Journal of Archaeological Science 39 (2012) 308–320

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Migration and Viking Dublin: paleomobility and paleodiet through isotopic analyses

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ARTICLE INFO

Article history:
Received 8 April 2011
Received in revised form
12 September 2011
Accepted 15 September 2011

Keywords:
Bioarcheology
Biogeochemistry
Carbon isotope analysis
Ireland
Nitrogen isotope analysis
Oxygen isotope analysis
Radiogenic strontium isotope analysis

ABSTRACT

During the early medieval period in Ireland, Dublin was established as the largest Viking settlement on the island in the ninth century AD. A previous biodistance study has suggested that the population of the town consisted of a polyethnic amalgam of immigrant and indigenous. In this study, we use biogeochemistry to investigate paleomobility and paleodiet in archeological human remains from the ninth to eleventh century levels at the sites at Fishamble Street II (National Museum of Ireland excavation number E172), Fishamble Street III (E190) and John's Lane (E173), as well as twelfth-century remains from Wood Quay (E132). Through radiogenic strontium isotope, stable oxygen, carbon, and nitrogen isotope, and elemental concentration analyses, we investigate the origins of the individuals who lived and died in early and late Viking Dublin. Mean archaeological human enamel and bone isotope values from Dublin are $^{87}Sr/^{86}Sr = 0.70975 \pm 0.00139$ (2σ, $n = 22$), $\delta^{13}C_{carbonate(V\text{-}PDB)} = -14.8‰ \pm 0.8‰$ (1σ, $n = 12$), and $\delta^{18}O_{carbonate(V\text{-}PDB)} = -7.2‰ \pm 1.0‰$ (1σ, $n = 12$). Archaeological human bone samples exhibit mean $\delta^{13}C_{collagen(V\text{-}PDB)} = -20.8‰ \pm 0.5‰$ (1σ, $n = 12$) and mean $\delta^{15}N_{collagen(AIR)} = +10.0‰ \pm 1.7‰$ (1σ, $n = 12$). Comparing these data with archaeological faunal data from Dublin and published data from northern Europe, we argue that there are no clear immigrants from other parts of the North Atlantic, although there is one clear outlier in both origins and diet. Overall, the relative homogeneity in both paleomobility and paleodiet may support models of acculturation in Viking Dublin, rather than a high number of first-generation immigrants or continued migration from Scandinavia.

1. Introduction

Viking expansion began at the end of the eighth century AD and resulted in the establishment of Scandinavian settlements in northwestern Europe and beyond. In Ireland, Dublin was established in the ninth century AD and became the largest and most powerful Viking settlement on the island. The early medieval core of Viking Dublin has been extensively excavated, and has produced a wealth of information regarding the nature of the early settlement and the daily life of its inhabitants between the ninth and thirteenth centuries. Material culture studies suggest considerable acculturation between colonial and native groups (Fanning, 1994; Hurley, 2010; Hurley et al., 1997; Lang, 1988; Wallace, 1992a,b). This model of interaction has been supported by a bioarcheological biodistance analysis (O'Donnabhain and Hallgrímsson, 2001), which suggested that the town was ethnically mixed with a significant representation of the indigenous population. Despite the evidence for acculturation and admixture, the town of Dublin maintained a distinctive identity from that of its immediate neighbors until its conquest by King Henry II of England in 1170 (Downham, 2007; O'Donnabhain and Hallgrímsson, 2001). Here, we use biogeochemistry to investigate paleomobility and paleodiet in archaeological human remains excavated from four sites from ninth through twelfth century levels in Viking Dublin. More specifically, we include archeological human remains from the ninth to eleventh century levels at the sites of Fishamble Street II (National Museum of Ireland excavation number E172), Fishamble Street III (E190) and John's Lane (E173), as well as twelfth-century remains from Wood Quay (E132). Through radiogenic strontium isotope, stable oxygen, carbon, and nitrogen isotope, and elemental concentration analyses, we investigate the geographic origins and dietary practices of the individuals who lived and died in Dublin through the Viking period.

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doi:10.1016/j.jas.2011.09.014

We first briefly introduce the use of biogeochemistry to investigate paleomobility and paleodiet. We then discuss expected radiogenic strontium and stable oxygen, carbon and nitrogen values in northern Europe and in the individuals analyzed here, based on published data. We follow these sections with a presentation of our materials, methods, and biogeochemical data from archeological human and faunal remains from Viking Dublin. We conclude with our interpretations of these data.

2. Paleomobility and paleodiet through biogeochemistry

Paleomobility is increasingly measured through isotopic values in archeological human remains. Briefly, radiogenic strontium isotope values ($^{87}Sr/^{86}Sr$) vary based on bedrock age and composition (Dickin, 1997; Faure, 1986). Radiogenic strontium isotopes do not fractionate appreciably in an ecosystem, so that the radiogenic strontium isotope signature in bedrock, soils, and plants will be reflected in the animals and humans that consume strontium from those sources (Bentley, 2006). If an individual consumed and imbibed locally procured strontium, enamel and bone radiogenic strontium isotope values can be used to reconstruct paleomobility (Ericson, 1985; Price et al., 1994a,b). In contrast, oxygen isotope signatures in water sources vary according to environmental factors including the oxygen isotope values in the source area, altitude, latitude, number of precipitation events, and temperature (Bowen and Wilkinson, 2002; Craig, 1961a; Gonfiantini, et al., 2001; Longinelli, 1984; Luz and Kolodny, 1985; Luz et al., 1984). Despite complexities in the movement and treatment of water sources in the past (Knudson, 2009), oxygen isotope analysis can also identify paleomobility (Evans et al., 2006a; White, et al., 2000).

Paleodietary studies using light stable isotopes of carbon utilize the fact that some plants, including tropical grasses, fix carbon using a different photosynthetic pathway (the C_4 or Hatch–Slack pathway) than most other plants, which use the C_3 (Calvin) photosynthetic pathway (Calvin, 1962; Calvin and Benson, 1948; Hatch and Slack, 1966; Hatch et al., 1967; Kortshack et al., 1965; Ranson and Thomas, 1960). Paleodietary analysis of hydroxyapatite carbonate elucidates whole diet carbon sources while collagen largely reflect protein sources in the diet (Ambrose and Norr, 1993; Jim et al., 2004; Kellner and Schoeninger, 2007; Lee-Thorp et al., 1989, Lee-Thorp and van der Merwe, 1991). In addition, marine and terrestrial resources exhibit distinct carbon and nitrogen isotope values (Chisholm et al., 1982; Schoeninger and DeNiro, 1984). Although stable nitrogen isotope values vary according to trophic level and are particularly useful in identifying the use of marine resources (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984; Schoeninger et al., 1983), we note that there are also climatic factors that affect nitrogen isotope values (Ambrose, 1991; Ambrose and DeNiro, 1987).

Finally, the concentrations of major, minor and trace elements have been used for paleodietary and paleomobility studies (Burton, 1996; Burton et al., 2003, Ezzo et al., 1995; Schoeninger, 1978, 1979; Schutkowski et al., 1999; Shaw et al., 2010). There are clear trophic level differences in barium and strontium concentrations when compared to calcium concentrations (Ba/Ca, Sr/Ca) (Blum et al., 2000; Burton et al., 1999; Elias, 1980; Price et al., 1985, Price et al., 1986). However, geographic variability and dietary sources can complicate the use of trace element concentrations in paleodietary studies (Burton and Price, 2000; Burton et al., 2003, Burton et al., 1999; Burton and Wright, 1995; Ezzo, 1994a,b). Here, we use major, minor and trace element data to evaluate diagenetic contamination and evaluate the presence of marine products in the diet through relative concentrations of barium and strontium (Ba/Sr) (Burton and Price, 1990).

3. Biogeochemical signatures in Northern Europe

3.1. Radiogenic strontium isotope signatures in Northern Europe

The geology of northern Europe contains a highly variable array of radiogenic strontium isotope ratios, although generally speaking some of the oldest rocks on the continent are in Norway, parts of Sweden and the northern parts of the United Kingdom and Ireland. Also in general terms, the oldest rocks and highest radiogenic strontium isotope values are to be found in the more northern parts of these areas (Voerkelius et al., 2010). For example, Scotland, the Northern Isles, and parts of County Antrim in Ireland have varying but generally high $^{87}Sr/^{86}Sr$ values (Voerkelius et al., 2010). Here, we focus on bedrock geology and radiogenic strontium isotope data, when available, from Ireland, the United Kingdom, and parts of Scandinavia, as discussed below, with additional sites included in Fig. 1 (Bendrey et al., 2009; Bentley et al., 2002; Budd et al., 2003; Chenery et al., 2010; Darbyshire and Shepherd, 1985; Gallet et al., 1998; Leach et al., 2010, Leach et al., 2009, Muldner et al., 2011; Negrel et al., 2003; Nehlich et al., 2009; Price et al., 2001; Sykes et al., 2006).

