Mobility during the Neolithic and Bronze Age in Northern Ireland explored using strontium isotope analysis of cremated human bone

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ABSTRACT

Objectives – As many individuals were cremated in Neolithic and Bronze Age Ireland, they have not featured in investigations of individual mobility using strontium isotope analysis. Here, we build on recent experiments demonstrating excellent preservation of biogenic $^{87}Sr/^{86}Sr$ in calcined bone to explore mobility in prehistoric Northern Ireland.

Materials and Methods – A novel method of strontium isotope analysis is applied to calcined bone alongside measurements on tooth enamel to human remains from five Neolithic and Bronze Age sites in Northern Ireland. We systematically sampled modern vegetation around each site to characterise biologically available strontium, and from this calculated expected values for humans consuming foods taken from within 1, 5, 10 and 20 Km catchments. This provides a more nuanced way of assessing human use of the landscape and mobility than the 'local' vs. 'non-local' dichotomy that is often employed.

Results – The results of this study 1) provide further support for the reliability of strontium isotope analysis on calcined bone, and 2) demonstrate that it is possible to identify isotopic differences between individuals buried at the same site, with some consuming food grown locally (within 1-5 Km) while others clearly consumed food from up to 50 Km away from their burial place.

Discussion – Hints of patterning emerge in spite of small sample numbers. At Ballynahatty, for instance, those represented by unburnt remains appear to have consumed food growing locally, while those represented by cremated remains did not. Furthermore, it appears that some individuals from Ballynahatty, Annaghmare and Clontygora either moved in the last few years of their life or their cremated remains were brought to the site. These results offer new insights into the choice behind coterminous cremation and inhumation rites in the Neolithic.

INTRODUCTION

After falling out of favour in Anglo-American archaeology for some decades (Clarke 1976; Shennan 1976), the investigation of individual and group mobility has recently undergone a remarkable renaissance. This has been partly fuelled by advances in scientific archaeology, including the application of strontium isotope analysis (e.g., Sealy et al. 1995; Bentley 2006; 2013; Montgomery 2010; Price et al. 2004). One limitation of this method has been the requirement for dental enamel for analysis, since bone is highly susceptible to contamination by groundwater strontium. Where the dominant funerary rite was cremation it results in the spalling and loss of enamel so it has not been possible to apply the method. This is the case for much of Neolithic and Bronze Age Ireland, partly because cremation was an important funerary rite – often alongside inhumation – but also because unburnt skeletal material survives poorly across much of the island due to soil acidity. Because both cremation and inhumation co-occurred in Neolithic Ireland, there are additional questions concerning the rationale behind the choice of one funerary rite over the other. One possibility is that those represented by cremated remains were brought from more distant locations, calcined bone being easier to transport. Here, we take advantage of the recent demonstration that *in vivo* strontium isotope signals survive both the cremation process and subsequent burial contexts to explore these questions in a pilot study on five Neolithic and Bronze Age sites in Northern Ireland.

Strontium isotopes in archaeology

Two isotopes of strontium, ^{86}Sr and ^{87}Sr, are widely used in mobility studies of humans and fauna. Strontium-87 is the product of the radioactive decay of Rubidium-87 (^{87}Rb), so strontium isotope ratios ($^{87}Sr/^{86}Sr$) vary between different types of bedrock, depending on the initial Rb-Sr ratio and the age. The older and more Rb-enriched the bedrock, the more enriched it is in ^{87}Sr (Faure & Powell 1972). Soluble strontium is then taken up by plants and enters the bones and teeth of humans and animals by replacing calcium in the bioapatite fraction of bone and teeth. Hence, strontium isotope ratios ($^{87}Sr/^{86}Sr$) can be measured on bone and teeth to suggest places of origin for animals and humans. However, the tissue of choice is dental enamel, as it has been shown to be resistant to recrystallization and exchanges with the burial environment compared to more labile bone mineral (Hoppe et al. 2003). Bone, if it is used at all, is often used to provide an indication of the 'local' strontium isotope composition, taking advantage of its assumed equilibrium with the soil values of the burial site (Tuross et al. 1989; Budd et al. 2000).

Recent studies have raised the possibility that the strontium isotope composition of bone survives calcination. Bone is termed 'calcined' when it attains a white colour, at which point it has lost all organic material and become highly crystalline in its structure (Lebon et al. 2010; Snoeck et al. 2014). A stepped heating experiment suggested that the strontium isotope composition of cow bone was preserved even under high temperatures (Harbeck et al. 2011), while Harvig et al. (2014) applied this principle to the measurement of $^{87}Sr/^{86}Sr$ in calcined high-density petrous bones from an archaeological context. Subsequently, a set of experiments involving the contamination of enamel and calcined bone fragments in an artificially enriched strontium isotope (^{87}Sr) solution demonstrated that all calcined bone preserves an *in vivo* signal, and indeed seems more resistant to diagenetic alteration than enamel (Figure 1) (Snoeck et al. 2015). This finding underpins the present study.

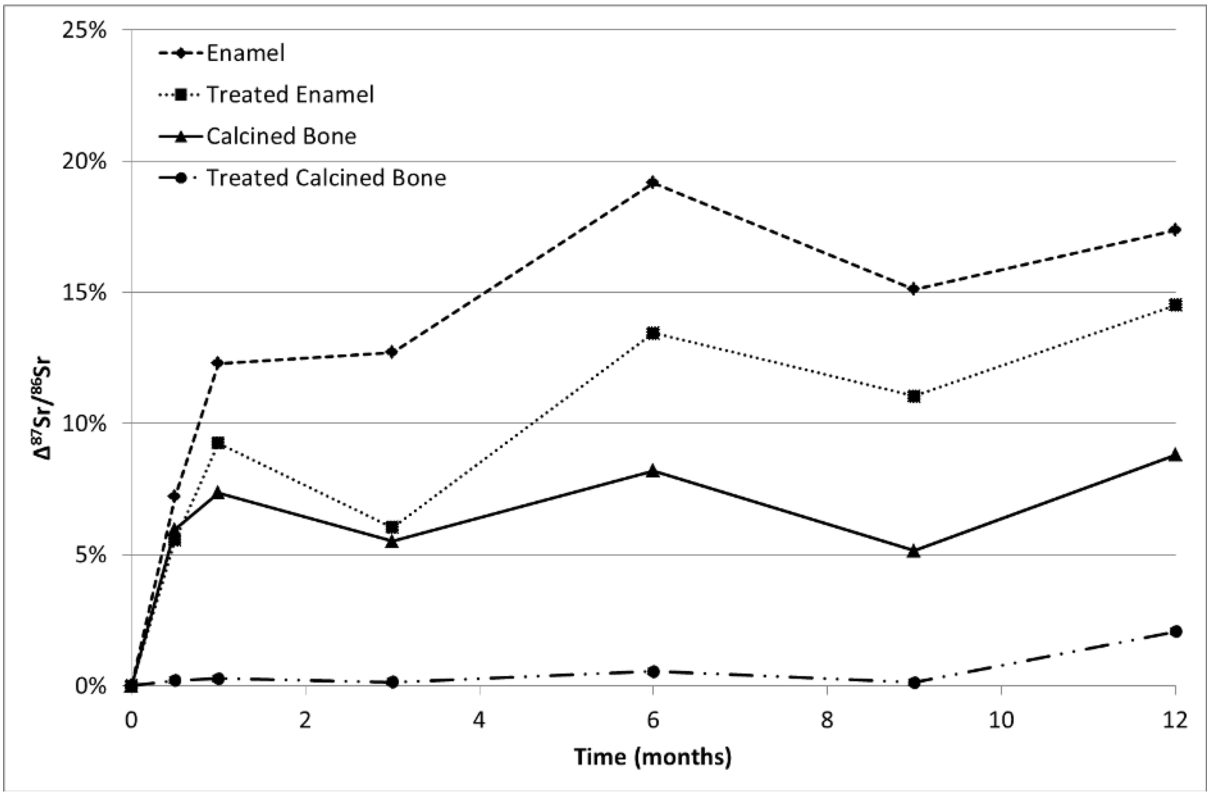


Figure 1 – Variation in the strontium isotopic ratio ($\Delta^{87}Sr/^{86}Sr$) over time of modern horse enamel and calcined modern cow tibia between uncontaminated samples and samples immersed in a ^{87}Sr-enriched solution (Snoeck et al. 2015: Fig. 3); this demonstrates that, once pre-treated, cremated bone is at least as reliable as tooth enamel for strontium isotope analyses, and hence, is a trustworthy substrate for such measurements

When comparing results obtained on unburnt tooth enamel and calcined bone, it is important to keep in mind that measurements on tooth enamel relate to the time during which the tooth crown formed, and reflect dietary intake of strontium during infancy through to early adolescence, depending on the tooth measured. Bone on the other hand continues to remodel, and so provides information relating to the last decade or more of adult life (Hedges et al. 2007; Robin & New 1997). This is a crucial difference in the isotopic analysis of enamel compared to calcined bone.

Defining 'local'

The common practice in mobility studies is to compare an individual's strontium isotope ratio to the 'local signal'. This crucial 'local signal' has been characterised in various ways. Most often, the enamel of one or another animal from the same archaeological site is chosen to represent the local signal, under the assumption that the animal in question fed locally. Pigs are often used where available (Bentley & Knipper 2005), though they may not always be as local as assumed (cf. Madgwick et al. 2012). Alternatively, the enamel of small rodents may be used (Price et al. 2002; Bentley et al. 2004), again assuming that these will reflect localised consumption (a potential problem is that their foraging ranges may be *too* local, and so not reflect realistic human subsistence catchments). This approach obviously requires the presence of such animal remains, which are rare to non-existent in the present study sites. In other studies bone and/or dentine are used, based on the assumption that these tissues have reached isotopic equilibrium with the immediate burial environment due to their greater susceptibility to contamination as a result of their low crystallinity (Bentley et al. 2003; Price et al. 2004; Evans et al. 2006). However, while diagenesis is highly likely under most circumstances, it is not certain the original signal has been replaced and to what extent. Moreover, the signal of the immediate *burial* environment is unlikely to be a good proxy for the much larger area that must have supplied the foods consumed by the individuals buried at the site. Another approach that avoids these problems is to compare the distribution of human $^{87}Sr/^{86}Sr$ results to a Gaussian ('normal') distribution, removing individual outliers until the distribution passes the Shapiro-Wilks test for normality (Wright 2004). While a very interesting approach, it suffers from two drawbacks. Firstly, it relies on substantial sample sizes for each site being analysed, which are not always available (certainly not in the present study), and, secondly, while identifying 'locals', it does not address the scale of landscape use in the way that our new method proposes. This problem is shared with the first two site-specific approaches.

