DIETARY RECONSTRUCTION AND RESERVOIR CORRECTION OF ^{14}C DATES ON BONES FROM PAGAN AND EARLY CHRISTIAN GRAVES IN ICELAND

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ABSTRACT. In this study, $\delta^{13}C$ and $\delta^{15}N$ of bone samples from 83 skeletons (79 humans, 2 horses, and 2 dogs) excavated from pagan and early Christian graves from 21 localities in Iceland are used to reconstruct diet of the early settlers in Iceland and possible differences in diet depending on the distance between the excavation site and the seashore. We have radiocarbon dated 47 of these skeletons and used the carbon isotopic composition ($\delta^{13}C$) to estimate and correct for the marine reservoir effect (the ^{14}C difference between terrestrial and mixed marine organisms). The reservoir-corrected ages lie in the range of AD 780–1270 (68.2% probability). Reservoir age corrections were checked by comparing ^{14}C dates of a horse (terrestrial diet), a dog (highly marine diet), and a human (mixed diet) from the same burial. The range in measured marine protein percentage in individual diet is from about 10% up to 55%, mostly depending on the geographical position (distance from the sea) of the excavation site. We had access to the skeleton (AAR-5908) of the Skálholt bishop Páll Jónsson whose remains are enshrined at the Episcopal residence in Skálholt, southern Iceland. According to written sources, the bishop died in AD 1211. Using our dietary reconstruction, his bones were about 17% marine, which is within the range of human skeletons from the same area, and the reservoir-corrected calibrated ^{14}C age of the skeleton is in accord with the historical date.

INTRODUCTION

Bone Dating and Reservoir Correction

Radiocarbon dating of bones is now well established (e.g. Brown et al. 1988). The accelerator mass spectrometry (AMS) dating technique makes it possible to date very small samples of bone collagen and thus allows selection of the best samples from a skeleton, minimizing problems with degradation and contamination. If the bone collagen is of terrestrial origin, it is possible to convert the measured (conventional) ^{14}C age into calendar age by using the tree-ring calibration curve (Reimer et al. 2004). However, if some of the collagen is from marine carbon, which appears several hundred ^{14}C years older than the corresponding terrestrial carbon, it becomes necessary to correct the ^{14}C conventional age for this reservoir effect. To perform that correction, the marine food fraction and reservoir age at the particular region at the time the protein was produced must be known.

Dietary Reconstruction: Examples from the Norse Colonies in Greenland

The stable carbon isotopic ratio is expressed as $\delta^{13}C$ and defined as the relative deviation (in ‰) of the $^{13}C/^{12}C$ ratio of a sample from that of a standard (PDB). Natural variation in $\delta^{13}C$ is large and makes it a good indicator of the origin of carbon. Plant material from terrestrial and marine environment, for example, is different in $\delta^{13}C$ by 7–10‰ as terrestrial plants assimilate carbon from the atmospheric CO_2 while marine plants assimilate carbon from dissolved bicarbonate. This difference persists in the terrestrial and marine food chains. Thus, previous investigations have shown that $\delta^{13}C$ of bone collagen can be used to construct the fraction of marine carbon in protein diet with reason-

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able precision (±10%) (Tauber 1981; Chisholm et al. 1982; Johansen et al. 1986; Lovell et al. 1986; Arneborg et al. 1999). Furthermore, data have shown that $\delta^{13}C$ distribution for a single population group can be extremely narrow; thus, it has been concluded that differences in $\delta^{13}C$ of human bone collagen from high latitudes (where C_4 plants are not present) must reflect real differences in the average diet consumed by the individual over about 4–20 yr, which represents the collagen turnover time in human bone, depending on the compactness of the different bone types (Martin et al. 1998; Wild et al. 2000; Geyh 2001).

Arneborg et al. (1999) demonstrated the use of $\delta^{13}C$ of bone collagen to reconstruct diet. They obtained precise ^{14}C dates on the remains of humans from a Greenland Viking colony who depended on food of mixed marine and terrestrial origin. In their study, Arneborg et al. (1999) adopt the $\delta^{13}C$ value of bone collagen of 21‰ for a 100% terrestrial diet and 12.5‰ for a 100% marine diet based on previous investigations on humans from Sweden (Lidén and Nelson 1994), Norway (Johansen et al. 1986), Canada (Chisholm et al. 1983; Lovell et al. 1986), and western Greenland (Heinemeier and Rud 1997). Arneborg et al. (1999) showed that the diet of the Greenland Viking colony changed dramatically from predominantly terrestrial food at the time of Eric the Red around AD 1000 to predominantly marine food toward the end of the settlement period around AD 1450.

Here, we have attempted a similar study of the Icelandic community, starting with the earliest settlers in Iceland. The settlers of Iceland were farmers from northwestern Norway and the northern British Isles. They sailed around AD 874 across the sea with families and domestic animals such as cattle, sheep, goats, horses, pigs, cats, and dogs. According to the sagas written in Iceland around AD 1200, the Norse colonies in Greenland were founded from Iceland around AD 1000 and established by the Icelandic outlaw Eric the Red on the southwestern coast of Greenland.

The samples studied here are both from pagan and early Christian Icelandic graves, but Iceland was converted to Christianity around AD 1000. We use $\delta^{13}C$ and $\delta^{15}N$ of bone samples excavated from 21 localities in Iceland to reconstruct the diet of the early settlers in Iceland and to study possible differences in diet over time or depending on distance between excavation site and the seashore. The $\delta^{13}C$ of the bone collagen is also used to correct ^{14}C age of the bones for the marine reservoir effect (i.e. the ^{14}C difference between terrestrial and marine organism), to give accurate ^{14}C dates.

METHODS AND ANALYSES

Samples were taken from 83 skeletons (79 humans, 2 horses, and 2 dogs) excavated from pagan and early Christian graves from 21 localities in Iceland for $\delta^{13}C$ and $\delta^{15}N$ analyses. $\delta^{13}C$ analyses were performed at the Science Institute, University of Iceland; at Simon Fraser University, Canada; and the AMS ^{14}C Dating Centre at Aarhus University, Denmark. $\delta^{15}N$ analyses were performed at Simon Fraser University, Canada, and Aarhus University, Denmark, and ^{14}C dating was carried out at the AMS ^{14}C Dating Centre at Aarhus University, Denmark. The procedures of sample pretreatment and analyses are fully described in Arneborg et al. (1999).

The excavation sites are shown in Figure 1. Samples from sites 1–20 in Figure 1 were selected from the collections at the National Museum in Iceland. Site 21 (Keldudalur in Skagafjördur, northern Iceland) was excavated in 2002–2003, and from there we report analyses of 18 skeletons from a small Christian/conversion period cemetery site and 3 pagan graves, including bones from 3 humans and a dog (Zoëga and Traustadóttir 2007). The results are given in Table 1.

