The application of strontium and oxygen isotope analysis to study land use and mobility patterns during the earlier Neolithic in England and Wales

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Abstract

The transition to agriculture in Britain was associated with a significant shift in both culture and subsistence patterns, with the introduction of non-native domesticated species and new traditions, such as pottery manufacturing and burial monument construction, from the European mainland during the early 4th millennium BC. However, the processes underlying this transition have been heavily debated. Some argue that farming was adopted by local hunter-gatherers who lived within Britain. However, others suggest that migration of farming communities to Britain from the European mainland played a role in the development of agriculture. The nature of Neolithic subsistence and settlement patterns has also been debated. Some authors place emphasis on evidence for substantial timber buildings of early 4th millennium BC date and argue that early agriculturalists were fully sedentary, obtaining all their resources through keeping livestock and cultivating cereals close to permanently occupied settlements. Others, however, highlight the varied range of archaeological evidence for settlement and subsistence during this period, including ephemeral structures, pits and lithic scatters, which they interpret as the remains of temporary camps. Rather than communities obtaining all of their dietary resources through intensive mixed farming at a single geographical location, these authors suggest that patterns of land use may have been more complex, with groups routinely moving between different locations to exploit a more diverse range of dietary resources.

To contribute to these debates this thesis applies strontium and oxygen isotope analysis of tooth enamel as a means to evaluate where populations buried in Neolithic monuments in Britain during the 4th millennium BC obtained their childhood diet. Individuals buried within two of the long barrows and cairns that were studied have strontium isotope ratios that exceed all presently known biosphere $^{87}Sr/^{86}Sr$ values in England and Wales. All current scientific understanding suggests that these individuals sourced their diet from outside England and Wales. These individuals have radiocarbon dates that fall within the few centuries of the 4th millennium and the results support previous arguments that migration, the movement of groups over significant distances, occurred during the transition to agriculture early in the 4th millennium BC. In contrast, all individuals with calibrated radiocarbon date ranges that fall after 3700 cal BC exhibit strontium isotope ratios consistent with values bioavailable in England and Wales and could therefore have obtained their childhood diet from these regions. At Hazleton North, a monument constructed during the first half of the 37th century BC in Gloucestershire, England, large shifts in $^{87}Sr/^{86}Sr$ values and elemental concentration between adjacent permanent molar teeth indicate that individuals routinely changed the location from which they sourced their diet during early life. Rather than obtaining all their resources through sedentary intensive mixed farming at a single geographical location, the results provide evidence for more complex patterns of land use and support the interpretation that individuals were residentially mobile. Results from earlier Neolithic long barrows and cairns are also compared and contrasted with those from the causewayed enclosure complex at Hambledon Hill in Dorset, England. This site was in use from the 37th century BC and the population exhibit strontium isotope ratios comparable to ranges bioavailable on lithologies in the regions of southern England from which the majority of artefacts that were deposited at the site are likely to originate.

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This thesis is dedicated to my family, without whose support it would not have been possible.

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During the course of writing this thesis strontium and oxygen isotope analysis, radiocarbon dating and dietary (carbon and nitrogen) isotope analysis was also undertaken on osteological collections curated by the Duckworth Laboratory, University of Cambridge and Maidstone Museum which had previously been attributed to a Neolithic monument at Coldrum, Kent and thought to have been recovered during antiquarian (early 20th century) excavations at this site. For reasons discussed in the Conclusion to the thesis, the results of this work are being published separately, as a fifth paper, additional to the four papers that form the thesis. I would very much like to thank both Giles Guthrie and Samantha Harris, for access to and permission specimens from the collection attributed to Coldrum within Maidstone Museum. I am very much indebted to Maggie Bellatti and Dr Marta Lahr, for enabling me to visit the Duckworth Laboratory, University of Cambridge and for permitting me to sample their collections. I would in addition like to thank Rob Kruszynski for providing further advice on the history of collections in the Natural History Museum, London and specimens that they curate. During the course of the thesis radiocarbon dating of specimens have attributed to Coldrum was undertaken following a NERC radiocarbon dating award (NERC grant number NF/2012/2/13). I would very much like to thank the University of Oxford Radiocarbon Accelerator Unit and Professor Tom Higham for undertaking the analysis and providing advice. We are also grateful to Andy Gledhill and the University of Bradford for undertaking carbon and nitrogen analysis on samples of dentine from individuals in the collections attributed to Coldrum and would like to thank Professor Alistair Whittle, Dr Seren Griffiths and Dr Mick Wysocki for their advice.

Finally, before the reader begins to consider the results within this thesis, the author would add a caveat: the interpretations presented herein are predicated on understanding of the methodology and archaeology as it was at the time the thesis was written. As with all scientific endeavour, interpretations of results may be subject to revision as knowledge in the field increases, with production of further evidence in future.

Contents

1. Introduction

This thesis describes the results of strontium and oxygen isotope analysis of tooth enamel from human populations buried in Neolithic monuments in England and Wales during the 4th millennium BC. The first half of the 4th millennium BC, the early Neolithic, is a critical period in British prehistory as it is associated with the development of farming. Establishment of agriculture involved both a transformation in subsistence practice, as well as the appearance of new technologies and cultural traditions. The importation of non-native domesticated species of plants and animals from the European mainland, such as sheep and cereals, which are not native to Britain, was associated with the appearance of pottery manufacturing and burial monument construction, that also derive from established pre-existing traditions on the near Continent (e.g. Tresset and Vigne 2011: 184; Tresset 2015; Scarre 2015: 79-81).

Current radiocarbon dating suggests that the transition to agriculture in Britain took place during the first few centuries of the 4th millennium BC: Bayesian modelling indicates that Neolithic material culture and practices began to appear in different regions at different times during this period, developing at approximately 4,000 BC in the south-east of England, and between approximately the 39th to 37th centuries BC, in other regions, such as Wales, Scotland, northern England and Ireland (Whittle *et al.* 2011; Griffiths 2011). In Britain, there is currently no directly dated evidence for the exploitation of domesticated species of plants and animals any earlier in date (Brown 2007; Whittle et al. 2011). Identification of wheat DNA in waterlogged sediments within contexts of Mesolithic date, at Bouldner Cliff, on the coastline of the Isle of Wight in southern England has recently been used to argue that cereals may have been present in Britain during the 6th millennium BC (Smith *et al.* 2015). However, there are presently no directly dated cereal remains at this site and as discussed by Larson (2015: 946) this study rests on the assumption that DNA does not move vertically between archaeological strata. Recent analysis of damage patterns to the DNA that was recovered from this site suggests it is likely not to be of ancient origin and may represent contamination of submerged sediments with exogenous modern DNA (Weiß *et al*. 2015).

1.1 Understanding the development of farming in Britain: an overview of current debates

The processes underlying the transition to farming in Britain during the early 4th millennium BC are poorly understood and the question of how agriculture developed has been heavily debated. Britain was separated from the European mainland by the English Channel at this time (Sturt *et al.* 2013) and new species of domesticated animals and plants were therefore imported by boat. Some authors suggest that local Mesolithic populations who were living within Britain during the 4th millennium BC instigated the development of farming, selectively adopting Neolithic material culture and practices from the near Continent by obtaining domesticated species through trade and exchange (e.g. Thomas 2003: 73, 2004: 125-126, 2007: 426; 2008: 65, 2013; Cummings and Harris 2011). Although noting that, in Britain, archaeological evidence for contact between local hunter-gatherer groups and farmers on the European mainland presently remains limited, these authors draw on wider evidence for interaction between hunter-gatherers and farmers during the transition to the Neolithic within other regions of Europe (Thomas 2013: 265, 271-272) to suggest that in Britain domesticated species were fitted into the existing scheme of Mesolithic activities (Cummings and Harris 2011: 368). They argue that both domesticated species and objects imported to Britain from the European mainland (see below) were viewed them as prestige goods and deliberately obtained by local Mesolithic communities (2013: 272-273).

In contrast to this approach, other authors suggest that as the development of farming involved the appearance of traditions, such as burial monument construction and pottery manufacturing, that were long established on the European mainland, it is likely that these practices were introduced to Britain by migrant farming groups from the near Continent who were familiar with these traditions (e.g. Sheridan 2003, 2004, 2005, 2007, 2010a; Pailler and Sheridan 2009; Whittle *et al.* 2011: 858-861; Rowley-Conwy 2011 Anderson-Wymark and Garrow 2015; Bradley *et al.* 2015). Authors who advocate this position point to the current absence of direct archaeological evidence for contact and interaction between local Mesolithic groups within Britain and farming populations on the near Continent (Sheridan 2010a: 90; 2011: 390). These authors point to evidence for importation of objects from sources on the European mainland (e.g. fibrolite and dolerite attributed to sources in Brittany and Jadeite axes, e.g. Pitts 2009; Clough and Cummins 1988; Sheridan and Pailler 2012; Sheridan *et al.* 2010; Pétrequin *et al.* 2008; for further discussion of other worked stone objects that could also be attributed to sources on the European mainland see Peacock *et al.* 2010). They also highlight the lack evidence for continuity in subsistence practice, including a decline in hunting of wild animals beyond the turn of the 4th millennium BC (e.g. Serjeantson 2014). Study of fossil insect assemblages, has also been used to support arguments for an abrupt transition, identifying an increase in the presence of dung beetles during the early 4th millennium BC commensurate with the rapid expansion in the number of grazing animals during this period (Whitehouse and Smith 2010: 11). Both zooarchaeological analysis and carbon and nitrogen isotope analysis of bone collagen have also been argued to support a shift in subsistence patterns at this time, away from a diet dominated by exploitation of marine resources during the Mesolithic to the routine exploitation of terrestrial domesticated resources (Richards and Hedges 1999: 892; Richards *et al.* 2003; Richards and Schulting 2006; Schulting 2013).

Whilst the area from which such groups might have originated remains disputed (see below), many of the authors who advocate the argument that Neolithic material culture and practices were introduced to Britain by the arrival of groups from near Continent also suggest there may have been more than one episode of migration during the early 4th millennium BC (e.g. Whittle *et al.* 2011; Sheridan 2011; Anderson Whymark and Garrow 2015; Pioffett 2015). Whittle *et al.*, for example, propose that the initiation of agriculture in Britain to have been a consequence of the "small-scale, piecemeal and perhaps episodic fissioning from continental communities" during the first few centuries of the 4th millennium BC (2011: 858). Whilst employing Bayesian modelling of radiocarbon dates to identify regional variability in the timing of the initial appearance of agriculture (see above), Whittle *et al.* (2011) also used this to examine variation in the tempo of cultural change as development of the Neolithic progressed. They argue that the late 39th to 38th century cal BC was associated with a "significant gear shift: an impressive acceleration" in the pace of Neolithisation, which they suggest may have been a consequence of "further filtered colonization" at this time (ibid. 862; also see Bayliss *et al.* 2011a: 801).

Whilst many authors argue that movement of communities to Britain from the near Continent during the early 4th millennium BC may have played a role during the transition to farming, the region from which such groups could have originated, remains the subject of debate. The earliest dated evidence for the appearance of agriculture is found within the south-east of England. Whittle *et al.* (2011) therefore suggest that Neolithic material culture and practices are most likely to have been introduced by the arrival of communities from the area of the near Continent located closest to this region, north-eastern France and Belgium, and propose there may have been further episodes of migration to Britain from this area as development of the Neolithic progressed (ibid. 852-853; Bayliss et al. 2011a: 739-740). Others, however, argue that archaeological evidence supports the arrival of communities from at least two different areas of the near Continent, with groups coming to Britain from both north-eastern France and Belgium, as well from Lower Normandy in north-western France (ibid.; Sheridan 2010; Darvill 2010: 79-80; Anderson-Wymark and Garrow 2015: 64, 69-70; Bradley 2007: 86; Bradley *et al.* 2015: 77, 80-81, 332; Pioffet 2015). Recent detailed comparative analysis of ceramics found in Britain with those on the near Continent has been used to support this argument, suggesting that groups arrived from at least two different regions of the near Continent at different times during the early 4th millennium (Pioffet 2015). Ceramics found in western Britain reflect influences from Lower Normandy and Brittany in north-western France, whilst those in eastern Britain reflect traditions within north-eastern France and the Scheldt Valley (Pioffet 2015; cf. Sheridan 2010a & 2010b). Pioffet (2015: 18, 540-552), who conducted this analysis suggests that this distinction in pottery production, is further supported by differences in other forms of material culture, with lithic industries and the morphology of early Neolithic timber buildings in western Britain exhibiting greater similarity to those on the western near Continent, and those in eastern Britain paralleling traditions on the eastern near Continent. Recent analysis of material culture therefore appears to support the argument that Neolithic traditions found in Britain reflect influences from at least two different regions of Continental Europe and that development of agriculture could as such have been a consequence of the arrival of groups from more than one region during the early 4th millennium BC. Arguably, radiocarbon evidence for regional variation in the timing of the first appearance of the Neolithic material culture and practices identified by Bayesian modelling (see above; Whittle *et al.* 2011; also see Griffiths 2011), with the early appearance of agriculture in south-eastern England at around 4,000 BC and subsequent later development, between approximately the 39th to 37th centuries BC, in other regions, such as Wales, northern England, Scotland, and Ireland, could also be interpreted to support this.

1.2 The nature of subsistence and settlement patterns during the earlier Neolithic

The nature of subsistence and settlement patterns during the Neolithic in Britain also been the subject of competing interpretations. Some authors argue the first farmers were fully sedentary and argue that communities obtained the majority of their resources through cultivating cereals and keeping livestock close to permanently occupied settlements (Rowley-Conwy 2003, 2004, 2011; Bogaard *et al.* 2013: 12589). They suggest that permanent year round occupation of a fixed location may assist with the regular tending of cereal crops to maximize yield and that livestock are likely to have been kept close to settlements, enabling use of manuring as a means to enhance soil productivity (e.g. Rowley-Conwy 2004: 96; Jones 2005: 172-173; Bogaard *et al.* 2013: 12589; Rowley Conwy and Legge 2015: 430). It is assumed that in temperate environments sedentary intensive mixed agriculture is inherently most productive, facilitating further demographic expansion of farming communities and acting as the foundation for the development of complex societies (e.g. Bocquet-Appel 2008: 42-43, 2011: 560). Those who support this model suggest that sedentary mixed agriculture may therefore have provided the template for development of the Neolithic across Europe, and propose that regimes during the early Neolithic in Britain may have been comparable to those of the Linearbandkeramik (LBK), farming systems that developed in central Europe over a millennium and a half earlier (Rowley-Conwy 2003; Rowley-Conwy 2011). These authors place strong emphasis on and the discovery of timber buildings dating to the first few centuries of the 4th millennium BC in Britain, which they argue were permanently occupied settlements (ibid). For an excellent compilation of examples of Neolithic buildings see Darvill (1996; also see Rowley-Conwy 2003) and for examples of the most recent discoveries of such structures see Rees and Jones (2015) on excavations at Llanfaethlu, Anglesey in Wales, or Chaffey and Brook (2012) on excavations at Horton, Berkshire.

Proponents of the sedentary settlement model also highlight evidence for the importance of cereal cultivation during the early Neolithic in Britain (Jones and Rowley-Conwy 2007; Rowley-Conwy 2000: 51; Jones 2000: 83). Arable weed evidence is interpreted to suggest that, as with the LBK, communities in Britain invested considerable labour in the maintenance of long-established cultivation plots (Bogaard and Jones 2007) and it is argued that mobility of early farming communities as a whole was limited by the demands of cereal cultivation (e.g. Jones 2005: 172-173).

In marked contrast to these interpretations, other authors reject the universality of sedentary intensive mixed agriculture and instead emphasize the importance of understanding socio-cultural variation, in both subsistence and settlement patterns, during the transition to farming (Thomas 2016: 3-6). These authors highlight evidence for the exploitation of a diverse range of subsistence resources during the early Neolithic in Britain, including use of both wild plant resources in addition to cereals (e.g. Stevens 2007: 381-382; Bishop *et al.* 2009: 86 and 90). They also suggest that evidence for the importance of cattle could indicate that some members of the community were residentially mobile, moving between occupation sites with cattle herds (Thomas 2013: 408-411; e.g. Serjeantson 2011; Viner 2011, 2014; Schulting 2013: 321).

In Britain, the varied nature of evidence for occupation may also be indicative of diversity in early Neolithic settlement systems (e.g. Anderson-Whymark and Thomas 2012; Sheridan 2013; Brophy 2015). In addition to the remains of substantial timber buildings, occupation evidence also includes pits, ephemeral structures and lithic scatters, which are often interpreted as the remains of temporary camps (e.g. Bradley 2007: 43; Pollard 1999: 82). This has also prompted some authors to suggest that, rather than the population as a whole being sedentary, residence patterns may have been based on a system of "tethered mobility", with some members of the community repeatedly visiting favoured occupation sites located in different geographical areas to exploit a range of dietary resources (Whittle 1997: 21; 2003: 43). In south-east Wales, for example, lithic scatters, which dominate the archaeological record in this region have been interpreted to be indicative of transient, short term settlement (e.g. Olding 2000: 17; Makepeace 2006: 59). Whilst, the excavators of the Benson pit complex in Oxfordshire, suggest that the quantity and spread of deposits at this site indicate it is likely that it was "repeatedly visited over a span of time" (Pine and Ford 2003: 173). Likewise, excavators of pit clusters and hearths at Wellington-Moreton in the Severn-Wye region of Herefordshire, also interpret these to be consistent with repeated visitation to this site, suggesting that communities "returned to it time and time again and completed both very short lived activities and ones of longer, possibly seasonal, duration" (Jackson and Ray 2012: 153). At Kilverstone in Norfolk re-fitting of ceramics that were deposited within clusters of pit supports the interpretation that each pit group was the product of a discrete episode of activity and the excavators here also argue, that rather than representing the remains of permanent settlement this is consistent with repeated "visits by a single group, or a number of different groups, at irregular intervals" (Garrow *et al.* 2005: 155).

It is therefore possible that archaeological evidence could support recent arguments for cultural variation and diversity in the patterns of land use, subsistence and occupation during the Neolithic in Britain (Thomas 2013: 417-418; Thomas 2015: 1075). Rather than mobility of the population as a whole being limited by the demands of cultivation and groups obtaining all of their dietary resources through intensive mixed farming at a single location, patterns of land use and subsistence could have been more complex, with communities, for example, exploiting resources in a variety of different geographical locations by dividing tasks on the basis of social status, age or gender (e.g. see Leary and Kador 2016).

1.3 The application of ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotope analysis: principles and procedures

To assist in the evaluation of these questions and to contribute to debates regarding patterns of land use and mobility during the 4th millennium BC in Britain this thesis applied strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotope analysis of tooth enamel.

Strontium has four naturally occurring isotopes (^{88}Sr, ^{87}Sr, ^{86}Sr and ^{84}Sr). Unlike the other isotopes of strontium ^{87}Sr is radiogenic, the product of the radioactive decay of another chemical element, rubidium-87 (^{87}Rb; Faure 1986: 117-8; Faure & Mensing 2005: 76; Dicken 2005: 42-43). The amount of ^{87}Sr gradually increases over geological timescales and $^{87}Sr/^{86}Sr$ therefore varies geographically according to the age and initial isotope composition of bedrock (ibid.). Use of strontium isotope analysis for geographic provenancing in archaeology is well established, having been first employed over thirty years ago (Ericson 1985). The application of strontium isotope analysis is based on the principle that strontium weathers out from rocks, into soils and ground waters where it becomes bioavailable, being incorporated into plants and, in turn, into animals (Capo *et al*. 1998: 202-203. Conventionally measured $^{87}Sr/^{86}Sr$ values do not vary significantly between trophic levels (0) and the $^{87}Sr/^{86}Sr$ values in tooth enamel directly reflect the sources of dietary strontium to which human individuals were exposed whilst their teeth were forming (Graustein 1989: 492; e.g. Blum *et al.* 200; Bentley 2006; Montgomery 2002, 2010; Slovak and Paytan 2011: 743-744; Price 2015: 78).

Tooth enamel is used for analysis, as it does not remodel once mineralized and unlike other skeletal tissues such as dentine, enamel is highly resistant to diagenesis (e.g. Budd *et al.* 2000; Trickett *et al.* 2003; Montgomery 2002: 330-333; Montgomery 2010: 329; although recent studies suggest that calcined bone and petrous bone may also be suitable for analysis, Harvig *et al.* 2014; Snoeck *et al.* 2015). Strontium isotope ratios vary in plants and water depending on the underlying age and composition of bedrock (e.g. Evans *et al.* 2010; Voerkelius *et al.* 2010; Warham 2011; Willmes *et al*. 2013).

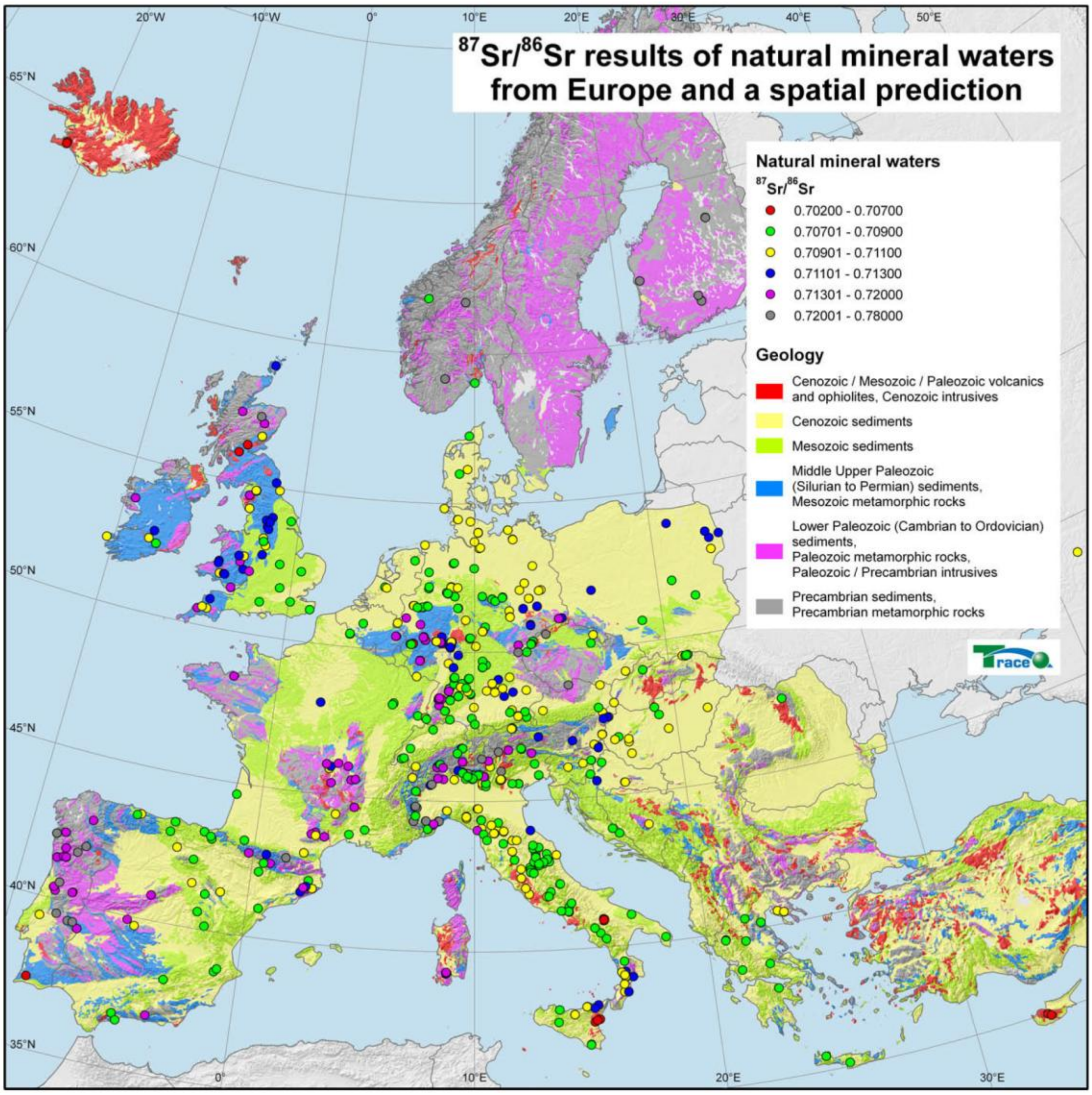

Fig. 1. Example of variation in $^{87}Sr/^{86}Sr$ values in natural mineral waters according to age and composition of underlying geology in Europe (figure reproduced from Voerkelius *et al.* 2010)

Comparison of the isotope ratios preserved in tooth enamel to mapped bioavailable ranges in modern plants and water may therefore be used to help establish where an individual obtained their diet and analysis of teeth that form at different stages of childhood enables us to evaluate whether individuals obtained dietary resources from more than one geographical area during early life (e.g. Montgomery 2002; Bentley

2006; Slovak and Paytan 2011: 743-744; Montgomery 2010: 328). During the present study, consecutively mineralizing permanent molars were chosen for sampling, wherever possible, to enable comparison of isotope ratios at successive stages childhood: formation of the first permanent adult molar tooth commences in-utero, just prior to birth and completes by approximately 4.5 ± 0.5 years of age; formation of the second molar crown occurs between approximately 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31, 55-56); the timing of third molar formation is most variable (Liversidge 2008: 313), with initial cusp formation from approximately 8.5 ± 0.5 years of age and crown completion by approximately 14.5 ± 0.5 years (AlQahtani *et al.* 2010).

Strontium isotope analysis has been systematically employed to study the development of the Neolithic across several other regions in Europe, most recently in central Europe, Scandinavia and Northern Ireland (e.g. Price *et al.* 2006; Sjögren *et al.* 2009; Nehlich *et al.* 2009; Smits *et al.* 2010; Snoeck *et al.* 2016; Gron *et al.* 2016). Recent use of the technique to study of the Linearbandkeramic (LBK) in central Europe, for example, showed how it can enhance understanding of the transition to farming in this region (e.g. Bentley *et al.* 2002a, 2002b, 2003; Bentley & Knipper 2005a, 2005b; Bentley 2007; Bentley *et al.* 2012; Bickle and Whittle 2013; Bentley 2013). However, in Britain, the technique has yet to be systematically applied to study the early Neolithic (with the unpublished exception of recent application of the technique to Wor barrow, a long barrow dated to the earlier Neolithic in Dorset, Montgomery *et al.* in prep.; Allen *et al.* 2016). Burials of middle Neolithic date have so far formed the focus of investigation, with pilot studies having been undertaken at Monkton-up-Wimborne, Dorset, Duggleby Howe, Yorkshire and Balevullin, Tiree, western Scotland (Montgomery *et al.* 2000, Montgomery 2002;

Montgomery *et al.* 2007a & b; Armit *et al.* 2015). Strontium isotope analysis recently been applied to a Mesolithic burial at Langford in Essex (Schulting *et al.* 2016) and has also been used to study mobility patterns during the later Neolithic at Durrington Walls, Wiltshire (Viner *et al.* 2012; Madgwick pers comm.), as well as to examine the transition to the Chalcolithic-early Bronze Age (e.g. Parker Pearson *et al.* 2016).

The present study is the first to systematically employ this technique to study burial assemblages of earlier Neolithic date. It also employs systematic analysis of adjacent consecutively mineralising molar teeth, to evaluate whether individuals obtained dietary resources from different geographical areas at different stages of childhood and adolescence and may therefore have moved between localities during early life.

Whilst employing strontium isotope analysis this study also undertook oxygen isotope analysis of enamel samples from each tooth. The ratio of $^{18}O/^{16}O$ (expressed as $\delta^{18}O$, as it is measured relative to standard reference materials) also varies geographically within water, influenced by factors such as latitude, altitude, temperature and distance from the coast (e.g. Mook 2005: 89-98; Gat 2010). Use of oxygen isotope analysis for geographic provenancing in archaeology is based on the premise that, whilst there is some contribution from respiratory oxygen and chemically-bound oxygen in food, a significant component of the $\delta^{18}O$ values within mammalian bioapatite (tooth enamel and bone) derives from ingested fluids, which in turn reflect values in local drinking water (e.g. Luz *et al.* 1984; Longinelli 1984; Luz and Kolodny 1985; Levinson *et al.* 1987; Daux *et al.* 2008: 1146).

Oxygen isotope ratios exhibited by human populations are argued to reflect underlying differences in the isotope composition of drinking water: Evans *et al.*

(2012: 759), for example, argue that a statistically significant difference in the mean $\delta^{18}O$ values of tooth enamel from groups excavated within buried in western Britain (mean 18.2 ‰ ± 1.0 ‰, 2σ) to those buried in eastern Britain (mean 17.2 ± 1.3 ‰, 2σ) reflects differences in the oxygen isotope composition of local drinking water between these two areas as local groundwaters in western Britain are associated with higher $\delta^{18}O$ values than those in eastern Britain (Darling *et al.* 2003: 189-190). The most recent review of published human bioapatite data has also shown that oxygen isotope values exhibited by human archaeological burial populations correlate with environmental factors, such as latitude, longitude, altitude (Lightfoot and O'Connell 2016). However, this study also highlights the way in which the oxygen isotope ranges exhibited by populations buried in temperate Europe can overlap (ibid.) $\delta^{18}O$ values found amongst populations buried in Britain can, for example, overlap with those recorded in populations excavated on the adjacent near Continent (e.g. see Brettell *et al.* 2012b: 127).

Whilst there is evidence for variation in the $\delta^{18}O$ values recorded in human populations according to climate, a factor that must be considered when interpreting oxygen isotope results is the potential influence of culturally mediated behaviour on the oxygen isotope composition of ingested fluids. In contrast to conventionally measured $^{87}Sr/^{86}Sr$ values which are not subject to significant change through biological, chemical or physical processes (see above), the isotope ratios of light elements, such as oxygen can be subject to mass dependent fractionation (variation in the isotope ratio) as a result of culturally mediated behaviour (e.g. Brettell *et al.* 2012a; Daux 2008: 1144).. The influence of human culinary activity, for example, boiling water or stewing foods, is therefore considered when evaluating the results of oxygen isotope analysis (as will be described in the chapters that follow). Breast feeding may also be particularly influential in influencing the oxygen isotope composition of human tooth enamel, since breast milk has higher $\delta^{18}O$ value relative to fluids consumed by the mother (Roberts *et al.* 1988: 625). Several studies have observed that teeth which form whilst an infant is being breast fed (e.g. deciduous molars or first molars) may therefore record higher $\delta^{18}O$ values than teeth that form later in childhood (Wright and Schwartz 1998: 14; Britton 2015: 8). The present study also therefore considers the potential influence of breast feeding on the $\delta^{18}O$ the oxygen isotope composition of enamel samples from early forming teeth.

The processes used to prepare enamel samples for isotope analysis and laboratory procedures that were applied by the present study are well established (e.g. see Montgomery 2002) and are further detailed in the chapters that follow (**Chapters 2 to 5**). Initial preparation of all enamel samples for isotope analysis was undertaken in laboratories at Durham University following procedures developed by Montgomery (2002). Prior to sampling a photographic record of the occlusal, mesial, distal, buccal and lingual surfaces of each extracted tooth was made in the photography studios at Durham University using a Nikon D700 camera. The museums who participated in this study have received copies of the photographs that were taken. Creation of a physical dental impression of each tooth was also pre-requisite of obtaining permission for destructive sampling from the museums involved in the study. This was achieved using polyvinylsiloxane moulding material (Coltène President Jet Plus Light Body), a product that is routinely employed in modern dentistry and is specifically designed for taking impressions of human dentition, recording surface features at a high resolution, suitable for study with scanning electron microscopy (Galbany *et al.* 2006). Before to taking dental impressions teeth any dental calculus that was present on teeth was removed prior and retained in labelled sealed sterile containers and teeth lightly cleaned using de-ionized water and a tooth brush.

As described above, once fully mineralized tooth enamel is considered to be highly resistant to diagenesis and to retain *in-vivo* $^{87}Sr/^{86}Sr$ values (e.g. Budd *et al.* 2000; Trickett *et al.* 2003; Montgomery 2002: 330-333; Montgomery 2010: 329), however, following the recommendation of Montgomery (2002) all teeth were visually inspected under a magnifying light prior to sampling, to ensure enamel was completely mineralized and that none of the sampled teeth exhibited any visual evidence of diagenetic change (e.g. caries, or staining to enamel). Core enamel chips were then prepared by first mechanically cleaning the exterior surface of the tooth crown, using tungsten carbide dental burrs to remove any adhering dirt and particulates. A core enamel chip was then excised using a flexible diamond edged rotary saw. An enamel chip of approximately 20 to 30mg in weight was taken from each tooth for strontium isotope analysis and of approximately 10mg in weight for oxygen isotope analysis. Once excised, the exposed surfaces of each enamel chip were then again thoroughly abraded using dental burrs to ensure any adhering dentine was removed, as in contrast to tooth enamel dentine is susceptible to diagenetic alteration (Montgomery 2002: 91). Resulting chips of core enamel were transferred to individual clean sealed and labelled containers.

Between preparation of samples all dental saws and burs were cleaned ultrasonically for approximately five minutes and rinsed three times in high purity de-ionized water in order to ensure any adhering particulates that could cross-contaminate subsequent samples were removed. Once prepared, chips of core enamel were transferred to the British Geological Survey in Keyworth, Nottingham, England, where isotope analysis was conducted in the Class 100, HEPA-filtered laboratory facilities at the

Natural Environment Research Council Isotope Geosciences Laboratory (NIGL) (**Chapters 2 to 5**).

Strontium and oxygen isotope analysis was undertaken on samples of tooth enamel from five populations from burial monuments dated to the 4th millennium BC in different regions of Britain. Four of these burial populations were excavated from long barrows and cairns: Whitwell, Derbyshire (Vyner and Wall 2011); Penywyrlod and Ty Isaf, Brecon, Powys, Wales (Savory 1973, 1984; Grimes 1939) and Hazleton North, Gloucestershire, England (Saville 1990; Rogers 1990; Meadows *et al.* 2007). Criteria used for selection of samples from each site are detailed in each of the chapters that follow.

In addition to the study of burial populations from long barrows and cairns, strontium and oxygen isotope analysis was also undertaken on enamel samples from individuals buried at another monument type, a causewayed enclosure. Causewayed enclosures are characterized by single or multiple concentric circuits of interrupted ditches and represent a new tradition of earthwork construction that developed in southern Britain from the late 38th century BC, at least one to two centuries after the first long barrows and cairns (Bayliss *et al.* 2011aa: 684, 722). They are interpreted as monuments that provided a focus for temporary gatherings of dispersed populations, being used for burial of human remains and commemoration of the dead (see **Chapter 5;** Whittle *et al.* 2011: 893-895). Analysis was undertaken on the burial population from the causewayed enclosure complex at Hambledon Hill in Dorset, England (Mercer and Healy 2008; McKinley 2008) and results were compared with those of the burial populations from the long barrows and cairns that were studied.

1.4 Thesis structure

Thesis chapters are drafts of academic papers, some of which will have been published, or will have been submitted to journals for review, at the time the final corrected version of this thesis is submitted. Each paper further describes the background to the research questions outlined above, explains how strontium and oxygen isotope analysis was applied to assist in resolving these debates and presents the results of analysis:

Chapter 2. Neil, S., Evans, J., Montgomery, J. and Scarre, C. Isotopic evidence for migration during the transition to agriculture in Britain.

Chapter 3. Neil, S., Montgomery, J., Evans, J. and Cook, G.T., Scarre, C. 2017. Land use and mobility during the Neolithic in Wales explored using isotope analysis of tooth enamel. *American Journal of Physical Anthropology* 00:1–23. https://doi.org/10.1002/ajpa.23279

Chapter 4. Neil, S., Evans, J., Montgomery, J., Scarre, C. 2016. Isotopic evidence for residential mobility of farming communities during the transition to agriculture in Britain. *Royal Society Open Science* 3: 150522. http://dx.doi.org/10.1098/rsos.150522

Chapter 5. Neil, S., Evans, J., Montgomery, J. and Scarre, C. Isotopic evidence for land use and the role of causewayed enclosures during the earlier Neolithic in southern Britain.

The first paper **(Chapter 2)** describes the results of strontium and oxygen isotope analysis from Whitwell cairn, Derbyshire, in the English Midlands. It compares strontium and oxygen isotope results from this site to local biosphere data and to the results from the other sites sampled during the course of the project, to examine the question of migration. Individuals within the burial population at Whitwell have strontium isotope ratios that exceed all presently known biosphere $^{87}Sr/^{86}Sr$ values in England and Wales. All present scientific understanding suggests that these individuals obtained their childhood diet from regions further afield. The results may therefore support previous arguments that migration, the movement of groups over significant distances early in the 4th millennium BC, played a role during the transition to agriculture (see above, e.g. Sheridan 2010a, 2010b; Rowley-Conwy 2011; Bradley et al. 2015; Anderson-Whymark and Garrow 2015; Pioffet 2015).

Chapter 3 builds on this theme, detailing the results of both strontium and oxygen isotope analysis and radiocarbon dating of individuals buried in two monuments, Penywyrlod and Ty Isaf, which are located less than 5 miles apart, in Brecon, Powys, southern Wales. Isotope values measured in tooth enamel at Penywyrlod may also be interpreted to support the argument for migration, as one of the individuals within this group also has values that exceed all currently recorded biosphere $^{87}Sr/^{86}Sr$ values in England and Wales. Results from this site contrast with those exhibited by individuals from Ty Isaf, the majority of whom exhibit strontium isotope ratios that fall within with the measured local biosphere range in southern Wales, the area in which they were buried.

Chapter 4 considers the results of isotope analysis of enamel from the burial population at Hazleton North, Gloucestershire, England. At Hazleton North, large shifts in $^{87}Sr/^{86}Sr$ values and elemental concentration between adjacent permanent molar teeth indicate that individuals within the group changed the geographical location from which they sourced their diet during childhood and support the interpretation that individuals were residentially mobile. **Chapter 5** describes the results of strontium and oxygen analysis of a population buried at the Hambledon

Hill causewayed enclosure complex, comparing and contrasting these results with data from the other sites studied during the project.

Papers within the thesis are multi-authored. Each paper contains an author contributions statements which details the contributions made by each author. The first author (Samantha Neil, the author of this PhD) designed the research, drafted research grant applications that were made to undertake analysis and those that were made to cover costs of radiocarbon dating (see below); obtained permission for sampling from the museums and institutions who participated in the study and wrote all the papers within the thesis. Supervisors (Prof. Chris Scarre, Dr Janet Montgomery and Prof. Jane Evans) provided feedback on drafts of these papers. Strontium isotope analysis was conducted by Samantha Neil under the supervision of Prof. Jane Evans at Natural Environment Research Council Isotope Geosciences Laboratory (NIGL), in Nottingham, England. Enamel samples were selected and enamel chips were prepared for oxygen isotope analysis by Samantha Neil and mass spectrometry to obtain oxygen isotope ratios was undertaken Hillary Sloane at NIGL. Radiocarbon dating of individuals from Ty Isaf and Penywyrlod (**Chapter 3**) was part funded by a radiocarbon dating award from the Prehistoric Society (awarded to Samantha Neil), by a Durham University Faculty of Social Sciences and Health Student Project and Initiatives Award (awarded to Samantha Neil) and by the Scottish Universities Environmental Research Centre and NERC Radiocarbon Facility (SUERC). Radiocarbon dating of dentine samples that were taken from Ty Isaf and Penywyrlod (see **Chapter 3**) was conducted at SUERC by Professor Gordon Cook. Dr Janet Montgomery obtained the biosphere $^{87}Sr/^{86}Sr$ data from samples of plant taken in the vicinity of Whitwell cairn and provided permission to reproduce this biosphere data for the purpose of this thesis (see **Chapter 2.9: Supplementary Information: table 1**).

Papers are formatted according to general criteria (e.g. approximate word length and structure) specified by journals, however, for the purpose of the thesis the same style of referencing has been applied throughout. Tables of results appear within the body of each paper, or within the supplementary supporting material that accompanies each manuscript. The final chapter concludes the thesis, summarizing the results and discussing steps which could be taken to further build on the data that has been produced by the present project.

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2. Isotopic evidence for migration during the transition to farming in Britain

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2.1 Abstract

The transition to farming in Britain during the early 4th millennium BC was associated with the importation of non-native domesticated species and the introduction of new technologies and cultural traditions, such as burial monument construction and pottery manufacturing, from the European mainland. However, the processes underlying the development of agriculture have been heavily debated. Some suggest that agriculture was adopted by local hunter-gatherers who lived within Britain. However, others argue that migration of farming communities to Britain from the European mainland played a role in the development of agriculture. Here we use strontium and oxygen isotope analysis of tooth enamel to evaluate where populations buried within early Neolithic monuments in Britain obtained their

childhood diet. The results provide evidence for migration of farming communities during the transition to agriculture.

2.2 Introduction

The transition to farming in Britain was marked by a radical transformation in subsistence patterns, culture and technology. The importation of non-native domesticated species of plants and animals from the European mainland, such as sheep and cereals (Tresset and Vigne 2011: 184; Tresset 2015), was accompanied by the introduction of new cultural traditions from the near Continent, including pottery manufacturing and burial monument construction (Scarre 2015: 79-81; Cummings 2017: 36). Radiocarbon dating suggests that this transformation took place during the early 4th millennium BC and that Neolithic material culture and practices began to appear across different regions of the mainland Britain at different times during this period, developing in south-east England at approximately 4000 BC and subsequently appearing across a large area of western and northern Britain from the mid 39th to late 37th centuries cal BC (Bayliss *et al.* 2011: 729, 838-842; Griffiths 2011: 298-300). Britain was separated from the European mainland by the English Channel at this time and new species of domesticated animals and plants were therefore imported by boat (Sturt *et al.* 2013).

However, the processes underlying the transition to the Neolithic during the early centuries of the 4th millennium BC have been heavily debated. Some authors suggest that farming became established following the development of trade networks between hunter-gatherer communities living in Britain and farming groups on the near Continent, and argue that local Mesolithic groups who lived in Britain adopted

Neolithic material culture and practices during the early 4th millennium (Thomas 2013; Cummings and Harris 2011). Others, however, suggest that, as the development of the Neolithic in Britain was associated with importation of new species, traditions and practices from the near Continent, the arrival of migrant farming groups from the European mainland played a role in the transition (e.g. Sheridan 2010a; Whittle *et al.* 2011: 858-861; Collard *et al.* 2010; Rowley-Conwy 2011; Bradley *et al.* 2015; Anderson-Whymark and Garrow 2015; Pioffet 2015). The region from which communities may have originated remains debated. However, recent analysis of ceramics indicates that Neolithic pottery found within Britain exhibits similarities to manufacturing traditions in at least two different regions of the near Continent (Pioffet 2015). This suggests that agriculture was introduced to Britain more than once, through the movement of communities from both north-eastern France and the Scheldt Valley, as well as Brittany and Lower Normandy in the north-west of France at different times during the early 4th millennium BC (ibid; Sheridan 2010a, 2010b).

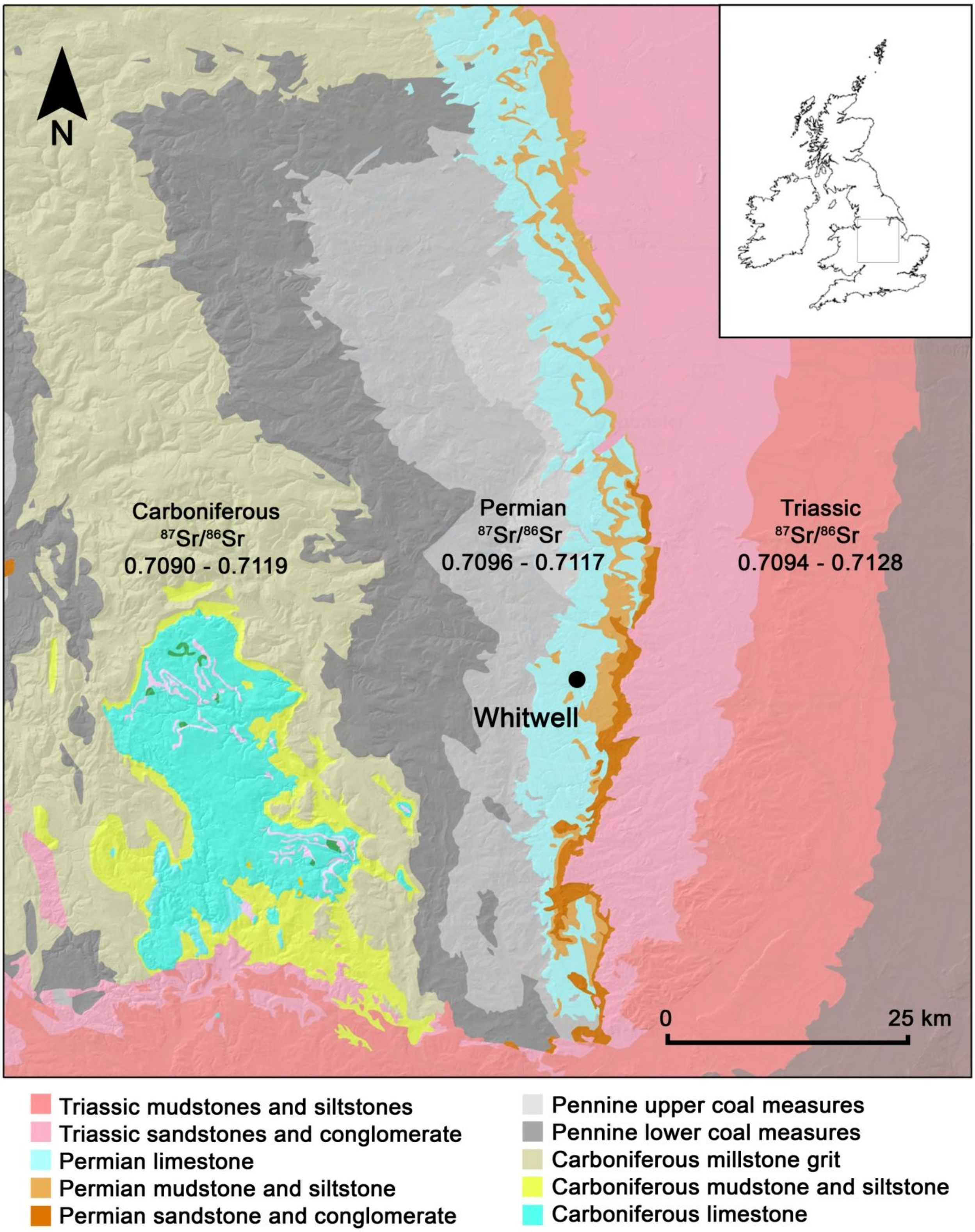
Here we apply strontium isotope ($^{87}Sr/^{86}Sr$) and oxygen isotope ($\delta^{18}O$) analysis to evaluate where individuals buried in Britain during the earlier 4th millennium BC obtained their childhood diet. We compare isotope ratios measured in tooth enamel from ten individuals buried at Whitwell cairn, in the English Midlands, to mapped modern bioavailable values and to previously published data from populations buried in other areas of England and Wales during the 4th millennium BC to provide evidence for migration during the early Neolithic.

