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Deciphering Diet and Monitoring Movement: Multiple Stable Isotope Analysis of the Viking Age Settlement at Hofstaðir, Lake Mývatn, Iceland.

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ABSTRACT

Objectives:

A previous multi-isotope study of archaeological faunal samples from Skútustaðir, an early Viking age settlement on the southern shores of Lake Mývatn in north-east Iceland, demonstrated that there are clear differences in $\delta^{34}S$ stable isotope values between animals deriving their dietary protein from terrestrial, freshwater and marine reservoirs. The aim of this study was to use this information to more accurately determine the diet of humans excavated from a nearby late Viking age churchyard.

Materials and Methods:

$\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analyses were undertaken on terrestrial animal (n = 39) and human (n = *46*) bone collagen from Hofstaðir, a high-status Viking-period farmstead ~10 km north-west of Skútustaðir.

Results:

$\delta^{34}S$ values for Hofstaðir herbivores were ~6‰ higher relative to those from Skútustaðir ($\delta^{34}S$: 11.4 ± 2.3‰ *vs* 5.6 ± 2.8‰), while human $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values were broad ranging (–20.2‰ to –17.3‰, 7.4‰ to 12.3‰, and 5.5‰ to 14.9‰, respectively).

Discussion:

Results suggest that the baseline $\delta^{34}S$ value for the Mývatn region is higher than previously predicted due to a possible sea-spray effect, but the massive deposition of *Tanytarsus gracilentus* (midges) ($\delta^{34}S$: –3.9‰) in the soil in the immediate vicinity of the lake is potentially lowering this value. Several terrestrial herbivores displayed higher bone collagen $\delta^{34}S$ values than their contemporaries, suggesting trade and/or movement of animals to the

region from coastal areas. Broad ranging $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values for humans suggest the population were consuming varied diets, while outliers within the dataset could conceivably have been migrants to the area.

INTRODUCTION

Over the last 20 years, Iceland has been the subject of an increasing number of archaeological, environmental and geological investigations, yet very few in-depth palaeodietary studies of early settler communities have been undertaken (Sveinbjörnsdóttir et al., 2010, Ascough et al., 2012). While it has been common practice for several decades to employ $\delta^{13}C$ and $\delta^{15}N$ stable isotope analyses to decipher diet (DeNiro and Epstein 1978, 1981; Schoeninger et al., 1983; Schoeninger and DeNiro 1984), the exploitation of sulphur isotope ($\delta^{34}S$) values to determine a person's place of residence and the source of their food supply has been a more recent development (Richards et al., 2001, 2003; Vika, 2009; Craig et al., 2010; Nehlich et al., 2012). Furthermore, sulphur isotopes have been utilized to examine the variability in terrestrial-, marine- and freshwater-based diets (Craig et al., 2006; Privat et al., 2007; Nehlich et al., 2010, 2011; Lamb et al., 2012). In a previous examination of Icelandic biota, Ascough et al. (2010) demonstrated that an overlap existed between the $\delta^{15}N$ values of both modern and archaeological-age terrestrial herbivores and the $\delta^{15}N$ values of modern and archaeological-age freshwater fish, while the $\delta^{13}C$ values of freshwater biota were also found to be similar to those of marine resources. Consequently, the identification of herbivore, freshwater fish and marine fish components in the human diet in this region is not possible using only $\delta^{13}C$ and $\delta^{15}N$ analyses. The examination of 129 animal bones from a midden at Skútustaðir, an early Viking-age settlement on the southern shores of Lake Mývatn in north-east Iceland, demonstrated that there was a significant offset in $\delta^{34}S$ values between animals deriving their dietary resources from terrestrial, freshwater or marine reservoirs (Sayle et al., 2013). The farmstead of Hofstaðir, located ~10 km north-west of the midden at

Skútustaðir is where, at present, approximately 170 bodies have been excavated from a late Viking-age/high medieval cemetery. The purpose of this study was to use the previous results from Skútustaðir in conjunction with new $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ measurements on 39 animal bones from excavations at Hofstaðir, to determine the diet and mobility of 46 adult humans interred at the cemetery.

The colonization of Iceland

During the latter quarter of the 9th century, the shorelines of Iceland experienced a steady influx of people from throughout Scandinavia who sought to make the remote island their permanent home (Vésteinsson, 1998). Settlers were quick to establish themselves at coastal sites and exploited marine resources to subsidize their diet while their farmsteads were growing. As people began moving inland, they supplemented their diet with freshwater fish from lakes and rivers when animal husbandry practices were in their developmental phase, crops were failing or during the harsh winter months (Vésteinsson, 1998). Prior to settlement, or *landnám*, the Icelandic terrain was dominated by birch trees, however, early immigrants quickly cleared forests to erect their farmsteads and the felled wood was used as a source of fuel and for construction (Vésteinsson, 1998). Inevitably, colonization had an almost immediate impact on the landscape; the introduction of domestic animals led to significantly eroded soils that became infertile and unmanageable, while freshwater ecosystems were also altered (Arnalds et al., 1997; Vésteinsson et al., 2002; Dugmore et al., 2005; Lawson et al., 2007). Vésteinsson and McGovern (2012) have hypothesized that, based on their research within the Mývatnssveit region of north-east Iceland, at least 24,000 people must have settled in Iceland in less than 20 years in the latter quarter of the 9th century. However, this theory has been disputed by others and the debate on how quickly Iceland was populated continues (Barrett, 2012; Edwards, 2012; Sigurðsson, 2012; Sveinbjarnardóttir, 2012; Urbańczyk, 2012).

The settlement of Hofstaðir

Hofstaðir is situated approximately 50 km inland at an altitude of 277 m above sea level (Fig. 1), and has been recognized as a site of major archaeological importance with regards to the settlement of Viking communities during the *landnám* (Vésteinsson, 1998; McGovern et al., 2007; Lucas, 2009). During a nationwide archaeological survey in 1817, the ruins of a large hall-like building at Hofstaðir were first mentioned; however, the initial excavation of the area did not take place until almost a hundred years later (Bruun and Jónsson 1909, 1910, 1911). They concluded that the hall, measuring over 45 m in length and over 10 m wide, was a Pagan temple. An additional circular ruin to the south of the main structure contained a pit full of ash, stones and animal remains, and was believed to be for the disposal of rubbish after temple feasts. However, this suggestion was dismissed by Olsen (1965), who proposed that the site was in fact a large farmstead where non-Christian chieftains held religious feasts, and that the midden was actually a cooking pit used for the preparation of large scale banquets.

