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Finding Vikings with Isotope Analysis: The View from Wet and Windy Islands

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Abstract - Identifying people of exotic origins with isotopes depends upon finding isotopic attributes that are inconsistent with the indigenous population. This task is seldom straightforward and may vary with physical geography, through time, and with cultural practices. Isotopes and trace elements were measured in four Viking Age (8th to 10th centuries A.D.) skeletons from Dublin, Ireland, and three from Westness, Orkney. These were compared with other data from these locations and contemporaneous skeletons from Britain. We conclude that the male skeletons from Dublin have disparate origins, two originating beyond the shores of Ireland, and that the female and two male skeletons from Westness are not indigenous to Orkney. However, the homeland of the female, in contrast to the males, is unlikely to be in Scandinavia.

Introduction

> "Time was when we knew where our Vikings came from, and why and when they came" (Ó Corráin 1998:432).

The first violent "Viking" confrontation on British soil is probably that at Portland in Dorset between A.D. 786 and 802 based on a cautious reading of late 9th-century sources (Keynes 1997:50). Three ships of "Northmen" (there is contradictory evidence regarding whether they were from Norway or Denmark) killed an unsuspecting royal representative. Starting in A.D. 794, the Irish Annals report that there were also frequent Scandinavian raids in the Irish Sea region, including (from A.D. 795) western Scottish targets such as Iona (Barrett 2010 and references therein). These events heralded almost three centuries of episodic raiding, invasion, and the settlement of large parts of Ireland and Britain by people of presumed Scandinavian origin. Central western Norway is regarded as the likely origin of the first raiding parties, due to finds in Norwegian graves of insular (British and Irish) metalwork. However, the geographic origins and cultural affiliations of even these early Viking raiders in Ireland and Britain remain hypothetical and open to debate. Moreover, the notion of geographical origin becomes increasingly complex through time, in the context of documented instances of mixed raiding armies (MacAirt and MacNiocaill 1983), the emergence of Scandinavian colonies in northern Britain and Ireland characterized by cultural hybridity (Barrett 2003b, Downham 2012), and the secondary migration from "Norse" settlements in the west to new destinations such as Iceland (Goodacre et al. 2005, Stefánsson 2003).

The question of how many individuals of Scandinavian origin, and of what sex, settled in Britain in the 8th to 10th centuries A.D., and how varied their places of origin were, can be investigated using isotope analysis. There is a strong possibility that significant differences in stable isotopes (carbon, nitrogen, and oxygen) and radiogenic isotopes (strontium and lead) may arise as a result of cultural and environmental differences in diet, geology, anthropogenic pollution, and climate between Viking Age inhabitants of Scandinavia, and those of Ireland and Britain (Barrett et al. 2001, Fricke et al. 1995, Montgomery and Evans 2006, Montgomery et al. 2003, Price and Gestsdottir 2006). This paper reviews the data for indigenous inhabitants of these wet and windy islands and discusses ways in which individuals of Norwegian or Danish origin may be identified amongst the indigenous population.

Context

The physical presence of Scandinavian raiders, migrants, and/or settled communities is deduced from place-names, sculpture, settlements, artifacts, and texts (Brink and Price 2008). Parts of Scotland may have been colonized as early as A.D. 839, when an army of pagans defeated the kings of Scotland's

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two main polities (Fortriu and Dál Riata; Woolf 2007:66). A Viking army first overwintered in Dublin in A.D. 841, leading to the emergence of the most substantial of several Hiberno-Scandinavian towns (Simpson 2010). By A.D. 847, the Frankish *Annals of St. Bertin* record that the *Scotti* (meaning the Irish or the Scots) "after being attacked by the Northmen for very many years, were rendered tributary and (the Northmen) took possession, without resistance, of the islands that lie all around and dwelt there" (Graham-Campbell and Batey 1998:45). Virtually no pre-Norse place-names survive in the Northern and Western Isles of Scotland (Gammeltoft 2004, Jennings and Kruse 2005). The Hebrides (the Western Isles) even became known as *Innse Gall* or "Islands of the Foreigners" (Ritchie 1993:94, Woolf 2005). Genetically, the modern populations of northern and western Scotland have significant Scandinavian ancestry in both the female and male lines (Goodacre et al. 2005). Significant Scandinavian ancestry has not yet been discovered in Ireland (e.g., McEvoy et al. 2006). However, elsewhere around the Irish Sea elegant studies linking Y-chromosomes and surnames of the modern population suggest enduring male Scandinavian genetic legacy in the Wirral in northwest England—a region potentially colonized from Dublin in the 10th century (Bowden et al. 2007).

Collectively, this evidence implies that Scandinavian settlement in parts of Scotland and Ireland was significant, instigating cultural and/or genetic (through migration and intermarriage) changes in some of the indigenous communities affected (Barrett 2008, Ó Corráin 2008, Wallace 2008). Nonetheless, despite the ample evidence for considerable cultural and population change during this period, only a modest number of burials that are characteristically Scandinavian—identified by cremation, barrows, or the presence of Scandinavian grave goods—have been identified anywhere in Britain or Ireland (Graham-Campbell and Batey 1998, Harrison 2001, Richards 2002). In Scotland, around 130 ninth- to tenth-century burials of Scandinavian style (based on grave-goods) have been identified (Graham-Campbell and Batey 1998). Numerous "Christian" cemeteries (without grave goods) dating to the mid-10th century and later also presumably included the burials of Scandinavian settlers and their descendants (Barrett 2003a:219). In Ireland, the number of Viking graves is below 100 and, in contrast to the scattered distribution in Britain, approximately 80% of these have been excavated in the vicinity of Dublin, in Kilmainham and Islandbridge in particular (Harrison 2001). Although not the focus of this paper, even fewer "Viking" graves are known from England (Buckberry et al. 2014, Halsall 2000, Richards 2002). It is clear that the number of characteristically Scandinavian graves is unlikely to represent a migrating population that had such a large cultural and (in some places) genetic legacy.

Clearly some burial groups in Britain and Ireland, such as those with predominantly or completely male interments at the grave-field in South Great Georges Street, Dublin (O'Donovan 2008, Simpson 2005), Heath Wood, Ingleby (Richards et al. 2004), Repton (Biddle and Kjølbye-Biddle 1992), Oxford (Pollard et al. 2012), and Weymouth (Chenery et al. 2014 [this volume]), are not cemeteries normally associated with settlement. The presence and cultural impact of these individuals on the surrounding populations may have been fleeting. Conversely, those at Cnip (Dunwell et al. 1996) and Westness (Kaland 1993, Sellevold 1999) in Scotland contain burials of men, women, and children and have been interpreted as family burial sites.

But why are there so few? Likely explanations include rapid conversion to Christianity (and thus the abandonment of diagnostic grave goods), the adoption of indigenous burial customs by migrants, reduced archaeological visibility of the cremation rite (especially to Antiquarians), and a simple lack of identifiably Viking burial assemblages (Hadley 2006, Halsall 2000, Richards 2002). Indeed, in many cases the presence of grave goods during a period characterized by unaccompanied burials is often interpreted as an indication of Viking identity—regardless of whether or not those grave goods have Scandinavian parallels (Hadley 2006, Halsall 2000). In Scotland particularly, Viking burials have been reported and excavated by Antiquarians, and the assemblages subsequently lost (Batey 1993). Examples with poorly documented grave goods include three male burials from Eigg excavated in the 19th century and a female burial found near Bhaltos school on the Isle of Lewis in 1915 (Armit 1996:201–202).

A further problem for archaeologists hoping to carry out osteological or isotopic analysis of the skeletons is that even when the artifactual or burial evidence strongly suggests a Viking burial, in many cases there is no surviving bone. Antiquarian excavations of what are believed to be Viking grave goods are often so poorly documented that it is unclear if any evidence of a body was also revealed (Crawford 1987, Hadley 2006). This dearth of documentation was often due to a lack of interest in the study and hence recording and subsequent curation of human remains (Harrison 2001). However, skeletal survival during burial depends on soil conditions, and the regions that were targeted for Scandinavian settlement in the north and west of Britain, where high rainfall, silicate rocks, and acidic soils predominate, are often not conducive to bone preservation. As a result, grave goods are sometimes found where there is no recoverable bone. This was, unfortunately, the case at the rare cemetery of male and female Viking inhumation graves discovered in 2004 at Cumwhitton in Cumbria, England. Although the six graves were richly furnished with swords, spears, jewellery, and horse-riding equipment, no bones or teeth could be recovered from the red, sandy soils for analysis (Paterson 2014).