We have ^{14}C dated 47 of these skeletons and used the stable carbon isotopic composition ($\delta^{13}C$) to correct for the marine reservoir effect. Based on the calculated marine fraction, we use the corre-

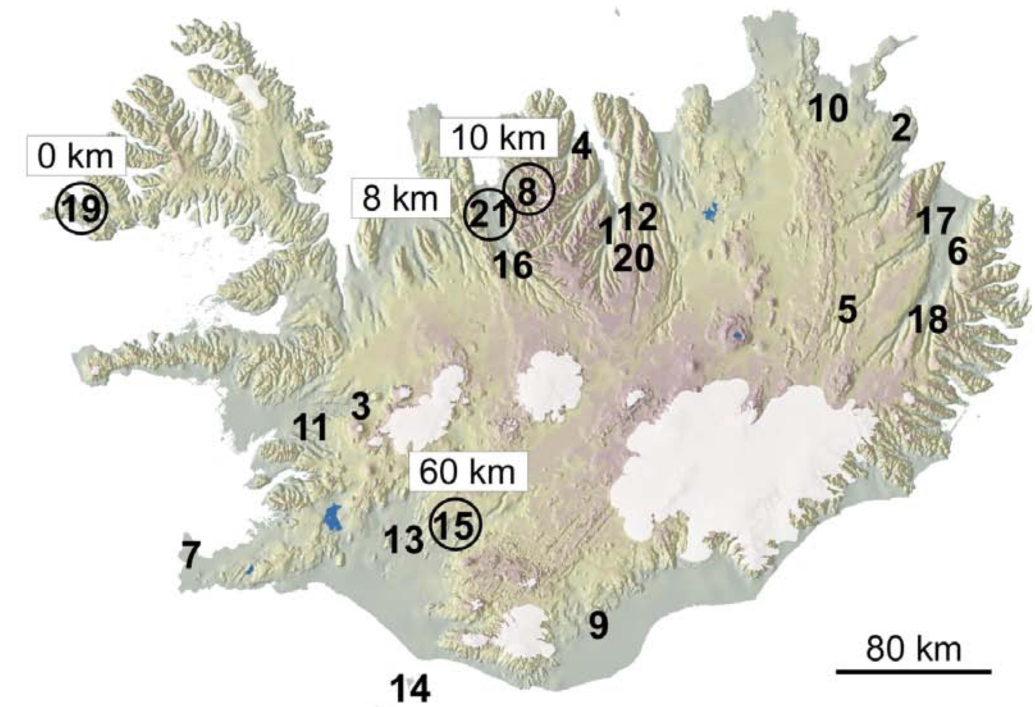

Figure 1 Locations of graves studied. The encircled locations (8, 15, 19, 21), with the distance from the sea indicated in km, represent localities where more than 1 individual is ^{14}C dated. Site 21 represents a small cemetery site that was fully analyzed and some pagan graves nearby (21 skeletons). Names of localities are given in Table 1.

sponding mixture of the modeled marine calibration curve Marine04 (Hughen et al. 2004) and the terrestrial calibration curve IntCal04 (Reimer et al. 2004) to get the reservoir-corrected calibration age, using the OxCal calibration program v 3.10 and 4.0 (Bronk Ramsey 1995, 2001). The marine curve is shifted relative to the global curve by a local offset, ΔR (^{14}C yr), which reflects the difference in reservoir age of the local sea from that of the model world ocean (Stuiver et al. 1998). In our calculation, we assume $\Delta R = 50$, corresponding to a reservoir age of ~450 yr. This value is based on the average value $\Delta R = 52$, calculated for 11 recent pre-bomb shells around Iceland with an observed standard deviation of 71 ^{14}C yr (^{14}CHRONO Marine Reservoir Database: http://intcal.qub.ac.uk/marine). Longer-term ΔR variations have been observed on the shelf north of Iceland (Eiríksson et al. 2004; Wanamaker et al. 2008), but the choice of $\Delta R = 50$ fits well with our data from terrestrial control samples as discussed below.

RESULTS

$\delta^{13}C$ and $\delta^{15}N$

Figure 2 shows the results of the $\delta^{13}C$ and $\delta^{15}N$ measurements. The human bones show large variation in $\delta^{13}C$ values (16.4 to 20.3‰ VPDB), although most of the data lie in the range of about 18–20‰. Only 12 individuals (out of 79) show relatively high $\delta^{13}C$ values, ranging from 18.2‰ to 16.4‰. The dogs analyzed are highly marine and one of them is more marine than any of the humans with ~16‰ in $\delta^{13}C$, whereas the horses are ~1‰ lower in $\delta^{13}C$ (22‰) than the terrestrial end-point for humans. The latter may be understood in terms of both $\delta^{13}C$ and $\delta^{15}N$ values of consumer bone collagen being higher than the corresponding values of their dietary protein with the generally accepted shifts of ~1‰ for $\delta^{13}C$ and 3.5‰ for $\delta^{15}N$ (Minagawa and Wada 1984; Schoeninger and DeNiro 1984; Lidén 1995; Richards and Hedges 1999). In the present study, the fraction of marine food consumed by each human individual ranges from 8% to 54% (Table 1) as calculated from the measured $\delta^{13}C$ values. The calculation is based on the assumption of linear mixing by linear interpolation between the end-point values 12.5‰ (100% marine) and 21‰ (100% terrestrial) as described by Arneborg et al. (1999).

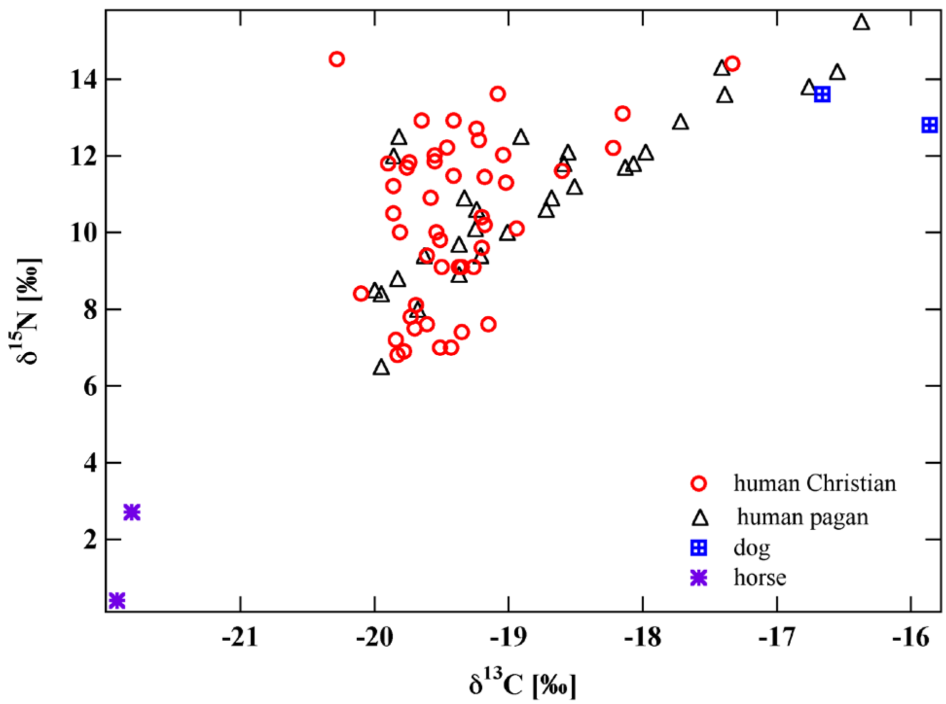

Figure 2 The relationship between $\delta^{13}C$ and $\delta^{15}N$ of collagen from humans, dogs, and horses. The general trend between the human isotope values suggests that individuals are consuming from the same trophic level of the long marine food chain in different amounts.

