RESERVOIRS AND RADIOCARBON: ^{14}C DATING PROBLEMS IN MÝVATNSSVEIT, NORTHERN ICELAND

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ABSTRACT

This paper examines two potential sources of the ^{14}C offset between human and terrestrial mammal (horse) bones recovered from Norse (c.870-1000 AD) pagan graves in Mývatnssveit, North Iceland. These are the marine and freshwater ^{14}C reservoir effects that may be incorporated into human bones from dietary sources. The size of the marine reservoir ^{14}C effect (MRE) during the Norse period was investigated by measurement of multiple paired samples (terrestrial mammal and marine mollusc shell) at two archaeological sites in Mývatnssveit and one on the North Icelandic coast. These produced three new ΔR values for the North coast of Iceland, indicating a ΔR of +106 ± 10 ^{14}C yr at 868-985 AD, and of +144 ± 28 ^{14}C yr at

1280-1400 AD. These values are statistically comparable and give an overall weighted mean ΔR of +111 ± 10 ^{14}C yr.

The freshwater reservoir effect was similarly quantified using freshwater fish bones from a site in Mývatnssveit. These show an offset of between 1285 and 1830 ^{14}C yr, where the fish are depleted in ^{14}C relative to the terrestrial mammals. This is attributed to the input of geothermally derived CO_2 into the groundwater and subsequently into Lake Mývatn. We conclude that: i.) some of the Norse inhabitants of Mývatnssveit incorporated non-terrestrial resources into their diet that may be identified from the stable isotope composition of their bone collagen, ii.) the MRE off the North Icelandic coast during the Norse period fits a spatial gradient of wider North Atlantic MRE values with increasing values to the northwest, and iii.) it is important to consider the effect that geothermal activity could have on the ^{14}C activity of samples influenced by groundwater at Icelandic archaeological sites.

KEYWORDS

Marine Reservoir Effect, Freshwater Reservoir Effect, Norse period, North Iceland, Mývatnssveit

INTRODUCTION

The human colonization of Iceland occurred in relatively recent prehistory in a period directly associated with the *landnám* tephra layer, (Dugmore et al. 2000; Dugmore et al. 2005), dated to 871 ± 2 AD (Grönvold et al. 1995). This resulted in a relatively recent human alteration of an ecosystem that has continued to the present and includes several climatic variations, for example the series of cooling episodes from AD 1200 that culminated in the "Little Ice Age" interval (Bond et al 2001; Mann et al 1999). Iceland is therefore an important location for the research of human-environment interactions, where human action had a pronounced effect upon Icelandic environments. For example, it is estimated that 40% of soils present at *landnám* have been lost as a result of human actions (Arnalds et al. 1997). The interplay between Icelandic societies, climate and environmental change is readily investigated, due to the existence of areas rich in archaeological and palaeoenvironmental resources. One of these is Lake Mývatn, a highland lake basin in the interior of North Iceland (See Fig 1). Investigations of the surrounding area (Mývatnssveit) have revealed over 1200 archaeological sites that demonstrate excellent organic preservation (McGovern et al. 2007), and a wide range of palaeoenvironmental records providing detailed landscape reconstruction (Lawson et al. 2007). These resources are being used to investigate many aspects of human-environment interaction since *landnám*, particularly given the apparent early time of settlement in the area, with definite midden deposits in contact with the *landnam* tephra layer (McGovern et al. 2006). This challenges the view that the Norse settlement in Iceland involved gradual expansion from a limited number of coastal centres, and supports the hypothesis that in some areas settlers dispersed swiftly inland. However, interpretation of the data will only be accurate if based upon reliable chronological information.

Dating of archaeological remains in Mývatnssveit within the Leverhulme Trust funded project 'Landscapes circum *landnám*'(Edwards et al. 2004) has included a large number of ^{14}C measurements of bone collagen from humans and domesticated animals (e.g. cattle, pigs, and horses). As well as these animals, the Norse settlers in Mývatnssveit also exploited resources from both the surrounding area and coastal regions, including terrestrial plants, freshwater fish and wildfowl, along with marine fish and molluscs, transported inland via extensive trade and exchange networks (McGovern et al. 2006; in press). The dating program indicated a possible influence of ^{14}C reservoir effects when measurements from human and horse bones, found in close association in pre-Christian graves were compared. At some sites the human bone appears older than the horse, for example by c. 200 ^{14}C years at Ytri-Neslönd (McGovern et al. 2006) (see Table 1). In this example, the human burial was also stratigraphically above the *Landnám* tephra fall, and therefore the radiocarbon determination on the human bone collagen appeared to be too old. This effect is most readily explained if the diet of the human within this grave had included resources that are ^{14}C-depleted.