Here, we sampled modern vegetation to characterise the strontium isotope values for the different geological formations represented around each of our study sites (cf. Evans et al. 2009; 2010). An advantage of this approach is that it enables full coverage of the region of interest, rather than relying on the recovery of archaeological sites with suitable sample materials (which may be heavily biased towards particular geologies). These data are employed in a new approach, avoiding the simple dichotomy of 'local' versus 'non-local' in favour of a series of nested catchments with projected strontium isotope values. Combined with bedrock geological formations, these catchment values are used to create an 'isoscape' in ArcGIS. As the strontium isotope composition of the biosphere is primarily influenced by the local bedrock geology, geological maps can be used as an initial template to create boundaries between zones with distinct biologically available strontium (hereafter BASr) isotope compositions. However, differences observed between the strontium isotope compositions of the biosphere and the underlying bedrock geology (e.g. Sillen et al. 1998) shows the importance of evaluating the biologically available strontium isotope values for the specific study area.

The geology of Ireland

The island of Ireland exhibits highly diverse bedrock geology of sedimentary, igneous and metamorphic rocks, spanning 2000 Ma of the Earth's history (Holland & Sanders, 2009). Palaeozoic lithologies (545-248 Ma) predominate, especially Carboniferous sedimentary rocks (350-290 Ma); there are several large granitic bodies and, in Co. Antrim in the northeast, an extensive outcrop of mantle-derived Tertiary (60 Ma) basalt lavas. Consequently, and relevant to this research, there is a large range of present-day strontium isotope compositions, from below 0.7040 in some Antrim basalts to over 1.15 in certain Mourne Mountains granites (Wallace et al. 1994; Meighan et al. 1988). The superficial geology is composed, among other things, of Holocene peat bogs and glacial till originating mostly from the last deglaciation around 14 kya. Holocene peat is mostly present in the western and central parts of the island (Hammond 1978; Connolly et al. 2007), and is found in only a few limited locations in Northern Ireland.

The sites

Five archaeological sites dating from the Neolithic to the Middle Bronze Age feature in this pilot study: three Neolithic court tombs (Annaghmare, Co. Armagh, Clontygora, Co. Armagh, and Legland, Co. Tyrone), a megalithic circular chamber close to the Ballynahatty timber circle and the Giant's Ring henge monument, Co. Down, and Middle Bronze Age urns from Ballymacaldrack, Co. Antrim (Figure 2).

MAP (A) to be created with geology (not BASr)

Figure 2 – Geological map of Northern Ireland (GSNI; GSI) showing the location of the archaeological sites (A – Annaghmare; BM – Ballymacaldrack; BN – Ballynahatty; C – Clontygora; L – Legland) and the coordinates of the various plant samples

Annaghmare (Co. Armagh)

The Neolithic court tomb of Annaghmare is composed of three chambers, two of which were reportedly undisturbed and contained both unburnt and cremated skeletal material together with pottery and flint. It appears that the tomb was sealed following a period of use for burial (Waterman 1965; Jones 2007). The site is located ca. 7 Km west of the Slieve Gullion/Newry igneous complexes, on a Silurian mudstone formation that remains unchanged in a 5 Km radius around the site (GSNI – Geological Survey of Northern Ireland).

Table 1 – Radiocarbon dates obtained on charcoal (Smith et al. 1970) and an unburnt child mandible (Schulting et al. 2012) from Annaghmare, and for unburnt and calcined human bone from the megalithic circular tomb from Ballynahatty excavated in 1855 (Schulting et al. 2012) (IntCal 09)

Sample	*Lab code*	*^{14}C*	*calBC (95%)*
Annaghmare			
Charcoal	UB-241	4310 ± 70	3317 – 2678
Child mandible	UB-6741	4556 ± 35	3486 – 3104
Ballynahatty			
AX34.2 unburnt human mandible	UB-6723	4165 ± 36	2882 – 2629
A.64 unburnt human maxilla M1	UB-7059	4465 ± 38	3343 – 3020
AX34.6 unburnt human mandible LM2	UB-7194	4587 ± 34	3501 – 3116
AX34.8 cremated human cranium Grp.1	UB-7247a, b	4446 ± 24	3331 – 3013
AX34.10 cremated human cranium Grp.3	UB-7248	4507 ± 36	3355 – 3095
AX34.11 unburnt human mandible RM1	UB-7521	4584 ± 37	3501 – 3106

A radiocarbon date was obtained for this site on charcoal found behind the blocking of the forecourt (UB-241– Smith et al. 1970) with a second determination on a child mandible from chamber 2 (UB-6741) (Table 1). Here, two calcined bone fragments – a long bone from chamber 3 (A1) and a cranial fragment from chamber 4 (A2) – are analysed. The latter has also been radiocarbon dated. There seems to be some confusion over the numbering of the chambers in the surviving documentation as no 'chamber 4' appears in the excavation report; this is being investigated, but at least the samples are clearly labelled as deriving from Annaghmare.

Ballymacaldrack (Co. Antrim)

The townland of Ballymacaldrack is better known for its Neolithic court tomb, Dooey's Cairn, in which cremated human remains were found (Collins 1976). Unfortunately, it was not possible to locate this material. Here, we analyse cremated human remains from Middle Bronze Age urns discovered in a nearby quarry (Tomb & Davies 1938; 1941). The geology around the site is the Lower Basalt Formation with Upper Basalt and some Interbasaltic Formation clay outcrops ca. 9 Km north-east of the site. To the south and west, the Lower Basalt Formation remains unchanged for about 20 Km (GSNI).

Two calcined bone fragments from urns 3, 4 and 5 were selected. As far as can be determined, the urns each contain the remains of a single individual (Tomb & Davies 1938). The urns themselves were discovered close to the basalt bedrock, under about one meter of glacial clay (Tomb & Davies 1941).

Ballynahatty '1855' (Co. Down)

Several Neolithic monuments can be found at Ballynahatty (Co. Down). The best known is the Giant's Ring henge, consisting of a circular rampart (or ring-bank) of about 180 meters of diameter with a megalithic monument in its center (Collins 1957). Aerial photographs revealed a massive timber circle complex in the adjacent field that became the focus of a series of excavations (Hartwell 2002). The sites are on a small plateau of Mid-Upper Ordovician formation, with Tertiary basalt about 5 Km to the north and Silurian sedimentary rocks less than 2 Km to the south (GSNI).

The site of interest for this project is a megalithic circular chamber excavated in 1855, about 300 meters north-west of the Giant's Ring (MacAdam 1855; Hartwell 1991). The circular chamber, separated into six compartments (A to F – Figure 3), was apparently used for different funeral practices: in compartments A and B several urns were found containing calcined human bone; D contained calcined bone on which were resting up to five unburnt skulls; several groups of cremated bone lying on the floor separated by stones were found in chambers E and F suggesting these were from different individuals (MacAdam 1855; Hartwell 1991). The combination of inhumation and cremation suggests a certain number of interments on different occasions during the Neolithic (Hartwell 1991). The Neolithic attribution has been confirmed for both unburnt and calcined bone (Table 1; Schulting et al. 2012).

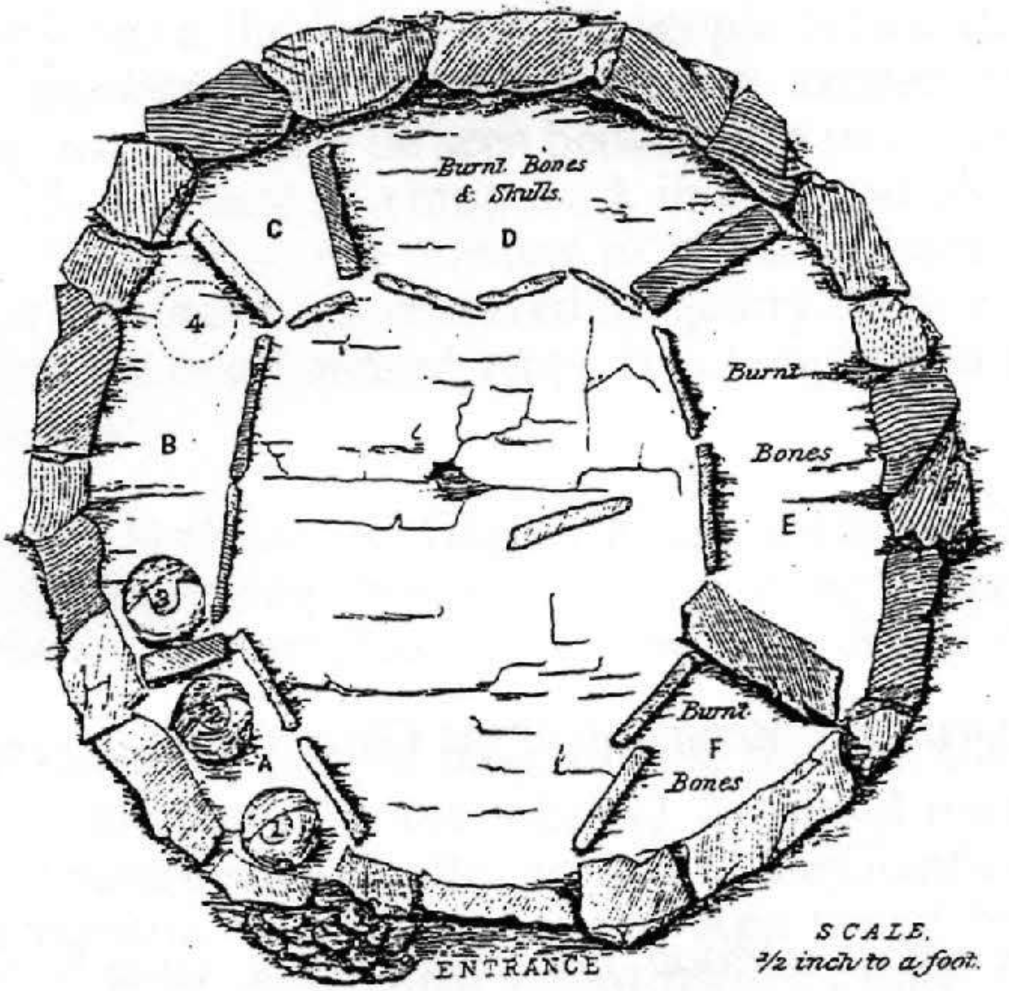


Figure 3 – Plan of the Ballynahatty '1855' megalithic circular chamber (McAdam 1855)

Seven samples were analysed: three unburnt tooth enamel and four calcined bone fragments (two long bone and two cranial). The teeth came from three different mandibles (one of which was radiocarbon dated: AX34.2) and the calcined bone came from four different groups of calcined bone found in compartments E and F, suggesting that seven different individuals are represented.

