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UTILIZATION OF $\delta^{13}C$, $\delta^{15}N$, AND $\delta^{34}S$ ANALYSES TO UNDERSTAND ^{14}C DATING ANOMALIES WITHIN A LATE VIKING AGE COMMUNITY IN NORTHEAST ICELAND

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ABSTRACT. Previous stable isotope studies of modern and archaeological faunal samples from sites around Lake Mývatn, within the Mývatnssveit region of northeast Iceland, revealed that an overlap existed between the $\delta^{15}N$ ranges of terrestrial herbivores and freshwater fish, while freshwater biota displayed $\delta^{13}C$ values that were comparable with marine resources. Therefore, within this specific ecosystem, the separation of terrestrial herbivores, freshwater fish, and marine fish as components of human diet is complicated when only $\delta^{13}C$ and $\delta^{15}N$ are measured. $\delta^{34}S$ measurements carried out within a previous study on animal bones from Skútustaðir, an early Viking age settlement on the south side of Lake Mývatn, showed that a clear offset existed between animals deriving their dietary resources from terrestrial, freshwater, and marine reservoirs. The present study focuses on $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analyses and radiocarbon dating of human bone collagen from remains excavated from a churchyard at Hofstaðir, 5 km west of Lake Mývatn. The results demonstrate that a wide range of $\delta^{34}S$ values exist within individuals, a pattern that must be the result of consumption of varying proportions of terrestrial-, freshwater-, and marine-based resources. For that proportion of the population with ^{14}C ages that apparently predate the well-established first human settlement of Iceland (*landnám*) circa AD 871 ± 2, this has enabled us to explain the reason for these anomalously old ages in terms of marine and/or freshwater ^{14}C reservoir effects.

INTRODUCTION

The settlement, or *landnám*, of Iceland is believed to have occurred shortly after the eruption of the Veiðivötn and Torfajökull volcanoes in AD 871 ± 2 (Grönvold et al. 1995), and by the early 10th century, Viking Age communities from across Scandinavia had established themselves not only at Icelandic coastal sites, but also within the less inhabitable interior highlands of the island (Vésteinsson 1998). Understanding the nature and timing of Icelandic settlement patterns is of considerable interest in Viking period archaeology, particularly as archaeological and paleoenvironmental records demonstrate large-scale post-*landnám* human environmental impacts, climatic variations, and societal changes (Vésteinsson 1998, 2000; Buckland 2000; Andrews et al. 2001; Dugmore et al. 2007; Lawson et al. 2007). ^{14}C dating is invaluable in understanding these changes in regions such as the area surrounding Lake Mývatn (Mývatnssveit), which contains a wealth of archaeological sites (McGovern et al. 2006, 2007). However, radiocarbon dating in Mývatnssveit is complicated by the impact of marine and freshwater reservoir effects on both human and certain faunal remains (Ascough et al. 2007, 2010, 2011, 2012), as a result of the consumption of both marine fish transported from coastal sites and local freshwater resources (e.g. freshwater fish and waterfowl) (McGovern et al. 2006, 2007). A ^{14}C reservoir effect results in older ^{14}C ages for samples from this reservoir compared to material from the contemporaneous terrestrial/atmospheric C reservoir. Importantly, this effect extends to terrestrial organisms obtaining dietary carbon from within the affected reservoir. In Mývatnssveit, anomalously early calibrated age ranges were noted for human, pre-Christian burials that stratigraphically overlay the *landnám* tephra, yet predated AD 871, indicating the influence of a ^{14}C reservoir effect (McGovern et al. 2006; Ascough et al. 2007, 2012). It was possible that in some instances the observed age offset resulted entirely from the marine reservoir effect (MRE), which extends to ~500 ^{14}C yr (Ascough et al. 2007) for marine samples from

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Icelandic waters during the Viking to Medieval period. However, the offset in some human and pig bone samples from Mývatnssveit (up to ~1100 ^{14}C yr) was too large to be explained solely by the MRE, suggesting the presence of a large freshwater reservoir effect (FRE) in the region. This was confirmed by measurement of samples from Lake Mývatn, which showed a spatially and temporally variable FRE in lake biota that extended to ~10,000 ^{14}C yr (Ascough et al. 2010, 2011), consistent with the release of ^{14}C-depleted carbon during geothermal activity (Sveinbjörnsdóttir et al. 1992, 1995).

Correcting for a ^{14}C reservoir effect requires knowledge not only of the size of the effect itself, but also of the proportion of reservoir-affected carbon within a sample. For bone collagen, this can be achieved using the stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$), usually expressed as $\delta^{13}C$ and $\delta^{15}N$, respectively (Arneborg et al. 1999; Cook et al. 2001; Coplen 1995). Other than in low-protein diets, human bone collagen $\delta^{13}C$ values predominantly reflect the $\delta^{13}C$ values of dietary protein with a 1‰ trophic level shift. The typical ranges are significantly different in high-latitude terrestrial and marine systems, allowing quantification of the proportion of marine versus terrestrial dietary protein. Unfortunately, the $\delta^{13}C$ values of freshwater biota from Lake Mývatn overlap those of marine resources (Ascough et al. 2010), meaning that it is not possible to identify from $\delta^{13}C$ measurements whether a non-terrestrial dietary component is marine or freshwater in origin, or indeed a combination of both. Bone collagen $\delta^{15}N$ values also reflect those of dietary protein, but with a trophic level shift of up to +5.3‰ (Minagawa and Wada 1984; Cabana and Rasmussen 1994, 1996). For samples from Mývatnssveit, $\delta^{15}N$ values allowed discrimination of marine versus non-marine resources, as the $\delta^{15}N$ values of marine resources were significantly greater than those of freshwater resources. However, the $\delta^{15}N$ values of terrestrial and freshwater resources for the region showed considerable overlap, again precluding discrimination of terrestrial versus marine and freshwater components (Ascough et al. 2010). Ascough et al. (2012) used $\delta^{13}C$, $\delta^{15}N$, and ^{14}C in combination to discriminate between marine and freshwater dietary contributions in samples showing a ^{14}C reservoir effect. There is, however, considerable potential to improve on previous work in this area using stable isotopes of sulfur ($\delta^{34}S$). The present study describes the results of an investigation applying $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analyses and ^{14}C dating to archaeological samples from the site of Hofstaðir to address the problems of marine and freshwater reservoir effects in Mývatnssveit.