In 1991, an archaeological project was initiated that aimed to establish a more precise time-frame for the occupation of Hofstaðir, and determine what role the site played in the early settlement history of Iceland (Friðriksson and Vésteinsson, 1997). Over the course of a decade, the project rapidly expanded and the Icelandic Institute of Archaeology, in collaboration with the North Atlantic Biocultural Organisation (NABO), gradually exposed the complete structure. Excavations revealed that although the site was abnormally large, it was similar to other settlement farms, and additionally, the supposed cooking pit was actually a sunken building that had been filled with midden debris (Lucas, 2009). The discovery of 23 weathered cattle skulls with unusual butchery marks suggested that ritual decapitations, possibly part of religious ceremonies, were also taking place at the site, and thereafter, the skulls adorned the outer walls of the hall (Lucas and McGovern, 2007).

Tephrochronological studies initially indicated that settlement at Hofstaðir occurred shortly after the AD 871 ± 2 eruption of Veiðivötn (the *landnám* tephra layer); yet by the time Hekla had erupted in AD 1104, the site had been abandoned for approximately 70 years (Sigurgeirsson, 1998; Lucas, 2009). However, re-evaluation of the earlier *landnám* tephra layer revealed that it had been wrongly identified, and it was instead acknowledged as a tephra layer originating from the Veiðivötn volcanic system from around AD 940 (Sigurgeirsson, 2001). This layer has since been more accurately dated to AD 933 ± 2, thereby shortening the chronology of Hofstaðir by approximately 60 years (Sigurgeirsson et al., 2013). Radiocarbon dating of terrestrial animal remains from various sites in the surrounding Lake Mývatn region have shown that settlers populated the area from the late 9th century onwards, with Hofstaðir sporadically occupied during this time (McGovern et al., 2006, 2007; Ascough et al., 2007, 2010, 2012, 2014; Lucas, 2009).

In 1999, excavations were extended south-west of the feasting hall to excavate a chapel and cemetery that had been referenced previously in a property transfer dating back to AD 1477 (Gestsdóttir, 1999). At the time of writing, field studies are still on-going, but it is currently believed that there have been at least three phases to the church structure at Hofstaðir. The youngest construct, built from turf, post-dates AD 1477, while earlier buildings were erected from timber. Birch wood samples thought to be part of the earliest structure gave calibrated radiocarbon dates of cal AD 890–1120 and cal AD 890–1160 (Gestsdóttir, 2004). Due to the very short early settlement period it is unclear whether the first church pre- or post-dates the abandonment of the feasting hall around AD 1030. However, documentary sources suggest that Iceland had been Christianized by AD 1000, and Lucas (2009, p407) has suggested Hofstaðir may have been “a centre of resistance to Christianity” for over a quarter of a century. To date, 170 bodies have been excavated from within the churchyard, yet determining the chronology of the cemetery has been problematic as the site was leveled in the 1950s. It is thought that the cemetery was in use between the 10^{th} and 13^{th} centuries, with most interments occurring during the earliest phases and all burials post-dating the Veiðivötn AD 933 tephra and pre-dating the Hekla AD 1300 tephra deposit (Gestsdóttir, 2006; Gestsdóttir and Isaksen, 2011).

ISOTOPIC BACKGROUND

When any living creature ingests another animal and/or plant, an isotopic trace of the food source is incorporated into the tissues of the consumer species (Sealy, 2001), and the stable isotope ratios of carbon ($^{13}C/^{12}C$, expressed as $\delta^{13}C$), nitrogen ($^{15}N/^{14}N$, expressed as $\delta^{15}N$) and sulphur ($^{34}S/^{32}S$, expressed as $\delta^{34}S$) present in the tissues of the consumer can be used to determine whether it had consumed terrestrial-, marine- or freshwater-based resources, or a combination of all three (DeNiro and Epstein, 1978, 1981; Richards et al., 2001). Due to isotopic fractionation, herbivores have $\delta^{13}C$ bone collagen values enriched by *ca*. 5‰ relative to their diet (Van Der Merwe and Vogel, 1978). Terrestrial C_3 plants exhibit $\delta^{13}C$ values of *ca*. –26.5‰ (Smith and Epstein, 1971), and consequently, an individual that has consumed a wholly terrestrial C_3 plant diet would display a bone collagen $\delta^{13}C$ value of *ca*. –21.5‰. However, when comparing the $\delta^{13}C$ value of bone collagen in a consumer relative to the source of their dietary protein, there is an increase of *ca*. +1‰ in this value (DeNiro and Epstein, 1978). Therefore, carnivores that consume solely terrestrial protein would display bone collagen $\delta^{13}C$ values of *ca*. –20.5‰, while individuals that consume an exclusively marine-based diet would have bone collagen $\delta^{13}C$ values *ca.* –12‰ (Schoeninger et al., 1983).

In general, terrestrial nitrogen-fixing plants have $\delta^{15}N$ values that range between –2‰ and 2‰ (Peterson and Fry, 1987). However, plants can also uptake nitrogen in the form of ^{15}N-depleted ammonia from decomposing organic matter, and their $\delta^{15}N$ values can be as low as –8‰ (Nadelhoffer and Fry, 1994). Unlike carbon, nitrogen isotopes can increase significantly between diet and consumer, and Schoeninger and DeNiro (1984) estimated that this trophic level shift is approximately +3‰ to +5‰ in marine and terrestrial food chains. However, more recently, Fernandes (2015) estimated the δ^{15}N offset between dietary protein and human bone collagen to be +5.5 ± 0.5‰. Hence, by taking an average trophic shift value of +4.5‰, herbivores and carnivores could conceivably exhibit δ^{15}N values of approximately 2.5‰ to 6.5‰ and 7‰ to 11‰, respectively, in a simple terrestrial food web. Within the marine environment, baseline oceanic nitrate δ^{15}N values are approximately 5.0‰, and as a consequence of marine food webs being considerably longer and more complex than in the terrestrial biosphere, δ^{15}N values of the apex predators can range between *ca.* 15‰ and 20‰ (DeNiro and Epstein, 1981; Schoeninger et al., 1983; Schoeninger and DeNiro, 1984).