Clontygora (Co. Armagh)

The large court tomb at Clontygora is situated on the granitic plateau south-east of Newry, about 2.5 Km from Carlingford Lough opening directly onto the Irish Sea. The bedrock is of Tertiary microgranite with Silurian mudstone around it and other granite formations within 20 Km. Small dolerite and gabbro outcrops are also present nearby (GSNI). The tomb, one of the most impressive monuments of this type, is composed of three chambers. Unfortunately, while the first chamber was more or less intact, the other two have almost disappeared. Cremated human bone was recovered along with charcoal from Chambers I and II. While most court tombs were ritually sealed after use, it appears that Clontygora was not (Davies & Paterson 1937). The three calcined long bone fragments analysed here – one of which was also radiocarbon dated (C2) – originate from an undisturbed layer in Chamber 1.

Legland (Co. Tyrone)

The Neolithic court tomb at Legland presents similarities with Clontygora, but it comprises only two chambers and the forecourt seems to have been incorporated into the cairn. Cremated human bone was found in the forecourt and Chamber 1 together with charcoal and fire-reddened earth. Furthermore, some parts of Chamber 1 were blackened as if burnt, perhaps suggesting on-site cremation. This was not the case in Chamber 2 suggesting different uses for the chambers (Davies 1939). The geology around the site is quite varied with a mixture of Neoproterozoic outcrops and Carboniferous sandstones. The site itself is on a Dalradian (Neoproterozoic) formation (GSNI). Radiocarbon dating of two unburnt animal bones yielded very recent dates unrelated to the Neolithic use of the site (AD 1529–1955; Schulting et al. 2012). Here, two calcined bone fragments were analysed, one of which was also radiocarbon dated (L1).

MATERIALS AND METHODS

Archaeological samples

Calcined bone from each site of the above sites was analysed, comprising 17 long bone and cranial fragments (Table 5). For Ballynahatty '1855', three unburnt tooth enamel samples were also analysed, for a combined total of 20 measurements.

Strontium isotopes

Strontium isotope ratios were measured by Multi-Collector Induced-Coupled-Plasma Mass-Spectrometry (MC-ICP-MS) following the procedure detailed in Snoeck et al. (2015). Cremated bone and tooth enamel samples were pretreated with 1M acetic acid (1 mL per 10 mg of sample) for 3 min in an ultrasonic bath, followed by three rinses with milliQ water and 10 min ultrasonication. The enamel samples were ultrasonicated for 30 minutes in acetic acid and then rinsed as above. Plant samples were simply ashed in a muffle furnace at 650ºC. The entire acid digestion process and subsequent Sr purification was achieved under a class 100 laminar flow hood in a class 1000 clean room (Université Libre de Bruxelles, Belgium, hereafter ULB). Fifty mg of sample were digested in subboiled HNO_3 at 120˚C for 24h. The isotope ratios of the purified strontium samples were then measured on a Nu Plasma MC-ICP Mass Spectrometer (Nu015 from Nu Instruments, Wrexham, UK) at ULB. During the course of this study, repeated measurements of the NBS987 standard yielded $^{87}Sr/^{86}Sr$ = 0.710214±40 (2SD for 15 analyses), which is, for our purposes, sufficiently consistent with the mean value of 0.710252±13 obtained by TIMS (Thermal Ionization Mass Spectrometry). All the sample measurements were normalised using a standard bracketing method with the recommended value of $^{87}Sr/^{86}Sr$ = 0.710248 (Weis et al. 2006). For each sample a 2σ error (absolute error value of the individual sample analysis – internal error) was calculated.

Strontium concentration

Small sample fractions (~1 to 3 mg) pre-treated as above were digested in precleaned Teflon beakers (Savillex) using subboiled 7 M HNO_3 at 120˚C for 24h, evaporated to near-dryness and subsequently digested with a drop of concentrated HNO_3. Following dilution with 2% HNO_3, Sr and Ca concentrations (ppm) in the sample digests were determined using a Thermo Scientific Element 2 sector field ICP-mass spectrometer at the Vrije Universiteit Brussel in low (^{86}Sr and ^{88}Sr) and medium (^{43}Ca and ^{44}Ca) resolution using Indium (In) as an internal standard and external calibration versus a calibration curve. Accuracy was evaluated by the simultaneous analysis of limestone reference material NISTSRM8544 (NBS19) and comparison to available published literature data (Crowley 2010; Fernandez et al. 2010). Based on repeated digestion and measurement of this reference material, the analytical precision (1SD) of the procedure outlined above is estimated to be better than 3% relative to standard deviation.

Calculation of the BASr of different catchment areas

A map of the biologically available strontium (BASr) is created for the regions around the archaeological sites using a Geographic Information System (ArcGIS 10.2 coupled with Geostatistical Analyst). It is based on 88 modern plants sampled from 40 locations across the studied region, with a focus on the various geologies represented around each archaeological site (Table 3). A map was then created using areal interpolation (Krivoruchko et al. 2011) based on the geological outcrops of the bedrock geological map (1:500.000 from GIS public data). Only the values obtained for a single geological entity are averaged. In other words, two entities having the same geology but being separated by another formation are considered to be independent regions. The latter map avoids the simplification that the underlying bedrock geology is the only controlling factor of the BASr. Considering each entity individually allows factors such as variable rainfall and superficial geology to be taken into account. When a region was not sampled, it was assigned the value of the closest entity of the same geological formation. The selection of the classes (or ranges) is based on geometric intervals. Here we focus on the catchments around each study site: a more comprehensive map of Ireland using GIS modelling is currently in preparation. The boundaries between areas with different BASr signatures are based on the bedrock geological maps from the Geological Survey of Ireland (GSI) and the Geological Survey of Northern Ireland (GSNI).

The interpretation of strontium isotopes measured on human remains aims at assessing whether or not particular individuals originated from the place where they were buried, or more precisely, whether or not they consumed foods acquired/grown locally. However, the geology of the burial place may be very restricted spatially and assuming that only food from there was consumed is an over-simplification. To circumvent that problem, an average value of the BASr was calculated for different catchment areas around the burial sites (1, 5, 10 and 20 Km radii). In the absence of information linking specific burial sites with living settlements, we assume that the two were in relatively close proximity to one another (Cooney 1983). In the absence of wheeled transport, most farmers will focus most of their efforts on fields within 1 Km of their settlements (Chisholm 1968; Jones et al. 1999). This is particularly important in that the Sr/Ca ratio is approximately five times higher in plants, particularly cereals, than in meat, with milk having an even lower ratio, and so the former will be more strongly represented in human consumer $^{87}Sr/^{86}Sr$ values (Elias 1980; Burton et al. 1999; Bentley et al. 2003).

To calculate the BASr values of the catchment areas, the values of the plants from the geological formations were averaged, weighted by their proportional representation in the catchment. Formations covering less than 2% of the catchment were excluded. It is assumed that plants growing on all the different soil types within a catchment contribute to this average according to their proportional representation. This is clearly an over-simplification, since different soils and food sources (e.g. meat, different parts of plants) will have different strontium concentrations, and more refined ways of calculating expected BASr values relevant to human consumers in the selected catchment radii are currently being developed. Nevertheless, even this preliminary approach allows for a more nuanced consideration of 'local' and 'non-local' individuals, moving beyond a simple dichotomy, taking into account nested spatial scales of expected isotopic variability across the landscape. It would be impossible to take this approach with site-based methods of defining the 'local' catchment, as they rely on the measurement of fauna, usually rodents or pigs, or of human bone/dentine, from the archaeological site itself.

Definition of non-locals

The observation that an individual has a strontium isotope ratio similar to the BASr value of the location where their remains were found does not necessarily mean that they lived there. Rather, he or she could have lived somewhere else but consumed food growing in that area, or lived on the same geological occurrence but not close to the site (e.g. the geology around Ballymacaldrack remains similar for more than 20 Km to the south), or originated from another area with similar geology and BASr values. Furthermore, it is possible that an individual consumed food from two or more different geological occurrences with distinct BASr values that in combination produced a mixed $^{87}Sr/^{86}Sr$ value similar to that of the place where they were buried (Montgomery 2010).

Notwithstanding these caveats, we assume here that most individuals exhibiting strontium isotope ratios compatible with the BASr values of catchment areas up to 5 Km from the site are likely to be 'locals'. Farmers are likely to grow most of their crops and keep their animals within this range most of the time (Chisholm 1968; Jones et al. 1999). Individuals are defined as 'regional' if they exhibit a strontium isotope ratio consistent with the 5–20 Km catchments, and as 'outsiders' if their strontium isotope ratio is outside two standard deviations of the average BASr value of the 20 Km catchment. This approach allows a more meaningful assessment of 'localness', one that highlights different scales of mobility. However, as discussed below, it can be difficult to clearly differentiate local from regional individuals.

Radiocarbon dating

Prior to radiocarbon dating, the calcined bone fragments (A2, C2, L1) were treated with acetic acid (1M) for 24 hours to minimise calcite and adsorbed carbonates (Snoeck et al. 2016). Sample A2 also underwent the former standard method employed at Oxford Radiocarbon Accelerator Unit (ORAU) with sodium chlorite (1.5% at pH3) for 48 hours to remove any remaining organic matter followed by a 24-hour treatment with 1M acetic acid

(Brock et al. 2010). Samples were then reacted with phosphoric acid (85%), and the CO_2 released was distilled cryogenically, collected and converted into graphite before being radiocarbon dated (Lanting et al. 2001; Brock et al. 2010). The dates were obtained by AMS at the Oxford Radiocarbon Accelerator Unit. The IntCal13 calibration curve was applied (Reimer et al. 2013), using OxCal ver. 4.2.4 (Bronk Ramsey 2013).