The farmstead of Hofstaðir lies on the River Laxá, 5 km west of Lake Mývatn in northeast Iceland (Figure 1). After the discovery of a large Viking feasting hall, the site was documented as an area of major archaeological importance with respect to the settlement of Viking communities in Iceland (Friðriksson and Vésteinsson 1997; Vésteinsson 1998; Lucas and McGovern 2007; McGovern et al. 2007; Lucas 2009). Tephrochronological studies indicate that settlement at Hofstaðir occurred shortly after AD 940, yet by the time Hekla had erupted in AD 1104, the Viking site had been abandoned for approximately 70 yr (Sigurgeirsson 2001; Lucas 2009). Situated southwest of the feasting hall was a chapel and cemetery that had been previously referenced in a property transfer dating back to AD 1477 (Gestsdóttir 1999).

It is currently believed that there have been at least three phases of church structures at Hofstaðir, with the youngest turf construction postdating AD 1477. Earlier buildings were erected from timber, with birch wood samples thought to be part of the earliest structure, giving ^{14}C ages of 1035 ± 35 BP (cal AD 896–1118, 95.4% probability) and 1015 ± 45 BP (cal AD 897–1155, 95.4% probability) (AA-53125 and AA-53126, respectively) (Gestsdóttir 2004). Due to the very short early settlement period, it is unclear whether the first church pre- or postdates the abandonment of the feasting hall around AD 1030; however, it is thought that the cemetery was in use between the 10th and 13th centuries, with all the burials predating the H-1300 tephra deposit. In addition, the stratigraphy at

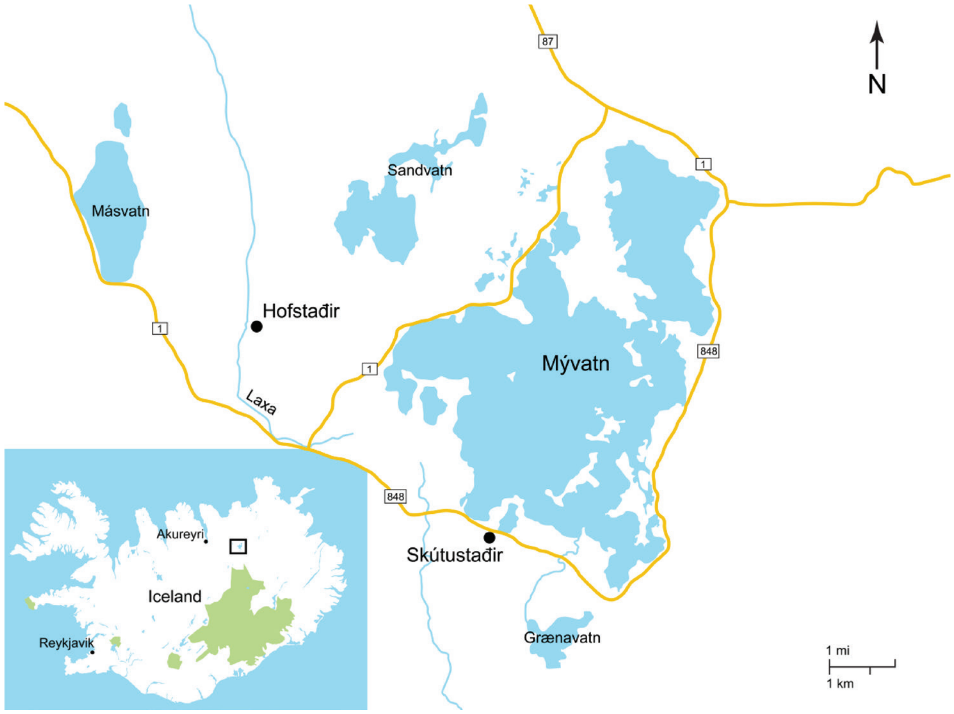

Figure 1 Lake Mývatn in northeast Iceland and the archaeological sites of Hofstaðir and Skútustaðir

the site indicates that the intensity of burials in the cemetery was much greater in the earlier phases (Gestsdóttir 2006; Gestsdóttir and Isaksen 2011). ^{14}C dating of terrestrial animal remains, primarily recovered from the midden deposits of 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, in press; Lucas 2009).

Results from previous stable isotope studies of archaeological mammal, fish, and bird bone samples discovered at Hofstaðir revealed that $\delta^{13}C$ values for terrestrial herbivores averaged –21.0 ± 1.1‰ while $\delta^{15}N$ values averaged +1.3 ± 1.5‰ (Ascough et al. 2007, 2012, in press; McGovern et al. 2007; Lucas 2009). Two freshwater fish samples gave $\delta^{13}C$ and $\delta^{15}N$ values of –12.5‰ and –12.2‰, and +5.7‰ and +6.8‰, respectively (Ascough et al. 2010), and are in keeping with modern arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta*) samples (n = 116) from Lake Mývatn ($\delta^{13}C$: –14.3‰ to –7.9‰, mean –11.5 ± 1.7‰, and $\delta^{15}N$: +3.1‰ to +8.5‰, mean +5.8 ± 1.4‰) (P Ascough, personal communication). Omnivorous pigs and various birds displayed a large range of $\delta^{13}C$ values (–21.7‰ to –16.9‰ and –21.4‰ to –10.1‰, respectively) and $\delta^{15}N$ values (+0.3‰ to +7.4‰ and +2.7‰ to +13.9‰, respectively), reflecting the mixed terrestrial, freshwater, and marine dietary resources they would have been consuming (Ascough et al. 2012, in press). Sayle et al. (2013) measured $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values on the collagen of a large number and variety of animal bones discovered in a midden at the early Viking settlement of Skútustaðir on the southern banks of Lake Mývatn (Figure 1). $\delta^{13}C$ and $\delta^{15}N$ values for terrestrial herbivores, freshwater fish, omnivorous pigs, and birds were comparable with previous samples analyzed at Hofstaðir (Figure 2), while marine fish $\delta^{13}C$ and $\delta^{15}N$ values were similar to cod samples from four archaeological sites in the northeast Atlantic (Barrett et al. 2008, 2011; Russell et al. 2011) (Table 1).