When the $\delta^{13}C$ values are plotted against the distance from gravesite to the sea, a clear pattern is obvious, despite the scatter in the data (Figure 3). Samples excavated very close to the sea display extreme variation and range in $\delta^{13}C$ from 19.7‰ to 16.4‰ with an average value of 17.94 ± 0.95‰ (observed standard deviation). Samples farthest away from the sea range in $\delta^{13}C$ from 20.5‰ to 19.1‰ with a mean value of 19.7 ± 0.24‰.

$\delta^{15}N$ measurements of the human bones lie in the range 6.5–15.5‰ (Table 1). As demonstrated in Figure 2, there is a general trend between $\delta^{15}N$ and $\delta^{13}C$, where the bone collagen with the lowest $\delta^{13}C$ value also has the lowest $\delta^{15}N$ value and vice versa. While the $\delta^{13}C$ values of bone collagen reflect the fraction of marine carbon in diet, the $\delta^{15}N$ values are believed to give information on trophic level of the food, i.e. the position in the food chain. Deduced from the good correlation between the 2 isotopes, individuals moving up the curve have had an increasing amount of carbon from the long marine food chain.

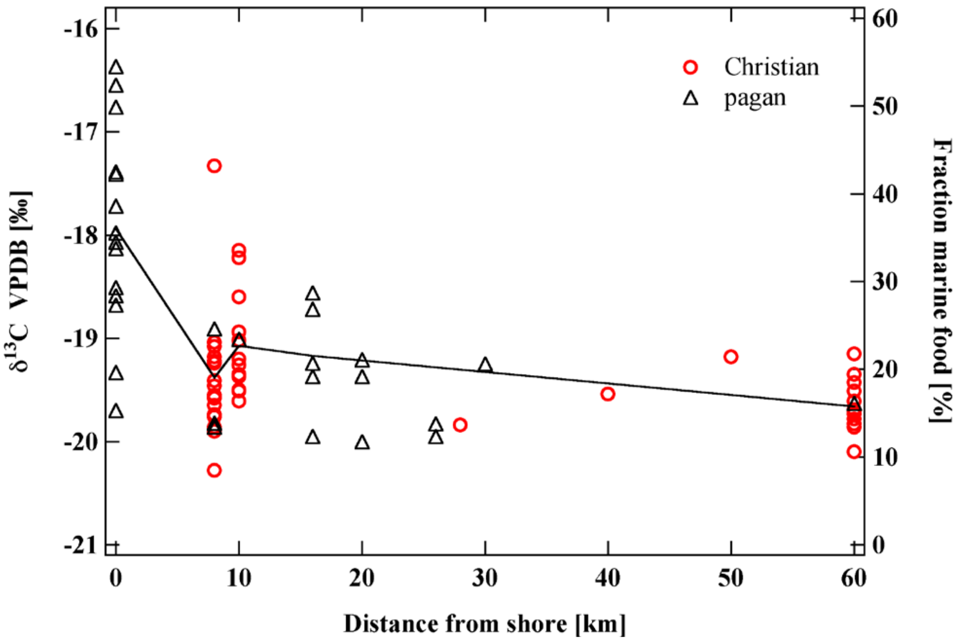

Figure 3 $\delta^{13}C$ values of human bone collagen in relation to distance of excavation site from the seashore. The corresponding range of marine food in individual diet is indicated to the right of the plot and range from about 10% to 54%. The largest variation is seen among individuals living at or close to the seaside, whereas the range is much more limited for those who live more inland.

Many of our human bone samples lie in the narrow $\delta^{13}C$ range of –20‰ to –19‰, but show considerable variation in $\delta^{15}N$ (from about 6‰ to 14‰) (Figure 2). The difference in $\delta^{15}N$ from the 2 cemeteries from which we have studied many human burials is noticeable. Bone collagen form the burials in the cemetery located in the southern lowlands (Skeljastaðir in Thjórsárdalur) has a mean $\delta^{15}N$ value of 7.68 ± 0.97‰ (13 burials), whereas the mean value for the 18 burials from the cemetery in Keldudalur, northern Iceland, is 12.33 ± 1.02‰ (Table 1). This is a difference of more than the generally assumed value of 3.5‰ of the ^{15}N enrichment in humans.

Table 1 ^{14}C dates and $\delta^{13}C$ values of bone collagen from early Christian and pagan graves in Iceland. Number in parentheses after location name refers to number on map of Iceland in Figure 1.

Lab nr[a] (AAR-)	Location/ ID nr[b]	Sample sex[c], age	$\delta^{13}C$[d] [‰ VPDB]	$\delta^{15}N$ [‰ AIR]	Conv. ^{14}C age[e] [yr BP]	% marine diet[f]	cal AD range 68.2% prob. (IntCal/ Marine04)
	Northern Iceland						
Pagan	*Brimnes vid Dalvík (4), shore dist. 0 km*						
5906	Grave 12/Vikisl-51	*Canis familaris*	–15.86	12.8	1292 ± 48	60	940–1040
5905	Grave 12/Vikisl-50	*Equus caballus*	–21.81	2.7	1080 ± 30		890–1020
5858	DAV-A-1/Vikisl-2	human M	–18.51	11.2		29	
5859	DAV-A-5/Vikisl-3	human M	–18.68	10.9		27	
5860	DAV-A-9/Vikisl-4	human F	–18.59	11.8	1150 ± 35	28	978–1027
Pagan	*Sílastaðir, Glæsibæjarhreppur (12), shore dist. 0 km*						
5907	Grave 1/Vikisl-52	*Equus caballus*	–21.92	0.4	1155 ± 43		780–970
5863	SSG-A-1/Vikisl-8	human M	–19.33	10.9	1238 ± 35	20	810–950
Christian	*Audbrekka, Hörgárdalur (1), shore dist. 10 km*						
5896	AUB-A-1/Vikisl-41	human F	–18.60	11.6		28	
5897	AUB-A-2/Vikisl-42	human F	–18.94	10.1		24	

Table 1 ^{14}C dates and $\delta^{13}C$ values of bone collagen from early Christian and pagan graves in Iceland. Number in parentheses after location name refers to number on map of Iceland in Figure 1. *(Continued)*