This lack of skeletal remains has severely hampered the application of isotopic techniques to investigate the number and demographic make-up of the initial Scandinavian settlers of Britain. To date, a number of small studies have been carried out on skeletons from sites at Adwick-le-Street (Speed and Walton Rogers 2004), Cnip (Montgomery and Evans 2006), Repton (Budd et al. 2004), Riccall (Hall et al. 2008), Oxford (Pollard et al. 2012), and Weymouth (Chenery et al. 2014 [this volume]); These results will be combined with new data presented in this paper from Viking Age burials from two prime locations of Viking influence in the western seaways: Westness, Orkney, and Dublin, Ireland (Fig. 1).

Study Sites

South Great Georges Street, Dublin

South Great Georges Street (SGGS) is an early to mid-9th-century habitation and burial site located near the "Black Pool" region in Dublin, Ireland, along the south bank of the River Liffey (Simpson 2005). It was excavated in 2003 by Linzi Simpson (Margaret Gowan and Co., Ltd.) as part of contracted archaeological investigations preceding urban development in the area. The site is of particular archaeological interest since it may represent the *longphort*, or ship camp, that was suggested in the *Annals of Ulster* to be in Dublin along the Liffey in the 9th century A.D. Four male skeletons between 17 and 30 years of age were uncovered, but only three had extant teeth that could be sampled for strontium, lead, and oxygen isotopes (Table 1). These three burials contained a variety of weaponry consistent with a "warrior" class and Norse cultural affiliation (Simpson 2005). Included in the fourth burial (F342), but absent from the others, were over 100 fragmented remains of several animal species. Previously published data (Knudson et al. 2012) and two humans buried nearby at Rath (Montgomery et al. 2006) and Ratoath (Montgomery and Grimes 2010) that are believed to pre-date the Viking Age were used to provide comparative evidence.

Westness, Orkney

The Viking cemetery at Westness, Rousay, was found in 1963 when the skeleton of a young woman with a newborn child was uncovered (Kaland 1993). Subsequent excavations discovered an earlier Pictish cemetery in use from the middle of the first millennium A.D. (Barrett and Richards 2004, Sellevold 1999). Two Viking boat burials (11 and 34) and

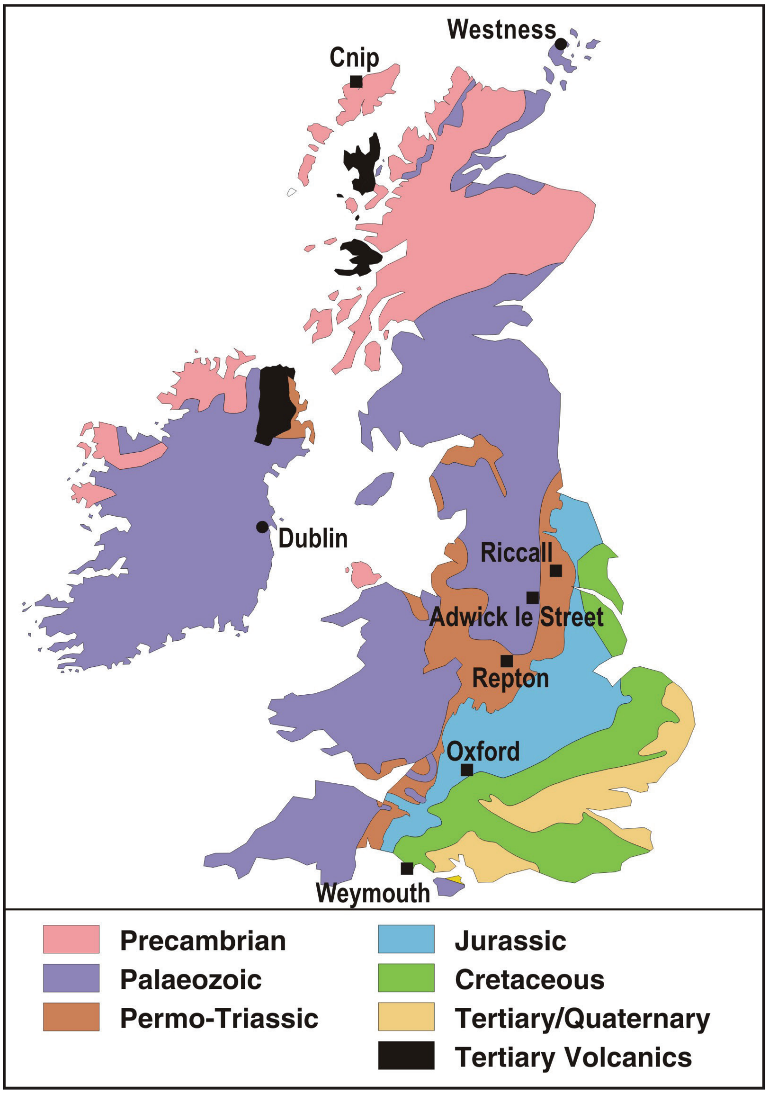

Figure 1. A simplified schematic geology map of Britain and Ireland showing the location of the two sites in this study (circles) and sites from which comparative data have been used (squares).

other oval and boat-shaped graves with Viking burial assemblages were found alongside but respecting the Pictish rectangular graves aligned roughly E–W with a supine body and no grave goods (Sellevold 1999). A previous stable isotope and radiocarbon dating study at Westness had found that two Viking male skeletons at the site (11 and 12) had δ^{13}C and δ^{15}N values that indicated a significantly higher marine protein intake than the Pictish-affiliated burials and the female Viking burials at the site (Barrett and Richards 2004). Three Viking and three Pictish burials included in this earlier study were selected for strontium, lead, and oxygen isotope analysis (Table 1) to investigate whether this dietary difference could be explained by origins in Scandinavia where fish consumption would be hypothesized to be higher or whether these individuals heralded the onset of marine resource intensification in the Orkney Islands. Two skeletons from the Iron Age site of Mine Howe, Tankerness, a medieval burial from Graemsay, and a group of medieval burials from St. Thomas's Kirk, Rendall (Toolis 2008), were included for comparison.

Materials and Methods

Samples

Human dental tissue (enamel and dentine) samples for isotope and trace-element analysis were obtained from the skeletal remains at South Great Georges Street in Dublin and Westness in Orkney (Table 1). Tooth enamel has been shown to preserve the chemical traces of food and drink ingested during tooth-mineralization periods (<15 years of age for most human populations) and is considered more robust than both tooth dentine and bone to post-depositional diagenetic alteration of mineral elements such as strontium and lead (Budd et al. 2000, Chiaradia et al. 2003, Hoppe et al. 2003, Trickett et al. 2003). Enamel and primary crown dentine, i.e., that which forms in the tooth crown during initial tooth formation (van Rensberg 1986) are broadly co-genetic; within a tooth, they commence mineralization almost simultaneously and, unlike bone, neither tissue is subject to post-mineralization remodelling (Hillson 1996:194). Consequently, in modern people, these tissues have very similar lead and strontium isotope ratios and concentrations deriving

Table 1. Strontium and oxygen isotope data. $\delta^{18}O_{dw}$ values are converted from $\delta^{18}O_p$ values using the equation of Longinelli (1984). Osteological information for Westness and Dublin are from Sellevold (1999) and Buckley (2004), respectively. Data for Mine Howe, Rath, and Ratoath are from Montgomery et al. (2007b), Montgomery et al. (2006), and Montgomery and Grimes (2010), respectively.