Use of strontium isotope analysis for geographic provenancing is based on the principle that strontium isotope ratios ($^{87}Sr/^{86}Sr$) in plants and water vary geographically, depending on the age and composition of underlying bedrock (e.g. Evans *et al.* 2010; Warham 2011; Willmes *et al.* 2011; Montgomery *et al*. 2006). Tooth enamel is highly resistant to diagenesis and $^{87}Sr/^{86}Sr$ values in enamel therefore directly reflect the geographical location from which dietary sources were obtained during childhood (e.g. Montgomery 2002, 2010; Bentley 2006; Slovak and Paytan 2011; Price 2015: 78). Wherever possible, adjacent permanent molar teeth that form at different stages of childhood and adolescence were also sampled by the present study, to establish whether individuals changed the location from which they sourced their diet during early life (see Materials and Methods).

Whitwell cairn is located approximately 30 kilometres to the north of the city of Nottingham in the county of Derbyshire, England (Vyner and Wall 2011). Radiocarbon dating suggests that Neolithic material culture and practices began to appear in the English Midlands from the mid 39th century cal BC to late 37th century cal BC (Griffiths 2011: 298-300). Bayesian modelling of radiocarbon dates estimates that in the East Midlands Neolithic traditions and practices began to appear from *3990–3800 cal BC (95% probable*; Griffiths 2011: 116) and in the West Midlands between *3810–3540 cal BC* (*95% probable*; ibid. 281, 286, 300). Modelling suggests that in the East Midlands of England, the area in which Whitwell is located, the first dated event associated with appearance of cereals occurred between *3930–3770 cal BC* (*95% probable*); the first dated event associated with use of Plain bowl pottery in this region took place between *3950–3790 cal BC* (*95% probable*); the first event associated with the deposition of Carinated bowl pottery within this region occurred between *3840–3720 cal BC* (*87.8% probable*, or *3920–3860 cal BC, 7.6% probable*) and it is estimated that the first individuals to be buried at Whitwell died between *3780–3700 cal BC* (*95% probable*, OxCal v4.1; IntCal04; Griffiths 2011: 85, 124-126; Vyner and Wall 2011).

Whitwell cairn was constructed on Permian limestone (Zechstein Formation), which is overlain by late Quaternary loess (figs. 1 and 2; BGS 2016; Frederick 2011). Plant samples taken on lithology of Permian age close to the site have given $^{87}Sr/^{86}Sr$ values between 0.7096 and 0.7117 (mean 0.7107 ± 0.0010, 1σ, n = 3; data produced by Janet Montgomery, see Supplementary Information: table 1), consistent with values that may be expected on lithology of this age and composition in Britain (Evans *et al.* 2010; Chenery *et al.* 2011). Samples of plants and water taken on Triassic rocks within a radius of 100 km of Whitwell record $^{87}Sr/^{86}Sr$ values between 0.7094 and 0.7128 (mean 0.7109 ± 0.0013, 1σ, n = 8), whilst those on lithology of Carboniferous age to the west of Whitwell record values between 0.7090 and 0.7119 (mean 0.7106 ± 0.0010, 1σ, n = 18; Evans *et al.* 2010; Montgomery *et al.* 2006 and Montgomery, Supplementary Information: table 1).

Figure 1. Location of Whitwell cairn in relation to measured local $^{87}Sr/^{86}Sr$ biosphere values and bedrock geology. Based on British Geological Survey and Ordnance Survey map data, reproduced with permission of the British Geological Survey and Ordnance Survey, © NERC / Crown copyright [2016]. Measured bioavailable $^{87}Sr/^{86}Sr$ ranges after Evans *et al.* (2010); Montgomery *et al.* (2006) and Montgomery, Supplementary Information: table 1.



2.3 Results

In contrast to the local biosphere range, seven of the ten sampled individuals from Whitwell have tooth enamel with $^{87}Sr/^{86}Sr$ values between 0.7163 and 0.7211 (fig. 2). These values are higher than the local measured biosphere range and are higher than all currently available $^{87}Sr/^{86}Sr$ biosphere data from England and Wales (Evans *et al.* 2010; Warham 2011; the highest presently recorded biosphere value within England and Wales is 0.7162, Chenery *et al.* 2010).

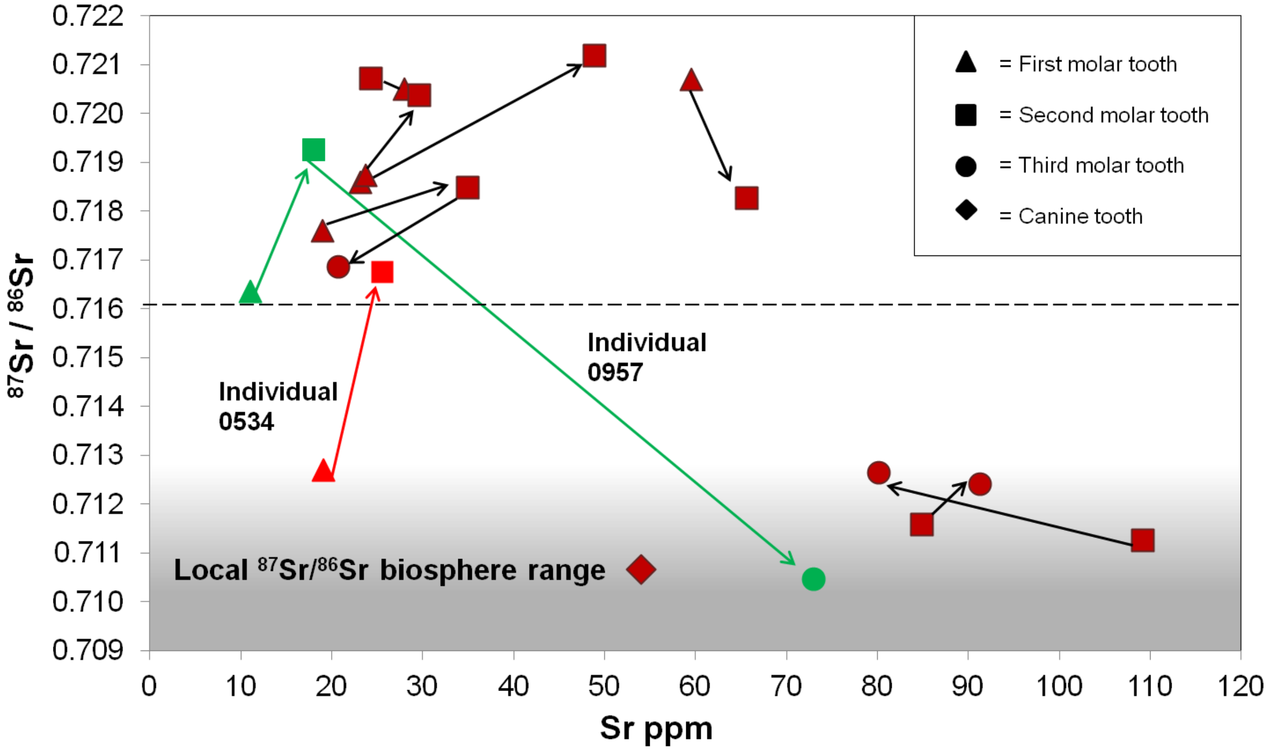


Figure 2. $^{87}Sr/^{86}Sr$ isotope ratios and strontium concentrations measured in tooth enamel from individuals buried at Whitwell. Tooth types are denoted by the key in the upper right of the diagram. Arrows illustrate variation in ratio and concentration between adjacent molar teeth of the same individual. Shading illustrates the local bioavailable range at Whitwell (after Evans *et al.* 2010; Montgomery *et al.* 2006 and Montgomery, Supplementary Information: table 1). The dashed line represents the highest currently recorded biosphere value in England and Wales (Chenery *et al.* 2010). 2σ analytical errors for $^{87}Sr/^{86}Sr$ are within the symbol.

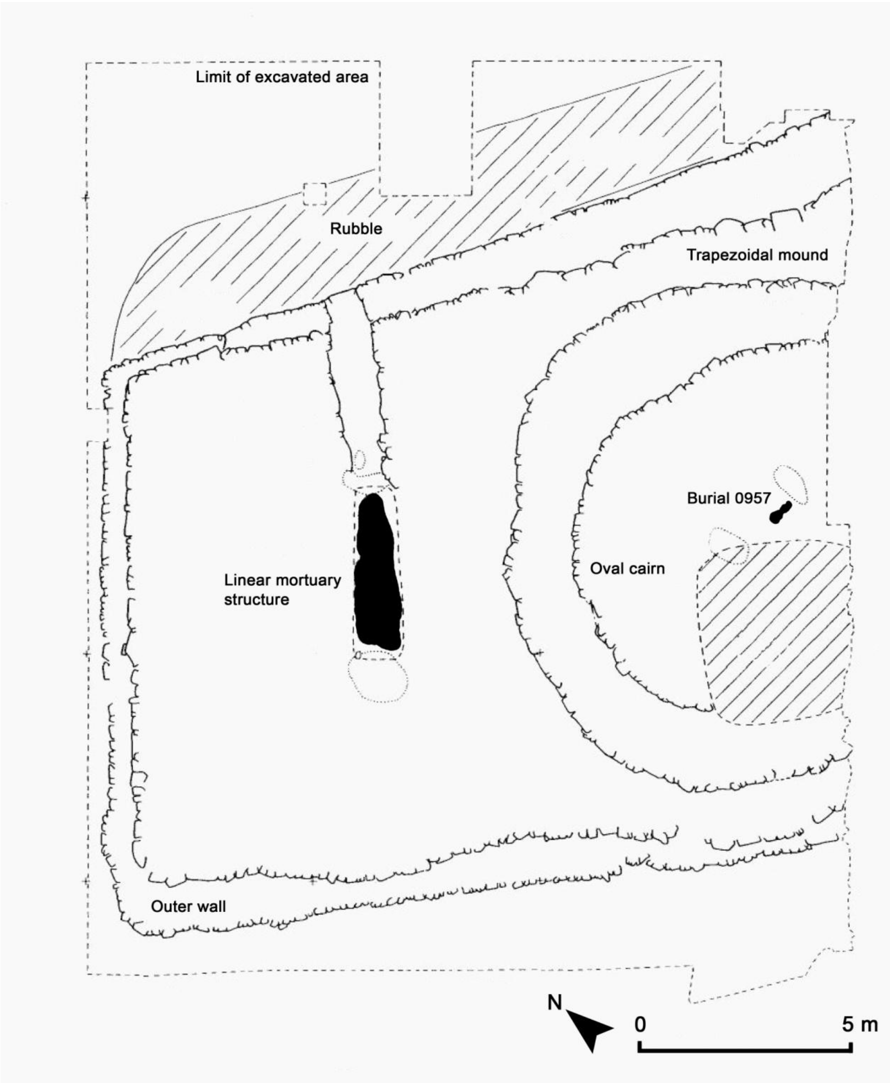


Figure 3. Plan of Whitwell cairn (after Vyner and Wall 2011; reproduced with permission).

Burials at Whitwell were located within a linear mortuary enclosure and a circular cairn, both of which were enclosed underneath a trapezoidal shaped mound (fig. 3). The linear mortuary enclosure was used for burial of multiple individuals. The remains of a small number of individuals, found stratified under a series of limestone slabs within the linear mortuary enclosure, date the first use of Whitwell for burial, to between *3780–3700 cal BC* (*95% probability*, Griffiths 2011: 85; Vyner and Wall

2011). One individual associated with this phase of use had dentition that was suitable for sampling. Enamel from the first and second molars of this individual, an adult, gave $^{87}Sr/^{86}Sr$ values of 0.7127 to 0.7168 respectively (individual 0534; fig. 2; Supplementary Information: table 2). The $^{87}Sr/^{86}Sr$ value of 0.7127 measured in their first molar enamel could fall within bioavailable ranges from England and Wales, however, comparable values are also bioavailable on European mainland (Willmes *et al.* 2013). The value of 0.7168 recorded in enamel from the second molar tooth of this individual is higher than all currently measured bioavailable values in England and Wales (Evans *et al.* 2010). The second molar tooth crown forms between approximately 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31 & 55-56) and according to all presently available evidence, this individual therefore obtained their diet from outside England and Wales during the formation of this tooth.

Following placement of the limestone slabs the linear mortuary enclosure continued to be used for burial. Five individuals in the sampled group are attributed to phase 4B/5, which radiocarbon dating suggests dates to the end of the 38th century cal BC (Vyner and Wall 2011: 29-30). Three of these individuals also exhibit strontium isotope ratios that are inconsistent with current measured biosphere ranges in England and Wales. However, two of the adults in this group have $^{87}Sr/^{86}Sr$ values that are comparable to the local bioavailable range and could have sourced their childhood diet locally, from the area within which they were buried (individuals 0512/2 and 0359/1; Supplementary Information: table 2).

The remains of three other individuals sampled during the present study were also found from within the linear mortuary structure, but are not stratigraphically associated and could have been buried within the monument either before or after placement of the limestone slabs (Supplementary Information: table 2). Radiocarbon dating of a sample of stratigraphically unrelated skeletal elements from the linear mortuary enclosure indicates that these remains date to between *3760–3660 cal BC (95% probability*, Griffiths 2011: 85). Two of the sampled individuals in this group (0487 and 0451) have values that are inconsistent with current measured biosphere ranges in England and Wales, whilst one adult has values that are comparable to the local biosphere range (0420/1) and could also have obtained their diet locally.

The oval cairn next to the linear mortuary structure (fig. 3) contained the burial of a single individual, a young woman (0957; figs. 2 and 3), who died between *3770–3670 cal BC* (*95% probability*, Griffiths 2011: 85). Enamel from the first and second permanent molars of this individual recorded $^{87}Sr/^{86}Sr$ values of 0.7164 and 0.7192 respectively (Supplementary Information: table 2). This individual obtained their diet from sources outside England and Wales during the earlier part of their childhood. However, enamel from third molar tooth, which begins to form at approximately eight to nine years of age (AlQahtani *et al.* 2010; Materials and Methods) has an $^{87}Sr/^{86}Sr$ value of 0.7105. The shift in $^{87}Sr/^{86}Sr$ values this individual exhibits between their second and third molar teeth, from a value of 0.7192 to 0.7105 (fig. 2), is consistent with a change in the geographical location from which the individual sourced their diet at this time. The strontium isotope ratio of enamel from the third molar is comparable to the local $^{87}Sr/^{86}Sr$ range within area in which the individual was buried (fig. 1). The change in values this individual exhibits between teeth may be plausibly interpreted to suggest that the individual moved from a location outside England and Wales to reach the area in which she was buried at approximately eight to nine years of age. The individual died at approximately sixteen to seventeen years of age, following the formation of her third molar tooth (Chamberlain and Witkin 2011: 74-75).

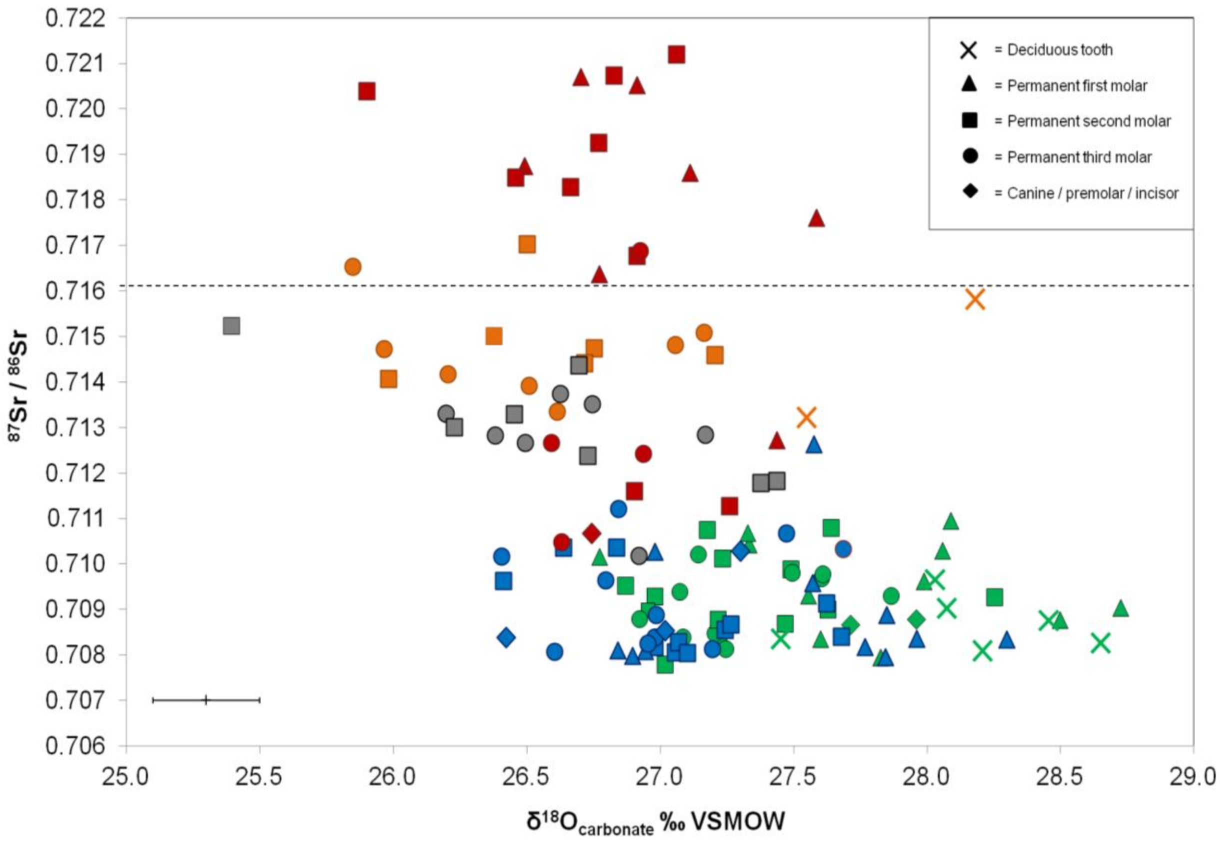


Figure 4. $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{carbonate}$ values of enamel from earlier Neolithic populations buried in England and Wales. Red symbols = Whitwell cairn; Orange symbols = Penywyrlod long cairn, Powys, southern Wales; Grey symbols = Ty Isaf long cairn, Powys, southern Wales; Blue symbols = Hazleton North long cairn, Gloucestershire, England; Green symbols = Hambledon Hill causewayed enclosure complex, Dorset, England (Data: Neil *et al.* 2016; **Chapters 2 to 5, this thesis**). The dashed line represents the highest currently recorded biosphere value in England and Wales (Chenery *et al.* 2010). Tooth types are denoted by the key in the upper right of the diagram. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2 ‰ (2σ).

$\delta^{18}O_{carbonate}$ values of enamel from second and third permanent molars with strontium isotope ratios comparable to those bioavailable in England and Wales range between 26.6 - 27.3 ‰ (mean 26.9 ± 0.3 ‰, 1σ, n = 5; fig. 4). If converted to $\delta^{18}O_{phosphate}$ these values range between 17.8 - 18.5 ‰ (mean 18.0 ± 0.3 ‰, 1σ, n = 5; Materials and Methods; Chenery *et al.* 2012). Teeth with $^{87}Sr/^{86}Sr$ values that exceed the current known bioavailable range within England and Wales exhibit a comparable range of $\delta^{18}O_{carbonate}$ values, ranging between 25.9 - 27.0 ‰ (mean 26.7 ± 0.4, 1σ, n = 8; or $\delta^{18}O_{phosphate}$ 17.0 - 18.3 ‰, mean 17.9 ± 0.4 ‰, 1σ, n = 8). Oxygen isotope ratios recorded in enamel at Whitwell are therefore comparable to those found within human archaeological populations buried in temperate regions of Europe (Lightfoot and O'Connell 2016). Due to climatic similarities, $\delta^{18}O_{phosphate}$ values exhibited by archaeological populations buried in Britain may overlap with those found on the adjacent near Continent, which may preclude distinction between these areas using oxygen isotope analysis (Lightfoot and O'Connell 2016; e.g. Evans *et al.* 2012; Brettell *et al.* 2012: 127). Values found at Whitwell do, however, contrast with oxygen isotope ratios measured amongst human burial populations that are associated with regions of cooler climate in Europe (e.g. Scandinavia, Montgomery *et al.* 2014; Chenery *et al.* 2014; Price and Naumann 2015, or the Alps, Müller *et al.* 2003), where lower values can be recorded ($\delta^{18}O_{carbonate}$ below approximately 24.5‰ or $\delta^{18}O_{phosphate}$ below approximately 15.5 ‰; ibid.).

First molar teeth were excluded from these comparisons, as with deciduous teeth formation of the first molar crown begins *in-utero* and continues during the months following birth and values may therefore be influenced by consumption of breast milk (Materials and Methods; Hillson 2014: 31 & 55-56; AlQahtani *et al.* 2010; Roberts *et al.* 1988: 625; Wright and Schwartz 1998: 14; Britton 2015: 8). However, at Whitwell $\delta^{18}O_{carbonate}$ values of enamel from first molar teeth (fig. 4) range between 26.5 - 27.6 ‰ (mean 27.0 ± 0.4 ‰, 1σ, n = 7; $\delta^{18}O_{phosphate}$ 17.7 - 18.8 ‰, mean 18.2 ± 0.4 ‰, 1σ, n = 7) and values are therefore comparable to those measured in enamel from second and third molar teeth (see above).

Strontium concentrations at Whitwell range between 11 - 109 ppm (mean 45 ± 29 ppm, 1σ, n = 21) and are therefore consistent with values previously recorded in human archaeological populations buried in north-western Europe (e.g. Evans *et al.* 2012: 755-756; Brettell *et al.* 2012: 127). $\delta^{13}C$ values of tooth enamel samples from Whitwell range between and -17.5 and -15.5 ‰ (mean -16.3 ± 0.6 ‰, 1σ, n = 21; Supplementary Information: table 2; fig. 5). Analysis of bone collagen from populations buried in Britain during the early Neolithic suggests that dietary protein was primarily derived from C_3 terrestrial sources during this period (e.g. Richards and Hedges 1999: 893; Richards *et al.* 2003; Schulting 2013: 327). At Whitwell $\delta^{13}C_{carbonate}$ values in tooth enamel, which reflect the isotope composition of the diet as a whole, including lipids and carbohydrates (Materials and Methods; Ambrose and Norr 1993; Jim *et al.* 2004), are consistent with those measured within other earlier Neolithic populations excavated within Britain, falling within the expected range for individuals who have obtained the majority of their diet from C_3 terrestrial sources (between approximately -17.0 to -14.0 ‰, Kellner and Schoeninger 2007; Froehle *et al.* 2012; Supplementary Information: fig. S1).

2.4 Discussion

According to current understanding of the principles of strontium isotope analysis and the analytical methodology as it is presently employed for the purpose of geographic provenancing the majority of individuals buried at Whitwell cannot have obtained their childhood diet from within England or Wales (e.g. Montgomery 2002; 2010, Bentley 2006; Slovak and Paytan 2011; Price 2015: 78; Materials and Methods). Biosphere $^{87}Sr/^{86}Sr$ values within the range that the individuals exhibit are associated with regions of ancient or granitic lithology located further afield: several regions within Europe can record biosphere $^{87}Sr/^{86}Sr$ values comparable to those exhibited by the burial group at Whitwell, such as the Massif Central, southern France, the Black Forest, south-western Germany, Norway and Sweden and the Alps (e.g. Willmes *et al.* 2013; Oelze *et al.* 2012; Bentley 2006: 145; Bentley and Knipper 2005; Price *et al.* 2015: 112; Müller *et al.* 2003; Voerkelius *et al.* 2010). However, these areas are not considered to provide parallels for the range of Neolithic material culture which is found within Britain during the early 4th millennium BC and the possibility that these individuals obtained their diet from these regions may therefore be ruled out on archaeological grounds.

Strontium isotope ratios found at Whitwell are higher than the present know biosphere $^{87}Sr/^{86}Sr$ range in Ireland (Snoeck *et al.* 2016). Bioavailable $^{87}Sr/^{86}Sr$ values higher than 0.7170 have been recorded in the Scottish highlands, in regions such as the Cairngorm mountains (Evans *et al.* 2010). However, current Bayesian modelling of presently available radiocarbon dates suggests that Neolithic material culture and practices appeared here in the decades around 3800 cal BC, and may therefore only recently have been established within this region of Scotland at the time of the deaths of the first individuals to be buried at Whitwell (Bayliss *et al.* 2011a: 822-824, 838-840).

Biosphere $^{87}Sr/^{86}Sr$ values within the range that individuals buried at Whitwell exhibit have been recorded in Lower Normandy and Brittany in north-western France (Willmes *et al.* 2013; Négrel and Pauwels 2004). Comparative analysis of Neolithic material culture has been used to argue that communities may have moved to Britain from this area during the early 4th millennium BC (e.g. Pioffet 2015; Sheridan 2010a, 2010b). The results may plausibly be interpreted to suggest that these individuals obtained their diet from this region during childhood.

Strontium isotope ratios comparable to those found at Whitwell, that exceed the current known bioavailable range for England and Wales, have also been recorded within another Neolithic monument, at Penywyrlod long cairn, in Powys, southern Wales (fig. 4). One individual buried within this monument also has $^{87}Sr/^{86}Sr$ values higher than 0.7170 (**Chapter 3, this thesis**). This individual has a calibrated radiocarbon date range (3770-3630 cal BC; 95% confidence; ibid), which may coincide with current radiocarbon dating estimates for the initiation of farming in southern Wales, toward the end of the 38th century BC (Bayliss *et al.* 2011: 736; Whittle *et al.* 2011: 836). This individual could have obtained their childhood diet from a similar region to that exploited by individuals buried at Whitwell. In contrast to Whitwell and Penywyrlod, all other earlier Neolithic individuals so far sampled with calibrated radiocarbon date ranges that fall after 3700 cal BC (fig. 4; at Hazleton

North, Gloucestershire, England; Hambledon Hill, Dorset, England and Ty Isaf, Powys, Wales), exhibit $^{87}Sr/^{86}Sr$ values that are consistent with those bioavailable within England and Wales and could therefore have obtained their childhood diet from these regions (Neil *et al.* 2016; **Chapters 3 to 5, this thesis**).

2.5 Conclusions

Radiocarbon dating suggests development of farming in Britain was an asynchronous process, that occurred over the first few centuries of the 4th millennium BC, with variation in both the regional timing and tempo of establishment of new cultural practices during this period (Bayliss *et al.* 2011; Whittle *et al.* 2011; Griffiths 2011). Mobility of communities during the early Neolithic has often been proposed to have played a role in this transition, with both the arrival of individuals from different regions of the near Continent at different times during first few centuries of the early 4th millennium BC, as well as interaction between local Mesolithic groups who lived within Britain and farming communities from the near Continent (e.g. Whittle *et al.* 2011: 861-863; Anderson-Whymark and Garrow 2015: 70; Cummings 2017). Bayesian modelling of radiocarbon dates indicates that the 38th century cal BC was associated with rapid acceleration in development of the Neolithic and intensification in the establishment of new cultural practices (Bayliss *et al.* 2011: 801). Whitwell cairn began to be used for burial at this time (Griffiths 2011: 85). According to all current understanding of the principles underlying strontium isotope analysis and the analytical methodology as it is currently employed (see Materials and Methods), the results provide evidence that the majority of the sampled group obtained their dietary resources outside England and Wales and suggest that these individuals moved over a very significant distance during the early Neolithic. Whilst a few of the individuals buried at Whitwell have values that may be comparable to the locally bioavailable range, according to all current scientific understanding, the majority of those buried at Whitwell cannot have obtained their diet locally during childhood. Biosphere $^{87}Sr/^{86}Sr$ values comparable to the range the majority of individuals within the group exhibit are recorded in regions more than 400 km away from Whitwell. Several regions within Europe have recorded bioavailable values that would be consistent with those found within the Whitwell burial population and the region from which of these individuals obtained their childhood diet cannot therefore be determined the basis on strontium isotope results alone. However, Neolithic material culture and practices, including the tradition of constructing burial monuments of the type in which these individuals were found, derive from established traditions on the European mainland (e.g. Scarre 2015; Cummings 2017). Recent comparative analysis of material culture suggests that these traditions may have been introduced to Britain from north-western France during the early 4th millennium BC (Pioffet 2015; Sheridan 2010a, 2010b). The individuals buried at Whitwell exhibit values that could be comparable to those bioavailable in this area (Négrel and Pauwels 2004; Wilmes *et al.* 2013) and the results may be interpreted to suggest these individuals obtained their childhood diet from that region.

2.6 Materials and Methods

2.6.1 Sample selection

Burials at Whitwell were located within a linear mortuary structure and a circular cairn, both of these structures were enclosed under a trapezoidal shaped mound. The linear mortuary structure was used for the collective burial of multiple individuals: over 900 disarticulated skeletal elements and bone fragments, representing a minimum number of 16 individuals (12 adults and 4 children), were recovered from within this structure (Chamberlain and Witkin 2011: 71-73). The circular cairn adjacent to the linear mortuary structure within the monument contained a single articulated inhumation burial (ibid. 2011: 74-75).

As the burial assemblage within the linear mortuary structure contained disarticulated and co-mingled human remains, care was taken to avoid the possibility of duplicating results through inadvertent sampling of mandibular and maxillary teeth that may have belonged to the same individual. To ensure all samples originated from discrete individuals only teeth that remained in-situ in mandibles were used for analysis. Loose teeth and teeth from maxillary fragments were not sampled. To avoid the potential for sampling antimeres, where mandibular dentition fragmented and incomplete only teeth from left mandibular fragments were sampled. Teeth in right sided mandibular fragments were not analysed unless the cross matching had side of the mandible was present.

To compare isotope ratios within the enamel of teeth that form at successive stages of early life, wherever possible, adjacent permanent molar teeth that mineralize at different stages of childhood and adolescence were sampled. Development of the crown of the first permanent adult molar tooth commences in-utero, just prior to birth and completes by approximately 4.5 ± 0.5 years of age, whilst the second molar crown forms between approximately 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31 & 55-56). The timing of formation of the human third permanent molar crown is more variable (Liversidge 2008: 313), with initial cusp formation beginning at approximately 8.5 ± 0.5 years of age and formation of the crown completing at around 14.5 ± 0.5 years (AlQahtani *et al.* 2010). Other teeth were selected if sampling of permanent molars was precluded by ante- or post- mortem tooth loss: in the case of individual 0359/1 all permanent molar teeth on both sides of the mandible had been lost ante-mortem and only one tooth remained in situ in the mandible, the right canine. This tooth was therefore chosen for sampling, the crown of this tooth begins to form between approximately 10.5 months and completes at around 7.5 ± 0.5 years of age (AlQahtani *et al.* 2010).

During sampling the approximate age at death of each individual included in the study was determined through visual assessment of the stage of tooth eruption and root development following AlQahtani (*et al.* 2010; table 2). Individuals with fully erupted permanent dentition are denoted as 'adult' in table 2 (see Supplementary Information). Due to disarticulation of skeletal elements in the burial assemblage from the linear mortuary structure and the inability to associate mandibles with other skeletal elements which conventional osteological methods use to assist in determination of sex, such as the pelvis, the sex of the majority individuals who cannot be stated with confidence. Only the skeleton of individual 0957, whose remains were recovered from the circular cairn within the monument, was found in an almost complete and fully articulated state (Vyner and Wall 2011). Osteological examination that was undertaken by Chamberlain and Witkin (2011: 74-75) suggests that this individual may have been female and aged between approximately 16-17 years of age at death.

2.6.3 Sample preparation and laboratory analysis

Procedures developed by Montgomery (2002) were used for processing of all teeth sampled during the study. Unlike other skeletal tissues, such as dentine, tooth enamel is considered to be highly resistant to diagenesis and to retain in-vivo $^{87}Sr/^{86}Sr$ values (e.g. Montgomery 2010: 329; Trickett *et al.* 2003; Montgomery 2002: 330-333; Budd *et al.* 2000). All the sampled teeth were completely mineralized. None of the sampled teeth exhibited any indication of visual changes to the surface of the enamel (e.g. caries, staining or opacity). To ensure removal of any exogenous soil-particulates the exterior enamel surface was removed through abrasion with a tungsten carbide dental burr. Chips of core enamel were then cut using a flexible diamond-edged rotary saw. Surfaces of each core enamel chip were then again mechanically cleaned using a tungsten carbide dental burr to ensure any adhering dentine was removed. To avoid cross contamination during sampling all dental burrs and saws were cleaned ultrasonically for 5 minutes and rinsed three times in high purity de-ionized water between preparation of samples. For strontium isotope analysis a chip of core enamel chip of approximately 20–30mg in weight was taken from each tooth. A chip of approximately 10mg in weight was taken for oxygen isotope analysis. Sampling was conducted on samples of bulk core enamel and isotope ratios are therefore considered to represent the weighted average of the sources of strontium to which the individual was exposed during the period the tooth was mineralizing (Montgomery 2010: 333).

Following preparation of core enamel chips in the laboratory facilities at Durham University all enamel samples were transferred to the Class 100, HEPA-filtered laboratory facilities at the Natural Environment Research Council Isotope

Geosciences Laboratory, (Keyworth, Nottingham, England). Here the enamel chips were cleaned ultrasonically, rinsed in high purity water (Millipore Alpha Q) and then dried and weighed into pre-cleaned Teflon beakers. To obtain strontium concentrations samples were spiked with a known amount of ^{84}Sr tracer solution. Each sample was then dissolved in Teflon distilled 8M HNO_3. Samples were converted to Chloride using 6M HCl, taken up in titrated 2.5M HCl and pipetted onto ion exchange chromatography columns. Strontium was separated with Dowex® (AG50-X8) resin (200-400 mesh). Procedural blanks were below 150 pg. Samples were loaded on to Re filaments using a method adapted from Birck (1986: 79). Strontium isotope composition and concentrations were then determined by Thermal Ionisation Mass spectroscopy (TIMS) using a *ThermoTriton* automated multi-collector mass spectrometer. $^{87}Sr/^{86}Sr$ values were normalised to the accepted value for $^{88}Sr/^{86}Sr$ = 0.1194 to correct for fractionation that occurs during the mass spectrometry process. During the period of this study the machine gave a value for the international standard for $^{87}Sr/^{86}Sr$ (NBS 987) of 0.710253 ± 0.000012 (2σ, n = 350).

Initial preparation of core enamel chips for $\delta^{18}O$ and $\delta^{13}C$ analysis was undertaken using the same methods employed for strontium isotope analysis. Samples were transferred as clean core enamel chips to the Natural Environment Research Council Isotope Geosciences Laboratory (Keyworth, Nottingham, England) where they were then powdered. Oxygen ($\delta^{18}O_{carbonate}$) and carbon ($\delta^{13}C_{carbonate}$) isotope ratios in the carbonate fraction of enamel were determined using the method outlined in Chenery *et al.* (2012: 310). Isotope ratios are reported as delta (δ) values, in parts per thousand (per mil; ‰) that are normalized to the VPDB scale using an in-house carbonate reference material, Keyworth Carrera Marble (KCM) which is calibrated against NBS19 certified reference material. For this run of KCM analytical reproducibility was ± 0.04 ‰ for $\delta^{13}C$ (1σ, n = 14) and ± 0.09 ‰ (1σ, n = 14) for $\delta^{18}O$. $\delta^{18}O_{carbonate}$ values were normalized to the VSMOW scale using the equation of Coplen 1988 (VSMOW = 1.03091 x $\delta^{18}O$ VPDB + 30.91). There are two ionic forms of oxygen within mammalian enamel that are suitable for oxygen isotope analysis: the present study undertook analysis on the structural carbonate (CO_3^{2-}) fraction of enamel. To enable comparison of these results to data from obtained from archaeological studies that have sampled the phosphate (PO_4^{3-}) fraction (e.g. Evans *et al.* 2012) conversion between $\delta^{18}O_{carbonate}$ to $\delta^{18}O_{phosphate}$ was undertaken, using the regression equation of Chenery *et al.* (2012: 310; $\delta^{18}O_{phosphate} = 1.0322 \times \delta^{18}O_{carbonate} - 9.6849$). In temperate climates, $\delta^{18}O$ values of the $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ fractions are considered to be well correlated and the error involved in calculating $\delta^{18}O_{phosphate}$ using this equation is considered to be low (0.28 ‰, 1σ, Chenery *et al.* 2012: 313).

2.7 Acknowledgements and author contributions statement

S.N. designed the research; S.N. and J.E. undertook the analysis; J.M. provided local biosphere data cited in Supplementary Information: table 1; S.N. wrote the paper. All authors discussed drafts of the manuscript. S.N. was funded through a Durham University Doctoral Studentship award; strontium and oxygen isotope analysis was funded through NIGFSC grant IP-1290-0512. We would particularly like to thank Hilary Sloane (NERC Isotope Geosciences Laboratory) for analytical support and Andrew Chamberlain, Blaise Vyner, Ian Wall, Maria Smith and Creswell Crags Museum for access to collections and for permission to undertake sampling.

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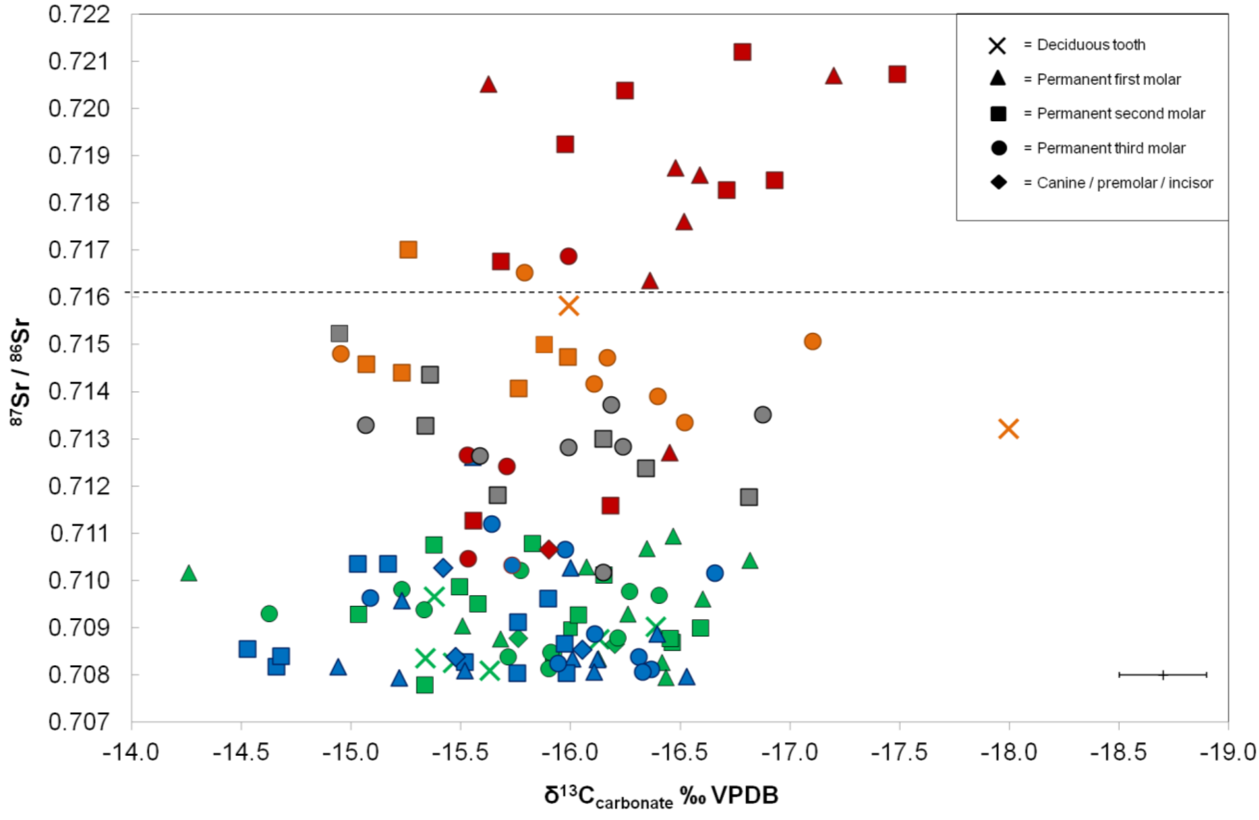
2.9 Supplementary information: figures and tables



Supplementary Information: figure S1. $^{87}Sr/^{86}Sr$ and $\delta^{13}C_{carbonate}$ values of enamel from earlier Neolithic burial populations in England and Wales. Tooth types are denoted by the key in the upper right of the diagram. The dashed line represents the highest currently recorded biosphere value in England and Wales (Chenery *et al.* 2010). Red symbols = Whitwell cairn; Orange symbols = Penywyrlod long cairn, Powys, southern Wales; Grey symbols = Ty Isaf long cairn, Powys, southern Wales; Blue symbols = Hazleton North long cairn, Gloucestershire, England; Green symbols = Hambledon Hill causewayed enclosure complex, Dorset, England (Data: Neil *et al.* 2016; **Chapters 2 to 4,** this thesis). Analytical error for $\delta^{13}C$ is shown as ± 0.2 ‰ (2σ). 2σ analytical errors for $^{87}Sr/^{86}Sr$ are within the symbol.

Supplementary Information: table 1 (over page). $^{87}Sr/^{86}Sr$ values used to calculate local bioavailable ranges. Samples taken on lithology of Permian age within 6 km of Whitwell cairn. Samples taken on lithology of Triassic and Carboniferous lithology within a radius of 100 km of Whitwell cairn. Data sources are as cited in the main text of the paper.

Supplementary Information: table 1

Latitude	Longitude	Sample	Sample name	$^{87}Sr^{86}Sr$	Source	Age	Geology
53.01983	-1.635328	plant	JMPD_03	0.709047	Janet Montgomery	Carboniferous	Bowland High Group and Craven Group
53.07121	-1.686982	plant	JMPD_05	0.710285	Janet Montgomery	Carboniferous	Bowland High Group and Craven Group
53.06438	-1.653008	plant	JMPD_06	0.709578	Janet Montgomery	Carboniferous	Bowland High Group and Craven Group
53.11237	-1.520559	plant	JMPD_10	0.711489	Janet Montgomery	Carboniferous	Bowland High Group and Craven Group
53.07964	-1.616462	plant	JMPD_07	0.7097	Janet Montgomery	Carboniferous	Dinantian rocks
53.12147	-1.526285	plant	JMPD_11	0.709535	Janet Montgomery	Carboniferous	Millstone Grit Group
53.14218	-1.450562	plant	JMPD_12	0.709117	Janet Montgomery	Carboniferous	Pennine Lower Coal Measures
53.22522	-1.374157	plant	JMPD_13	0.710648	Janet Montgomery	Carboniferous	Pennine Lower Coal Measures
53.22213	-1.349938	plant	JMPD_14	0.711395	Janet Montgomery	Carboniferous	Pennine Middle Coal Measures
53.21269	-1.33331	plant	JMPD_15	0.710967	Janet Montgomery	Carboniferous	Pennine Middle Coal Measures
52.58273	-1.600001	plant	JMPD_20	0.711836	Janet Montgomery	Carboniferous	Pennine Middle Coal Measures
53.3698	-1.3116	water	HWP-17	0.709378	Evans *et al.* 2010	Carboniferous	Pennine Middle Coal Measures
53.3056	-1.6253	water	JMW 25	0.711943	Montgomery *et al.* 2006	Carboniferous	Millstone Grit Group
53.2591	-1.9148	water	JMW 01	0.710184	Montgomery *et al.* 2006	Carboniferous	Bowland High Group and Craven Group
53.2165	-2.028	water	JMW 24	0.711923	Montgomery *et al.* 2006	Carboniferous	Millstone Grit Group
53.5841	-1.7088	water	JMW 68	0.711747	Montgomery *et al.* 2006	Carboniferous	Pennine Lower Coal Measures
53.6572	-1.7865	water	JMW 32	0.711462	Montgomery *et al.* 2006	Carboniferous	Pennine Lower Coal Measures
53.9875	-1.5638	water	JMW 11	0.711026	Montgomery *et al.* 2006	Carboniferous	Bowland High Group and Craven Group
53.24256	-1.153477	plant	JMPD_16	0.711651	Janet Montgomery	Permian	Sandstone and conglomerate
53.24359	-1.134126	plant	JMPD_17	0.709575	Janet Montgomery	Permian	Sandstone and conglomerate
53.24777	-1.179151	plant	JMPD_18	0.710829	Janet Montgomery	Permian	Mudstone, siltstone and sandstone
52.96401	-1.410986	plant	JMPD_01	0.71174	Janet Montgomery	Triassic	Mudstone, siltstone and sandstone
52.97475	-1.419627	plant	JMPD_02	0.712392	Janet Montgomery	Triassic	Mudstone, siltstone and sandstone
53.01326	-1.695003	plant	JMPD_04	0.709921	Janet Montgomery	Triassic	Sandstone and conglomerate
52.74651	-1.420737	plant	JMPD_19	0.712834	Janet Montgomery	Triassic	Sandstone and conglomerate
53.7696	-1.1504	plant	Hull-5	0.709372	Evans *et al.* 2010	Triassic	Sandstone and conglomerate
53.8298	-0.8255	plant	Hull-4	0.710181	Evans *et al.* 2010	Triassic	Mudstone, siltstone and sandstone
53.2874	-2.4166	water	Tabley Mere	0.710934	Montgomery *et al.* 2006	Triassic	Mudstone, siltstone and sandstone
52.7106	-1.1878	water	JMW 35	0.709631	Montgomery *et al.* 2006	Triassic	Mudstone, siltstone and sandstone

Supplementary Information: table 2. Results of $^{87}Sr/^{86}Sr$, $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ analysis of tooth enamel from Whitwell cairn. All teeth are from the mandibular dentition: L = left; R = Right; M1 = permanent first molar; M2 = permanent second molar; M3 = permanent third molar; C = canine. Phasing and contexts for skeletal remains are as documented by the excavators (Vyner and Wall 2011). U = statigraphically unassociated skeletal remains excavated from the linear mortuary structure. Radiocarbon dating of a sample of statigraphically unassociated remains from the linear mortuary structure estimates that they date to between *3760–3660 cal BC* (*95% probability*, Griffiths 2011: 85).