The geology of Ireland is complex and consists, at the base, of the remains of ancient mountain ranges with heavily folded crystalline and metamorphic rocks. These rock formations are exposed as the hills and mountains of the north and the west of the island. These rocks, particularly in the north, are of substantial age and likely have quite high radiogenic strontium isotope ratios. Tertiary basalts in northeast Ireland, on the other hand, are relatively young and low in rubidium and exhibit radiogenic strontium isotope values between $^{87}Sr/^{86}Sr = 0.704$ and $^{87}Sr/^{86}Sr = 0.707$ (O'Connor, 1988; Wallace et al., 1994). Limestone deposits are found in limited areas, largely in the west and southwest of Ireland; these marine sediments will have radiogenic strontium isotope values closer to modern seawater, in which $^{87}Sr/^{86}Sr = 0.709$ (Burke et al., 1982; McArthur et al., 2001; Veizer, 1989). The bedrock under Dublin consists primarily of marine basinal facies and argillaceous and cherty limestone and shale that formed during the late Paleozoic (Geological Survey of Ireland, 2009). However, much of the solid geology of the island is buried under glacial moraine that was deposited during the Pleistocene when the ice sheets covered most or all of Ireland (McCabe, 2007). Some of the glaciated lowlands of Ireland have moraine deposits over 30 m thick and form a landscape independent of the rock formations buried deeply beneath the ground (Clayton, 1963; Geikie, 1910). The material in the glacial moraine likely originated in part from the rocky structures of Ireland as the ice passed over the land surface and in part as detritus from the sea floor and Scandinavia was transported by the ice. Thus, the bedrock geology of much of Ireland, including the Dublin region, is not a good guide to bioavailable radiogenic strontium isotope ratios.

Radiogenic strontium isotope values in England and Scotland in the United Kingdom are better understood (see overviews in Evans et al., 2010; Montgomery et al., 2005, Montgomery et al., 2006). In the United Kingdom, soil leachate values suggest labile $^{87}Sr/^{86}Sr$ variations among soils overlying sedimentary rocks from approximately $^{87}Sr/^{86}Sr = 0.7073$ on Cretaceous chalk to $^{87}Sr/^{86}Sr = 0.7115$ on Triassic sandstone (Budd et al., 2000). Soils formed on igneous and metamorphic rocks as well as rubidium-rich clay soils are likely to have far higher strontium isotope ratios. Finally, Evans et al. (2010) provide bioavailable strontium isotope data from modern plants across the United Kingdom that show a general trend toward values between $^{87}Sr/^{86}Sr = 0.707–0.712$ in the south and east, $^{87}Sr/^{86}Sr = 0.711–0.713$ in the west, and $^{87}Sr/^{86}Sr = 0.712–0.720$ in the north.

Based on bedrock geology, England is dominated by Cretaceous chalks in the south and east and Jurassic clays in the west and north

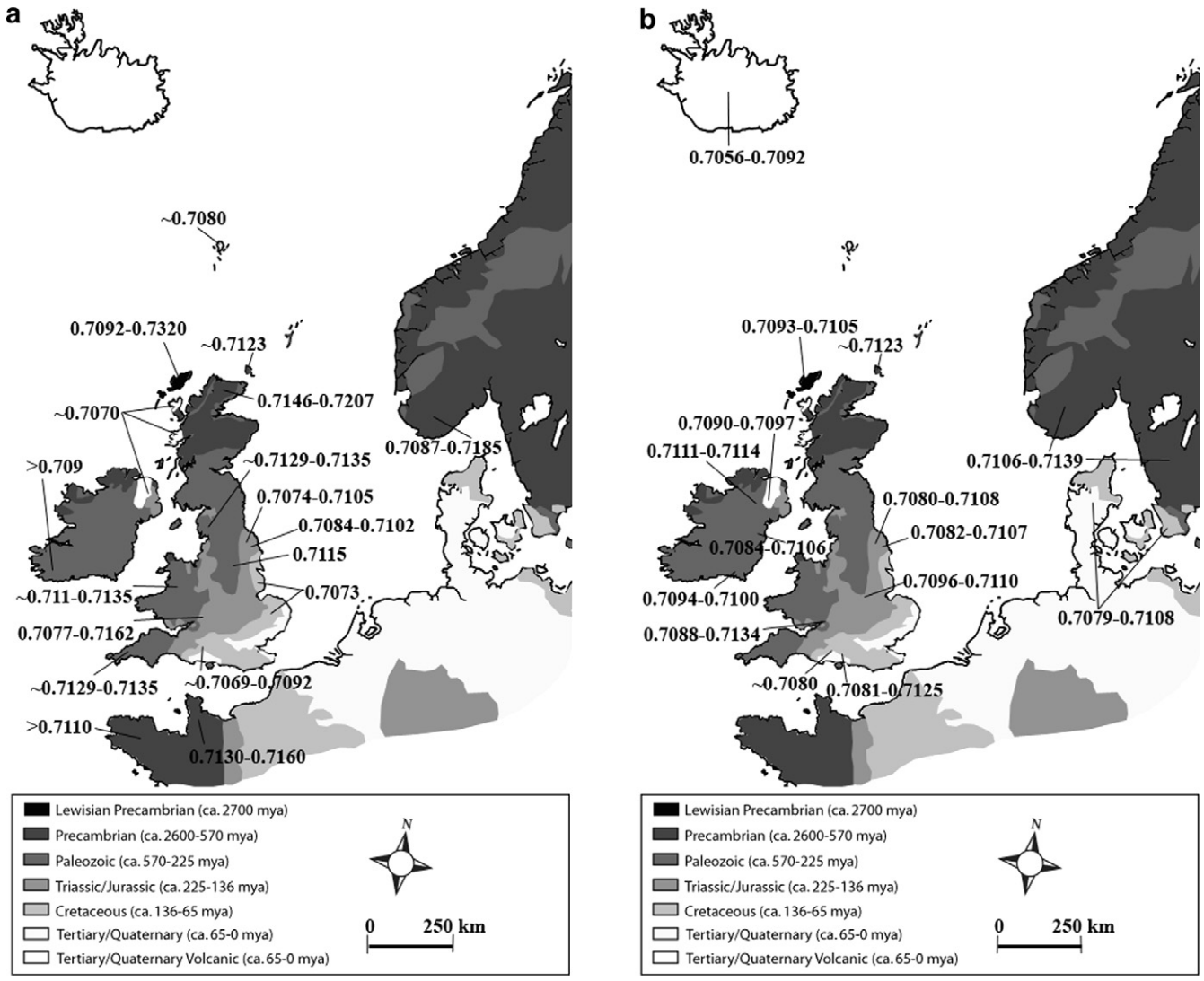

Fig. 1. a). Published radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values from bedrock and water sources in Northern Europe (Aberg et al., 1998; Budd et al., 2000; Burke et al., 1982; Darbyshire and Sheperd, 1985; Dickin, 1997; Gallett et al., 1998; McArthur et al., 2001; Negrel et al., 2003; O'Connor, 1988; Voerkelius et al., 2010; Wallace et al., 1994; Wilson et al., 1977). b). Published bioavailable radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) values from human and faunal remains in Northern Europe (Bendrey et al., 2009; Bentley et al., 2002; Budd et al., 2003, Budd et al., 2004; Chenery et al., 2010; Evans et al., 2006a,b, Evans and Tatham, 2004; Frei and Price, in press; Leach, et al., 2009, Leach et al., 2010, Nehlich et al., 2009; Montgomery et al., 2003, Montgomery et al., 2005, Muldner et al., 2011; Price and Gestsdóttir, 2005; Price et al., in press, Price et al., 2001; Sykes et al., 2006; Sjögren et al., 2009).

(see overviews in Evans et al., 2010; Montgomery et al., 2005, Montgomery et al., 2006). Radiogenic strontium isotope ratios in soil leachates from southern England exhibited mean $^{87}Sr/^{86}Sr = 0.7084 \pm 0.0011$ (2σ, $n = 9$) (Budd et al., 2004). Individuals interpreted as "local" who were living on Jurassic clay-carbonates in eastern England exhibited mean $^{87}Sr/^{86}Sr = 0.7098 \pm 0.0018$ (2σ, $n = 22$) (Evans and Tatham, 2004). In southern England, which is dominated by chalk with Oligocene and Eocene sands, clays and limestone, archeological human samples from "local" Romano-British burials exhibited $^{87}Sr/^{86}Sr = 0.7085 \pm 0.0004$ (2σ, $n = 7$) (Evans et al., 2006b); similar values were obtained in "local" individuals buried near Stonehenge in southern England (Evans et al., 2006a).