RESULTS

Radiocarbon dating

The results of the three samples submitted for radiocarbon dating (Table 2) place two in the Middle Neolithic II (A2 and L1) (see Whitehouse et al. (2014) for a discussion of the phases of the Irish Neolithic), while the third (C2) dates to the early part of the Early Bronze Age, about one millennium younger.

Table 2 – Radiocarbon results for archaeological calcined bone samples from Northern Ireland (IntCal 13)

Site	*Lab code*	*Date (uncal BP)*	*cal BC (95%)*
Annaghmare (A2)	OxA-32110	4572 ± 28	3494–3116
	OxA-30188	4532 ± 36	3364–3101
Legland (L1)	OxA-32117	4515 ± 28	3353–3105
Clontygora (C2)	OxA-32118	3706 ± 27	2199–2026

Strontium isotopes of modern plant samples

Because of the wide range of potential contamination sources (e.g. pesticides, aerosols, etc.) it is first necessary to detect outliers in the modern plant sample data (Table 3). For each geological formation, if more than three samples were available any value being three standard deviations or more from the average value (calculated excluding the potential outlier) was considered as an outlier. Following that rationale, 4 of the 88 samples (ca. 5%) were considered as outliers (bold values in Table 3). The values of the modern plant samples show, a wide range of values (0.7065–0.7195) similar to the range observed for the UK (0.7070–0.7222; Evans et al. 2010) except for one samples from the site I93 with a value of 0.7663 that has also been considered as an outlier and excluded from this study. Once the outliers were excluded, a BASr map was created using ArcGIS following the protocol described above (Figure 4).

Table 3 – GPS locations and strontium isotope measurements of modern plant samples (values in brackets represent outliers – see text)

Site	**GPS-location**		**Values (± 2σ)**		
	North	**West**	**Grasses**	**Shrubs**	**Trees**
Formation 0 – Coastal Zone					
I17	53-58-788	006-11-439	/	0.709449 ± 13	0.709373 ± 6

I20	53-46-110	006-14-657	0.709397 ± 7 0.709177 ± 10 0.709179 ± 9	/	/
Formation 5 – Lower Palaeozoic gabbro, dolerite and diorite (416–542 Ma)					
A03(1)	54-37-159	007-00-040	0.709500 ± 10 (0.712242 ± 10)	0.709789 ± 9	/
A03(2-bog)	54-37-055	006-59-735	0.709752 ± 10	/	/
Formation 8 – Caledonian (Silurian - Devonian) granite and granodiorite (359–444 Ma)					
I93	54-19-382	006-01-209	(0.766315 ± 95)	0.711756 ± 9	/
Formation 9 –Tertiary (Palaeogene) granite, felsite and granophyre (23–65 Ma)					
A18 – C	54-06-737	006-19-257	/	0.713011 ± 9	0.710335 ± 9
I94	54-11-394	006-04-566	0.713979 ± 8	0.716419 ± 41	0.712585 ± 11
I95	54-02-995	006-16-226	0.711108 ± 8	0.719498 ± 25	/
Formation 10 – Tertiary (Palaeogene) rhyolite (23–65 Ma)					
I06	54-46-718	006-09-100	/	0.707862 ± 7	0.708582 ± 7
Formation 11 – Tertiary (Palaeogene) basic intrusion, dolerite and gabbro (23–65 Ma)					
I15	54-03-435	006-16-174	/	0.708154 ± 12	0.708157 ± 6
Formation 19 – Slishwood Division (Neoproterozoic); Quartzo-feldspathic paragneiss (>542 Ma)					
A10	54-31-094	007-56-861	/	0.710009 ± 9	0.709352 ± 14
Formation 27 – Dalradian Argyll group; Psammitic and pelitic schist, marble, amphibolite, diamictite (>542 Ma)					
A08 – L	54-40-234	007-25-063	/	0.714330 ± 12	0.712345 ± 9
A09	54-40-844	007-27-526	/	0.711579 ± 12	0.709974 ± 7
Formation 29 – Sperrins Dalradian Southern Highland Group; Pelitic & psammitic schist, phyllite & marble (>542 Ma)					
I88	55-07-211	006-06-594	0.712568 ± 10	0.714015 ± 12	0.712568 ± 10
I89	55-01-443	006-56-216	/	0.708649 ± 10	0.708385 ±10
Formation 33 – Lower-Mid Ordovician basic volcanic basalt (444–488 Ma)					
A04	54-36-956	007-04-698	0.709147 ± 11	0.708897 ± 12	0.711065 ± 11
A05	54-36-831	007-08-523	0.710569 ± 9	0.712146 ± 9	/
Formation 40 –Mid-Upper Ordovician Derryveeny formation; Marine to fluvial; Greywacke, shale, sandstone & conglomerate (444–488 Ma)					
A01 – BN	54-32-428	005-57-107	/	0.708457 ± 6	0.708310 ± 9
A16	54-13-862	006-52-225	/	0.712152 ± 11	0.712751 ± 7
Formation 49 – Silurian deep marine turbidite sequence; mudstone, sandstone, greywacke, shale and conglomerate (416–444 Ma)					
A02	54-31-183	005-57-646	/	0.710811 ± 8	0.710373 ± 8
A17 – A	54-05-391	006-36-648	/	0.711202 ± 6	0.710512 ± 7
I19	53-48-127	006-22-125	0.711762 ± 7 0.710486 ± 8	/	/
I27	53-47-678	007-02-930	0.710315 ± 7 (0.708119 ± 8)	(0.708328 ± 12)	/
I91	53-47-584	006-17-304	0.711300 ± 9 0.711027 ± 8	0.711445 ± 11	/
I92	53-47-291	006-18-867	(0.714687 ± 11) 0.710293 ± 9	/	/
Formation 52 – Upper Silurian – lower Devonian continental redbed facies; Sandstone, siltstone & mudstone (359–444 Ma)					
A13	54-28-704	007-44-037	0.708946 ± 8	0.710409 ± 8	/
Formation 59 – Carboniferous shallow marine & coastal plain (basal clastics); Sandstone, mudstone and conglomerate (299–359 Ma)					
A06	54-38-672	007-19-694	/	0.709748 ± 11	0.710950 ± 7
Formation 63 – Carboniferous shallow marine & coastal plain (basal clastics); Sandstone, mudstone & conglomerate (299–359 Ma)					
A07	54-38-504	007-23-282	0.709613 ± 8	0.712556 ± 11	/
Formation 64 – Carboniferous marine shelf facies; Limestone & calcareous shale (299–359 Ma)					
A12	54-30-613	007-40-158	/	0.708305 ± 7	0.708167 ± 8
Formation 65 – Carboniferous Visean basinal limestone; Marine basinal facies (Tobercolleen and Lucan Formations); Dark-grey argillaceous and cherty limestone & shale (299–359 Ma)					
I26	53-50-313	006-40-346	/	0.709575 ± 9	0.709248 ± 6
I28	53-46-909	007-19-785	0.708228 ± 7	0.708305 ± 13	/
Formation 66 – Carboniferous Tyrone GP; Visean mudstone, sandstone and evaporite; Marginal marine (Mullaghmore, Downpatrick & Clogher Valley Formations) (299–359 Ma)					
A11	54-30-842	007-49-981	/	0.710056 ± 10	0.708650 ± 9
Formation 68 – Carboniferous Leitrim GP; Visean mudstone, sandstone and evaporite; Marginal marine (Meenymore Formation) (299–359 Ma)					
A15	54-15-992	007-23-407	/	0.708212 ± 9	0.708897 ± 9

Formation 70 – Carboniferous (Late Visean-Westphalian) continental redbed; Sandstone, conglomerate & mudstone (299–359 Ma)					
A14	54-24-437	007-35-923	/	0.709173 ± 12	0.712266 ± 9
Formation 75 – Triassic sandstone and mudstone with evaporite; Continental redbed facies, lagoonal & shallow marine (200–251 Ma)					
I31	53-54-574	006-47-298	0.710008 ± 8	0.708955 ± 8	/
Formation 79 – Palaeocene Lower Basalt Formation; Olivine basalt lava (56–65 Ma)					
I01 – BM	55-00-106	006-24-266	0.706915 ± 8	0.707287 ± 12	0.706485 ± 13
Formation 82 – Palaeocene Upper Basalt Formation; Olivine basalt lava (56–65 Ma)					
I03	55-06-749	006-40-060	0.710448 ± 9	0.709116 ± 14	0.709987 ± 12
I05	54-43-869	006-12-243	/	0.706724 ± 12	0.707360 ± 8
Formation 83 – Oligocene Lacustrine; Clay, sand & lignite (23–34 Ma)					
I02	55-06-617	006-26-261	/	0.707089 ± 12	0.707743 ± 7
I04	54-33-359	006-17-596	/	0.708187 ± 13	0.708123 ± 7

MAP (B) to be created with the data of the above table following the protocol described above

Figure 4 – Map of the biologically available strontium isotope ratios for the study area based on modern plant samples (filled black circles represent modern plant sample locations)

Strontium concentration of calcined bone

The strontium concentrations of 6 selected samples (Table 4; Figure 5) are between 62 and 121 ppm. Calcium concentrations are around 40% (wt.) in all samples, higher than the 20–30% concentration observed in unburned archaeological human bone (Grupe 1988; Mahanti & Burnes 1983) but this is to be expected since no organic matter remains after calcination and large amounts of carbonates and water have been lost in calcined bone. The highest concentration is recorded in samples BM1b found in a basalt formation which follows the fact that in the studied regions, basalts are amongst the geologies with the highest strontium concentrations compared to granites and other geologies (Meighan et al. 1984; 1988; O'Connor 1988; Wallace et al. 1994).