Museum accession number	Location	Phase	Age at death	Tooth	Sr ppm (mg/kg)	$^{87}Sr/^{86}Sr$	$\delta^{13}C_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VSMOW	$\delta^{18}O_{phosphate}$ ‰ VSMOW
WHIT 0534	Linear mortuary structure	2B	adult	LM1	19	0.71271	-16.5	-3.4	27.4	18.6
				LM2	26	0.71676	-15.7	-3.9	26.9	18.1
WHIT 0487	Linear mortuary structure	U	sub-adult (12 - 15 yrs)	RM1	28	0.72051	-15.6	-3.9	26.9	18.1
				RM2	24	0.72073	-17.5	-4.0	26.8	18.0
WHIT 0543	Linear mortuary structure	4B/5	sub-adult (12 - 15 yrs)	RM1	60	0.72070	-17.2	-4.1	26.7	17.9
				RM2	66	0.71827	-16.7	-4.1	26.7	17.8
WHIT 0420/1	Linear mortuary structure	U	adult	LM2	109	0.71126	-15.6	-3.5	27.3	18.5
				LM3	80	0.71266	-15.5	-4.2	26.6	17.8
WHIT 0451	Linear mortuary structure	U	sub-adult (10 -11 yrs)	RM1	23	0.71859	-16.6	-3.7	27.1	18.3
				RM2	30	0.72038	-16.2	-4.9	25.9	17.1
WHIT 0334	Linear mortuary structure	4B/5	adult	LM1	24	0.71874	-16.5	-4.3	26.5	17.7
				LM2	49	0.72119	-16.8	-3.7	27.1	18.2
WHIT 0512/2	Linear mortuary structure	4B/5	adult	LM2	85	0.71159	-16.2	-3.9	26.9	18.1
				LM3	91	0.71242	-15.7	-3.9	26.9	18.1
WHIT 0219	Linear mortuary structure	4B/5	adult	LM1	19	0.71760	-16.5	-3.2	27.6	18.8
				LM2	35	0.71849	-16.9	-4.3	26.5	17.6
				LM3	21	0.71687	-16.0	-3.9	26.9	18.1
WHIT 0359/1	Linear mortuary structure	4B/5	adult	RC	54	0.71067	-15.9	-4.1	26.7	17.9
WHIT 0957	Circular cairn		16 - 17 yrs	LM1	11	0.71636	-16.4	-4.0	26.8	18.0
				LM2	18	0.71925	-16.0	-4.0	26.8	17.9
				RM3	73	0.71047	-15.5	-4.2	26.6	17.8

3. Land use and mobility during the Neolithic in Wales explored using isotope analysis of tooth enamel

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Keywords:

Neolithic, strontium isotope analysis, radiocarbon dates, development of farming, Wales

3.1 Abstract

Objectives: The nature of land use and mobility during the transition to agriculture has often been debated. Here we use isotope analysis of tooth enamel from human populations buried in two different Neolithic burial monuments, Penywyrlod and Ty Isaf, in south-east Wales, to examine patterns of land use and to evaluate where individuals obtained their childhood diet.

Materials and Methods: We employ strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope analysis of enamel from adjacent molars. We compare strontium isotope values measured in enamel to locally bioavailable $^{87}Sr/^{86}Sr$ values. We combine discussion of these results with evaluation of new radiocarbon dates obtained from both sites.

Results: The majority of enamel samples from Penywyrlod have strontium isotope ratios above 0.7140. In contrast, the majority of those from Ty Isaf have $^{87}Sr/^{86}Sr$ values below 0.7140. At Penywyrlod oxygen isotope ratios range between 25.9 and 28.2 ‰ (mean 26.7 ± 0.6 ‰, 1σ, n = 15) and enamel $\delta^{13}C_{carbonate}$ values range between -18.0 and -15.0 ‰ (mean -16.0 ± 0.8 ‰, 1σ, n = 15). At Ty Isaf oxygen isotope ratios exhibited by Neolithic individuals range between 25.4 and 27.7 ‰ (mean 26.7 ± 0.6 ‰, 1σ, n = 15) and enamel $\delta^{13}C_{carbonate}$ values range between -16.9 and -14.9 ‰ (mean -16.0 ± 0.6 ‰, 1σ, n = 15).

Discussion: The strontium isotope results suggest that the majority of individuals buried at Penywyrlod did not source their childhood diet locally. One individual in this group has strontium isotope ratios that exceed all current known biosphere values within England and Wales. This individual is radiocarbon dated to the first few centuries of the 4th millennium BC, consistent with the period in which agriculture was initiated in Wales: the results therefore provide evidence for migration during the transition to farming in Wales. In contrast, all individuals sampled from Ty Isaf post-date the period in which agriculture is considered to have been initiated and could have sourced their childhood diet from the local region in which they were buried.

3.2 Introduction

The transition to farming in Britain during the 4th millennium BC was associated with the introduction of non-native domesticated species from the European mainland and the appearance of new cultural traditions and technologies, such as pottery manufacturing and burial monument construction. However, the mechanisms underlying this transition have been heavily debated. Both agriculture and traditions such as monument construction and pottery manufacturing were well established on the Continent at this time (e.g. Tresset 2015; Scarre 2015; Bradley 2015). Some authors suggest that local Mesolithic communities within Britain chose to adopt these practices, importing domesticated species from the near Continent during the early 4th millennium BC (Thomas 2003: 73, 2004: 105, 2007: 426; 2008: 77, 2013: 273; Cummings and Whittle 2004: 88-91; Cummings and Harris 2011). In contrast, others argue that these traditions were introduced by migration of farming communities to Britain from the European mainland (Sheridan 2004, 2007: 465-467, 2010a; Pailler and Sheridan 2009: 29; Collard *et al.* 2010; Whittle *et al.* 2011: 858-861; Rowley-Conwy 2011: 443; Anderson-Wymark and Garrow 2015). These authors suggest that a transformation in subsistence practices during the early 4th millennium BC and a shift from hunting of wild animals and routine exploitation of marine foods toward heavy reliance on terrestrial domesticated resources, was a consequence of the arrival of farming groups (e.g. Richards and Hedges 1999; Richards *et al.* 2003; Richards and Schulting 2006: 453; Schulting 2008: 93-95; Serjeantson 2014: 261). The area of the European mainland from which such groups may have originated, however, remains the subject of debate (e.g. Sheridan 2010a, Whittle *et al.* 2011: 848-853; Anderson-Wymark and Garrow 2015). Radiocarbon dating suggests that Neolithic material culture and practices began to appear in different regions of Britain at different times (Bayliss *et al.* 2011a: 839). Whilst agriculture is thought to have become established in south-eastern England at approximately 4,000 BC, in other regions, such as Wales, Scotland and Ireland, Neolithic material culture and practices began to appear during the following two to three centuries (Bayliss *et al.* 2011a, 2011b; Cooney *et al.* 2011; Whittle *et al.* 2011: 861-862). Recent comparative analysis of pottery could indicate that farming populations arrived from different regions of the European mainland at different times during the early 4th millennium BC, as pottery found in eastern Britain appears to reflect influences from north-eastern France and the Scheldt valley, whilst that found in Western Britain is considered to derive from traditions in Brittany and Lower Normandy, in north-western France (Pioffet 2015; cf. Sheridan 2010b).

The nature of land use and residence patterns during the Neolithic in Britain has also been the subject of intense debate. Some authors suggest the first farmers in Britain were fully sedentary and argue that communities obtained the majority of their dietary resources, keeping livestock and cultivating crops, close to permanently occupied settlements (Rowley-Conwy 2003, 2004, 2011; Bogaard *et al.* 2013: 12589). These authors place emphasis on the discovery of substantial timber buildings and argue that mobility of early farming communities was limited by the demands of cereal cultivation (Rowley-Conwy 2000, 2003; Jones 2000; Jones and Rowley-Conwy 2007; Jones 2005: 172-173; Rowley-Conwy and Legge 2015).

Others, however, suggest that there was greater diversity in subsistence and settlement patterns. These authors highlight evidence for exploitation of a varied range of resources during the early Neolithic in Britain, including use of both wild plants and cereals (e.g. Stevens 2007: 381-382; Bishop *et al.* 2009: 86 and 90) and suggest that evidence for cattle herding could indicate that some members of the community were residentially mobile (Thomas 2013: 411; e.g. Serjeantson 2011; Viner 2011; Schulting 2013: 321). A varied range of evidence for occupation may also be indicative of diversity in settlement systems during the early Neolithic in Britain (e.g. Sheridan 2013; Brophy 2015; Anderson-Whymark and Thomas 2012). In addition to the remains of substantial timber buildings, the presence of ephemeral structures, pits, lithic scatters and middens could indicate communities moved episodically between occupation sites that were located in different geographical areas to obtain their dietary resources (Whittle 2003: 43; Garrow *et al.* 2005: 155).

In view of these debates we applied strontium ($^{87}Sr/^{86}Sr$) and oxygen ($\delta^{18}O$) isotope analysis of tooth enamel, which can be used to provide evidence for the location from which individuals may have obtained their childhood diet (e.g. Montgomery 2002, 2010; Bentley 2006; Slovak and Paytan 2011: 743-744), to explore patterns of land use and mobility during the Neolithic. Here we present the results of analysis of individuals from two burial monuments, the long cairns of Penywyrlod (Talgarth) and Ty Isaf, located less than 5 miles (8 km) apart amongst a cluster of monuments in the Black Mountains, Powys, south-eastern Wales (fig. 1). Currently archaeological evidence for the nature of settlement in this region is very limited, few structural remains of Neolithic date have so far been discovered and surface lithic scatters dominate the archaeological record (Olding 2000; Makepeace 2006).

The long cairns of Penywyrlod (Talgarth) and Ty Isaf are part of the Cotswold-Severn group, a concentration of burial monuments located in the regions around the Severn Estuary: south-east Wales, the Cotswolds, Somerset and Wiltshire in southern Britain (Darvill 2004: 71-72). Although sharing a common geographical distribution, long cairns within the Cotswold-Severn group are diverse in form. Penywyrlod (Talgarth) is a substantial long cairn over 60 metres in length. Partial excavation of the north-eastern side of the monument revealed three lateral chambers which contained co-mingled and disarticulated human remains (fig. 2, Savory 1973: 187, 1984; Luff 1984). Following excavation a sample of human bone recovered from one of the excavated chambers (chamber NEII) was radiocarbon dated to between 3960-3640 cal BC (95% confidence, OxCal v. 4.2; Britnell and Savory 1984: 29). In contrast, Ty Isaf is approximately 30 metres in length and is a composite monument consisting of two distinct elements: a long cairn with two opposing lateral chambers (chambers 1 and 2; fig. 3 over page) and a circular rotunda containing a transepted passage grave (chamber 3; fig. 3; Grimes 1939: 123-124). Human remains within the transepted passage grave in the rotunda date from the mid 4th to earlier 3rd millennium BC (Bayliss *et al.* 2011b: 537, 546-547, see Radiocarbon Dating below).

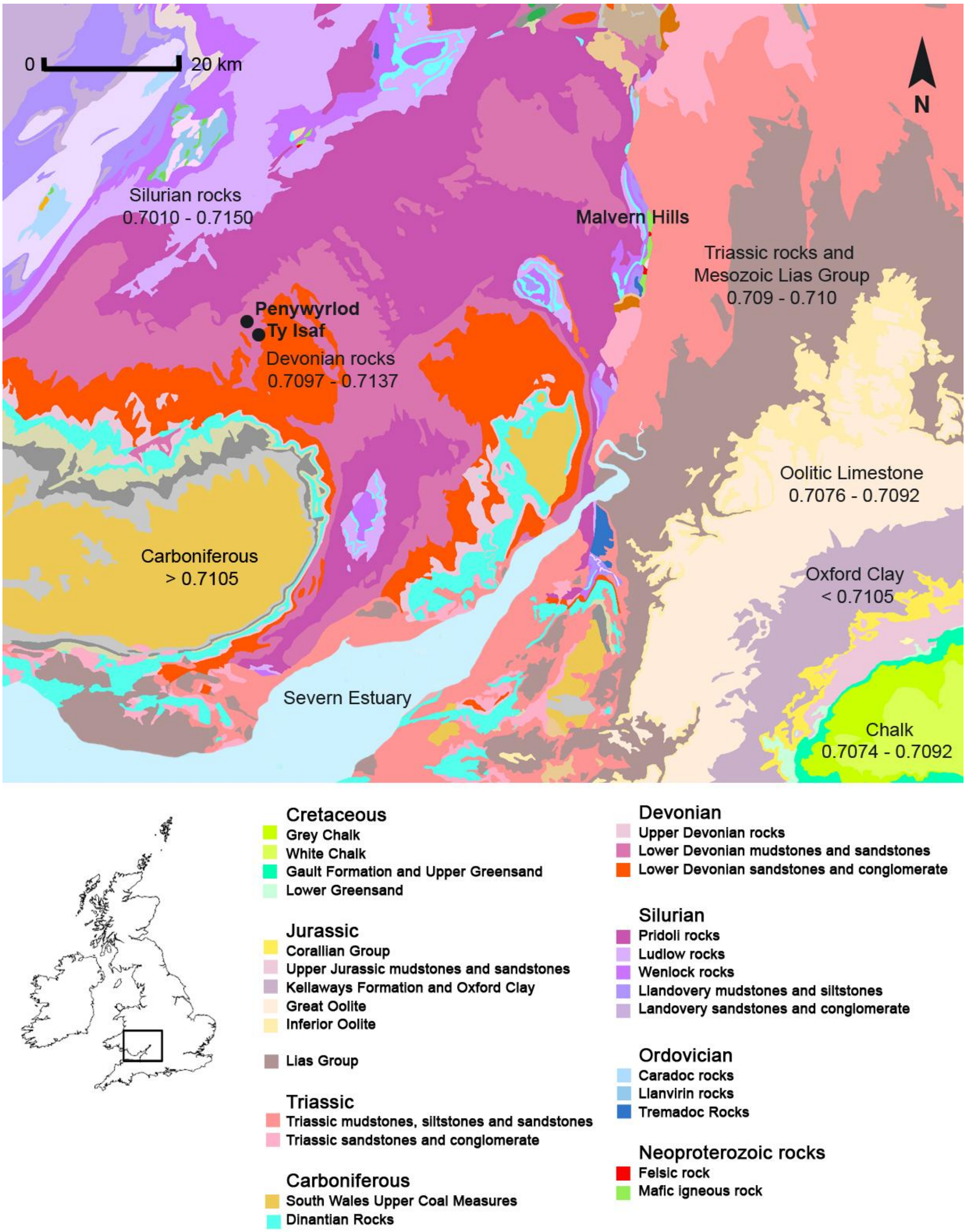


Figure 1. Map of bedrock geology illustrating sites and locations discussed in the text. Based on British Geological Survey and Ordnance Survey map data, reproduced with permission of the British Geological Survey and Ordnance Survey, © NERC / Crown copyright [2016]. Bioavailable $^{87}Sr/^{86}Sr$ ranges based on current measured values in Warham (2011: 70-96); Evans *et al.* (2010); Chenery *et al.* (2010); Montgomery *et al.* (2006) and Spiro *et al.* (2001). Locally bioavailable strontium isotope ratios on Devonian sandstones derived from measured values in plants collected within a radius of 10 miles, approximately 16 km, of Penywyrlod and Ty Isaf (table 3).

Figure 2. Penywyrlod (Talgarth) long cairn. Grey shaded areas are those which have been excavated. Image by Clwyd-Powys Archaeological Trust; after Britnell and Savory 1984. Reproduced with permission of W.J. Britnell.

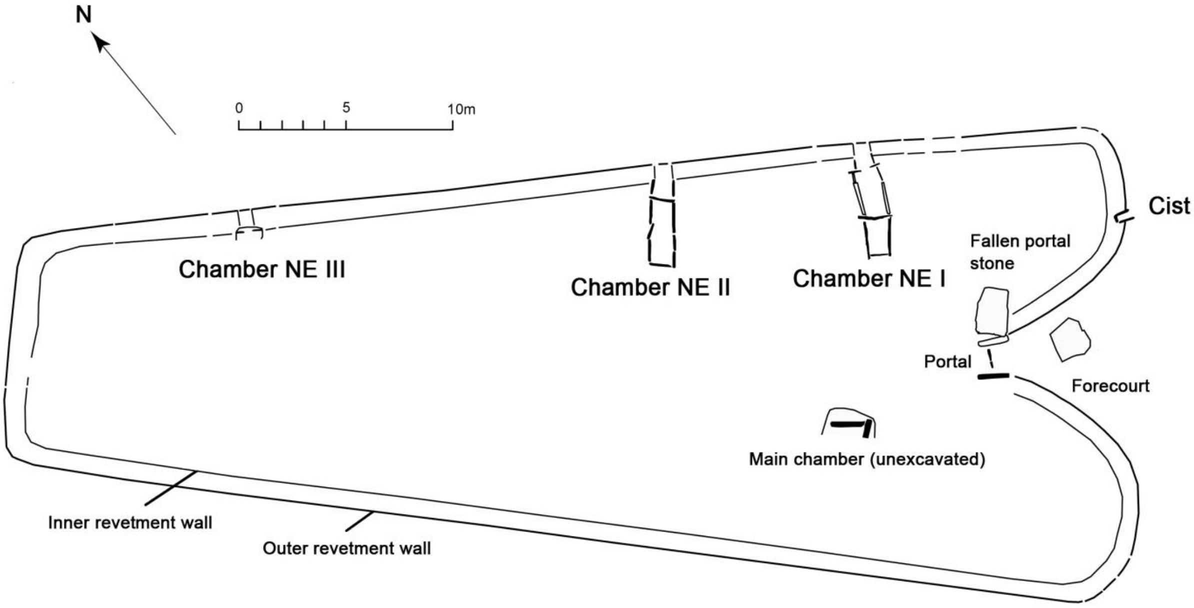
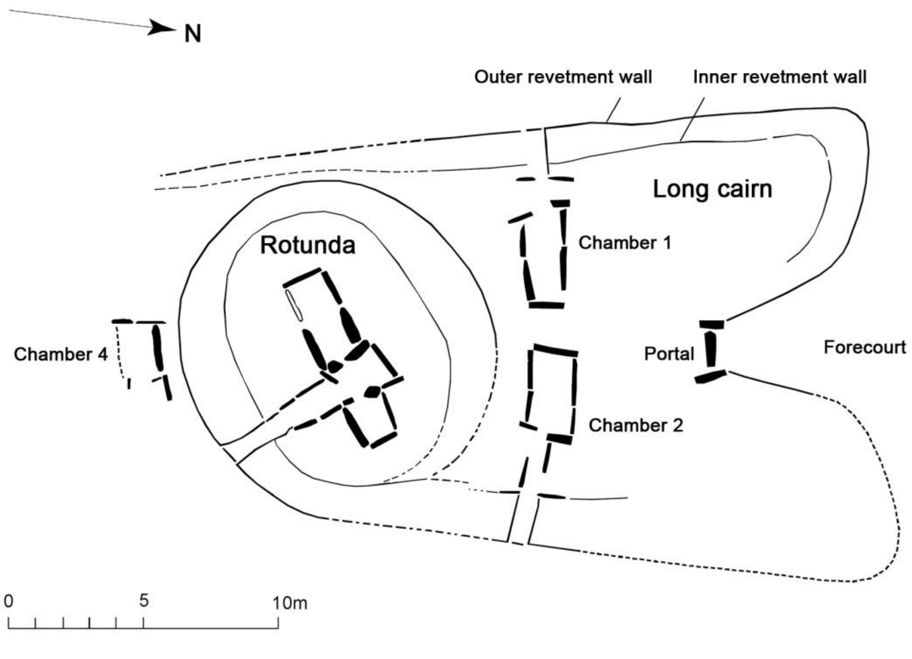


Figure 3. Ty Isaf long cairn. Image by Clwyd-Powys Archaeological Trust; after Grimes 1939: 123. Reproduced with permission of W.J. Britnell.



3.2.1 Strontium isotope analysis: principles

Use of strontium ($^{87}Sr/^{86}Sr$) isotope analysis for geographic provenancing is based on the principle that $^{87}Sr/^{86}Sr$ varies geographically depending on the age and composition of bedrock (Faure 1986: 183-199; Faure and Mensing 2005: 76; Dicken 2005: 42-43) and that humans derive strontium in their diet from biosphere sources (e.g. Montgomery 2002: 17, 24 and 36; Bentley 2006: 141; Montgomery 2010: 328). Strontium weathers from rocks, entering soils and ground waters where it becomes available to plants and is transferred up the food chain (Capo *et al.* 1998: 202-203), and incorporated into the mammalian skeleton. Tooth enamel is composed of carbonated hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (Hillson 2005: 146-147); the calcium phosphate lattice, however, permits incorporation of other ions, such as strontium which is substituted for calcium (Johnson *et al.* 1966; Rokita *et al.* 1993). Strontium isotope analysis is undertaken on enamel as it is highly resistant to diagenesis (e.g. Budd *et al.* 2000; Trickett *et al.* 2003). As conventionally measured $^{87}Sr/^{86}Sr$ values do not vary significantly between trophic levels (Graustein 1989: 492; e.g. Blum *et al.* 2000) and as enamel does not remodel once mineralized, strontium isotope ratios directly reflect sources to which an individual was exposed during tooth formation (Montgomery 2002; Bentley 2006). Strontium isotope ratios in modern plants and waters have been shown to vary with the age and composition of the underlying lithology (e.g. Evans *et al.* 2010; Warham 2011; Willmes *et al.* 2013). Comparison of $^{87}Sr/^{86}Sr$ values to mapped bioavailable values can therefore be used to evaluate whether an individual obtained dietary resources from the area in which they were later buried or whether they sourced their diet from a region further afield.

As indicated above there are particularly dense concentrations of Neolithic burial monuments in some regions of Britain, such as the Black Mountains in south-eastern Wales. Isotope analysis of tooth enamel may assist in understanding why particular regions were chosen for monument construction: if individuals have values comparable to the local $^{87}Sr/^{86}Sr$ biosphere range it could suggest that monuments were located in areas used for settlement. Early Neolithic monuments contain the remains of multiple indivduals (see Materials and Method, below). Comparison of the isotope ratios exhibited by different individuals within a monument may be used to infer whether they could have sourced their childhood diet from a similar geographical location. Likewise, comparison of isotope ratios in teeth that form at successive stages of childhood and adolescence can also be used to evaluate whether an individual obtained their diet from a similar geographical location throughout early life.

Both Penywyrlod and Ty Isaf are located on mudstones and sandstones formed during the early Devonian period (St Maughans Formation, BGS 2016). Samples of plants and water taken on Devonian lithology of similar age in Hereford, south-east Gloucestershire, east Somerset and north Devon have previously recorded $^{87}Sr/^{86}Sr$ values between 0.7113 - 0.7129 (mean 0.7121 ± 0.0005, 1σ, n = 6, Evans *et al.* 2010; Chenery *et al.* 2010: 155; Montgomery *et al.* 2006: 1628). All currently available measured biosphere data therefore suggests that $^{87}Sr/^{86}Sr$ values above 0.7140 are not bioavailable on Devonian lithology (ibid). To provide further direct evidence for the range of locally bioavailable $^{87}Sr/^{86}Sr$ values at Penywyrlod and Ty Isaf the present study presents the results of analysis of modern plants growing on lithology of

Devonian age within radius of 10 miles (approximately 16 km) of both sites (Materials and Methods).

Samples of plants and water taken on lithology of Silurian age in Wales have previously recorded values between 0.7010 and 0.7150 (mean 0.7120 ± 0.0012, 1σ, n = 16) whilst those taken on Ordovician rocks have recorded a range of values between 0.7093 - 0.7152 (mean 0.7128 ± 0.0002, 1σ, n = 64,) Evans *et al.* 2010; Shand *et al.* 2007: 254, 256; Montgomery *et al.* 2006: 1628), highlighting the potential for heterogeneity in bioavailable strontium isotope ratios on lithology of Lower Palaeozoic age. Samples of deep groundwater taken on lithology of Lower Palaeozoic age in central Wales can give values up to 0.7152 (Shand *et al.* 2007: 256), however, all presently available biosphere data suggests that lithologies of this age in Wales are routinely associated with lower mean values.

The oldest rocks in England and Wales crop out approximately 16 miles (26 km) to the north-east of Penywyrlod and Ty Isaf at Stanner Hill close to the English-Welsh border and just over 35 miles (56 km) to the east within the Malvern Hills in the counties of Herefordshire and Worcestershire (BGS 2016; Woodcock and Strachan 2012: 140). A single sample of plants growing on rocks of Neoproterozoic age in the Malvern Hills produced the highest bioavailable $^{87}Sr/^{86}Sr$ value currently known within England and Wales (0.7162, Chenery *et al.* 2010: 155). However, as rocks of this age crop out in a very limited geographical area, values such as this have so far remained difficult to reproduce (Lucie Johnson, pers. comm.), with water sampled close to the Malvern Hills having given a value of 0.7132 (Montgomery *et al.* 2006: 1628) and plants recording a mean $^{87}Sr/^{86}Sr$ value of 0.7128 ± 0.0040 (2σ, n = 13, Chenery *et al.* 2010: 155-156).

3.2.2 Oxygen and carbon isotope analysis: principles

The oxygen isotope composition of water also varies geographically with factors such as temperature, latitude, altitude and distance from the coast (e.g. Mook 2005: 89-98; Gat 2010). Britain receives most of its rainfall from a westerly direction and contemporary groundwaters in western Britain therefore record higher $\delta^{18}O$ values than those in eastern Britain (Darling *et al.* 2003: 189-190). The use of oxygen isotope analysis for geographic provenancing of human individuals is based on the premise that, although there is some contribution from respiratory oxygen and chemically-bound oxygen in food, a significant component of the $\delta^{18}O$ values in mammalian bioapatite derives from ingested fluids which can therefore reflect values in drinking water (e.g. Luz *et al.* 1984; Longinelli 1984; Luz and Kolodny 1985; Levinson *et al.* 1987; Daux *et al.* 2008: 1146; Podlesak *et al.* 2008; Kirsanow and Tuross 2011). Evans *et al.* (2012: 759) argue that a statistically significant difference in the mean $\delta^{18}O$ values of tooth enamel from multi-period archaeological populations buried in western Britain (18.2 ‰ ± 1.0 ‰, 2σ) to those buried within eastern Britain (17.2 ± 1.3 ‰, 2σ) reflects differences in the oxygen isotope composition of local drinking water between these two regions. A recent overview of all currently published human tooth enamel and bone bioapatite data demonstrates that oxygen isotope values exhibited by human archaeological populations are correlated with environmental factors such as latitude, longitude, altitude (Lightfoot and O'Connell 2016). However, it also highlights the way in which the oxygen isotope ranges of populations buried in different areas of temperate Europe can overlap (ibid.). As such, $\delta^{18}O$ values exhibited by individuals excavated on the immediate European mainland may be similar to those recorded in Britain (e.g. see Brettell *et al.* 2012b: 127).

The above $\delta^{18}O$ ranges for multi-period archaeological populations buried in Britain were determined from the phosphate (PO_4^{3-}) fraction of tooth enamel. However, just as calcium can be replaced by strontium in the bioapatite lattice (see above), both the hydroxyl $(OH)^-$ and phosphate (PO_4^{3-}) groups can also be substituted by carbonate (CO_3^{2-}) (LeGeros 1991: 119-121; Sønju Clasen and Ruyter 1997). The structural carbonate (CO_3^{2-}) fraction of tooth enamel of Holocene age is considered to be resistant to diagenesis (e.g. Zazzo 2014; Koch 1997) and was analysed in the present study. $\delta^{18}O$ values of the $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ fractions are considered to be well correlated and conversion between the two was therefore undertaken using the equation of Chenery *et al.* (2012; see Materials and Method, below). The interpretation of results must, however, give consideration to the potential influence of culinary practice (e.g. stewing foods and brewing: Brettell *et al.* 2012a; Daux *et al.* 2008: 1144), or the consumption of fluids that have undergone fractionation through biological processes (e.g. cow's milk, Kornexl *et al.* 1997: 22; Camin *et al.* 2008: 1695; Lin *et. al.* 2003: 2193), on the $\delta^{18}O$ values of ingested fluids (Lightfoot and O'Connell 2016). Breast milk can have a higher $\delta^{18}O$ value relative to fluids consumed by the mother and teeth which form whilst an infant is being breast fed (e.g. deciduous molars) may therefore have higher values than teeth that form later in childhood (Roberts *et al.* 1988: 625; Wright and Schwartz 1998: 14; Britton *et al.* 2015: 8).

Isotope analysis of the structural carbonate fraction of enamel simultaneously yields carbon isotope ratios ($\delta^{13}C_{carbonate}$) which provide additional dietary information. Use of carbon isotope analysis for this purpose exploits the large natural variation in $\delta^{13}C$ values of plants that use the two dominant (C_3 or C_4) photosynthetic pathways during fixation of CO_2 energy, and contrasting $\delta^{13}C$ values of terrestrial C_3 and marine ecosystems (Schwarcz and Schoeninger 2011; Sponheimer and Cerling 2014). Current understanding of dietary composition in the European Neolithic is primarily based on analysis of $\delta^{13}C$ and $\delta^{15}N$ values in bone collagen, which predominantly reflect the protein component of the diet and support routine exploitation of C_3 terrestrial sources of protein during the early Neolithic in Britain (e.g. Richards and Hedges 1999: 893; Richards *et al.* 2003). In contrast, $\delta^{13}C_{carbonate}$ values in bioapatite reflect the isotope composition of the diet as a whole, including lipids and carbohydrates (Ambrose and Norr 1993: 2; Jim *et al.* 2004). Individuals who obtain the majority of their diet from C_3 terrestrial sources may be predicted to have $\delta^{13}C_{carbonate}$ values between approximately -17.0 to -14.0 ‰ (Kellner and Schoeninger 2007; Froehle *et al.* 2012).

3.2.3 Radiocarbon dating

The program of radiocarbon dating conducted by Bayliss *et al.* (2011b: 537, 546-547) found that the majority of sampled individuals buried in the transepted passage grave within the rotunda at Ty Isaf dated from the mid to late 4th millennium BC. However, individuals buried in the adjoining long cairn (fig. 3) have not been radiocarbon dated. The excavator was unable to determine which of the two monuments was constructed first: it is possible that both of these monuments were in use at the same time; alternatively, the rotunda could have been inserted into the long cairn at a later date (Grimes 1939: 137-8). In addition, radiocarbon dating of bone from the rotunda also revealed the presence of several individuals dated to the earlier third millennium BC (OxA-14248, 2900-2670 cal BC and OxA-14250, 2860-2490 cal BC, Bayliss *et al.* 2011b: 537; OxCal v4.2, IntCal13), which is argued to indicate that Ty Isaf was the focus of secondary burial activity during the later Neolithic (ibid.). Fragments of Bronze Age pottery found during excavation could also suggest the site was a focus for activity during later periods (Grimes 1939: 125, 130 and 135-6). All burials sampled by the present study from Ty Isaf were therefore radiocarbon dated to assist in evaluating whether individuals buried in the long cairn are contemporary with those in the rotunda and whether the site remained of importance to communities beyond the 4th millennium BC.

3.3 Materials and methods

3.3.1 Sample selection

Burial assemblages from Penywyrlod and Ty Isaf long cairns consist of highly fragmentary disarticulated and co-mingled human remains. Care therefore had to be taken to avoid the potential for duplication of isotope results through inadvertent sampling of cross matching fragments of dentition (e.g. mandibular and maxillary) that could belong to the same individual. Only teeth from the left mandibular dentition were selected for sampling. Nine different human individuals from Ty Isaf were sampled (table 1). Left mandibular dentition from nine different individuals from Penywyrlod was sampled (table 2). In addition, two pre-existing chips of core enamel taken in 2003-2004 from right mandibular third molars from Penywyrlod by a project unrelated to the present study were also analysed to obtain isotope ratios: 74.23H/9.5.19/P27 and 74.23H/9.16/P27 (table 2).

Information on the contexts of sampled specimens (where available) is given on the labelling and documentation associated with the collections now stored in the National Museum Wales and is provided in tables 1 and 2. No dentition attributed to the rotunda monument at Ty Isaf could be located that met the criteria for sampling specified above. Four of the specimens from Ty Isaf lacked documentation detailing their excavation context (those listed in table 1 as being of 'undocumented' context). These specimens could either have been excavated from the rotunda or the lateral chambers of the long cairn at Ty Isaf.

The human burial assemblage from Penywyrlod was recovered during a partial rescue excavation that was instigated following damage to the monument (Savory 1973, 1984). It therefore represents a sample of what may be present at the site. The current study undertook analysis of tooth enamel from individuals buried in two of the three excavated chambers (Chambers NE II and NE III) and in a cist in the forecourt, within the lower revetment wall of the south-east horn of the monument (figure 2). Few remains were recovered during excavation of Chamber NE I (Savory 1984: 18; Britnell and Savory 1984: 6) and no dentition from this chamber was available that met the criteria for sampling specified above. During assessment of the collections it was found that several specimens from Penywyrlod possessed the same generic museum accession number. In order to differentiate between specimens, each was assigned an additional unique code, corresponding to the page number on which the specimen is listed in the sampling application made to the National Museum Wales (e.g. P21 refers to page 21 of the sampling application).

The sex of the majority of sampled individuals cannot be determined with confidence owing to the fragmentary nature of the assemblages and disarticulation of cranial remains from other skeletal elements used for sex attribution. Facial reconstruction commissioned by the National Museum Wales for the purpose of gallery display suggests individual 74.23H/9.23/P22 is male. Wherever possible, the approximate age of individuals at death (tables 1 and 2) was determined from stage of dental eruption and tooth root development, following AlQahtani *et al.* (2010). Individuals who have fully erupted permanent dentition with fully formed third molar tooth roots are denoted as 'adult' in tables 1 and 2. Where possible, consecutively mineralizing molars were sampled to compare isotope ratios at different stages of childhood: formation of the second molar crown occurs between approximately 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31, 55-56). Timing of third molar formation is more variable (Liversidge 2008: 313), with initial cusp formation from approximately 8.5 ± 0.5 years of age and crown completion by approximately 14.5 ± 0.5 years (AlQahtani *et al.* 2010). Strontium and oxygen isotope analysis was undertaken on samples of bulk enamel, and isotope ratios therefore represent the weighted average of all dietary sources exploited during the period in which the enamel was forming (Montgomery 2010: 333). An enamel chip of approximately 20–30mg in weight from each tooth was utilized for strontium isotope analysis and of approximately 10mg in weight for oxygen isotope analysis.

A limited number of fragmentary animal remains were also recovered during the excavation of Ty Isaf (Cowley 1939: 141-142), including a loose cattle third permanent premolar tooth (table 1). This was sampled to compare strontium isotope ratios with those of the human burial group. Although formation of the tooth crown proceeds from cusp to cervix (Hillson 2005: 156), complexity in the process of enamel maturation and averaging of strontium in the body pool prior to incorporation into enamel may limit the study of $^{87}Sr/^{86}Sr$ values at high chronological resolution in human populations (e.g. Montgomery *et al.* 2010). In bovine high crowned (hypsodont) teeth it may, however, be possible to detect variation in strontium isotope ratios by taking spatially separated samples along the axis of tooth formation (e.g. Viner *et al.* 2010). One sample of enamel, of a similar size to those sampled from each human tooth, was therefore excised from the top (cusp) and one at the bottom (cervix) of the tooth crown. As the earliest forming enamel at the cusp can be eliminated through dental attrition the location from which these samples were excised was recorded in millimetres with respect to the cervical margin (table 1). The sampled cattle tooth was a loose permanent third molar. In modern cattle the third permanent premolar crown begins to form at approximately 11-12 months of age and formation of the crown of this tooth is complete by approximately 24-30 months (Brown *et al*. 1960).

3.3.2 Sample preparation and laboratory analysis

Initial preparation of enamel samples for isotope analysis was undertaken in the laboratories at Durham University following procedures developed by Montgomery (2002: 131-138). The enamel surface was mechanically cleaned using tungsten carbide dental burrs and a flexible diamond edged rotary saw was then used to excise a chip of core enamel. To remove any adhering dentine, exposed surfaces of the enamel chip were again thoroughly abraded using dental burrs. Resulting chips of core enamel were transferred to clean sealed containers. Dental saws and burrs were cleaned ultrasonically for five minutes and rinsed three times in high purity de-ionized water between preparation of samples.

$^{87}Sr/^{86}Sr$ analysis was undertaken in the Class 100, HEPA-filtered laboratory facilities at the Natural Environment Research Council Isotope Geosciences Laboratory (Keyworth, Nottingham, England). Dried plant samples were lightly crushed and placed into pre-cleaned pressure vessels in a clean laboratory environment. They were digested using 8M HNO_3 and a trace of hydrogen peroxide in a microwave oven at 175^{o}C for 20 minutes according to methods described in Warham (2011). Enamel chips were cleaned ultrasonically, rinsed in high purity (Millipore Alpha Q) water and dried. They were then weighed into pre-cleaned Teflon beakers and spiked with a known amount of ^{84}Sr tracer solution to obtain strontium concentrations. Each enamel chip was then dissolved in Teflon distilled 8M HNO_3, then converted to chloride using 6M HCl, taken up in titrated 2.5M HCl and pipetted onto ion exchange chromatography columns. Strontium was separated with Dowex® (AG50-X8) resin (200 - 400 mesh). Procedural blanks were below 150 pg. Samples were loaded on to Re filaments following the method adapted from Birck (1986: 79). Strontium isotope composition and concentrations were determined by thermal ionisation mass spectrometry (TIMS) using a *ThermoTriton* automated multi-collector mass spectrometer. To correct for fractionation during the process of mass spectrometry $^{87}Sr/^{86}Sr$ values are normalised to the accepted value for $^{88}Sr/^{86}Sr$ = 0.1194. During the period of this study the machine gave a $^{87}Sr/^{86}Sr$ value for the international standard, NBS 987, of 0.710253 ± 0.000012 (2σ, n = 350). An estimate of the reproducibility of strontium concentration (Sr ppm) is provided by replicate analyses of an aliquot of bone standard solution (NIST1486) which gave 7.22 ± 0.27 ppm (± 3.75%, 1σ, n = 16).

Initial preparation of core enamel chips for $\delta^{18}O$ and $\delta^{13}C$ analysis was undertaken at Durham University using the same methods employed above for strontium isotope analysis. Core enamel chips were then transferred to the laboratory facilities at the Natural Environment Research Council Isotope Geosciences Laboratory (Keyworth, Nottingham, England), where they were powdered. Oxygen ($\delta^{18}O_{carbonate}$) and carbon ($\delta^{13}C_{carbonate}$) isotope ratios in the carbonate fraction of enamel were determined according to the methodology outlined in Chenery *et al.* (2012: 310): approximately 3 mg of clean powdered enamel was placed in glass vials which were sealed with septa and transferred to a hot block at 90°C on a Multiprep system (GV Instruments, Manchester, UK). Vials were evacuated and four drops of anhydrous phosphoric acid added and resultant CO_2 collected cryogenically for 14 min. A GV IsoPrime dual inlet mass spectrometer was used to measure $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ values. Isotope ratios are reported as delta (δ) values, in parts per thousand (per mil; ‰) normalized to the VPDB scale using an in-house carbonate reference material, Keyworth Carrera Marble (KCM) calibrated against NBS19 certified reference material. Analytical reproducibility for this run of KCM was ± 0.09 ‰ (1σ, n = 14) for $\delta^{18}O$ and for $\delta^{13}C$ ± 0.04 ‰ (1σ, n = 14). $\delta^{18}O_{carbonate}$ values were normalized to the VSMOW scale using the equation of Coplen 1988 (VSMOW = 1.03091 x $\delta^{18}O$ VPDB + 30.91) and the regression equation of Chenery *et al.* (2012: 310; $\delta^{18}O_{phosphate} = 1.0322 \times \delta^{18}O_{carbonate} - 9.6849$) used to convert $\delta^{18}O_{carbonate}$ values to $\delta^{18}O_{phosphate}$. The error involved in calculating $\delta^{18}O_{phosphate}$ is considered to be low (0.28 ‰, 1σ, Chenery *et al*. 2012: 313).

Radiocarbon dating was conducted at the Scottish Universities Environmental Research Centre according to the methods described in Dunbar *et al.* (2016) using collagen extracted from the root of one tooth of each dated individual (tables 1 and 2). ^{14}C results are reported as conventional radiocarbon ages, quoted in conventional years BP (before 1950 AD) (Stuiver and Polach 1977; Millard 2014). Calibrated ages (tables 1 and 2) were determined and Bayesian modelling undertaken using the University of Oxford Radiocarbon Accelerator Unit calibration program, OxCal v4.2 (Bronk Ramsey 2009) and IntCal13 (Reimer *et al.* 2013). Calibrated date ranges are quoted in the form recommended by Millard (2014), rounded outwards by 10 years, and posterior density estimates are quoted in italics and rounded outwards to the nearest 5 years.

3.4 Results

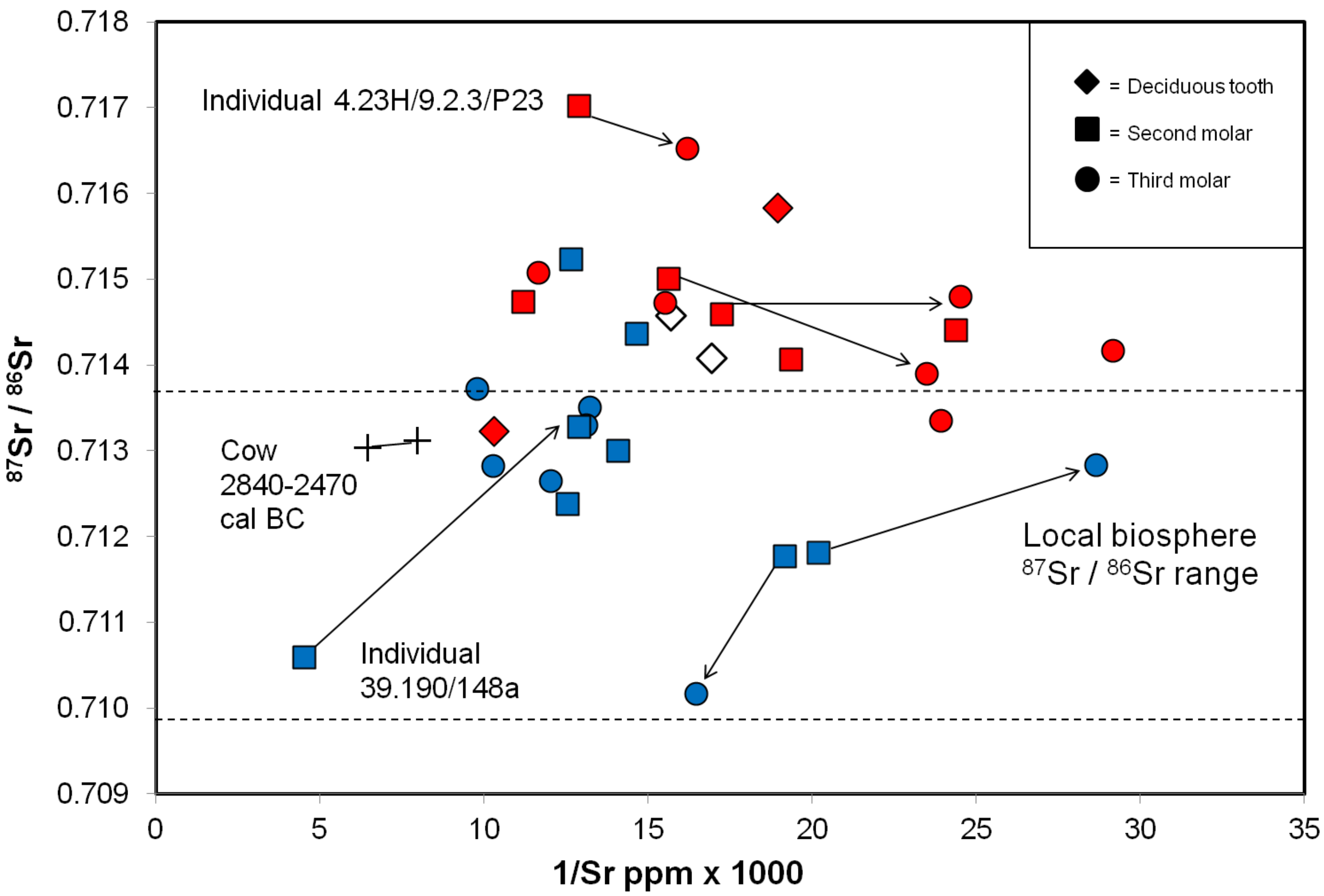


Figure 4. Plot of strontium isotope ratio versus the inverse of concentration (1/Sr ppm x 1000) for human and cattle enamel from Penywrylod (Talgarth) long cairn and Ty Isaf, Powys, Wales. Dashed lines delineate locally bioavailable $^{87}Sr/^{86}Sr$ values measured in plants growing within a radius of 10 miles (approximately 16 km) of both sites (table 3). Arrows illustrate adjacent molars from the same individual. Red symbols: human individuals from Penywyrlod. Blue symbols: human individuals of mid to late 4th millennium date sampled from Ty Isaf. Crosses: samples from the cusp and cervix of the third permanent premolar of a cow of later Neolithic date from Ty Isaf. Radiocarbon dates cited at 95% confidence. Open white symbols: first and second deciduous premolars of a child of Bronze Age date from Ty Isaf. Tooth types are denoted by the key in the upper right of the diagram. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.