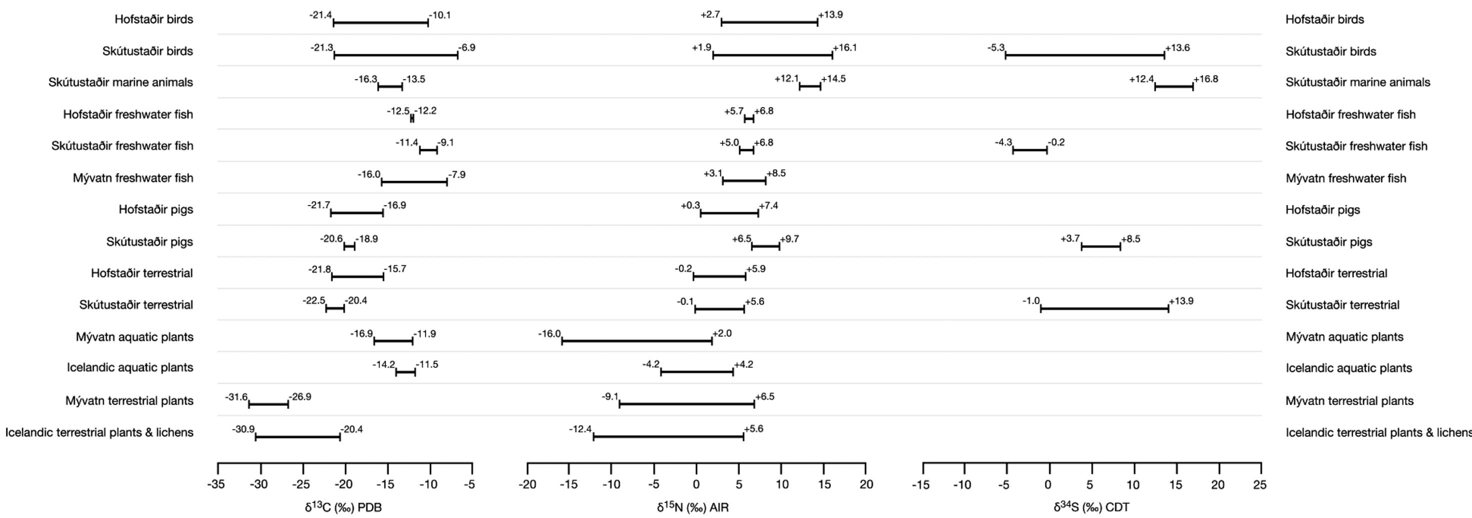

Figure 2 $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values for various flora and fauna from around Iceland and the Lake Mývatn region

Table 1 Summary of animal bone collagen results from Skútustaðir, Iceland (Sayle et al. 2013).

Species	*n*	$\delta^{34}S$ (‰)	%S	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Cow (*Bos* sp.)	32	4.1 ± 3.2	0.21 ± 0.05	−21.5 ± 0.4	3.9 ± 1.0
Sheep/goat (*Ovis*/*Capra* sp.)	48	6.7 ± 1.9	0.21 ± 0.05	−21.2 ± 0.4	2.5 ± 1.1
Horse (*Equus* sp.)	5	5.7 ± 3.2	0.20 ± 0.02	−21.8 ± 0.4	1.9 ± 1.3
Brown Trout (*Salmo trutta*)	5	−2.4 ± 1.5	0.53 ± 0.04	−9.6 ± 0.2	6.1 ± 0.7
Arctic Charr (*Salvelinus alpinus)*	7	−3.0 ± 1.3	0.58 ± 0.03	−10.0 ± 0.8	5.9 ± 0.5
Haddock (*Melanogrammus aeglefinus*)	3	14.0 ± 1.8	0.46 ± 0.03	−14.3 ± 0.3	12.6 ± 0.3
Cod (*Gadus morhua)*	6	16.8 ± 0.9	0.50 ± 0.02	−14.2 ± 0.4	13.9 ± 0.5
Seal (*Phocid* sp.)	6	15.9 ± 1.0	0.21 ± 0.05	−15.3 ± 0.5	12.7 ± 0.5
Pig (*Sus* sp.)	3	5.3 ± 2.7	0.17 ± 0.01	−19.5 ± 1.0	8.5 ± 1.7
Birds*	11	3.0 ± 5.0	0.29 ± 0.03	−13.6 ± 4.2	6.5 ± 3.9
Arctic fox (*Alopex lagopus*)	3	1.4 ± 0.7	0.25 ± 0.03	−14.9 ± 1.3	9.0 ± 1.5

*Water and domestic fowl including chicken (*Gallus gallus*), mallard (*Anas platyrhynchos*), tufted duck (*Aythya fuligula*), swan (*Cygnus* sp.), and common scoter (*Melanitta nigra*).

Sayle et al. (2013) demonstrated a clear offset of ~8‰ in $\delta^{34}S$ values between terrestrial herbivores (mean = +5.6 ± 2.8‰) and freshwater fish (–2.7 ± 1.4‰), while marine fish $\delta^{34}S$ values were ~10‰ higher than terrestrial herbivores (mean = +15.9 ± 1.5‰) and ~18.5‰ more enriched with respect to $\delta^{34}S$ than their freshwater counterparts (Tables 1 and 2). The isotopic values obtained for the marine fish are also similar to eight archaeological cod samples measured from Skriðuklaustur in eastern Iceland ($\delta^{34}S$: +15.1‰ to +16.7‰, mean = +15.7 ± 0.6‰) (Nehlich et al. 2013). Sayle et al. (2013) were able to distinguish between animals that had consumed either freshwater or marine protein as part of a mixed diet by the additional use of $\delta^{34}S$, something that carbon and nitrogen isotopes alone could not discriminate (Figure 2). Three pigs and two arctic foxes from Viking-age contexts were ^{14}C dated and all appeared to be significantly older than the *landnám* settlement date of AD 871 ± 2. Their depleted $\delta^{34}S$ values suggested that they had been consuming freshwater fauna, and while correcting for the freshwater ^{14}C reservoir effect at Lake Mývatn is problematic, the results provided information about whether the anomalously old ^{14}C ages were due to a marine or freshwater ^{14}C reservoir effect, or a combination of both. Drawing on these findings, our objective here was to use $\delta^{34}S$ analyses to more accurately determine the diet of humans within the region and to utilize these results to assist in the interpretation of ^{14}C dates of individuals who may have consumed a partly non-terrestrial diet.