While plants and algae at the base of the marine food web display δ^{34}S values between 17‰ and 21‰, values for terrestrial and freshwater vegetation can vary extensively between –22‰ and 22‰, depending on local geology (Peterson and Fry, 1987). Plants primarily assimilate sulphur in the form of sulphate via their root systems by absorbing sulphates and oxidized sulphides that have leached into ground and stream water systems during the weathering of bedrock. This process occurs with little fractionation, and thus, sulphur isotopes can provide additional information about the geographical origin of a plant as its δ^{34}S value will be similar to its surrounding environment (Trust and Fry, 1992). Some plants, such as mosses and lichens, are capable of absorbing atmospheric SO_2 with little or no fractionation (Krouse, 1977), while the wet deposition of SO_2 in the form of acid rain (H_2SO_4) can provide soils with an additional source of sulphur, however, isotopic fractionation can be large during the oxidation process (Harris et al., 2012). Most of the earth's sulphur supply originates from either the lithosphere or hydrosphere, with sulphides in shale and sulphates in evaporites exhibiting δ^{34}S values between −40‰ and 30‰ (Claypool et al., 1980; Strauss, 1997) and marine waters currently providing a very isotopically uniform reservoir of 21‰ (Rees et al., 1978). However, in areas closer to the coast, soil $\delta^{34}S$ values are comparable to seawater due to sulphur-containing particles being blown inland; this is known as the sea-spray effect (Wadleigh et al., 1994). Similarly to carbon, an increase of *ca.* 1‰ is observed in bone collagen $\delta^{34}S$ values compared to the source of dietary protein. (Peterson and Howarth, 1987).

Geology and isotope geochemistry of Iceland

Iceland is a very volcanically active country and approximately 85–90% of the landscape is dominated by igneous rocks. The Krafla volcanic system near Lake Mývatn is composed of basaltic, intermediate and silicic rocks of the tholeiitic series, with the porous lava fields that surround the lake readily absorbing any available surface water (Jakobsson et al., 2008). Iceland's young volcanic soils are largely categorized as andosols, with gleyic and brown andosols, which contain <12% organic carbon, covering the Lake Mývatn region (Arnalds, 2004). Desert andosols cover between 35 and 45% of Iceland, and have a low organic content and very low nitrogen levels (Arnalds and Kimble, 2001). South-westerly winds have been known to drive sand north-east towards Lake Mývatn, burying some of the vegetation and replacing the organically rich soil with infertile sand (Arnalds et al., 2001). Surface sediment samples from four sites in Iceland, with soil types similar to those at Lake Mývatn, were measured for total organic carbon (TOC), total organic nitrogen (TON) and stable carbon and nitrogen isotopes. TOC and TON values varied from 3.1% to 12.8% and 0.3% to 2.2%, respectively, while $\delta^{13}C$ and $\delta^{15}N$ values varied from –28.6‰ to –19.8‰ and –1.5‰ to –0.1‰, respectively (Wang and Wooler, 2006).

Hot springs from the Námafjall geothermal field and cold springs from its eastern shores feed Lake Mývatn's two basins before it drains west into the River Laxá (Ólafsson, 1979).

$\delta^{13}C$ values for dissolved inorganic carbon in low temperature (< 100°C) geothermal Icelandic waters can vary between –24.0‰ and 2.0‰ (Kjartandóttir, 2014; Sveinbjörnsdóttir et al., 1995; Sveinbjörnsdóttir and Arnórsson, 2010), while $\delta^{13}C$ values for water from Lake Mývatn were found to be between –8.1‰ and –5.2‰ (Ascough et al., 2010). The Brúarfossar Waterfalls, situated in the Laxárgljúfur Canyon approximately 35 km from Lake Mývatn, act as a natural barrier between the upper and lower Laxá, and prevent fish migrating from the Arctic Ocean towards the lake (Gíslason et al., 2002a).

Torssander (1989) established that basalts from the Krafla-Námafjall fissure swarm displayed total sulphur $\delta^{34}S$ values ranging between –2.0‰ and 4.2‰, hence the weathering of rocks in the Mývatn region should yield similar spring and groundwater sulphate $\delta^{34}S$ values. Rocks of a similar type from the Katla Volcanic Centre in southern Iceland gave comparable $\delta^{34}S$ values ranging between –1.8‰ and 2.4‰ (Hildebrand and Torssander, 1998). However, water samples collected from sites around Iceland following volcanic eruptions demonstrated increased $\delta^{34}S$ values accompanying an increase in sulphate concentration, with some sources displaying sulphate $\delta^{34}S$ values as positive as 10.0‰ (Gíslason et al., 2002b; Gíslason and Torssander, 2006; Robinson et al., 2009; Holm et al., 2010), while SO_2 gas produced during the eruption of Krafla in July 1980 yielded $\delta^{34}S$ values between –1.8‰ and 3.4‰ (Torssander, 1988).

It is estimated that there are approximately 20–25 volcanic eruptions per century in Iceland and during the last 300 years, two major events have occurred within the Krafla volcanic system (Thordarson and Larsen, 2007). Although there are no written records of eruptions that pre-date the Mývatn Fires of AD 1724–1729, it’s unlikely that this active system would have lain dormant throughout the settlement period and not have had an influence on the sulphate $\delta^{34}S$ values of the water sources feeding the lake and the $\delta^{34}S$ value of atmospheric SO_2 in the region. However, despite Icelandic rock and water samples displaying $\delta^{34}S$ values between –2‰ and 10‰, and atmospheric SO_2 $\delta^{34}S$ values varying between –1.8‰ and 3.4‰, they are clearly isotopically different from the $\delta^{34}S$ value of seawater.