Lab nr[a] (AAR-)	Location/ ID nr[b]	Sample sex[c], age	$\delta^{13}C$[d] [‰ VPDB]	$\delta^{15}N$ [‰ AIR]	Conv. ^{14}C age[e] [yr BP]	% marine diet[f]	cal AD range 68.2% prob. (IntCal/ Marine04)
5912	HFH-A-5/Vikisl-57	human M?	–18.22	12.2		19	
5913	HFH-A-6/Vikisl-58	human M	–19.26	9.1		23	
5914	HFH-A-7/Vikisl-59	human M	–19.51	9.8		21	
5915	HFH-B-1/Vikisl-60	human F	–19.20	10.4		16	
5916	HFH-B-2/Vikisl-61	human F	–18.15	13.1	949 ± 28	18	
5917	HFH-B-3/Vikisl-62	human F	–19.35	9.1	861 ± 36	33	
5893	HRB-A-1/Vikisl-38	human M	–19.01	10.0		20	
5898	AUB-A-3/Vikisl-43	human F	–19.37	9.1		18	
5899	AUB-A-4/Vikisl-44	human F	–19.02	11.3		21	
Christian	*Hof í Hjaltadal (8), shore dist. 10 km*						
5909	HFH-A-1/Vikisl-54	human M	–19.20	9.6		34	1216–1261
5910	HFH-A-2/Vikisl-55	human M	–19.61	9.4		19	1224–1269
5911	HFH-A-3/Vikisl-56	human F	–19.50	9.1			
	Laxárdalur, N-Thingeyjarsysla (10), shore dist. 6 km						
5894	LAD-A 1./Vikisl-39	human u	–19.32	9.6		20	
5895	u.nr/Vikisl-40	human u	–18.79	13.1		26	
Christian	*Steinsstaðir, Skagafjordur (16), shore dist. 28 km*						
5878	SSS-A-1/Vikisl-23	human M	–19.81	10.0		14	
Christian	*Keldudalur (21), shore dist. 8 km*						
9234	KEH-A-05/Vikkeld01	human F 50+	–19.22	12.4	1011 ± 37	21	1040–1160
9235	KEH-A08, K8/Vikkeld02	human M 35–50	–19.65	12.92	1065 ± 50	16	980–1150
9236	KEH-A-20, K20/Vikkeld03	human M 35–50	–19.41	12.92	973 ± 39	19	1050–1210
9237	KEH-A-07, K7/Vikkeld04	human F? 50+	–19.86	11.21	1055 ± 50	13	980–1150
9238	KEH-A-06, K6/Vikkeld05	human F 20–35	–19.74	11.83	1027 ± 49	15	1020–1160
9239	KEH-A-11, K11/Vikkeld06	human M 35–50	–20.28	14.52	949 ± 37	8	1040–1160
9241	KEH-B-08, F43Vikkeld08	human M 50+	–19.18	11.44	1054 ± 37	21	1020–1160
9242	KEH-A-22, K22/Vikkeld09	human M 50+	–19.24	12.7	1110 ± 42	21	970–1045
9243	KEH-A-13, K13/Vikkeld10	human M 50+	–19.76	11.69	1153 ± 50	15	895–995
9244	KEH-A-28, K28Vikkeld11	human M 20–35	–17.33	14.4	1265 ± 55	43	890–1010
9245	KEH-B-16, K51Vikkeld12	human F 35–50	–19.55	12.01	1135 ± 39	17	900–1020
9246	KEH-B-10, K45/Vikkeld13	human F 35–50	–19.46	12.21	988 ± 42	18	1040–1170
9247	KEH-B-07, K42/Vikkeld14	human 12–15	–19.08	13.61	1156 ± 38	23	900–1020
9248	KEH-B-15, K50/Vikkeld15	human F?	–19.58	10.9	1116 ± 44	17	900–1030
9249	KEH-A-02, K2/Vikkeld16	human F 20–35	–19.04	12.02	1010 ± 39	23	1040–1170
9250	KEH-A-15, K15/Vikkeld17	human 8–10	–19.55	11.85	952 ± 38	17	1050–1220
9251	KEH-A-29, K29/Vikkeld18	human M? 15–20	–19.41	11.48	979 ± 45	19	1040–1190
9240	KEH-A-07, K7/Vikkeld07	human M? 50+	–19.9	11.8	1004 ± 29	13	1020–1160
pagan	*Keldudalur (21), shore dist. 8 km*						
9253	Kuml-04/Vikkeld20	human M	–18.91	12.5	1150 ± 49	25	900–1030
9254	Kuml-03Vikkeld21	human	–19.86	12	1148 ± 36	13	895–990
9252	Kuml-01/Vikkeld19	human F	–19.82	12.5	1220 ± 30	14	780–940
9255	Kuml-03/Vikkeld22	*Canis familiaris*	–16.66	13.6	1334 ± 34	51	885–975
	NW Peninsula						
Pagan	*Vatnsdalur, Patreksfjordur (19), shore dist. 0 km*						
5864	VDP-A-1/Vikisl-9	human u	–17.41	14.3		42	
5865	VDP-A-2/Vikisl-10	human u	–16.76	13.8	1330 ± 42	50	870–990
5866	VDP-A-3/Vikisl-11	human M	–16.37	15.5	1320 ± 35	54	900–985
5867	VDP-A-4/Vikisl-12	human F	–16.55	14.2	1263 ± 28	52	976–1022
5868	VDP-A-5/Vikisl-13	human F	–17.39	13.6	1289 ± 37	42	890–975
5869	VDP-A-6/Vikisl-14	human M	–17.98	12.1	1308 ± 30	36	810–940
5871	VDP-A-7/Vikisl-16	human M	–17.72	12.9	1259 ± 26	39	895–985
	Western Iceland						
Christian	*Bjarnastaðir, Borgarfjordur (13), shore dist. 50 km*						
5879	BSJ-1999-1-1/Vikisl-24	human u	–19.18	10.2		21	

Table 1 ^{14}C dates and δ^{13}C values of bone collagen from early Christian and pagan graves in Iceland. Number in parentheses after location name refers to number on map of Iceland in Figure 1. *(Continued)*