Eight of the nine human individuals from Ty Isaf are assigned by AMS radiocarbon dating to the mid 4th to early 3rd millennium BC (table 1). The ninth is assigned to the Bronze Age. This individual, a child (39.190/324) aged approximately 3-4 years at death was excavated from the north side of the monument outside Chamber 2 and is dated to 1663-1506 cal BC (95% confidence, SUERC-57789; table 1). Enamel from the deciduous first and second molars of this individual gave $^{87}Sr/^{86}Sr$ values of 0.7141 and 0.7146, with strontium concentrations of 59 and 64 ppm respectively.

Tooth enamel from the human individuals of Neolithic date who were buried at Ty Isaf gave a range of $^{87}Sr/^{86}Sr$ values between 0.7101 - 0.7152 (mean 0.7128 ± 0.0013, 1σ, n = 15), with only two individuals recording strontium isotope ratios higher than 0.7140 (figure 4): adult 39.190/310 excavated from Chamber 2 of the long cairn and sub-adult 39.190/58 from Chamber 1, who have $^{87}Sr/^{86}Sr$ values of 0.7144 and 0.7152 respectively (table 1). Fourteen of the fifteen teeth sampled from the group dated to the Neolithic at Ty Isaf have strontium concentrations between 35 and 102 ppm (mean 72 ± 18.0 ppm, 1σ). However, the second molar tooth of one individual (39.190/148a) in the group exhibits a particularly high strontium concentration of 222 ppm.

The loose third permanent premolar of the cow from Ty Isaf, excavated from the west compartment of Chamber 1, is dated to the late Neolithic (2831-2474 cal BC). Enamel sampled close to the cusp of the crown of this tooth gave an $^{87}Sr/^{86}Sr$ value of 0.7130 with a strontium concentration of 155 ppm (table 1), whilst that taken close to the cervix had an $^{87}Sr/^{86}Sr$ value of 0.7131 and a strontium concentration of 126 ppm.

Individuals buried at Penywyrlod have strontium isotope ratios between 0.7132 and 0.7170 (mean 0.7148 ± 0.0011, 1σ, n = 15) and strontium concentrations between 34 and 97 ppm (mean 60.2 ± 19.6 ppm, 1σ, n = 15). In contrast to Ty Isaf, the majority of the teeth (12 of 15) sampled from Penywyrlod have strontium isotope ratios that are higher than 0.7140, including both individuals from excavated chambers NE II and III (see figure 2) and the child whose remains were recovered from a cist in the lower part of the outer revetment wall close to the forecourt of the monument (Savory 1984: 22-23). Enamel samples from the second and third molars of one adult individual (74.23H/9.2.3/P23) from Penywyrlod gave particularly high $^{87}Sr/^{86}Sr$ values of 0.7170 and 0.7165 respectively (figure 4). This individual was excavated from NE chamber II at Penywyrlod and is radiocarbon dated to 3770-3630 cal BC (95% confidence, SUERC-63414; table 2). In contrast to the $^{87}Sr/^{86}Sr$ values exhibited by this individual, the samples of modern plants that were collected within a radius of 10 miles (approximately 16 km) of Penywyrlod and Ty Isaf gave strontium isotope ratios between 0.7097 - 0.7137 (mean 0.7107 ± 0.001, 1σ, n = 12, table 3).

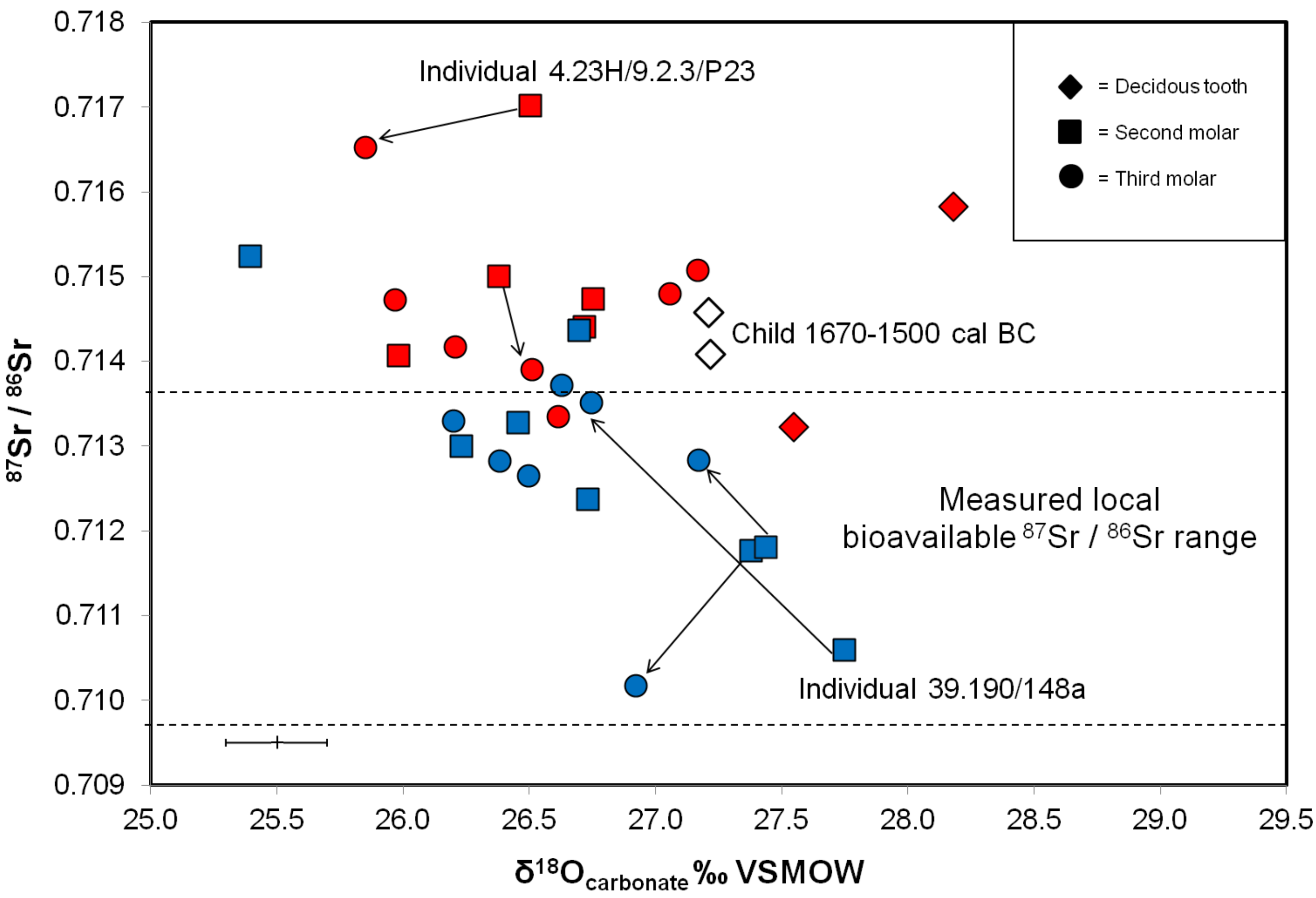


Figure 5. Plot of $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{carbonate}$ values of human and cattle enamel from Penywyrlod (Talgarth) and Ty Isaf, Powys, Wales. Dashed lines delineate locally bioavailable $^{87}Sr/^{86}Sr$ values measured in plants growing within a radius of 10 miles (approximately 16 km) of both sites (table 3). Red symbols: human individuals from Penywyrlod long cairn. Blue symbols denote human individuals of mid to late 4th millennium date from Ty Isaf. Open white symbols: first and second deciduous premolars of a child of Bronze Age date from Ty Isaf. Radiocarbon dates cited at 95% confidence. Tooth types are denoted by the key in the upper right of the diagram. Arrows illustrate adjacent molars from the same individual. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2 ‰ (2σ).

$\delta^{18}O_{carbonate}$ values of enamel from the second and third permanent molars of individuals of Neolithic date at Ty Isaf range between 25.4 and 27.7 ‰ (mean 26.7 ± 0.6 ‰, 1σ, n = 15; figure 5): there are no discernible trends in enamel oxygen isotope composition according to excavation context or radiocarbon date within this group.

Enamel samples from the first and second deciduous molars of the child of Bronze Age date (39.190/324) both gave $\delta^{18}O_{carbonate}$ values of 27.2 ‰. $\delta^{18}O_{carbonate}$ values of enamel from second and third permanent molars of individuals buried at Penywyrlod range between 25.9 and 27.2 ‰ (mean 26.5 ± 0.5 ‰, 1σ, n = 13), including adult individual (74.23H/9.2.3/P23) who has the highest strontium isotope ratio (0.7170) in the group and whose second and third molars gave $\delta^{18}O_{carbonate}$ values of 26.5 ‰ and 25.9 ‰ respectively. Enamel from the second deciduous molars of two children from Penywyrlod (74.23H/9.18/P20 and 74.23H/9.7/P25) gave $\delta^{18}O_{carbonate}$ values of 28.2 ‰ and 27.5 ‰ respectively.

Enamel $\delta^{13}C_{carbonate}$ values of individuals sampled from Penywyrlod range between -18.0 and -15.0 ‰ (mean -16.0 ± 0.8 ‰, 1σ, n = 15). Enamel $\delta^{13}C_{carbonate}$ values of individuals dated to the Neolithic at Ty Isaf range between -16.9 and -14.9 ‰ (mean -16.0 ± 0.6 ‰, 1σ, n = 15), whilst enamel from the first and second deciduous molars of the Bronze Age child from Ty Isaf gave $\delta^{13}C_{carbonate}$ values of -15.2 ‰ and -15.6 ‰ respectively.

Table1. Results of radiocarbon dating and $^{87}Sr/^{86}Sr$, $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ analysis of individuals excavated from Ty Isaf. Information on the contexts of sampled specimens (where available) is as recorded on labelling and documentation associated with the collections in the National Museum Wales. All human teeth derive from mandibular dentition: L = left; DM1 = deciduous first molar; DM2 = deciduous second molar; M2 = permanent second molar; M3 = permanent third molar. PM3 = the loose third permanent premolar of a cow.

Accession number	**Location/ context**	**Age category/ age at death**	**Tooth**	**Laboratory number (SUERC)**	**$\delta^{13}C$ ‰ VPDB collagen**	**Radiocarbon age (BP)**	**Calibrated date range (cal BC, 95% confidence)**	**Sr ppm (mg/kg)**	**1/Sr ppm x 1000**	**$^{87}Sr/^{86}Sr$**	**$\delta^{13}C_{carbonate}$ ‰ VPDB enamel**	**$\delta^{18}O_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VSMOW**	**$\delta^{18}O_{phosphate}$ ‰ VSMOW**
39.190/317	Undocumented	Adult	LM2	SUERC-57795 (GU36260)	-20.7	4772 ± 30	3650-3380	50	20.00000	0.71181	-15.7	-3.4	27.4	18.6
			LM3					35	28.57143	0.71284	-16.2	-3.6	27.2	18.4
39.190/312	Undocumented	Adult	LM2					71	14.08451	0.71300	-16.1	-4.6	26.2	17.4
			LM3	SUERC-57796 (GU36261)	-20.8	4755 ± 31	3640-3380	83	12.04819	0.71265	-15.6	-4.3	26.5	17.7
39.190/148b	Chamber 1, East compartment	Adult	LM2	SUERC-57787 (GU36255)	-21.0	4680 ± 30	3630-3370	80	12.50000	0.71238	-16.3	-4.1	26.7	17.9
			LM3					102	9.80392	0.71372	-16.2	-4.2	26.6	17.8
39.190/310	Chamber 2, South side of entrance passage	Adult	LM2	SUERC-57786 (GU36254)	-20.7	4672 ± 31	3630-3360	68	14.70588	0.71436	-15.4	-4.1	26.7	17.9
			LM3					76	13.15789	0.71330	-15.1	-4.6	26.2	17.4
39.190/201	Undocumented	Adult	LM2	SUERC-57794 (GU36259)	-20.6	4672 ± 31	3630-3360	78	12.82051	0.71328	-15.3	-4.3	26.5	17.6
			LM3					97	10.30928	0.71282	-16.0	-4.4	26.4	17.5
39.190/58	Chamber 1, North East corner of East compartment	Sub-adult (> 12 years)	LM2	SUERC-57784 (GU36252)	-20.9	4616 ± 30	3520-3340	79	12.65823	0.71524	-14.9	-5.4	25.4	16.5
39.190/148a	Chamber 1, East compartment	Adult	LM2	SUERC-57785 (GU36253)	-21.2	4594 ± 30	3500-3120	222	4.50450	0.71059	-16.7	-3.1	27.7	19.0
			LM3					76	13.15789	0.71351	-16.9	-4.0	26.7	17.9
39.190/59	Undocumented	Adult	LM2	SUERC-57790 (GU36258)	-20.6	4430 ± 33	3330-2920	52	19.23077	0.71177	-16.8	-3.4	27.4	18.6
			LM3					61	16.39344	0.71017	-16.2	-3.9	26.9	18.1
39.190/324	Chamber 2, Outside chamber on North side	Child (3-4 years)	LDM1					59	16.94915	0.71409	-15.2	-3.6	27.2	18.4
			LDM2	SUERC-57789 (GU36257)	-20.7	3309 ± 32	1670-1500	64	15.62500	0.71458	-15.6	-3.6	27.2	18.4
39.190/cow	Chamber 1, West compartment	Unknown	PM3 Cervix (0.5 - 5.0 mm)	SUERC-57788 (GU36256)	-22.9	4039 ± 30	2840-2470	126	7.93651	0.71312				
			PM3 Cusp (12.5 -17.5 mm)					155	6.45161	0.71304				

Table 2. Results of radiocarbon dating and $^{87}Sr/^{86}Sr$, $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ analysis of individuals from Penywyrlod (Talgarth). All teeth sampled derive from mandibular dentition: L = left; R= right; DM2 = deciduous second molar; M2 = permanent second molar; M3 = permanent third molar. Location and context of specimens is as stated on documentation associated with the collection held by the National Museum Wales.

Museum accession number	**Location / context**	**Age category / age at death**	**Tooth**	**Laboratory number (SUERC)**	**$\delta^{13}C$ ‰ VPDB collagen**	**Radiocarbon age (BP)**	**Calibrated date range (cal BC, 95 % confidence)**	**Sr ppm (mg/kg)**	**1/Sr ppm x 1000**	**$^{87}Sr/^{86}Sr$**	**$\delta^{13}C_{carbonate}$ ‰ VPDB enamel**	**$\delta^{18}O_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VSMOW**	**$\delta^{18}O_{phosphate}$ ‰ VSMOW**
74.23H/9.18/P20	Cist in forecourt	Child (4 years)	LDM2					53	18.86792	0.71583	-16.0	-2.7	28.2	19.4
74.23H/9.23/P21	NE chamber II	Adult	LM2					58	17.24138	0.71459	-15.1	-3.6	27.2	18.4
			LM3					41	24.39024	0.71480	-15.0	-3.7	27.1	18.2
74.23H/9.23/P22	NE chamber II	Adult	LM2					64	15.625	0.71501	-15.9	-4.4	26.4	17.5
			LM3					43	23.25581	0.71390	-16.4	-4.3	26.5	17.7
74.23H/9.5.11/P23	NE chamber II, half way along chamber on south side	Sub-adult (> 12 years)	LM2					52	19.23077	0.71406	-15.8	-4.8	26.0	17.1
74.23H/9.2.3/P23	NE chamber II, north-east end of north-west side	Adult	LM2	SUERC-63414 (GU38967)	-20.6	4888 ± 37	3770-3630	78	12.82051	0.71702	-15.3	-4.3	26.5	17.7
			LM3					62	16.12903	0.71653	-15.8	-4.9	25.9	17.0
74.23H/9.5.1/P24	NE chamber II	Adult	LM2					89	11.23596	0.71473	-16.0	-4.0	26.8	17.9
			LM3					42	23.80952	0.71335	-16.5	-4.2	26.6	17.8
74.23H/9.7/P25	NE chamber III	Child (2 years)	LDM2					97	10.30928	0.71323	-18.0	-3.3	27.5	18.7
74.23H/9.7/P26	NE chamber III	Sub-adult (> 12 years)	LM2					41	24.39024	0.71441	-15.2	-4.1	26.7	17.9
74.23H/9.7/P27	NE chamber III	Sub-adult (> 12 years)	LM3					86	11.62791	0.71508	-17.1	-3.6	27.2	18.4
74.23H/9.5.19/P27	NE chamber II	Adult	RM3					34	29.41176	0.71417	-16.1	-4.6	26.2	17.4
74.23H/9.16/P27	NE chamber II, west end of chamber, south side of paving slab	Adult	RM3					65	15.38462	0.71472	-16.2	-4.8	26.0	17.1

3.5 Discussion

The majority of sampled individuals from Penywyrlod have $^{87}Sr/^{86}Sr$ values that are not consistent with the local biosphere range. They exhibit strontium isotope ratios above 0.7140 (fig. 4). These values exceed those measured in plants within a radius of 10 miles, approximately 16 km, of the site, which recorded $^{87}Sr/^{86}Sr$ values between 0.7097 - 0.7137 (mean 0.7107 ± 0.001, 1σ, n = 12; table 3). This suggests that individuals buried at Penywyrlod did not source their childhood diet locally. They may not, however, have obtained their diet from a great distance outside the local region: as discussed above, $^{87}Sr/^{86}Sr$ values up to 0.7162 have been recorded just over 35 miles (approximately 56 km) to the east of Penywyrlod in the Malvern Hills (Chenery *et al.* 2010: 155). Although plants sampled in the Malverns routinely give lower $^{87}Sr/^{86}Sr$ values (mean 0.7128 ± 0.0040, 2σ, n = 13, Chenery *et al.* 2010: 155-156) the possibility that these individuals obtained their childhood diet from this area cannot be excluded. Strontium isotope ratios between 0.7140 and 0.7150 have previously been recorded in human burials excavated close to the Malvern Hills, at the medieval cemeteries of Hereford Cathedral (Evans *et al.* 2012: 756) and Blackfriars, Gloucester (Montgomery 2002).

Alternatively, the possibility that individuals with $^{87}Sr/^{86}Sr$ values between approximately 0.7140 and 0.7150 spent their childhood further afield within central Wales could be considered. Currently available biosphere data from plants and water sampled on Ordovician and Silurian rocks in central Wales suggests that lithologies of this age in Wales are routinely associated with $^{87}Sr/^{86}Sr$ values lower than 0.7140 (see above, Evans *et al.* 2010; Shand *et al.* 2007: 254, 256; Montgomery *et al.* 2006:

1628). However, deep groundwaters sampled on lithology of Lower Palaeozoic age in central Wales have recorded $^{87}Sr/^{86}Sr$ values up to 0.7152 (Shand *et al.* 2007: 256) and a single high value of 0.7147 has also been recorded in plants growing on Silurian mudstones in this region (FISH-4, Evans *et al.* 2010). The possibility that individuals with strontium isotope ratios between approximately 0.7140 and 0.7150 sourced their diet from this area cannot be excluded.

Enamel from the second and third permanent molars of one individual in the burial population from Penywyrlod (adult 74.23H/9.2.3/P23; fig. 4) gave $^{87}Sr/^{86}Sr$ values of 0.7170 and 0.7165. These values are higher than all currently recorded biosphere values in England and Wales (Evans *et al.* 2010; Chenery *et al.* 2010: 155). Current understanding of the methodology (as outlined in the Introduction and Materials and Methods) and all presently available measured biosphere $^{87}Sr/^{86}Sr$ data suggests that this individual obtained their childhood diet from outside England and Wales. The values this individual exhibits support the interpretation that this individual moved a significant distance after the formation of their third permanent molar tooth crown (i.e. after approximately 14.5 ± 0.5 years of age, AlQahtani *et al.* 2010; see Materials and Method).

This individual is dated to 3770-3630 cal BC (95% confidence, SUERC-63414; table 2), consistent with the radiocarbon result previously obtained from human bone excavated from Chamber NEII at Penywyrlod (3960-3640 cal BC, 95% confidence, OxCal v. 4.2; Britnell and Savory 1984: 29). Bayesian modelling of currently available radiocarbon dates from southern Wales suggests that agriculture first began to develop in this region from the 38th century BC, first appearing here between *3765–3655 cal BC, 95% probability,* probably in *3725–3675 cal BC, 68% probability* (Bayliss *et al.* 2011b: 548; OxCal v.3.10). The AMS radiocarbon evidence therefore suggests the individual could be contemporary in date with the first appearance of Neolithic material culture and practices in southern Wales. Recent comparative analysis of ceramics has been used to argue that Neolithic material culture and practices were introduced to western Britain by the arrival of groups from Lower Normandy and Brittany in north-western France during the early 4th millennium BC (Pioffet 2015). The strontium isotope ratios that this individual exhibits could be consistent with such an origin: plants in Lower Normandy, Brittany and Pays de la Loire give $^{87}Sr/^{86}Sr$ values higher than 0.7165 (Willmes *et al.* 2013; Négrel and Pauwels 2004). Both the strontium isotope results and radiocarbon dating may therefore support the hypothesis that development of agriculture in southern Wales was associated with arrival of migrant individuals from outside the region during the early 4th millennium BC. The oxygen isotope ratios that the individual exhibits could also be consistent with an origin in north-western France (see below).

Biosphere $^{87}Sr/^{86}Sr$ values higher than 0.7165, such as those this individual exhibits, have been recorded in regions further afield, in areas such as the Cairngorm mountains in north-east Scotland, over 500 km from Penywyrlod (Evans *et al.* 2010). However, current Bayesian modelling suggests that Neolithic material culture and practices may only recently have become established within this region of Scotland at this time: it is argued that they appeared here in the decades around 3800 cal BC (Bayliss *et al.* 2011a: 822-824, 838-840). $^{87}Sr/^{86}Sr$ values close to 0.7170 have similarly been recorded in Northern Ireland (Snoeck *et al.* 2016). However, with the exception of Ferriter's Cove in the far south-west of Ireland, where cattle bone in Mesolithic contexts has been interpreted as a failed episode of colonization during the mid 5th millennium BC (Woodman *et al.* 1999; Sheridan 2010a) and Magheraboy causewayed enclosure, Co. Sligo, the dating of which is currently regarded as problematic, there is at present limited evidence to suggest the Neolithic was established in Ireland any earlier than the 38th century BC (Cooney *et al.* 2011: 663-668; Bayliss *et al.* 2011a: 805-808; Schulting *et al.* 2012: 31; Whitehouse *et al.* 2014).

Although areas in closer geographic proximity within England and Wales have been considered (see above) to explain the prevalence of $^{87}Sr/^{86}Sr$ values between 0.7140 and 0.7150 within the population at Penywyrlod, the possibility that the majority of individuals who are buried at this site spent their childhood further afield must also be considered. Plants sampled in regions such as north-western France can, for example, record a range of values comparable to those exhibited by this burial group (i.e. between approximately 0.7140 and 0.7170). As such, it is possible that the majority of those buried at Penywyrlod could have obtained their childhood diet outside England and Wales: the possibility that they originated from a similar region to the individual who exhibits the highest values in the group cannot be excluded.

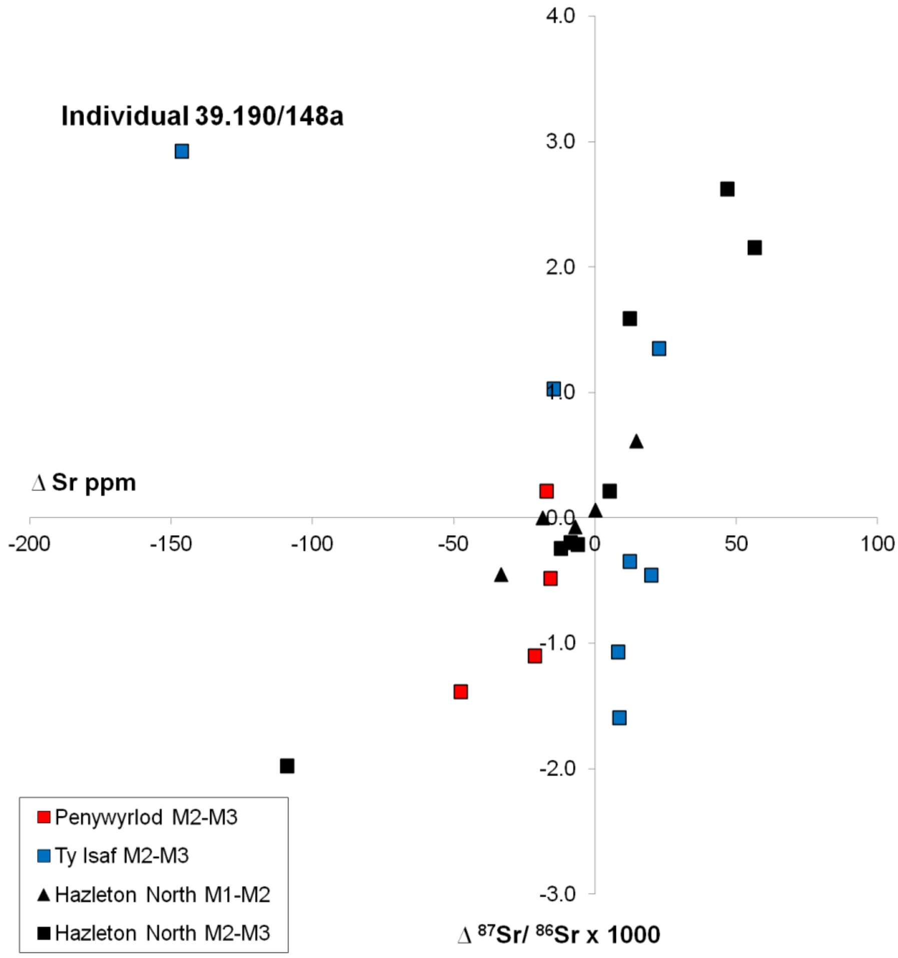
In contrast to Penywyrlod, all individuals in the group sampled from Ty Isaf have calibrated radiocarbon dates that fall after 3650 cal BC (table 1) and therefore post-date the first appearance of Neolithic material culture and practices in southern Wales (see above; Bayliss *et al.* 2011a: 738; 2011b: 548). The majority have strontium isotope ratios that are consistent with local biosphere values and could therefore support the interpretation that these individuals obtained their childhood diet locally. Irrespective of calibrated date or excavation context, the strontium isotope ratios exhibited by most of this group fall within the range of values measured within 10 miles (approximately 16 km) of the site (between 0.7097 - 0.7137, mean 0.7107 ± 0.001, 1σ, n = 12, table 3; fig. 4), although the possibility that individuals obtained their childhood diet further afield, from areas with a similar biosphere range, cannot be excluded. For example, sandstones of Devonian age in east Somerset and north Devon also record $^{87}Sr/^{86}Sr$ values between approximately 0.7120 and 0.7130 (Evans *et al.* 2010; Montgomery *et al.* 2006: 1628). Individuals who exhibit these values could equally have obtained their childhood diet from these regions. Likewise, although individuals with strontium isotope ratios between approximately 0.7100 and 0.7110 plot within range of biosphere $^{87}Sr/^{86}Sr$ values measured locally, other areas, either within Wales (e.g. coastal regions of Pembrokeshire), or further afield (e.g. Cornwall, England), also record similar biosphere values (ibid.). With the exception of individual 39.190/59 who has a $^{87}Sr/^{86}Sr$ value of 0.7102, strontium isotope results from Ty Isaf (and Penywyrlod) appear to rule out the possibility that individuals obtained a significant component of their childhood diet from south-central and eastern regions of England. In the latter regions, lithologies of Jurassic and Cretaceous age routinely record biosphere values below $^{87}Sr/^{86}Sr$ 0.7105 (Warham 2011: 79; see fig. 1). Only two individuals in the burial group from Ty Isaf have strontium isotope ratios higher than 0.7140. Both adult 39.190/310 and sub-adult 39.190/58 were exposed to more radiogenic sources of strontium than are known to be bioavailable locally during formation of their second permanent molar crown, between approximately 2.5 ± 0.5 years to 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31, 55-56). These two individuals could have derived their childhood diet from similar source areas to those discussed above for the group sampled from Penywyrlod.

Penywyrlod and Ty Isaf are part of a cluster of early Neolithic long cairns in the Black Mountains. Whilst their construction appears to reflect a common theme, it is argued that differences in the morphology of these monuments may indicate they were built and used by different social groups (Wysocki and Whittle 2000: 600). The strontium isotope results could support this suggestion. Whilst they are situated less than 5 miles (8 km) apart, these monuments differ in their morphology and the $^{87}Sr/^{86}Sr$ results are consistent with the two burial groups having obtained their diet from different geographical locations. The majority of those buried at Penywyrlod appear to have obtained their childhood diet from outside the immediate area in which they were buried, whereas results from Ty Isaf could support the hypothesis that individuals sourced their diet locally. It is possible that this contrast may be the result of a difference in the chronology of the two burial groups as, unlike the individual from Penywyrlod who was radiocarbon dated by this study, all individuals from Ty Isaf post-date 3650 cal BC. Further radiocarbon dates are being sought from Penywyrlod to examine this possibility.

The rules defining who was selected for burial in such monuments have also often been debated (e.g. Whittle *et al.* 2007: 134). The results of this study suggest that, rather than acting as a focus for burial of individuals who sourced their diet from a diverse range of geographical areas, the individuals who were chosen for burial within each monument could have obtained their diet from a similar geographical location.

Where adjacent consecutively mineralizing second and third molar teeth were available for sampling from Ty Isaf, the majority of tooth pairs (6 of 7) have values that plot within the local biosphere range (the exception being individual 39.190/310, discussed above, who may have obtained their diet outside the local area during childhood). For example, adult 39-190/312 has adjacent second and third molar teeth with $^{87}Sr/^{86}Sr$ values of 0.7130 and 0.7126 respectively. This could be consistent with the individual having obtained their diet from a similar geographical location, such as the local area, for a prolonged period during early life. Alternatively, however, they could have sourced their diet from different geographical locations that conferred a similar averaged $^{87}Sr/^{86}Sr$ value (close to 0.7130) during the formation of each tooth. Similarly, individuals buried at Penywyrlod who have high strontium isotope ratios (above 0.7140) on each of their adjacent teeth (illustrated with arrows in figure 4) could either have obtained their diet from one of the areas discussed as potential sources for this value over a prolonged period during early life; or alternatively they could have sourced their diet from several different geographical locations that conferred a similar averaged $^{87}Sr/^{86}Sr$ value (i.e. higher than approximately 0.7140).

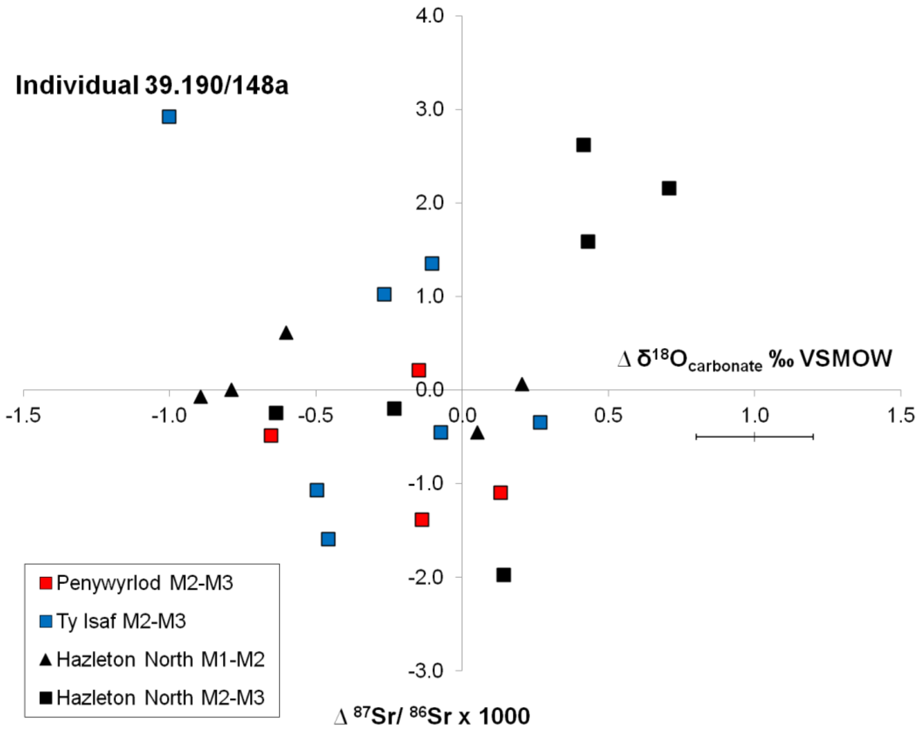
Figure 6. Plot of the difference in strontium isotope ratio (Δ $^{87}Sr/^{86}Sr$ x 1000) and elemental concentration (Δ Sr ppm) between adjacent permanent molar teeth of individuals excavated from Penywyrlod (Talgarth) individuals of Neolithic date from Ty Isaf long cairn, Powys, Wales. Red symbols: Penywyrlod; Blue symbols: Ty Isaf. Black symbols: Hazleton North long cairn, Gloucestershire, England. Triangles denote the difference in strontium isotope ratio and Sr ppm between first and second molars. Squares denote the difference in strontium isotope ratio and elemental concentration between second and third molars. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.



Individual 39.190/148a (labelled on figure 4 and figure 6) from Ty Isaf exhibits the largest shift in isotope ratio of all sampled individuals in the present study: from an $^{87}Sr/^{86}Sr$ value of 0.7106 in their second permanent molar enamel to a value of 0.7135 in enamel from their third permanent molar. Although this shift is accompanied by a change in oxygen isotope ratio (fig. 7) and a drop in strontium

concentration, from 222 to 76 ppm (discussed below), since both the $^{87}Sr/^{86}Sr$ values fall within the measured local biosphere range, the possibility that this individual sourced their diet from the local area throughout the period both teeth were forming cannot be excluded. In contrast, a change in the geographical location from which individuals obtained their diet can be inferred from shifts in strontium isotope ratio and elemental concentration at Hazleton North long cairn, Gloucestershire (figs. 6 and 7). At this site, several individuals exhibited a change in strontium isotope ratios from a value lower than 0.7085 to higher than 0.7105 between adjacent teeth. In southern Britain, with the possible exception of the Lizard Peninsula in Cornwall, lithologies that routinely give measured biosphere $^{87}Sr/^{86}Sr$ values below 0.7085 are geographically separated from those that give values higher than 0.7105 and the shift between these two values can therefore be interpreted to indicate that individuals changed the location from which they obtained their diet during childhood (Evans *et al.* 2010; Neil *et al.* 2016a; **Chapter 4, this thesis**).

Figure 7. Plot of the difference in oxygen (Δ $\delta^{18}O_{carbonate}$ ‰ VSMOW) and strontium (Δ $^{87}Sr/^{86}Sr$ x 1000) isotope ratios between adjacent permanent molar teeth of individuals excavated from Penywyrlod (Talgarth) and individuals of Neolithic date from Ty Isaf long cairn, Powys, Wales. Red symbols: Penywyrlod; Blue symbols: Ty Isaf. Black symbols: Hazleton North long cairn, Gloucestershire, England. Triangles denote the difference in strontium and oxygen isotope ratio between first and second molars. Squares denote the difference in strontium and oxygen isotope ratio between second and third molars. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2 ‰ (2σ).



If $\delta^{18}O_{carbonate}$ results are converted to $\delta^{18}O_{phosphate}$ values using the equation of Chenery *et al.* (2012), individuals of Neolithic date from Ty Isaf with strontium isotope ratios comparable to the local measured biosphere range have $\delta^{18}O_{phosphate}$ values between 17.4 and 19.0 ‰ (mean 18.0 ± 0.5 ‰, 1σ, n = 13). This comparison could be used to suggest that the majority of the group from Ty Isaf obtained their diet from the local region in which they were buried, as their $\delta^{18}O_{phosphate}$ values fall close to the mean value that Evans *et al.* (2012: 759; mean 18.2 ‰ ± 1.0 ‰, 2σ) argue to be representative of occupation of western Britain where the site is located. At Hazleton North long cairn, also located in western Britain, conversion of $\delta^{18}O_{carbonate}$ values of second and third permanent molars gave a similar range of $\delta^{18}O_{phosphate}$ values (17.6 - 18.9 ‰, mean 18.2 ± 0.4 ‰, n = 20, 1σ; Neil *et al.* 2016a). In both cases, however, this comparison assumes that $\delta^{18}O$ values in human enamel directly reflect geographical variation in the oxygen isotope composition of drinking waters and that values have not been significantly elevated as a result of culinary practice (e.g. Brettell *et al.* 2012a), or by consumption of fluids that have undergone fractionation through biological processes (e.g. cow's milk; Camin *et al.* 2008: 1695; Lin *et. al.* 2003: 2193; Kornexl *et al.* 1997: 22).

Only one individual in the sampled group from Ty Isaf has an $\delta^{18}O_{phosphate}$ value that falls outside the range suggested to represent occupation of western Britain. This individual, (39.190/58; table 1), is one of the two buried at Ty Isaf who has a strontium isotope ratio (0.7152) higher than the local biosphere range. Their $\delta^{18}O_{phosphate}$ value of 16.5 ‰ is lower than the range of values considered to represent occupation of western Britain (17.2 to 19.2 ‰; mean 18.2 ‰ ± 1.0 ‰, 2σ, Evans *et al.* 2012: 759). However, it does fall within the range for eastern Britain (15.9 to 18.5 ‰; mean 17.2 ± 1.3 ‰, 2σ; ibid.). The combination of oxygen isotope and strontium isotope ratios exhibited by this particular individual, who is dated to 3520-3340 cal BC (table 1), could therefore suggest that they derived their childhood diet from a region further afield, such as north-east Scotland which records biosphere $^{87}Sr/^{86}Sr$ values higher than 0.7140 and low $\delta^{18}O$ values in ground waters (Darling *et al.* 2003: 189 & 191; Evans *et al.* 2010). However, before reaching this conclusion the possibility that there is greater spatial and temporal variability in the oxygen isotope composition of groundwaters of closer regions that can record biosphere $^{87}Sr/^{86}Sr$ values higher than 0.7140 (e.g. central Wales) might be considered. It is possible that altitude effects, for example, may induce greater local variability in the isotopic composition of groundwaters within Wales (Darling *et al.* 2003: 189), resulting in lower $\delta^{18}O$ values in areas of higher elevation (Mook 2005: 94). In addition, although it has been argued that climatic variation during the Holocene is unlikely to have been sufficiently significant to have influenced $\delta^{18}O$ values exhibited by human populations (Evans *et al.* 2012: 758), the precise effect of local climatic variability on $\delta^{18}O$ values in groundwaters over time (e.g. at a seasonal, inter-annual or decadal scale) in north-western Europe remains poorly understood and new proxies are currently being sought to study localized variation in past precipitation levels and temperature (e.g. Young *et al.* 2012; Young *et al.* 2015).

$\delta^{18}O_{phosphate}$ values for second and third molar teeth of individuals excavated from Penywyrlod range between 17.0 and 18.4 ‰ (mean 17.7 ± 0.5 ‰, 1σ, n = 13). These values are therefore comparable to the ranges proposed by Evans *et al.* (2012) to represent occupation of Britain. However, as discussed in the introduction, oxygen isotope ranges of burial populations excavated in Britain overlap with those of burial groups found on the European mainland (see Lightfoot and O'Connell 2016). Modern groundwaters and precipitation in north-western France can record a comparable range of $\delta^{18}O$ values to those in Wales (between approximately −5 to −7 ‰, Lécolle 1985; IAEA/WMO 2016; Millot *et al.* 2010; Darling *et al.* 2003) and archaeological populations excavated in Lower Normandy (e.g. Brettell *et al.* 2012b: 127 & 132) have also recorded values comparable to those exhibited by individuals buried at Penywyrlod.

The deciduous molars of two children sampled by this study (from Penywyrlod) have not been included in the above comparison of oxygen isotope ranges, as they begin formation *in utero* (AlQahtani *et al.* 2010) and, following birth, values within these teeth may be influenced by consumption of breast milk, which has a higher $\delta^{18}O$ value relative to fluids consumed by the mother (Roberts *et al.* 1988; Wright and Schwarcz 1998; Britton *et al.* 2015). The deciduous second molar of child 74.23H/9.18/P20 from Penywyrlod (figure 5) exhibits the highest $\delta^{18}O_{carbonate}$ value (28.2 ‰; $\delta^{18}O_{phosphate}$ 19.4 ‰) of all the individuals sampled in the present study: the possibility that this is a consequence of breastfeeding cannot be excluded.

Enamel $\delta^{13}C_{carbonate}$ values of individuals from Penywyrlod range between -18.0 and -15.0 ‰ (mean -16.0 ± 0.8 ‰, n = 15), whilst enamel $\delta^{13}C_{carbonate}$ values of individuals dated to the Neolithic at Ty Isaf range between -16.9 and -14.9 ‰ (mean -16.0 ± 0.6 ‰, n = 15). These values fall within the range that may be predicted for a diet dominated by C_3 terrestrial resources (between approximately -17.0 and -14.0 ‰; Kellner and Schoeninger 2007; Froehle *et al.* 2012). The majority of human individuals sampled at both Penywyrlod and Ty Isaf have strontium concentrations comparable to those exhibited by the early Neolithic burial population at Hazleton North, where concentrations ranged between 22 and 144 ppm (mean 54 ± 25 ppm, n = 35, Neil *et al.* 2016a; **Chapter 4, this thesis**). Strontium concentrations recorded at Penywyrlod and Ty Isaf are also close to the median value of 84 ppm (n = 614) reported by Evans *et al.* (2012: 756) for archaeological populations dating from the Neolithic to the 19th century in Britain as a whole. However, one individual (39.190/148a) at Ty Isaf exhibited a particularly high strontium concentration: enamel from their second permanent molar tooth had a value of 222 ppm (figs. 4 and 6). Enamel from their third molar, however, recorded a strontium concentration of 76 ppm, comparable to the rest of the group.

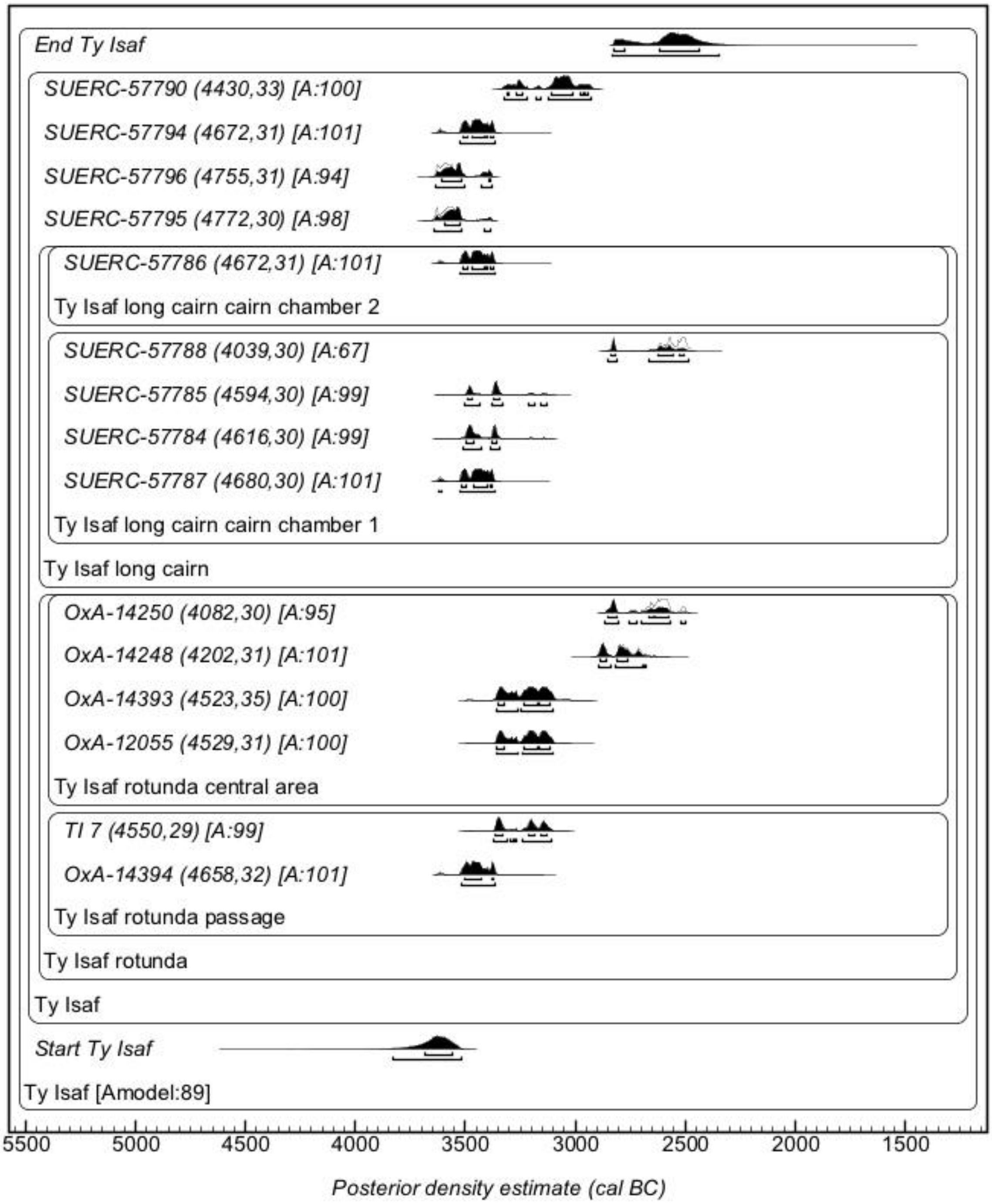
Multiple factors may be influential in determining strontium concentrations in mammalian tissues (see reviews by Montgomery 2002: 36-39; Montgomery 2010: 328; Burton and Wright 1995: 280), including the trophic level of an individual. Progressive biopurification, discrimination against strontium in favour of calcium (in the digestive tract, Sips *et al.* 1997, and kidneys, Kobayashi and Suzuki 1990) occurs at successive trophic levels within a food chain (Burton *et al.* 1999; Blum *et al.* 2000). As a consequence, herbivores can record higher strontium concentrations than human populations. Strontium concentrations in cattle enamel of prehistoric date excavated in Britain frequently exceed 150 ppm (e.g. Viner *et al.* 2010; Towers *et al.* 2010: 511; Minniti *et al.* 2014: 310; also see Neil *et al.* 2016; **Chapter 4, this thesis**). Enamel samples from the later Neolithic cow tooth at Ty Isaf (dated to 2840-2470 cal BC; see below; table 1) gave strontium concentrations of 126 and 155 ppm, consistent with those reported for later Neolithic cattle of similar date sampled at Durrington Walls, Wiltshire (Viner *et al.* 2010: 2185).