The evidence for consumption of marine and freshwater resources in Mývatnssveit, together with the ^{14}C measurement results discussed above, mean that it is important to examine the nature and size of ^{14}C reservoir effects that may influence sample material available for dating in the region. This paper investigates the hypothesis that food resources present in Norse archaeological deposits in Mývatnssveit were affected by a ^{14}C offset between the atmospheric reservoir and the contemporaneous (marine or freshwater) reservoir in which the resources were grown, and seeks to quantify the size of these offsets.

Reservoir effects exist when the internal transport and circulation of carbon atoms within a reservoir occurs over longer time periods than within the coeval global atmosphere or through the introduction of ‘old’ carbon from another reservoir. This results in a depletion of ^{14}C activity in a reservoir, relative to the atmosphere, at any point in time. The ^{14}C activity of organisms inhabiting the terrestrial biosphere can also be depleted if they consume material that is itself influenced by a marine reservoir effect (MRE) or freshwater reservoir effect (FRE). As a result, the problem cannot simply be excluded in areas such as Mývatnssveit by avoiding measurement of organisms living in the marine or freshwater system. Therefore, to assess the impact of reservoir effects upon chronologies in this region requires a comparison of the ^{14}C activities of the local freshwater and marine systems with the contemporaneous atmosphere.

The MRE is a result of the extended residence time of ^{14}C in the global ocean (up to 1000 years (Mangerud 1972)) relative to that of the atmosphere (approximately 5 years (Levin and Hesshaimer 2000)). A time-dependant MRE for the global average ocean is quantified by a separate calibration curve, MARINE04 (Hughen et al. 2004). However, geographic variations in climate and circulation mean that the MRE for a specific ocean area may differ from that of the MARINE04 global average. This deviation is known as ΔR (Stuiver et al. 1986), and modern (pre-bomb) ΔR assessments for surface waters (<3 m depth) around Iceland are available from the online marine reservoir correction database at http://calib.qub.ac.uk/marine (Reimer and Reimer 2001). These values are generally higher than the global average MRE (i.e. positive ΔR), however there is a wide range of measured values, from ΔR = –56 ± 85 ^{14}C yr (Olsson 1980), to ΔR = 225 ± 51 ^{14}C yr (Broecker and Olson 1961). The weighted mean of these values gives ΔR = 106 ± 89 ^{14}C yr, while a weighted mean of all values (including waters >3m depth) gives a ΔR = 52 ± 53 ^{14}C yr. This variability makes it difficult to define a modern ΔR value for Iceland that is both accurate and precise. However, the majority of values are positive, potentially reflecting the contribution of Arctic-derived currents to surface ocean water around Iceland. These tend to have a lower ^{14}C content than Atlantic Current waters, which undergo gaseous exchange with contemporary atmospheric CO_2 during northward transport in the Gulf Stream (Campin et al. 1999).

As the MRE for a specific ocean area reflects local climatic and oceanographic variables, changes in these parameters of a sufficient magnitude may result in observable MRE fluctuations. Temporal variations in the MRE of ocean waters around Iceland (modern values are estimated at c. 450 yr) include measurements of c. 950 yr at c. 25,000 cal yr BP, c. 2,240 yr at c. 18,000 cal yr BP, between c. 630 and c. 1,160 yr at 14,600-18,100 cal yr BP (Voelker et al. 1998) and 750-800 yr at c. 12,000 cal yr BP (Hafliðason et al. 2000). Variations have also been observed during the Holocene, with an MRE of 730 years at c. 9,000 ^{14}C yr BP off the North Icelandic coast (Hafliðason et al. 2000). Fluctuations over the past 4,600 cal years include lower MRE values (c. 400 ^{14}C y) associated with dominance of the Irminger Current, while an increase in MRE to 530 ^{14}C yr is linked to increasing influence of the East Icelandic Current in the area (Eiríksson et al. 2000; Eiríksson *et al*., 2004).

