$). Six of the plant samples have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios which fall more than 3 MAD below the median for the formation, including two plant samples from the deposits of till overlaying the formation in County Kildare to the south of Annaghmare, and two plant samples from the gravel deposits overlying the formation in County Cavan to the west of Annaghmare. In theory, the low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for these plant samples raise the possibility that Individual 2 could have originated from areas to the south and west of Annaghmare where the Silurian sandstone, greywacke and shale are locally overlain by drift deposits. In practice, these plant samples are outliers – the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from cremated bone represents an average all of the foods consumed by an individual over c.10 years and given the localised nature of the till and gravel Individual A2 is unlikely to have only eaten foods corresponding to these outliers (Warham, 2011).

<FIGURE 2 HERE>

Point-based comparisons between observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for archaeological samples and expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratios based on baseline data from modern plants are problematic for several reasons: they fail to account for imprecision in the coordinates for the sites from

¹ The expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is quoted as the median \pm median absolute deviation for the geological formation.

which samples were taken – a particular problem with legacy samples from nineteenth century excavations; they do not account for localised differences in surface geology; and past populations would not have obtained their food from a single source. These problems can in part be addressed by calculating BASr catchments, with focal medians calculated based on the expected values of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for all of the BASr comparanda within a specified distance of a site (cf. Snoeck, Pouncett, et al., 2016). The size of the BASr catchment should be appropriate to the scale of analysis and the distance from which food would have been sourced, with catchments <5km representing locally sourced food, catchments <20km representing food sourced from the wider region and catchments >20km representing food sourced from further afield based on analysis of comparable Neolithic and Bronze Age sites in Ireland. In contrast to point-based comparisons which will only reflect the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of food sourced from a single geological formation, comparisons based on BASr catchments will also reflect the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of food sourced from multiple geological formations depending upon the spatial extent of the geological formations and the size of the BASr catchments.

<FIGURE 3 HERE>

The BASr baseline for Ireland was converted to a raster dataset with a cell size of 100m to preserve localised outcrops of bedrock and focal medians, representing the expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for 5km BASr catchments, were calculated for each cell in the raster dataset (Figure 3, left). Residuals between the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Individual A2 and the expected values of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the 5km BASr catchments were subsequently calculated (Figure 3, right). The residuals were symbolised using graduated colours with defined values based on the sum of the sampling error for the baseline data – defined as the median absolute deviation for the geological formation - and the analytical error for the observed isotope ratio for Individual A2. Residuals with a magnitude less than the sum of the sampling error and the analytical error, represent possible locations from which Individual A2 could have originated, i.e. spent the last decade or so of their lives. The possible locations from which Individual A2 could have originated are largely confined to the area to the south of Annaghmare, including the Boyne Valley, and the area to the west of Annaghmare. These areas mirror the spatial distribution of passage tombs – in contrast, the distribution of court tombs is confined to the northern third of Ireland (Darvill, 1979). The radiocarbon dates from Annaghmare fall within a similar time-frame to the megalithic tombs at Ballynahatty 1855 and Millin

Bay in County Down, both of which have an affinity with the developed passage tomb tradition of the late fourth millennium BC (Schulting et al., 2012).

Case Study 2: Duggleby Howe, Yorkshire Wolds

The Neolithic round barrow at Duggleby Howe is located c.300m to the south-east of the village of Duggleby at the head of the Great Wold Valley and lies at the centre of a circular enclosure that was constructed during the Late Neolithic or Early Bronze Age, close to the head of the Great Wold Valley (Gibson et al., 2011; Gibson & Bayliss, 2009; Riley, 1980). It was partially excavated during the late eighteenth century by the Reverend Christopher Sykes and was re-opened by John Robert Mortimer in July and August 1890 (Cole, 1901; Mortimer, 1892, 1893, 1905). The structural sequence at Duggleby Howe is complex, with five phases of construction proposed (Pouncett, 2019) on the basis of recent radiocarbon dates (Gibson et al., 2011; Gibson & Bayliss, 2009):

- Phase 1 (Early Neolithic) – the earliest phase of the monument was characterised by a shaft grave (Grave B), marked by an up-cast mound of chalk;
- Phase 2 (Middle Neolithic) – two burials on the old land surface and a burial in a shallow grave (Grave A) were added respecting the position of the shaft grave;
- Phase 3 (Late Neolithic) – an interim mound was constructed, and a series of burials and cremations were inserted into the mound;
- Phase 4 (Chalcolithic) – a circular enclosure, defined by a causewayed ditch c.350m in diameter, was built around the interim mound;
- Phase 5 (Early Bronze Age) – the interim mound was enlarged substantially with the construction of a chalk outer mound over 22 feet in height.