One factor that has been invoked to explain the particularly high strontium concentrations observed within human archaeological populations in an Atlantic facing island such as Britain is the potential for marine-derived strontium to contribute to diet, owing to the high concentration of strontium in seawater (Odum 1957) and aerial deposition through seaspray (e.g. Whipkey *et al.* 2000). High strontium concentrations are also recorded in association with other types of environment (e.g. hot arid climates, e.g. Buzon *et al.* 2007), but in Britain, high strontium concentrations are frequently recorded in populations excavated at coastal island locations (e.g. Armit *et al.* 2015: 8-9; also see Montgomery *et al.* 2007: 1509; Hemer *et al.* 2014: 245). It has been argued that high strontium concentrations may either result from individuals obtaining dietary resources from geographical areas that receive high levels of seaspray, or from exploitation of seaweed as fertilizer and deliberate strategies that lead to increased salt intake (e.g. preserving food with sea salt, Montgomery *et al.* 2003: 651; Montgomery 2010: 334). The shift in strontium concentration from 222 to 76 ppm that the individual from Ty Isaf exhibits is accompanied by both a shift in strontium isotope ratio from 0.7106 to 0.7135 and a shift in oxygen isotope ratio (see figs. 4, 5, 6 and 7). This could tentatively provide support for the argument that the individual changed the location from which they obtained their diet during childhood (although see discussion of the caveats relating to the local $^{87}Sr/^{86}Sr$ biosphere range, above).

Using Bayesian modelling of seven radiocarbon determinations obtained from human bone within the rotunda, Bayliss *et al.* (2011b: 537, 546-547) suggest that use of Ty Isaf for burial began in *3825-3345* cal BC (*95% probability*), probably in *3520-3360* cal BC (*68% probability*) and that burial activity ended between *3365-2780* cal BC (*95% probability*), probably in *3355-3065* (*68% probability*; ibid. re-calibrated using OxCal v4.2, IntCal13). However, it should be noted that contra Bayliss *et al.* (2011b: 546-547), as these radiocarbon determinations were obtained from disarticulated bones, they date the deaths of the individuals who were sampled, rather than providing a date for burial activity or use of the monument itself. Like the individuals dated by the present study (table 1) all those dated by Bayliss *et al.* from the rotunda have calibrated radiocarbon dates that fall after 3650 cal BC (ibid. 2011b: 537). Bayesian modelling of the sample of early Neolithic long cairns and barrows in southern Britain for which radiocarbon chronologies have currently been constructed suggests the majority were only used for relatively short periods of time, often for only two to three generations, during the 4th millennium BC, between approximately 3750-3550 cal BC (Whittle *et al.* 2007: 129, 131 and 137). When modelling dates from the rotunda, Bayliss *et al*. (2011b) therefore excluded two individuals who were dated to the earlier 3rd millennium BC. These individuals were assumed to belong to a distinct phase of secondary burial activity during the later Neolithic (ibid. 546), rather than being indicative of long-lived and episodic use of the monument over an extended time period, spanning the mid 4th to earlier 3rd millennium BC. The latter scenario cannot, however, be ruled out. Documentation of the precise stratigraphic context of remains excavated from Ty Isaf is limited. However, that which is available does not support the argument that these individuals belong to a discrete phase of later Neolithic secondary burial activity as remains dated to the 3rd millennium BC were found in both the lower and upper stratigraphic levels in the rotunda (OxA-14248 dated to 2900-2670 cal BC and OxA-14250 dated to 2860-2490 cal BC respectively, 95% confidence, Bayliss *et al.* 2011b: 537; calibrated using OxCal v4.2, IntCal13).

Calibrated date ranges of human remains selected for sampling by the present study also span the mid 4th to earlier 3rd millennium BC, with the latest human individual dating to 3330-2920 cal BC (95% confidence; 39.190/59; SUERC-57790; table 1). This individual is of undocumented context and could have been excavated from either the rotunda or the long cairn (see Materials and Method). Bayesian modelling of the radiocarbon determinations obtained from four human individuals excavated from the lateral chambers of the long cairn (table 1) suggests that they died between *3630-3365 (95% probability*, or *3545-3460*, *68% probability)* and *3500-3235* cal BC *(95% probability*, or *3485-3335* cal BC, *68% probability)*. However, this model excludes the radiocarbon determination obtained from the cattle tooth, found in Chamber 1 of the long cairn, which is dated to the 3rd millennium BC (2840-2470 cal BC, 95% confidence; SUERC-57788; table 1). Modelling of all currently available radiocarbon determinations of Neolithic age obtained from Ty Isaf (figure 8; excluding child 39.190/324 dated to the Bronze Age) suggests that individuals who were buried at the site died between 3835-3515 cal BC (*95% probability*, or *3690-3555 cal BC*, *68% probability*) and 2830-2345 cal BC (*95% probability*, or *2825-2435 cal BC*, *68% probability*) and the possibility that the monument continued to be used for burial throughout this period cannot be ruled out.

Figure 8. Probability distributions of radiocarbon dates from Ty Isaf. Determined using OxCal v4.2 (Bronk Ramsey 2009) and IntCal13 (Reimer *et al.* 2013). Brackets within the diagram and OxCal keywords define the overall model. Radiocarbon dates obtained on human bone from the rotunda derive from Bayliss *et al.* (2011b: 537). Individual 39.190/324 who is dated to the Bronze Age (1670-1510 cal BC; table 1) has been excluded from this model.



Like the majority of the Neolithic human population buried at Ty Isaf, enamel from the cattle tooth exhibits strontium isotope ratios that are comparable to the local biosphere range (figure 4) and could be interpreted to indicate that the animal was raised locally. The animal derived strontium from sources that conferred a similar averaged value during both earlier and later stages of tooth formation, with samples from the cusp and cervix both giving $^{87}Sr/^{86}Sr$ values close to 0.7130. In contrast to this animal and the majority of the Neolithic human population buried at Ty Isaf, tooth enamel from the child of Bronze Age date (figures 4 and 5) gave $^{87}Sr/^{86}Sr$ values of 0.7141 and 0.7146 that are higher than the current recorded local biosphere range. This suggests that this individual was exposed to non-local sources of strontium and obtained their diet from further afield, with the closest areas to record comparable values being the Malvern Hills and central Wales, as discussed above. These isotope ratios were recorded in enamel of deciduous first and second molars which begin formation *in utero*. As such, it is possible that they could reflect dietary resources that were exploited by the mother (Montgomery 2002: 44). If $\delta^{18}O_{carbonate}$ results from this individual are converted to $\delta^{18}O_{phosphate}$ values using the equation of Chenery *et al.* (2012), both teeth give values of 18.4 ‰. This falls close to the mean value that Evans *et al.* (2012: 759) argue to represent occupation of western Britain. However, as formation of deciduous molars continues in the months following birth, it is possible that oxygen isotope ratios in enamel from these teeth could also be influenced by consumption of breast milk, which may confer higher $\delta^{18}O$ values than drinking water (Roberts *et al.* 1988; Wright and Schwarcz 1998; Britton *et al.* 2015). The remains of this individual, dated to 1670-1500 cal BC (95% confidence; SUERC-57789), were found outside Chamber 2 of the long cairn (table 1). As prominent features in the landscape, Neolithic long cairns were sometimes re-used for burial in later periods (Darvill 2004: 214-232). The AMS radiocarbon results support the suggestion of the excavator that Ty Isaf was re-used for burial during the Bronze Age (Grimes 1939: 135-6).

3.6 Conclusions

The majority of individuals buried at Penywyrlod have strontium isotope ratios that exceed the local biosphere range, suggesting they sourced their childhood diet outside the local region. Biosphere $^{87}Sr/^{86}Sr$ values comparable to those exhibited by this group (i.e. between 0.7140 and 0.7150) have been recorded in the Malvern Hills in England and central Wales. However, the possibility that the majority of these individuals obtained their childhood diet in areas further afield cannot be excluded.

One individual in the burial group from Penywyrlod (74.23H/9.2.3/P23) has strontium isotope ratios (0.7165 and 0.7170) that exceed all currently recorded biosphere values in England and Wales. All current understanding of the methodology suggests this individual cannot have obtained their childhood diet from England and Wales. The period to which this individual is dated, to between 3770-3630 cal BC (95% confidence), is consistent with recent dating estimates for the first appearance of agriculture in southern Wales between *3765–3655 cal BC* (*95% probability*; *3725–3675 cal BC, 68% probability*, Bayliss *et al.* 2011b: 548). The individual is associated with Neolithic material culture: monuments of the type in which this individual was buried derive from Continental traditions (Scarre 2015). The $^{87}Sr/^{86}Sr$ values they exhibit are comparable to ranges bioavailable in Lower Normandy, Brittany and Pays de la Loire in north-western France (Willmes *et al.* 2013; Négrel and Pauwels 2004) and the results may plausibly be interpreted to suggest that this individual obtained their childhood diet within this region. The results could support the argument that development of agriculture in southern Wales was associated with the arrival of migrant individuals from outside the region.

Biosphere $^{87}Sr/^{86}Sr$ values higher than 0.7165, such as those this individual exhibits, have been recorded in regions further afield, in areas such as the Cairngorm mountains in north-east Scotland, over 500 km from Penywyrlod (Evans *et al.* 2010). However, current Bayesian modelling suggests that Neolithic material culture and practices may only recently have become established within this region of Scotland at this time, beginning to appear in this area from the decades around 3800 cal BC (Bayliss *et al.* 2011a). Biosphere $^{87}Sr/^{86}Sr$ values close to 0.7170 have similarly been recorded in Northern Ireland (Snoeck *et al.* 2016). However, the attribution of this individual to this area may also be problematic on archaeological grounds as at present there is limited evidence to suggest that Neolithic material culture and practices were established in Ireland any earlier than the 38th century BC (Cooney *et al.* 2011: 663-668; Bayliss *et al.* 2011a: 805-808; Schulting *et al.* 2012: 31; Whitehouse *et al.* 2014).

Unlike the burial group at Penywyrlod, the majority of individuals who were buried at Ty Isaf exhibit strontium isotope ratios that are consistent with the local biosphere range and could have sourced their diet locally. In contrast to individual 74.23H/9.2.3/P23 from Penywyrlod, none of the individuals sampled at Ty Isaf have calibrated radiocarbon dates that fall within the period in which agriculture is considered to have been first initiated in southern Wales. The program of radiocarbon dating undertaken by the present study at Ty Isaf also identified the presence of cattle remains dated to the later Neolithic and a child of Bronze Age date, suggesting that this monument may have remained of importance to communities beyond the 4th millennium BC.

3.7 Acknowledgements and author contributions statement

S.N. designed the research; S.N., J.E. and G.C. undertook the analysis; J.E. provided strontium isotope results from locally collected modern plants (table 3); S.N. wrote the paper. All authors discussed drafts of the paper and approved the final manuscript. S.N. was funded through a Durham University Doctoral Studentship. Strontium and oxygen isotope analysis was funded through NIGFSC grant IP-1290-0512. Radiocarbon dating was funded by a Prehistoric Society radiocarbon dating award (to S.N.), a Durham University Projects and Initiatives Grants Scheme award (to S.N.) and the Scottish Universities Environmental Research Centre.

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3.8 Supplementary information

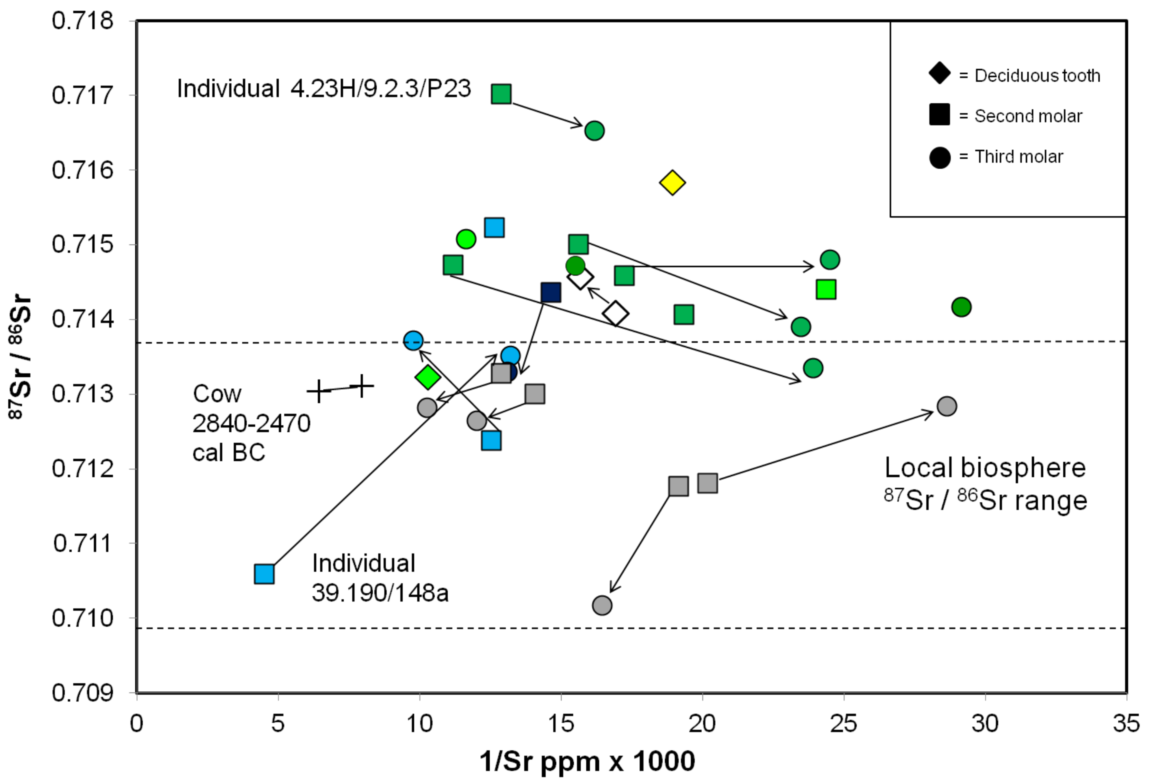

Figure 9. Plot of strontium isotope ratio versus the inverse of concentration (1/Sr ppm x 1000) for human and cattle enamel from Penywrylod (Talgarth) long cairn and Ty Isaf, Powys, Wales illustrating linked adjacent molars from each individual with symbols coloured according to the context from which each individual is recorded to have been excavated within each monument. Dashed lines delineate locally bioavailable $^{87}Sr/^{86}Sr$ values measured in plants growing within a radius of 10 miles (approximately 16 km) of both sites (table 3). Dark green symbols: individuals excavated from Penywyrlod NE chamber II; Light green symbols: Individuals excavated from Penywyrlod NE chamber III; Yellow symbol: Child excavated from Penywyrlod cist in forecourt. Light blue symbols: human individuals of mid to late 4th millennium date attributed to Chamber 1 of Ty Isaf. Dark blue symbols: human individuals of mid to late 4th millennium date attributed to Chamber 2 of Ty Isaf. Grey symbols: human individuals of mid to late 4th millennium date of unattributed context from Ty Isaf. Crosses: samples from the cusp and cervix of the third permanent premolar of a cow of later Neolithic date from Ty Isaf. Radiocarbon dates cited at 95% confidence. Open white symbols: first and second deciduous premolars of a child of Bronze Age date from Ty Isaf. Tooth types are denoted by the key in the upper right of the diagram. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.

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4. Isotopic evidence for residential mobility of farming communities during the transition to agriculture in Britain

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4.1 Abstract

Development of agriculture is often assumed to be accompanied by a decline in residential mobility and sedentism is frequently proposed to provide the basis for economic intensification, population growth and increasing social complexity. In Britain, however, the nature of the agricultural transition (c. 4,000 BC) and its effect on residence patterns has been intensely debated. Some authors attribute the transition to the arrival of populations who practised a system of sedentary intensive mixed farming similar to that of the very earliest agricultural regimes in central Europe, c. 5,500 BC, with cultivation of crops in fixed plots and livestock keeping close to permanently occupied farmsteads. Others argue that local hunter-gatherers within Britain adopted selected elements of a farming economy and retained a mobile way of life. We use strontium and oxygen isotope analysis of tooth enamel from an early Neolithic burial population in Gloucestershire, England, to evaluate the residence patterns of early farmers. Our results are consistent with

the hypothesis that early farming communities in Britain were residentially mobile and were not fully sedentary. Results highlight the diverse nature of settlement strategies associated with early farming in Europe and are of wider significance to understanding the effect of the transition to agriculture on residence patterns.

4.2 Introduction

The transition from hunting and gathering to farming is often considered to be accompanied by a decline in residential mobility as sedentism is assumed to facilitate economic intensification, leading to population expansion and the development of complex societies (e.g. Bocquet-Appel 2011: 560; Price and Bar-Yosef 2011:172; Bellwood 2005: 18 & 26). The agricultural transition in Britain (c. 4000 - 3500 BC) is marked by the importation of non-native species of domesticated animals from continental Europe, evidence for cereal cultivation and the appearance of new traditions of pottery manufacturing, lithic technologies and monument construction. However, both the processes that facilitated the transition and the nature of the first farming systems associated with it remain intensely debated (e.g. Sheridan 2010; Whittle *et al.* 2011, Whittle 2007: 390-394; Thomas 2008, 2013). Some authors attribute development of farming in Britain to the arrival of settled agriculturalists from continental Europe who practised a similar system of intensive-mixed agriculture to that of the Linearbandkeramik, the first farming systems that developed in central Europe from approximately 5,500 BC (Rowley-Conwy 2011; Rowley-Conwy 2003). Arable production is proposed to have been closely integrated with livestock keeping: cultivation is suggested to have taken place in fixed plots with animals being kept close to permanently occupied farmsteads (Rowley-Conwy 2004: 96; Rowley-Conwy and Legge 2015; Bogaard *et al.* 2013: 12589).

Archaeobotanical evidence is considered to rule out shifting cultivation and agricultural regimes in early Neolithic Britain are proposed to have been similar to those of the Linearbandkeramik (Bogaard and Jones 2007). Cereals are argued to have been a dietary staple (Jones and Rowley-Conwy 2007; Rowley-Conwy 2000: 51; Jones 2000: 83) and, due to the demands of cultivation, it is suggested that the first agriculturalists in Britain were fully sedentary (Rowley-Conwy 2011; Jones 2005: 172-173; Whitehouse and Kirleis 2014: 9).

In contrast, other authors argue that unlike the very first agriculturalists in central Europe, early farmers in Britain were not fully sedentary and farming regimes were based on agro-pastoralism (Thomas 2013, 2007: 434, 1999: 29, Barker 2006: 380). These authors suggest that the number of substantial timber buildings so far discovered that date to this period is limited and question the interpretation that they functioned as permanently occupied farmsteads (Thomas 1996: 10). Rather than a fully arable economy, subsistence practice is proposed to have been predicated on routine exploitation of wild plant species as well as cereals (Stevens 2007: 381-382; Bishop *et al.* 2009: 86 & 90; Robinson 2000: 89; Moffett *et al.* 1989) and intensive dairying (Copley *et al.* 2003, 2005: 531; Cramp *et al.* 2014; Serjeantson 2011: 25; Viner 2012: 344-345, 2014: 161). This is in turn argued to demonstrate that the transition to agriculture occurred through adoption of selected elements of a farming economy by local Mesolithic populations, who retained a mobile way of life considered to be characteristic of hunter-gatherers (Thomas 2004: 126; 2013; Cummings and Harris 2011). Recent analysis of temporal changes in the robusticity of lower limb bones of prehistoric populations is also considered to support continued residential mobility during the Neolithic and a gradual, rather than abrupt, transition to sedentism (Ruff *et al.* 2015: 3). In Britain, early Neolithic occupation evidence frequently comprises pits, stakeholes, lithic scatters and middens which are interpreted as the remains of temporary camps that were occupied episodically (Bradley 2007: 43; Garrow *et al.* 2005: 155; Pollard 1999: 82). Rather than sedentism, residence patterns are argued to have been based on "tethered mobility" (Whittle 1997: 21; 2003: 43), a system of cyclical transhumance in which communities repeatedly moved between favoured occupation sites.

In view of these debates we applied strontium and oxygen isotope analysis of tooth enamel to evaluate the land use and residence patterns of the first farmers in Britain. Strontium isotope analysis of tooth enamel is a robust and highly reliable technique that is routinely used for geographic provenancing (Montgomery 2010; Slovak and Paytan 2011: 743-744). Strontium ($^{87}Sr/^{86}Sr$) isotope ratios vary with the age and composition of bedrock (Faure and Mensing 2005: 76). Strontium weathers from rocks into soils where it becomes available to plants and enters the human food chain (Bentley 2006: 141). Tooth enamel is highly resistant to diagenesis (Budd *et al.* 2000; Madgwick *et al.* 2012: 741) and as mass dependent fractionation does not affect conventionally measured $^{87}Sr/^{86}Sr$ values (Graustein 1989: 492) strontium isotope ratios in enamel directly reflect the location from which an individual obtained food during the period in which a tooth was mineralizing (Montgomery 2002; Budd *et al.* 2003: 128). Comparison of $^{87}Sr/^{86}Sr$ values in teeth that form at successive stages of childhood to mapped values in modern vegetation and water (e.g. Evans *et al.* 2010; Warham 2011) can therefore be used to evaluate whether an individual was residentially mobile.

The oxygen isotope composition of water also varies geographically with factors such as temperature, latitude and altitude (e.g. Gat 2010; Mook 2005). In Britain, $\delta^{18}O$ values of contemporary groundwaters are primarily influenced by rainfall: Britain receives its rainfall from a westerly direction and modern groundwaters in western Britain therefore record higher $\delta^{18}O$ values than those in eastern Britain (Darling *et al.* 2003: 189-190). A statistically significant difference in the mean $\delta^{18}O$ values measured in tooth enamel of multi-period archaeological populations buried in western Britain (18.2 ‰ ± 1 ‰, 2σ) from the eastern side of Britain (17.2 ± 1.3 ‰, 2σ), is considered to reflect the underlying geographic variation in the oxygen isotope composition of local drinking water between the two areas (Evans *et al.* 2012: 759). Evans *et al.* therefore suggest that occupation of these different regions of Britain is associated with 95 per cent ranges of 17.2 to 19.2 ‰ and 15.9 to 18.5 ‰ respectively (ibid.). These ranges were determined using isotope analysis of the phosphate (PO_4^{3-}) fraction of tooth enamel. However the carbonate (CO_3^{2-}) fraction is equally suitable for analysis and, as the $\delta^{18}O$ values in the $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ fractions are considered to be well correlated, conversion between the two can be undertaken using the equation developed by Chenery *et al.* (2012; see Materials and Methods). Interpretation of $\delta^{18}O$ results must, however, give consideration to the potential influence of culturally mediated behaviour, such as culinary practice (e.g. stewing foods and brewing) or consumption of fluids that have undergone fractionation through biological processes (e.g. breast milk or cow's milk) on the oxygen isotope composition of ingested fluids (Brettell *et al.* 2012; Camin *et al.* 2008: 1695; Lin *et. al.* 2003: 2193; Kornexl *et al.* 1997: 22; Roberts *et al.* 1988; Wright and Schwarcz 1998; Britton *et al.* 2015).

Isotope analysis of the structural carbonate fraction of enamel simultaneously yields carbon isotope ratios ($\delta^{13}C_{carbonate}$) which provide additional dietary information. The use of carbon isotope analysis for this purpose exploits the large variation in natural abundance of $\delta^{13}C$ between plants that use the two dominant (C_3 or C_4) photosynthetic pathways during fixation of CO_2 energy and variation in $\delta^{13}C$ values between terrestrial C_3 and marine ecosystems (Schwarcz and Schoeninger 2011; Sponheimer and Cerling 2014). Current understanding of dietary composition in the European Neolithic is based on analysis of $\delta^{13}C$ and $\delta^{15}N$ values in bone collagen, which predominantly reflect the protein component of the diet and support the exploitation of C_3 terrestrial sources of protein during the early Neolithic in Britain (e.g. Richards and Hedges 1999: 893; Richards *et al.* 2003; Hedges *et al.* 2008: 121). In contrast, $\delta^{13}C_{carbonate}$ values in bioapatite reflect the isotope composition of the diet as a whole, including lipids and carbohydrates (Ambrose and Norr 1993: 2; Jim *et al.* 2004). Individuals who obtain all of their diet from C_3 terrestrial sources may be predicted to have $\delta^{13}C_{carbonate}$ values between approximately -17.0 to -14.0 ‰ (Kellner and Schoeninger 2007; Froehle *et al.* 2012).

Thirty eight teeth, including the consecutively mineralizing molars of eighteen different individuals, were analysed to obtain strontium, oxygen and carbon isotope ratios (see Materials and Methods; table 1). The sampled population derives from Hazleton North long cairn, one of the few early Neolithic monuments which has been completely excavated to modern standards (Saville 1990; Rogers 1990). The monument, which is estimated to have been constructed between *3710-3655* cal BC and used for burial over at least two to three generations (*95% probability*, OxCal version 3.5, Meadows *et al.* 2007: 54) is situated in the Cotswold region of England (fig 1.). In addition to analyses undertaken on individuals buried in chambers on the north and south sides of the monument, a tooth from a small scatter of human remains found stratified underneath the long cairn that is considered to represent the earliest dated burial activity at the site (Meadows *et al.* 2007: 54) was also analysed. The presence of a hearth, post holes, a midden and evidence for cultivation directly beneath the monument are argued to indicate that it was constructed at a site previously used for occupation (Saville 1990: 20, 240-241; Macphail 1990: 225). Samples of enamel from the three main domesticated species found in the midden (cattle, sheep/goat and pig, Levitan 1990: 200) were also taken for analysis.

The lithology at the site and in the surrounding Cotswold region of Gloucestershire is composed of Oolitic limestone (BGS 2015; Worssam 1990: 228), a marine carbonate rock which has an $^{87}Sr/^{86}Sr$ value equivalent to seawater in the Middle Jurassic period (0.7068–0.7073, McArthur *et al.* 2012: 129; LOWESS version 5). However, the bioavailable $^{87}Sr/^{86}Sr$ range on Oolitic limestone is also influenced by rainwater (Capo *et al* 1998: 208). In an island facing the Atlantic such as Britain, the value of rainwater is close to that of seawater, which throughout the Holocene has had a ratio close to 0.7092 (Veizer 1989: 142; McArthur *et al.* 2012: 129, LOWESS version 5). Due to the combination of these two sources of strontium, samples from plants and waters on Oolitic limestones in the Cotswolds give $^{87}Sr/^{86}Sr$ values between 0.7076-0.7092, with a mean of 0.7086 ± 0.0004 (1σ, n = 17, Chenery *et al.* 2010: 155; Montgomery 2006: 1628; Warham 2011: 79 & 103). A sedentary self-sufficient population subsisting solely on resources obtained from a homogeneous lithological unit such as Oolitic limestone would be predicted to plot on a diagonal mixing array between two sources of dietary strontium (end-members): the ratio bioavailable on that lithological unit and that of rainwater (Montgomery *et al.* 2007; Montgomery 2010: 333). Had the sampled population derived all their resources locally, cultivating fields and keeping herds of animals around a permanently occupied settlement at the site or in the surrounding Cotswold region of England, they would therefore be expected to plot between the minimum value bioavailable on Oolitic limestone (0.7076) and rainwater (~ 0.7092).

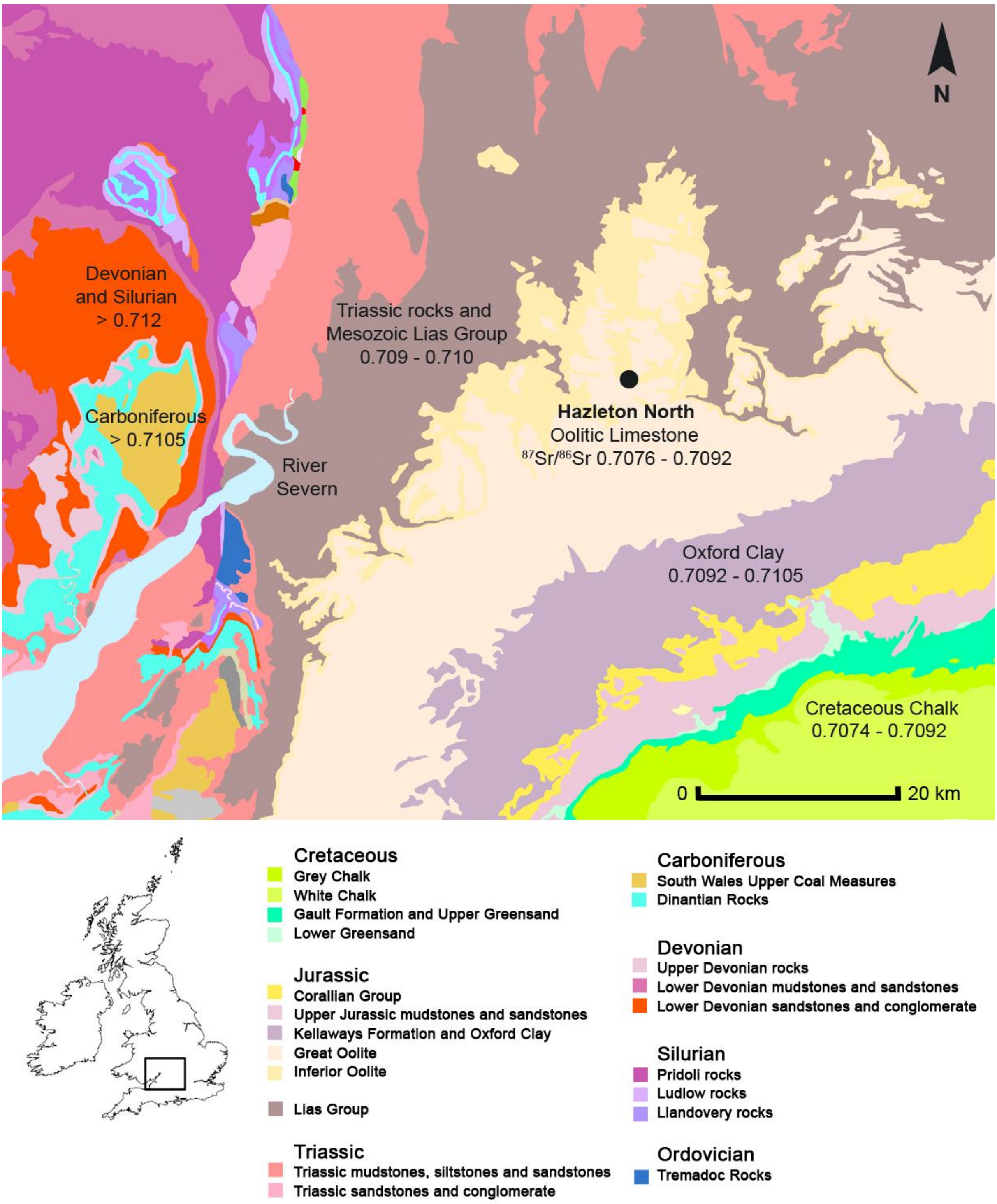


Figure 1. Map of bedrock geology based illustrating sites and locations discussed in the text. Based on British Geological Survey and Ordnance Survey map data, reproduced with permission of the British Geological Survey and Ordnance Survey, © NERC / Crown copyright [2015]. Bioavailable $^{87}Sr/^{86}Sr$ ranges associated with different lithologies are based on current measured values in Evans *et al.* (2010); Chenery *et al.* (2010) and Warham (2011: 70-96).

4.3 Materials and Methods

4.3.1 Sample selection

The human burial assemblage from Hazleton North consists of disarticulated and co-mingled human remains. Care was therefore taken to avoid the potential for duplication of isotope results through inadvertent sampling of antimeres which could belong to the same individual. Teeth that remained in-situ in left sided mandibular fragments were therefore selected for sampling. Teeth in right sided mandibular fragments were not sampled unless the refitting left hand side of the dentition was present. Maxillary teeth were only utilized if the re-fitting mandible belonging to the individual was present. In total 18 different individuals (14 adults and 4 pre-adults) were sampled. In addition to the 18 discrete individuals sampled by this project, two chips of core enamel taken during sampling of maxillary dentition by a project unrelated to the present study were also analysed to obtain isotope ratios: 4786 (LM2) and 10494 (LM3). Like the human assemblage, the pre-cairn animal assemblage from Hazleton North is also highly fragmentary. Cranial remains are dominated by loose teeth which cannot be assigned to specific individuals (Levitan 1990). One tooth from each of the three main domesticated species (cattle, sheep/goat and pig) present in the pre-cairn assemblage (Levitan 1990: 200) was sampled in order to compare $^{87}Sr/^{86}Sr$ values with those of the human group.

Due to the fragmentary nature of the assemblage and disarticulation of cranial remains from other skeletal elements the sex of the majority of sampled individuals cannot be stated with confidence. Only one individual, Skeleton 1, was found in a virtually-complete fully articulated state and may be sexed as male (Rogers 1990: 184). Where available, information on the approximate age of the individuals, as determined by dental eruption, is provided in table 1 (after Rogers 1990: 190-191). Wherever present, consecutively mineralizing molar teeth were selected in order to examine the variability in isotope ratios between teeth that form at different stages of childhood. Development of the crown of the first permanent adult molar commences in-utero, just prior to birth and completes by approximately 4.5 ± 0.5 years of age, whilst the second molar crown forms between 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31 & 55-56). The timing of third molar formation is most variable (Liversidge 2008: 313), with initial cusp formation taking place at approximately 8.5 ± 0.5 years and crown completion by 14.5 ± 0.5 years (AlQahtani *et al.* 2010). Strontium and oxygen isotope analysis was conducted on samples of bulk enamel, and isotope ratios therefore represent the weighted average of the sources to which the individual was exposed during the period the tooth was mineralizing. As the process of enamel formation is highly complex (e.g. Hillson 2014), and as strontium may have an extended residence time within the body prior to its incorporation in enamel (Montgomery 2010: 330), it is currently uncertain that greater chronological resolution can be achieved by serial sampling of human tooth enamel.

4.3.2 Sample preparation and laboratory analysis

Teeth were processed following procedures developed by Montgomery (2002: 131-138). Surface enamel was thoroughly abraded using a tungsten carbide dental burr. Enamel chips were then cut using a flexible diamond-edged rotary saw and surfaces again mechanically cleaned using a tungsten carbide dental burr to remove any adhering dentine. An enamel chip of approximately 20–30mg in weight from each tooth was taken for strontium isotope analysis and of approximately 10mg in weight for oxygen isotope analysis. Dental saws and burrs were cleaned ultrasonically for 5 min and rinsed three times in high purity de-ionized water between preparation of samples.

Samples were taken to the Class 100, HEPA-filtered laboratory facilities at the Natural Environment Research Council Isotope Geosciences Laboratory, (Keyworth, Nottingham, England). Enamel chips were cleaned ultrasonically and rinsed in high purity water (Millipore Alpha Q). They were then dried, weighed into pre-cleaned Teflon beakers and spiked with a known amount of ^{84}Sr tracer solution to obtain strontium concentrations. Each sample was dissolved in Teflon distilled 8M HNO_3. Samples were converted to Chloride using 6M HCl, taken up in titrated 2.5M HCl and pipetted onto ion exchange chromatography columns. Strontium was separated with Dowex® (AG50-X8) resin (200 - 400 mesh). Procedural blanks were below 150 pg. Samples were loaded on to Re filaments using a method adapted from Birck (1986: 79). Strontium isotope composition and concentrations were then determined by Thermal Ionisation Mass spectroscopy (TIMS) using a *ThermoTriton* automated multi-collector mass spectrometer. To correct for fractionation during the process of mass spectrometry $^{87}Sr/^{86}Sr$ values are normalised to the accepted value for $^{88}Sr/^{86}Sr = 0.1194$. During the period of this study the machine gave a value for the international standard for $^{87}Sr/^{86}Sr$ (NBS 987) of 0.710253 ± 0.000012 (2σ, $n = 350$). An estimate of the reproducibility of strontium concentration (Sr ppm) is provided by replicate analysis of an aliquot of bone standard solution (NIST1486) which gave 7.22 ± 0.27 ppm ($\pm$ 3.75%, 1σ, $n = 16$).

Initial preparation of core enamel chips for $\delta^{18}O$ and $\delta^{13}C$ analysis was undertaken at Durham University using the same methods employed above for strontium isotope analysis. Core enamel chips were then transferred as clean core enamel chips to the Natural Environment Research Council Isotope Geosciences Laboratory (Keyworth, Nottingham, England) where they were powdered. Oxygen ($\delta^{18}O_{carbonate}$) and carbon ($\delta^{13}C_{carbonate}$) isotope ratios in the carbonate fraction of enamel were determined using the method outlined in Chenery *et al.* (2012: 310). Isotope ratios are reported as delta (δ) values, in parts per thousand (per mil; ‰) normalized to the VPDB scale using an in-house carbonate reference material, Keyworth Carrera Marble (KCM) which is calibrated against NBS19 certified reference material. Analytical reproducibility for this run of KCM was ± 0.09 ‰ (1σ, n = 14) for $\delta^{18}O$ and for $\delta^{13}C$ ± 0.04 ‰ (1σ, n = 14). $\delta^{18}O_{carbonate}$ values were normalized to the VSMOW scale using the equation of Coplen 1988 (VSMOW = 1.03091 x $\delta^{18}O$ VPDB + 30.91). Conversion between $\delta^{18}O_{carbonate}$ to $\delta^{18}O_{phosphate}$ was then undertaken using the regression equation of Chenery *et al.* (2012: 310; $\delta^{18}O_{phosphate}$ = 1.0322 x $\delta^{18}O_{carbonate}$ – 9.6849). The error involved in calculating $\delta^{18}O_{phosphate}$ is considered to be low (0.28 ‰, 1σ, Chenery *et al*. 2012: 313).

Table 1. Strontium isotope ratios, strontium concentrations and $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ values in enamel of humans and animals from Hazleton North. Approximate age at death is based on tooth eruption (after Rogers 1990: 190-191; tables 65-70); L = left, R= right; mandibular first, second and third permanent molar teeth are designated as M1, M2 and M3 respectively; second permanent premolar teeth are designated as PM2; first mandibular central permanent incisor teeth designated as LI1.

Sample Number	Location	Context/ box number	Age at death	Tooth	$^{87}Sr/^{86}Sr$	Sr ppm (mg/kg)	1/Sr ppm x 1000	$\delta^{13}C_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VSMOW	$\delta^{18}O_{phosphate}$ ‰ VSMOW
10414/Individual G	North Chamber basal fill	336	3-4 years	Mandibular LM1	0.71027	54	18.51852	-16.0	-3.8	27.0	18.2
10494	South Chamber fill	412	Adult	Maxillary LM3	0.70963	49	20.40816	-15.1	-4.0	26.8	18.0
11456	South Chamber fill	412	Adult	Mandibular LM2	0.71036	67	14.92537	-15.2	-4.2	26.6	17.8
				Mandibular LM3	0.71016	58	17.24138	-16.7	-4.4	26.4	17.6
11903	Pre-cairn; SW Quad Cell S	211	Unknown	Loose premolar	0.70866	45	22.22222	-16.0	-3.5	27.3	18.5
12527	South Chamber	453	6-9 years	Mandibular RM1	0.70833	62	16.12903	-16.1	-2.5	28.3	19.5
3596	South Entrance fill	354	Adult	Mandibular RPM2	0.70853	47	21.2766	-16.1	-3.8	27.0	18.2
3793	South Entrance fill	354	Adult	Mandibular RM1	0.70818	63	15.87302	-14.9	-3.1	27.8	19.0
				Mandibular RM2	0.70818	44	22.72727	-14.7	-3.8	27.0	18.2
				Mandibular RM3	0.71033	101	9.90099	-15.7	-3.1	27.7	18.9
3831	South Entrance fill	354	Adult	Mandibular RM2	0.71036	144	6.944444	-15.0	-4.0	26.8	18.0
				Mandibular RM3	0.70838	35	28.57143	-16.3	-3.8	27.0	18.2
4077/4169	South Entrance fill	354	Adult	Mandibular RM1	0.70835	37	27.02703	-16.0	-2.9	28.0	19.2
				Mandibular RM2	0.70827	30	33.33333	-15.5	-3.7	27.1	18.3
				Mandibular RM3	0.70806	24	41.66667	-16.3	-4.2	26.6	17.8
4118	North Entrance fill	267	Adult	Mandibular LI1	0.71027	65	15.38462	-15.4	-3.5	27.3	18.5
4786	South Chamber Passage	187	Adult	Maxillary LM2	0.70839	48	20.83333	-14.7	-3.1	27.7	18.9
4806/7387	South Chamber Passage	323	Adult	Mandibular LM1	0.70887	39	25.64103	-16.4	-3.0	27.8	19.1
5037/Skeleton 1	North Entrance	267	Adult	Maxillary LM1	0.70797	22	45.45455	-16.5	-3.9	26.9	18.1
				Maxillary RM2	0.70804	22	45.45455	-16.0	-3.7	27.1	18.3
				Maxillary RM3	0.70825	27	37.03704	-15.9	-3.8	27.0	18.1
5880	North Chamber basal fill	336	Adult	Mandibular LM1	0.70957	85	11.76471	-15.2	-3.2	27.6	18.8
				Mandibular LM2	0.70912	52	19.23077	-15.8	-3.2	27.6	18.8
				Mandibular LM3	0.70888	40	25	-16.1	-3.8	27.0	18.2
7386/6815	South Chamber Passage	323	Adult	Mandibular LPM2	0.70838	45	22.22222	-15.5	-4.4	26.4	17.6

Table 1. *Continued from over page.*

Sample Number	**Location**	**Context/ box number**	**Age at death**	**Tooth**	**$^{87}Sr/^{86}Sr$**	**Sr ppm (mg/kg)**	**1/Sr ppm x 1000**	**$\delta^{13}C_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VSMOW**	**$\delta^{18}O_{phosphate}$ ‰ VSMOW**
7656	South Chamber Passage	323	Adult	Mandibular RM1	0.70794	41	24.39024	-15.2	-3.0	27.2	19.1
				Mandibular RM2	0.70855	55	18.18182	-14.5	-3.6	27.2	18.4
				Mandibular RM3	0.70813	32	31.25	-16.4	-3.6	27.2	18.4
8701/Individual E	South Chamber fill	412	12-15 years	Mandibular RM1	0.70807	40	25	-16.1	-3.9	26.9	18.1
8751	South Chamber fill	412	Adult	Mandibular LM2	0.70804	37	27.02703	-15.8	-3.7	27.1	18.2
				Mandibular LM3	0.71066	84	11.90476	-16.0	-3.3	27.5	18.7
8974	South Entrance fill	353	Adult	Mandibular LM2	0.70962	76	13.15789	-15.9	-4.4	26.4	17.6
				Mandibular LM3	0.71120	88	11.36364	-15.6	-4.0	26.8	18.0
9025	North Chamber fill	435	Adult	Mandibular LM1	0.71262	74	13.51351	-15.6	-3.2	27.6	18.8
9951	South Chamber fill	412	9-10 years	Mandibular LM1	0.70810	62	16.12903	-15.5	-4.0	26.8	18.0
HBG HN82/15374 Cow	Pre-cairn/NW Quad Cell R	211/box 23	Unknown	Loose molar tooth	0.71059	180	5.555556				
HBG HN82/16065 Pig	Pre-cairn/NW Quad Cell R	211/box 29	Unknown	Maxillary LM3	0.70774	82	12.19512				
HBG HN82/18304 Sheep/goat	Pre-cairn/SW Quad Cell S	211/box 31	Unknown	Loose molar tooth	0.70821	216	4.62963				

4.4 Results

The majority of the population plot on a diagonal array in which $^{87}Sr/^{86}Sr$ increases with elemental concentration between a lower value < 0.7085 and an upper value > 0.7105. Adjacent molar teeth of individuals in the group also exhibit a shift in strontium isotope ratio and concentration between a lower value < 0.7085 and an upper value > 0.7105, or vice versa (fig. 2). Isotope ratios do not vary with burial context: individuals from chambers on both the north and south side of the monument plot on the same array. Only one individual appears to be an outlier from the strontium isotope array with a value higher than 0.7125. Three individuals have an $^{87}Sr/^{86}Sr$ value that is consistent with the local biosphere $^{87}Sr/^{86}Sr$ range on all three of their consecutively mineralizing molar teeth (highlighted in light green, fig. 2).