Table 4 – Strontium and calcium concentration of 6 selected cremated bone fragments

	A1	A2	BM1b	C1	C2	C3
Sr (ppm)	62.3	79.9	121.2	74.5	77.3	78.8
Ca (wt%)	38.9	44.4	43.9	40.0	40.7	42.4
Sr/Ca (mmol/mol)	0.07	0.08	0.13	0.09	0.09	0.08

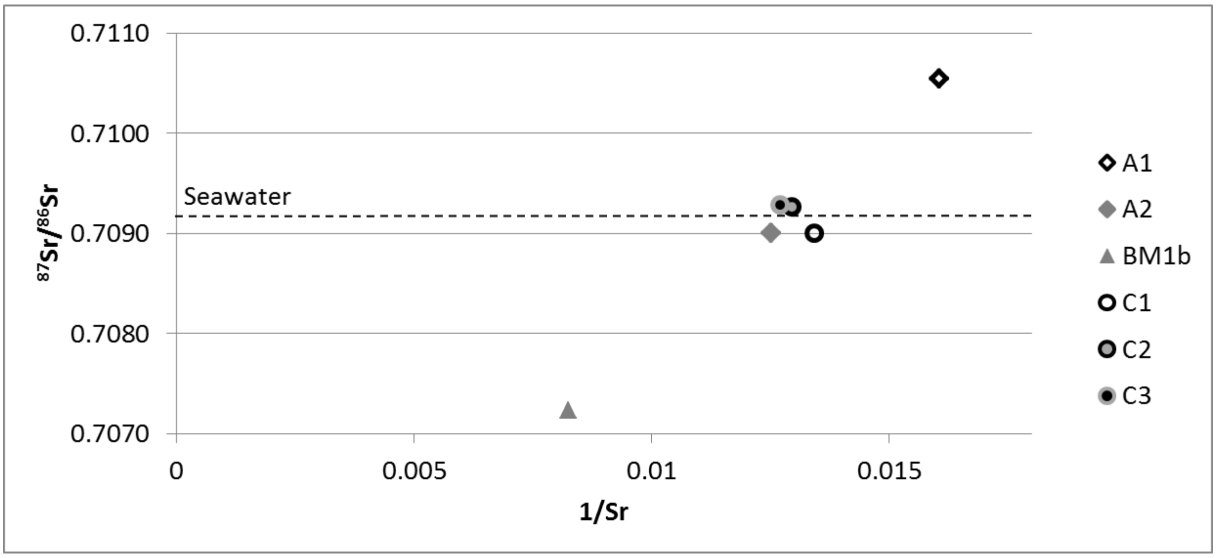


Figure 5 – Strontium isotope ratio ($^{87}Sr/^{86}Sr$) and concentration (1/Sr) of 6 cremated bone samples

Strontium isotopes of unburned teeth and calcined bone

The $^{87}Sr/^{86}Sr$ results range from 0.7066 to 0.7136 (Table 5; Figure 6), falling within the range seen in modern plants sampled of the studied region (0.7065 to 0.7195). The BASr value of the immediate site is calculated as well as the averages for 1, 5, 10 and 20 Km catchments (Table 6). When compared to these values, individuals can be characterised as being most consistent with local, regional, or distant catchments, with only the latter being designated outsiders (Table 7).

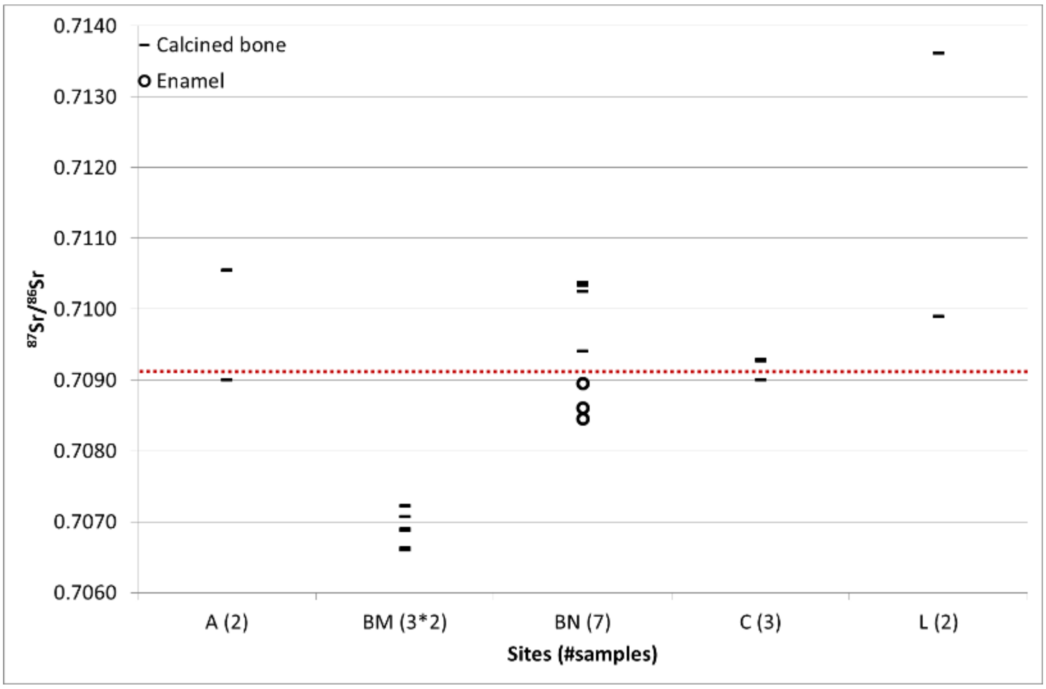


Figure 6 – Strontium isotope ratios ($^{87}Sr/^{86}Sr$) for each site; the dotted red line represents the modern seawater value of 0.7092 (Hess et al. 1986). For BM, each of the three individuals represented were measured twice.

Table 5 – Archaeological sites with unburnt tooth enamel and cremated bone samples together with strontium isotope results

	Samples	*Element*	*Context*	^{87}Sr/^{86}Sr (± 2σ**)
Annaghmare, Co. Armagh				
A1	Calcined bone	Long bone	Chamber 3	0.710551 ± 09
A2		Cranial bone	Chamber 4	0.709003 ± 06
Ballymacaldrack, Co. Antrim				
BM1a	Calcined bone	Cranial bone	Urn 3	0.707072 ± 08
BM1b		Long bone		0.707232 ± 08
BM2a		Long bone	Urn 4	0.706603 ± 09
BM2b		Long bone		0.706628 ± 10
BM3a		Long bone	Urn 5	0.706899 ± 07
BM3b		Long bone		0.706883 ± 08
Ballynahatty '1855', Co. Down				
BN1	Calcined bone	Cranial bone	E/F - Group 1	0.710377 ± 09
BN2		Long bone	E/F - Group 2	0.709410 ± 07
BN3		Cranial bone	E/F - Group 3	0.710258 ± 08
BN4		Long bone	E/F - Group 4	0.710338 ± 08
BNT1	Unburnt tooth enamel*	Right pre-molar 3 (PM3)	D - AX34.1	0.708455 ± 29
BNT2		Left molar 1 (M1)	D - AX34.2	0.708610 ± 08
BNT3		Right molar 3 (M3)	D - AX34.3	0.708962 ± 08
Clontygora, Co. Armagh				
C1	Calcined bone	Long bone	Chamber 1 - 76 / 120.1938	0.709006 ± 09
C2		Long bone	Chamber 1 - 175 / 120.1938	0.709271 ± 08
C3		Long bone	Chamber 1 - 175.2 / 120.1938	0.709291 ± 09
Legland, Co. Tyrone				
L1	Calcined bone	Cranial bone	Chamber 1 - 47	0.709896 ± 12
L2		Long bone	Chamber 1 - 139	0.713614 ± 08

*crown formation ages for M1 are ca. 1-3 years, PM3 ca. 3-6 years; and for M3 ca. 10-15 years; **2σ has been calculated following the equation: 2 x mean of the 60 ratio measurements x standard error (Snoeck et al. 2015)

Table 6 – BASr (± 1SD) for the local area ('local BASr') and the average BASr values calculated for 1, 5, 10 and 20 Km catchments (whole area); the values between brackets represent the number of different geological formations included in the calculation of the average BASr

	Local BASr	*1km BASr*	*5km BASr*	*10km BASr*	*20km BASr*
Annaghmare	0.7109 ± 0.0005	0.7109 ± 0.0005 (1)	0.7109 ± 0.0005 (2)	0.7109 ± 0.0004 (5)	0.7108 ± 0.0005 (6)
Ballymacaldrack	0.7069 ± 0.0004	0.7069 ± 0.0004 (1)	0.7069 ± 0.0004 (1)	0.7069 ± 0.0003 (2)	0.7078 ± 0.0003 (4)
Ballynahatty	0.7084 ± 0.0001	0.7088 ± 0.0002 (2)	0.7098 ± 0.0003 (3)	0.7098 ± 0.0003 (5)	0.7094 ± 0.0003 (5)
Clontygora	0.7117 ± 0.0019	0.7117 ± 0.0011 (2)	0.7113 ± 0.0005 (5)	0.7116 ± 0.0007 (6)	0.7113 ± 0.0005 (6)
Legland	0.7133 ± 0.0014	0.7117 ± 0.0013 (3)	0.7116 ± 0.0011 (3)	0.7106 ± 0.0006 (6)	0.7099 ± 0.0004 (9)

Table 7 – Number of individuals from the immediate site, 1, 5, 10 and 20 Km catchments

	Local (0–5 Km)	*Regional (5–20 Km)*	*Outsider (> 20 Km)*
Annaghmare	A1		A2
Ballymacaldrack	BM1, BM2, BM3	/	/
Ballynahatty	BNT1, BNT2, BNT3	BN1, BN2, BN3, BN4	/
Clontygora	/	/	C1, C2, C3
Legland	L2	L1	/

Annaghmare (Co. Armagh)

Only two samples were analysed from Annaghmare, as only a few small calcined bone fragments were available from the site. The difference in ^{87}Sr/^{86}Sr value of c. 0.0016 between the two (A1: 0.7106; A2: 0.7090) is much greater than that observed for duplicate samples for the same individuals from Ballymacaldrack (0.0002 – see below) and thus can be taken to represent two distinct individuals (alternatively, it is possible that different elements of the same individual might return different values because of varying turnover rates; this seems unlikely in this case since both samples were thick cortical bone subject to similar turnover). The radiocarbon date obtained for Annaghmare (A2: 3494–3116 cal. BC) falls within the range of previous radiocarbon dates obtained for the site (Schulting et al. 2012). The average BASr values calculated for the different catchment areas are similar to the $^{87}Sr/^{86}Sr$ value of A1 (Figure 8). BASr values similar to the $^{87}Sr/^{86}Sr$ value of A2 (0.7090) can only be found in coastal regions located about 20 Km from the site, or on the Carboniferous limestone outcrops 50 Km or more to the south. A2 is clearly an outsider but since the BASr values measured for the different catchment areas remain the same, A1 could be either local or from the region as defined here.