Sample	Period	Age	Sex	Tooth	Tissue	Sr ppm	1/Sr x 10^3	^{87}Sr/^{86}Sr	$\delta^{18}O_p$‰	$\delta^{18}O_{dw}$‰
Dublin, Ireland										
SGGS F598-2T	Viking	Adult	Male	M2?	Enamel	69	14.5	0.71978	13.5	-13.9
					Dentine	260	3.8	0.71046		
SGGS F598-B		17–25 yrs			Bone				15.2	-11.2
SGGS F196-3T	Viking	25–29 yrs	Male	M2	Enamel	120	8.3	0.70964	17.4	-7.8
					Dentine	354	2.8	0.70913		
SGGS F223-1T	Viking	17–20 yrs	Male	C	Enamel	111	9.0	0.71054	15.5	-10.7
					Dentine	236	4.2	0.70948	15.9	-10.1
SGGS F342	Viking	< 25 yrs	Male		Bone				17.6	-7.5
SGGS F77 - Horse					Bone				17.6	-7.5
SGGS F471.2 - Cow					Bone				17.3	-7.9
Ratoath 03E1781 B38	Iron Age	18–25yrs	Female	M^{2}L	Enamel	82	12.2	0.70905	17.6	-7.5
					Dentine	236	4.2	0.70859		
Rath-848 03E1214	Iron Age?	Adult	Female	M$_2$R	Enamel	65	15.5	0.71060	17.5	-7.5
					Dentine	333	3.0	0.70908		
Orkney										
Westness Grave 5	Viking	35–45yrs	Female	P$_2$R	Enamel	65	15.5	0.70729	17.2	-8.1
					Dentine	68	14.7	0.70778		
Westness Grave 11	Viking	45–55yrs	Male	M^{2}R	Enamel	89	11.3	0.71015	15.5	-10.7
					Dentine	792	1.3	0.70958		
Westness Grave 12	Viking	35–45yrs	Male	P$_1$L	Enamel	102	9.8	0.71197	15.4	-10.9
					Dentine	112	9.0	0.71039		
Westness Grave 25	Pictish	7–8yrs	n/a	M$_1$	Enamel	139	7.2	0.70987		
Westness Grave 28A	Pictish	25–30yrs	Female	M^{3}L	Enamel	170	5.9	0.70942	17.8	-7.1
					Dentine	695	1.4	0.70949		
Westness Grave 32	Pictish	50–70yrs	Female	M$_2$L	Enamel	185	5.4	0.70977		
Graemsay 1	Medieval	Adult	n/k	M$_2$	Enamel	231	4.3	0.70939	17.9	-7.0
					Dentine	443	2.3	0.70949		
Mine Howe 1861	Iron Age	25–35yrs	Male	M^{2}R	Enamel	406	2.5	0.70940	17.6	-7.4
					Dentine	453	2.2	0.71009		
Mine Howe 897	Iron Age	16–20yrs	Female	P$_1$L	Enamel	419	2.4	0.70941	17.7	-7.3
					Dentine	463	2.2	0.70975		

from childhood (Montgomery 2002). During burial in soil, however, the dentine will start to equilibrate with elements in the groundwaters and can be used as an indicator of diagenetic vectors and thus local values (Montgomery et al. 2007a). Dentine samples were measured as a means to provide additional information, along with environmental data, on strontium isotope values. Modern plants were collected across a transect from the coast at Westness to within one mile inland.

Phosphate oxygen isotope ($\delta^{18}O_p$) analysis

The sample preparation and oxygen isotope analysis were conducted at the Department of Archaeological Sciences, University of Bradford, UK. Bone and enamel samples were taken as powder using a handheld dental drill and burr and processed to produce silver phosphate (Ag_3PO_4) using a modification of Stephan (2000) as described in Grimes and Pellegrini (2013). Samples weighing approximately 10–20 mg were pretreated in 2.3% NaOCl followed by 0.125 M NaOH for 24 hours. After each step, the samples were centrifuged and the solutions removed and rinsed with deionized water until the supernatant was neutral. The residual sample powders were then reacted with 2 M HF for 24 hours, which produced a solid precipitate of calcium fluoride (CaF_2) and a solution containing the phosphate ions (PO_4^-). The phosphate solution was neutralized with 2 M KOH and a buffered silver amine solution (0.2 M $AgNO_3$; 0.35 M NH_4NO_3; 0.75 M NH_4OH) was added followed by heating on a hotplate to 60 °C for several hours. During the heating stage, Ag_3PO_4 crystals slowly precipitated from the solution. The Ag_3PO_4 crystals were then filtered from the solution using 0.2-mm acetate-membrane filters (Sartorius AG, Germany), dried in a warming cabinet, and transferred to storage vials. Following homogenization, 0.160–0.200 mg of the Ag_3PO_4 crystals were weighed into clean 3.5 mm x 4.0 mm silver capsules (Elemental Microanalysis, UK) and loaded into a standard autosampler of a ThermoFisher temperature-conversion elemental analyzer (TC/EA) coupled to an isotope ratio mass spectrometer (ThermoFisher DeltaPlus^{XL}). Pyrolysis of the Ag_3PO_4 crystals occurred in a glassy carbon reactor at a temperature of 1400 °C. The resultant CO gas was carried via a He stream (90 ml/min) through a GC column consisting of a 0.6 m 5 Å molecular sieve at a temperature of 85 °C. Oxygen isotope ratios are reported in delta units (per mil [‰]) and referenced to the Vienna-standard mean ocean water (V-SMOW) scale. Three in-house Ag_3PO_4 standards with $\delta^{18}O_p$ values determined through the off-line fluorination technique (TU1 = 21.1‰; B1 [Sigma Aldrich silver phosphate] = 13.45‰; TU1 = 21.1‰) were run along with the samples to enable normalization of the data according to the procedure outlined in Vennemann et al. (2002). All the data presented here are normalized mean values of two or more replicate measurements with analytical errors better than 0.4‰ (1 σ).

Strontium isotope ($^{87}Sr/^{86}Sr$) analysis

Core enamel and primary crown dentine subsamples were removed from the teeth using tungsten carbide dental burrs following the procedure in Montgomery (2002) at the University of Bradford, UK. Samples were sealed in containers and transferred to the clean laboratory suite at the NERC Isotope Geosciences Laboratory, Keyworth, UK, for further processing for lead and strontium isotopes and trace-element analysis. Enamel and dentine were cleaned and processed using previously published methods for strontium (Brettell et al. 2012a, Montgomery 2002). Enamel lead isotope and concentration methods, results, standards, and errors are published elsewhere (Montgomery et al. 2010). Samples were spiked with ^{84}Sr-enriched tracer solution, and strontium was extracted from the matrix using conventional ion-exchange chromatography. Plant samples (~0.1 g) were digested in a microwave oven using Teflon-distilled 16 M HNO_3 and Romil high-purity H_2O_2 using the method described in Warham (2012). Strontium isotope composition and concentrations were determined by thermal ionization mass spectrometry (TIMS) using a Thermo Triton automated multi-collector. Samples were loaded onto outgassed rhenium filaments with TaF after the method of Birck (1986). $^{87}Sr/^{86}Sr$ was normalized to an accepted NBS 987 value of 0.710250. External reproducibility was ± 0.004% (2 σ, *n* = 15). Laboratory contamination, monitored by procedural blanks, was negligible (<100 pg).

Results

The strontium and oxygen isotope and concentration data are detailed in Tables 1 and 2.

Table 2. Strontium isotope data for modern plant samples from Westness, Orkney.

Sample No.	Material	Co-ordinates		$^{87}Sr/^{86}Sr$
Westness1	Plant	E 338259	N 1029029	0.71007
Westness2	Plant	E 338480	N 1020049	0.71048
Westness3	Plant	E 338431	N 1030724	0.70990
Westness4	Plant	E 340070	N 1029680	0.70959
Westness5	Plant	E 339452	N 1029483	0.70975
Westness6	Plant	E 338837	N 1029183	0.70949
Westness7	Plant	E 338582	N 1029093	0.71045

Strontium results for South Great Georges Street, Dublin

Strontium isotope analysis ($^{87}Sr/^{86}Sr$) of the three male skeletons from Dublin produced enamel values ranging 0.7096–0.7198, while the Sr concentrations (69–120 mg/kg) were consistent with expected variation in modern enamel tissues. Figure 2 illustrates these data against comparative human and environmental data from the vicinity of Dublin and other regions of limestone. Samples of soil leaches, plants, human bone, and animal bone cluster tightly within the range of $^{87}Sr/^{86}Sr$ values that would be expected for coastal regions of limestones overlain by boulder clay, i.e., 0.7088–0.7100 (Evans et al. 2010). Dentine samples from all individuals have, in all cases, higher strontium concentrations than the co-genetic enamel coupled with isotope ratios that are converging on the values obtained from the environmental samples. Four of the enamel samples range from 0.7090 to 0.7106, which is comparable with the local strontium isotope range and within the range of enamel values obtained by Knudson et al. (2012) from Dublin. Conversely, Skeleton 598 has a high $^{87}Sr/^{86}Sr$ and is clearly distinct from the other individuals.