In Scotland, the Scottish Highlands are dominated by very old Precambrian bedrock (Drury, 1973; Negrel et al., 2003), which exhibit high $^{87}Sr/^{86}Sr$ values; Scottish mineral waters from the highlands exhibited $^{87}Sr/^{86}Sr = 0.7146–0.7207$ (Montgomery et al., 2006). The northern islands of Scotland, which include the Orkney Islands, the Shetland Islands, and the Hebrides, exhibit high radiogenic strontium isotope ratios. For example, the Orkney and Shetland Islands predominately consist of Devonian sedimentary rocks such as sandstones (British Geological Survey, 2010, see also Read, 1934); a modern faunal sample from the Orkney Islands exhibited $^{87}Sr/^{86}Sr = 0.7123$ (Price and Getsdóttir, 2006). In the Inner and Outer Hebrides, the bedrock is largely Precambrian metamorphic and sedimentary rock with some Paleogene igneous formations (British Geological Survey, 2010). Archeological human remains interpreted as "local" to the Isle of Lewis in the Hebrides exhibited approximately $^{87}Sr/^{86}Sr = 0.7092$ (Montgomery et al., 2003).

Bedrock geology in Norway, Sweden, and Denmark, likely sources of Viking migrants to Ireland (Blum et al., 2000; Holm, 2000), implies that individuals who lived in these areas would be distinguished between individuals who lived in or around Dublin. More specifically, granites and gneiss samples from southern Norway exhibited $^{87}Sr/^{86}Sr = 0.7087–0.7185$, with one extremely high value of $^{87}Sr/^{86}Sr = 0.7519$ (Wilson et al., 1977). Archological and modern human enamel samples from southern Norway exhibited

$^{87}Sr/^{86}Sr = 0.7077–0.7323$ (Aberg et al., 1998). However, this is quite variable, and more recent comparisons of archeological faunal and human remains as well as modern faunal samples provide a range of $^{87}Sr/^{86}Sr = 0.7090–0.7108$ for southern Scandinavia (Price et al., in press). Other potential Viking homelands in Sweden have some radiogenic strontium isotope data available. Sjögren et al. (2009) report bioavailable radiogenic strontium isotope values of $^{87}Sr/^{86}Sr = 0.711–0.714$ from Bohuslan along the west coast of Sweden. Lower values in a range from $^{87}Sr/^{86}Sr = 0.7079$ to $^{87}Sr/^{86}Sr = 0.7108$ are reported from Scania, the southernmost province of Sweden, with a landscape very similar to much of Denmark (see discussion in Sjögren et al., 2009). In Denmark, the bedrock exhibits distinct radiogenic strontium isotope values when compared to the higher Norwegian values. Frei and Price (in press) have measured bioavailable strontium isotope ratios on modern and archeological fauna in Denmark and report a generally homogeneous range within the country between $^{87}Sr/^{86}Sr = 0.7079–0.7108$ (see also Price et al., in press). In general, the surface geology in Denmark is Tertiary and Quaternary in origin, with some Cretaceous chalk in the north and east in Denmark (see overview in Montgomery et al., 2005).

However, radiogenic strontium isotope values in bedrock do not necessarily reflect the bioavailable strontium ratios, as previously discussed. For example, sea spray contributes $^{87}Sr/^{86}Sr = 0.7092$ from seawater (Veizer, 1989; Whipkey et al., 2000). It is preferable to establish a "local" signature using faunal samples local to the area (Fig. 1) (Evans and Tatham, 2004; Price et al., 2002). A potential confounding factor is that many Viking settlements across the North Atlantic tend to cluster along the coast (Clarke and Ambrosiani, 1991) and thus may have similar $^{87}Sr/^{86}Sr$ values due to the effect of sea spray or the consumption of strontium from marine sources.

3.2. Bioavailable strontium sources in Viking Dublin

Strontium substitutes for calcium in hydroxyapatite (Carr et al., 1962). The main source of strontium found in the body is through ingested food that is high in calcium (Burton and Price, 1990, 2000; Burton et al., 1999; Burton and Wright, 1995). Therefore, understanding Viking paleodiet, and likely strontium sources, is necessary when using radiogenic strontium isotopes to understand Viking mobility.

A tenth-century poem notes that Dublin was known for the good quality of its wheat and cheese, suggesting considerable production (Holm, 2000). Additionally, the Irish word for bean, *ponair*, is of Norse origin, suggesting that legumes too were grown with some frequency (Holm, 2000); in fact, cereals (*Triticum* sp.), beans (*Vicia faba*), sloe berries (*Prunus spinosa*), rowan berries (*Sorbus aucuparia*), bilberries (*Vaccinium* sp.), and hazelnuts (*Corylus* sp.) are present in the fecal matter from Dublin (Geraghty, 1996). The $^{87}Sr/^{86}Sr$ values in these foods will reflect that of the soil in which they were growing.

Given the large number of cattle (*Bos taurus*) bones found from a range of Viking sites including Orkney, Dublin, and York (Barrett, 1995: 112, McCormick, 1982: 152–156, O'Connor, 1989: 151, 156) and literary references to Dublin cheese (Barrett, 1995; Holm, 2000), dairy products were likely a primary source of calcium. However, biopurification ensures that strontium is discriminated against in ingested elemental uptake by mammals (Burton, 1996; Burton and Price, 2000), so the overall strontium concentration in dairy products is relatively low.

One possible confounding factor is that mineral consumption, like that of sea salt, can provide both calcium and strontium and could therefore have a major impact on radiogenic strontium isotope values (Wright, 2005). Furthermore these items are often traded over long distances, possibly influencing the radiogenic strontium isotope values found in humans across a wide geographic area (Wright, 2005). It is possible that individuals in Dublin were consuming salt from non-local, terrestrial sources, or sea salt. A further possible confounding factor is the tradition of the consumption of edible seaweeds in Ireland, specifically dulse (*Palmaria palmata*). Consumption of dulse is mentioned in early medieval law tracts from Ireland and it seems to have been used on a seasonal basis as a condiment or relish (Kelly, 1988; Sexton, 1998).

In addition, since seawater has an isotopic signature of $^{87}Sr/^{86}Sr = 0.7092$ (Veizer, 1989), radiogenic strontium isotope values may reflect the consumption of large amounts of strontium from marine sources, including marine products and/or marine salt (Wright, 2005). As discussed below, marine sources were an important part of Viking diets (e.g., Barrett, et al., 2001; Kosiba et al., 2007; Richards et al., 2006). Marine contributions of strontium and calcium will be greater if the bones were consumed. If so, gastric etching, or stomach acid etching of the bone as it passes through the digestive tract, is to be expected on the faunal material. However, faunal reports from York (O'Connor, 1989), Lincoln (O'Connor, 1982), and Orkney (Barrett, 1995) do not mention gastric etching. This suggests that fish vertebra and crania (fish ribs are rarely found due to their small size and delicate nature), were not consumed. The fish bones from Dublin are currently being examined and gastric etching has not been noted (McCarthy, personal communication). However, wet-sieving was not standard practice on archeological excavations in the 1970s and this may have resulted in the under-representation of fish bones of a size that were likely to have been consumed.

3.3. Oxygen isotope signatures from Northern Europe

In Ireland, mean annual oxygen isotope signatures in precipitation, or meteoric water, range from $\delta^{18}O_{mw(V\text{-}SMOW)} = -5‰$ to $\delta^{18}O_{mw(V\text{-}SMOW)} = -8‰$ (IAEA/WMO, 2006). This is in contrast to mean annual oxygen isotope signatures in meteoric water in much of Scandinavia, which range from $\delta^{18}O_{mw(V\text{-}SMOW)} = -8‰$ to $\delta^{18}O_{mw(V\text{-}SMOW)} = -11‰$ (IAEA/WMO, 2006). Similar trends are present in oxygen isotope signatures in migratory bird feathers (Hobson et al., 2004) as well as in archeeological human remains from northern Europe (e.g., Bentley and Knipper, 2005; Eckhardt et al., 2009; Evans et al., 2006a, 2006b; Fricke, et al., 1995).

However, we note that oxygen isotope data are complex and affected by many factors (Knudson, 2009). For example, in European studies that utilize oxygen isotope data, controversy surrounds the role of environmental variables and the role of human behavioral changes, such as weaning, diet and mobility and their effects on oxygen isotope signatures (Bryant and Froelich, 1996; Fricke et al., 1995). In addition, the consumption of ^{18}O-enriched breast milk before and during the weaning process will also affect the oxygen isotope values in enamel and bone that formed before and during weaning (Dupras and Tocheri, 2007; Herring et al., 1998; Knudson, 2009; Williams et al., 2005; Wright and Schwarcz, 1998).

3.4. Carbon and nitrogen isotope signatures from Northern Europe

In general, C_4 plants exhibit $\delta^{13}C_{(V\text{-}PDB)} = -9‰$ to $\delta^{13}C_{(V\text{-}PDB)} = -14‰$ while C_3 plants exhibit $\delta^{13}C_{(V\text{-}PDB)} = -20‰$ to $\delta^{13}C_{(V\text{-}PDB)} = -35‰$ (e.g., DeNiro and Epstein, 1978; Tieszen and Chapman, 1992). Plants consumed in Viking Dublin, as previously discussed, are C_3 plants. Similarly, terrestrial animals likely to have been consumed exhibit low $\delta^{13}C_{collagen(V\text{-}PDB)}$ values. For example, archeological terrestrial fauna in the Orkney Islands exhibited $\delta^{13}C_{collagen(V\text{-}PDB)} = -21.8‰ \pm 0.2‰$ (2σ, $n = 9$) in cattle (*B. taurus*),

$\delta^{13}C_{collagen(V\text{-}PDB)} = -21.8‰ \pm 0.8‰$ (2σ, $n = 5$) in sheep and/or goats (*Ovis aries/Capra hircus*), and $\delta^{13}C_{collagen(V\text{-}PDB)} = -20.6‰ \pm 1.3‰$ (2σ, $n = 6$) in pigs (*Sus scrofa*) (Richards et al., 2006).