Thirteen inhumations and fifty-three cremations, spanning a period of more than 1,000 years from the middle of the fourth millennium BC to the late third millennium BC, were found within or beneath the inner mound. This sequence of burials represents the full spectrum of Middle and Late Neolithic funerary practices and is considered pivotal in understanding the transition between inhumation and cremation as the dominant funerary rite during the Neolithic (Loveday, 2002). Prestige goods, including a polished flint adze, a polished discoidal knife, a perforated antler mace head and a series of boar's tusk blades,

were found with inhumations from the shaft grave and the old land surface. Duggleby Howe was a lynch-pin in the framework established for the classification and dating of Neolithic round barrows and ring ditches (Kinnes, 1979).

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}_\text{p}$ values have been obtained for tooth enamel from seven of the burials from Duggleby Howe, including the inhumation that was buried at the base of the shaft grave (Burial K: $^{87}\text{Sr}/^{86}\text{Sr} = 0.70859$; $\delta^{18}\text{O}_\text{p} = 18.9 \text{ ‰}$) associated with the earliest phase of the monument (Evans, Chenery, & Montgomery, 2012; Montgomery, Cooper, & Evans, 2007; Montgomery, Evans, et al., 2007). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}_\text{p}$ values have been used to suggest that none of the individuals from Duggleby Howe spent their childhood on the chalk of the Yorkshire Wolds and that Burial K could have come from as far away as Western Scotland or Cornwall –assertions which have been woven into narratives about mobility during the Neolithic and Early Bronze Age (Gibson, 2016; Hutton, 2014; Loveday, 2016). These assertions have been accepted at face value for several reasons: 1) they fit with current models of settlement practice which regard the uplands of the Yorkshire Wolds as a place where people buried their dead and the lower-lying areas to the south and east as the epicentre of Neolithic settlement (Carver, 2012; Harding, 2006; Manby, 1988); 2) they explain the prestige goods found with several of the burials, including the polished flint adze and discoidal knife thought to have been manufactured in the specialist workshops at North Dale and South Landing (Durden, 1995; Loveday, 2011; Pierpoint, 1980); 3) they fit with narratives about mobility which prioritise the exotic over the mundane, with the possible origins of the Amesbury Archer in the Austrian Alps (Evans et al., 2006) more captivating than an ‘everyday tale of country folk’ in Wiltshire. Although the individuals buried at Duggleby Howe might not have spent their childhood on the chalk of the Yorkshire Wolds, this does not necessarily mean that they were not locals.

The geographic origins of Burial K from Duggleby Howe are re-evaluated below using Bayesian statistics and maximum likelihood estimated, by calculating probability density surfaces for the burials and assigning each burial to the geographic region with the highest probability density. In contrast to the Annaghmare case study that was reliant upon a single isotope tracer, two isotope tracers can be used to determine locations from which Burial K could have originated. Two baselines were consequently used for the purposes of the geographic assignment of Burial K (Figure 4): 1) a BASr baseline for mainland