Lab nr[a] (AAR-)	Location/ ID nr[b]	Sample sex[c], age	δ^{13}C[d] [‰ VPDB]	δ^{15}N [‰ AIR]	Conv. ^{14}C age[e] [yr BP]	% marine diet[f]	cal AD range 68.2% prob. (IntCal/ Marine04)
Pagan	*Nedranes, Stafholtstunga (11), shore dist. 16 km*						
5900	NNS-A-1/Vikisl-45	human F?	–19.95	6.5		12	
5901	NNS-A-2/Vikisl-46	human M?	–18.72	10.6		27	
5902	NNS-A-5/Vikisl-47	human M	–19.37	9.7		19	
5903	NNS-A-6/Vikisl-48	human F	–18.56	12.1		29	
5904	NNS-A-7/Vikisl-49	human F	–19.24	10.6		21	
	Eastern Iceland						
Pagan	*Bakki, Borgarfjordur Eystra (2), shore dist. 0 km*						
5857	BBE-1-112/4/Vikisl-1	human F	–18.13	11.7		34	
Pagan	*Brú í Jökuldal (5), shore dist. 60 km*						
5874	BAJ-A-1/Vikisl-19	human F	–19.63	9.4	1145 ± 34	16	890–1010
Pagan	*Gilsárteigur, Eidathing (6), shore dist. 26 km*						
5872	GTE-A-1/Vikisl-17	human M	–19.83	8.8		14	
5873	GTE-A-2/Vikisl-18	human F	–19.95	8.4		12	
Pagan	*Straumur, Tunguhreppur (7), shore dist. 20 km*						
5875	STT-A-2/Vikisl-20	human u	–19.21	9.4	1135 ± 35	21	960–1030
5876	STT-A-3/Vikisl-21	human F	–20.00	8.5		12	
Pagan	*Vad, Skriddalur (18), shore dist. 20 km*						
5877	VAS-A-1Vikisl-22	human M	–19.37	8.9	1060 ± 35	19	1010–1150
	Southern Iceland						
Pagan	*Hafurbjarnastaðir (7), shore dist. 0 km*						
5861	HBS-A-1/Vikisl-5	human M	–18.07	11.8		34	
Pagan	*Hrifunes, Skaftártunguhreppur (9), shore dist. 30 km*						
5862	HRS-A-1/Vikisl-7	human F	–19.25	10.1		21	
Christian	*Skálholt (13), shore dist. 40 km*						
5908	Bisp Páll/Vikisl-53	human M	–19.54	10.0	918 ± 28	17	1165–1220
Christian	*Skeljastaðir, Thjórsárdalur (15), shore dist. 60 km*						
5880	Grave 39d/Vikisl-25	human F	–19.86	10.5	1075 ± 35	13	984–1032
5881	Grave 2/Vikisl-26	human F	–19.70	7.5		15	
5882	Grave 48s/Vikisl-27	human M	–19.43	7.0		18	
5883	Grave 41as/Vikisl-28	human M	–19.73	7.8	1094 ± 27	15	991–1021
5884	Grave 26s/Vikisl-29	human M	–19.83	6.8		14	
5885	Grave 15s/Vikisl-30	human F	–19.61	7.6		16	
5886	Grave 16s/Vikisl-31	human F	–20.10	8.4	907 ± 31	11	1155–1220
5887	Grave 60s/Vikisl-32	human M	–19.35	7.4	1058 ± 29	19	1010–1150
5888	Grave 47/Vikisl-33	human M	–19.78	6.9	922 ± 28	14	1155–1220
5889	Grave 34s/Vikisl-34	human M	–19.69	8.1		15	
5890	Grave 38/Vikisl-35	human M	–19.51	7.0	1154 ± 66	18	890–1020
5891	Grave 12s/Vikisl-36	human F	–19.15	7.6	1183 ± 40	22	895–990
5892	Grave 5g/Vikisl-37	human F	–19.84	7.2		14	
Pagan	*Skansinn, Vestmannaeyjar (14), shore dist. 0 km*						
5870	SVE-A-1/Vikisl-15	human M	–19.68	8.0	1210 ± 26	16	870–970

[a]AAR- refers to the AMS ^{14}C dating sample.

[b]Object ID number is the registration number of the National Museum of Iceland for the present project.

[c]F = female, M = male, u = unknown sex.

[d]δ^{13}C values are given with respect to the VPDB standard; uncertainty is ±0.05‰ (1 σ).

[e]Conventional ^{14}C ages were converted into calendar year by using a mixed calibration curve interpolated between the terrestrial curve IntCal04 and the model-calculated marine curve Marine04 (R = 50) with the fraction of marine diet as an input parameter.

[f]The percentage of marine diet is calculated by linear interpolation between the end-point values 12.5‰ (100% marine) and 21‰ (100% terrestrial). We estimate an uncertainty of 10% in the percentage value.

Variation in $\delta^{15}N$ values of human bone collagen is poorly understood and interpretation of $\delta^{15}N$ values in human archaeological assemblages and their relation to food consumption is complex (Hedges and Reynard 2007). To attempt such a connection, a good understanding of the possible food resources is vital as well as knowledge of their isotopic composition. This work is in progress for our assemblages, but as it is lacking from the present study, we will not attempt to interpret the observed $\delta^{15}N$ difference between different localities and individuals in the present contribution. We will therefore concentrate on the $\delta^{13}C$ values and their indication of marine resources in the individual's diet and accordingly the importance of reservoir correcting ^{14}C dates of bone collagen.

^{14}C Reservoir Age Correction

We have ^{14}C dated 47 of the 83 skeletons studied and used the carbon isotopic composition ($\delta^{13}C$) to correct for the marine reservoir effect based on the calculated marine percentage in the diet (Table 1). The reservoir age corrections were checked by comparing ^{14}C dates of a horse (terrestrial), a dog (highly marine), and a human (mixed diet) from the same pagan burial in Brimnes, northern Iceland (Figure 4a). When no reservoir correction is applied to the ^{14}C age, the dog is ~140 ^{14}C yr older than its master and ~210 ^{14}C yr older than the horse (Table 1). Furthermore, as seen from Figure 4a, the uncorrected calibrated age of the dog is inconsistent with the conventional time of the Norse settlement of Iceland around AD 874 and is also incompatible with that of the horse. This discrepancy is explained by the marine reservoir effect as the $\delta^{13}C$ values of the dog's bone show a highly marine diet (60%), while the average food protein composition for the human was ~28% marine and for the horse 0% marine (100% terrestrial). When the calibrated ^{14}C age is corrected for this reservoir effect by use of the mixed marine calibration curve, the 3 calibrated ^{14}C age probability distributions coincide (Figure 4a). Another example is shown in Figure 4b where 4 human skeletons and a skeleton of a dog from the same pagan grave in Keldudalur, northern Iceland, are compared before and after the reservoir correction. After our correction procedure, all the dates are consistent both with the settlement time of Iceland AD 874 and the assumption that Christianity was introduced around AD 1000 (Figure 4b).

^{14}C Age

The reservoir-corrected calibrated ages (68.2% probability) lie in the range between AD 780 and 1270 (Table 1). Figure 5 shows the relationship between $\delta^{13}C$ and ^{14}C age, where we have used the mid-point values of the cal AD range given in Table 1. In 4 locations, we have dates for more than 1 individual as indicated in Figure 5. These locations are Skeljastaðir in southern Iceland (~60 km from the sea), Vatnsdalur in the northwest peninsula (at the seaside), Hof in Hjaltadalur, northern Iceland (~10 km from the sea), and Keldudalur in northern Iceland (~8 km from the sea) (Figure 1). The coastal humans from Vatnsdalur are all from pagan graves and are highly marine. The samples from the cemetery site in southern Iceland (Skeljastaðir) are much more uniform in their $\delta^{13}C$ values, reflecting ~20% marine diet over the time for which we have data. The 2 samples from the location in northern Iceland (Hof in Hjaltadalur) show more scatter and may reflect their relatively easy access to the sea. To further strengthen our reservoir correction procedure, we report measurements of 18 human skeletons from the Christian/conversion period cemetery site at Keldudalur, northern Iceland, and from 4 pagan graves close by with bones from 3 humans and a dog, excavated in 2002–2003 (Table 1). AMS reservoir-corrected ^{14}C dates of the 18 skeletons from the cemetery confirm that the cemetery dates between about AD 1000 up to early the 12th century, suggesting that it was in use only for 100–150 yr. The dates of 3 humans and a dog from the pagan graves are shown in Figure 4b. After our correction procedure, all the dates are consistent both with the settlement time of Iceland around AD 874–930 and the assumption that Christianity was being introduced around