Figure. 2. Plot of strontium isotope ratio versus the inverse of concentration (1/Sr ppm x 1000) for individuals and animals. Dashed lines delineate the approximate $^{87}Sr/^{86}Sr$ biosphere range available on Oolitic limestone. Tooth types are denoted by the key in the upper right of the diagram. Light green symbols indicate individuals who could be interpreted to be sedentary and red symbols denote the rest of the population buried within the cairn. Open white symbol: loose premolar tooth found below the cairn. Cow, sheep/goat and pig labelled within the diagram are also from sub-cairn contexts. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.

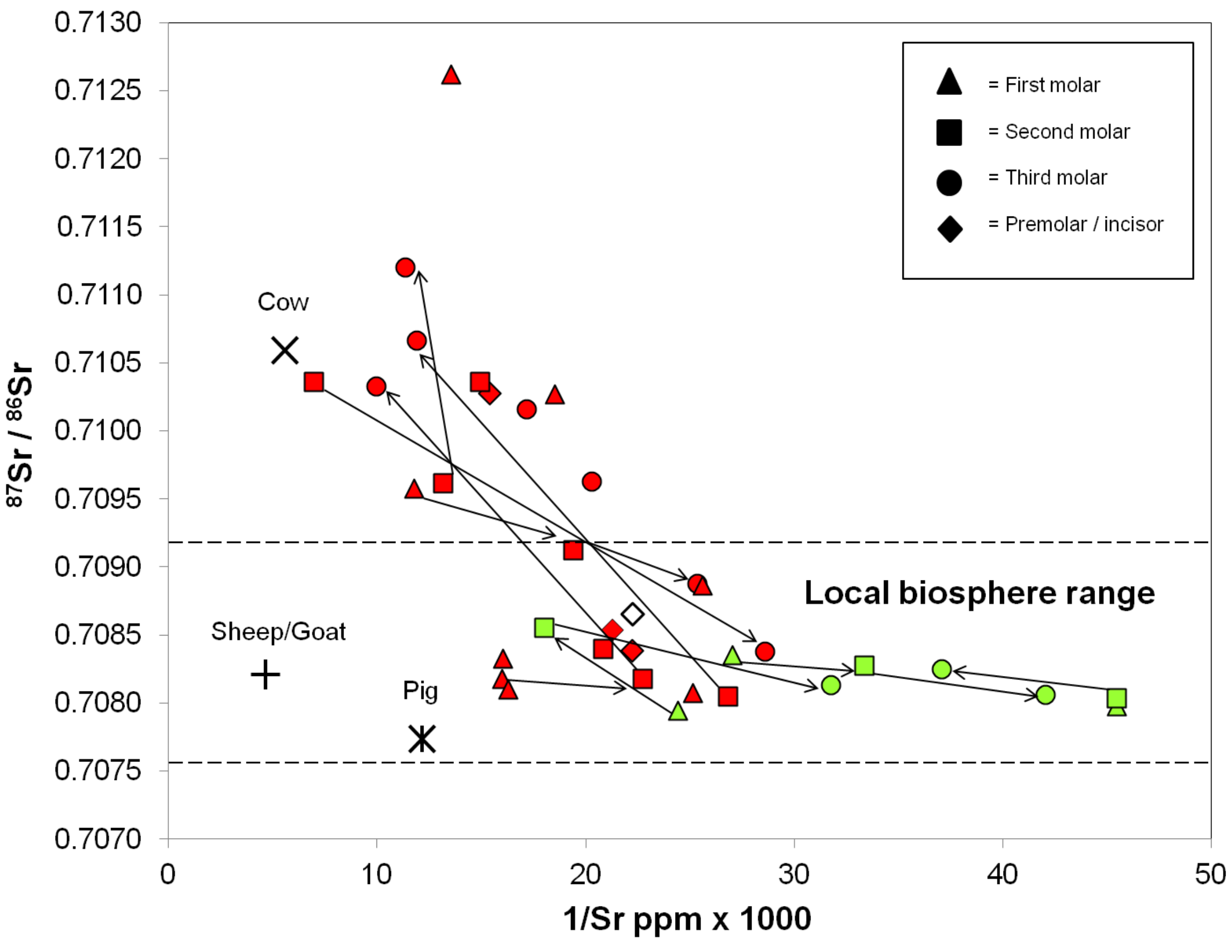
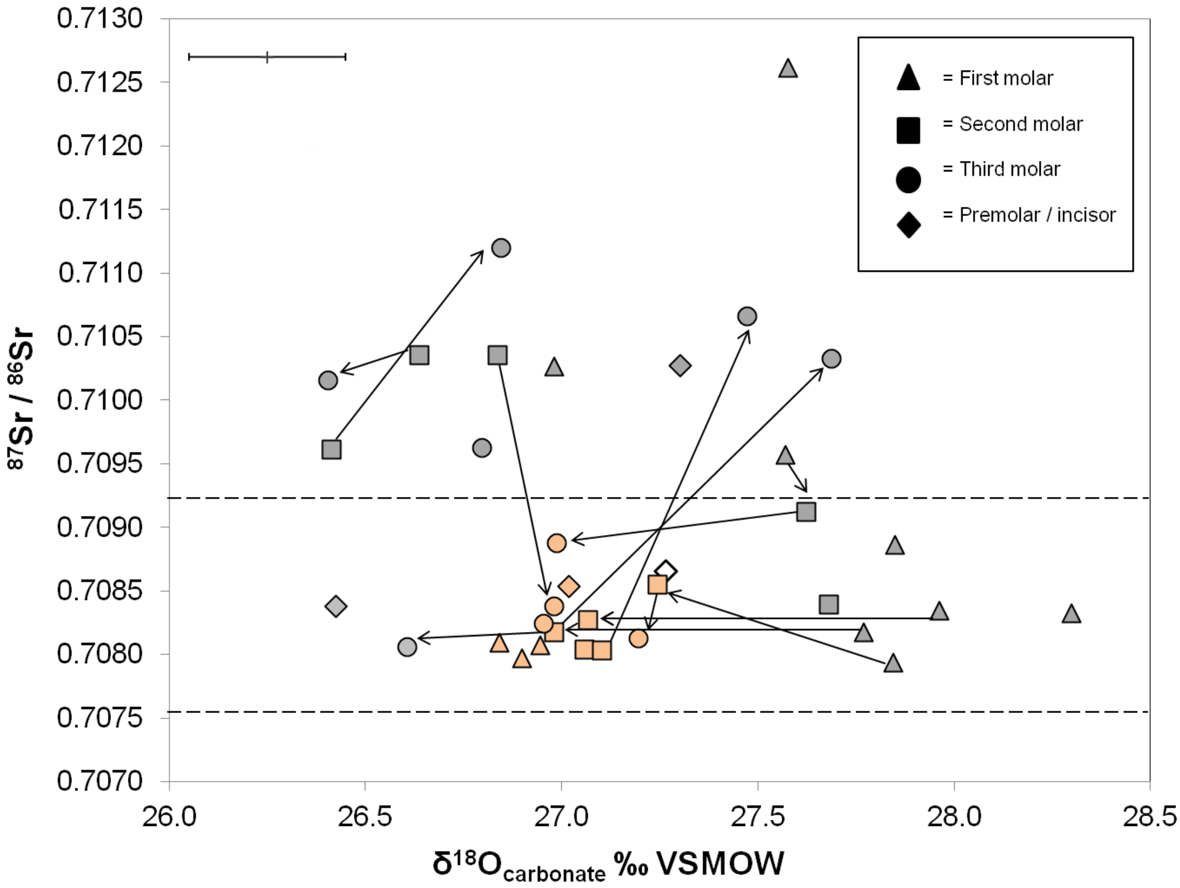


Figure 3. Plot of $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{carbonate}$ results. Dashed lines denote the local $^{87}Sr/^{86}Sr$ biosphere range. Teeth highlighted in orange have $^{87}Sr/^{86}Sr$ values that are comparable to the local biosphere range and $\delta^{18}O_{carbonate}$ values that cluster close to 27.0 ‰. Open white symbol: loose premolar tooth found below the cairn. Tooth types are illustrated within the key in the upper right of the diagram. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2‰ (2σ).



$\delta^{18}O_{carbonate}$ values range between 26.4 - 28.3 ‰, with a mean of 27.1 ± 0.4 ‰ (n = 35, 1 σ). With the exception of first molar teeth which more frequently plot with oxygen isotope values higher than 27.5 ‰ (fig. 3), the majority of teeth that have $^{87}Sr/^{86}Sr$ values near to 0.7085 have $\delta^{18}O_{carbonate}$ values that plot in a cluster close to 27.0 ‰. In contrast, teeth with higher strontium isotope ratios (> 0.7105) that plot above the local biosphere range exhibit a less constrained range of $\delta^{18}O_{carbonate}$ values. $\delta^{13}C_{carbonate}$ values of the sampled human population range between -16.6 and -14.5 ‰ (mean 15.6 ± 0.5 ‰, n = 35, 1σ; table 1) and therefore fall within the range of values expected for a diet dominated by C_3 terrestrial sources. Animals sampled from the pre-cairn contexts (fig. 3) exhibit a comparable range of $^{87}Sr/^{86}Sr$ values to the human group. Whilst the sheep/goat and pig have strontium isotope ratios comparable to the local biosphere range, the cow has a value which is higher than 0.7105. The herbivores that were sampled exhibit higher strontium concentrations than the human population. This is consistent with the progressive discrimination against strontium which results from bio-purification of calcium with increasing trophic level within a food chain (e.g. Burton *et al.* 1999; Blum *et al.* 2000).

4.5 Discussion

A sedentary self-sufficient population subsisting solely on resources obtained from a homogeneous lithological unit such as Oolitic limestone would be predicted to plot on a diagonal mixing array between two sources of dietary strontium (end-members), the ratio bioavailable on that lithological unit and that of rainwater (Montgomery *et al.* 2007; Montgomery 2010: 333). The majority of individuals do plot on a diagonal array, which indicates that they derived dietary strontium from two dominant sources (dietary end-members) that were incorporated in differing proportions during tooth mineralization (Montgomery *et al.* 2007; Montgomery 2010: 333). However, the strontium isotope array does not conform to that predicted for a sedentary self-sufficient population who had subsisted solely on locally bioavailable resources. One of the two dietary sources exploited by the group had a $^{87}Sr/^{86}Sr$ value close to 0.7085 and is therefore comparable to the local $^{87}Sr/^{86}Sr$ biosphere range. However, the other dietary end-member (> 0.7105) is not (Evans *et al.* 2010; Chenery *et al.* 2010; Warham 2011: 79). In southern Britain lithologies that routinely give measured biosphere $^{87}Sr/^{86}Sr$ values below 0.7085 are geographically separated from those that give values higher than 0.7105, with the exception of the Lizard Peninsula in Cornwall where a small area of serpentinite crops out next to Devonian rocks, approximately 300 kilometres away from Hazleton North (Evans *et al.* 2010). With the exception of the latter area, all current measured $^{87}Sr/^{86}Sr$ biosphere values suggest that strontium isotope ratios below 0.7085 and values above 0.7105 are not routinely bioavailable in close proximity in southern Britain. Therefore, to generate the array seen in figure 2 a population who inhabited southern Britain would have to have sourced their diet from at least two different geographical locations. In the absence of any evidence for a market economy during this period to suggest communities derived a significant component of their diet through trade, the strontium isotope array is consistent with movement of individuals between different localities to obtain dietary resources. The closest proximal area to the site where $^{87}Sr/^{86}Sr$ values above 0.7105 are routinely bioavailable is more than 40 kilometres to the west or south-west. Plants and waters on lithologies of Carboniferous, Devonian or Silurian age in areas of south-western Britain such as Gloucestershire, Herefordshire or Worcestershire routinely give values higher than 0.7105 (Chenery *et al.* 2010: 155), although areas further afield, for example in Wales or Somerset, cannot be excluded (Evans *et al.* 2010). The interpretation that the group routinely derived dietary strontium from at least two separate locations is also supported by strontium isotope results from adjacent molar teeth which plot on the same strontium isotope array. Several individuals in the group exhibit a shift in $^{87}Sr/^{86}Sr$ values from the upper (> 0.7105) to the lower end-member (< 0.7085), or vice versa (illustrated by arrows in figure 2). This shift in values between consecutively mineralizing molar teeth is consistent with regular movement backward and forward between at least two different geographical locations.

$\delta^{18}O_{carbonate}$ results may also support the interpretation that the group derived their diet from more than one location. The majority of teeth with $^{87}Sr/^{86}Sr$ values that are comparable to the local biosphere range have $\delta^{18}O_{carbonate}$ values that plot in a cluster close to 27.0 ‰. Individuals who plot within this cluster appear to have derived ingested fluids from a source which conferred a very similar oxygen isotope value. Deviation in values from the cluster, which appears to represent one of the dietary sources exploited by the sampled group, could be a consequence of localized variation in the oxygen isotope composition of groundwaters between the different geographical locations used by the population. Adjacent molar teeth of different individuals within the sampled group exhibit a shift in oxygen isotope values backward and forward, into and out of this cluster, with those teeth which have higher strontium isotope ratios (> 0.7105) being associated with a less constrained range of $\delta^{18}O_{carbonate}$ values. First molar teeth, which begin to form just prior to birth (Hillson 2014: 31, 55-56) more frequently plot with $\delta^{18}O_{carbonate}$ values that are higher than 27.5 ‰ (fig. 3) and it is possible that the values within these teeth may be influenced by consumption of breast milk which has a higher $\delta^{18}O$ value relative to meteoric water as a result of the metabolic fractionation that occurs in the mother's body (Roberts *et al.* 1988; Wright and Schwarcz 1998; Britton *et al.* 2015). The mean $\delta^{18}O_{phosphate}$ value for second and third molar teeth 18.2 ± 0.4 ‰ (n = 20, 1σ) is, however, comparable to that which has been proposed to represent occupation of the western side of Britain (18.2 ‰ ± 1 ‰, 2σ, Evans *et al.* 2012: 759) and could support the interpretation that the group routinely moved around lithologies within this region.

The majority of the population, both adults and children of different ages at death, and consecutively mineralizing molars of different individuals, have $^{87}Sr/^{86}Sr$ values which conform to the same strontium isotope array. As such it is highly likely that the sampled group participated in a very similar residential routine throughout the period to which the burials are dated, over at least two to three generations during the 37th century BC (Meadows *et al.* 2007: 54). The tooth from pre-cairn contexts (table 1) plots within the cluster of individuals who have teeth with $^{87}Sr/^{86}Sr$ values comparable to the local biosphere range and $\delta^{18}O_{carbonate}$ values close to 27.0‰. This individual could therefore have derived their diet from one of the locations which was exploited by the population who were buried within the cairn. The $^{87}Sr/^{86}Sr$ value of the lower dietary end member that was exploited by the human burial population (< 0.7085) is consistent with the local bioavailable range and, in conjunction with the presence of a hearth, midden and evidence for cultivation at the site, supports the hypothesis that the site at which the monument was constructed was one of the two locations exploited during childhood and adolescence by the population who were subsequently buried in the cairn. Occupation of other areas in southern Britain, such as the Cotswolds, or Cretaceous Chalk, which afford a similar bioavailable range cannot be excluded (fig. 1, Evans 2010; Viner *et al.* 2010: 2816). However, the inference that the site itself may have been significant in the residential tradition of the group buried in the cairn is further supported by the presence of fragments of worked quartzitic sandstone found in pre-cairn contexts. These fragments were imported to the site from at least 40 kilometres away and derive from lithologies of Carboniferous or older age (Worssam 1990: 230) which are routinely associated with bioavailable $^{87}Sr/^{86}Sr$ values comparable to those in the area that provided the upper end member (> 0.7105) for the group buried in the cairn (Evans *et al.* 2010). Strontium isotope ratios of animals in the midden below the cairn also appear to reflect the residential regime of the human population in the cairn. The animals in the midden were raised at more than one geographic location. They have $^{87}Sr/^{86}Sr$ values that are comparable to the upper and lower dietary end members exploited by the human group and thus are consistent with those of the two areas utilized by the population who were buried at the site.

Only three individuals in the sampled human population (highlighted in light green, fig. 2) possess values below 0.7085 on each of their consecutively mineralizing molar teeth. This could be consistent with sedentism. Although it is possible that these individuals moved between different areas which afford the same $^{87}Sr/^{86}Sr$ bioavailable range (e.g. between Oolitic limestone and Cretaceous Chalk), the presence of similar values on adjacent molar teeth may support the interpretation that they occupied one of the locations exploited by the group for a longer period during their early life. Unlike these individuals the majority of the sampled population do not exhibit values that are consistent with permanent occupation of the same location during early life, or with "radial mobility", brief visits to temporary outlying camps from a single permanent settlement (Rowley-Conwy 2003: 115 & 123). Ratios in bulk enamel are considered to represent the weighted average of all sources of strontium to which the individual had been exposed during the period the tooth was mineralizing (Montgomery 2010: 333). To gain a value higher than $^{87}Sr/^{86}Sr$ 0.7105 an individual would need to have derived a significant part of their diet from an area of radiogenic geology, more than would be obtained by a brief visit away from an area with a value below 0.7085. In addition, the regular shift in values individuals exhibit between adjacent molar teeth, from 0.7105 to 0.7085 or vice-versa, is also consistent with a change in location between the two areas used by the group. The possibility that the array seen in figure 2 represents a migrant population who had been fully sedentary at a distant location, for example on the Continent, where lithologies that provided biosphere values above 0.7085 and below 0.7105 cropped out close together (i.e. in the same field system) should also be considered. However, evidence for cultivation and occupation beneath the cairn

(Saville 1990: 20, 240-241; Macphail 1990: 225) in conjunction with evidence for the sourcing of artefacts (above) and strontium isotope results from animals in pre-cairn contexts support the hypothesis that this location was of pre-existing importance within the residential tradition of a group who inhabited southern Britain.

Results therefore support the model of "tethered mobility" proposed by Whittle (1997: 21; 2003: 43), a system in which individuals repeatedly moved between favoured occupation sites. Strontium isotope ratios in tooth enamel are a reflection of sources to which individuals were exposed during early life and as such the results could be compatible with routine movement of individuals during childhood and adolescence between two communities living in different areas. Alternatively, the array seen in figure 2 could be consistent with a system of cyclical transhumance in which people routinely moved between pastures with their livestock, between for example the Oolitic limestone in the vicinity of the site and older lithologies to the west of the river Severn, as the animals sampled possess $^{87}Sr/^{86}Sr$ values which are comparable to those exhibited by the human group and reflect exploitation of at least two different geographical locations.

The results may therefore be contrasted with the system of sedentary intensive mixed farming that has been proposed to characterize the Linearbandkeramik (LBK, c. 5,500 - 4,900 BC), in which arable production was closely integrated with livestock keeping close to permanently occupied hamlets and village (Bogaard 2004: 159; Fraser *et al.* 2013: 510). Whilst there is evidence for cultural variability in lifeways during the LBK (e.g. Bickle *et al.* 2013; Bentley 2013; Nehlich *et al.* 2009; Knipper 2009), the majority of strontium isotope results support a system of inherited male access to local plots of land that were located close to permanent settlements (Bentley *et al.* 2012: 3929), with livestock being routinely kept near to the homebase (Knipper 2011; Bentley *et al.* 2004: 372). Our results from Britain contrast with this. The majority of individuals in the sampled group from Hazleton North did not derive dietary resources from sedentary intensive mixed farming at a single geographical location. Results are instead consistent with individuals having participated in a regular routine of residential mobility between different geographical locations.

4.6 Conclusions

Agricultural development across Europe has been proposed to have been predicated on a similar system of sedentary intensive mixed farming, with close integration of arable production and livestock keeping at permanently occupied settlements (Bogaard *et al.* 2013; Bogaard 2005; Jones 2005; Rowley-Conwy 2003, 2004, 2011). However, whilst there is strong evidence that this may have provided the basis for the earliest farming systems in central Europe during the 6^{th} millennium BC, the argument that this model can be use as a template for subsequent developments in Britain during the 4^{th} millennium has been challenged (Thomas 2013; Thomas 1999) due to the highly varied nature of occupation evidence which suggests that early farming communities in Britain may have been residentially mobile (e.g. Sheridan 2013; Anderson-Wymark and Thomas 2012; Brophy 2015). Our results are consistent with the hypothesis that early farming communities in Britain participated in a regular routine of mobility between different geographic areas and were not fully sedentary. Whilst some individuals within the sampled group may have obtained their dietary resources from a single location the majority of the sampled group do not have values that would be consistent with this. The results support the interpretation that individuals participated in a regular routine of movement between different geographic areas. Evidence for residential mobility need not, however, imply continuity from the local Mesolithic within Britain, as the presence of similar settlement systems on the continent during the 4th millennium BC cannot be ruled out. The results do, however, highlight the diverse nature of residence patterns associated with early agriculture in Europe and provide evidence for cultural variability in settlement practices during the development of farming.

4.7 Acknowledgements and author contributions statement

S.N. designed the research; S.N. and J.E. undertook the analysis; S.N. wrote the paper. Strontium and oxygen isotope analysis was funded through NIGSFC grant IP-1290-0512. All authors discussed drafts of the paper and approved the final manuscript. Analysis was funded by the Natural Environment Research Council (NIGFSC IP-1290-0512). S.N. was funded through a Durham University Doctoral Studentship. We would particularly like to thank Hilary Sloane (NERC Isotope Geosciences Laboratory) for analytical support and Dr Alison Brookes for access to collections and for permission to undertake sampling.

4.8 Supplementary information

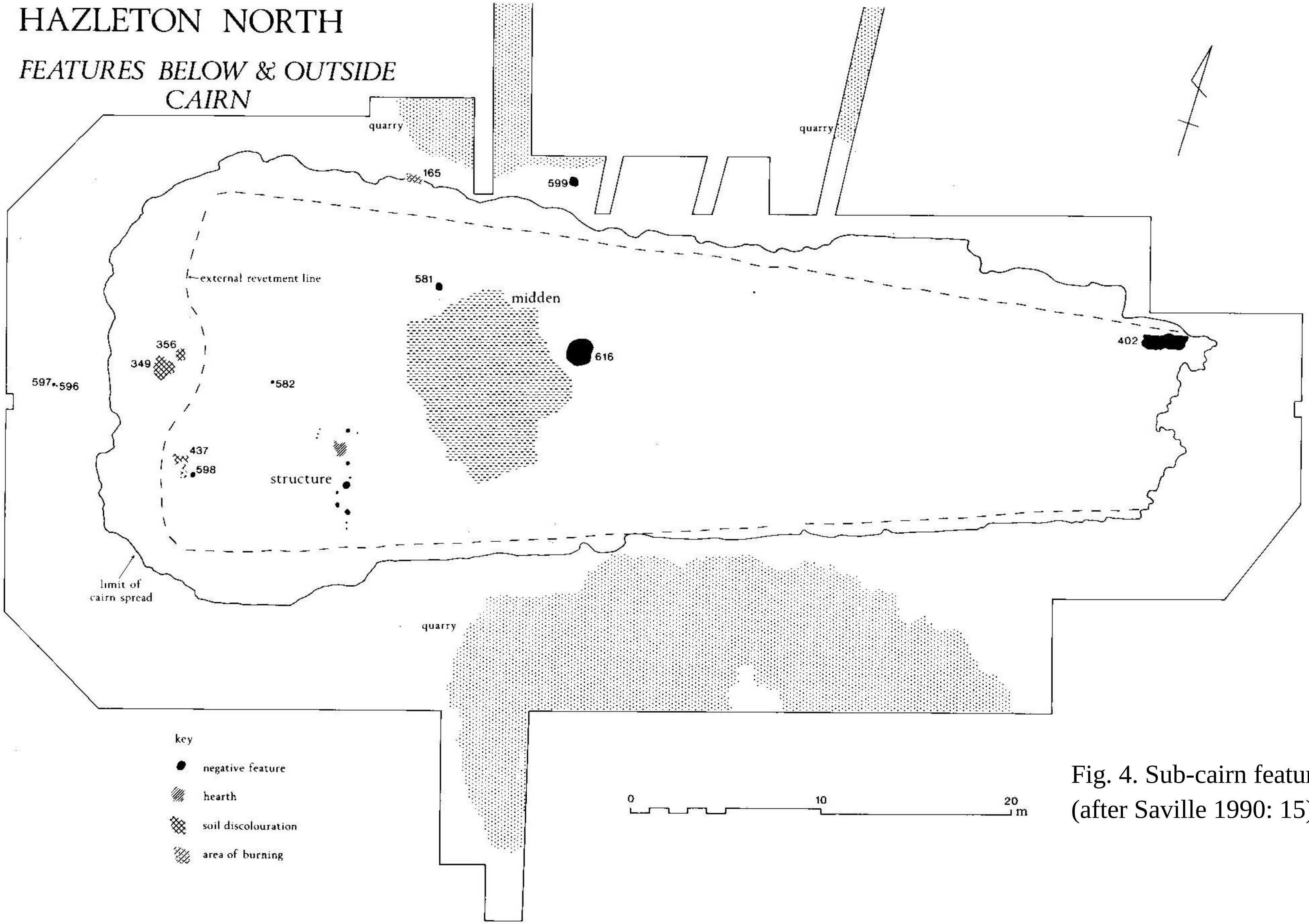


Fig. 4. Sub-cairn features (after Saville 1990: 15)

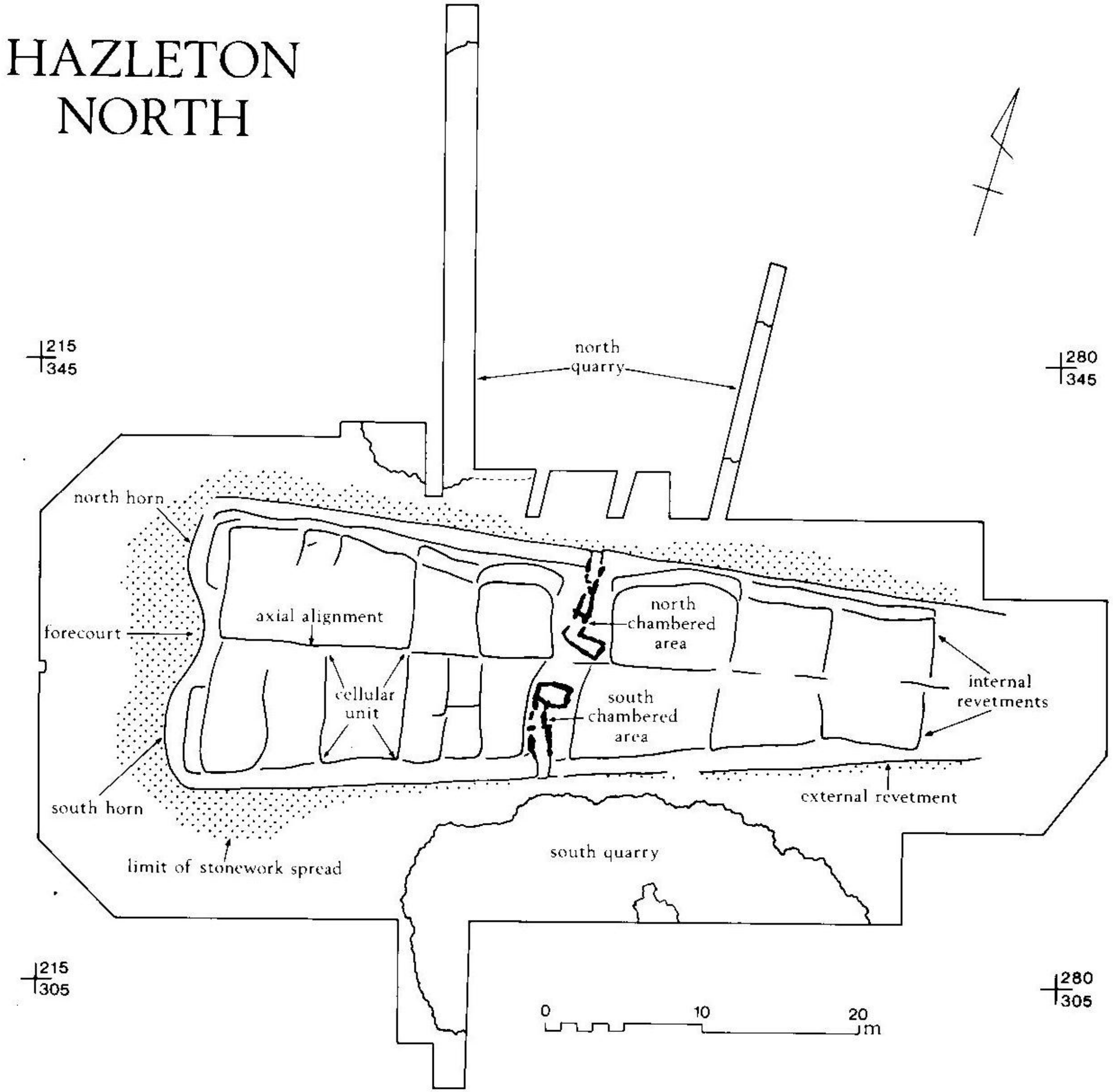
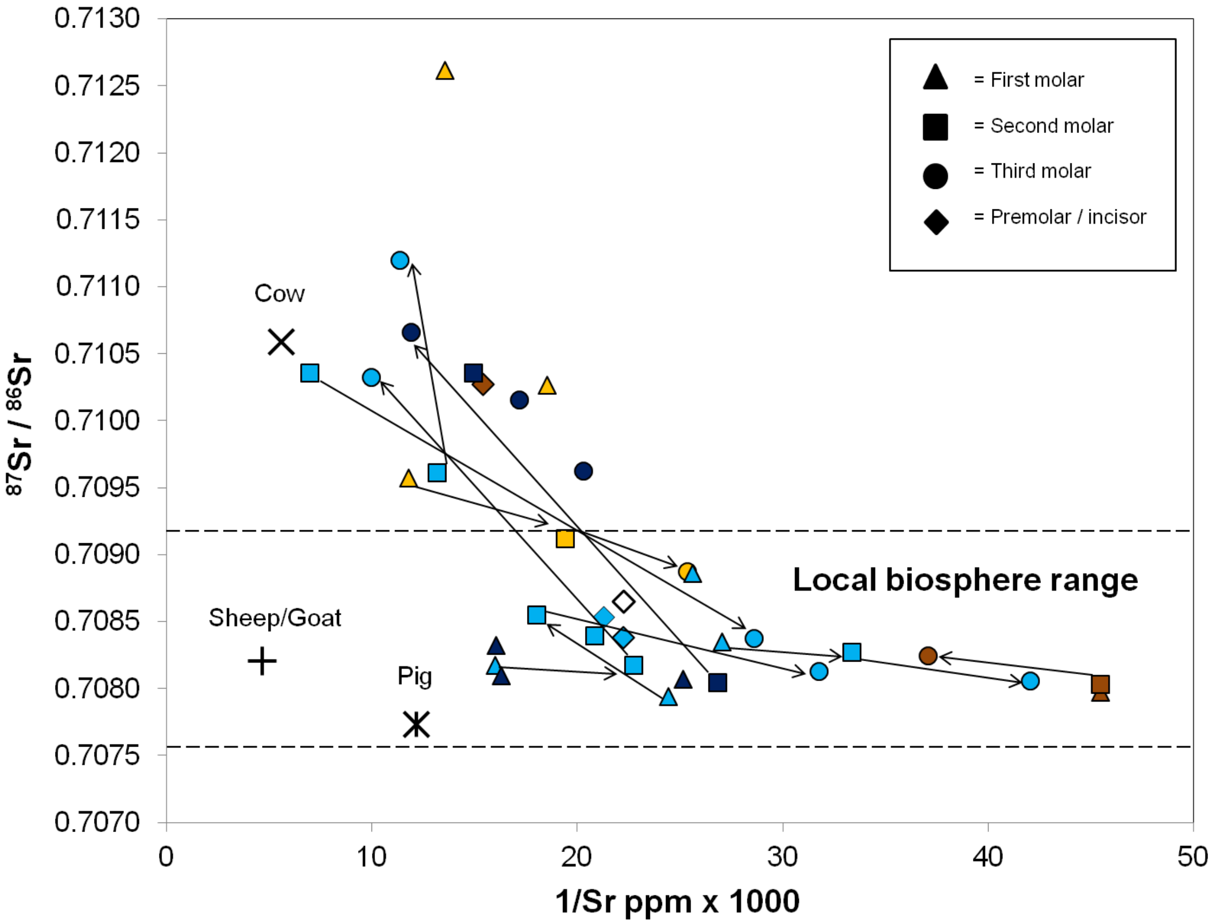


Fig. 5. Plan of Hazleton North (after Saville 1990: 11)

Figure 6. Plot of strontium isotope ratio versus the inverse of elemental concentration (1/Sr ppm x 1000) illustrating all adjacent linked molars; symbols coloured according to the context from which each individual is recorded to have been excavated. Dashed lines delineate the approximate $^{87}Sr/^{86}Sr$ biosphere range available on Oolitic limestone. Tooth types are denoted by the key in the upper right of the diagram. Open white symbol: loose premolar tooth found below the cairn. Cow, sheep/goat and pig labelled within the diagram are also from sub-cairn contexts. Brown symbols: human individuals buried in the north chamber entrance; light orange symbols: north chamber fill. Light blue symbols: south chamber entrance fill and passage; dark blue symbols: south chamber fill. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.



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5. Isotopic evidence for land use and the role of causewayed enclosures during the earlier Neolithic in southern Britain

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5.1 Abstract

The nature of land use and residence patterns during the British earlier Neolithic has often been debated. Here we use strontium and oxygen isotope analysis of tooth enamel, from individuals buried at the Hambledon Hill causewayed enclosure monument complex, in Dorset, England to evaluate patterns of land use during the earlier Neolithic. Previous analysis suggests that a significant proportion of the artefacts found at the site may originate from lithology of Eocene and Upper to Middle Jurassic age that the enclosures overlook to the immediate west and south. The excavators of this site therefore argue that that sector of landscape visible from Hambledon Hill provides an approximate index for the catchment occupied by the communities that it served. Most of the burial population exhibit isotope ratios that could be consistent with this argument. Connections between Hambledon Hill and regions much further afield are also hypothesized, based on the presence of artefacts within the assemblage that could have been sourced from lithology in

Somerset, Devon and Cornwall in the south-western peninsula of England. However, few of the individuals who were sampled have strontium isotope ratios that would be consistent with having obtained the majority of their diet from such areas during childhood. The individuals who exhibit the highest strontium isotope ratios within the sampled burial population are adult males, whom the excavators suggest to have died during an episode of conflict at the site, following the burning and destruction of defensive outworks that were built to surround the complex during the 36th century BC. At least one of these individuals did not obtain his childhood diet locally. This individual, who was found with an arrowhead amongst his ribs, sourced his diet from further afield and has $^{87}Sr/^{86}Sr$ values that could be comparable to those bioavailable in the south-west peninsula of England.

5.2 Archaeological evidence for land use and the role of causewayed enclosures during the earlier Neolithic

Causewayed enclosures began to be constructed in southern Britain from the late 38th century BC (Whittle *et al.* 2011: 878-885; Bayliss *et al.* 2011: 684). The role of these earthworks, which are characterized by single or multiple concentric circuits of interrupted ditches, has been heavily debated (e.g. Evans 1988; Edmonds 1993: 102-134; Thomas 1999: 38–45; Whittle *et al.* 2011: 5-12; Albrecht 2011: 8-50). The presence of substantial amounts of pottery, flint knapping debris and animal bones within the ditches initially prompted excavators to suggest they were settlements (e.g. Leeds 1928: 466; Curwen 1931: 108-109; Crawford 1933: 344, 1937: 210; Wheeler 1943: 81; Case 1982: 2; Avery *et al.* 1982: 25; Robertson-Mackay 1987: 59-60). However, in recent decades with the exception of earlier Neolithic enclosures that are found in the far south-west of England that may have been used for permanent settlement (Mercer 1981, 1997, 2001: 43-44;

although see Davies 2010: 162-164 and 176-177), causewayed enclosures are interpreted as monuments which hosted temporary gatherings, playing a role in bringing together communities who usually resided elsewhere (Smith 1965: 19; Thomas 1999: 42; Oswald *et al.* 2001: 123-126, 132; Cummings 2008: 142; Beadsmoore *et al.* 2010: 129; Whittle *et al.* 2011: 893-895; Thomas 2016: 7, 12). The presence of natural silting at several of these sites, interspersed with features that may demonstrate the ditches were intermittently re-cut, could suggest that visits to causewayed enclosures were episodic and may have been seasonal (e.g. Smith 1965: 7, 20, 1966: 471; Mercer 1988: 94; Mercer and Healy 2008: 755; Pryor 1998: 364; Legge 2008: 554). Archaeological evidence also suggests that many of the artefacts found within the enclosure ditches were selectively deposited and that the butchered remains of cattle, also frequently found within enclosure ditches, could also be associated with feasting activity (e.g. Smith 1971: 100; e.g. Whittle *et al.* 1999: 357; Evans and Hodder 2006: 319; Mercer and Healy 2008: 755, 762; Darvill *et al.* 2011: 139, 195; Thomas 2016, although see Parmenter *et al.* 2016). The presence of both articulated formal burials and disarticulated human remains within the enclosure ditches demonstrates that these sites were also associated with mortuary rites and the commemoration of the dead (e.g. Drewett 1977: 225-6; Pryor 1998: 362; Mercer and Healy 2008: 759-760).

Archaeological evidence for settlement patterns during this period has also been the subject of competing interpretations. Discovery of substantial timber buildings of early 4th millennium BC date has been used by some authors to argue that early agriculturalists were fully sedentary and heavily reliant on intensive mixed farming, with individuals obtaining all their resources through keeping livestock and cultivating cereals close to permanently occupied settlements (e.g. Rowley-Conwy and Legge 2015; Rowley-Conwy 2011; Rowley-Conwy 2004: 96; Rowley-Conwy 2003). Others, however, suggest there may have been greater and temporal and regional diversity in subsistence and settlement strategies during the course of the Neolithic (e.g. Thomas 2013: 418). In Britain, substantial timber buildings are part of a diverse range of evidence for occupation, that also includes pits, lithic scatters and more ephemeral structural remains (e.g. Anderson-Whymark and Thomas 2012; Brophy 2014). The latter are frequently interpreted as temporary camps and could suggest that some members of early farming communities were residentially mobile, moving episodically between occupation sites and visiting a variety of different geographical locations to obtain dietary resources (e.g. Whittle 1997: 21, Whittle 2003: 43; Pollard 1999: 82; Garrow *et al.* 2005: 155). Some authors suggest that patterns of land use and mobility may also have been structured around visitation of causewayed enclosures and argue that these monuments "acted as staging posts in an annual cycle of movement around loosely defined territories" (Oswald *et al.* 2001: 119). Rather than Neolithic communities obtaining all of their resources through year round sedentary intensive mixed farming at permanently occupied settlements, these authors argue that patterns of land use, subsistence and mobility were complex and socio-culturally varied (e.g. Thomas 2013: 411; Leary and Kador 2016).

Analysis of material culture and the derivation of raw materials that were used to manufacture many of the artefacts found at causewayed enclosures, such as pottery and worked stone, has also been used as a proxy for reconstructing patterns of land use. Causewayed enclosures are frequently located on the slopes of elevated promontories (Oswald *et al.* 2001: 91, 109-110), and are sometimes found in pairs, situated side by side on adjacent spurs of the same hilltop (ibid. 112-113, e.g. Allen *et al.* 2008; Healy 2008: 3; Darvill *et al.* 2011: 196; Dixon *et al.* 2011: 465). Some researchers suggest that the contrasting form and fabric of artefacts found in adjacent enclosures may indicate that each had a different functional role (Allen *et al.* 2008: 308-312). However, at the Hambledon Hill complex in Dorset, England, which includes two early Neolithic long barrows and two causewayed enclosures, a larger main enclosure and the smaller Stepleton enclosure situated side by side on adjacent spurs of the hill (fig. 1), analysis of raw materials used to manufacture the majority of artefacts found within the adjacent enclosures suggests that these may have been sourced from the sector of landscape each enclosure overlooks (Smith *et al.* 2008: 646). This discovery prompted the excavators to argue that each enclosure served a distinctive social group, who occupied a specific sector of the landscape (Roe 2009: 28) and that the immediate sector of landscape visible from each enclosure provides an approximate index of the catchment occupied by the community it served (Mercer and Healy 2008: 767; Healy 2004: 31).

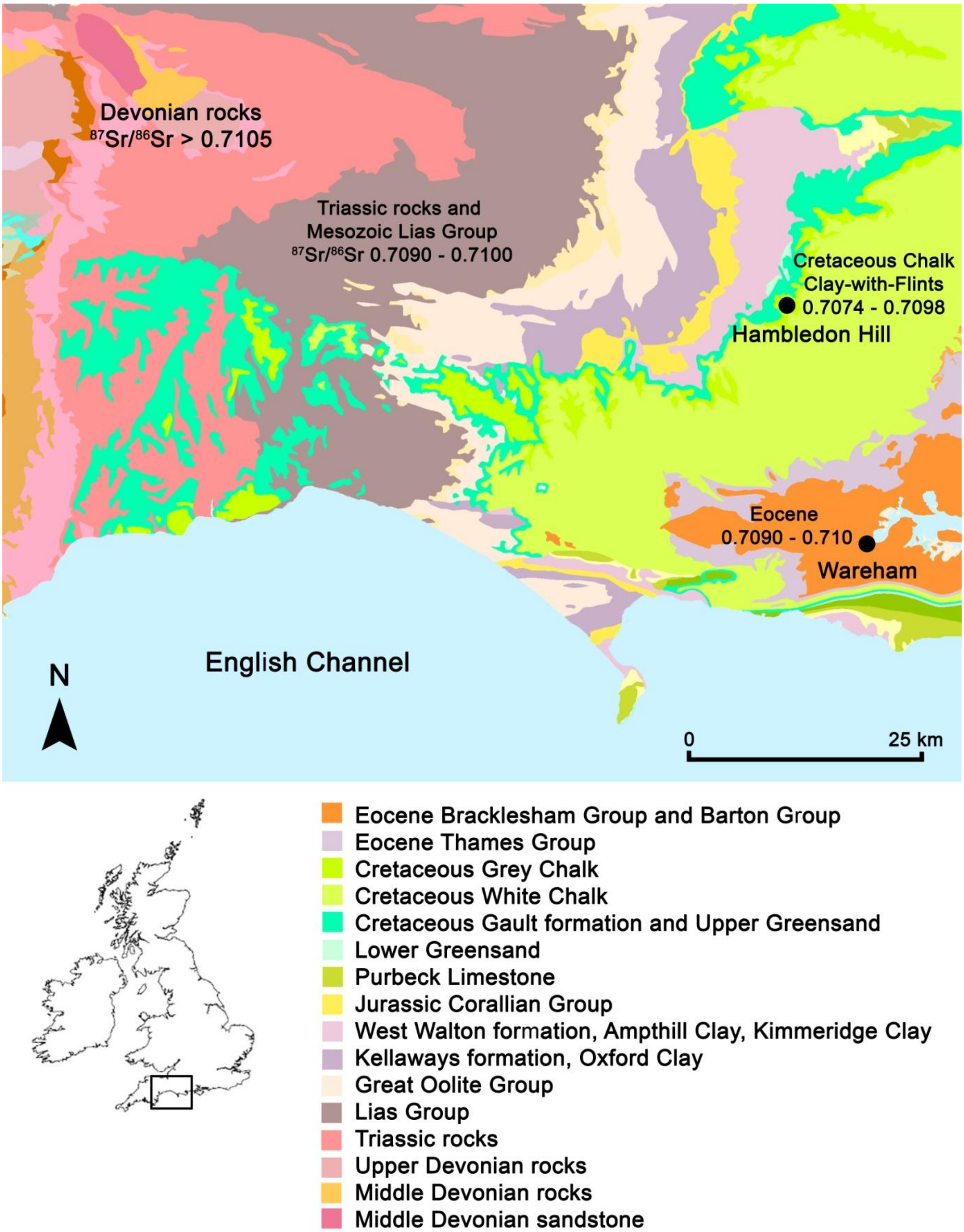
Figure 1. Plan of Hambledon Hill, after Mercer and Healy 2008; reproduced with permission.

The Hambledon Hill complex was the subject of a major campaign of rescue excavation between 1974 and 1986 (Mercer and Healy 2008: 11; Mercer 1988, 1980): Bayesian modelling of radiocarbon dates suggests early Neolithic activity on the hill began between *3685-3640 cal BC* and ended between *3345-3305 cal BC* (*95% probability*, OxCal v.3.10; Healy *et al.* 2011: 145; also see Bayliss *et al.* 2008). The architecture of the very earliest dated phases of the complex includes the south long barrow and the excavators of Hambledon Hill suggest that the morphology of this monument bears affinities to the architecture of long barrows found on the Cretaceous Chalk downs to the east (fig. 2; Mercer and Healy 2008: 766; Mercer 2006: 70, 2009). However, despite being located in very close proximity to the Cretaceous Chalk, to the immediate east and north-east (fig. 2), few of the objects found at Hambledon Hill were manufactured from Cretaceous Chalk, or Sarsen, sources of which lie in this direction (Roe 2008: 633, Mercer and Healy 2008: 767; Roe 2009: 27). Likewise, Decorated Bowl pottery, which is a frequently found at early Neolithic sites in the east and north-east of England (e.g. in the Thames valley, Sussex, East Anglia and Wessex, e.g. Zienkiewicz 1999: 286; Bayliss *et al.* 2011: 762-763) was only a minor part of the ceramic assemblage at Hambledon (Smith 2008a: 592; also see Pioffet 2015).