Table 2 Mean and standard deviations (1σ) of terrestrial, freshwater and marine animal bone collagen from Skútustaðir, Iceland (Sayle et al. 2013).

Species group	*n*	$\delta^{34}S$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Terrestrial	85	5.6 ± 2.8	−21.3 ± 0.4	3.0 ± 1.3
Freshwater	12	−2.7 ± 1.4	−9.8 ± 0.6	5.9 ± 0.6
Marine	15	15.9 ± 1.5	−14.7 ± 0.7	13.2 ± 0.7

METHODOLOGY

Sampling Location

Hofstaðir, situated to the west of Lake Mývatn (65°61′N, 17°16′W) on the banks of the river Laxá (Figure 1), is one of many Viking Age sites in the Mývatnssveit region that have been investigated as part of the *Landscapes of Settlement Project* (McGovern et al. 2007; Lucas 2009). The bones from nine adult humans analyzed in this study were excavated between 1999 and 2004 from a cemetery located 80 m southwest of the Viking feasting hall (Gestsdóttir 1999, 2001, 2002, 2003, 2004).

Extraction of Bone Collagen

A modified version of the Longin (1971) method was used to extract the collagen component from all bone samples. Sample surfaces were initially cleaned using a Dremel® multitool, before they were lightly crushed into smaller fragments and immersed in 1M HCl at room temperature for approximately 24 hr until demineralization. The acid solution containing bone mineral components was then decanted and samples were rinsed with ultrapure water to remove any remaining dissociated carbonates, acid-soluble contaminants, and solubilized bioapatite. The gelatinous-like material was washed and then heated gently to ~80°C in ultrapure water to denature and solubilize the collagen. After cooling, the solution was filtered, reduced to ~5 mL, and freeze-dried.

Radiocarbon Dating

CO_2 was generated from collagen via combustion following the method of Vandeputte et al. (1996). Following cryogenic purification, $\delta^{13}C$ was measured on an aliquot of the CO_2 for normalization of sample $^{14}C/^{13}C$ ratios. This was achieved on a VG SIRA 10 isotope ratio mass spectrometer, using

NBS 22 (oil) and NBS 19 (marble) as standards. A 3-mL aliquot of the CO_2 was converted to graphite for ^{14}C measurement by accelerator mass spectrometry (AMS) using the method of Slota et al. (1987), and sample $^{14}C/^{13}C$ ratios were measured with carbon in the +1 charge state on the SUERC SSAMS instrument at 245 keV. All calibrated age ranges discussed within the text are presented at 95.4% confidence and were obtained from sample ^{14}C ages using the atmospheric IntCal09 curve (Reimer et al. 2009) and OxCal v 4.2.2 (Bronk Ramsey 1995, 2001, 2009).

Carbon, Nitrogen, and Sulfur Isotope Ratio Analyses

$\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ stable isotope measurements were carried out using a continuous-flow isotope ratio mass spectrometer (Thermo Scientific Delta V Advantage; Bremen, Germany) coupled to a Costech ECS 4010 elemental analyzer (EA) (Milan, Italy) fitted with a pneumatic autosampler. Samples were weighed into tin capsules (~600 µg for $\delta^{13}C$ and $\delta^{15}N$ and ~10 mg for $\delta^{34}S$) and were measured as described in Sayle et al. (2013).

RESULTS

A summary of the ^{14}C ages and stable isotope results for the human adult bone collagen samples are presented in Table 3; calibrated ^{14}C dates can be seen in Figure 3. $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values ranged from –20.2 to –17.3‰, +7.4 to +12.3‰ and +5.5 to +14.9‰, respectively, while the 95.4% probability calibrated ages ranged from 157 cal BC to cal AD 1148. All of the samples analyzed had C:N atomic ratios that fell within the range of 2.9 to 3.6, indicating good preservation of the bone collagen (DeNiro 1985). Nehlich and Richards (2009) analyzed a variety of mammalian archaeological samples, with the objective of introducing quality control standards for measuring sulfur isotopes in bone collagen. They found that, on average, mammalian collagen had an atomic C:S ratio of 600 ± 300, an atomic N:S ratio of 200 ± 100, and contained between 0.15 and 0.35% sulfur. One sample in this study (SK061) has an atomic N:S ratio of slightly less than 100, but it has not been excluded as the bone collagen passes all other quality criteria.

DISCUSSION

Arneborg et al. (1999) state that northern European populations with no access to marine food and who have consumed a diet based wholly on terrestrial plants and animals would be expected to have a bone collagen $\delta^{13}C$ value of approximately –21‰, while those such as the west Greenland Eskimo population, who consumed an exclusively marine-based diet, would have a $\delta^{13}C$ value of about –12.5‰. However, by using the average $\delta^{13}C$ values for terrestrial herbivores (–21.3 ± 0.4‰) and marine fish (–14.7 ± 0.7‰) at Skútustaðir as end-members (Table 2) (Sayle et al. 2013), and taking into account the subsequent trophic level shift of about +1‰ that would occur between animal and human bone collagen (DeNiro and Epstein 1978), we would expect that humans at Hofstaðir consuming a wholly terrestrial diet would display $\delta^{13}C$ values of approximately –20‰, while those eating solely marine produce would have a $\delta^{13}C$ value of approximately –13.5‰.