Strontium results for Westness, Orkney

Strontium isotope analysis ($^{87}Sr/^{86}Sr$) of enamel from the three Viking and three Pictish skeletons from Westness, a later medieval skeleton from nearby Graemsay, and two individuals from Mine Howe produced a range of 0.7073–0.7120, with the Viking skeletons providing the lowest (Westness 5; female) and highest (Westness 11 and 12; male) values. The range of strontium concentrations was large (65–419 mg/kg); the three Viking skeletons were all below 102 mg/kg, and the remaining six individuals were above 139 mg/kg. The majority of humans in mainland Britain have enamel strontium concentrations between ~30 to 150 mg/kg (Evans et al. 2012, Montgomery 2002). Higher concentrations appear to be a characteristic of populations inhabiting the specific coastal environmental niche of small, maritime, islands such as the Outer Hebrides where there is a tradition of using seaweed as fodder, fertilizer, and possibly food (Montgomery et al. 2007a). Medieval individuals from St. Thomas's Kirk, Rendall, also displayed such high concentrations (250–380 mg/kg), and together with the data presented here, suggest this observation applies equally to the

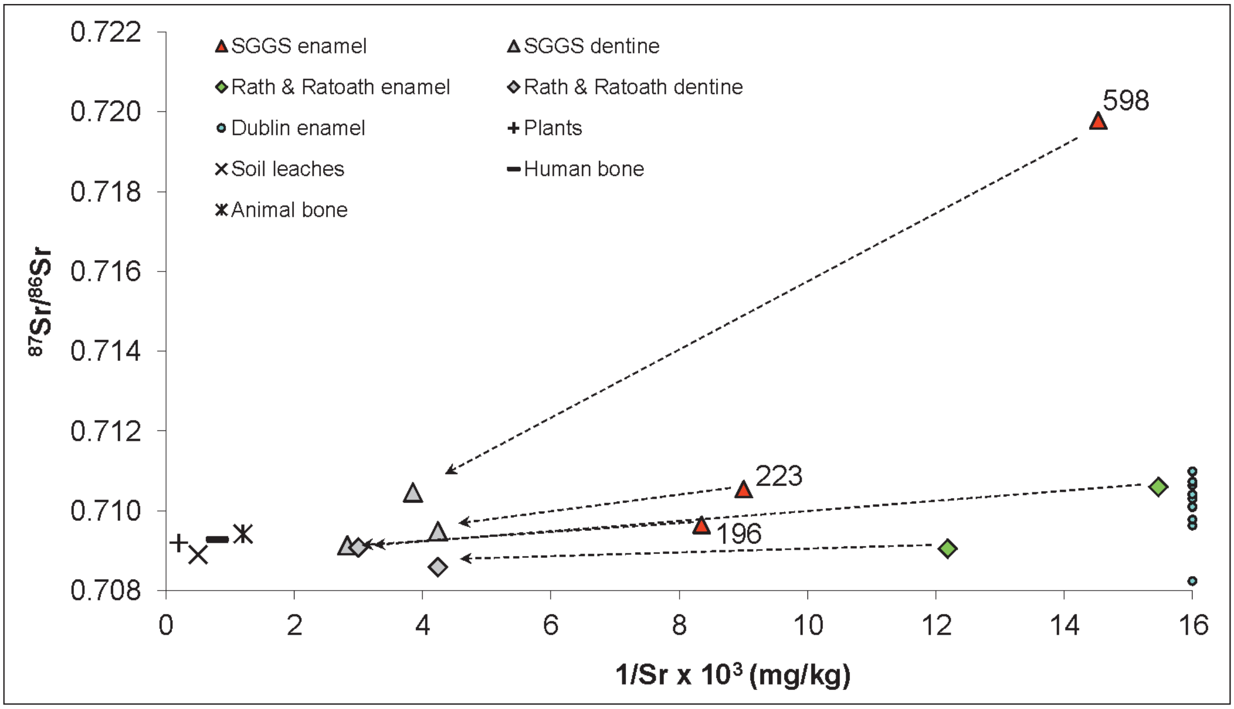

Figure 2. A plot of $^{87}Sr/^{86}Sr$ against strontium concentration (1/Sr) for burials from the Dublin area. Enamel samples have low strontium concentrations (i.e., high 1/Sr values) and variable isotope ratios. Comparative enamel data from Dublin (Knudson et al. 2012) appear as a row of dots with notional strontium concentrations. Corresponding crown dentine samples from the same teeth (linked by arrows) have higher strontium concentrations and convergent isotope ratios that define a diagenetic vector towards the environmental samples. Mean isotope ratios for soil leach ($n = 5$) and plant ($n = 11$) samples from Carboniferous limestones are taken from Evans et al. (2010), human ($n = 10$) and animal ($n = 11$) bone samples from Dublin are taken from Knudson et al. (2012); none have Sr concentrations and hence are plotted with notional x-values. 2 σ analytical errors are within the symbol.

Orkney Islands. The modern plant and grain data predominantly fall between the value of modern seawater (~0.7092) and 0.7100 (Table 2). Primary crown dentine has higher concentrations than the co-genetic enamel coupled with isotope ratios that define a diagenetic strontium vector converging on the plant and seawater values. Higher ^{87}Sr/^{86}Sr ratios approaching ~0.713 have been obtained from plants and waters in regions of Devonian Sandstone in Britain (Evans et al. 2010). However, there is evidence from geological and environmental studies (Capo et al. 1994, Raiber et al. 2009, Whipkey et al. 2000) and from archaeological investigations on small islands such as the Hebrides which include measurements of modern plants (Evans et al. 2009, Montgomery 2002, Montgomery et al. 2007a) that a combination of high rainfall, sea-splash, seaweed fertilization, and coastal marine sands can introduce sufficient strontium of marine origin into soils and plants to significantly dampen biosphere and human ratios towards the seawater strontium ratio. With the exception of the three Viking skeletons, all the individuals from Orkney exhibit the characteristic high strontium concentrations coupled with marine-dominated ^{87}Sr/^{86}Sr observed amongst other island-dwelling individuals from both Orkney and the Hebrides (Fig. 3). In contrast, the three Viking individuals have lower strontium concentrations and variable ^{87}Sr/^{86}Sr and do not fall within the range of island dwellers, although with ^{87}Sr/^{86}Sr alone it would be difficult to exclude Westness 11.

Oxygen isotope results for South Great Georges Street, Dublin

Phosphate oxygen isotope values ($\delta^{18}O_p$) from the Dublin samples ranged from 13.5‰ to 17.4‰ (Fig. 4). Conversion of the $\delta^{18}O_p$ values to drinking-water oxygen values ($\delta^{18}O_{dw}$) using the equation of Longinelli (1984) gave corresponding values ranging from -13.9‰ to -7.8‰. The local $\delta^{18}O_p$ was