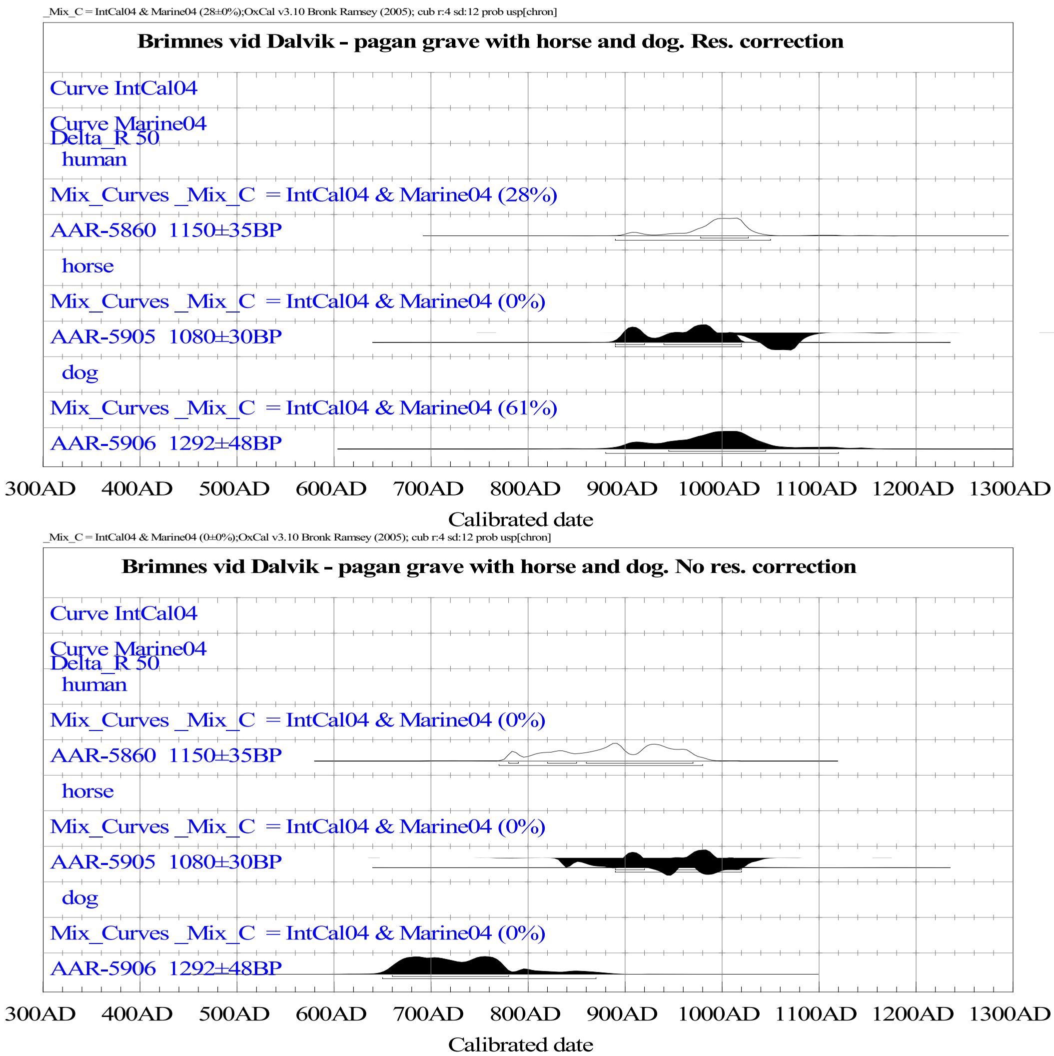

Figure 4 Reservoir age corrections were checked by comparing a) (above) ^{14}C dates of a horse (100% terrestrial), a dog (highly marine), and a human (mixed diet) from the same pagan burial in Brimnes, N Iceland, and b) (following page) by comparing ^{14}C dates of 3 human skeletons and a dog from the same burial close to Keldudalur in N Iceland. When the ^{14}C age is calibrated with correction for the marine reservoir effect (based on the $\delta^{13}C$ measurements), the 3 ^{14}C age determinations from Brimnes become identical. If no reservoir correction is applied, the dog appears considerably older than his master, and its age is inconsistent with the time of Norse settlement of Iceland around AD 874, indicated by the vertical bar. This is also the case for the Keldudalur pagan gravesite where after our correction procedure, all the dates are consisted both with the settlement time of Iceland AD 874 and that Christianity being introduced around AD 1000.

AD 1000. Even though some of the mid-point values used in Figure 5 superficially appear to be in conflict with Christianity being adopted around AD 1000, all the AD cal ranges are compatible with that date (Table 1). At Keldudalur, ~20% of individual diet was from marine resources, very similar to the humans at the cemetery site of Skeljastaðir in S Iceland (Figure 5).