Unlike carbon, nitrogen isotopes can increase significantly with each trophic level shift (about +3 to +5‰) in marine and terrestrial food chains (Schoeninger and DeNiro 1984). Again, using isotope values for animals from Skútustaðir as a baseline (Table 2) (Sayle et al. 2013), humans consuming a wholly terrestrial, freshwater, or marine diet at Hofstaðir should accordingly exhibit a maximum range of $\delta^{15}N$ values of approximately +4.7 to +9.3‰, +8.3 to +11.5‰, and +15.5 to +18.9‰, respectively. Similar to carbon, trophic level shifts in sulfur isotopes are small (about +1‰) (Richards et al. 2003), and those consuming a wholly terrestrial, freshwater, or marine diet within the community at Hofstaðir would display $\delta^{34}S$ values of approximately +3.8 to +9.4‰, –3.1 to –0.3‰, and +15.4 to +18.4‰, respectively.

Table 3 Radiocarbon ages and stable isotope results for Hofstaðir human bone collagen.

Skeleton ID	Lab ID	^{14}C age (yr BP)	Calibrated date*	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	$\delta^{34}S$ (‰)	%C	%N	%S	C:N ratio	C:S ratio	N:S ratio	Diet
SK009	SUERC-39947	1060 ± 30	cal AD 896–1024	−18.7	12.3	13.8	41.3	14.8	0.18	3.3	612	188	M
SK016	SUERC-39952	2030 ± 30	157 cal BC–cal AD 53	−17.3	10.3	5.5	41.0	14.8	0.18	3.2	615	190	F
SK053	SUERC-39955	1130 ± 30	cal AD 782–989	−20.1	7.7	10.3	40.3	14.5	0.19	3.2	555	171	T
SK061	SUERC-39956	1560 ± 30	cal AD 424–565	−19.0	10.6	6.3	31.4	10.7	0.25	3.4	331	96	F
SK066	SUERC-39957	1705 ± 30	cal AD 255–409	−18.0	11.2	6.6	44.9	15.6	0.19	3.3	616	184	F
SK013	SUERC-41975	1123 ± 24	cal AD 878–988	−20.1	7.4	11.6	40.3	14.4	0.20	3.3	537	164	T
SK047	SUERC-41982	1005 ± 24	cal AD 986–1148	−20.2	8.5	9.8	42.8	15.4	0.26	3.2	433	134	T
SK007	SUERC-43994	1212 ± 29	cal AD 695–890	−19.2	10.6	12.3	42.7	15.2	0.33	3.3	344	105	M
SK056	SUERC-44122	1184 ± 29	cal AD 726–950	−19.3	10.9	14.9	41.9	15.0	0.22	3.3	498	153	M

Note: Estimated age ranges are based on measured ^{14}C ages presented in the text following calibration with the IntCal09 atmospheric calibration curve and OxCal v 4.2.2 (*95.4% probability). T = primarily terrestrial, M = marine component present, F = freshwater component present.

Table 4 Marine reservoir corrected ^{14}C calibrated dates for humans consuming non-terrestrial protein.

Skeleton ID	Lab ID	^{14}C age (yr BP)	Calibrated date*	$\delta^{13}C$ (‰)	% Marine diet#	Adjusted calibrated date*†
SK009	SUERC-39947	1060 ± 30	cal AD 896–1024	−18.7	20	cal AD 980–1160
SK016	SUERC-39952	2030 ± 30	157 cal BC–cal AD 53	−17.3	42	cal AD 27–231§
SK061	SUERC-39956	1560 ± 30	cal AD 424–565	−19.0	15	cal AD 434–640§
SK066	SUERC-39957	1705 ± 30	cal AD 255–409	−18.0	31	cal AD 356–564§
SK007	SUERC-43994	1212 ± 29	cal AD 695–890	−19.2	12	cal AD 773–976
SK056	SUERC-44122	1184 ± 29	cal AD 726–950	−19.3	11	cal AD 780–988

*95.4% probability.

#The percentage marine diet was calculated by linear interpolation between the end-point values –13.5‰ (100% marine) and –20‰ (100% terrestrial).

†^{14}C ages were converted into calendar years using a mixed calibration curve interpolated between the terrestrial curve IntCal09 and the model-calculated Marine09 ($\Delta R = 58 \pm 75$, calculated from the Marine Reservoir Database, Queen's University, Belfast; http://calib.qub.ac.uk/marine/) with the fraction of marine diet as an input parameter.

§Although adjusted dates are calibrated based on % of marine protein in the diet, these individuals favored consumption of freshwater protein. As such, the adjusted calibrated date provides a *terminus post quem* for these individuals since there is no known method for correcting freshwater offsets due to the variability of the freshwater reservoir effect.

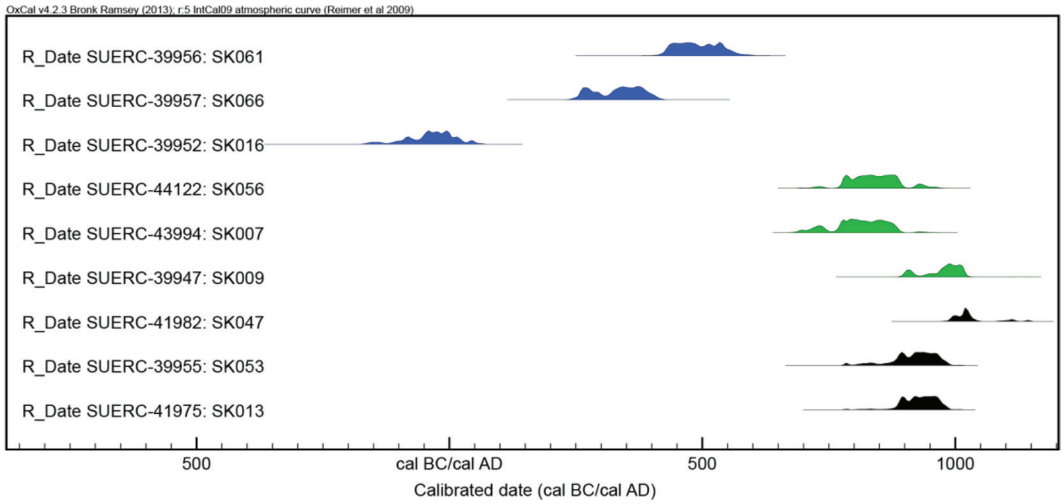

Figure 3 Standard calibrated dates from nine human bodies excavated at Hofstaðir. The black probabilities are on humans with a predominately terrestrial diet, while those in green and blue are from humans that had stable isotope values indicative of marine and freshwater protein, respectively, in their diets. The ages were calibrated using the terrestrial calibration curve of Reimer et al. 2009 (IntCal09) and following the probability method of Stuiver and Reimer (1993).