Instead, analysis of material culture suggests that, for the majority of the period Hambledon Hill was in use, it was closely connected to the area of landscape that lies to the south and west (Mercer and Healy 2008: 767; Healy 2004: 31). Ceramics found at the site reflect styles common to the south-western region of England (ibid.: 591; Healy 2006: 11). The larger main enclosure overlooks the landscape to the west (fig 1.) and analysis of clays used to manufacture the pottery found in this enclosure suggests the majority could have been sourced from the Upper to Middle Jurassic lithologies that lie in this direction (fig. 2): fabric groups 7, 8 and 2 may have been manufactured from Kimmeridge Clay and Oolitic limestone, which crop out to the west of the hill (Smith 2008a: 587 and 595 - 596; Darvill 2008: 615, 617, 620-621; Healy 2006: 11). Many of the worked stone objects found within the main enclosure may also originate from sources that lie in this direction, with querns frequently being manufactured from Greensand, the closest source of which is located to the immediate west of the hill (fig. 2; Roe 2008: 632-633).

In contrast to the main enclosure, the Stepleton enclosure (fig. 1) which is situated on the adjacent spur of the hill faces toward the coastal zone of southern Dorset. Analysis of objects suggests that both the clays used to make ceramics (fabric group 6) and worked stone found within this enclosure may derive from lithology of Eocene age that is located in this direction, close to the coast, approximately 25 km away (near to Wareham, Dorset, fig. 2; Roe 2008: 633, 2009: 28-29; also see Smith 2008a: 587, 595; Darvill 2008: 619; Smith *et al.* 2008: 646; Mercer and Healy 2008: 767). High densities of recorded finds along the coastal zone of southern Dorset indicate this region may have been a particular focus for activity during the early Neolithic (Field 2008: 46-48). Analysis of lithics found at Hambledon Hill, which were manufactured from chert, suggests these could also have been sourced from a similar area (Saville 2008: 651).

Figure 2. Location of Hambledon Hill in relation to bedrock geology and measured $^{87}Sr/^{86}Sr$ bioavailable values. Based on British Geological Survey and Ordnance Survey map data, reproduced with permission of the British Geological Survey and Ordnance Survey, © NERC / Crown copyright [2016]. Bioavailable $^{87}Sr/^{86}Sr$ ranges after Montgomery *et al.* (2006); Evans *et al.* (2010); Chenery *et al.* (2010) and Warham (2011).



Links between Hambledon and regions within the west and south-west of England are also implied by the presence of other materials that were imported from much further afield in this direction. Many of the quernstones found at the site were manufactured from Old Red Sandstone (Roe 2008: 632-633; Smith *et al.* 2008: 645-646). Devonian Old Red Sandstone crops out in several areas of Britain (Barclay 2005: 3-4), the closest sources to Hambledon Hill being found in Somerset and north Devon, approximately 40 km away, to the west of the site. Connections between Hambledon and areas even further afield in the south-west peninsula of England are also implied by the presence of Gabbroic pottery, which was imported to Hambledon from the Lizard Peninsula in Cornwall (Smith 2008a: 587, 590; Darvill 2008: 615; cf. Piggott 1969: 146-147). The majority of axes and adzes found at the complex also originate from sources in Cornwall (Smith 2008b: 630). Use of the causewayed enclosure complex at Hambledon was long-lived, lasting over 300 years, with both the adjacent enclosures on the hill remaining in use for much of this time (Healy *et al.* 2011: 145). Consistency in the sourcing of artefacts throughout this period suggests that links between Hambledon and regions to the west and south of the enclosures were maintained over time (Smith *et al*. 2008: 646; Mercer and Healy 2008: 756-757).

Whilst being significant locations in the landscape that may have played a role in social gatherings and bringing together communities, enclosures also appear to have been the focus of episodic conflict (Oswald *et al.* 2001*:* 128-130; Bayliss *et al.* 2011: 718; Whittle *et al.* 2011: 520). This interpretation arises from the frequent discovery of arrowheads and evidence for burning at enclosures, particularly those located within south-western England (e.g. Maiden Castle, Dorset, Sharples 1991: 51; Crickley Hill, Gloucestershire, Dixon 1988: 82, Dixon 2011: 460; Hembury, Devon, Mercer 1999: 151 and Carn Brae, Cornwall, Mercer 1981: 68, 2003: 61). The excavators of Hambledon Hill suggest that the deaths of four individuals, all adult males, may have occurred during episodes of conflict at the site (Mercer and Healy 2008: 760-761). The deaths of two of these individuals appear to have been associated with the burning of outworks that were built to surround the site (ibid. 761): the excavators suggest individual ST79 2726, who was found on the base of the inner Stepleton outwork ditch, "may have been the victim of the catastrophe in which the defences were fired" during the mid 36th century (Healy *et al.* 2011: 140-141; cf. Mercer and Healy 2008: 408), whilst the death of individual ST81 3181, who is dated to a similar period and was found in a pit containing scorched rubble and burnt clay, may also have been associated with this event (ibid.; Mercer and Healy 2008: 275, 408). The deaths of both of these individuals appear to have been shortly followed by that of a third adult male (ST80 1875), who died between 3630-3360 cal BC (95% confidence) and was found lying within the Stepleton outworks, with an arrowhead amongst his ribs (Healy *et al.* 2011: 129, 142-143). A fourth individual, who was also found within the Stepleton outworks with an arrowhead amongst his ribs, may have died later in the history of the complex, between 3500-3130 cal BC (95% confidence, individual ST78 2755, Healy *et al.* 2011: 128, 143; McKinley 2008: 512).

5.3 The application of isotope analysis: principles and limitations

The excavation of the Hambledon Hill complex led to the discovery of one of the most substantial osteological assemblages of earlier Neolithic date so far found in Britain (McKinley 2008: 504). Use of isotope analysis offers a new means to examine patterns of land use during this period (e.g. Bentley 2006; Montgomery 2010; Slovak and Paytan 2011; Price 2015: 75-78). This study applies isotope analysis of tooth enamel to evaluate where the individuals who were buried at Hambledon Hill obtained their childhood diet.

5.3.1 Strontium isotope analysis

Strontium has four naturally occurring isotopes, atoms of the same chemical element that differ in atomic mass as they possess a different number of neutrons: ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr (Faure 1986: 118). Strontium-87 is radiogenic, a product of the radioactive decay of rubidium-87 (^{87}Rb; Faure and Mensing 2005: 76; Dickin 2005: 42-43). Unlike the other isotopes of strontium, the amount of ^{87}Sr gradually increases on geological time scales and ^{87}Sr/^{86}Sr varies geographically according to the age and initial isotope composition of bedrock (ibid.). Use of strontium isotope analysis for geographic provenancing is based on the principle that humans and animals derive their dietary strontium from biosphere sources. Strontium weathers from rocks, entering soils and ground waters where it becomes available to plants (Capo *et al.* 1998: 202-203) and is transferred up the food chain and becomes incorporated into the mammalian skeleton (Bentley 2006: 141; Slovak and Paytan 2011: 743-744; Montgomery 2010: 328; Montgomery 2002: 17, 24 and 36). Conventionally measured ^{87}Sr/^{86}Sr values do not vary significantly between trophic levels (Graustein 1989: 492; e.g. Blum *et al.* 2000) and as tooth enamel is highly resistant to diagenesis the isotope ratios in teeth are considered to reflect sources to which an individual was exposed whilst the tooth was mineralizing (e.g. Montgomery 2002; Budd *et al.* 2000, 2001; Madgwick *et al.* 2012: 741). Measured values in modern plants and waters vary with the age and composition of the underlying lithology (e.g. Montgomery *et al.* 2006; Evans *et al* 2010; Warham 2011; Willmes *et al.* 2013; Frei and Frei 2011). Comparison of ^{87}Sr/^{86}Sr values in teeth that form at successive stages of childhood to mapped bioavailable values can as such be used to evaluate whether an individual derived dietary resources from the area in which they were buried or whether they may have obtained their childhood diet from further afield (e.g. Bentley 2006; Montgomery 2010; Slovak and Paytan 2011: 743-744). The strontium isotope ratios that human individuals exhibit can also be compared to $^{87}Sr/^{86}Sr$ ranges bioavailable on lithologies from which artefacts (e.g. clays for pottery or worked stone, see above) may have been sourced.

Strontium isotope ratios of teeth are therefore a direct proxy for the geographical location from which an individual derived their childhood diet. However, use of this methodology is also subject to limitations: when interpreting results consideration must be given to the fact that different geographical areas may have the same bioavailable range and can confer similar $^{87}Sr/^{86}Sr$ values. An individual with an $^{87}Sr/^{86}Sr$ value comparable to the local range at the site where they are buried may not therefore have obtained their diet locally and could have inhabited another region with the same biosphere value. This is similarly problematic when applying the technique to study consecutively mineralizing molars: if an individual exhibits the same $^{87}Sr/^{86}Sr$ value in teeth that mineralize at successive stages of childhood they could either have obtained their dietary resources from the same area throughout a prolonged period during early life, alternatively they could have exploited two different geographically separate areas with similar bioavailable ranges.

For this reason there are limitations to use of this technique at Hambledon Hill, since the two immediate geographical areas to which the excavators suggest each enclosure may have been linked through artefact analysis have overlapping $^{87}Sr/^{86}Sr$ bioavailable ranges. Upper Jurassic Kimmeridge Clay formation may have been the source for the clays used to make pottery deposited within the main enclosure (figure 2; see above) and samples of plants and water taken on this formation in southern Britain record measured biosphere $^{87}Sr/^{86}Sr$ values between 0.7086 and 0.7091 (n = 10, mean 0.7088 ± 0.0003, 2σ, Warham 2011: 79). The latter lies close to the Weymouth Member of the Oxford Clay Formation, which may record biosphere values between 0.7092 - 0.7097 (n = 6, mean 0.7094 ±

0.0003, 2σ, Warham 2011: 79). The region of southern Dorset to which the excavators suggest that the Stepleton enclosure was linked (Roe 2008: 633; Smith *et al* 2008: 646) has been associated with a bioavailable range between 0.7090 - 0.7100 (fig. 2; Evans *et al* 2010). As such, if individuals exhibit $^{87}Sr/^{86}Sr$ values between approximately 0.7090 and 0.7100 they could have sourced their diet from either of the two immediate regions to which the enclosures have been linked through analysis of material culture.

The $^{87}Sr/^{86}Sr$ ranges that are bioavailable on these lithologies may also overlap with the predicted bioavailable range at Hambledon Hill itself and that associated with the Cretaceous Chalk to the immediate east of the site. Like the lithologies that lie to the immediate east, Hambledon Hill is composed of Cretaceous Chalk (BGS 2016). In Britain, samples of plants and water taken on Cretaceous Chalk record $^{87}Sr/^{86}Sr$ values between 0.7074 and 0.7087 (mean 0.7080 ± 0.0008, 2σ, n = 14, Evans 2010; Warham 2011: 124), in areas of high rainfall this may extend close to 0.7092 (Montgomery *et al.* 2007: 1503; Montgomery 2010: 333; although see Warham 2011: 161-162). However, superficial deposits that are characteristic of Clay-with-Flints have also been found on Hambledon Hill, although due to modern ploughing activity the past extent of these deposits at this site is uncertain (Mercer and Healy 2008: 1-5). They are also recorded on the Cretaceous Chalk directly to the east of the hill (BGS 2016). These deposits have been shown to further extend the bioavailable range on the Chalk (Warham 2011: 123-124): in southern Britain the maximum biosphere $^{87}Sr/^{86}Sr$ value currently recorded on Clay-with-Flints in an area of Chalk is 0.7098 (Warham 2011: 120; fig. 2).

In contrast to Cretaceous Chalk and Clay-with-Flints to the east, or to Kimmeridge Clay to the immediate west, lithology that lies further afield to the west and south-west of

Hambledon is associated with higher bioavailable values (fig. 2). The Peterborough Member of the Oxford Clay crops out just over 8 km to the west of Hambledon Hill (BGS 2016) and in southern Britain samples of plants growing on this lithology record bioavailable $^{87}Sr/^{86}Sr$ values between 0.7103 - 0.7105 (mean 0.7104 ± 0.0001, 2σ, n = 4, Warham 2011: 79, 82-83). Whilst biosphere $^{87}Sr/^{86}Sr$ values higher than 0.7105 are routinely associated with lithology of Devonian and Carboniferous age, such as that found in Somerset and north Devon to the west and south-west of Hambledon Hill (fig. 2), and with lithology of similar age that is located beyond this in Cornwall (fig. 2; Evans *et al.* 2010; Montgomery *et al.* 2006).

5.3.2 Oxygen and carbon isotope analysis

The isotope ratios of light elements, such as oxygen ($^{18}O/^{16}O$) and carbon ($^{13}C/^{12}C$), have a relatively low atomic mass and can be readily altered as a result of mass dependent fractionation, during biological, chemical and physical processes (Hoefs 2009: 35-36). The ratio of $^{18}O/^{16}O$ (expressed as $\delta^{18}O$, see methodology below) varies geographically, due to discrimination between the heavier and lighter isotopes of oxygen that is induced by evaporation and condensation during the hydrological cycle (Sharp 2007: 74-80). The oxygen isotope composition of ground water, which ultimately derives from meteoric water, is influenced by factors such as temperature, latitude, altitude and distance from the coast (Mook 2005; Gat 2010: 58-63). Britain receives most of its rainfall from a westerly direction and modern groundwaters in western Britain therefore record higher $\delta^{18}O$ values than those in eastern Britain (Darling *et al.* 2003: 189-190). A statistically significant difference between the mean $\delta^{18}O$ values measured in tooth enamel of multi-period archaeological populations buried in western Britain (18.2 ‰ ± 1 ‰, 2σ) from those buried in eastern Britain (17.2 ± 1.3 ‰, 2σ) may reflect the underlying geographic variation in the oxygen isotope composition of local drinking water between these two areas (Evans *et al.* 2012: 759). These ranges were determined using the phosphate (PO_4^{3-}) fraction of tooth enamel ($\delta^{18}O_{phosphate}$). The structural carbonate (CO_3^{2-}) fraction of enamel, which is equally suitable for analysis, was utilized by the present study. Chenery *et al.* (2012) suggest that, as values of both fractions are well correlated, conversion between the two may be undertaken to facilitate comparison between published $\delta^{18}O_{phosphate}$ and $\delta^{18}O_{carbonate}$ datasets (see Materials and methods, below).

When interpreting the results of oxygen isotope analysis consideration also needs to be given to the role of culturally mediated behaviour: both culinary practices and consumption of ingested fluids that have been subject to fractionation through biological processes (e.g. cow's milk, Camin *et al.* 2008: 1695; Lin *et al.* 2003: 2193; Kornexl *et al.* 1997: 22; or breast milk, Roberts *et al.* 1988, Wright and Schwarcz 1998; Britton *et al.* 2015) may play a role in altering $\delta^{18}O$ values, conferring higher values relative to local drinking water (Brettell *et al.* 2012; Daux *et al.* 2008: 1145).

Isotope analysis of the structural carbonate fraction of enamel simultaneously yields carbon isotope ratios ($\delta^{13}C_{carbonate}$) which provide additional dietary information. The use of carbon isotope analysis for this purpose exploits the large variation in natural abundance of the isotopes of carbon ($^{13}C/^{12}C$) between plants that use the two dominant (C_3 or C_4) photosynthetic pathways during fixation of CO_2 energy and the large variation in $\delta^{13}C$ values between terrestrial C_3 and marine ecosystems (Sponheimer and Cerling 2014; Schwarcz and Schoeninger 2011; Lee-Thorp 2008). Current understanding of dietary composition in the European Neolithic is based on analysis of $\delta^{13}C$ and $\delta^{15}N$ values in bone collagen, which predominantly reflect the protein component of the diet and supports the exploitation of C_3 terrestrial sources of protein (e.g. Richards and Hedges 1999: 893; Richards *et al.* 2003; Hamilton and Hedges 2011; Schulting 2013, 2015). In contrast, $\delta^{13}C_{carbonate}$ values in bioapatite reflect the isotope composition of the diet as a whole (Ambrose and Norr 1993: 2; Jim *et al.* 2004). Individuals who obtain all of their diet, including carbohydrates and lipids, from C_3 terrestrial sources may be predicted to have $\delta^{13}C_{carbonate}$ values between approximately -17.0 to -14.0 ‰ (Kellner and Schoeninger 2007; Froehle *et al.* 2012).

5.4 Materials and methods

5.4.1 Sample selection

Despite the size of the excavated osteological assemblage from Hambledon Hill complex taphonomic factors influence sample selection and hence the representativeness of isotope results. As discussed above, strontium isotope analysis is undertaken on tooth enamel, therefore ante-mortem tooth loss or severe attrition to enamel can preclude sampling. Mortuary practice is also influential in determining whether dentition is present and therefore whether an individual will be represented within the sampled group. The human burial assemblage from Hambledon Hill is estimated to contain a minimum number of 75-77 individuals (McKinley 2008: 490). Not all of these individuals, however, have dentition. The assemblage comprises skeletons in varied states of articulation (McKinley 2008: 512-514) and the presence of partly articulated skeletons and cutmarks on human bone suggest that excarnation may have been practised in the vicinity of the complex (ibid. 516; Mercer and Healy 2008: 759; Mercer 1980: 63). Fragmentary and disarticulated skeletal remains exhibit signs of weathering and whilst they could represent the terminal phase of a mortuary rite that was practised within the confines of the complex itself, it is also possible that elements were curated and brought to the complex from burial contexts elsewhere (McKinley 2008: 514; Mercer and Healy 2008: 760; cf. Whittle *et al.* 1999: 362). Construction of the complex and its duration of use are very well dated, with dates having been obtained from short-lived material that was deposited in the ditches and from articulated skeletal remains (Bayliss *et al.* 2008; Healy *et al.* 2011: 111-157). However, it remains a possibility that disarticulated skeletal elements, which are identified in table 1, are older than the contexts in which they were deposited. Were this the case, the isotope results from teeth in disarticulated mandibles, could represent a population older than, or ancestral to, the community who deposited them.

As the burial assemblage contains fragmentary disarticulated remains, care had to be taken to avoid the potential for duplication of isotope results through sampling of cross matching elements belonging to the same individual. To avoid this, a consistent strategy of sampling the left mandibular dentition was adopted. Maxillary teeth were not sampled. Loose teeth or teeth from right mandibular fragments were not used, unless it could be stated with confidence that they derived from an individual who had not previously been sampled. This strategy was only varied if it was possible to determine that the same individual would not be sampled twice (e.g. teeth from the right-hand side of a complete mandible could be used if those on the left had been lost ante/post-mortem). As noted above, once formed, enamel is considered to be highly resistant to diagenesis; however, following Montgomery (2002: 128) all the teeth selected were completely mineralized and none of the teeth that were sampled exhibited any visual evidence of poor preservation (e.g. carious lesions, discolouration or staining to the enamel).

Dentition that met these criteria was sampled, wherever present, from all excavated Neolithic contexts, including both causewayed enclosures (the main enclosure and that on Stepleton spur), the south long barrow which is also located on the hill and the Hanford Outworks and the inner east cross dyke that surround the causewayed enclosures (figure 1; table 1). Due to the various factors considered above a total of 22 individuals, just under a third of the minimum number of individuals estimated to be present within the burial population, possessed dentition that was suitable for sampling. Wherever present, samples were also taken from consecutively mineralizing molars, to facilitate comparison of isotope ratios at different stages of childhood and adolescence. Development of the crown of the first permanent adult molar commences *in utero*, just prior to birth and completes by approximately 4.5 ± 0.5 years of age, whilst the second molar crown forms between 2.5 ± 0.5 years and 8.5 ± 0.5 years of age (AlQahtani *et al.* 2010; Hillson 2014: 31, 55-56). The timing of third molar formation is most variable (Liversidge 2008: 313), with initial cusp formation taking place at approximately 8.5 ± 0.5 years and crown completion by approximately 14.5 ± 0.5 years (AlQahtani *et al.* 2010).

5.4.2 Sample preparation and laboratory analysis

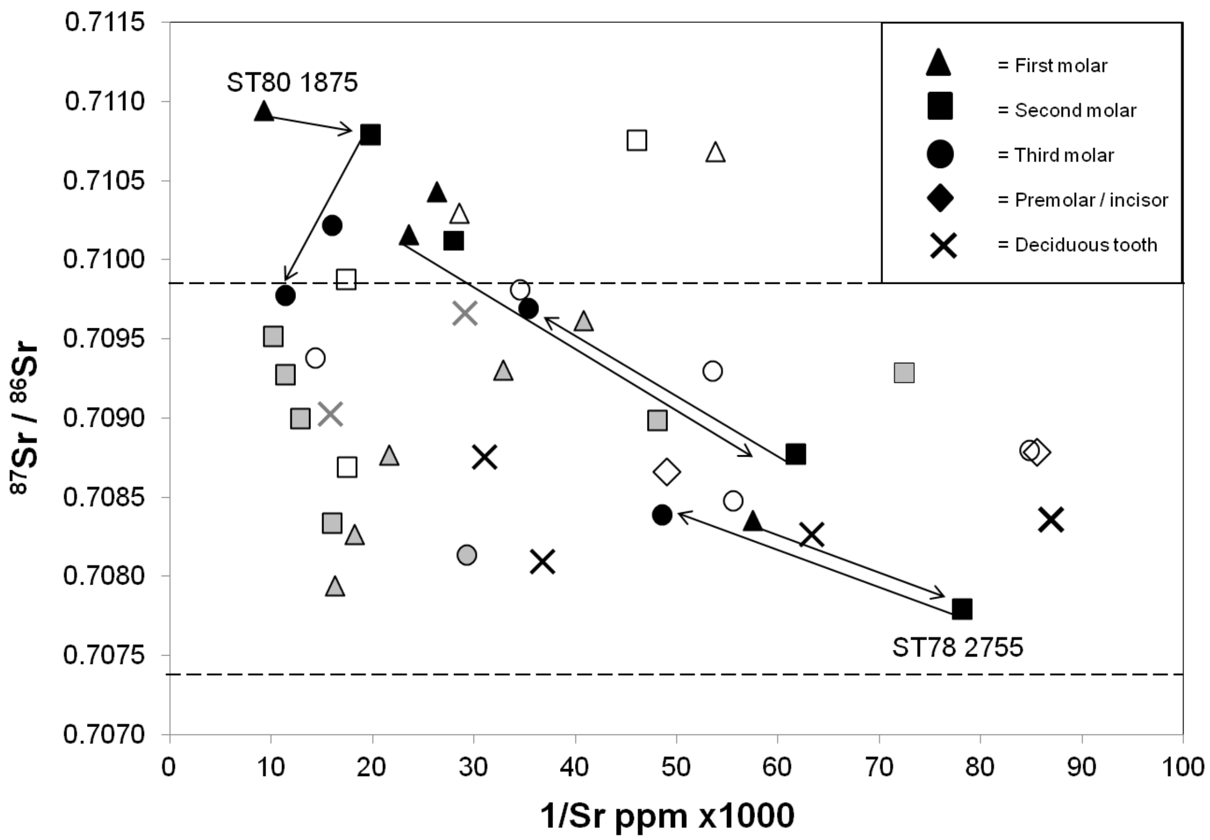
A total of 43 samples were processed following procedures developed by Montgomery (2002: 131-138). Surface enamel was thoroughly abraded using a tungsten carbide dental burr. Enamel chips were then cut using a flexible diamond-edged rotary saw and surfaces again mechanically cleaned using a tungsten carbide dental burr to remove any adhering dentine. The resulting chips of core enamel were transferred to clean sealed containers. Dental saws and burrs were cleaned ultrasonically for five minutes and rinsed three times in high purity de-ionized water between preparation of samples.

Core enamel chips were transferred to the Class 100, HEPA-filtered laboratory facilities at the Natural Environment Research Council Isotope Geosciences Laboratory (NIGL, Keyworth, Nottingham, England). Enamel chips were cleaned ultrasonically and rinsed in high purity water (Millipore Alpha Q). They were then dried, weighed into pre-cleaned Teflon beakers and spiked with a known amount of ^{84}Sr tracer solution to obtain strontium concentrations. Each sample was dissolved in Teflon distilled 8M HNO_3. Samples were converted to Chloride using 6M HCl, taken up in titrated 2.5M HCl and pipetted onto ion exchange chromatography columns. Strontium was separated with Dowex® (AG50-X8) resin (200-400 mesh). Procedural blanks were below 100 pg. Samples were loaded on to Re filaments using a method adapted from Birck (1986: 79). Strontium isotope composition and concentrations were then determined by Thermal Ionisation Mass spectroscopy (TIMS) using a *ThermoTriton* automated multi-collector mass spectrometer. To correct for fractionation during the process of mass spectrometry $^{87}Sr/^{86}Sr$ values are normalised to the accepted value for $^{88}Sr/^{86}Sr = 0.1194$. During the period of this study the machine gave a value for the international standard for $^{87}Sr/^{86}Sr$ (NBS 987) of 0.710253 ± 0.000012 (2 σ, n=350).

Preparation of core enamel chips for $\delta^{18}O$ and $\delta^{13}C$ analysis was undertaken using the same methods employed above for strontium isotope analysis. Following preparation chips of core enamel were transferred to NIGL where they were powdered. Oxygen ($\delta^{18}O_{carbonate}$) and carbon ($\delta^{13}C_{carbonate}$) isotope ratios in the carbonate fraction of enamel were determined using the method outlined in Chenery *et al.* (2012: 310). Isotope ratios are reported as delta (δ) values, in parts per thousand (per mil; ‰) normalized to the VPDB scale using an in-house carbonate reference material, Keyworth Carrera Marble (KCM) which is calibrated against NBS19 certified reference material. Analytical reproducibility for this run of KCM was ± 0.09 ‰ (1 σ, n = 14) for $\delta^{18}O$ and for $\delta^{13}C$ ± 0.04 ‰ (1 σ, n = 14). $\delta^{18}O_{carbonate}$ values were normalized to the VSMOW scale using the equation of Coplen 1988 (VSMOW = 1.03091 x $\delta^{18}O$ VPDB + 30.91). Conversion between $\delta^{18}O_{carbonate}$ to $\delta^{18}O_{phosphate}$ was then undertaken using the regression equation of Chenery *et al.* (2012: 310; $\delta^{18}O_{phosphate}$ = 1.0322 x $\delta^{18}O_{carbonate}$ – 9.6849). The error involved in calculating $\delta^{18}O_{phosphate}$ is considered to be low (0.28 ‰, 1 σ, Chenery *et al.* 2012: 313).

5.5 Results

Figure 3. Plot of strontium isotope ratio and elemental concentration. Dashed lines denote the predicted biosphere range at Hambledon Hill, in an area of Chalk where superficial deposits of Clay-with-Flints are known to be present (based on current measured values by Warham 2011: 120 and 124). Black triangles, squares and circles: adult males buried on Stepleton spur who are inferred to have died during episodes of conflict at the site, labelled individuals are those who were found in association with arrowheads. Open white symbols: individuals excavated from Stepleton spur, the south long barrow and the inner east cross dyke. Grey triangles, squares and circles: individuals excavated from the main enclosure. Grey crosses: deciduous teeth of children excavated from the main causewayed enclosure. Black crosses: deciduous teeth of children excavated from Stepleton spur and the Hanford outworks. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.



Seventeen of the twenty-two sampled individuals have $^{87}Sr/^{86}Sr$ values between 0.7074 and 0.7098. This $^{87}Sr/^{86}Sr$ range is common to the majority of individuals from a variety of different excavated contexts, including the main enclosure, the Stepleton spur enclosure and south long barrow and to individuals of different age and sex (where this information is available, table 1, following McKinley 2008). The majority of both those individuals who are represented by disarticulated mandibles and those whose skeletal remains were found in an articulated state exhibit values in this range (table 1). With the exception of the adult males whose deaths are suggested to have been associated with a specific episode during the history of the complex (see below), the majority of individuals who have been directly radiocarbon dated also possess values within this range. For example, both an adult male (ST79 2025) who is dated early in the history of the site to between 3710 and 3530 cal BC and a child who died between five to six years of age (HH76 3046) and was buried toward the end of use of the complex (3500-3090 cal BC, 95% confidence, Healy *et al.* 2011: 121, 127) both exhibit similar $^{87}Sr/^{86}Sr$ values of 0.7087 and 0.7090 respectively. Strontium concentrations range between 12 - 108 ppm (mean 41 ± 26 ppm, 1σ, n = 43), consistent for with values previously reported for human populations buried in Britain (Evans *et al.* 2012: 756).

Only five individuals possess at least one tooth with an $^{87}Sr/^{86}Sr$ value higher than 0.7098. All are adults. Two of these individuals are represented by disarticulated fragmentary remains: individual ST78 1100/ST78 204, who may be female, was excavated from the inner Stepleton outwork (McKinley 2008: 487) and has $^{87}Sr/^{86}Sr$ values higher than 0.7105 in both their first and second permanent molars, whilst enamel from the permanent molar of individual HH75 1340, whose fragmentary mandibular remains were found in the inner east cross dyke, gave an $^{87}Sr/^{86}Sr$ value of 0.71029. The other individuals who exhibit values higher than $^{87}Sr/^{86}Sr$ = 0.7098 are three of the adult males whose deaths are inferred by the excavator to have been associated with episodes of violence at the complex during the mid to later 36th century BC (ST79 2726, ST81 3181 and ST80 1875; illustrated as black symbols in figs. 3 and 4). Individual ST80 1875, who is one of the two individuals who was found with an arrowhead located amongst his ribs, has the highest $^{87}Sr/^{86}Sr$ values and the highest strontium concentration (>100 ppm) in the sampled burial population, with enamel from both their first and second permanent molar teeth giving strontium isotope ratios higher than 0.7105 (figs. 3 and 4; Mercer and Healy 2008: 325). In contrast to these individuals, the fourth adult male, who like these individuals was also found in the Stepleton outworks with an arrowhead amongst his ribs but may have died later in the history of the complex (individual ST78 2755, labelled in fig. 3; McKinley 2008: 512; Healy *et al.* 2011: 128, 143), has the lowest $^{87}Sr/^{86}Sr$ value (0.7077) within the sampled population, with enamel from all three permanent molars recording values below 0.7085.

Enamel $\delta^{18}O_{carbonate}$ values range between 26.8 and 28.7 ‰ (mean 27.6 ± 0.5 ‰, 1σ, n = 43). With the exception of early forming deciduous teeth and first molars which more frequently plot with values that are higher than 28.0 ‰ (illustrated as crosses in figure 4), the majority of enamel samples gave $\delta^{18}O_{carbonate}$ values between 27.0 and 28.0 ‰. This range of values is common amongst both males and females (where sexing information is available, following McKinley 2008: 478-489; table 1) and to both articulated and non-articulated individuals from different contexts, from Stepleton spur, the main enclosure, long barrow and inner east cross dyke. $\delta^{13}C_{carbonate}$ values range between -16.8 and -14.2 ‰ (mean 15.9 ± 0.5 ‰, 1 σ, n = 43; table 1). There is no discernible variation in $\delta^{13}C_{carbonate}$ values with tooth type, with $^{87}Sr/^{86}Sr$ or $\delta^{18}O_{carbonate}$ values, or with burial context or sex (where this information is available). All enamel samples from Hambledon Hill fall within the range of values that may be expected for individuals who had a diet dominated by C_3 terrestrial sources.

Figure 4. Plot of $^{87}Sr/^{86}Sr$ versus $\delta^{18}O_{carbonate}$. Dashed lines denote the predicted biosphere range at Hambledon Hill, in an area of chalk where superficial deposits of clay-with-flints are known to be present (based on current measured values by Warham 2011: 120 and 124). Symbols as for fig. 3 (above). 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2 ‰ (2σ).

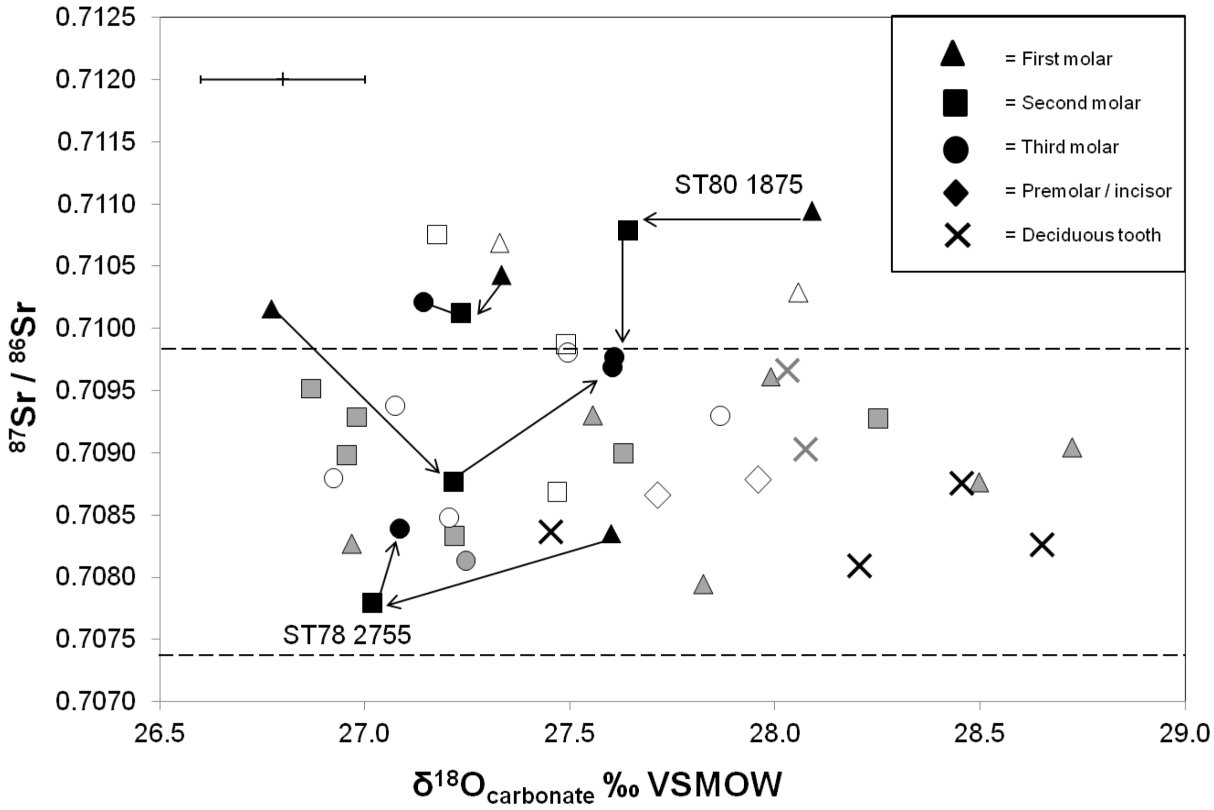


Table 1. (over page). Results of strontium, oxygen and carbon isotope analysis of tooth enamel. Age categories, sexing information and relative completeness of skeletons after McKinley (2008), where M = Male; F = Female; U = Unsexed; '?' = PROBABLE and '??' = POSSIBLE, the latter notations are as used by McKinley (2008: 490-491) to denote different levels of certainty in the attribution of sex. Approximate age of death is as determined by tooth eruption and stage of root development following AlQahtani *et al.* (2010). All sampled teeth derive from mandibles. L = Left; R = right; DM1 = first deciduous molar tooth; DM2 = second deciduous molar tooth; M1 = first permanent molar tooth; M2 = second permanent molar; M3 = third permanent molar; PM1 = first premolar tooth; PM2 = second premolar tooth. The location and context of skeletal remains is as documented by Mercer and Healy (2008: 41-377). Radiocarbon dates after Healy *et al.* (2011: 118-131) are calibrated date ranges at 95% confidence (cal. BC; OxCal v.3.10).

Table 1.

Museum accession number	Box	Location	Context	Phase	Calibrated date range (cal. BC, 95% confidence)	Sex	Age category / estimated age at death	Completeness of skeleton	Tooth	Sr ppm (mg/kg)	1/Sr ppm x 1000	$^{87}Sr/^{86}Sr$	$\delta^{13}C_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VPDB	$\delta^{18}O_{carbonate}$ ‰ VSMOW	$\delta^{18}O_{phosphate}$ ‰ VSMOW
ST79 2025/ST79 2386	437	Pit, Stepleton spur	2A/F200		3710-3530	?? M	Older adult	40%	LPM1	20	50	0.70866	-16.2	-3.1	27.7	18.9
									LM3	12	83.33333	0.70879	-16.2	-3.9	26.9	18.1
HH76 1948	414	Main enclosure	18	i/ii	3650-3520	U	Juvenile (7 years)	85%	LM1	61	16.39344	0.70794	-16.4	-3	27.8	19
ST78 2755a	433	Inner Stepleton outwork	7	iii	3640-3380	U	Young child (1.5 - 2 years)	Disarticulated	LDM1	12	83.33333	0.70836	-15.3	-3.4	27.5	18.7
ST79 2726	430	Inner Stepleton outwork	7	i	3640-3370	M	Older mature adult	95%	LM1	42	23.80952	0.71016	-14.3	-4	26.8	18
									LM2	16	62.5	0.70877	-16.5	-3.6	27.2	18.4
									LM3	28	35.71429	0.70969	-16.4	-3.2	27.6	18.8
ST78 964/ST78 710	424	Pit, Stepleton spur	1A/F70		3640-3360	U	Older child / young juvenile (5 years)	80%	LDM2	32	31.25	0.70876	-16.1	-2.4	28.5	19.7
ST81 3181	427	Pit, Stepleton spur	4B/F712		3630-3370	M	Young adult	98%	LM1	38	26.31579	0.71043	-16.8	-3.5	27.3	18.5
									LM2	36	27.77778	0.71012	-16.2	-3.6	27.2	18.4
									LM3	63	15.87302	0.71022	-15.8	-3.7	27.1	18.3
ST80 1875	435	Outer Stepleton outwork	3	i	3630-3360	M	Young adult	98%	LM1	108	9.259259	0.71094	-16.5	-2.7	28.1	19.3
									LM2	51	19.60784	0.71079	-15.8	-3.2	27.6	18.8
									LM3	88	11.36364	0.70977	-16.3	-3.2	27.6	18.8
ST78 2755	433	Inner Stepleton outwork	7	iii	3500-3130	M	Older sub-adult / young adult	98%	LM1	17	58.8235294	0.70835	-16.1	-3.2	27.6	18.8
									LM2	13	76.9230769	0.70779	-15.3	-3.8	27	18.2
									LM3	21	47.6190476	0.70839	-15.7	-3.7	27.1	18.3
HH76 3046	413	Main enclosure	17	vii	3500-3090	U	Young juvenile (5 - 8 years)	70%	LDM2	63	15.8730159	0.70903	-16.4	-2.8	28.1	19.3
HH76 3034/HH76 3030	413	Main enclosure	6.2	i	Undated	U	Older Juvenile (10 - 15 years)	Disarticulated	LM1	55	18.1818182	0.70827	-16.4	-3.8	27	18.2
									LM2	63	15.8730159	0.70833	-15.9	-3.6	27.2	18.4

Table 1. Continued from over page.

Museum accession number	**Box**	**Location**	**Context**	**Phase**	**Calibrated date range (cal. BC, 95% confidence)**	**Sex**	**Age category / estimated age at death**	**Completenes s of skeleton**	**Tooth**	**Sr ppm (mg/kg)**	**1/Sr ppm x 1000**	**$^{87}Sr/^{86}Sr$**	**$\delta^{13}C_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VPDB**	**$\delta^{18}O_{carbonate}$ ‰ VSMOW**	**$\delta^{18}O_{phosphate}$ ‰ VSMOW**
HH75 2183/HH75 2136	416	Main enclosure	8	ii	Undated	U	Sub-adult / adult (c. 15 years)	Disarticulated	LM1	30	33.3333333	0.7093	-16.3	-3.3	27.6	18.8
									LM2	14	71.4285714	0.70929	-15	-3.8	27	18.2
HH75 1848	417	Main enclosure	11	ii	Undated	??M	Older mature adult	Disarticulated	LM2	78	12.8205128	0.70900	-16.6	-3.2	27.6	18.8
									LM3	34	29.4117647	0.70813	-15.9	-3.6	27.2	18.4
HH74 HB 2	417	Main enclosure	4	iii	Undated	U	Sub-adult (> 11 years)	Disarticulated	LM1	46	21.7391304	0.70876	-15.7	-2.3	28.5	19.7
									LM2	21	47.6190476	0.70898	-16	-3.8	27	18.1
HH74 HB 5	418	Main enclosure	4	iii	Undated	??F	Sub-adult (> 11 years)	Disarticulated	LM1	67	14.9253731	0.70904	-15.5	-2.1	28.7	20
									LM2	88	11.3636364	0.70927	-16	-2.6	28.3	19.5
HH76 2741/2792	418	Main enclosure	17	iv	Undated	U	Sub-adult (8 - 10 years)	Disarticulated	LM1	25	40	0.70962	-16.6	-2.8	28	19.2
									RM2	98	10.2040816	0.70952	-15.6	-3.9	26.9	18
HH75 2023/HH75 2138	418	Main enclosure	8	iii	Undated	U	Child (3 years)	Disarticulated	LDM2	34	29.4117647	0.70966	-15.4	-2.8	28	19.2
HH77 80	422	Long barrow	1	viii	Undated	U	Young / younger mature adult	Disarticulated	LM2	57	17.5438596	0.70869	-16.5	-3.3	27.5	18.7
									LM3	18	55.5555556	0.70848	-15.9	-3.6	27.2	18.4
HH75 1340	421	Inner East Cross Dyke	5	v	Undated	??M	Young adult	Disarticulated	LM1	35	28.5714286	0.71029	-16.1	-2.8	28.1	19.3
									LM2	58	17.2413793	0.70987	-15.5	-3.3	27.5	18.7
									LM3	70	14.2857143	0.70938	-15.3	-3.7	27.1	18.3
ST79 1428	429	Inner Stepleton outwork	5	i	Undated	??M	Older adult	Disarticulated	LPM1	12	83.3333333	0.70878	-15.8	-2.9	28	19.2
									LPM2	19	52.6315789	0.7093	-14.6	-3	27.9	19.1
ST78 1100/ST78 2047	431	Inner Stepleton outwork	9	iii	Undated	F	Young / younger mature adult	Disarticulated	LM1	19	52.6315789	0.71068	-16.3	-3.5	27.3	18.5
									RM2	22	45.4545455	0.71075	-15.4	-3.6	27.2	18.4
									RM3	29	34.4827586	0.70981	-15.2	-3.3	27.5	18.7
ST78 2248	431	Inner Stepleton outwork	9	iii	Undated	U	Child (3 years)	Disarticulated	LDM2	27	37.037037	0.7081	-15.6	-2.6	28.2	19.4
HN82 365 LDM2	438	Inner Hanford outwork	2	iii	Undated	U	Child (3 years)	Disarticulated	LDM2	16	62.5	0.70826	-15.5	-2.2	28.7	19.9

5.6 Discussion

The presence of artefacts at Hambledon Hill that were manufactured from imported materials which originate from at least 40 km away within regions such as Somerset, Devon and Cornwall, suggests there were long distance connections between the site and the south-west peninsula of England (e.g. Smith 2008a: 587, 590; Darvill 2008: 615; Smith 2008b: 630; Roe 2008: 632-633; Mercer 2008: 775). However, with the exception of those individuals whose deaths the excavators suggest to have died during an episode of violence at the site and exhibit more radiogenic $^{87}Sr/^{86}Sr$ values (close to 0.7105, fig. 2), most of the burial population do not exhibit strontium isotope ratios consistent with having sourced the majority of their childhood diet from these regions in the south-west peninsula.

Rather than routinely exploiting more distant radiogenic terrains, the majority of the sampled burial group have values that fall within locally bioavailable $^{87}Sr/^{86}Sr$ ranges (fig. 2; Warham 2011; Evans *et al.* 2010; Montgomery *et al.* 2006). Although alternative areas further afield also afford similar bioavailable $^{87}Sr/^{86}Sr$ values (see below), a large proportion of the artefact assemblage may originate from lithologies that the causewayed enclosures directly overlook, within approximately 30 km of Hambledon Hill, to the immediate south and west (Smith *et al.* 2008: 645-646; Mercer and Healy 2008: 767). Individuals who plot with strontium isotope ratios between 0.7086 - 0.7091 have values that are comparable to those recorded on Kimmeridge Clay formation (mean 0.7088 ± 0.0003, 2σ, n = 10, Warham 2011: 79). This crops out to the immediate west of the hill and was used to manufacture a large proportion of the pottery deposited within the main enclosure (Smith 2008a: 587, 595 - 596; Darvill 2008: 620-621). Lithology of Eocene age in southern Dorset (near Wareham, fig. 2), which could have been the source for much of the worked stone found at Hambledon Hill (Roe 2008: 633; Smith *et al.* 2008: 646), has also been associated with a similar bioavailable $^{87}Sr/^{86}Sr$ range, between approximately $^{87}Sr/^{86}Sr$ 0.7090 - 0.7100 (fig. 2; Evans *et al.* 2010). Individuals who plot with $^{87}Sr/^{86}Sr$ values between approximately 0.7090 and 0.7100 could therefore have sourced the majority of their diet from either of the immediate areas to the west and south to which the enclosures are linked through derivation of artefacts.