Britain, based on published $^{87}\text{Sr}/^{86}\text{Sr}$ measurements (Chenery, Müldner, Evans, Eckardt, & Lewis, 2010; Evans, Montgomery, Wildman, & Boulton, 2010; Schulting et al., 2019; Snoeck et al., 2018) and British Geological Survey DiGMapGB-625 bedrock geology data (https://www.bgs.ac.uk/products/digitalmaps/digmapgb_625.html); and 2) a $\delta^{18}\text{O}$ baseline for mainland Britain, based on modern groundwater values (Darling, Bath, & Talbot, 2003) converted to phosphate values using the equation $\delta^{18}\text{O}_p = 0.501 \delta^{18}\text{O}_w + 20.71$ published by Daux et al. (2008). Both of these baselines are suitable for geographic assignment at a national or regional scale. The expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the Cretaceous chalk of the Yorkshire Wolds from the BASr baseline is 0.708175 ± 0.000359 and the expected $\delta^{18}\text{O}_p$ for the Yorkshire Wolds from the converted modern $\delta^{18}\text{O}_w$ values is $16.7 \pm 0.3\text{‰}$. No baseline is without limitations and the drawback of the baselines currently available for mainland Britain is that they are based on bedrock geology and modern groundwater and do not directly take into account the other factors which might influence spatial variation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios or $\delta^{18}\text{O}$ values highlighted in the introduction to this chapter.

<FIGURE 4 HERE>

Building on the approach used for the Annaghmare case study, the BASr and $\delta^{18}\text{O}_p$ baselines were converted into raster datasets with a cell size of 100m, and focal means were calculated to represent 5km BASr and $\delta^{18}\text{O}$ catchments for every cell in the resultant raster datasets. Probability density surfaces were calculated from the focal means using Bayes' theorem, with the prior probability distribution defined using either the probability density function for a continuous distribution as a non-informative prior (single) or using the posterior density distribution for strontium (dual), and the sampling probability distribution defined using the probability density function for a normal distribution with location μ and scale σ . Parameters for the normal distribution for each of the isotope tracers were estimated using the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and $\delta^{18}\text{O}_p$ value for the burial and the standard deviation of the expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and the converted modern $\delta^{18}\text{O}_w$ value for the Cretaceous chalk respectively, and the resultant posterior probability densities were rescaled by the largest observed density with values ranging between 0 and 1. A Euclidean distance surface with a cell size of 100m was calculated for Duggleby Howe. Zonal statistics were then calculated from the probability density and Euclidean distance surfaces using geographic regions based on National Character Areas

(<https://naturalengland-defra.opendata.arcgis.com/datasets/national-character-areas-england>), National Landscape Character Areas (<https://landmap-maps.naturalresources.wales>) and Landscapes of Scotland (<https://gateway.snh.gov.uk/natural-spaces/>). Geographic assignments were determined for Burial K based on the zonal statistics, with the regions ranked by highest probability density and lowest Euclidean distance (Figure 5).

<FIGURE 5 HERE>

The geographic assignments for Burial K based on Bayesian statistics and maximum likelihood estimation paint a different picture to the previous analysis (Montgomery, Evans et al., 2007; Montgomery, Cooper et al., 2007; Evans et al., 2012; Montgomery & Jay 2013). Where a single isotope tracer is used, the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Burial K suggests that the individual spent their childhood in Eastern Britain with the closest match on the Yorkshire Wolds while the observed $\delta^{18}\text{O}_\text{p}$ value suggests that the individual spent their childhood in Western Britain with the closest match on Barra and Uist, Outer Hebrides (Table 1). The geographic assignment based on the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Burial K reflects averaging of the expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Cretaceous Chalk of the Yorkshire Wolds, and the Jurassic Clay of the Howardian Hills and the Triassic Rocks of the Humberhead Levels, the Vale of Pickering and the Vale of York adjacent to the Yorkshire Wolds. In contrast to point-based comparisons, comparisons based on catchments take into account the possibility of locally obtaining food/drink from more than one source (cf. Montgomery, 2010). Where multiple isotope tracers are used, the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and $\delta^{18}\text{O}_\text{p}$ value for Burial K suggest that the individual spent their childhood in Western Britain with the closest match on The Lizard Peninsula, Cornwall. Links with Western Scotland and Cornwall cannot be evidenced on the basis of the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the burial and are instead based on the observed $\delta^{18}\text{O}_\text{p}$ value for the burial. This discrepancy is repeated for the other burials from Duggleby Howe (Pouncett, 2019).