SK053 (δ^{13}C: –20.1‰ and δ^{15}N: +7.7‰), SK013 (δ^{13}C: –20.1‰ and δ^{15}N: +7.4‰), and SK047 (δ^{13}C: –20.2‰ and δ^{15}N: +8.5‰) all exhibit δ^{13}C and δ^{15}N values that are consistent with a wholly terrestrial diet (Table 3); however, SK053 (δ^{34}S: +10.3‰) and SK013 (δ^{34}S: +11.6‰) are considerably more enriched in ^{34}S than Skútustaðir's terrestrial animals (mean = +5.6 ± 2.8‰). Grasslands to the west of Lake Mývatn are rainwater fed, unlike the vegetation to the east of the lake, which is also irrigated by geothermal springs (A Einarsson, personal communication). Therefore, it is possible that the δ^{34}S value of sulfate in the water at both Hofstaðir and Skútustaðir is different, which would result in the δ^{34}S values of terrestrial animals at these two sites potentially being different too. However, δ^{13}C, δ^{15}N, and δ^{34}S analyses of archaeological faunal remains from Hofstaðir need to be undertaken to test this hypothesis. Alternatively, SK053 and SK013 may have spent the majority of their lives outside the Mývatn region, perhaps living closer to the coast where their δ^{34}S values may have been affected by sea-spray (Wadleigh et al. 1994). It is also possible that SK053 (SUERC-39955: cal AD 782–989, 95.4% probability) and SK013 (SUERC-41975: cal AD 878–988, 95.4% probability) may have been immigrants to Iceland as their calibrated ^{14}C dates are close to the *landnám* date of AD 871 ± 2; however, further studies including strontium and oxygen stable isotope analyses need to be undertaken to test this hypothesis. What is clear is that, even if there is a slight marine or freshwater reservoir effect, both individuals likely died before the feasting hall at Hofstaðir was abandoned in AD 1030. SK047 (SUERC-41982: cal AD 986–1148) also had a δ^{34}S value (+9.8‰) more enriched than would be expected if the person had been consuming terrestrial animals reared in the Lake Mývatn area, suggesting that they may have been eating terrestrial products with a different δ^{34}S value to that of the terrestrial animals at Skútustaðir, or alternatively, this individual also may have migrated to the region, however at a later date than SK053 and SK013.

The δ^{13}C and δ^{15}N values for the remaining bodies suggest that these individuals consumed sufficient non-terrestrial protein to impact the stable isotope values of their bone collagen (SK009: δ^{13}C: −18.7‰ and δ^{15}N: +12.3‰; SK016: δ^{13}C: –17.3‰ and δ^{15}N: +10.3‰; SK061: δ^{13}C: −19.0‰ and δ^{15}N: +10.6‰; SK066: δ^{13}C: −18.0‰ and δ^{15}N: +11.2‰; SK007: δ^{13}C: −19.2‰ and δ^{15}N: +10.6‰; and SK056: δ^{13}C: −19.3‰ and δ^{15}N: +10.9‰) (Table 3). However, these values alone cannot distinguish whether marine fish, freshwater fish, or a mixture of both were being eaten. SK016 (SUERC-39952: 2030 ± 30 BP, 157 cal BC–cal AD 53, 95.4% probability), SK061 (SUERC-39956: 1560 ± 30 BP, cal AD 424–565, 95.4% probability), and SK066 (SUERC-39957: 1705 ± 30 BP, cal AD 255–409, 95.4% probability) are clearly pre-*landnám*, yet after correcting for any possible marine reservoir effects, they still predate the Hofstaðir settlement date of AD 940 and *landnám* itself (Table 4). However, SK007 (SUERC-43994: 1212 ± 29 BP, cal AD 695–890, 95.4% probability) and SK056 (SUERC-44122: 1184 ± 29 BP, cal AD 726–950, 95.4% probability) have near identical $\delta^{13}C$ and $\delta^{15}N$ values to SK061, yet their adjusted calibrated dates are more in keeping with their contemporaries (SK053 and SK013) who consumed a terrestrial-based diet (Tables 3 and 4).

Based on previous stable isotope results for marine and freshwater fish from the Lake Mývatn region (Sayle et al. 2013), it can be assumed that individuals from Hofstaðir with enriched $\delta^{13}C$ and $\delta^{34}S$ values may have eaten some marine protein as part of their regular diet, while those with an enriched $\delta^{13}C$ value and a depleted $\delta^{34}S$ value may have consumed some freshwater protein. SK016 ($\delta^{34}S$: +5.5‰), SK061 ($\delta^{34}S$: +6.3‰), and SK066 ($\delta^{34}S$: +6.6‰) have $\delta^{34}S$ values that are depleted compared to SK009 ($\delta^{34}S$: +13.8‰), SK007 ($\delta^{34}S$: +12.3‰), and SK056 ($\delta^{34}S$: +14.9‰), suggesting they favored eating freshwater protein, while the latter were preferentially consuming marine protein. Their anomalously old ^{14}C ages, which are affected by a freshwater ^{14}C reservoir effect, corroborate this theory.