Isotope biochemistry of Iceland

Various isotopic studies of Icelandic flora have been undertaken and the results are summarized in Table 1 (Wang and Wooller, 2006; Skrzypek et al., 2008; Ascough et al., 2014). Terrestrial plants, mosses, and lichens produced $\delta^{13}C$ values that are typical of flora that use a C_3 photosynthetic pathway, while aquatic plants displayed less negative $\delta^{13}C$ values and are reflective of a ^{13}C-enriched carbon source (Keeley and Sandquist, 1992). $\delta^{15}N$ values for terrestrial and aquatic vegetation were wide ranging, with many samples far more negative than would be expected for typical terrestrial nitrogen-fixing plants. Wang and Wooler (2006) proposed two possible explanations for the negative $\delta^{15}N$ values in Icelandic flora: (1) low levels of phosphorous in the soil and (2) the uptake of ammonia from the atmosphere. Simpson et al. (2002) measured the total phosphorus in soils at two sites in Iceland where it was thought arable activity had previously taken place. Phosphorus levels usually increase when land has been settled due to the addition of organic material to the soil. However, levels were found to be low and McKee et al. (2002) suggested that when phosphorous availability is low, plants could yield negative $\delta^{15}N$ values. In addition to plants and lichens obtaining nitrogen from the atmosphere, they are also capable of sourcing it from ^{15}N depleted ammonia. Erskine et al. (1998) believe that the decomposition of penguin guano on Macquarie Island in the Sub-Antarctic, and the subsequent uptake of ammonia by plants situated further afield from the colonies, is the reason for their negative $\delta^{15}N$ values. However, plants growing closer to the nesting birds displayed highly positive $\delta^{15}N$ values, and were reflective of direct nitrogen enrichment of the soil from the guano.

A summary of results for previous stable isotope studies of modern and archaeological mammal, fish and bird bone samples from the Lake Mývatn region are shown in Table 1 (Sayle et al., 2013; Ascough et al., 2014, Ascough – unpublished data). $\delta^{13}C$ values for terrestrial herbivores were in the expected range for animals consuming Icelandic C_3 plants, while the wide ranging and sometimes negative $\delta^{15}N$ values are reflective of ingesting grasses and herbaceous plants that have obtained their nitrogen from various reservoirs. Pigs displayed higher $\delta^{13}C$ and $\delta^{15}N$ values than terrestrial herbivores, which is indicative of these omnivorous animals consuming protein from mixed dietary resources. $\delta^{13}C$ values for freshwater fish bone collagen are typically –30‰ to –20‰ (Fuller et al., 2012), however, the higher $\delta^{13}C$ values for arctic charr and brown trout from Lake Mývatn are comparable to the $\delta^{13}C$ values for dissolved inorganic carbon measured in water samples taken from the lake (Ascough et al., 2010). Since $\delta^{15}N$ values for terrestrial and aquatic plants overlap, freshwater fish $\delta^{15}N$ values are comparable with animals consuming a terrestrial based diet. $\delta^{13}C$ values for marine fish and mammals were similar to those for freshwater fish, however, their $\delta^{15}N$ values were higher and are within the expected range for species that live within the marine environment (Schoeninger and DeNiro, 1984). Various bird species displayed a large range of $\delta^{13}C$ and $\delta^{15}N$ values that are reflective of the mixed terrestrial, freshwater and marine resources they would have consumed. Using animal bones from a midden on the southern bank of Lake Mývatn, Sayle et al. (2013) determined that there was a clear offset in $\delta^{34}S$ values between species deriving their dietary resources from terrestrial, marine and freshwater reservoirs. Additionally, a number of terrestrial herbivores also displayed higher bone collagen $\delta^{34}S$ values compared to the geology of the Lake Mývatn region, indicating that they may have been moved or traded to the area from elsewhere.

Sayle et al. (2014) utilized $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values from the animals at Skútustaðir to better understand radiocarbon dating anomalies in 6 sets of human remains excavated at the cemetery in Hofstaðir. $\delta^{13}C$ and $\delta^{15}N$ values demonstrated the individuals were eating a protein enriched diet and their calibrated ^{14}C dates showed they pre-dated the settlement of Iceland in AD 871 ± 2. When their radiocarbon ages were re-calibrated to account for a marine reservoir effect, three of the adjusted dates were still earlier than *landnám*. These individuals had low $\delta^{34}S$ values and Sayle et al. (2014) concluded they had been consuming a proportion of freshwater protein as part of a mixed diet, and the older radiocarbon dates were due to the large spatially and temporally variable freshwater reservoir effect observed by Ascough et al. (2010).

MATERIALS AND METHODS

Sampling location

Hofstaðir is situated in north-eastern Iceland, 5 km to the west of Lake Mývatn on the banks of the River Laxá (65° 61′ N, 17° 16′ W). Preservation of all samples examined in this study was very good. Bones from 46 sets of adult human remains, excavated from a cemetery located 80 m south-west of the ruins of the Viking feasting hall were analyzed for $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$. Animal bones/teeth (n = 37) were excavated from the sunken pithouse to the south of the Pagan hall, while two equine samples were excavated from a sheet midden outside the north-west door of the hall. Vegetation samples were collected in July 2007 and 2008 from Kálfaströnd on the eastern shore of Lake Mývatn, and from Seljahjallagil, ~ 5 km south-east of Lake Mývatn, while adult midges (*Tanytarsus gracilentus*) were collected by sweep net at the lakeside (Ascough et al., 2010).

Sample preparation and isotopic analysis

Collagen from bone and teeth samples was extracted using a modified version of the Longin method (Longin, 1971). The samples were cleaned, crushed into smaller fragments and demineralized in 1M HCl, before warming the material in ultra-pure water to denature and solubilize the collagen. Water was then removed by lyophilization (Sayle et al., 2013). Vegetation and midge samples were washed with distilled water, oven dried and homogenized. $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ stable isotope measurements were carried out using a Thermo Scientific Delta V Advantage continuous-flow isotope ratio mass spectrometer (CF-IRMS) (Bremen, Germany) coupled to a Costech ECS 4010 elemental analyser (EA) (California, USA) fitted with a pneumatic autosampler. Samples were weighed into tin capsules and were measured as described in Sayle et al. (2013).