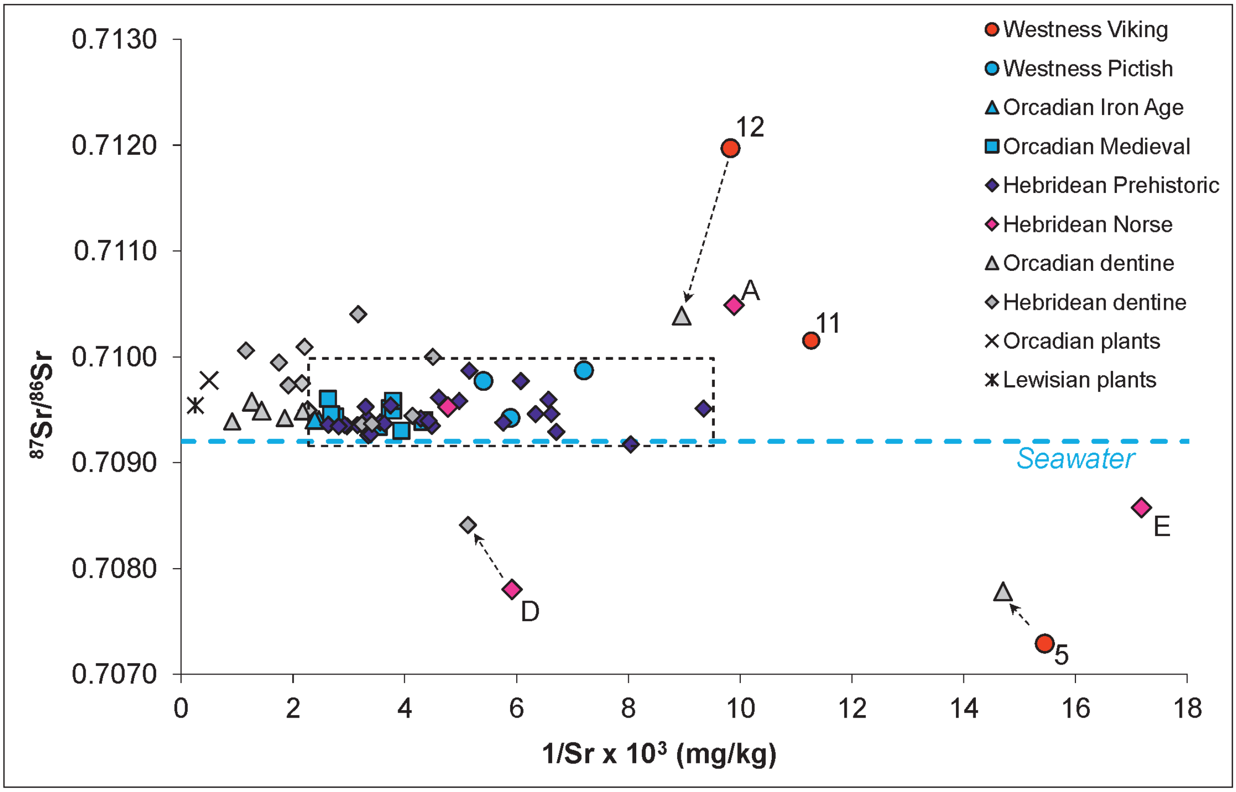

Figure 3. A plot of ^{87}Sr/^{86}Sr against strontium concentration (1/Sr) for humans from Orkney and the Hebrides. Skeletons A, D, and E are from Cnip and are discussed in the text. Enamel samples have low strontium concentrations (i.e., high 1/Sr values) and variable isotope ratios. Corresponding crown dentine samples from the same teeth (some linked by arrows) have higher strontium concentrations and convergent isotope ratios that define a diagenetic vector towards 0.7092–0.7100; this result is consistent with the local geology and environment. The box encloses individuals with the high Sr concentrations and marine-dominated Sr ratios characteristic of island/coastal/machair dwellers on the high-rainfall western and northern seaboard of Britain (Montgomery et al. 2007a). Humans dating to the Viking Age fall mostly outside the box. Isotope ratios for modern Orcadian plants ($n = 21$) and Lewisian plants ($n = 11$) are mean values taken from Table 2, Evans et al. (2010), Heier et al. (2009), and Montgomery et al. (2007a). Comparative enamel data are taken from Toolis (2008), Montgomery et al. (2003, 2007a, 2007b), Parker Pearson et al. (2005), and Evans et al. (2012). 2 σ analytical errors are within the symbol.

determined by the values obtained on horse and cow bones excavated from burial F342. Conversion of these values from $\delta^{18}O_p$ to $\delta^{18}O_{dw}$ using the equations of Sánchez Chillón et al. (1994) and D'Angela and Longinelli (1990) for horse and cattle, respectively, gave $\delta^{18}O_{dw}$ values consistent with the determined groundwater $\delta^{18}O$ values for this area (i.e., -6.5‰ to -7.0‰; Darling et al. 2003, Diefendorf and Patterson 2005). Two male individuals (F598 and F223) have low $\delta^{18}O_{dw}$ values that are largely inconsistent with Britain and Ireland (Fig. 5) irrespective of analytical errors, choice of conversion equation, or uncertainties associated with conversion of measured phosphate values to local drinking water (Evans et al. 2012).

Oxygen isotope results for Westness, Orkney

The phosphate oxygen isotope ratios obtained from the Orkney humans range from 15.4‰ to 17.9‰ with a mean of 17.0‰ ± 1.1‰ (n = 7, 1 σ). The corresponding $\delta^{18}O_{dw}$ values ranged from -10.9 ‰ to -7.1 ‰ using the equation of Longinelli (1984) and had a mean value of -8.4‰ ± 1.7‰ (n = 7, 1 σ). According to Darling et al. (2003), modern mean annual $\delta^{18}O_{dw}$ values for Orkney are -7‰ to -6 ‰. Two male Viking skeletons (11 and 12) have low $\delta^{18}O$ values that appear to be inconsistent with Britain and Ireland (Fig. 5), and they fall outside of the $\delta^{18}O_{dw}$ range for these areas even when errors associated with the isotope analysis and conversion equations are taken into account (Evans et al. 2012).

Discussion

Dublin and the "strontium of doom"

What is most striking about the male skeletons from Dublin is that all three have different strontium and oxygen isotope ratios (Fig. 5) suggesting disparate geographical origins. Whether this arises because Scandinavia (meaning Norway, Sweden, and Denmark in this context) is able to produce such very different strontium and oxygen isotopes in humans or because the Vikings who travelled to Ireland also included individuals from the British Isles, is a matter of debate. Skeleton 598 has a strontium isotope ratio ($^{87}Sr/^{86}Sr$ = 0.7198) that can only derive from ancient or granitic rocks, and such values are seldom found among British or Irish populations of any period (Evans et al. 2012). His extremely low oxygen isotope ratio ($\delta^{18}O_p$ = 13.4‰) is comparable

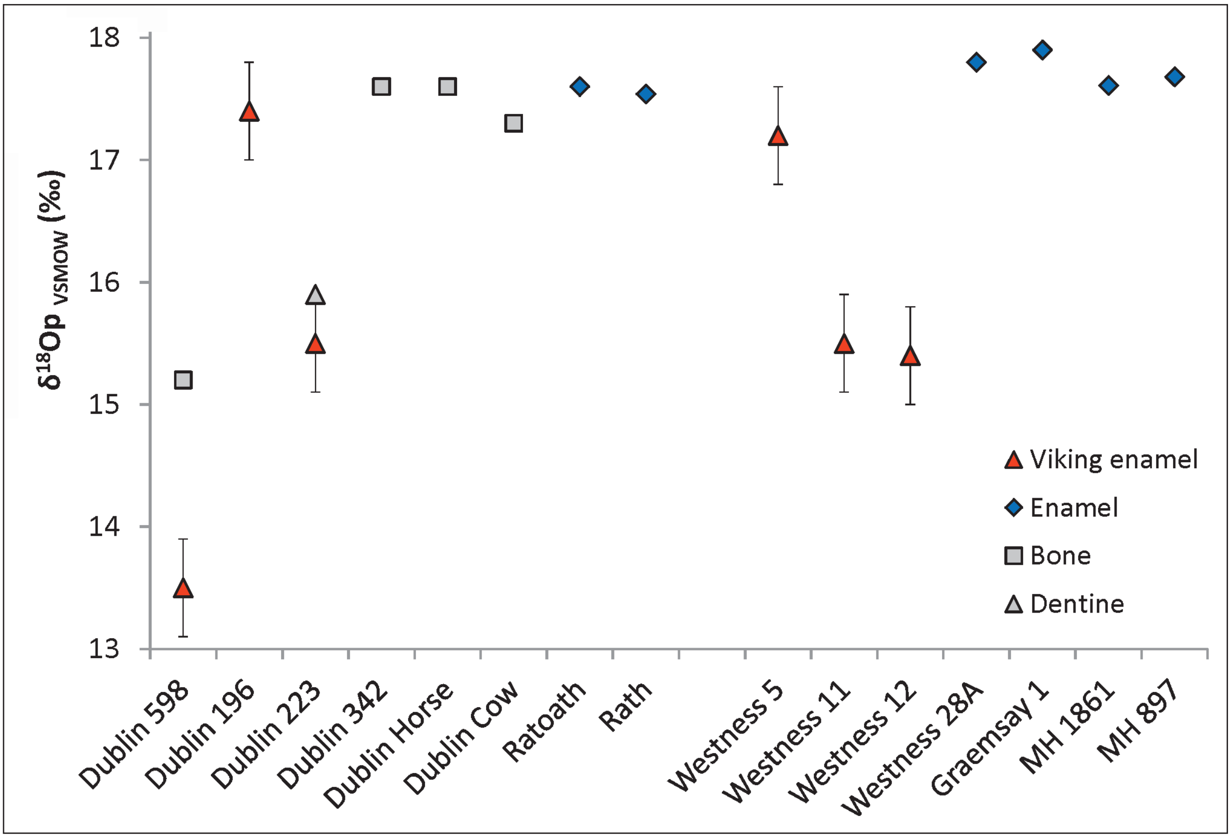

Figure 4. Oxygen isotope data for humans and animals from Dublin and Orkney. Error bars are ±0.4‰ (1 σ) and represent analytical error of repeated measurement on the same sample. They apply to all points but are shown on the red triangles only for simplicity.

with values obtained by Fricke et al. (1995) among the Inuit in Greenland, and together with the strontium isotope ratio, suggests origins in a granitic terrain somewhere very cold. There are relatively few places in the North Atlantic where this individual could originate. A homeland in northern Scandinavia is perhaps the most obvious choice. Nonetheless, the isotope data alone cannot rule out other comparable locations in the North Atlantic, such as Greenland or Newfoundland, but the late date of the first Scandinavian presence in the western North Atlantic (the end of the tenth century) makes them highly unlikely options in the present context (Arneborg 2003, Wallace 2003).