<TABLE 1 HERE>

Whilst $\delta^{18}\text{O}$ values are commonly used to narrow the range of possible locations based on $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in multi-isotope tracer approaches, the interpretation of Burial K from Duggleby Howe is disproportionately skewed by the $\delta^{18}\text{O}$ value – to the point where the

geographic assignments are effectively based on a single tracer isotope, with the local origins supported by the strontium isotope measurement overridden by the distant origins supported by the oxygen isotope measurement. This analysis raises significant questions about the utility of oxygen as a tracer isotope and the modern groundwater values that are used as a baseline for the study of mobility and migration in mainland Britain. Analysis of the oxygen isotope ratios carried out as part of the Beaker People Project has shown that burials from several of the burial mounds from Eastern Yorkshire, including Garton Slack 37 on the Yorkshire Wolds, exhibit more than half of the national variation (Pellegrini et al., 2016). This degree of variation is perhaps not surprising given that $\delta^{18}\text{O}_p$ values from tooth enamel can be affected by a wide range of factors, including short-term climate conditions, sourcing waters from reservoirs, preparation of food and drink, analytical errors and physiological differences between individuals. The uncertainty introduced by this variability is compounded by the process of converting from $\delta^{18}\text{O}$ values from modern water to $\delta^{18}\text{O}$ values for tooth enamel which is known to be problematic (Pollard, Pellegrini, & Lee-Thorp, 2011). Different formula for converting between $\delta^{18}\text{O}$ values for modern groundwater and $\delta^{18}\text{O}$ values for tooth enamel (Chenery, Pashley, Lamb, Sloane, & Evans, 2012; Daux et al., 2008; Longinelli, 1984; Luz et al., 1984; Pollard et al., 2011) would potentially result in an individual being assigned to geographic regions.

Conclusion

The case studies used to illustrate the spatial approaches to assignment which are commonly used to determine the possible geographic origins of humans and animals highlight two key points. First, the analysis of the individuals from Annaghmare and Duggleby Howe highlights the ambiguity in the possible geographic regions from which the individuals originated. Where a single isotope tracer is used more than one geographic region may have the same isotope measurement as the individual, and where multiple isotope tracers are used each isotope may suggest that the individual originated from a different geographic region. Secondly, the analysis of the individuals from Annaghmare and Duggleby Howe highlights the importance of the baseline data that are used for the purposes of geographic assignment. If the baseline data do not adequately account for key factors that influence variation in the isotope tracer measurements, the resultant geographic assignments will not be reliable.

At Annaghmare, the residuals calculated between the expected $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for 5km BASr catchments and the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from cremated bone suggested that Individual A2 was non-local and could have spent the last decade or so of their life in central or western Ireland. The baseline data for Ireland is based solely on bedrock geology and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios comparable to the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for Individual A2 can be found in the superficial deposits which locally overlay the geological formation on which the court tomb is located but are not reflected in the plant samples taken from the immediate vicinity of the tomb (Snoeck, Pouncett, et al., 2016). At Duggleby Howe, Bayesian statistics and maximum likelihood estimation highlighted a discrepancy between the geographic regions from which Burial K could have originated based on the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and $\delta^{18}\text{O}$ value. The geographic assignment based solely on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio suggested that the individual was local and could have spent part of their childhood on the Yorkshire Wolds or adjacent regions, while the geographic assignments based on the $\delta^{18}\text{O}_p$ value (either as a single isotope tracer or a multi-isotope tracer) suggested that the individual was non-local and could have spent part of their childhood on the Lizard Peninsula, Cornwall. This discrepancy raises significant questions about the utility of oxygen as an isotope tracer or the converted $\delta^{18}\text{O}$ values of modern groundwater which are often used as a baseline.

Although both of the case studies in this chapter related to the use of isotope tracers from tooth enamel or cremated bone to ascertain the likelihood that an individual spent the last c. 2-3 years or c. 10 years of their lives respectively in a particular geographic region, the spatial approaches that were introduced can be applied to other types of archaeological samples and analytic measurements providing that suitable comparative data are available to create a robust baseline for the purposes of geographic assignment. Both the approach based on the calculation of residuals and the approach based on Bayesian statistics and maximum likelihood estimation will yield similar results. The approach based on the calculation of residuals retains a direct link to the measured values and, as such, is perhaps more intuitive and easier to interpret – particularly in instances where sources of error are poorly understood at the time the analysis is carried out.

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