Since there was little use of C_4 plants in Viking Age North Atlantic Europe, carbon isotope analysis in Europe is generally used to distinguish between the consumption of marine and terrestrial resources. For example, in an individual who consumed a diet of 100% marine protein, $\delta^{13}C_{collagen(V\text{-}PDB)} = -12.0‰ \pm 1.0‰$, while an individual who consumed a diet of 100% terrestrial protein would exhibit approximately $\delta^{13}C_{collagen(V\text{-}PDB)} = -20.0‰$ 1.0‰ ‰ (Richards et al., 2006). Therefore, higher $\delta^{13}C_{collagen(V\text{-}PDB)}$ values in individuals buried in Viking Dublin are likely due to increased use of marine protein resources.

Since it is difficult to use carbon isotopes to estimate the precise percent of marine resources accounted for in diet, combining carbon and nitrogen isotope analyses helps address marine-product consumption. Nitrogen isotope analysis relies on trophic level variability in both marine and terrestrial ecosystems, with an approximate differences of 2–4‰ in $\delta^{15}N_{collagen(AIR)}$ values when comparing producers and consumers (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984; Schoeninger et al., 1983). The highest $\delta^{15}N_{collagen(AIR)}$ values generally result from top-level predators in marine ecosystems. For example, seals (species unidentified) from the Orkney Islands exhibited $\delta^{15}N_{collagen(AIR)} = +17.2‰ \pm 1.5‰$ (2σ, $n = 8$), while fish (species unidentified) bones exhibited $\delta^{15}N_{collagen(AIR)} = +13.6‰ \pm 1.0‰$ (2σ, $n = 4$) (Richards et al., 2006). Therefore, higher $\delta^{15}N_{collagen(AIR)}$ values in individuals buried in Viking Dublin are likely due to increased use of marine protein resources.

When data from both carbon and nitrogen isotope values are combined, a number of researchers have demonstrated paleodietary variability in Viking Age North Atlantic Europe. For example, Barrett et al. (2001) documented increased marine consumption during the Viking phase of occupation in Orkney. Similarly, Arneborg et al. (1999) documented marine consumption at Norse sites in Greenland. However, individual Viking diets could vary within the same population (Linderholm et al., 2008; Richards et al., 2006). Richards et al. (2006: 128) report that, "there is no shift in diet through times by all individuals, merely an increase in the frequency of individuals with marine isotope values in the Viking and Medieval periods". Further, they find a significant difference between males and females, with males eating more marine protein than females (Richards et al., 2006). In contrast, at Birka, Linderholm et al. (2008) find no significant difference in diet between individuals of different sexes, statuses, or burial locations within the site, although individuals buried with weapons consumed significantly more marine products. Overall, there is no one "typical" Viking diet. However, individuals from a contemporary Arctic hunter–gatherer group in Hudson Bay consumed more marine resources than individuals from the Viking sites (Coltrain, 2009; Coltrain et al., 2004). Therefore, Norse individuals likely consumed substantial amounts of terrestrial resources with variable amounts of marine products (Linderholm et al., 2008; Linderholm and Kjellstrom, 2011; Richards et al., 2006). Finally, the consumption of breast milk will affect $\delta^{15}N_{collagen(AIR)}$ values, since enamel or bone that formed before or during the weaning process, $\delta^{15}N_{collagen(AIR)}$ values will be 2–4‰ higher than the breast milk (Dupras et al., 2001; Dupras and Tocheri, 2007; Fuller et al., 2006; Herring et al., 1998; Richards et al., 2002; Schurr, 1998; Williams et al., 2005).

3.5. Trace element concentration data from Northern Europe

While the concentrations of major, minor, and trace elements can vary with trophic level, they are also influenced by geographic region and diagenetic contamination (Burton and Price, 2000; Burton et al., 2003, Burton et al., 1999; Burton and Wright, 1995; Ezzo, 1994a, Ezzo, 1994b; Ezzo, et al., 1995). However, there are clear differences in the ratios of barium to strontium (Ba/Sr) in marine and terrestrial environments, since most barium in seawater is found in insoluble barium sulfate (Burton and Price, 1990). Individuals who consumed large amounts of marine products should exhibit low log(Ba/Sr) values of approximately log(Ba/Sr) = −2.0 to log(Ba/Sr) = −1.0, while individuals who consumed largely terrestrial resources should exhibit higher log(Ba/Sr) values of approximately log(Ba/Sr) = −0.5 to log(Ba/Sr) = 0.0 (Burton and Price, 1990).

4. The archeological human remains from Viking Dublin

4.1. An introduction to the mortuary population of Viking Dublin and previous bioarcheological research

Viking territorial gains in Ireland were limited to a small number of coastal enclaves and the nucleated settlements established at these footholds are considered the first truly urban communities on the island. The Irish coastal towns were integrated into wider Viking trade networks in the North Atlantic and beyond, facilitating the exchange of goods, and likely personnel, through the period covered by this study. Established on the east coast of the island in the ninth century AD, Dublin grew to become the largest and most powerful of these settlements. Interpretations of the material culture evidence suggest that, by the eleventh century, a considerable degree of assimilation had occurred between Irish and Scandinavian groups (Hurley, 2010; Hurley et al., 1997; Wallace, 1992a). Other archeological studies have noted significant changes in material culture in the tenth century that may be attributed to interactions with polities around the Irish Sea (e.g., Cameron, 2007; Halpin, 2008). Biodistance analysis also implied that there was significant gene flow between the native and non-local populations (O'Donnabhain and Hallgrímsson, 2001). This model of gene flow has also been supported in the greater Irish Sea area and beyond by studies of the DNA of modern populations (e.g., Bowden, et al., 2008; Helgason et al., 2001). These archeological narratives of acculturation and assimilation contrast with the early medieval historical record where Irish chroniclers tended to portray the Dubliners in negative terms and up until the twelfth-century used terms like the 'foreigners of Dublin' to describe the inhabitants of the settlement (e.g., Annals of Ulster, 431–1131).

4.2. Archeological contexts of the human remains included in biogeochemical analyses

The National Museum of Ireland undertook a series of excavations in the Viking Age core of the city between 1974 and 1981 at a number of contiguous sites at Fishamble Street, John's Lane and Wood Quay under the direction of Dr. P.F. Wallace. The skeletal material recovered from these sites was sampled for this study. At these sites, some complete skeletons and portions of skeletons were recovered, although much of the assemblage consists of isolated bones that were found scattered in the general matrix at the sites (O'Donnabhain, 2010). The skeletal material from Fishamble St (I–III), John's Lane and Wood Quay represents the largest extant collection of archeological human remains from early and late Viking Dublin; while we acknowledge that this is not a typical mortuary population, we also note that the human remains from the ninth century cemeteries west of Dublin that were discovered in the nineteenth and early twentieth centuries were not curated (O'Brien, 1998), and the later cemeteries associated with the settlement have not be explored archeologically.

The curated mortuary assemblages from Fishamble Street II (E172), Fishamble Street III (E190), John's Lane (E173) and Wood Quay (E132) have a combined MNI of 70 individuals. For the current study, we analyzed dental and skeletal elements from 11 individuals for a total of 11/70 or 15.7% of the curated MNI. The more complete remains were not found in cemeteries or areas that are likely to have been regarded by the inhabitants of the town as formal areas for the disposal of the dead. The adult crania from these sites were all scored for the earlier biodistance study conducted by O'Donnabhain, in which sampling needs necessitated pooling data from the four sites and early and late periods.

The many excavations carried out in the historic core of Dublin over the last three decades have also produced Viking Age human remains. This has included some eighth/ninth century burials accompanied by Viking artefacts (Sikora, 2010, 2011; Simpson, 2005). Stable isotope analysis was carried out on five 'warrior' burials but only preliminary results have been published to date (Simpson, 2005). Similarly, Daly's (2010) preliminary study of a burial with Viking Age artifacts also indicates that this individual was of "non-local" origin (Sikora, 2011).