RESULTS AND DISCUSSION

All 39 animal bone or tooth collagen samples and 46 adult human bone collagen samples passed the quality criteria as set out by Ambrose (1990) and had C:N atomic ratios that fell within the range of 2.9 to 3.6, indicating good bone collagen preservation (DeNiro, 1985). All samples also passed the quality criteria for measuring sulphur isotopes in mammalian archaeological bone collagen as set out by Nehlich and Richards (2009), and displayed atomic C:S ratios within 600 ± 300, atomic N:S ratios within 200 ± 100 and contained between 0.15 and 0.35% sulphur.

A summary of the stable isotope results is presented in Tables 2–4 and the full dataset for humans and animals can be found in Tables S1–2 of the Supplementary Material section. Welch's unequal variance *t*-tests were conducted to compare the $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values for animals at Hofstaðir and Skútustaðir, where $p < 0.05$ indicates a statistical difference.

Hofstaðir's Animals

The most striking observation regarding the stable isotope values for the Hofstaðir herbivores is that, as a group, their $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values are significantly different from those of the animals previously analyzed from Skútustaðir, and although they are in close proximity to one another (~10 km apart), isotopically, they are very different (Table 2). Cows (*Bos taurus*) from Hofstaðir are ~7‰ higher in δ^{34}S and significantly different from Skútustaðir cows. Similarly, as a group, sheep (*Ovis aries*) and goats (*Capra hircus*) from Hofstaðir are ~5.5‰ higher in δ^{34}S, and are also significantly different from sheep and goats reared at Skútustaðir. While the δ^{13}C values for cows, sheep and goats from Hofstaðir are comparable to those from Skútustaðir, their δ^{15}N values are also significantly different. Horses (*Equus sp.*) from Hofstaðir have δ^{13}C and δ^{15}N values comparable to those from Skútustaðir but have significantly higher δ^{34}S values, while pigs (*Sus scrofa*) from Hofstaðir have comparable δ^{13}C, δ^{15}N and δ^{34}S values to those from Skútustaðir.

Lake Mývatn is renowned for its bi-annual hatching of the midge species, *Tanytarsus gracilentus*, as it is a crucial component of the lake's ecosystem and is a key food source for its aquatic and bird life (Gardarsson and Einarsson, 2004; Gudbergsson, 2004; Ives et al., 2008). Gratton et al. (2008, p764) observed an annual input of 1200 to 2500 kg of midges per hectare, and suggested that the midges can produce "a significant fertilization effect". This phenomenon decreases logarithmically with distance from the shore, such that at 5 km from Lake Mývatn, midge deposition is negligible. Previous investigations of midges at Lake Mývatn found δ^{15}N values to vary between –0.8‰ and 0.5‰ (Gratton et al., 2008; Ascough et al., 2014), while this study ascertained the value to be 1.3‰ (Table 3). Vegetation from Kálfaströnd, on the eastern shore of Lake Mývatn, was found to have δ^{15}N values on average ~8‰ higher than flora measured at Seljahjallagil, a gorge ~5 km south east of the lake (Table 3). It is therefore possible that midge deposition could be one of the reasons for higher δ^{15}N values in vegetation samples closer to the lake**.** Ives et al. (2008) suggested that the number of midges was not uniform on an annual basis and that the density fluctuated irregularly over a period of 4–7 years. It is therefore conceivable that animals grazing closer to Lake Mývatn could not only have ingested grasses that have been fertilized by the midges, but also may have consumed them directly due to the large quantities that surround the lake. Additionally, as the numbers of midges are known to fluctuate, the amount ingested could be directly linked to the cycle of a particular year (or years), and as a result, the $\delta^{15}N$ values could vary in animals at the same site from year to year. Hence, the decreasing density of midges on moving further from the lake, combined with a possible variation in annual numbers could account for the difference in $\delta^{15}N$ values observed for some of the animals at Hofstaðir compared to those at Skútustaðir. Additionally, the slightly more positive $\delta^{15}N$ values for pigs from Skútustaðir could be due to their closer proximity to the lake and their increased access to freshwater protein.

Lake Mývatn is also a haven for migrating birds and the increased amounts of guano in the region could also be affecting the $\delta^{15}N$ values of nearby vegetation. Plants growing closer to nesting birds have been shown to have higher $\delta^{15}N$ values, reflecting the enriched signature of the guano, while plants growing further away have been found to be lower due to sourcing their nitrogen from ^{15}N depleted ammonia produced during decomposition of the droppings (Erskine et al., 1998).

The geology in the Lake Mývatn region is homogenous, with postglacial lavas < 2900 years old dominating the circumference of the lake, and the bedrock around Hofstaðir comprising an assortment of interglacial lavas from the quaternary period (Sæmundsson et al., 2012). Therefore, the $\delta^{34}S$ values of rocks at Hofstaðir and Skútustaðir should be similar, and again, midges may be another factor to consider when looking at the $\delta^{34}S$ signature of the local area. As the larvae live in the sediment at the bottom of the lake and feed on detritus, their $\delta^{34}S$ values are likely to reflect the $\delta^{34}S$ value of the lake. Sayle et al. (2013) showed that freshwater fish had low $\delta^{34}S$ values compared to contemporaneous terrestrial fauna from the same area. Analysis of Lake Mývatn's midges show that they too have low $\delta^{34}S$ values