Strontium isotope ratios were not successful in assigning foreign origins to the two remaining individuals, 223 and 196. On the basis of strontium alone, it would be difficult to identify them as different from the local population of the Dublin area as they fall within the range of environmental strontium and other pre-Viking and Viking Age individuals (Fig. 2). Oxygen isotopes, however, show that skeleton 223 is very unlikely to be from the British Isles, because his $\delta^{18}O_p$ of 15.4‰ falls below the 15.6‰ to 19.8‰ (3 sd, *n* = 615) range for Britain defined by Evans et al. (2012). Consequently, there is less than 0.5% probability that this individual originates in Britain, or by extension, given the comparable $\delta^{18}O$ range of rainfall, Ireland. There are several sources of uncertainty and error associated with oxygen isotope ratios, not least being biological variability (Pollard et al. 2011, Puceat et al. 2010), and care needs to be taken in their interpretation. To this end, a range of uncertainty estimated to

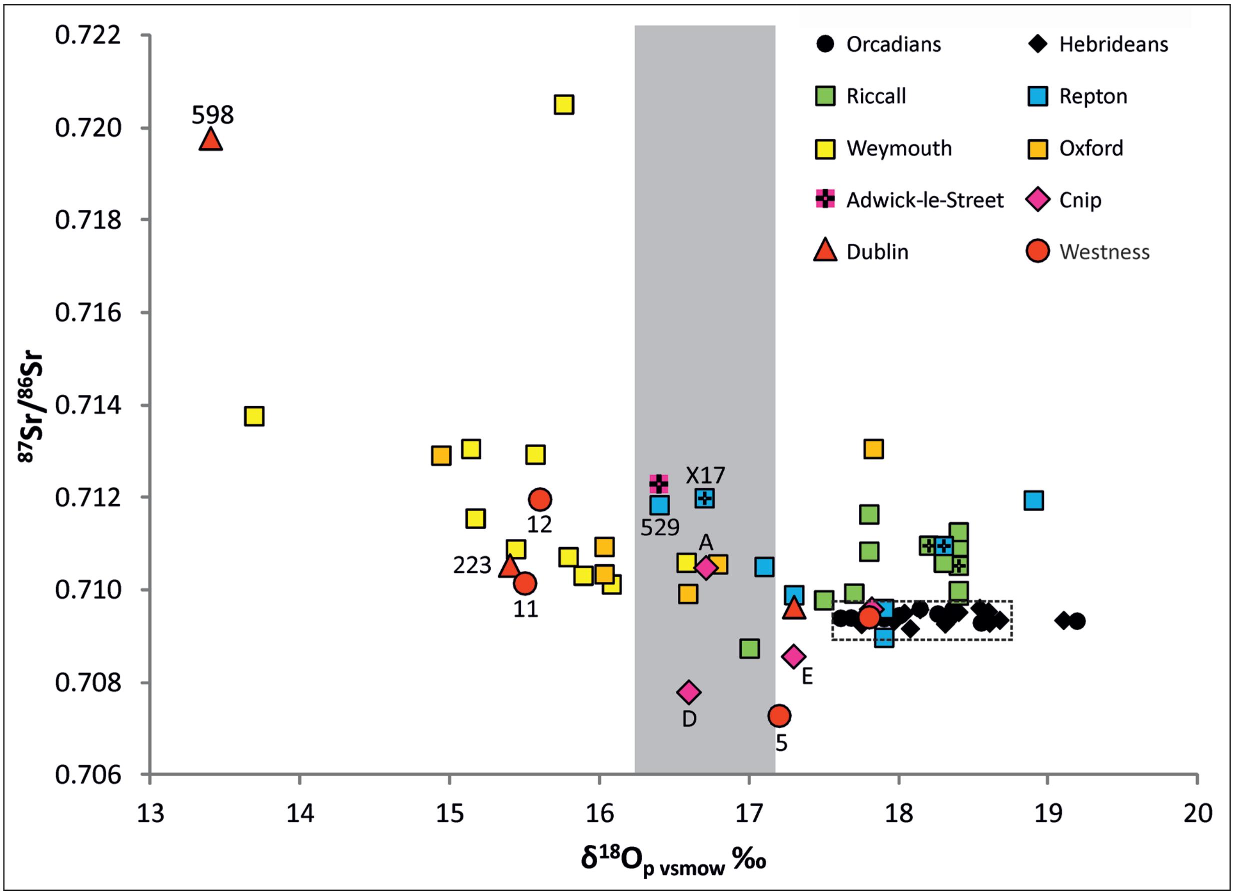

Figure 5. A plot of $^{87}Sr/^{86}Sr$ against $\delta^{18}O_p$ for human enamel samples. Labelled individuals are discussed in the text. The dashed box contains Hebrideans and Orcadians and shows that Sr does not discriminate between these two islands despite very different geology. The grey box indicates the zone of uncertainty: $\delta^{18}O_p$ values to the left are inconsistent with Britain (and by extension) Ireland at the 95% probability level (2 σ range for humans from Britain is 16.3‰ to 19.1‰; Evans et al. 2012), while those to right are consistent, whichever conversion equation is used. Individuals within the grey box could be consistent with the eastern seaboard of Ireland or Britain but are not consistent with Orkney or the Hebrides at the 95% probability level (2 σ range for humans from the west coast of Britain is 17.2‰ to 19.2‰ (Evans et al. 2012)). Females are denoted by a cross (+). Comparative enamel data are taken from Toolis (2008), Montgomery et al. (2003, 2007a, 2007b), Parker Pearson et al. (2005), Evans et al. (2012), Chenery et al. (2014 [this volume]), and Pollard et al. (2012). Typical analytical error is within symbol for Sr and is shown for $\delta^{18}O$ as ± 0.4‰ (1 σ).

encompass the large errors involved is highlighted in Figure 5. While few humans have to date been found in Britain and Ireland within this range of oxygen isotope ratios, it is nonetheless difficult, given the analytical error involved and the current state of knowledge, to be certain such values cannot be found in eastern and upland regions of Ireland and Britain. However, where human values are altered with respect to local water sources, most environmental, biological, or cultural modifications result in higher values than would be predicted from the local area (Brettell et al. 2012b); there are very few processes that can make values lower. Therefore, unless individuals were predominantly consuming glacial meltwater, rainwater that fell at high altitude, or distilled (rather than boiled) drinking water, all of which are highly unlikely in medieval Britain, such low values are more likely to indicate origins in a colder or more northerly climate. In studies such as this looking at migration in the Viking Age where the immigrant individuals are likely to be coming from regions significantly colder or at higher latitude than the place of burial, oxygen isotopes can thus be extremely useful to identify individuals' residential origin where strontium cannot.

For skeleton 196, neither strontium (0.7096) nor oxygen (17.3‰) isotopes can exclude origins in the Dublin region. Despite the great variety of rock types in Britain and Ireland, ~80% of individuals published to date have strontium isotope ratios within the range of 0.7090 and 0.7110 (Evans et al. 2012). The situation is very similar in northern Europe, as can be determined by a perusal of almost any paper containing strontium isotope data from the region. This result is partly due to a cultivation and excavation bias: soils with values within this range tend to be targeted by humans for settlement and agriculture because they provide fertile, arable land, and when the humans are buried, such soils are also conducive to good bone preservation. It also arises because such values are typical of the more easily weathered carbonate minerals in heterogeneous rocks of any age, and are characteristic of soils overlying most Mesozoic and Cenozoic sedimentary rocks, limestones, and glacial, alluvial, and marine drift deposits such as boulder clay, shell sands, and loess that occur across large areas of mainland Europe south of the Baltic Shield (Evans et al. 2010, Frei and Frei 2011, Gallet et al. 1998, Price et al. 2004, Warham 2012). Such biosphere strontium ratios are also produced in coastal regions subject to sea-splash, sea-spray, or high rainfall, which can supress rock-derived strontium (Bentley 2006, Capo et al. 1994, Evans et al. 2010, Montgomery et al. 2007a, Raiber et al. 2009, Whipkey et al. 2000). In coastal regions and small, wet, and windy islands, such processes can have a significant effect on strontium isotope biospheres and result in a dampening of the biosphere ratios towards those of seawater, irrespective of local geology. Human strontium ratios between 0.7090–0.7110 are, therefore, extremely common and frustratingly and often disappointingly undiagnostic because they could result from a wide range of geographical origins and environmental niches. Results that fall within this "strontium of doom" range almost always require additional evidence or measurements to constrain origins. Consequently, individuals originating in geologically disparate North Atlantic islands, much of southern and eastern England, coastal regions of Norway, or till-covered Denmark, may be impossible to discriminate using strontium isotopes alone.