4.3. Archeological human remains from Period I

The skeletal remains from the four excavations comprise two distinct temporal groups. The earlier of these (Period I) consists of the skeletal material recovered from ninth to eleventh century levels at the sites at Fishamble Street II (E172), Fishamble Street III (E190) and John's Lane (E173). These earlier archeological human remains consisted of a small number of skeletons that were found at the lowest levels of two of the sites (E190 and E173). These burials were not in formal cemeteries and some of them were in flexed and semi-flexed positions that would not have been standard among the contemporary Christian Irish. The bulk of the Period I assemblages though consisted of isolated skulls and skull fragments that were found in association with a succession of three earthen embankments that were built along the waterfront of the tidal estuary of the River Liffey. Many of these skulls and skull fragments have evidence of peri-mortem sharp-force trauma; there is also circumstantial evidence for the display of at least some of these skulls as trophy heads. At the time of excavation, these earlier remains were dated on stratigraphic evidence to the tenth and eleventh centuries. Recent radiocarbon dates have indicated that the actual range is from the ninth to eleventh centuries (O'Donnabhain, in press). The Period I contexts at the three sites listed above have an MNI of 34 individuals; we have included dental and skeletal samples from seven Period I individuals. Four of the Period I skulls sampled for this study may have been trophy heads (DUBL-0002; DUBL-0004; DUBL-0015; DUBL-0020), while three were complete skeletons that found at the earliest levels on two of the sites (DUBL-0013; DUBL-0024; DUBL-0025).

4.4. Archeological human remains from Period II

The later group of remains (Period II) consists of material found at Wood Quay (E132) from the estuarine mud on the north side of this wall that was built in approximately 1100 AD. Most of the skeletal material from Wood Quay can be shown to post-date the construction of the wall and to pre-date reclamation associated with a retaining bank built by the Anglo-Normans along the waterfront about 1200 AD (Halpin, 2000; Wallace, 2006). When the entire collection of articulated and disarticulated remains from Period II is combined, it has an MNI of 36 individuals. Evidence of trauma was significantly less common among the Period II human remains and, based on the demographic profile of these archeological human remains, they likely represent the hasty disposal of a cross section of the more vulnerable among the town's population at a time of stress (O'Donnabhain, 2010). We have included dental and skeletal samples from four Period II individuals, all from articulated skeletons found immediately north of wall constructed early in the twelfth century.

5. Materials and methods

5.1. Materials and sampling strategy

Archeological human samples collected for this research project are listed in Table 1 and represent a total of 11/70 or 15.7% of the curated MNI. Samples were collected from females and males who died at different ages, and represent enamel and bone samples from the Period I sites of Fishamble Street II (E172), Fishamble Street III (E190) and John's Lane (E173), as well as the Period II site of Wood Quay (E132). Few of the archeological human remains recovered from the Dublin sites consisted of complete skeletons, and some bones were commingled subsequent to their excavation. Where possible, enamel and bone samples were taken from each individual. To ensure that enamel and bone samples were from the same individual, whole or partial mandibles with teeth present were taken from 10 individuals, while a portion of a maxilla with teeth was used for one individual. Apart from the mandible or maxilla, other bones from the same individual were sampled where available. Due to the fragmentary nature of the remains, it was not possible to sample the same bone in each case. Bones of the skull vault were used in four individuals, long bones in two cases and ribs from four skeletons.

Archeological faunal samples collected for this research project are listed in Table 2. These faunal samples were collected from mature pigs (*S. scrofa*), and include both enamel and bone samples from both Period I and Period II. Samples of archeological faunal (*S. scrofa*) teeth and bones were collected from each of the following four sites: Fishamble Street II (E172), Fishamble Street III (E190), John's Lane (E173), and Wood Quay (E132).

5.2. Radiogenic strontium Isotope analysis

At Arizona State University, all samples were prepared in the Archaeological Chemistry Laboratory and analyzed in the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry. Tooth enamel powder or bone ash for radiogenic strontium isotope analysis was first dissolved in 500 μL of 5 M HNO_3. The strontium was then separated from the sample matrix using EiChrom SrSpec resin, a crown-ether strontium-selective resin (100–150 μm diameter) loaded into the tip of a glass column. The SrSpec resin was pre-soaked and flushed with H_2O to remove strontium present from the resin manufacturing process. The resin was further

Table 1
Archeological human remains from Viking Dublin included in this study. Bioarcheological data were determined by O'Donnabhain.

Laboratory number	Museum number	Age	Sex	Dates
DUBL-0002	E172:14526	M–O A	U	800–1000 AD
DUBL-0004	E172:16183	YA	M	800–1000 AD
DUBL-0013	E190:5529	OA	F	800–1000 AD
DUBL-0015	E190:5531	M-O A	M	800–1000 AD
DUBL-0020	E173:509	YA	M	800–1000 AD
DUBL-0024	E173:555	16–18	U	800–1000 AD
DUBL-0025	E173:602	Y–M A	F	800–1000 AD
DUBL-0027	E132:SkI	YA	F	1100–1200 AD
DUBL-0028	E132:SkII	M–O A	PF	1100–1200 AD
DUBL-0030	E132:SkIV	M–O A	F	1100–1200 AD
DUBL-0047	E132:SkXI	OA	M	1100–1200 AD

Table 2
Isotopic and elemental data from archeological human and faunal (*Sus scrofa*) remains from Dublin.

ACL laboratory number	Specimen number	Oxford laboratory number	Material	Ca/P	U/Ca	Nd/Ca	Ba/Sr	$^{87}Sr/^{86}Sr$ (MC-ICP-MS)	$\delta^{13}C$ carbonate (V-PDB) (‰)	$\delta^{18}O$ carbonate (V-PDB) (‰)	Mean $\delta^{13}C$ collagen (V-PDB) (‰)	SD	Mean $\delta^{15}N$ collagen (AIR) (‰)	SD	N	C:N	% C	% N	% Collagen
Archeological human remains																			
ACL-1941	DUBL-0030	NA	LRM2	NA	NA	NA	NA	0.71073	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1942	DUBL-0047	DUB12	Parietal	2.3	9.20E-08	6.10E-07	1.90E-01	0.70974	−15.4	−8.6	−20.9	0.1	11.0	0.0	2.0	3.2	43.8	16.0	18.1
ACL-1943	DUBL-0047	NA	LLM3	2.2	2.00E-07	8.50E-07	9.90E-02	0.70978	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1944	DUBL-0020	NA	UM1	NA	NA	NA	NA	0.70824	−14.2	−5.6	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1945	DUBL-0020	DUB6	Sphenoid	2.2	2.20E-06	1.10E-06	6.50E-01	0.70964	NA	NA	−21.9	0.0	4.9	0.2	2.0	3.2	37.7	13.7	16.2
ACL-1946	DUBL-0028	NA	LLM1	2.2	3.10E-09	1.80E-08	7.60E-02	0.71010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1947	DUBL-0028	DUB10	Rib	2.3	4.10E-09	8.80E-08	2.50E-01	0.70917	−14.0	−8.1	−20.7	0.0	9.5	0.1	2.0	3.2	40.9	15.0	20.0
ACL-1948	DUBL-0024	DUB7	Rib	2.1	2.30E-05	1.20E-05	5.90E-01	0.70906	−13.5	−8.0	−20.3	0.1	11.8	0.2	2.0	3.3	36.7	13.2	11.6
ACL-1949	DUBL-0024	NA	LRM2	NA	NA	NA	NA	0.70963	−14.9	−5.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1950	DUBL-0027	NA	UP3?	NA	NA	NA	NA	0.71030	−15.4	−6.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1951	DUBL-0027	DUB9	Rib	2.3	5.00E-07	2.70E-07	3.60E-01	0.70907	NA	NA	−20.6	0.1	10.4	0.0	2.0	3.2	40.2	14.8	19.5
ACL-1952	DUBL-0002	DUB1	Occipital	2.2	1.10E-05	7.30E-06	5.20E-01	0.70911	−14.2	−6.9	−21.0	0.0	10.1	0.1	2.0	3.2	38.1	13.7	9.5
ACL-1953	DUBL-0002	NA	LLM1	2.2	4.60E-08	8.50E-07	7.90E-02	0.71099	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1954	DUBL-0004	NA	LLM1	NA	NA	NA	NA	0.71009	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1955	DUBL-0015	DUB5	Parietal	2.2	3.60E-06	2.80E-06	7.90E-01	0.70936	−15.1	−8.2	−20.9	0.1	10.4	0.0	2.0	3.2	40.6	14.7	17.9
ACL-1956	DUBL-0015	NA	LLM1	NA	NA	NA	NA	0.71064	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1957	DUBL-0013	DUB4	Rib	2.2	1.30E-06	2.70E-07	5.60E-01	0.70910	−15.7	−7.0	−20.8	0.1	10.5	0.0	2.0	3.2	37.2	13.6	6.8
ACL-1958	DUBL-0013	NA	LLM1	2.2	1.00E-09	4.00E-08	1.20E-01	0.71010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1959	DUBL-0025	DUB8	Sphenoid	2.2	1.20E-06	5.20E-06	8.80E-01	0.70928	−13.8	−6.9	−21.2	0.1	10.8	0.2	2.0	3.2	40.5	14.9	16.2
ACL-1960	DUBL-0025	NA	Ulna	2.2	1.50E-06	1.00E-06	6.10E-01	0.70928	−15.2	−7.3	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1961	DUBL-0025	NA	LLM1	NA	NA	NA	NA	0.71098	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1962	DUBL-0025	NA	LRM2?	NA	NA	NA	NA	0.71041	−16.1	−7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	DUBL-0004	DUB2	Mandible	NA	NA	NA	NA	NA	NA	NA	−20.2	0.2	10.1	0.2	2.0	3.2	39.8	14.5	15.6
NA	DUBL-0013	DUB3	Fibula	NA	NA	NA	NA	NA	NA	NA	−20.7	0.0	9.9	0.1	2.0	3.2	38.9	14.3	7.2
NA	DUBL-0030	DUB11	Manidble	NA	NA	NA	NA	NA	NA	NA	−20.7	0.1	9.1	0.1	3.0	3.2	42.0	15.5	19.1
Archeological faunal (Sus scofra) remains																			
ACL-1929	DUBL-E132	DUB14	Femur	2.2	1.70E-07	1.10E-07	NA	0.70925	NA	NA	−20.5	0.0	6.4	0.2	2.0	3.2	42.4	15.5	13.9
ACL-1930	DUBL-E132	DUB16	Maxilla	2.3	1.30E-07	9.00E-08	NA	0.70988	NA	NA	−21.1	0.1	8.4	0.0	2.0	3.2	41.5	15.2	14.0
ACL-1932	DUBL-E172	DUB17	Radius	2.2	3.60E-07	2.10E-07	NA	0.70995	NA	NA	−21.9	0.2	6.3	0.1	2.0	3.2	41.5	15.2	15.8
ACL-1933	DUBL-E172	NA	LRM1	NA	NA	NA	NA	0.70914	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1934	DUBL-E172	NA	Mandible	2.3	2.00E-07	1.00E-07	NA	0.70917	NA	NA	−21.4	0.1	8.3	0.1	2.0	3.2	40.1	14.8	12.1
ACL-1935	DUBL-E190	DUB25	Humerus	2.2	1.50E-07	2.10E-07	NA	0.70951	−12.7	−8.3	−20.6	0.1	6.4	0.4	2.0	3.2	39.8	14.5	14.7
ACL-1936	DUBL-E190	NA	LRM1	NA	NA	NA	NA	0.70909	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1937	DUBL-E190	DUB23	Mandible	2.2	9.20E-08	3.00E-08	NA	0.70908	NA	NA	−21.1	0.1	7.2	0.1	2.0	3.2	40.7	15.0	13.2
ACL-1938	DUBL-E173	DUB21	Mandible	2.2	3.60E-08	1.90E-07	NA	0.70963	NA	NA	−20.0	0.0	5.0	0.0	2.0	3.2	40.6	15.0	13.2
ACL-1939	DUBL-E173	NA	Mandible	2.3	4.00E-08	1.40E-08	NA	0.70968	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ACL-1940	DUBL-E173	NA	Humerus	2.2	3.90E-07	2.70E-07	NA	0.70930	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	DUBL-E132	DUB15	Tibia	NA	NA	NA	NA	NA	NA	NA	−20.4	0.0	5.8	0.1	2.0	3.2	41.8	15.2	11.3
NA	DUBL-E172	DUB18	Ulna	NA	NA	NA	NA	NA	NA	NA	−21.9	0.2	9.2	0.2	2.0	3.2	41.3	15.2	16.1
NA	DUBL-E173	DUB22	Maxilla	NA	NA	NA	NA	NA	NA	NA	−21.4	0.0	5.8	0.2	2.0	3.2	37.6	13.8	12.7
NA	DUBL-E190	DUB24	Ulna	NA	NA	NA	NA	NA	NA	NA	−21.5	0.1	7.7	0.0	2.0	3.2	43.2	15.7	20.2
NA	DUBL-E190	DUB26	Axis	NA	NA	NA	NA	NA	NA	NA	−21.5	0.1	6.2	0.1	2.0	3.2	39.7	14.5	14.7