(Table 3), and consequently they could be decreasing the $\delta^{34}S$ value of the soil, and hence the flora around Skútustaðir. However, the question still remains as to why the average $\delta^{34}S$ value for Hofstaðir's terrestrial animals was so elevated compared to the $\delta^{34}S$ value for the local bedrock and the animals at Skútustaðir. Zazzo et al. (2011) found that relatively high $\delta^{34}S$ values were measured in wool samples taken from sheep living >100 km inland in Ireland, indicating that marine sulphur can be propelled over vast distances. The prevailing wind around north-east Iceland is predominantly southerly, however, during the summer months northerly winds dominate, which would allow for the inland propulsion of sulphate from seawater. As Lake Mývatn was formed ~2300 years ago (Einarsson, 1982), soils in the surrounding area are geologically very young and could be easily influenced by a sea-spray effect. Considering the lake is only 50 km from the coast, it is plausible that the entire region is affected by sea spray, and coupled with a possible midge effect around the lake shore, this could explain the difference in baseline $\delta^{34}S$ signatures observed between Skútustaðir and Hofstaðir. $\delta^{34}S$ values for flora samples taken from Kálfaströnd are comparable to those of Skútustaðir's terrestrial herbivores, while samples from Seljahjallagil, which is similar in distance from the lake as Hofstaðir, are ~ 3‰ higher (Table 3). Further studies on vegetation from around Lake Mývatn and the surrounding region are required to determine the 'true' sulphur baseline for the area.

Hofstaðir's herbivores have an average $\delta^{34}S$ value of 11.4 ± 2.3‰, however, at 2σ there are two outliers in the dataset; a sheep and a cow (Fig. 2). Thus far, these results represent the most positive $\delta^{34}S$ values for terrestrial animals that we have observed in the Lake Mývatn area, and in some cases, they are higher than some marine fish and mammals that have been previously measured (Sayle et al., 2013). The results suggest that both of these animals probably spent a significant proportion of their lives close to the coast and that their $\delta^{34}S$ values have undoubtedly been altered due to a sea-spray effect. Interestingly, both of these animals also have lower δ^{15}N values compared to their contemporaries, and supports McGovern's hypothesis that animals with lower δ^{15}N values were not reared in the Mývatn area (McGovern, 2009). There are therefore 3 possibilities: (1) these animals were traded from a coastal site within Iceland, (2) they were imported to Hofstaðir from overseas, or (3) as suggested by McGovern (2009), they were brought specifically to Hofstaðir as sacrificial gifts due to the higher status of the site. Further examination of these animals, including oxygen and strontium stable isotope analyses, is required to provide clarity on this point.

Hofstaðir's Human Population

No discrimination in stable isotope values exists between sexes, with males (n = 21) exhibiting average δ^{13}C, δ^{15}N and δ^{34}S values of –19.6 ± 0.4‰, 9.3 ± 0.8‰ and 10.6 ± 1.9‰, respectively, while females (n = 25) displayed average δ^{13}C, δ^{15}N and δ^{34}S values of –19.4 ± 0.7‰, 9.9 ± 1.0‰ and 11.1 ± 2.6‰, respectively (Table 4). Assuming the population were eating terrestrial animals reared in the area and their by-products (e.g. milk, cheese), and taking into account a subsequent trophic level shift of +1‰ for carbon, +4.5‰ for nitrogen, and +1‰ for sulphur, individuals consuming a wholly terrestrial diet should display a δ^{13}C value of approximately –20.7‰, a δ^{15}N value of around 6.3‰ and a δ^{34}S value of approximately 12.4‰. There are no individuals within the group that fit all these criteria, and even if we apply a trophic shift of +5.5 ± 0.5‰ for δ^{15}N, as suggested by Fernandes (2015), only two people (SK013: 7.4‰ and SK053: 7.7‰) could theoretically be consuming solely terrestrial resources. From the archaeological evidence, it is believed that people living at Hofstaðir were eating predominantly dairy produce, but their diet was also supplemented by freshwater fish, eggs, the flesh of domestic animals and dried marine fish (McGovern, *pers. comm.*). Based on previous stable isotope results for marine and freshwater fish found in a midden in Skútustaðir, it was assumed that individuals with a higher δ^{13}C and δ^{34}S value had eaten some marine protein as part of their daily diet, while those with a higher δ^{13}C value and a lower $\delta^{34}S$ value had consumed some freshwater protein (Sayle et al. 2014). This theory still holds true, however, $\delta^{34}S$ values for animals from Hofstaðir, presented here, demonstrate that the $\delta^{34}S$ baseline is higher than the previously determined baseline from Skútustaðir, and this in turn has made it more difficult to determine whether individuals with elevated $\delta^{34}S$ values consumed marine protein.

Three women, SK016, SK066 and SK009, displayed the highest $\delta^{13}C$ values within the group, however, SK016 had a lower $\delta^{15}N$ value than SK066, while SK009 had the highest $\delta^{15}N$ value within the entire group (Fig. 3A). While freshwater and marine fish contain very similar percentages of sulphur (*ca*. 0.5%, see Sayle et al., (2013) – Table 1), terrestrial herbivores have approximately half of this amount. Therefore, when considering consumption per unit of protein, fish would contribute doubly to the consumer's final $\delta^{34}S$ value. This assumes direct routing of protein versus scrambling into bone collagen, a process which is still not fully understood (Jim et al., 2006). The horse-shoe shaped pattern observed in Figure 3B is usually indicative of a concentration dependence effect (Phillips and Koch, 2002). However, it is not the case here as marine and freshwater fish have similar sulphur concentrations, and consumption of marine protein leads to elevated $\delta^{13}C$ and $\delta^{34}S$ values, while ingestion of freshwater protein leads to a higher $\delta^{13}C$ and a lower $\delta^{34}S$ value. Since SK009 has a higher $\delta^{34}S$ value than the other two women, this would suggest she consumed more marine protein than freshwater protein (Figs. 3B&C). These three women were arranged in the same burial series and therefore we would expect their ^{14}C ages to be similar, however, as shown previously by Sayle et al. (2014), due to the influence of a freshwater reservoir effect, SK016 (160 cal BC–cal AD 60) and SK066 (cal AD 250–410) appear to be much older than SK009 (cal AD 890–1030) and are also significantly pre-*landnám*. Similarly, another female, SK061 had higher $\delta^{13}C$ and $\delta^{15}N$ values but a lower $\delta^{34}S$ value, suggesting consumption of a large proportion of freshwater protein, and this too was reflected in her radiocarbon age (cal AD 420–570) (Sayle et al., 2014). Another two females, SK056 and SK075, have $\delta^{13}C$ and $\delta^{15}N$ values lower than SK009, yet their $\delta^{34}S$ values are more positive (Fig. 3C). This suggests that the results for both of these individuals are not comparable with someone indigenous to the Lake Mývatn region and that perhaps they lived a significant proportion of their lives in a coastal area where their $\delta^{34}S$ values were more altered by the sea-spray effect. Likewise, it could be proposed that SK022, a male with a $\delta^{34}S$ value of 13.6‰, was also a stranger to the area but over time the consumption of some freshwater protein lowered his previously elevated $\delta^{34}S$ value.