Orkney and the Hebrides—different but the same?

Figure 3 illustrates the problem of similar isotope ranges most clearly for Orkney and the Outer Hebrides. These two island groups have different, but largely uniform, geology. Orkney is composed of Palaeozoic (Devonian) sandstone and the Outer Hebrides of PreCambrian gneiss, and biosphere strontium ratios in the region of 0.712–0.713 and 0.715–0.720, respectively, would be predicted (Evans et al. 2010). Their inhabitants should be relatively easy to distinguish, but they are not. All have distinctively high strontium concentrations and fall within the lower range of 0.7092–0.7100 (i.e., the dashed box in Fig. 3), indicating a strong marine strontium influence with only a small contribution from rock-derived strontium (Montgomery 2010). Similarly "dampened" ratios have also been obtained from individuals from other islands of old or granitic rocks such as Shetland, Lundy, Guernsey, Anglesey, and Skye (Evans et al. 2009, 2012; Keefe 2007). The individuals who plot outside the box all date to the Viking Age. For the three (Cnip D and E, Westness 5) who fall below the seawater line, there are no sources of strontium in either the Outer Hebrides or Orkney that could produce such low strontium ratios, which are restricted to biospheres hosted by basalts or marine carbonates such as chalks or limestones (Evans et al. 2010, Montgomery and Evans 2006, Price and Gestsdottir 2006). For the three individuals above the seawater line (Cnip A and Westness 11 and 12), their ratios could feasibly be provided by the rocks on the islands where they were buried, but based on current evidence, the food chain appears to be dominated by strontium of marine origin. This interpretation of origins elsewhere is given further support from the oxygen isotope evidence for all six of these individuals (Fig. 5): Westness 11 and 12 have similar $\delta^{18}O_p$ values that are too low for either Britain or Ireland; the remaining four (Westness 5 and Cnip A, D, and E) have low $\delta^{18}O_p$ values that are inconsistent with both the Hebrides and Orkney (estimated by the box in Fig. 5) as well as Shetland and most of the western seaboard of Britain.

The isotope study of the burials from the Norse cemetery at Cnip was the first case study published on burials from northern Britain (Montgomery et al. 2003), and there was at the time no comparative data or isotopic context in which to place it. As a consequence, it was difficult to establish with any certainty whether Cnip A, the female interred with a characteristically Viking burial assemblage could have obtained such strontium ratios growing up in the Hebrides or if the value was consistent with origins in Scandinavia. Since then, the unusual nature (high strontium concentrations coupled with marine-dominated strontium isotope ratios) of the strontium compositions of inhabitants of the Outer Hebrides and other North Atlantic Islands has become defined (Montgomery 2010, Montgomery et al. 2007a). Individuals such as Cnip A are clearly not the same as indigenous Hebrideans.

What is particularly interesting, however, when the Viking Age skeletons from both Westness and Cnip are considered together, is that there are three displaced females but none of them can be confidently assigned origins in Norway. For example, the female Westness 5 is neither from Orkney nor from the same place as the two Viking males. This finding is discussed further below. The strontium and oxygen isotope data support the dietary distinction that the two Viking males consumed significantly more marine protein than the Viking female (Barrett and Richards 2004) and suggest this may be a result of different cultural or geographic origins rather than that the Viking Age men and women at this site ate a different diet.

When all isotope systems are considered together, the evidence is consistent with the two Viking males originating from a location with access to marine protein, at a higher latitude than Orkney, possibly in central or northern Norway. That very similar strontium and oxygen isotope results were obtained from these two Viking males at Westness and the Viking male 223 from Dublin (two places of recognized Viking colonization and settlement), and several of the unaccompanied male skeletons from Weymouth and Oxford in southern England, suggests a similarity of origins among the men in these geographically distant and very different graves. It therefore provides further support to the conclusions (Chenery et al. 2014 [this volume]; Pollard et al. 2012) that members of the groups of males buried in Weymouth and Oxford were indeed of Scandinavian origin despite the absence of characteristic Viking grave goods or burial rite.

Displaced women: Different gender, different origins?

Strontium, oxygen, carbon, and nitrogen isotopes indicate that the Viking female (Westness 5) has different origins than the two Viking males from Westness. The isotope data also indicate that Orkney is not her homeland, and it is perhaps worth noting that she was of significantly lower stature than the other women buried at Westness (Sellevold 1999). She appears to have originated in a place where the consumption of marine protein was uncommon, in a region of either basalt or, possibly, chalk. Her strontium isotope ratio of 0.7073 is, however, unusually low for a chalk-dweller. In the Beaker People Project, for example, almost all of the ~230 individuals from England were buried in regions of chalks and limestones, but none had values below 0.7077 (Montgomery et al., in press). In Britain and Ireland, basalt is principally found on the western seaboard, forming the Inner Hebridean islands of Skye, Muck, Eigg, and Canna, the Midland Valley of mainland Scotland around Glasgow and Edinburgh, and in northeastern Ireland (British Geological Survey 2001). Further afield, are Iceland and the Faroes. Her $\delta^{18}O_p$ of 17.2‰ suggests that a childhood spent in northeastern Ireland or eastern Scotland is more likely than one in the Inner Hebrides where higher $\delta^{18}O$ values would be expected (Fig. 5). Westness 5 appears, therefore, to have been born outside the original Viking homelands in Scandinavia, and to have travelled to Orkney from her birthplace elsewhere in the North Atlantic.

The same appears to be the case for the two females buried at Cnip. Cnip E has a strontium profile (low strontium concentration, $^{87}Sr/^{86}Sr = 0.7086$) typical of chalk and some limestones, and she sits comfortably within populations from such regions in England (Evans et al. 2012, Jay et al. 2013, Montgomery 2002, Warham 2012). Cnip A is also displaced and, although her strontium isotope ratio of 0.7105 is relatively undiagnostic and falls within the "strontium of doom" range, her $\delta^{18}O_p$ of 16.7‰ is low for Britain and Ireland and would confine her to eastern or upland regions of Scotland and northern England. As can be seen in Figure 5, a similar combination of oxygen and strontium isotope ratios has previously been obtained for three male burials from Weymouth and Oxford that are also inconsistent with their place of burial. Moreover, another Viking-type female burial at Adwick-le-Street in Yorkshire (Speed and Walton Rogers 2004), and two individuals from Repton, Derbyshire—Grave X17, a female, and Grave 529, a man aged 25-35 buried near the chancel with a gold finger ring and five silver pennies that date to the mid-870s (Biddle and Kjølbye-Biddle 2001)—have almost identical isotope values to each other, and while it is tempting to assign foreign origins, neither their strontium nor oxygen isotopes can place them securely beyond the shores of northeastern England. Conversely, the three females from Cnip and Westness are inconsistent with their places of burial in the Western and Northern Isles and originated elsewhere. No females measured to date fall within the cluster of male skeletons from Dublin, Westness, Weymouth, and Oxford whose low oxygen isotope ratios, i.e., <16.1‰ (Fig. 5), suggest a broadly similar place of origin beyond the British Isles for this group of men.

Can we find Scandinavians in the Danelaw?

One individual who does not cluster with this group of male skeletons with low oxygen isotope ratios is the most distinctively Viking male burial at Repton: Grave 511 contained a mature male presumed due to the nature of his injuries to have been killed in battle and buried with a sword, silver Thor's hammer, and boar's tusk (Biddle and Kjølbye-Biddle 1992, Richards 2003). The same is true for the younger male from Grave 295 buried alongside him. Despite the variability in isotope ratios among the small number of individuals analyzed to date at Repton (Budd et al. 2004), these two males have similar profiles, suggesting similar origins, but this does not appear on current evidence to be in Norway. They both plot within the dashed box in Figure 5, and thus appear to be broadly consistent with the Hebrides and Orkney, but may equally be of local origin in Derbyshire or many other places in England (Evans et al. 2012). The strontium isotope ratio of the young adult male in Grave 295 (0.7090) suggests some input from marine carbonates such as chalk and limestone, which are found extensively across central and eastern England and regions of Europe such as Denmark (Frei and Frei 2011).