cleaned in the column with repeated washes of deionized H_2O and conditioned with 750 μL of HNO_3. The dissolved sample was loaded in 250 μL of 5 M HNO_3, washed in 500 μL of 5 M HNO_3, and then the strontium was eluted with 1000 μL of H_2O. Radiogenic strontium isotope samples were analyzed on a Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at Arizona State University, where recent analyses of strontium carbonate standard SRM-987 yielded a value of $^{87}Sr/^{86}Sr = 0.71029 \pm 0.00003$ (2σ, $n = 10$).

A smaller number of archeological human bone samples from four different sites in Ireland were analyzed for additional baseline data. These samples were prepared in the Laboratory for Archaeological Chemistry at the University of Wisconsin at Madison, using the methods described above, and analyzed in the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the University of North Carolina at Chapel Hill. Radiogenic strontium isotope ratios were measured on a VG Sector 54 thermal ionization mass spectrometer (TIMS) at the University of North Carolina-Chapel Hill, where long-term analyses of strontium carbonate standard SRM-987 yielded a value of $^{87}Sr/^{86}Sr = 0.710242$.

5.3. Stable oxygen, carbon, and nitrogen isotope analysis

Oxygen and carbon isotope analysis of archeological hydroxyapatite carbonate ($\delta^{18}O_{carbonate}$, $\delta^{13}C_{carbonate}$) was performed using a Thermo-Finnigan MAT 253 stable isotope ratio mass spectrometer W.M. Keck Foundation Laboratory for Environmental Biogeochemistry. Enamel or bone powder samples were treated with 2% NaOCl and then 0.1 M CH_3COOH (Koch et al., 1997). Replicates of NBS-19 resulted in a reproducibility of ±0.2‰ for $\delta^{18}O$ and ±0.2‰ for $\delta^{13}C$. Oxygen and carbon isotope ratios ($\delta^{18}O_{carbonate}$, $\delta^{13}C_{carbonate}$) are reported relative to the V-PDB (Vienna PeeDee belemnite) carbonate standard and are expressed in per mil (‰) using the standard formula $\delta^{18}O = (((^{18}O/^{16}O_{sample})/(^{18}O/^{16}O_{standard})) - 1) \times 1000$ (Coplen, 1994; Craig, 1961b). When necessary, conversion equations were also used (Coplen et al., 1983; Iacumin et al., 1996; Müller et al., 2003; Wolfe et al., 2001).

Samples for carbon and nitrogen isotope analysis of archeological bone collagen ($\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$) were prepared using standard methods at the Stable Isotope Laboratory in the School of Archaeology at the University of Oxford, where they were analyzed using a Carlo-Erba Elemental Analyzer coupled to a Europa Geo 20–20 stable isotope ratio mass spectrometer. External and internal standards resulted in a reproducibility of ±0.2‰ for $\delta^{13}C$ and ±0.2‰ for $\delta^{15}N$. Carbon and nitrogen isotope ratios ($\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$) are reported relative to the V-PDB (Vienna PeeDee belemnite) carbonate standard and are expressed in per mil (‰) using the standard formula previously described.

5.4. Major, minor and trace element concentration analysis

In order to minimized post-depositional contamination of strontium at the Viking Dublin site, samples were chemically cleaned using a series of weak acetic acid washes (Sillen, 1989; Sillen and LeGros, 1991). Then, all archeological human and faunal bone samples and a subset of human enamel samples were analyzed to determine the extent of post-depositional contamination; additional enamel samples were excluded based on the lack of available enamel for analysis. Enamel and bone ash samples were analyzed for absolute concentrations of major, minor, and trace elements using a Thermo-Finnigan X-series quadrupole inductively coupled plasma mass spectrometer (Q-ICP-MS) in the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry, where accuracy and precision for elements analyzed was determined using international standard NIST-1400 as well as internal laboratory standards. In order to aid in comparisons with other published data sets, elemental concentration data is presented as ratios.

6. Results

Isotopic and elemental data from archeological human and faunal samples are shown in Tables 2 and 3. Mean archeological human enamel and bone strontium isotope values from Dublin are $^{87}Sr/^{86}Sr = 0.70975 \pm 0.00139$ (2σ, $n = 22$). Archeological human enamel strontium isotope values range from $^{87}Sr/^{86}Sr = 0.70824$ to $^{87}Sr/^{86}Sr = 0.71099$ while archeological human bone values range from $^{87}Sr/^{86}Sr = 0.70906$ to $^{87}Sr/^{86}Sr = 0.70974$. Mean archeological faunal pig (*S. scrofa*) enamel and bone exhibit mean $^{87}Sr/^{86}Sr = 0.70943 \pm 0.00144$ (2σ, $n = 11$).