Few objects made of Cretaceous Chalk, or Sarsen, were found at Hambledon Hill (Mercer and Healy 2008: 767; Roe 2008: 633). The excavators therefore suggest that connections between the site and this lithology, which is located to the immediate east, were limited (ibid.; fig. 2). However, several individuals within the burial population have low $^{87}Sr/^{86}Sr$ values that are comparable to those bioavailable on Cretaceous Chalk: in southern Britain this routinely records bioavailable values, between 0.7074 and 0.7087 (mean 0.7080 ± 0.0008, 2σ, n = 14, Evans 2010; Warham 2011: 124). Strontium isotope ratios in this range have previously been recorded amongst individuals buried at Monkton-up-Wimbourne, a site dated later in the 4th millennium BC, which is located on the Cretaceous Chalk downs directly to the east of Hambledon Hill in Cranborne Chase, Dorset (Montgomery *et al.* 2000: 375; Healy *et al.* 2011: 156). The possibility that those individuals buried at Hambledon who have $^{87}Sr/^{86}Sr$ values below approximately 0.7085 obtained their diet from a similar area on the Cretaceous Chalk cannot be ruled out (figs. 2, 3 and 4). The possibility that individuals who exhibit values up to ~0.7098 obtained their dietary resources on the Chalk downs to the immediate east of the hill should also be considered: extensive superficial deposits of Clay-with-Flints are present on the Cretaceous Chalk to the east of the hill (BGS 2016) and such deposits may further increase the bioavailable $^{87}Sr/^{86}Sr$ range up to this value (Warham 2011: 120 and 124).

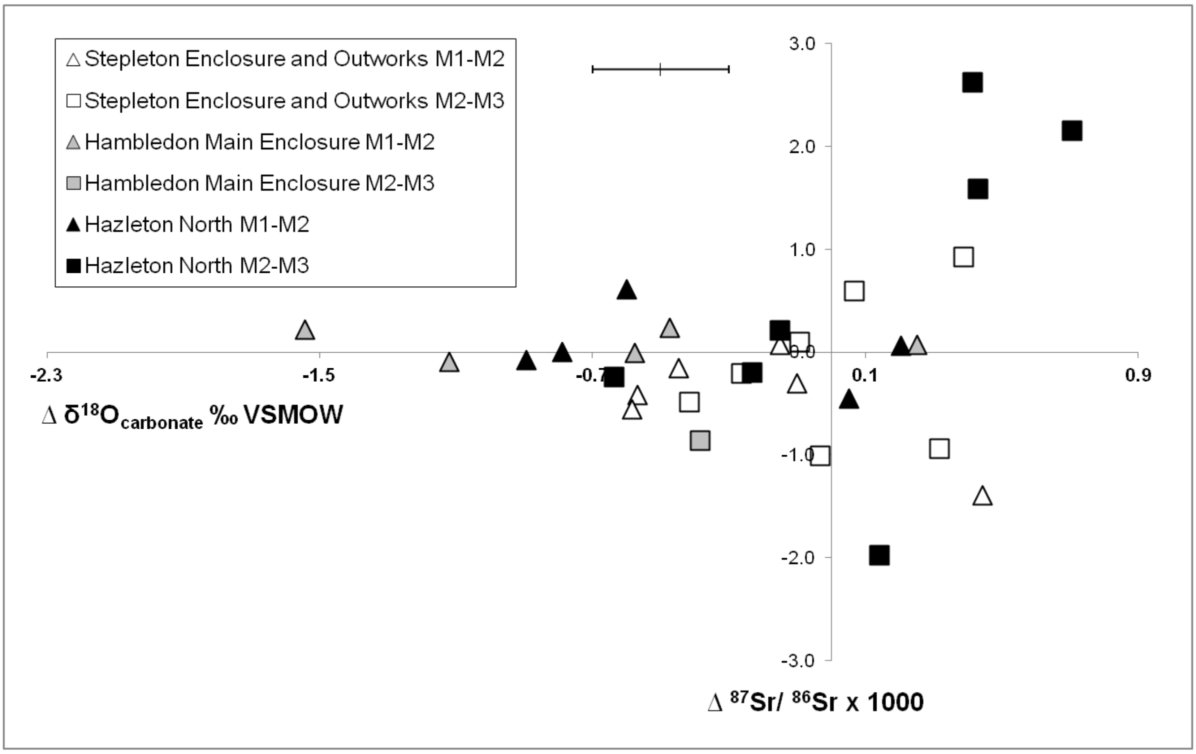
Although samples of plants and water taken on Cretaceous Chalk record low $^{87}Sr/^{86}Sr$ values, below 0.7085, other marine carbonates such as Oolitic limestone and Greensand and Gault, which crop out to the west of the hill (fig. 2) could alternatively confer similarly biosphere low values: in southern Britain, biosphere samples taken on Oolitic limestone can record strontium isotope ratios between 0.7076 and 0.7092 (mean 0.7086 ± 0.0004, 1σ, n = 17, Chenery *et al.* 2010: 155; Montgomery *et al.* 2006: 1628; Warham 2011: 79, 103; for values on Greensand and Gault also see Warham 2011: 79). Individuals who exhibit strontium isotope ratios below 0.7085 (figs. 3 and 4) could similarly have obtained their dietary resources on these lithologies. Analysis of the ceramics found at Hambledon suggests that Oolitic limestone may have been used to manufacture pottery fabric group 2 (Smith 2008a: 587, 595 - 596; Darvill 2008: 615, 617), whilst Greensand was also used to make many of the quern stones that were deposited at the complex (Roe 2008: 632).

Discussion of the range of strontium isotope ratios that the Hambledon burial population exhibit has focused on comparison of $^{87}Sr/^{86}Sr$ values to bioavailable ranges on lithologies used to manufacture the artefacts. Analysis of material culture provides persuasive evidence for links between Hambledon Hill and more immediate areas of lithology in south-west England. However, the possibility that $^{87}Sr/^{86}Sr$ values, between 0.7090 and 0.7100, for example, could reflect use of more distant terrains, rather than those within the immediate vicinity of the site, should also be considered. Strontium isotope ratios between 0.7090 and 0.7100 are widely bioavailable in eastern England for example (Evans *et al* 2010; or north-eastern France, or the Netherlands, Willmes *et al.* 2013; Kootker *et al.* 2016). The argument that the burial population at Hambledon Hill obtained childhood dietary resources locally from the west of England, the region in which the site is located, could be supported by the range of oxygen isotope ratios that this burial population exhibit.

If converted to $\delta^{18}O_{phosphate}$ using the equation of Chenery *et al.* (2012, Materials and methods), values in second and third permanent molars enamel range between 18.0 - 19.5 ‰ (mean 18.5 ± 0.4 ‰, 1σ, n = 23), which is close to the mean $\delta^{18}O_{phosphate}$ value that Evans *et al.* (2012: 759) suggest to be representative of burial populations excavated in western Britain (18.2 ‰ ± 1 ‰, 2σ), rather than eastern Britain (17.2 ± 1.3 ‰, 2σ, ibid.). However, use of this comparison assumes that $\delta^{18}O$ values in human enamel directly reflect underlying geographical variation in the oxygen isotope composition of drinking waters and that values at Hambledon Hill have not been significantly modified as a result of culinary practice (e.g. Brettell *et al.* 2012a), or influenced by consumption of fluids that have undergone fractionation through biological processes (e.g. cow's milk; Camin *et al.* 2008: 1695; Lin *et. al.* 2003: 2193; Kornexl *et al.* 1997: 22). Deciduous teeth and first permanent molars, which begin to form *in utero* and continue to form in the months following birth (Hillson 2014: 31 and 55-56), were excluded from the above comparisons. As development of these teeth may coincide with breastfeeding it is also possible that values may be influenced by consumption of breast milk, which has a higher $\delta^{18}O$ value relative to meteoric water as a result of the metabolic fractionation that occurs in the mothers body (Roberts *et al.* 1988: R625; Wright and Schwarcz 1998: 13-14; Britton 2015: 2). Unlike the majority of second and third permanent molar teeth, many deciduous teeth and first permanent molars in this study exhibit $\delta^{18}O_{carbonate}$ values that are higher than 28.0 ‰ (see fig. 4). These early forming teeth also have a higher mean $\delta^{18}O_{phosphate}$ value (19.0 ± 0.6 ‰, 1 σ, n = 18), than that of the second and third permanent molars discussed above. There is a drop in $\delta^{18}O_{carbonate}$ values between enamel from adjacent permanent first and second molars, illustrated in fig. 5 by a negative difference between the first and second molars, which may also be a consequence of weaning.

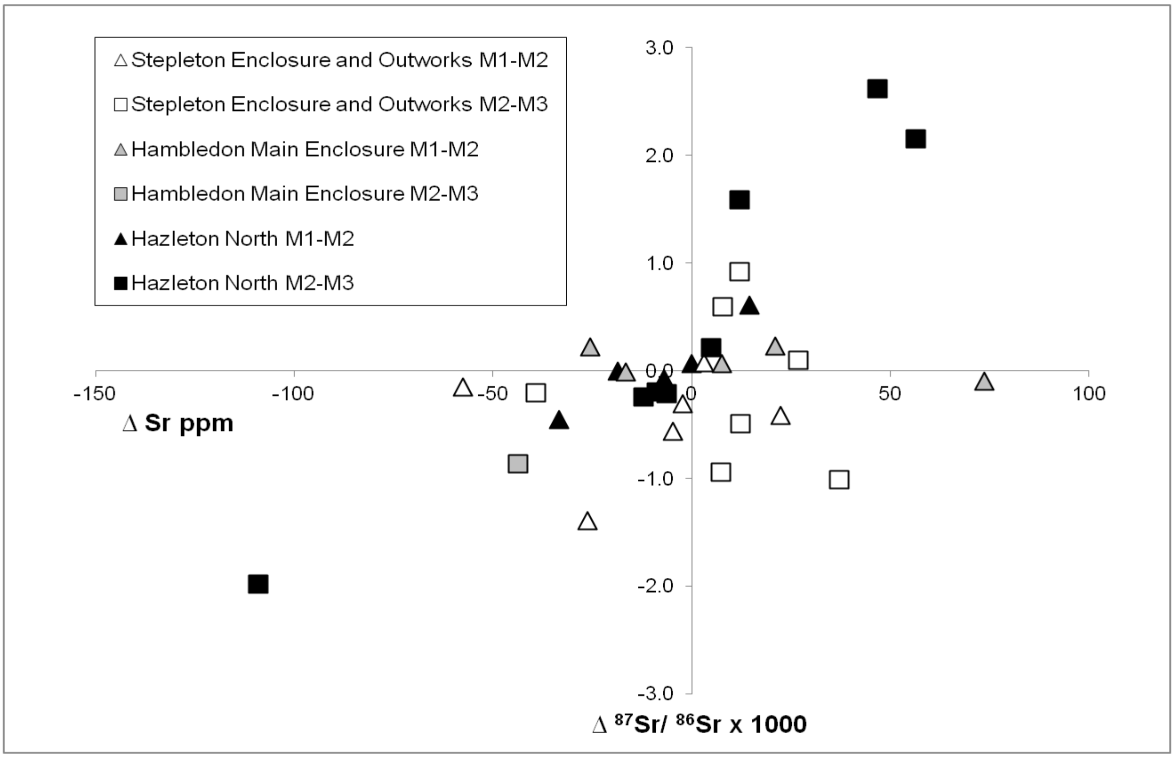
A similar drop in $\delta^{18}O$ carbonate values between adjacent permanent first and second molar enamel was also observed amongst another earlier Neolithic burial population, at Hazleton North long cairn, Gloucestershire, England (fig. 5; Neil *et al.* 2016; **Chapter 4, this thesis**).

Figure 5. Plot of the difference in oxygen ($\Delta\ \delta^{18}O_{carbonate}$ VSMOW ‰) and strontium ($\Delta\ ^{87}Sr/^{86}Sr$ x 1000) isotope ratios between adjacent permanent molar teeth of individuals excavated from the Hambledon Hill causewayed enclosure complex, Dorset and Hazleton North long cairn, Gloucestershire (Neil et al. 2016). Triangles denote the difference in oxygen and strontium isotope ratios between first and second permanent molar teeth. Squares denote the difference in oxygen and strontium isotope ratios between second and third permanent molar teeth. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol. Analytical error for $\delta^{18}O_{carbonate}$ is shown as ± 0.2 ‰ (2σ).



Hazleton North long cairn was constructed between *3710* and *3655 cal BC* (*95% probability*, OxCal v. 3.5) and use of this monument for burial may therefore be contemporary with the earliest phase of Neolithic activity at Hambledon Hill (Meadows *et al.* 2007: 54; Saville 1990). At Hazleton North, large shifts in $^{87}Sr/^{86}Sr$ values and elemental concentration between adjacent permanent molar teeth (fig. 6), are consistent with individuals having routinely changed the geographical location from which they sourced their diet during childhood and support the interpretation that individuals were residentially mobile (Neil *et al.* 2016; **Chapter 4, this thesis**).

Figure 6. Plot of the difference in strontium isotope ratio (Δ $^{87}Sr/^{86}Sr$ x 1000) and elemental concentration (Δ Sr ppm) between adjacent permanent molar teeth of individuals excavated from the Hambledon Hill causewayed enclosure complex, Dorset and Hazleton North long cairn, Gloucestershire. Triangles: the difference in strontium isotope ratio and Sr ppm between first and second permanent molars. Squares: the difference in strontium isotope ratios ratio and Sr ppm between second and third permanent molars. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.



Individuals who were buried at Hambledon Hill do not exhibit such large shifts in strontium isotope ratio and elemental concentration between adjacent molars (where these teeth were available for sampling; fig. 6). The majority of individuals have similar strontium isotope ratios on adjacent teeth, which could be consistent either with individuals having obtained all their dietary resources from the same locality over a prolonged period during early life, or with exploitation of different, geographically separate areas, that conferred a similar averaged $^{87}Sr/^{86}Sr$ value. For example, enamel samples from all three adjacent molars of individual ST78 2755 gave $^{87}Sr/^{86}Sr$ values below 0.7085 (labelled on fig. 3). This individual, who is one of the two adult males found within the Stepleton outworks with an arrowhead amongst his ribs, died toward the end of the period that the Neolithic monument complex at Hambledon Hill was in use (Healy *et al.* 2011: 128, 143). Similarly low values on all three adjacent molars could suggest that this individual sourced his diet from the same geographical location from birth until at approximately 15 years of age, at which time the crown of the third molar is usually complete (AlQahtani *et al.* 2010). Alternatively, this individual could have obtained his diet from geographically separate locations that have similar bioavailable $^{87}Sr/^{86}Sr$ ranges, for example, by moving backward and forward between an area of Oolitic limestone and the Chalk downs in southern England.

By contrast, the other three adult males who the excavators suggest could have died during a previous episode of conflict, following the burning of the outworks that surround the Stepleton enclosure earlier in the history of the site during 36th century BC (Mercer and Healy 2008: 760-761, have the highest $^{87}Sr/^{86}Sr$ values in the sampled group (illustrated as black symbols in figs. 3 and 4). These individuals have strontium isotope ratios that are higher than bioavailable ranges that are currently known to be associated with lithology in the immediate vicinity of Hambledon Hill: all these individuals possess at least one permanent molar tooth with an $^{87}Sr/^{86}Sr$ value greater than 0.7100 and which therefore exceed values that are currently known to be bioavailable on Kimmeridge Clay to the immediate west of the hill, on Cretaceous Chalk to the east, or on lithology of Eocene age along the south Dorset coast (fig. 2; Warham 2011; Evans *et al.* 2010). Two of these individuals (ST79 2726 and ST81 3181) have strontium isotope ratios between 0.7101 and 0.7104 (table 1). As described above, biosphere $^{87}Sr/^{86}Sr$ values up to 0.7105 can be recorded on the Peterborough member Oxford Clay in southern Britain (mean 0.7104 ± 0.0001, 2σ, n = 4, Warham 2011: 79, 82-83). This crops out just over 8 km to the west of Hambledon Hill (BGS 2016). As such it is possible that individuals who exhibit values up to 0.7105 need not have obtained their diet far from Hambledon Hill, if they sourced the majority of their diet from resources obtained on this formation. Alternatively, lithologies further afield within south-western England also record comparable values, for example, samples of plants and water taken on Devonian rocks within Cornwall can give measured values between 0.7100 and 0.7110 (Evans *et al.* 2010).

The third individual, ST80 1875, who was found with an arrowhead amongst his ribs, has the highest $^{87}Sr/^{86}Sr$ values of all of those who were sampled (figs. 3 and 4). Enamel samples from both the first and second molar teeth of this individual gave $^{87}Sr/^{86}Sr$ values greater than 0.7105. According to all currently available $^{87}Sr/^{86}Sr$ biosphere data, values above 0.7105 are not known to be associated with lithologies of comparable age and composition to those that surround Hambledon Hill (Eocene or Upper Cretaceous to Middle Jurassic series, Warham 2011: 79 and 82; also see Evans *et al.* 2010). This individual could not therefore have obtained his dietary resources locally. The individual derived their diet from more radiogenic sources further afield until at least 9 years of age, by which stage mineralization of the crown of the second molar tooth is normally complete (AlQahtani *et al.* 2010). Although other areas within Britain, or the European mainland, can record bioavailable values higher than 0.7105 (e.g. Evans et al. 2010; Willmes *et al.* 2013), analysis of artefacts found at Hambledon provides strong support for the existence of links between this site and lithology in the south-west peninsula of England (e.g. Smith 2008a: 590-591; Smith 2008b: 630; Smith *et al.* 2008: 645; Roe 2008: 632-633): Somerset, Devon and Cornwall in south western England record bioavailable values higher than 0.7105 and it is possible that this individual obtained dietary resources from these areas during childhood (Evans *et al.* 2010; Montgomery *et al.* 2006).

5.7 Conclusions

Previous analysis of material culture found at Hambledon Hill indicates that a significant proportion of the raw materials used to manufacture ceramics and worked stone may have originated from lithology of Eocene and Upper to Middle Jurassic age, in the more immediate local area which the enclosures overlook to the south and west of the hill, within approximately 30 km (Roe 2008; Darvill 2008; Smith *et al.* 2008). The excavators of the site therefore suggest that the immediate area of landscape visible from each enclosure provides an approximate index of the catchment which was occupied by the communities who used the site (Mercer and Healy 2008: 767; Healy 2004: 31). Whilst other areas have been considered that could provide comparable isotope ratios, the majority of the sampled group exhibit values that could be consistent with this hypothesis. Longer distance connections, between Hambledon Hill and areas further afield within the south-west peninsula of England, are implied by the presence of objects that could originate from lithology within Somerset, Devon and Cornwall (e.g. Roe 2008; Smith *et al.* 2008). However, few of the individuals in the sampled group have $^{87}Sr/^{86}Sr$ values that would be consistent with having obtained the majority of their diet from these regions during childhood and adolescence. The individuals who exhibit the highest values in the sampled group are those who the excavators suggest died during an episode of conflict, which involved burning and destruction of outworks that surround the hill, during the 36th

century BC (Mercer and Healy 2008; Healy *et al.* 2011). At least one of these adult males could not have sourced his childhood diet locally. This individual, who was found within the outworks that surround the site with an arrowhead amongst his ribs, obtained his diet from further afield during early life. The individual has $^{87}Sr/^{86}Sr$ values that are consistent with those bioavailable within Somerset, Devon and Cornwall within the south-west peninsula of England, the area from which previous analysis of material culture suggests that artefacts were imported.

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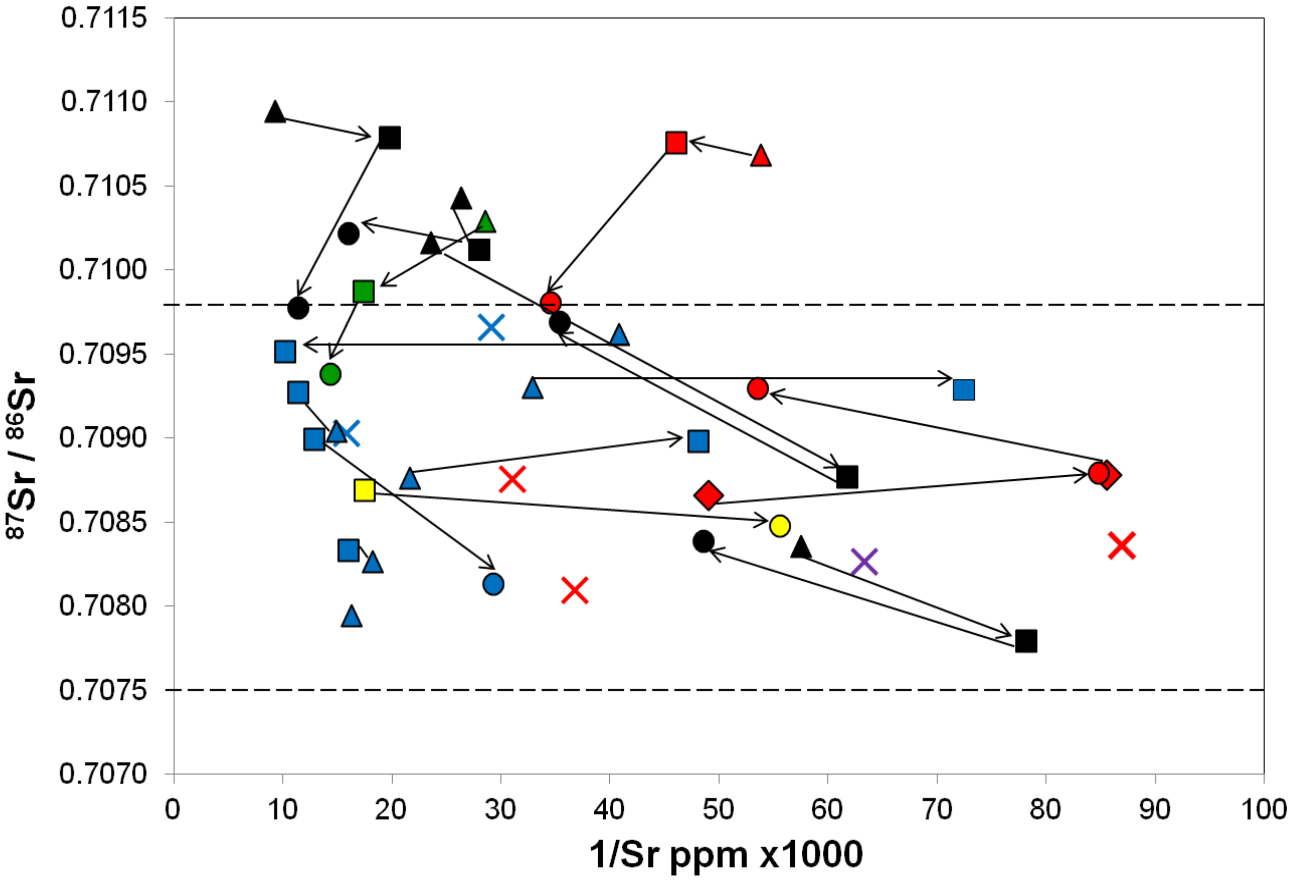
5.9 Supplementary information

Figure 3. Plot of strontium isotope ratio and elemental concentration illustrating all adjacent linked molars; symbols coloured according to the context from which each individual is recorded to have been excavated. Dashed lines denote the predicted biosphere range at Hambledon Hill, in an area of Chalk where superficial deposits of Clay-with-Flints are known to be present (based on current measured values by Warham 2011: 120 and 124). Triangles: first permanent molars. Squares: second permanent molars. Circles: third permanent molars. Diamonds: Crosses: premolars or incisors. Crosses: deciduous teeth. Black triangles, squares and circles: adult males buried on Stepleton spur who are inferred to have died during episodes of conflict at the site. Red symbols: individuals excavated from Stepleton spur enclosure. Red crosses: deciduous teeth of children excavated from Stepleton spur enclosure. Purple symbol: deciduous tooth of child excavated from the Hanford outworks. Yellow symbols: individual excavated from the south long barrow. Green symbols: individual excavated from the inner east cross dyke. Blue triangles, squares and circles: individuals excavated from the main enclosure. Blue crosses: deciduous teeth of children excavated from the main causewayed enclosure. 2σ errors for $^{87}Sr/^{86}Sr$ are within the symbol.



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6. Conclusions

A total of eight individuals from two of the sampled burial groups, Whitwell and Penywyrlod, have strontium isotope ratios that exceed all currently known biosphere $^{87}Sr/^{86}Sr$ values in England and Wales. The analytical methodology that has been employed by this thesis is well established, having been applied in archaeology for several decades (see reviews by Montgomery 2010; Bentley 2006; as discussed in **chapter 1** and further described in **chapters 2 to 5**). Bioavailable $^{87}Sr/^{86}Sr$ ranges in England and Wales are also well characterized (see Evans *et al.* 2010). At present the highest currently recorded biosphere value in England and Wales is 0.7162 (Chenery *et al.* 2010) and according to all current scientific understanding individuals who exhibit values that exceed this cannot have obtained their diet within England and Wales. Presently the only available explanation for such results is that the individuals who exhibit these values obtained their diet from outside England and Wales during early life.

As described in **chapter 2**, several regions within Europe can record bioavailable values that match those exhibited by individuals buried at Whitwell and Penywyrlod. As such, the region from which of these individuals obtained their childhood diet cannot be determined the basis of strontium isotope results alone on alone. Possible source areas have been explored on the basis of the dating of these individuals and their association with Neolithic material culture. Whitwell cairn began to be used for burial from the 38th century cal BC (Griffiths 2011: 85). Individual 74.23H/9.2.3/P23 who was buried at Penywyrlod has a calibrated radiocarbon date range (3770-3630 cal BC; 95% confidence; ibid) which coincides with current radiocarbon dating estimates for the initiation of farming in southern Wales, toward the end of the 38th century BC (**chapter 3**, Bayliss *et al.* 2011: 736; Whittle *et al.* 2011: 836).

The Scottish highlands cannot be ruled out as a source area on the basis of isotope analysis alone, as $^{87}Sr/^{86}Sr$ values higher than 0.7170 have been recorded in the Scottish highlands, in regions such as the Cairngorm mountains in north-east Scotland (Evans *et al.* 2010). However, assignment of these individuals to this region may be problematic on archaeological grounds, as current Bayesian modelling of radiocarbon dates suggests Neolithic material culture and practices appeared within this region of Scotland in the decades around 3800 cal BC and may have only recently been established at the time of the deaths of the first individuals to be buried at Whitwell (Bayliss *et al.* 2011a: 822-824, 838-840).

Individuals at Whitwell and Penywyrlod were found in association with Neolithic material culture: the practice of monument construction derives from well established traditions on the European mainland (e.g. Scarre 2015). Recent comparative analysis of material culture supports the interpretation that Neolithic traditions and practices were introduced by the arrival of groups from the near Continent during the early 4th millennium BC and suggests that north-western France was one of the source areas from which these traditions were introduced (Pioffet 2015; cf. Sheridan 2010a, 2010b). The individuals buried at Whitwell exhibit values comparable to those that are bioavailable in north-western France (Négrel and Pauwels 2004; Wilmes *et al.* 2013). The strontium isotope results from both Penywyrlod and Whitwell could as such plausibly be interpreted to suggest these individuals obtained their childhood diet from that region. The results may therefore support previous arguments for migration during the early Neolithic (e.g. Sheridan 2010a, 2010b; Rowley-Conwy 2011; Bradley *et al.* 2015; Anderson-Whymark and Garrow 2015; Pioffet 2015; see references cited in **chapter 1**).

In contrast individuals buried at Whitwell and Penywyrlod who exhibit $^{87}Sr/^{86}Sr$ values higher than 0.7170 and have calibrated radiocarbon date ranges that fall within the 38th century BC, all individuals who were sampled by this project with calibrated radiocarbon date ranges that fall after 3700 cal BC (Hazleton North, Ty Isaf and Hambledon Hill, **chapters 3 to 5**) have $^{87}Sr/^{86}Sr$ values that could be consistent with bioavailable ranges found in England and Wales and could have sourced their diet from these regions. All individuals sampled from Ty Isaf post-date 3650 BC and the majority of this burial group have strontium isotope ratios that are comparable to those bioavailable in south-east Wales, the region in which they were buried (**chapter 3**).

The long cairn at Hazleton North is estimated to have been constructed during the first half of the 37th century BC (Meadows *et al.* 2007) and individuals within this burial group also have strontium isotope ratios that are comparable to measured bioavailable ranges in southern Britain, the area in which this site is located (**chapter 4**; Evans *et al.* 2010; Chenery *et al.* 2010 and Warham 2011: 70-96). The majority of individuals in this group did not obtain their dietary resources from sedentary intensive mixed farming at a single geographical location and the strontium isotope results provide evidence for more complex patterns of land use. Large shifts in $^{87}Sr/^{86}Sr$ values and elemental concentration between adjacent permanent molar teeth are consistent with individuals having routinely changing the location from which they sourced their diet and having exploited at least two geographically separate locations during early life. Results support the interpretation that individuals participated in a regular routine of residential mobility between different geographical areas. Interpreted in conjunction with the diverse nature of archaeological evidence for occupation during the 4th millennium BC, which includes both the remains of substantial structures and more ephemeral structural remains, pits and lithic scatters, the results support previous arguments for cultural variation in settlement practices during the Neolithic.

Enamel from the majority of individuals sampled at the Hambledon Hill causewayed enclosure complex also recorded values that are consistent with bioavailable ranges in southern Britain, with most individuals exhibiting strontium isotope ratios below 0.7100 (**chapter 5**). Isotope ratios exhibited by the burial population at Hambledon Hill were compared to the results of previous analysis of material culture from this site. This analysis suggested that a significant proportion of the raw materials used to manufacture ceramics and worked stone may have originated from lithologies of Eocene and Upper to Middle Jurassic age, that the enclosures overlook within approximately 30 km to the south and west of the hill (Roe 2008; Darvill 2008; Smith *et al.* 2008). The majority of the sampled group exhibit isotope ratios exhibit isotope ratios that would be consistent with this. Longer distance connections, between Hambledon Hill and areas further afield within the south-west peninsula of England, are also implied by import of objects that could originate from lithology within Somerset, Devon and Cornwall (e.g. Roe 2008; Smith *et al.* 2008). However, few of the individuals in the sampled group have $^{87}Sr/^{86}Sr$ values above 0.7100 that would be consistent with having obtained the majority of their diet from such regions during childhood and adolescence. Those who have the highest values within the sampled group are the individuals who the excavators suggest to have died during an episode of conflict, which involved burning and destruction of outworks that surround the hill, during the 36th century BC (Mercer and Healy 2008; Healy *et al.* 2011). At least one of these adult males, who was found within the outworks on Stepleton spur with an arrowhead amongst his ribs, has strontium isotope ratios higher than 0.7105 and according to current bioavailable ranges, could not therefore have sourced his childhood diet locally. The individual obtained his diet from further afield during early life and exhibits $^{87}Sr/^{86}Sr$ values that are consistent with those bioavailable in the south-west peninsula of England in regions such as Somerset, Devon and Cornwall, the areas from which previous analysis of material culture suggests that artefacts imported.

As a whole $\delta^{18}O_{carbonate}$ values of enamel from all permanent second and third molar teeth that were sampled within this thesis (**chapters 2 to 5**) range between 25.4 and 28.3 ‰ (mean 26.9 ± 0.5 ‰, 1σ, n = 84). If these values are converted to $\delta^{18}O_{phosphate}$ using the equation of Chenery *et al.* (2012: 310) values of enamel from permanent second and third molar teeth range between 16.5 and 19.5 ‰ (mean 18.1 ± 0.5 ‰, 1σ, n = 84). Such values are routinely recorded within human archaeological populations excavated in Britain (e.g. Evans *et al.* 2012) or the immediate near Continent (see Brettell *et al.* 2012: 127). They contrast with those that can be associated with regions of cooler climate in Europe, where $\delta^{18}O_{phosphate}$ values below approximately 15.5‰, or $\delta^{18}O_{carbonate}$ values below approximately 24.5 ‰, may be recorded (e.g. in Scandinavia, Price and Naumann 2015, or the Alps, Müller *et al.* 2003).

Previous studies have suggested that oxygen isotope ratios measured in enamel from human teeth, such as permanent first molars or deciduous teeth, whose formation may coincide with breast feeding, can be influenced by consumption of breast milk which may confer higher $\delta^{18}O$ values relative to fluids consumed by the mother (Roberts *et al.* 1988: 625; Wright and Schwartz 1998: 14; Britton 2015: 8; see references cited in **Chapters 2 to 5**). As a whole, enamel from deciduous teeth and permanent first molars sampled by the present study gave $\delta^{18}O_{carbonate}$ values between 26.5 and 28.7 ‰ (mean 27.6 ± 0.6 ‰, 1σ, n = 38). If converted to $\delta^{18}O_{phosphate}$ these values range between 17.7 and 20.0 ‰ (mean 18.8 ± 0.6 ‰, 1σ, n = 38). The mean value of enamel from permanent first molars and deciduous teeth is therefore higher than that recorded in enamel from later forming permanent second and third molars (see above), supporting the interpretation that consumption of breast milk may influence oxygen isotope ratios.

As a whole $\delta^{13}C_{carbonate}$ values of enamel from all teeth sampled (**Chapters 2 to 5**; including other tooth types, incisors, canines or premolars, where sampled when molars were unavailable) range between -18.0 and -14.3 ‰ (mean -15.9 ± 0.6 ‰, 1σ, n = 129). Values therefore fall within the anticipated range for individuals who have obtained the majority of their diet from C_3 terrestrial sources (i.e. between approximately -17.0 to -14.0 ‰; diets derived primarily from C_4 or marine resources would be associated with higher values; Kellner and Schoeninger 2007; Froehle *et al.* 2012). $\delta^{13}C_{carbonate}$ results are as such consistent with previous arguments made based on $\delta^{13}C$ analysis of bone collagen, supporting the suggestion that C_3 domesticated resources were routinely exploited during the 4th millennium BC in Britain (e.g. Richards and Hedges 1999: 892; Richards *et al.* 2003; Richards and Schulting 2006; also see Schulting 2013). It should be noted that as $\delta^{13}C_{carbonate}$ analysis of bioapatite, the subject of the present study, is most often used to evaluate the contribution of C_4 plant resources to the diet, since values reflect the diet as a whole (including carbohydrates). The latter may not be visible if using $\delta^{13}C$ analysis of bone collagen alone as this primarily reflects dietary protein. However, there is no archaeological evidence that C_4 plant resources, such as millet, for example, were exploited in Britain during the Neolithic. For recent examples of how $\delta^{13}C_{carbonate}$ analysis of bioapatite is applied to identify the contribution of C_4 resources to diet in north-western Europe during later periods, such as the Bronze Age or Roman period, see Pollard *et al.* (2011), or Goude *et al.* (2016).

6.1 Future directions for research

The assemblages studied during this project were chosen to enable comparison of a sample of results from recently excavated sites located in different regions of England and Wales. The results represent a selection of the sites to which the method could be applied. More than 500 long barrows are currently known across Britain (Darvill 2004: 71; also see Smith and Brickely 2009). Sample selection is influenced by taphonomy and the presence of dentition suitable for analysis, however, future application of the techniques applied by this thesis could test the representativeness of the results of the present study. Assemblages which could be suitable for analysis in future could, for example, include collections from Ascott-Under-Wychwood long cairn (curated by Oxfordshire Museums Service and the Natural History Museum); Burn Ground, Gloucestershire (curated by Gloucester City Museum); Fussell's Lodge, Wiltshire (curated by the Natural History Museum and Salisbury and South Wiltshire Museum); Thornwell Farm, Monmouthshire, Wales (held by Chepstow Museum); Pipton, Powys, Wales (National Museum Wales) and Wayland's Smithy, Oxfordshire (curated by Reading Museum and Art Gallery and Natural History Museum).

Whilst undertaking corrections to this thesis preliminary results of an ancient DNA study reporting analysis of eighty individuals buried in Britain between approximately 3900–1200 BC, were released in pre-print form (Olalde *et al.* 2017). The study includes results from thirty-five Neolithic individuals, nineteen British Beaker Complex individuals, with the remainder of those sampled from Britain being dating to the mid to later Bronze Age. The paper has yet to be peer reviewed at the time of writing. It primarily focuses on the genomic transformation that occurred in during the Beaker period and Bronze Age. However, it also discusses the implications of this sample of new results for understanding development of the British Neolithic. The study suggests that the appearance of Beaker culture within Britain, from approximately 2400 BC, was associated with migration from the European mainland. Unlike the sampled British Neolithic population, Beaker-associated individuals are most closely related to populations in the Central European Beaker Complex within the Lower Rhine area, and in turn exhibit a high proportion of Steppe ancestry, reflecting earlier migration of Steppe populations into central and northern Europe in proceeding centuries. In marked contrast, individuals dated to the Neolithic in Britain exhibit no evidence of Steppe ancestry. Rather than bearing affinity to local hunter-gatherers in western Europe the sampled Neolithic population derive their ancestry from groups who arrived with the spread of farming into mainland Europe from Anatolia. However, the study suggests that, rather than clustering with central farming European farming populations who arrived via the Danubian LBK route of Neolithic expansion into Europe, Neolithic individuals buried in Britain predominantly derive their ancestry from populations who arrived along the Mediterranean route of farming expansion into Europe, descending from early Neolithic Iberian farming groups who subsequently spread along the Atlantic coast into north-western Europe in later millennia.

Results are similar to those of Cassidy *et al.* (2016), who presented the first Neolithic whole genome data from Ireland, from one middle Neolithic (3343–3020 cal BC) female buried at Ballynahatty, near Belfast. Based on their results both studies argue that expansion of farming into new regions of Europe was driven by migration. Both suggest data is difficult to reconcile with extensive indigenous adoption of agriculture by local hunter-gather populations. However, such conclusions remain preliminarily. As discussed above, the study by Olalde *et al.* (2017) remains in pre-print form and has yet to be peer reviewed at the time of writing. Genetic analysis of a wider sample of Neolithic individuals buried in Britain is also currently being undertaken (Tom Booth, pers. comm.).

The present thesis principally focused on the application of isotope analysis to study the early Neolithic, future application of the technique is also likely to augment and expand on the results of pilot studies undertaken on burial assemblages of sites of middle Neolithic date, such as that from Monkton-up-Wimbourne, Dorset (Montgomery *et al.* 2000). Here, strontium and lead isotope analysis of enamel from individuals who died during the late 4th millennium who BC, showed that at least one individual (individual C) within this burial group obtained their diet from outside the region in which they were buried and results may be interpreted to indicate they moved at least once prior to burial (ibid. 375; Healy *et al.* 2011: 156). A recent program of strontium isotope analysis undertaken on the osteological assemblage from a newly excavated middle Neolithic triple-ring-ditch monument at Banbury Lane, Northamptonshire, has also shown that several individuals buried at this site do not have $^{87}Sr/^{86}Sr$ values consistent with the local bioavailable range, these individuals also obtained their childhood diet from outside the local region in which they were buried and these results could also support the interpretation that these individuals were residentially mobile (Sophy Charlton, pers. comm.).

During the course of preparation of this thesis the author also conducted strontium and oxygen isotope analysis on a further collection, that which has been attributed to the megalithic burial monument of Coldrum, Kent in south-east England. This collection has a complex post-excavation history, having been excavated over 100 years ago (Bennett 1913, Keith 1913). The human osteological assemblage attributed to these excavations consists of disarticulated and fragmented skeletal elements. These are curated by three different museums, with the majority of the cranial remains residing in the Duckworth Laboratory at the University of Cambridge, post-cranial material being housed in the Natural History Museum, London and a further small collection of other skeletal elements being located in Maidstone Museum in Kent. Wysocki *et al.* (2013) recently undertook osteological analysis of the collections and radiocarbon dated a sample of skeletal remains that have been attributed to this site (fragments of cranial vault and femurs). The results showed that this dated sample of skeletal elements belonged to the 4^{th} millennium BC and it was therefore assumed that the collections as a whole were of Neolithic date (ibid.).

However, during a visit to the Duckworth laboratory at the University of Cambridge to examine these collections, the author of this thesis noted that many skeletal elements within the collection are unlabelled, or labelling is limited to the recent addition of museum accession numbers, added in the last few decades by the Duckworth Laboratory after they received the collection. Examination of the limited paperwork associated with the collections at the Duckworth showed that it was originally housed at the Hunterian Museum in London and transferred to the University of Cambridge shortly after the Second World War. Having been made aware of the highly complex post-excavation history of this collection and the discovery that there is no labelling to enable the direct attribution of the majority of skeletal elements within these collections to the original Coldrum excavations, the author of the thesis decided to radiocarbon date each of the disarticulated mandibles, from both the Duckworth and Maidstone Museum collections, prior to conducting strontium and oxygen isotope analysis of the dentition. The results of dating showed that, although some of the mandibular remains within these collections did indeed date to the 4th millennium BC, others were not in fact Neolithic and date to the 5th to 6th centuries AD, casting doubt on the provenance of remains within these collections.

These results illustrate the difficulties that can be encountered when using bioarchaeological analyses (e.g. techniques such as aDNA, proteomics or isotope analysis) to study remains antiquarian museum collections. Unlike collections from more recent archaeological excavations, such as those analysed within the rest of this thesis where all skeletal elements are well labelled and the context from which they originate is well documented, remains deriving from antiquarian excavations can have complicated post-excavation histories. However, the latter form a significant component of museum collections and if modern bioarchaeological techniques, such as aDNA or isotope analysis are applied in future, to study such museum assemblages it is advisable to combine analysis with direct radiocarbon dating of each specimen being studied. Due to the presence of individuals of dated to the 5th to 6th centuries AD within the museum collections that have been attributed to Coldrum, the decision was taken not to include the results of this analysis of the within the present thesis. In addition to strontium and oxygen isotope analysis and radiocarbon dating, the author of this thesis also sampled dentine from each of the individuals attributed to Coldrum for the purpose of carbon and nitrogen analysis (to obtain further dietary information). The results are being written up as a separate, fifth publication, additional to the four draft papers within this thesis.

The present project focused on analysis of assemblages excavated within England and Wales. To date the application of strontium isotope analysis to study osteological assemblages of Neolithic date in Scotland remains limited. A recent pilot study by Armit *et al.* (2015), provides for an excellent example of the application of strontium isotope analysis to study the Neolithic in this region, studying an individual dated to the last few centuries of the 4th millennium BC, to between 3340–3090 cal BC who was buried at Balevullin, Tiree, western Scotland (95% confidence, OxCal v.3.10, ibid). However, the technique has yet to be systematically, in particular to study the Orkney islands.

As in other regions of Britain, the nature of subsistence and residence patterns during the transition to agriculture in Scotland continues to be debated, with settlement patterns in Orkney frequently being contrasted with those on the Scottish mainland (e.g. Brophy 2006: 19, 25; Schulting 2013: 323). In combination, evidence from the study of both zooarchaeological and archaeobotanical remains may be indicative of the emergence of divergent settlement and subsistence regimes during the Neolithic in Scotland. On the Scottish mainland occupation evidence includes ephemeral structures and pit clusters, which have been interpreted as the remains of temporary camps and could be indicative of a greater degree of residential mobility during the development of agriculture in this region (e.g. Brophy 2006); in this region there is also evidence for exploitation of both wild plant resources as well as cereal cultivation, which is indicative of a mixed-plant subsistence economy (Bishop 2009: 86 , 90). In contrast, in Orkney the predominance of cereal remains is indicative of importance of arable agriculture (ibid.), study of zooarchaeological assemblages also suggest that in this region, sheep may have been greater importance, particularly when compared to southern Britain (e.g. Schulting 2013: 323).

In Orkney, occupation evidence is dominated by the remains of wooden and stone settlements (e.g. Richards and Jones 2016; Farrell *et al.* 2014). Here, evidence for permanent architecture, including the emergence of nucleated settlements during the course of the Neolithic could be consistent with development of fully sedentary agricultural communities. Recent evidence however, could however be indicative of greater complexity in mobility patterns: genetic evidence suggests that the Orkney vole (*Microtus arvalis)*, a species that is absent from mainland Britain, and red deer, were introduced to the islands from regions much further afield during the Neolithic (Martínková *et al.* 2013; Stanton *et al.* 2016). These recent studies therefore appear to support arguments for a high degree of maritime mobility and suggests that agricultural communities may have moved over long distances between regions during the Neolithic.

Ideally future studies could exploit the same techniques applied by the present thesis to study patterns of land use and mobility patterns during the 4th to 3rd millennium BC in Scotland, comparing values exhibited by human populations (e.g. from monuments in Orkney such as Point of Cott, Barber & Coy 1997; Holm of Papa Westray North, Ritchie & Ashmore 2009; Isbister, Lawrence 2006; Quanterness, Crozier 2016), to modern measured bioavailable $^{87}Sr/^{86}Sr$ values and to measured values of enamel from Neolithic dietary resources (sheep/cattle) from settlement sites (e.g. those of differing date in Orkney such as the Knap of Howar, Ritchie *et al.* 1983; Skara Brae, Childe 1950; Clarke 1976 and Tofts Ness, Nicholson & Davis 2007). Future studies could further combine $^{87}Sr/^{86}Sr$ analysis of enamel with sulphur isotope $\delta^{34}S$ analysis (e.g. of a sample of collagen from the root of each tooth). Variation in $\delta^{34}S$ is primarily driven by differences in values within the geosphere and hydrosphere (Nehlich 2015). When used in combination with strontium, analysis of sulphur isotopes provides further information, as it can help to distinguish whether an individual obtained their diet from coastal regions influenced by seaspray or from regions located inland: populations who obtain their dietary resources further inland can exhibit much lower $\delta^{34}S$ values than those who obtain their resources from coastal regions that are influenced by seaspray (Nehlich 2015: 10-11).

As with the study of the sites in England and Wales, selection of sites within Scotland would also be influenced by taphonomy: fewer Neolithic assemblages survive on the Scottish mainland, however, results from Orkney could be compared to those from burial groups excavated from sites such as Tulach an T'Sionnaich and Tulloch of Assery A and B in Caithness (Corcoran 1967) and Embo, Sutherland (Henshall & Wallace 1965). Application of this technique to assemblages from Orkney could particularly assist in evaluating the nature of inter-connections between these islands and other regions during the course of the Neolithic and would help to examine the extent of maritime mobility during this period. Study of sites in Scotland could as such further contribute to examination of regional variation in mobility patterns during the development of agriculture. It is with this consideration of the future prospects and potential for understanding cultural diversity and variation in land use and mobility during the Neolithic that this thesis concludes.

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