CONCLUSION

The results of this study indicate that clear differences exist in the $\delta^{34}S$ values of people who have consumed different diets. Individuals with enriched $\delta^{13}C$ and $\delta^{34}S$ values can be regarded as having eaten some marine-based products, and their pre-*landnám* ^{14}C ages can be calibrated through an approach that mixes the terrestrial and marine calibration curves to account for the marine ^{14}C reservoir effect. Individuals with an enriched $\delta^{13}C$ value and a depleted $\delta^{34}S$ value can be viewed as having consumed some freshwater-based foodstuffs, and while correcting for freshwater offsets remains problematic, especially at Lake Mývatn, which is known to have a large spatial and temporal offset of up to10,000 ^{14}C yr, these results have nevertheless enabled us to differentiate whether the anomalously old ^{14}C ages are due to a marine or freshwater ^{14}C reservoir effect. It is hoped that further studies, including $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ analysis of animal bones from Hofstaðir and additional strontium and oxygen stable isotope analyses of the human remains, will provide us with a more detailed picture of the diet and movement of these early Viking Age settlers.

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REFERENCES

Andrews JT, Caseldine C, Weiner NJ, Hatton J. 2001. Late Holocene (ca. 4 ka) marine and terrestrial environmental change in Reykjarfjördur, north Iceland: climate and/or settlement? *Journal of Quaternary Science* 16(2):133–43.

Arneborg J, Heinemeier J, Lynnerup N, Nielsen HL, Rud N, Sveinbjörnsdóttir ÁE. 1999. Change of diet of the Greenland Vikings determined from stable isotope analysis and ^{14}C dating of their bones. *Radiocarbon* 41(2):157–68.

Ascough PL, Cook GT, Church MJ, Dugmore AJ, McGovern TH, Dunbar E, Einarsson Á, Friðriksson A, Gestsdóttir H. 2007. Reservoirs and radiocarbon: ^{14}C dating problems in Mývatnssveit, northern Iceland. *Radiocarbon* 49(2):947–61.

Ascough PL, Cook GT, Church MJ, Dunbar E, Einarsson Á, McGovern TH, Dugmore AJ, Perdikaris S, Hastie H, Friðriksson A, Gestsdóttir H. 2010. Temporal and spatial variations in freshwater ^{14}C reservoir effects: Lake Mývatn, northern Iceland. *Radiocarbon* 52(2–3):1098–112.

Ascough PL, Cook GT, Hastie H, Dunbar E, Church MJ, Einarsson Á, McGovern TH, Dugmore AJ. 2011. An Icelandic freshwater radiocarbon reservoir effect: implications for lacustrine ^{14}C chronologies. *The Holocene* 21(7):1073–80.

Ascough PL, Church MJ, Cook GT, Dunbar E, Gestsdóttir H, McGovern TH, Dugmore AJ, Friðriksson A, Edwards KJ. 2012. Radiocarbon reservoir effects in human bone collagen from northern Iceland. *Journal of Archaeological Science* 39(7):2261–71.

Ascough PL, Church MJ, Cook GT, Einarsson Á, McGovern TH, Dugmore AJ, Edwards KJ. In press. Stable isotopic ($\delta^{13}C$ and $\delta^{15}N$) characterization of key faunal resources on Norse period settlements in North Iceland. *Journal of the North Atlantic*.

Barrett J, Johnstone C, Harland J, Van Neer W, Ervynck A, Makowiecki D, Heinrich D, Hufthammer AK, Enghoff IB, Amundsen C, Christiansen JS, Jones AKG, Locker A, Hamilton-Dyer S, Jonsson L, Lõugas L, Roberts C, Richards M. 2008. Detecting the medieval cod trade: a new method and first results. *Journal of Archaeological Science* 35(4):850–61.

Barrett JH, Orton D, Johnstone C, Harland J, Van Neer W, Ervynck A, Roberts C, Locker A, Amundsen C, Enghoff IB, Hamilton-Dyer S, Heinrich D, Hufthammer AK, Jones AKG, Jonsson L, Makowiecki D, Pope P, O'Connell TC, de Roo T, Richards M. 2011. Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones. *Journal of Archaeological Science* 38(7):1516–24.

Bronk Ramsey C. 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. *Radiocarbon* 37(2):425–30.

Bronk Ramsey C. 2001. Development of the radiocarbon program OxCal. *Radiocarbon* 43(2A):355–63.

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–60.

Buckland PC. 2000. The North Atlantic environment. In: Fitzhugh WW, Ward EI, editors. *Vikings: The North Atlantic Saga*. Washington, DC: Smithsonian Institution Press. p 146–53.

Cabana G, Rasmussen JB. 1994. Modelling food chain structure and contaminant bioaccumulation using stable nitrogen isotopes. *Nature* 372(6503):255–7.

Cabana G, Rasmussen JB. 1996. Comparison of aquatic food chains using nitrogen isotopes. *Proceedings of the National Academy of Sciences of the USA* 93(20):10,844–7.

Cook GT, Bonsall C, Hedges REM, McSweeney K, Boroneant V, Pettitt PB. 2001. A freshwater diet-derived reservoir effect at the Stone Age sites in the Iron Gates Gorge. *Radiocarbon* 43(2A):453–60.

Coplen TB. 1995. Discontinuance of SMOW and PDB. *Nature* 373(6529):285.

DeNiro MJ, Epstein S. 1978. Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* 42(5):495–506.

DeNiro MJ. 1985. Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317(6040):806–9.

Dugmore AJ, Church MJ, Mairs KA, McGovern TH, Perdikaris S, Vesteinsson O. 2007. Abandoned farms, volcanic impacts, and woodland management: revisiting þjórsárdalur, the "Pompeii of Iceland." *Arctic Anthropology* 44(1):1–11.

Friðriksson A, Vésteinsson O. 1997. Hofstaðir revisited. *Norwegian Archaeological Review* 30(2):103–12.

Gestsdóttir H. 1999. *"The Medieval Churchyard". Hofstaðir 1999. Interim Report*. Fornleifastofnun Islands: FS102–91017.

Gestsdóttir H. 2001. *"The Medieval Chapel and Churchyard." Hofstaðir 2000. Interim Report*. Fornleifastofnun Islands: FS130–91018.

Gestsdóttir H. 2002. *"Area Z". Hofstaðir 2001. Interim Report*. Fornleifastofnun Islands: FS167–91019.