For archeological faunal pig (*S. scrofa*) enamel and bone samples, mean $\delta^{13}C_{collagen(V\text{-}PDB)} = -21.1‰ \pm 0.6‰$ (1σ, $n = 12$) and mean $\delta^{15}N_{collagen(AIR)} = +6.9‰ \pm 1.3‰$ (1σ, $n = 12$). Archeological human enamel and bone samples exhibit mean $\delta^{13}C_{carbonate(V\text{-}PDB)} = -14.8‰ \pm 0.8‰$ (1σ, $n = 12$) and mean $\delta^{18}O_{carbonate(V\text{-}PDB)} = -7.2‰ \pm 1.0‰$ (1σ, $n = 12$) and range from $\delta^{13}C_{carbonate(V\text{-}PDB)} = -16.1‰$ to $\delta^{13}C_{carbonate(V\text{-}PDB)} = -13.5‰$ and $\delta^{18}O_{carbonate(V\text{-}PDB)} = -8.6‰$ to $\delta^{18}O_{carbonate(V\text{-}PDB)} = -5.2‰$. Archeological human bone samples exhibit mean $\delta^{13}C_{collagen(V\text{-}PDB)} = -20.8‰ \pm 0.5‰$ (1σ, $n = 12$) and mean $\delta^{15}N_{collagen(AIR)} = +10.0‰ \pm 1.7‰$ (1σ, $n = 12$) and range from $\delta^{13}C_{collagen(V\text{-}PDB)} = -21.9‰$ to $\delta^{13}C_{collagen(V\text{-}PDB)} = -20.2‰$ and $\delta^{15}N_{collagen(AIR)} = +4.9‰$ to $\delta^{15}N_{collagen(AIR)} = +11.8‰$.

For archeological enamel and bone samples, mean Ca/P = 2.2 ± 0.1 (2σ, $n = 14$), mean U/Ca = 3.18E-06 ± 6.39E-06 (2σ, $n = 14$), mean Nd/Ca = 2.31E-06 ± 3.52E-06 (2σ, $n = 14$), Additionally, mean Ba/Sr = 4.12E-01 ± 2.78E-01 (2σ, $n = 14$) for archeological human enamel and bone samples. For archeological faunal enamel and bone samples, mean Ca/P = 2.2 ± 0.0 (2σ, $n = 9$), mean U/Ca = 1.74E-07 ± 1.26E-07 (2σ, $n = 9$), and mean Nd/Ca = 1.36E-07 ± 8.81E-08 (2σ, $n = 9$).

7. Interpretations of paleomobility and paleodiet in Viking Dublin

7.1. Diagenetic contamination

Results from major, minor, and trace elemental concentration analyses run on the Dublin samples suggest that little diagenetic

Table 3
Isotopic data from archeological human remains from Armagh, Dunmisk, Tintern Abbey, and Waterford, Ireland.

Specimen number	Age	Sex	Dates	Material	$^{87}Sr/^{86}Sr$ (TIMS)
Armagh					
TR.4 333a	A	M	Early Christian	cranium	0.70948
TR.3.N 317	A	PM	Early Christian	cranium	0.70970
I	A	M	Post-1700 AD	L rib	0.70901
Dunmisk					
314 298	U	U	Early Christian	Bone	0.71139
190 183	U	U	Early Christian	Cranium	0.71111
95 97	U	U	Early Christian	Long bone	0.71129
Tintern Abbey					
5	U	U	NA	Rib	0.70966
16	U	U	NA	Rib	0.70999
17	U	U	NA	Rib	0.71012
34	U	U	NA	Rib	0.70953
59	U	U	NA	Bone	0.70951
Waterford					
II A180	A	M	1600–1700 AD	Long bone	0.70982
II A201	A	M	1600–1700 AD	Long bone	0.70979
II A160	A	F	1600–1700 AD	Bone	0.70979

activity took place that the site, since most of the samples match the expected ratio of Ca/P = 2.1:1 (Price et al., 1992). The U/Ca and Nd/Ca values are extremely low and are consistent with, and often below, values reported by Price and colleagues (2002) for burials from Bolivia (AD 450–950) and Germany (5050 BC). While there is variability in U/Ca and Nd/Ca values, particularly in the human enamel and bone values where U/Ca = 3.18E-06 ± 6.39E-06 (2σ, $n = 14$), mean Nd/Ca = 2.31E-06 ± 3.52E-06 (2σ, $n = 14$), even the samples with the highest concentrations of uranium and neodymium are consistent with published values from uncontaminated samples (Price et al., 2002). In addition, the molar ratio ranged from C:N = 3.2 to C:N = 3.3 and weight percent carbon, weight percent nitrogen, and collagen yields were all consistent with biogenic carbon and nitrogen isotope data (Table 2).

7.2. Paleomobility

Based on archeological faunal values (Evans and Tatham, 2004; Price et al., 2002), the "local" range for individuals living in and around Dublin is defined as $^{87}Sr/^{86}Sr$ = 0.7084–0.7106. Archeological pig (*S. scrofa*) samples are well suited to determine bioavailable radiogenic strontium isotope values for archeological populations, because these omnivores often consume strontium from the same sources as humans (e.g., Bentley and Knipper, 2005). However, we also note that these animals may have been imported, either from other parts of Ireland or via ships from other parts of North Atlantic Europe (e.g., Shaw, et al., 2009). In this case, the close relationship between the expected bioavailable radiogenic strontium isotope values and the archeological faunal data, as well as the homogeneity of the faunal dataset, suggest that these animals were local to the Dublin area, rather than imported from a variety of non-local regions. In this case, any samples from human bone and teeth deviating markedly from this range may indicate migration.

However, all of the human bone samples exhibit radiogenic strontium isotope values consistent with a local radiogenic strontium signature, indicating that all individuals sampled lived in or around Dublin for the last year of their lives. While most enamel samples fall within the "local" range, some are either higher or lower (Fig. 2). Interestingly, one individual (DUBL-0020) exhibits $^{87}Sr/^{86}Sr$ = 0.70824, below the "local" range. This individual may have originated from regions possessing relatively young geologic bedrock. Three other individuals also have radiogenic strontium isotope values higher than the "local" range, and likely originated from a region with higher $^{87}Sr/^{86}Sr$ values. However, we note that the radiogenic strontium isotope values are not much higher than the "local" range. Finally, when comparing mean radiogenic strontium isotope data from all enamel samples with mean radiogenic strontium isotope data from all bone samples, there is no statistically significant difference between the mean data ($t = 2.14$, df = 14, $p = 0.00$). Therefore, while there are some outliers in the radiogenic strontium isotope enamel data, the population as a whole does not exhibit significantly variable geographic origins despite eventual burial in Dublin.

For Period I archeological human enamel and bone, mean $^{87}Sr/^{86}Sr$ = 0.70973 ± 0.00079 (2σ, $n = 15$), while Period II archeological human enamel and bone exhibits mean $^{87}Sr/^{86}Sr$ = 0.70984 ± 0.00060 (2σ, $n = 7$). When comparing radiogenic strontium isotope values from individuals excavated from Period I and Period II contexts, there is no statistically significant difference ($t = 2.13$, df = 15, $p = 0.71$). Therefore, although the archeological human remains included in this study date from the early ninth through eleventh (Period I) and twelfth (Period II) centuries, there is no difference in the geographic origins of individuals from early and later phases of Viking Dublin.

In general, these radiogenic strontium isotope data are consistent with other archeological bone data from Ireland. Archeological human bone data from Waterford on the southeastern coast of Ireland, where mean $^{87}Sr/^{86}Sr = 0.70980 \pm 0.00002$ (2σ, $n = 3$), and Tintern Abbey, also on the southeastern coast of Ireland, where mean $^{87}Sr/^{86}Sr = 0.70976 \pm 0.00028$ (2σ, $n = 5$), are similar to the archeological enamel and bone data generated here (Table 3). Similarly, archeological human bone from Armagh in northeastern Ireland exhibited mean $^{87}Sr/^{86}Sr = 0.70940 \pm 0.00035$ (2σ, $n = 3$) (Table 3). However, at Dunmisk in northern Ireland, mean $^{87}Sr/^{86}Sr$ = 0.71126 ± 0.00014 (2σ, $n = 3$) (Table 3). Based on enamel and bone radiogenic strontium isotope values, there are no individuals analyzed who are clearly from northern Ireland, northern Scotland, including the Orkney and Shetland Islands,

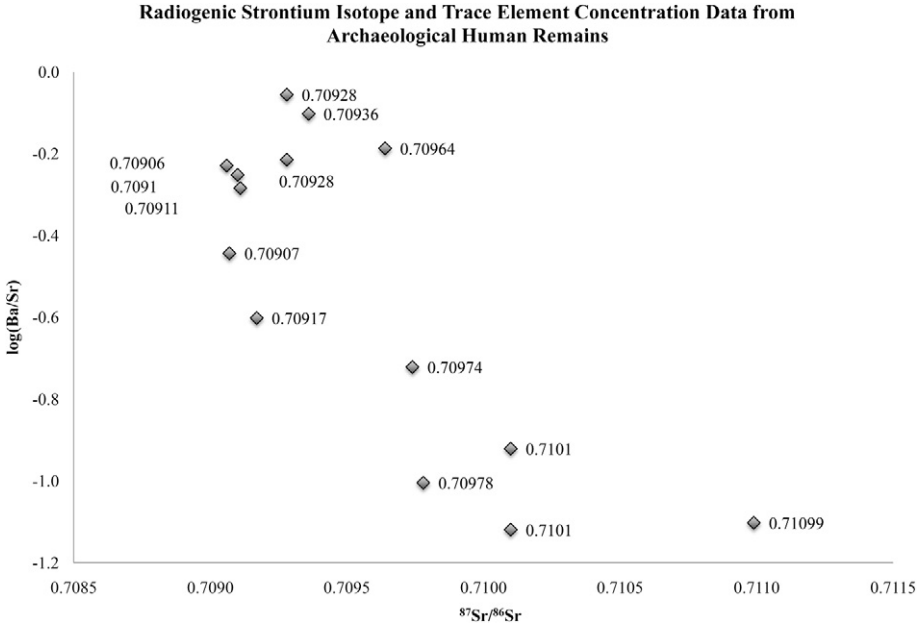

Fig. 2. Radiogenic strontium isotope ($^{87}Sr/^{86}Sr$) and trace element concentrations (log(Ba/Sr)) values for archeological human samples.