Ballymacaldrack (Co. Antrim)

The strontium isotope results from Ballymacaldrack show limited variation (max. 0.0008). For each pair of samples, the variation is even lower (max. 0.0002), consistent with the osteological report indicating that the remains in each urn represent a single individual (Tomb and Davies 1938; 1941). This variation may relate partly to different turnover rates for different parts of the skeleton. The results are also consistent with the immediate BASr value as well as those calculated for 1, 5, 10 Km catchments (all three individuals are hence designated as locals), which unsurprisingly are similar, as the geology does not change for some distance around the site, but not with the 20 Km catchment, which includes a small area of much older stone, the $^{87}Sr/^{86}Sr$ values of which are sufficiently high to raise that catchment's value significantly (Figure 9).

Ballynahatty (Co. Down)

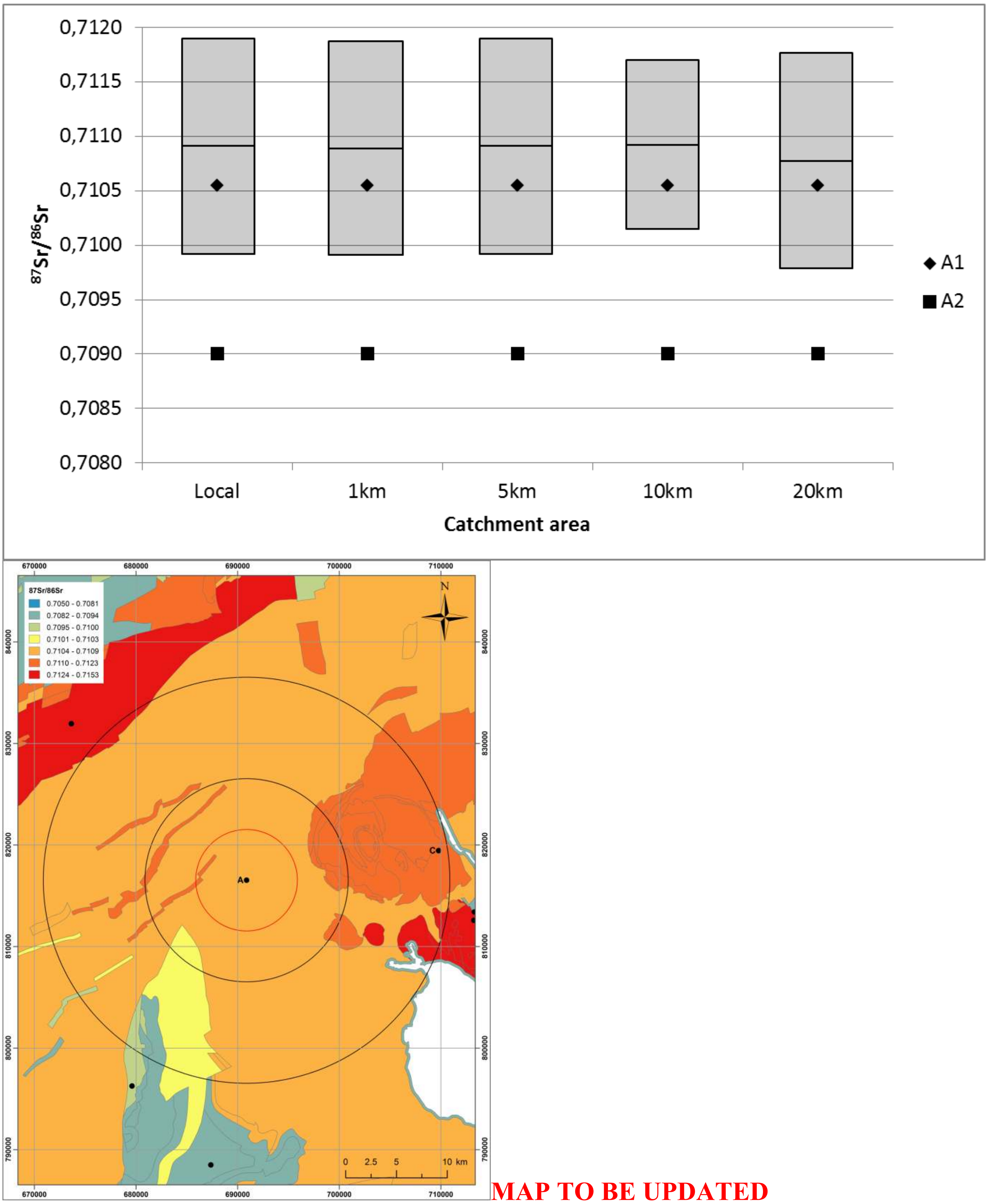
Since both unburnt tooth enamel and cremated bone were available, it was possible to compare strontium isotope ratios at Ballynahatty. Despite the small number of samples analysed, there is a convincing difference between the $^{87}Sr/^{86}Sr$ values of tooth enamel (0.7087 ± 0.0003) and calcined bone (0.7101 ± 0.0005) (heteroscedastic Student's *t*-test, t = 5.0, df = 5, p = 0.004); in fact, the ranges are entirely non-overlapping (Table 5). The lower enamel values are consistent with both the immediate site and 1 Km catchment BASr values, but not with the 5, 10 and 20 Km catchments (Figure 10). The cremated bone has values approaching those of the Silurian sandstone outcrop 2 Km south of the site (0.7109 ± 0.0005). Three of the four cremated samples are very similar at 0.7103–0.7104 (BN1, BN3 and BN4), while the fourth (BN2), has a slightly lower value of 0.7094, approaching the local range. All three unburnt individuals can be classified as locals, while those that were cremated have values similar to the BASr values of the 5 and 10 Km catchment areas and are therefore defined as regional individuals.

Clontygora (Co. Armagh)

The three calcined bone samples from Clontygora have indistinguishable $^{87}Sr/^{86}Sr$ values (0.7091–0.7093), consistent with the BASr value of the granite outcrop on which the site lies (though being based on only two plant values, variation in the outcrop itself is very large) but these are slightly lower than the BASr averages calculated for 1 Km and completely different to those for 5, 10 and 20 Km catchments. They have, however, values very similar to seawater at 0.7092 (Hess et al. 1986) (Figure 11). The single ^{14}C date for Clontygora (C2: 2199–2026 cal BC) lies at the beginning of the Early Bronze Age, indicating re-use of the monument, a relatively common phenomenon found across Ireland (Bayliss and O'Sullivan 2013; Schulting 2014; Schulting et al. 2012). It is not known whether all the cremated remains from the site represent EBA re-use, or whether some remains do date to the earlier Neolithic as would be expected for court tombs (Schulting et al. 2012). If so, it is interesting that all three samples show the same strontium results.

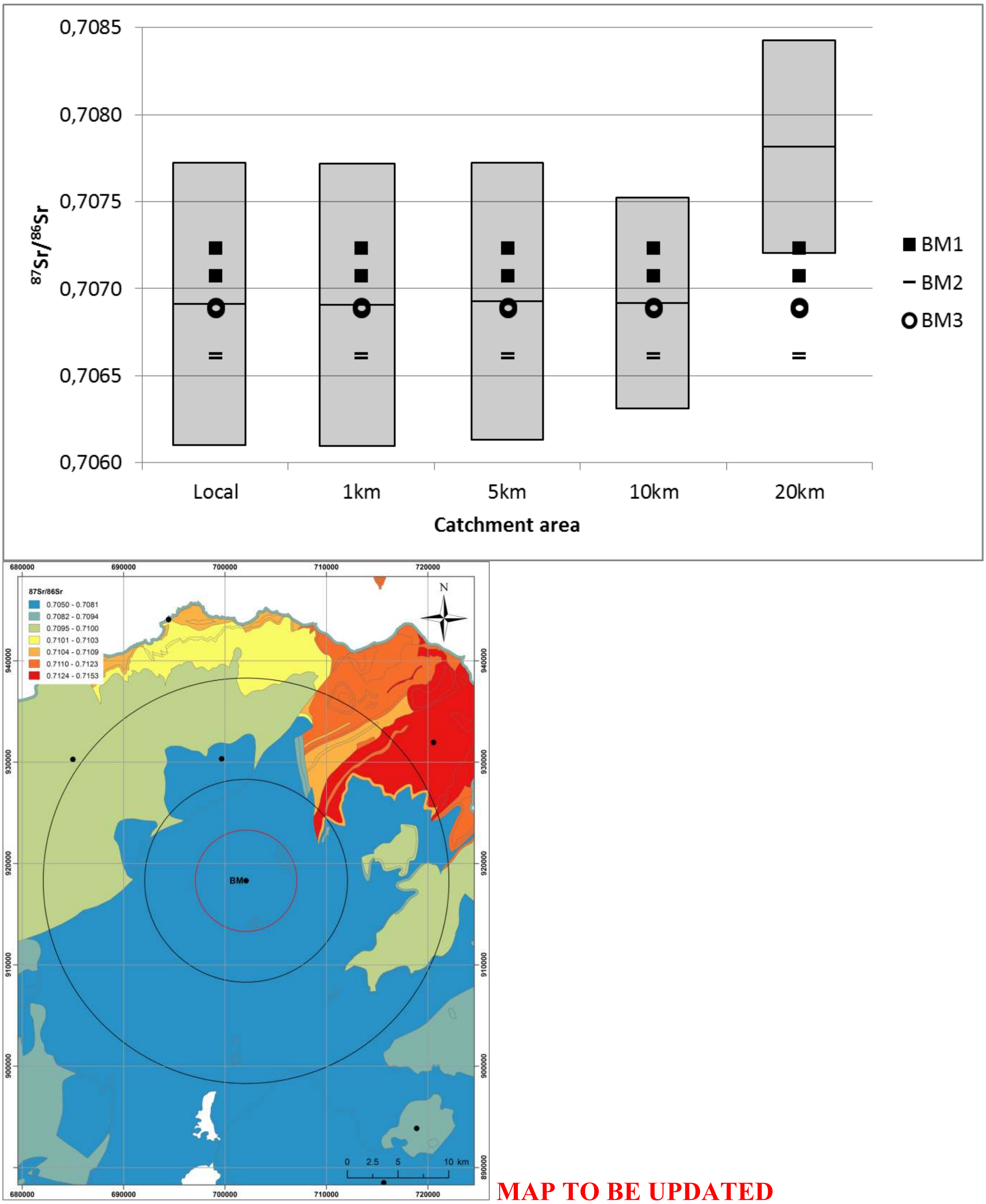
Legland (Co. Tyrone)

The two samples from Legland have distinct $^{87}Sr/^{86}Sr$ values (0.7136 and 0.7099). The first corresponds to the BASr value of the immediate vicinity (0.7133 ± 0.0014), while the second matches the average BASr calculated for the regional 10 and 20 Km catchments. Due to the large variability in geological formations around the site, both samples have values consistent with the BASr values calculated for the 1 and 5 Km catchments (Figure 12). The date of 3353–3105 cal BC for Legland L1 falls within the Middle Neolithic II period (Whitehouse et al. 2014).