CONCLUSIONS

Utilizing only $\delta^{13}C$ and $\delta^{15}N$ values to determine dietary information on the early settlers of Iceland can be problematic as $\delta^{13}C$ values for marine and freshwater fish are similar, while $\delta^{15}N$ values for freshwater and terrestrial fauna overlap. Exploiting $\delta^{34}S$ as a third isotope has been shown to be a valuable additional tool that can be used to 'unpick' palaeodiet. However, as demonstrated in this study, it cannot be assumed that animals reared near to one archaeological site will have similar $\delta^{34}S$ values to those animals raised at a closely neighbouring site. While Hofstaðir and Skútustaðir are only 10 km apart, animals from Hofstaðir were found to have $\delta^{34}S$ values almost 6‰ higher compared to their contemporaries at Skútustaðir. This demonstrates that a baseline specific to the site of interest must be established, especially when asking questions in relation to the origin and mobility of people and their animals. Here, using $\delta^{34}S$ analyses on human bones, distinctions have been made between those consuming marine or freshwater protein. Individuals that displayed higher $\delta^{13}C$ and $\delta^{34}S$ values were regarded as having consumed some marine-based produce, while those with a higher $\delta^{13}C$ value and a lower $\delta^{34}S$ value were viewed as having consumed some freshwater-based resources. $\delta^{34}S$ values also revealed outliers among the Hofstaðir burial set, as well as confirming that animals were being imported into the region, just as had been previously observed at Skútustaðir.

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Table 1: Previously published and unpublished stable isotope values for modern flora, and modern and archaeological fauna in Iceland. [Δ]Wang and Wooler, (2006), [‡]Skrzypek et al., (2008), *Sayle et al., (2013), [†]Ascough et al., (2014), [#]Ascough (unpublished data).

	$\delta^{13}C$ [‰]	$\delta^{15}N$ [‰]	$\delta^{34}S$ [‰]
Terrestrial plants & lichens [Δ‡†]	–30.9 to –20.4	–12.4 to 6.5	-
Aquatic plants [Δ†]	–16.9 to –11.5	–16.0 to 4.3	-
Terrestrial herbivores *[†]	–22.5 to –20.3	–1.5 to 5.9	–1.0 to 13.9
Pigs *[†]	–21.7 to –16.9	–1.2 to 9.7	3.7 to 8.5
Freshwater fish *[†#]	–16.0 to –7.9	3.1 to 8.5	–4.3 to –0.2
Marine fish & mammals *	–16.3 to –13.5	12.1 to 14.5	12.4 to 17.5
Birds *[†]	–23.6 to –6.9	–4.9 to 16.4	–5.3 to 13.6

Table 2: Mean values and standard deviations (1σ) of terrestrial animal bone collagen from Hofstaðir and *t*-test comparisons with Skútustaðir data (Sayle et al., 2013). **t*-tests were undertaken on the combined values for sheep and goats from Skútustaðir, as some of the animals were not identified separately.

Species	**Common name**	***N***	**δ^{34}S [‰]**	***t*-test**	**δ^{13}C [‰]**	***t*-test**	**δ^{15}N [‰]**	***t*-test**
Capra hircus	Goat	3	13.1 ± 1.2	$P < 0.001$*	–21.4 ± 0.3	$P = 0.10$*	0.8 ± 0.3	$P < 0.001$*
Ovis aries	Sheep	10	11.7 ± 2.8		–21.3 ± 0.4		1.5 ± 0.9	
Equus sp.	Horse	7	10.5 ± 0.7	$P = 0.03$	–22.1 ± 0.4	$P = 0.29$	2.2 ± 0.8	$P = 0.61$
Bos taurus	Cow	10	11.1 ± 2.7	$P < 0.001$	–21.8 ± 0.3	$P = 0.06$	2.0 ± 1.3	$P = 0.002$
Sus scrofa	Pig	9	10.5 ± 1.8	$P = 0.06$	–20.0 ± 1.4	$P = 0.53$	5.8 ± 2.4	$P = 0.08$
Herbivores	-	30	11.4 ± 2.3	$P < 0.001$	–21.7 ± 0.5	$P = 0.001$	1.8 ± 1.1	$P < 0.001$

Table 3: $\delta^{34}S$, $\delta^{13}C$ and $\delta^{15}N$ values for modern midge and flora samples from the Lake Mývatn region.

Lab ID	**Sample Type**	**$\delta^{34}S$ [‰]**	**%S**	**$\delta^{13}C$ [‰]**	**$\delta^{15}N$ [‰]**
GUsi-3513	*Tanytarsus gracilentus* (midge)	–3.9	0.86	–14.3	1.3
GUsi-3514	Meadow soft grass (Seljahjallagil)	9.8	0.19	–26.4	–3.6
GUsi-3515	Sedge (Seljahjallagil)	9.6	0.20	–27.3	–8.1
GUsi-3516	Purple moor grass (Kálfaströnd)	6.6	0.17	–27.9	2.6
GUsi-3517	Field Horsetail (Kálfaströnd)	6.4	0.11	–28.1	1.9

Table 4: Mean values and standard deviations (1σ) of human bone collagen from Hofstaðir, Iceland.