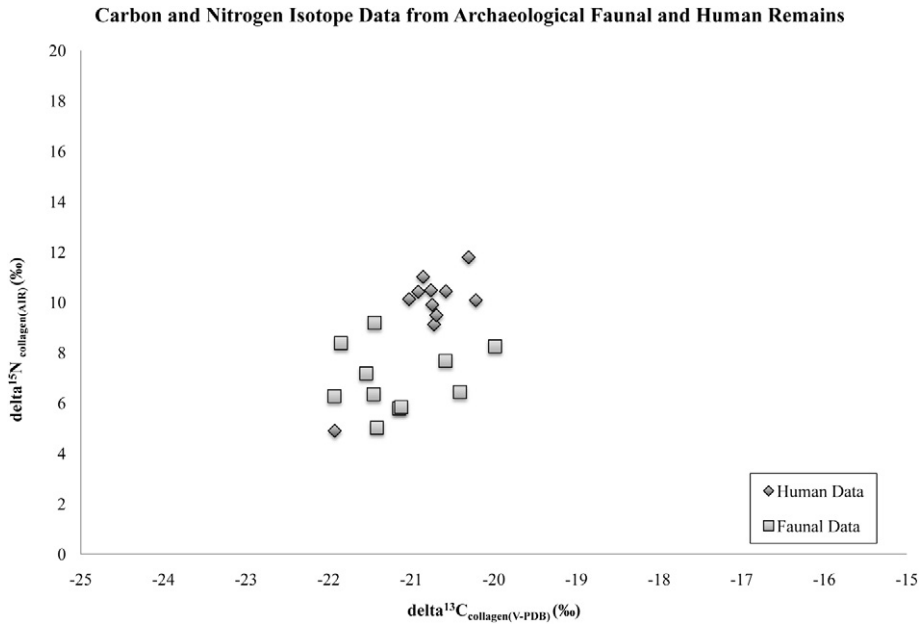

Fig. 3. Stable carbon and nitrogen isotope ($\delta^{13}C_{collagen(V\text{-}PDB)}$, $\delta^{15}N_{collagen(AIR)}$) values for archeological human and faunal samples.

southern Norway, or southern and western Sweden (Aberg et al., 1998; Evans et al., 2010; Montgomery et al., 2006; Sjögren et al., 2009; Voerkelius et al., 2010; Wilson et al., 1977).

Stable oxygen isotope data from the archeological human individuals included in this study are variable (Table 2). However, some of this variability likely results from the consumption of ^{18}O-enriched breast milk before and during the weaning process. The highest $\delta^{18}O_{carbonate(V\text{-}PDB)}$ values are found in enamel that formed in the first years of life (Table 3). When early-forming enamel samples are removed, bone mean $\delta^{18}O_{carbonate(V\text{-}PDB)} = -7.6‰ \pm 0.7‰$ (1σ, $n = 8$). In contrast, enamel mean $\delta^{18}O_{carbonate(V\text{-}PDB)} = -6.2‰ \pm 1.0‰$ (1σ, $n = 4$). Bone $\delta^{18}O_{carbonate(V\text{-}PDB)}$ values are relatively homogeneous, and likely reflect a common drinking water value. However, we note that a number of different factors can contribute to observed stable oxygen isotope values, and that identifying place of origin can be complicated (Bell et al., 2009, Bell et al., 2010; Knudson, 2009; Millard and Schroeder, 2010).

7.3. Paleodiet

Paleodietary inferences in the archeological human and faunal remains from Viking Age/Hiberno-Norse Dublin are based on a number of different lines of evidence. With the exception of one clear outlier (DUBL-0020, a younger adult male with peri-mortem sharp-force trauma whose remains were among the ninth to eleventh century isolated skulls from John's Lane, E173), the archeological human bone samples analyzed are relatively homogenous (Fig. 3). The combined $\delta^{13}C_{collagen(V\text{-}PDB)}$ and $\delta^{15}N_{collagen(AIR)}$ values point to a diet of terrestrial protein sources with some marine protein consumption. Archeological faunal (*S. scrofa*) remains indicate less consumption of marine protein (Fig. 3, Table 2). Interestingly, the archeological human sample that is a clear outlier (DUBL-0020) exhibits less marine protein consumption; this individual also has a lower enamel radiogenic strontium isotope value, indicating that geographic origins as well as adult diet may have differed from the other individuals analyzed here.

Variable amounts of marine product consumption is also supported by the log(Ba/Sr) values from archeological human remains buried in Viking Dublin (Fig. 3). Individuals who consumed large amounts of marine products should exhibit approximately log(Ba/Sr) = −2.0 to log(Ba/Sr) = −1.0 (Burton and Price, 1990). Based on relatively low log(Ba/Sr) values, some individuals consumed relatively large amounts of marine products, particularly calcium sources, during the last years of life, as evidenced by bone log(Ba/Sr) values or first years of life, as evidenced by enamel log(Ba/Sr) values. Although we note that very young infants who are still consuming primarily breast milk are unlikely to have consumed large amounts of marine products, first molar enamel formation times in the first three years of life ensure that early childhood diet is identified, rather than purely infant diets. It is important to note that consumption of calcium, and strontium, from marine resources is not masking the geologic variability in the radiogenic strontium isotope data (Fig. 2). As shown in Fig. 2, at least one individual who consumed high amounts of marine calcium and strontium also has a high radiogenic strontium isotope value, rather than the expected seawater value of $^{87}Sr/^{86}Sr = 0.7092$ (Veizer, 1989). Finally, while some individuals consumed larger amounts of marine products, others consumed calcium, strontium, and barium from largely terrestrial sources, as indicated by higher log(Ba/Sr) values of approximately log(Ba/Sr) = −0.5 to log(Ba/Sr) = 0.0 (Fig. 3) (Burton and Price, 1990).

8. Conclusions

In conclusion, we have used biogeochemistry to investigate paleomobility and paleodiet in archeological human remains excavated from both the early and late phases of Viking Dublin. Biogeochemical analyses of archeological human remains from the ninth to eleventh century levels at the sites at Fishamble Street II (E172), Fishamble Street III (E190) and John's Lane (E173), as well as twelfth-century remains from Wood Quay (E132) were analyzed. Interestingly, most individuals consumed and imbibed strontium, oxygen, carbon and nitrogen from the same or similar sources, indicating homogenous adult diets as well as geographic origins. Of the three skeletons dating from the early Viking Age, none was an immigrant or "non-local". However, one individual whose head may have been displayed on the ramparts of the settlement in the early phase of the settlement (DUBL-0020) is a clear outlier in both

geographic origins in the first years of life and in adult diet in the last years of life; however, the geologic source or sources of strontium in the last years of life were similar to other individuals excavated in Viking Dublin, likely indicating that this individual lived in or near the Viking town for the last years of life. Interestingly, the four individuals who heads may have been displayed on the embankments surrounding the settlement had lived in or near the town for the last years of their lives. Three of these individuals had probably lived there all of their lives. These were insiders whose treatment at death may suggest that they may have fallen foul of the civic authorities (O'Donnabhain, 2011). Overall, the relative homogeneity in paleomobility and paleodiet, particularly among the Period I remains, may support models of acculturation in Viking Dublin, rather than indicating a high number of first-generation immigrants from other parts of North Atlantic Europe.

Acknowledgments

We gratefully acknowledge the National Museum of Ireland, including Patrick Wallace, Adrienne Corless, and Piera Weir, for permission to export and analyze these samples and for funding these analyses. In addition, we thank Margaret McCarthy and Regina Sexton for discussions regarding early medieval diet, and Jamie Hodgkins and Teague O'Mara for laboratory assistance in the Archaeological Chemistry Laboratory, Finally, we are grateful to Ariel Anbar, Gwyneth Gordon and Everett Shock of the W.M. Keck Foundation Laboratory for Environmental Biogeochemistry at Arizona State University, Paul Fullagar of the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the University of North Carolina at Chapel Hill, and Peter Ditchfield of the Stable Isotope Laboratory in the School of Archaeology at the University of Oxford for invaluable laboratory access and assistance.

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