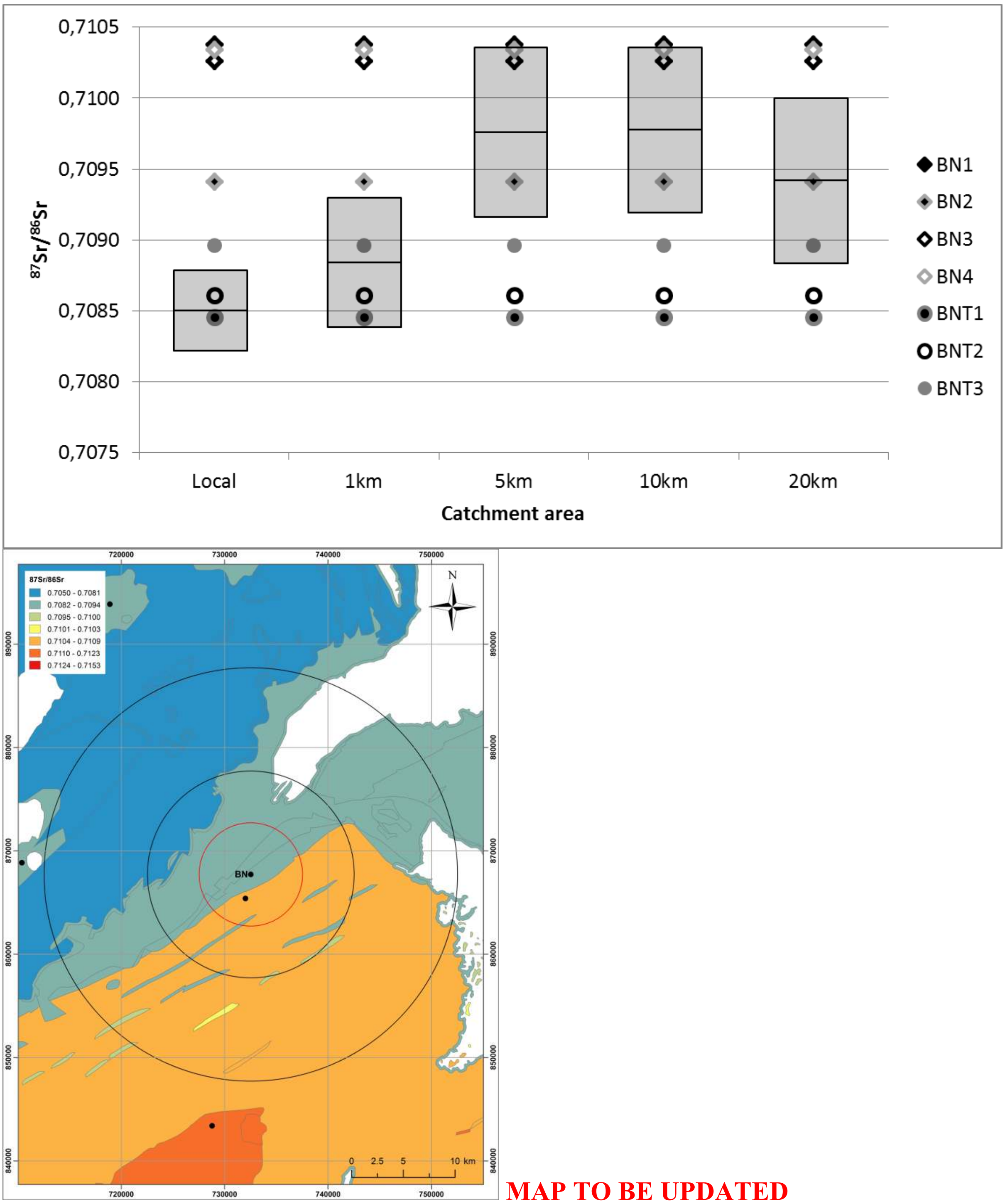
MAP TO BE UPDATED

Figure 8 – (a) Strontium isotope ratios; the grey shaded areas represent the average BASr values (± 2SD) for the immediate site, 1, 5, 10 and 20 Km catchments; (b) 5, 10 and 20 Km catchments around Annaghmare



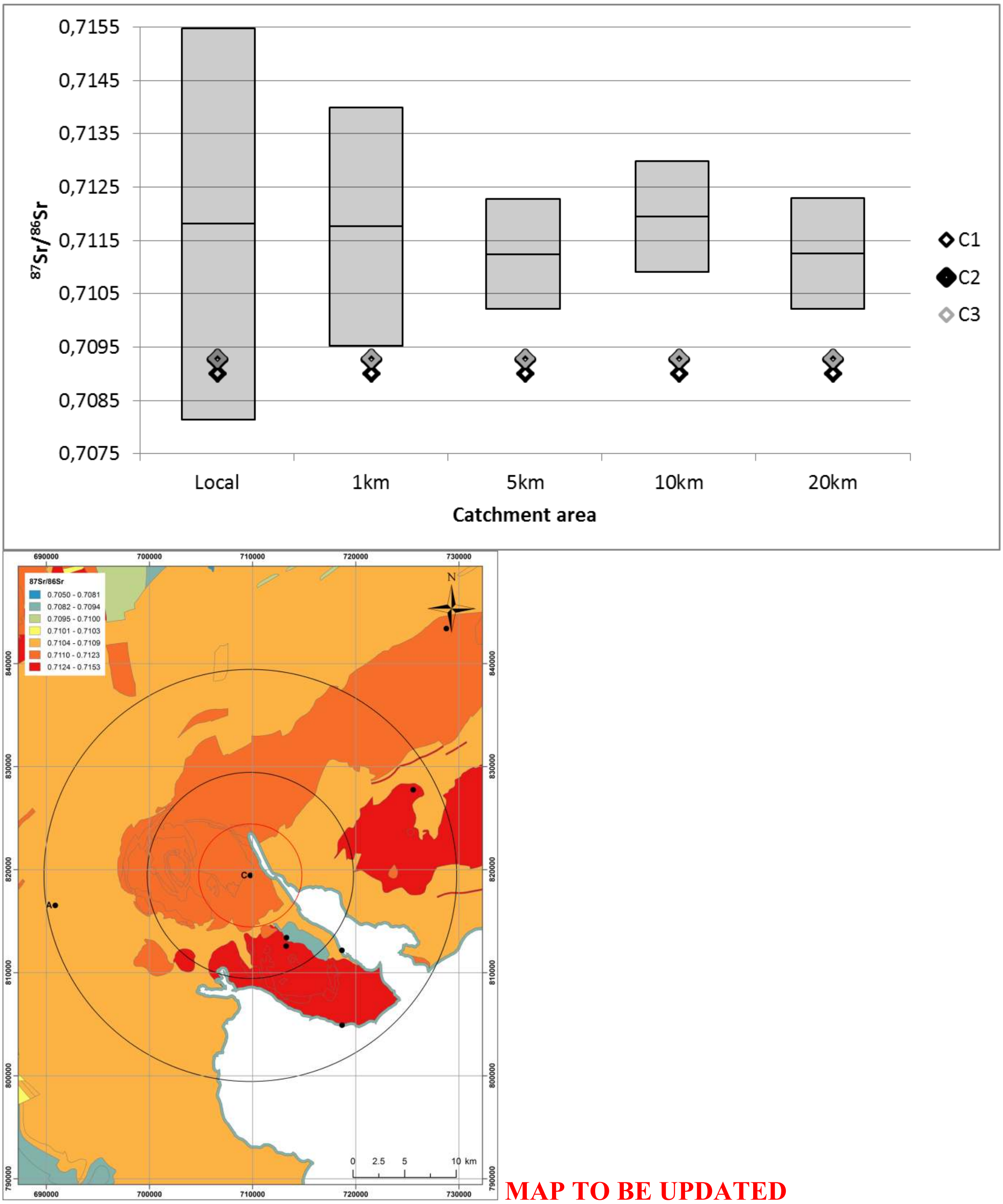
MAP TO BE UPDATED

Figure 9 – (a) Strontium isotope ratios; the grey shaded areas represent the average BASr values (± 2SD) for the immediate site, 1, 5, 10 and 20 Km catchments; (b) 5, 10 and 20 Km catchments around Ballymacaldrack