Sex	***N***	**$\delta^{34}S$ [‰]**	**$\delta^{13}C$ [‰]**	**$\delta^{15}N$ [‰]**
Male	21	10.6 ± 1.9	–19.6 ± 0.4	9.3 ± 0.8
Female	25	11.1 ± 2.6	–19.4 ± 0.7	9.9 ± 1.0

Figure 1: Location of Lake Mývatn, Iceland and the archaeological sites of Hofstaðir and Skútustaðir.
519x398mm (300 x 300 DPI)

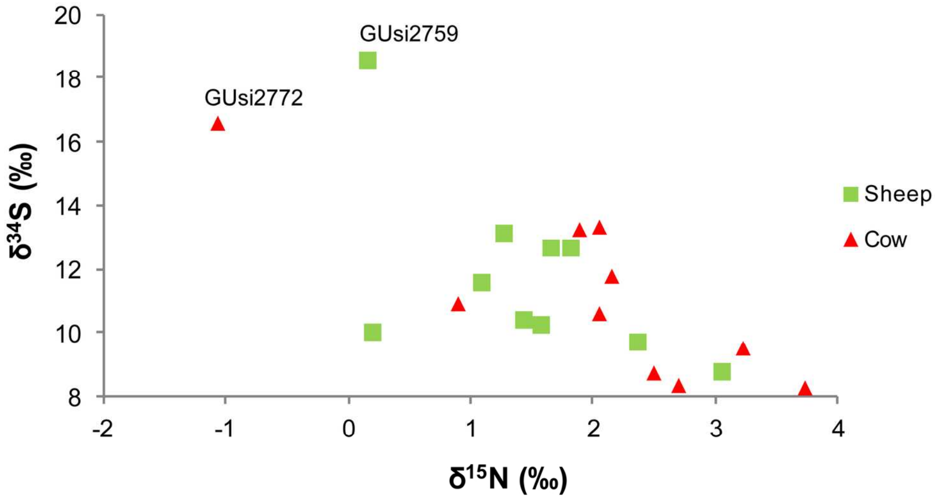

Figure 2: Plot of δ15N vs. δ34S for archaeological sheep and cow remains from Hofstaðir.
77x41mm (600 x 600 DPI)

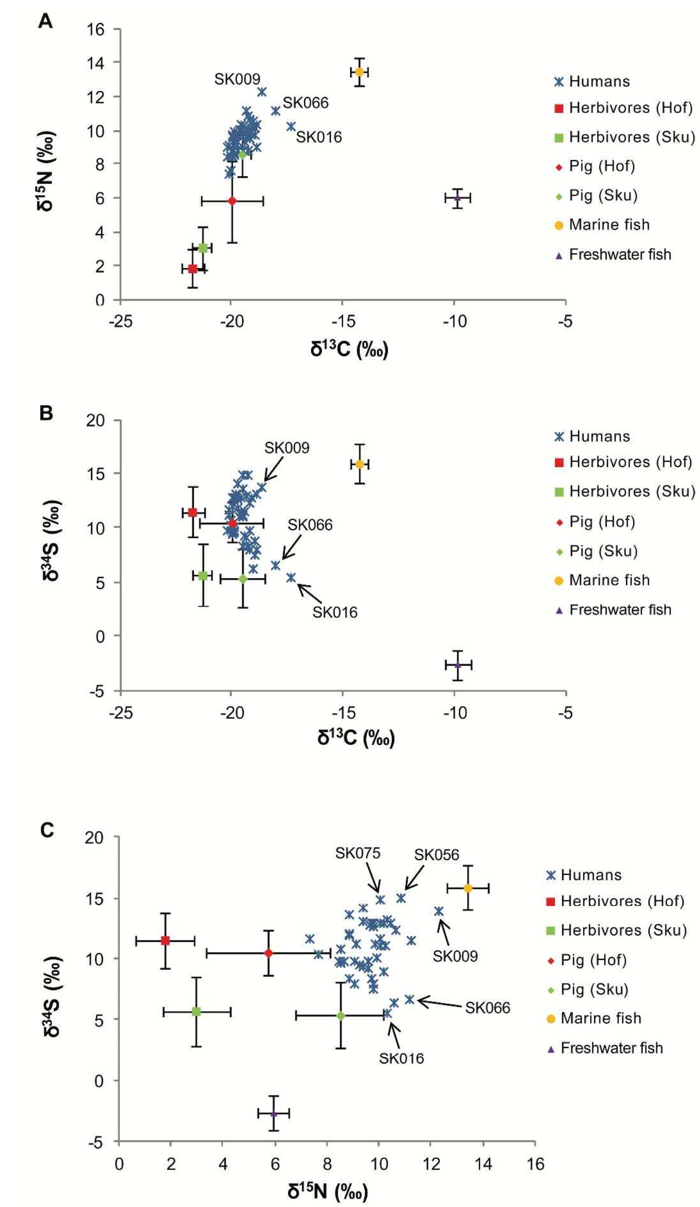

Figure 3: Plots of δ13C vs. δ15N (A), δ13C vs. δ34S (B) and δ15N vs. δ34S (C) for archaeological human and faunal remains from Hofstaðir. Skútustaðir, marine fish and freshwater fish isotope data is taken from Sayle et al (2013). Numbered arrows represent individual human bones samples mentioned in the text. Error bars show standard deviations (1σ) from the mean.
245x414mm (600 x 600 DPI)

Figure Legends:

Figure 1: Location of Lake Mývatn, Iceland and the archaeological sites of Hofstaðir and Skútustaðir.

Figure 2: Plot of δ^{15}N *vs*. δ^{34}S for archaeological sheep and cow remains from Hofstaðir.

Figure 3: Plots of δ^{13}C *vs*. δ^{15}N (A), δ^{13}C *vs*. δ^{34}S (B) and δ^{15}N *vs*. δ^{34}S (C) for archaeological human and faunal remains from Hofstaðir. Skútustaðir, marine fish and freshwater fish isotope data is taken from Sayle et al (2013). Numbered arrows represent individual human bones samples mentioned in the text. Error bars show standard deviations (1σ) from the mean.