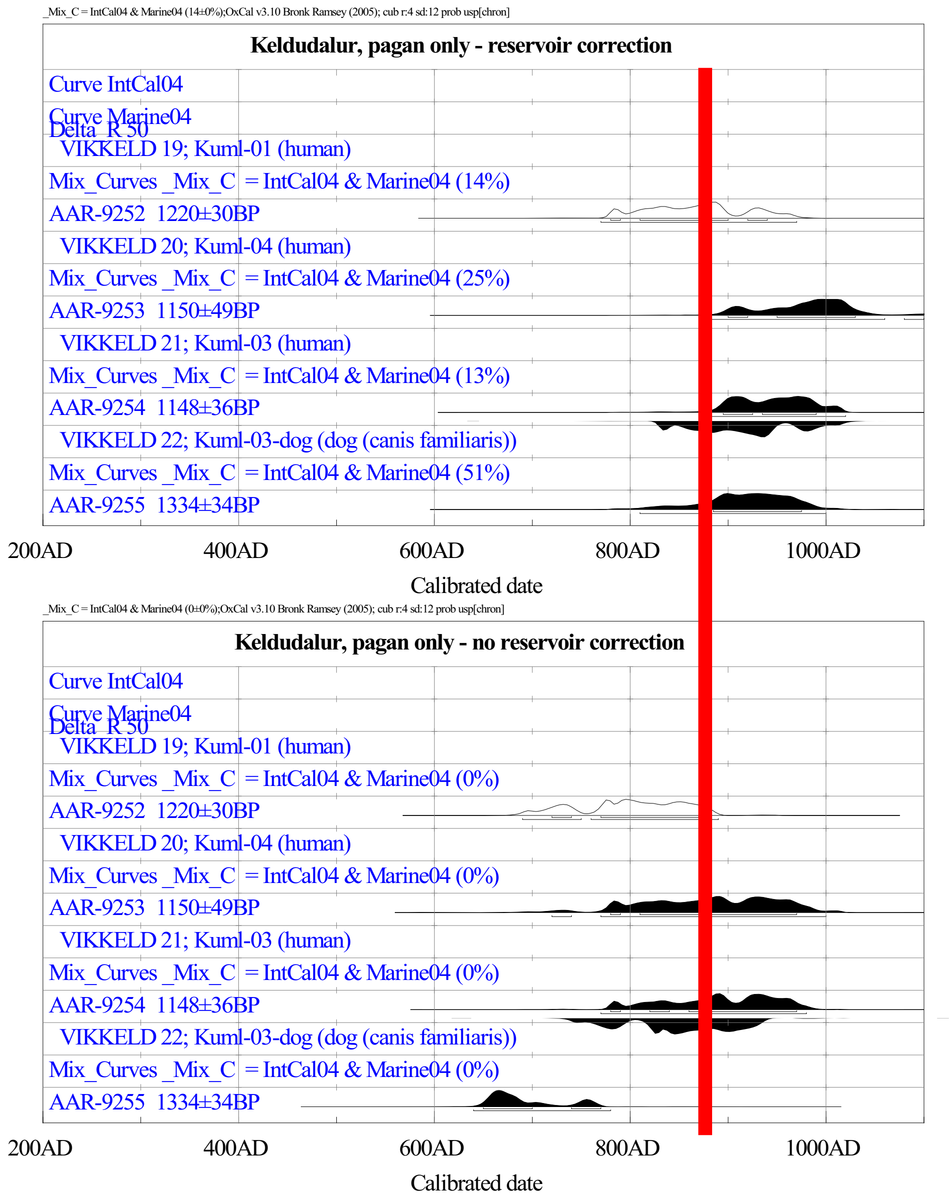

Figure 4b *(see caption on previous page)*

The Skálholt Bishop Páll Jónsson (AD 1155–1211)

The sarcophagus of the 12th century bishop Páll Jónsson was found in an archaeological excavation in 1954 and is presently located in the crypt of the Episcopal residence in Skálholt, southern Iceland. According to written sources, the bishop died in AD 1211. We had access to the skeleton (AAR-5908) of the bishop and according to our dietary reconstruction, his bones were about 17% marine, which is within the range of human skeletons from the same geographical location (Figure 5). The reservoir-corrected ^{14}C age of the skeleton is compatible with the historical date. The uncorrected calibrated date would, however, not fit, as demonstrated by Figure 6.

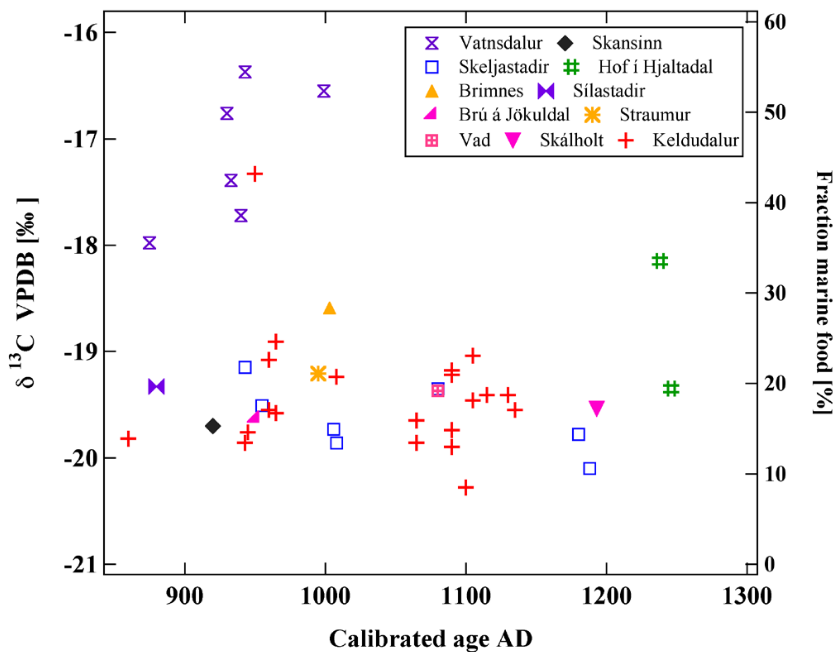

Figure 5 $\delta^{13}C$ of human bone collagen as a function of time of death as determined by reservoir-corrected calibrated ^{14}C dates. For clarity of the plot, we use the mid-point value of the cal AD range in Table 1. Even though some of the mid-points at first appear to be in conflict with Christianity being adopted around AD 1000, all the cal AD ranges are compatible with that date. To the right of the plot, $\delta^{13}C$ has been translated into percentage of marine content of the individual's diet.

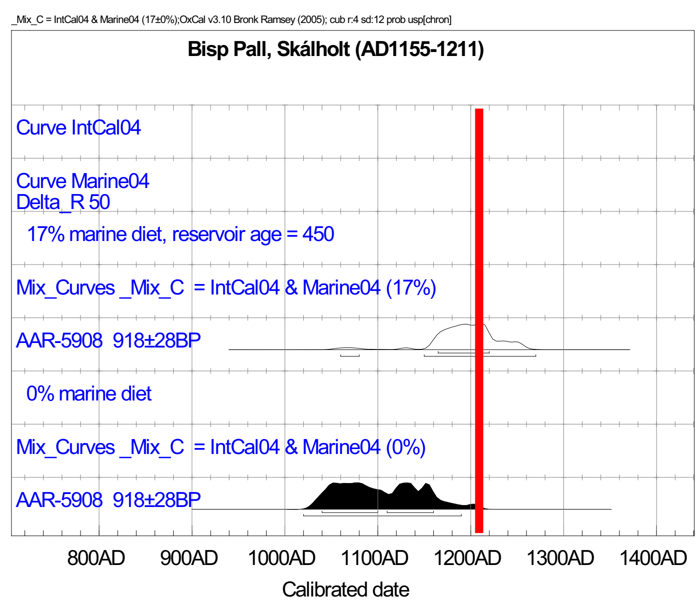

Figure 6 We had access to the skeleton of the 12th century bishop Páll Jónsson (AAR-5908). The reservoir-corrected ^{14}C age of the skeleton agrees with the historical date of his death in AD 1211, indicated by the vertical bar. The figure also demonstrates that the uncorrected calibrated date is considerably older than the historical date.

DISCUSSION AND CONCLUSIONS

The Norse people in Greenland arrived from Iceland around AD 1000 and disappeared suddenly from Greenland at about AD 1450. Arneborg et al. (1999) showed by isotope analyses that the Norse Vikings changed their dietary habits dramatically during that time. The diet of the first settlers consisted of ~80% agricultural products and 20% from the surrounding sea, whereas at the end of the period the Greenland Norse had ~50–80% of their dietary protein from the marine food chain. The main objective of the present study was to analyze human remains from Iceland for comparison. We present data for human remains from Iceland covering the period from about AD 900–1250.