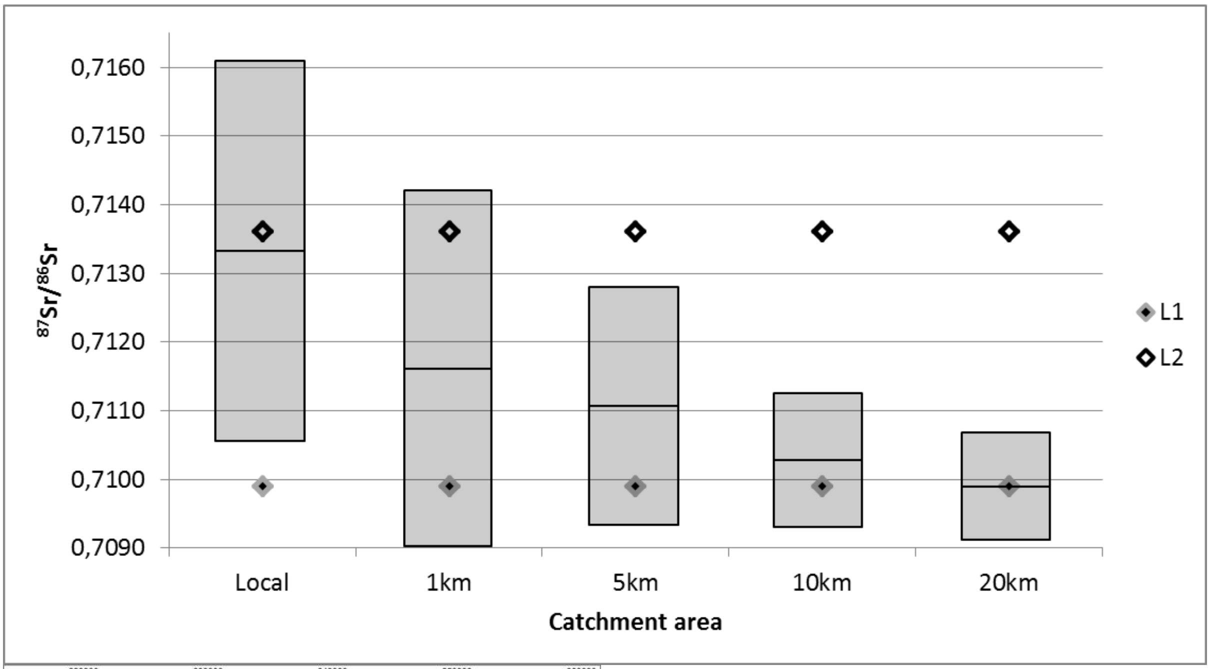
MAP TO BE UPDATED

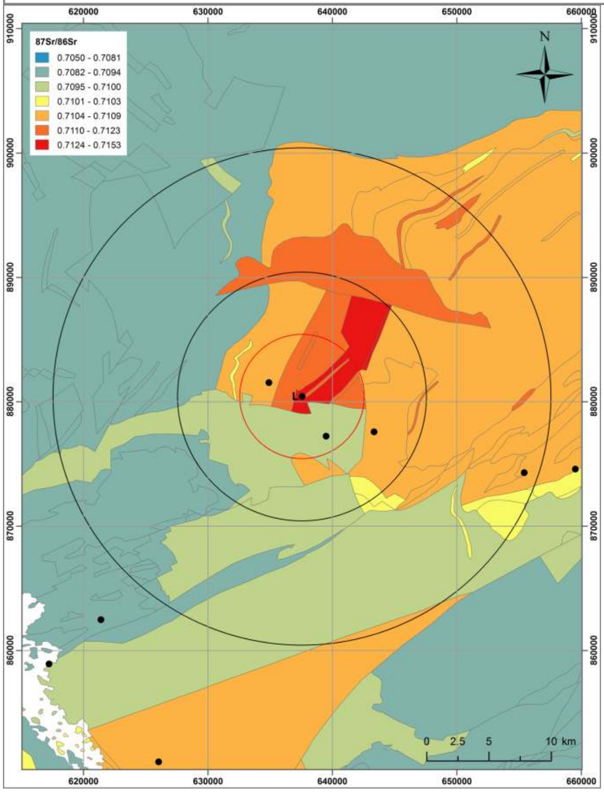
Figure 10 – (a) Strontium isotope ratios; the grey shaded areas represent the average BASr values (± 2SD) for the immediate site, 1, 5, 10 and 20 Km catchments; (b) 5, 10 and 20 Km catchments around Ballynahatty



MAP TO BE UPDATED

Figure 11 – (a) Strontium isotope ratios; the grey shaded areas represent the average BASr values (± 2SD) for the immediate site, 1, 5, 10 and 20 Km catchments; (b) 5, 10 and 20 Km catchments around Clontygora





MAP TO BE UPDATED

Figure 12 – (a) Strontium isotope ratios; the grey shaded areas represent the average BASr values (± 2SD) for the immediate site, 1, 5, 10 and 20 Km catchments; (b) 5, 10 and 20 Km catchments around Legland

DISCUSSION

Local, regional and outsider individuals

Following the rationale described in Materials and Methods, it is possible to identify local, regional and outsider individuals (Table 7). The number of outsiders at each site is extremely variable, ranging from 100% (Clontygora) to 0% (Ballymacaldrack). This method is one possible way to define locals, but each site should still be considered individually. In the case of Clontygora, for example, the three samples may only appear to be ‘locals’ because of the very high variability of the $^{87}Sr/^{86}Sr$ values measured in plant samples for the local area reflecting the high variability of the granite itself (Meighan 1988). However, it is unlikely that plants growing on Tertiary granitic formations will have values as low as 0.7093. Indeed, the plants from the granitic outcrop all gave ratios above 0.7100 suggesting that the three individuals from Clontygora are actually non-locals, which is consistent with the BASr average ratios calculated for the 5, 10 and 20 Km catchments.

Mobility

The number of samples for each site in this study is limited (between two and seven) making it difficult to evaluate the mobility of individuals within Neolithic and Bronze Age communities. Nevertheless, this pilot study highlight differences between the sites. The Neolithic court tombs of Annaghmare and Clontygora, only 20 Km apart, are on geological formations with high strontium isotope ratios and local BASr values above 0.7105. Yet, only one sample from Annaghmare has a $^{87}Sr/^{86}Sr$ value consistent with the immediate site. All others (one from Annaghmare and three from Clontygora) have values between 0.7090 and 0.7093, bracketing the seawater value of 0.7092. Yet the use of marine foods has been shown to be minimal during the Irish and British Neolithic (Richards et al. 2003; Schulting et al. 2012; forthcoming; Schulting 2013; Ditchfield 2014) and the sea spray effect is limited to coastal regions (Snoeck 2014). These individuals may have consumed food from the dolerite/gabbro formation close to Clontygora but this is rather restricted and so unlikely to have made a major contribution, suggesting that these four individuals likely spent the last decade or so of their lives some distance away. This may include, for instance, the region ca. 50 Km to the south/south-west where limestone is the main geology, or the basalt formations of Co. Antrim more than 50 Km to the north. However, the basalt formations still exhibit lower values than the human remains. The measurement of strontium concentrations of those samples having strontium isotope values close to seawater (A2, C1 and C2) show that intake of marine resources in the form of algae or salt (Montgomery et al. 2007; Montgomery 2010) – the latter potentially important for both taste and food preservation, but concerning which we have no information for the British or Irish Neolithic – is unlikely. The strontium concentration in these samples is low (Figure 5) and these individuals are unlikely to have consumed large amounts of marine algae and salt in the last decade of their life (Montgomery 2010).

While the two previous sites clearly showed the presence of outsiders, none were found at Ballymacaldrack, where the $^{87}Sr/^{86}Sr$ values on calcined bone are entirely consistent with the site's BASr value. The strontium concentration of BM1b further highlight the use of resources from the basalt region, although the geology remains the same for about 10 Km to the north and more than 20 Km to the south. In this case, any individual consuming food from these areas will appear to be local but could equally be from the wider region. In the absence of other information, it is reasonable to provisionally conclude that they are local. This can be revisited as more data accumulate on individual mobility in the Bronze Age in general.

The situation at Ballynahatty and Legland is more complex. Both sites lie on small geological formations with significant variation in the surrounding area (Figures 10 & 12). At Legland, one of the individuals has a $^{87}Sr/^{86}Sr$ ratio consistent with the 'local' BASr but this area is very small and it is unlikely that anyone would have consumed foods only from that particular location for over a decade. The isotope ratio is inconsistent with the values calculated for all 10–20 Km catchments. It is, however, consistent with the geological formations northeast of the site included within the 1 Km catchment, suggesting that this individual may have originated from – or consumed food growing – there. The second individual from Legland exhibits an isotope ratio inconsistent with the site's immediate BASr values but consistent with the 1–20 Km catchments. Even though it is not possible to completely exclude other possibilities, the most plausible explanation is that both individuals at Legland are local/regional individuals but consumed foods from different parts of the landscape.

At Ballynahatty, enamel and calcined bone exhibit distinct values. The enamel values are consistent with the immediate BASr and those of the geological formation to the north, while the cremated bone is more consistent with the BASr values of the geology commencing 2 Km south of the site, and extending for about 70 Km to the south/southwest. Different funerary rites – secondary inhumation and cremation – are represented in the circular chamber and it appears that this may relate to individuals with different life histories, with those consuming food grown at or to the north of the site represented by unburnt remains, and those consuming food grown south of the site represented by cremated remains. This observation is reinforced by the values calculated for the different catchment areas falling between the two groups.

One cremated individual (BN2), however, could have consumed food growing both north and south of the site. These results, incidentally, provide further support for the reliability of strontium isotope measurements on calcined bone, since had they equilibrated with the burial environment they would have been indistinguishable from the values for of immediate outcrop. The same applies to a number of samples from the other sites considered here.

An additional observation can be made for the three sites located within 50 Km of the Mourne Mountains (Annaghmare, Ballynahatty, and Clontygora). The cremated individuals from Ballynahatty seem to have consumed food originating from the Silurian mudstone formation (on which Annaghmare lies – Figure 4) while one of the two individuals from Annaghmare and all those from Clontygora that are actually on the Silurian mudstone formation, or very close to it, have ^{87}Sr/^{86}Sr values completely inconsistent with its BASr. Instead, these have values more consistent with the limestone formation to the southwest or the basalt formations to the north (though the latter's BASr values are probably too low). This observation poses the question for future research of why those not buried directly on the Silurian mudstone outcrop consumed food from that outcrop while those buried on the outcrop apparently did not use the available local resources to any extent.

CONCLUSION

The recently demonstrated ability to obtain *in vivo* strontium isotope signals from calcined bone opens up many new possibilities for the analysis of human and animal mobility in archaeological contexts. This is particularly important in situations where, as in Neolithic and Bronze Age Ireland, cremation featured as a funerary rite. The analysis of cremated human remains from five sites in Northern Ireland presented here highlights the potential of this approach, used in conjunction with targeted sampling of modern plant remains to characterise the biologically available strontium isotope values for a series of nested catchments. Most previous strontium isotope studies have used unburnt tooth enamel comparing their childhood origins to their burial place. A comparison of childhood and adult diet is also possible with cremated remains, wherever single individuals are represented and tooth roots are present alongside bone. Unfortunately, such an approach has not been possible in the mainly commingled remains represented here (Ballymacaldrack presents possibilities in this regard that are currently being explored). What the analysis of calcined bone provides is a view of the last decade or so of an individual's life, and as such offers a different, but complementary, approach to that obtained through dental enamel.

In Ireland, many Neolithic monuments contain a combination of unburnt and cremated bone and the reasons for this dual burial practice are unclear. The Ballynahatty results provide an intriguing hint that the two burial rites may reflect individuals with access to different parts of the wider landscape, yet brought together for burial in a single monument. Such a view has resonance with the interpretation of passage tombs as providing an integrative function in late Middle Neolithic society, compared to the more local orientation of Early Neolithic court and portal tombs (Cooney 2000). Further work is underway on a wider sample of calcined bone and unburnt enamel from a range of Irish Neolithic tomb types, and will no doubt provide new insights into individual mobility at this time, as well as the choice of funerary rite.

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