At first glance, the oxygen isotope ratio may appear too high for Denmark, but individuals with such values have been found at Danish sites (Fricke et al. 1995). Higher-than-expected $\delta^{18}O$ values in humans may be explained by the observation that drinking water sources such as lakes and rivers in this region of northern Europe have been shown to have higher $\delta^{18}O$ values than would be predicted from precipitation maps alone (Evans et al. 2012, Fronval et al. 1995). As a consequence, individuals from Migration Period cemeteries dating to the 5th to 7th centuries A.D. in eastern England, who are often found to have $\delta^{18}O$ values that are anomalously high for their location (Brettell et al. 2012a, Evans et al. 2012, Montgomery et al. 2009), may have originated in Denmark and northern Germany. It is also possible, therefore, that later individuals buried in the Danelaw of eastern England with high $\delta^{18}O$ values and strontium isotope ratios in the range of ~0.708 to 0.711 indicative of origins on the Mesozoic or Cenozoic sediments present in both locations, may have originated in Denmark. Consequently, for people migrating westwards from Denmark to eastern England in the 5th to 10th centuries A.D., oxygen isotopes may distinguish them from the indigenous population of eastern England when strontium isotopes cannot.

Using lead to distinguish individuals from polluted and unpolluted environments

Lead isotope ratios and lead concentrations have also been obtained for many of the individuals discussed above and permit the question of origins to be addressed from a somewhat different standpoint. Lead isotopes can provide information on geographic origins in a similar manner to strontium, i.e., it provides a link between the surface or drift geology in a region and the humans who live there. However, in England, the Roman Period heralds a fundamental change in how they can be used (Montgomery 2002). The large-scale extraction and smelting of lead ore for silver, lead products, and compounds and its consequent introduction into the human environment swamps natural background lead derived from country rocks and severs the link between a person and the location where they obtained their food and drink. In prehistory, all humans in Britain measured to date have enamel lead concentrations below 0.5 mg/kg and highly variable ratios reflecting geological variation (Montgomery et al. 2010). From the Roman Period onwards, there is a rise in human enamel lead concentrations, and while the level of lead exposure can be variable between individuals, those with more than 0.5 mg/kg of lead have uniform lead isotope ratios which are characteristic of galena, i.e., $^{207}Pb/^{206}Pb \approx 0.846$ (Montgomery et al. 2005, 2010). Essentially, from the Roman Period, the lead isotope ratios of humans in England appear to be culturally defined and reflect their access to lead products such as pewterware and exposure to environmental pollutants rather than their geographic place of origin. Thus, indigenous Britons with enamel lead levels above 0.5 mg/kg have similar anthropogenic lead isotope ratios.

Figure 6 demonstrates this radical shift using data from the prehistoric period and the Viking Age. Most of the individuals excavated from Riccall and Repton have English galena lead isotope ratios and lead concentrations often considerably in excess of the "natural" upper limit for lead exposure of 0.5 mg/kg. These individuals are consistent with childhood origins in a lead-polluted environment such as medieval England or places to which English lead was exported. Their strontium and oxygen isotope ratios would support this conclusion as all, given the uncertainties associated with the oxygen isotope data, could have origins in England (Fig. 5). In sharp contrast, all of the individuals from Dublin and Westness, and the male skeletons in Graves 511 and 295 at Repton, have low lead concentrations comparable with prehistoric humans. The lead data, therefore, would suggest that these two males buried at Repton spent their childhood in a land untouched by the Roman Empire's legacy of anthropogenic lead pollution, and had been exposed to low natural levels of lead comparable with the other Viking burials from Dublin and Orkney. However, while the strontium and oxygen isotope data would support a Norwegian origin for the Westness and Dublin Vikings, if the two Repton individuals had Scandinavian origins, they are more likely to be from Denmark.

Conclusions

The isotope data for Westness and Dublin, indicating as it does varied origins among even small numbers of individuals, supports similar conclusions reached by Price et al. (2011) at Trelleborg and the observation that the "Viking Armies were not homogeneous groups; they contained those of diverse beliefs and ideologies" (Richards 2003:394). It would appear that such observations apply to both men and women but, as was found at Westness, displaced Viking women do not appear to hail from the same places as the men: no women were among the group of men with low oxygen isotope ratios suggestive of more northerly origins, possibly in central or northern Norway. Given the varied but

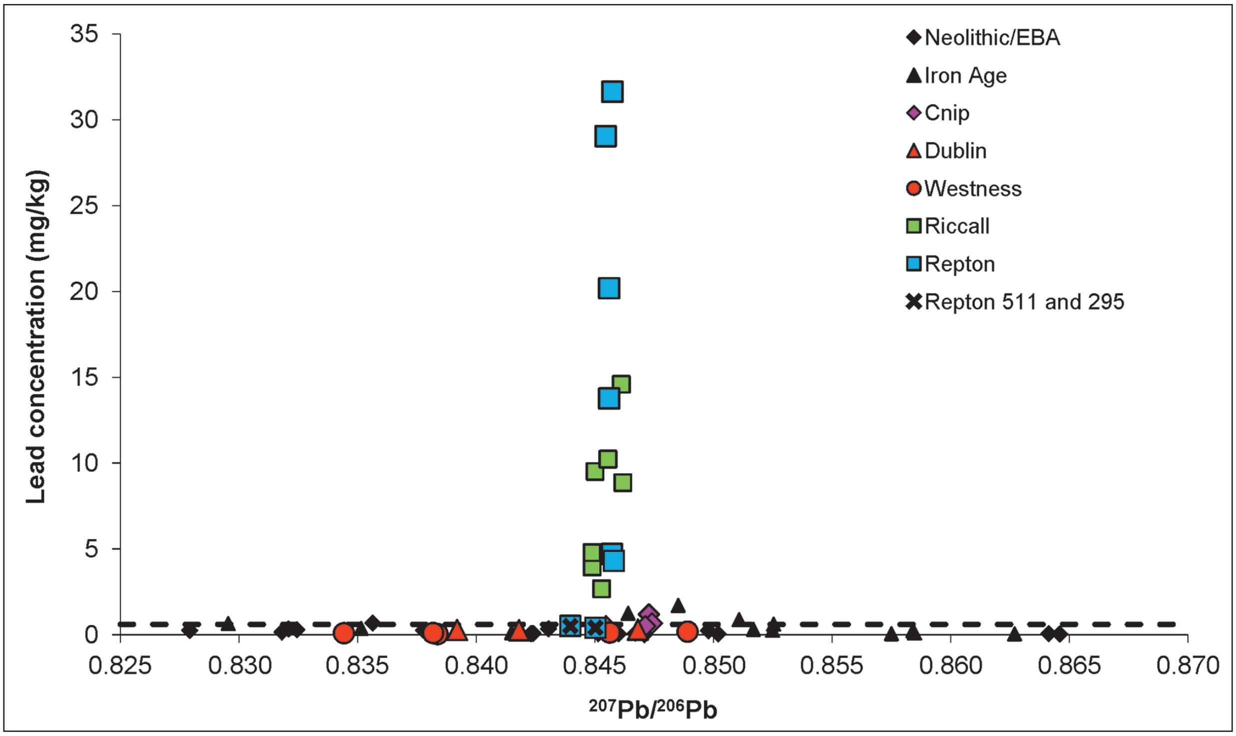

Figure 6. A plot of $^{207}Pb/^{206}Pb$ against lead concentration (mg/kg) showing cultural focusing of lead isotope ratios. The dotted line defines the upper limit for natural lead exposure at 0.5 mg/kg. Prehistoric and Viking Age individuals with low lead concentrations have variable lead isotope ratios indicating their lead comes from natural and varied rock sources unaffected by pollution. Individuals from Repton and Riccall have high lead concentrations and uniform lead isotope ratios of ≈0.846, consistent with English sources of galena and indicating exposure to anthropogenic pollutants. Data source: Montgomery et al. (2010).

predominantly maritime and coastal origins of individuals in the Viking World, it is not surprising that one isotope system alone does not always provide a clear discriminant. This paper, however, attempted to illustrate how when one isotope system fails, another can be successful given prior knowledge of what is normal for the location and time period under investigation. To this end, it is hoped that the observation that trace elements such as strontium and lead can identify migrants to and from wet and windy isles in the Viking Age will be of particular use.

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