Gestsdóttir H. 2003. *"Area Z (Farm Mound)". Hofstaðir 2002. Interim Report*. Fornleifastofnun Islands: FS193–910110.

Gestsdóttir H. 2004. *Hofstaðir 2003. Interim Report*. Fornleifastofnun Islands: FS230–910111.

Gestsdóttir H. 2006. *Hofstaðir 2004. Interim Report*. Fornleifastofnun Islands: FS311–910112.

Gestsdóttir H, Iskasen O. 2011. *Fornleifarannsóknir á kirkjugarði á Hofstöðum í Mývatnssveit sumarið 2010 (Framvinduskýrsla). Interim Report*. Fornleifastofnun Islands: FS455–910113.

Grönvold K, Óskarsson N, Johnsen SJ, Clausen HB, Hammer CU, Bond G, Bard E. 1995. Tephra layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land-based sediments. *Earth and Planetary Science Letters* 135(1–4):149–55.

Lawson IT, Gathorne-Hardy FJ, Church MJ, Newton AJ, Edwards KJ, Dugmore AJ, Einarsson Á. 2007. Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern

Iceland. *Boreas* 36(1):1–19.
Longin R. 1971. New method of collagen extraction for radiocarbon dating. *Nature* 230(5291):241–2.
Lucas G, McGovern TH. 2007. Bloody slaughter: ritual decapitation and display at the Viking Settlement of Hofstaðir, Iceland. *European Journal of Archaeology* 10(1):7–30.
Lucas G. 2009. *Hofstaðir. Excavations of a Viking Age Feasting Hall in North-Eastern Iceland, Institute of Archaeology, Reykjavík, Monograph Series 1*. Reykjavík: Institute of Archaeology.
McGovern TH, Perdikaris S, Einarsson Á, Sidell J. 2006. Coastal connections, local fishing, and sustainable egg harvesting: patterns of Viking Age inland wild resource use in Mývatn district, northern Iceland. *Environmental Archaeology* 11(2):187–205.
McGovern TH, Vésteinsson O, Friðriksson A, Church M, Lawson I, Simpson IA, Einarsson Á, Dugmore A, Cook G, Perdikaris S, Edwards KJ, Thomson AM, Adderley WP, Newton A, Lucas G, Edvardsson R, Aldred O, Dunbar E. 2007. Landscapes of settlement in Northern Iceland: historical ecology of human impact and climate fluctuation on the millennial scale. *American Anthropologist* 109(1):27–51.
Minagawa M, Wada E. 1984. Stepwise enrichment of ^{15}N along food chains: further evidence and the relation between $\delta^{15}N$ and animal age. *Geochimica et Cosmochimica Acta* 48(5):1135–40.
Nehlich O, Richards MP. 2009. Establishing quality criteria for sulphur isotope analysis of archaeological bone collagen. *Archaeological and Anthropological Sciences* 1:59–75.
Nehlich O, Barrett JH, Richards MP. 2013. Spatial variability in sulphur isotope values of archaeological and modern cod (*Gadus morhua*). *Rapid Communications in Mass Spectroscopy* 27(20):2255–62.
Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4):1111–50.
Richards MP, Fuller BT, Sponheimer M, Robinson T, Ayliffe L. 2003. Sulphur isotopes in palaeodietary studies: a review and results from a controlled feeding experiment. *International Journal of Osteoarchaeology* 13(1–2):37–45.
Russell N, Cook GT, Ascough P, Barrett JH, Dugmore A. 2011. Species specific marine radiocarbon reservoir effect: a comparison of ΔR values between *Patella vulgata* (limpet) shell carbonate and *Gadus morhua* (Atlantic cod) bone collagen. *Journal of Archaeological Science* 38(5):1008–15.
Sayle KL, Cook GT, Ascough PL, Hastie HR, Einarsson Á, McGovern TH, Hicks MT, Edwald Á, Friðriksson A. 2013. Application of ^{34}S analysis for elucidating terrestrial, marine and freshwater ecosystems: evidence of animal movement/husbandry practices in an early Viking community around Lake Mývatn, Iceland. *Geochimica et Cosmochimica Acta* 120:531–44.
Schoeninger MJ, DeNiro MJ. 1984. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta* 48(4):625–39.
Sigurgeirsson M. 2001. Greinargerð um gjóskulög. In: Vesteinsson O, editor. *Archaeological Investigations at Sveigakot 1998–2000*. p 39–42. Fornleifastofnun Islands: FS134-00211. http://www.nabohome.org/uploads/fsi/FS134-00211_Sveigakot_1998-2000.pdf.
Slota Jr PJ, Jull AJT, Linick TW, Toolin LJ. 1987. Preparation of small samples for ^{14}C accelerator targets by catalytic reduction of CO. *Radiocarbon* 29(2):303–6.
Stuiver M, Reimer PJ. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35(1):215–30.
Sveinbjörnsdóttir ÁE, Heinemeier J, Rud N, Johnsen SJ. 1992. Radiocarbon anomalies observed for plants growing in Icelandic geothermal waters. *Radiocarbon* 34(3):696–703.
Sveinbjörnsdóttir ÁE, Heinemeier J, Arnórsson S. 1995. Origin of ^{14}C in Icelandic groundwater. *Radiocarbon* 37(2):551–65.
Vandeputte K, Moens L, Dams R. 1996. Improved sealed-tube combustion of organic samples to CO_2 for stable isotopic analysis, radiocarbon dating and percent carbon determinations. *Analytical Letters* 29(15):2761–73.
Vésteinsson O. 1998. Patterns of settlement in Iceland: a study in prehistory. In: *Saga-Book Vol XXV.* London: Viking Society for Northern Research UCL. p 1–29.
Vésteinsson O. 2000. The archaeology of Landnám Icelandic settlement. In: Fitzhugh WW, Ward EI, editors. *Vikings: The North Atlantic Saga*. Washington, DC: Smithsonian Institution Press. p 164–74.
Wadleigh MA, Schwarcz HP, Kramer JR. 1994. Sulphur isotope tests of seasalt correction factors in precipitation: Nova Scotia, Canada. *Water, Air and Soil Pollution* 77(1–2):1–16.