Our study of 79 human skeletons shows a fairly large variation in $\delta^{13}C$ of human bone collagen, from about 10–55% marine protein in the individual diet. The mean $\delta^{13}C$ value of human bone collagen of the 45 skeletons studied from Christian gravesites is 19.39 ± 0.46‰. Only 3 of those are <18.5‰, corresponding to a >30% marine diet component. If those samples are excluded, the mean $\delta^{13}C$ value for Christian humans becomes 19.48 ± 0.34‰. The mean $\delta^{13}C$ value of human bone collagen of the 30 skeletons studied from pagan gravesites is 18.73 ± 1.05‰. Nine of those, all from the sites at the seashore, are <18.5‰, corresponding to a >30% marine diet component. If those samples are excluded, the mean $\delta^{13}C$ value for pagan humans becomes 19.31 ± 0.51‰, almost identical to the Christian mean value.

So far, the only cases of a high marine diet component (>30% marine) are found for all 7 of the samples from the pagan gravesite in Vatnsdalur (site 19), the only sample from the Bakki pagan gravesite (site 2), the 1 sample from the pagan site at Hafurbjarnarstaðir (site 7), 2 samples of 9 from the Christian gravesite at Hof in Hjaltadalur (site 8), and 1 sample of 18 from the Christian gravesite at Keldudalur (site 21). All individuals that show high marine component are from gravesites at the seashore or within ~10 km from the sea. Bone collagen from the rest of the human remains excavated from either Christian or pagan graves covering the time period AD 900–1250 has fairly uniform $\delta^{13}C$ values (ranging only from 20.3‰ to 18.5‰), reflecting that only about 8–28% of their diet was from the marine food chain. No evolution in food consumption is found with time over the period studied.

Geographical differences in the dietary economy in Iceland are shown in Figure 3. The gravesites at the seashore show extreme variation in $\delta^{13}C$ from 19.7‰ to 16.4‰, with a mean value of 17.94 ± 0.95‰, while a much smaller range is observed for the individuals living inland (20.1–19.2‰), with a mean value of 19.66 ± 0.24‰. All of the seashore localities are from pagan gravesites; thus, the large range in $\delta^{13}C$ values might indicate different lifestyles of the pagan and Christian people. However, where we have skeletons from both pagan and Christian gravesites at the same distance from the sea, no difference can be detected in $\delta^{13}C$ values of their bone collagen. Thus, in the present data, no systematic difference in subsistence can be isolated as reflecting cultural differences. The only evidence for higher social status in the present data set is the remains of the 12th century bishop Páll Jónsson. As no difference can be seen in his marine intake and others from the same geographical location, it is suggested that in the present data, we cannot see any evidence of social hierarchy. Further research on isotopic composition of possible food resources will, however, give more information, which might suggest that social status is reflected in the isotopic composition of the human bone collagen.

The differences in $\delta^{13}C$ values of human bone collagen probably mainly reflect the geographical locations of their farms: people living at the seashore had a choice between marine food and agricultural products, whereas people living inland had poor access to the sea and were forced to subsist mainly on agricultural products.

Another possibility for the large variation in $\delta^{13}C$ of bone collagen of humans living at the same distance from the sea is movement of people. For example, the least marine individual (16%) living at the seashore is from the Vestman Islands, south of Iceland (site 14), where the economy of people living there has always depended heavily on the surrounding sea. The non-marine $\delta^{13}C$ value of the skeleton (19.7‰) therefore came as a surprise. However, our early ^{14}C date of the skeleton (AAR-5870) of around AD 870–970 may indicate that he had arrived a short time before his death from Norway and, therefore, still reflects the agricultural diet characterizing Norwegians at that time.

Figure 7 shows the Icelandic results in comparison with the results for the Greenland Norse colony studied by Arneborg et al. (1999). Contrary to the Norse Greenland samples where the dependence on the marine resources increased through time, the Icelandic samples show large variation in $\delta^{13}C$ of bone collagen of humans that lived close to the sea; a much smaller range is found for individuals living inland (Figure 3). In general, the pastoral economy seem to have had better conditions in Iceland compared to Greenland, and the Medieval climate changes may have affected the Icelandic farmers less than their Greenlandic neighbors. It is, however, important to note that our Icelandic data cover only up to AD 1250 and for further comparison with the Norse people in Greenland, it is essential to extend our data set to post-AD 1250.

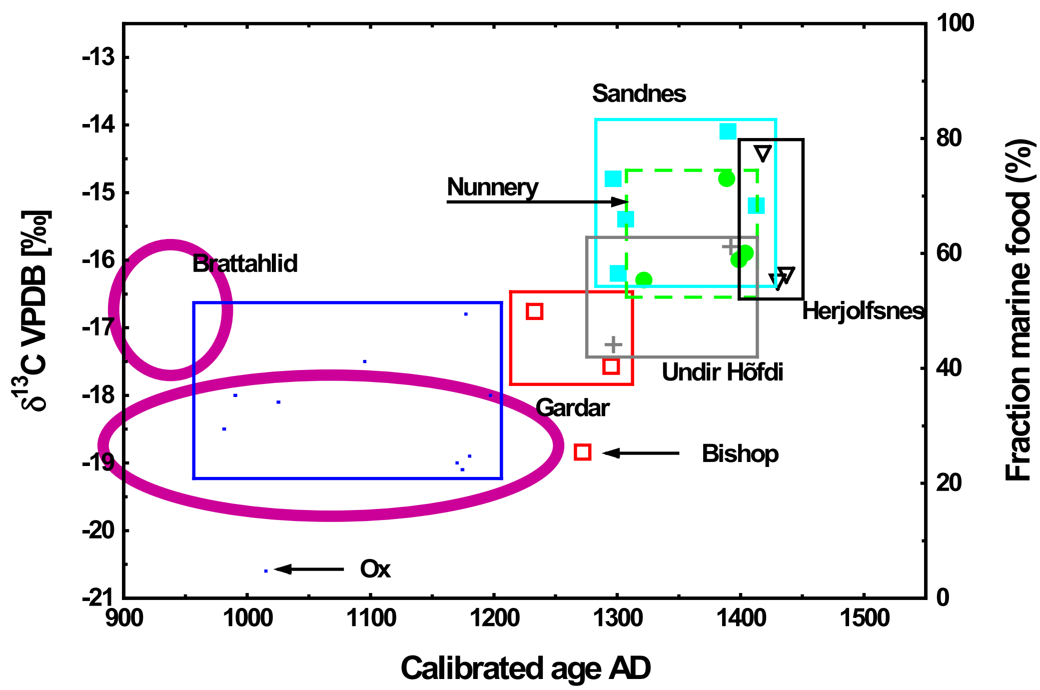

Figure 7 The main ranges of $\delta^{13}C$ values (ovals) of Icelandic human skeletons as a function of time of death determined by ^{14}C dating shown in comparison to the results of the Greenland Norse skeletons described in Arneborg et al. (1999).

Our ^{14}C dates for bones with carbon of mixed marine and terrestrial origin are consistent with the age of associated terrestrial samples and historical information. We therefore conclude that our reservoir correction procedure, based on the bone collagen $\delta^{13}C$ values, gives reliable ^{14}C dates for mixed marine bone samples.

The considerable variability in the observed $\delta^{15}N$ values may indicate differences in the dietary patterns between geographical locations as wells as social status. However, detailed isotopic investigation on the possible food resources at the different geographical locations is necessary before the $\delta^{15}N$ results can be interpreted in detail.

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