In addition to marine ^{14}C offsets, processes within freshwater systems (rivers and lakes) can result in a freshwater reservoir effect (FRE). This is then apparent in ^{14}C measurements of organisms inhabiting the freshwater system and in organisms incorporating freshwater-derived dietary components (Cook et al. 2001, Fischer and Heinemeier 2003, Fallu et al 2004). Globally, the size of FREs is highly variable, dependant upon the specific local causes of the offset. The principle sources of ^{14}C in freshwater systems are gaseous exchange with atmospheric CO_2 and incorporation of dissolved inorganic carbon from groundwater entering the system (Geyh et al. 1998). It is the latter that often results in depleted ^{14}C levels in freshwater relative to the coeval atmosphere. Groundwater and runoff can contain quantities of ^{14}C-free carbon in the form of bicarbonate ions (HCO_3^-) by dissolution of calcareous bedrock, old soil carbonates, or geothermal processes. Although Iceland does not contain calcareous bedrock, it has a high level of geothermal activity, to which highly depleted ^{14}C activities in modern Icelandic groundwater have been attributed (Sveinbjörnsdóttir *et al.*, 2000). As a result of geothermal processes, low ^{14}C-activity CO_2 is leached from the underlying bedrock, sediments, and soils, into groundwater in a series of interactions, resulting in high apparent groundwater ^{14}C ages (Sveinbjörnsdóttir et al. 1995). Lake Mývatn is fed almost exclusively by groundwater sources, and groundwater in Mývatnssveit is affected by geothermal activity in the surrounding region, which greatly influences the lake chemistry (Kristmannsdóttir and Ármannsson 2004). Direct ^{14}C measurements of the water in Lake Mývatn are not available; however it is very likely that the influence of ^{14}C-depleted groundwater input to the lake has resulted in a high FRE.

To quantify a MRE or FRE requires knowledge of the ^{14}C activity of both the atmospheric and marine/freshwater reservoirs at an equivalent point in time and from a specific location. The methodology adopted in this paper is the paired sample approach described in Ascough et al. 2004, which compares ^{14}C measurements of coeval samples from the atmospheric (terrestrial biosphere) and marine/freshwater reservoirs. The material chosen to represent the terrestrial biosphere, which is well mixed with respect to the coeval atmospheric reservoir, was cattle (*Bos* sp.) bone as, in Iceland, these animals have a terrestrial (C_3) plant diet. This is confirmed by the stable isotope (i.e. $\delta^{13}C$ and $\delta^{15}N$) analyses of the bone collagen (Table 2). The material used to represent the marine ^{14}C reservoir was marine mollusc shells (*Mytilus edulis* or *Mya* sp.). These organisms precipitate their shell carbonate in isotopic equilibrium with the ambient water (Keith *et al.*, 1964; Grossman and Ku, 1986; Forman and Polyack, 1997) and have limited mobility, making them a good record of surface water ^{14}C for a specific area. ^{14}C measurements of marine mammals show depletion due to the MRE, however the feeding range of these animals can be extremely large. This wide geographic feeding range has been used to explain the observed variability in marine mammal ^{14}C ages (Dumond and Griffon 2002) as their diet may include food from a variety of ocean areas and water depths. If these areas have a variety of different ΔR values, the ^{14}C age of the bone will reflect an averaging of these values and would be unsuitable for determining a ΔR value for one specific ocean area. To test whether we could identify a difference between the MRE represented in marine mammal bone and the marine mollusc shells we measured the bone of a harbour seal (*Phoca vitulina*) from one of the sites included in the study (Gásir).

The $\delta^{13}C$ of mammalian bone collagen reflects mainly the dietary protein sources (Ambrose and Norr 1993; Jim et al. 2004). This shows a slight enrichment at higher trophic levels, for example a 2‰ increase between herbivores and carnivores (van der Merwe, 1992). In addition, there are distinct differences in $\delta^{13}C$ signatures within different ecosystems, for example, the primary producers (phytoplankton) in the marine environment are enriched in ^{13}C relative to the primary producing C_3 plants of the terrestrial biosphere. This allows identification of marine vs. terrestrial dietary sources, as the marine $\delta^{13}C$ enrichment is transferred to organisms formed in the marine reservoir. This also applies to terrestrial organisms consuming marine resources. For example, Neolithic sheep from the Orkney Isles in Scotland that fed on seaweed give bioapatite $\delta^{13}C$ values as high as −5.7‰ (Balasse et al. 2005), reflecting the $\delta^{13}C$ of the seaweed consumed, which was measured at –18.5 to -13.1‰. These values for seaweed are significantly heavier than terrestrial (C_3) plants, which have a mean value of -27‰ (Raven et al. 2002). The $\delta^{15}N$ value of bone collagen increases with each successive trophic level above that of the primary producer by 1.3–5.3‰, depending upon the specific consumer-food source combination (Minagawa and Wada 1984; Cabana and Rasmussen 1994, 1996). As both marine and freshwater ecosystems have complex food webs with several trophic levels, the $\delta^{15}N$ of bone collagen from terrestrial animals consuming these resources is often enriched (Schoeninger and DeNiro 1984; Bonsall et al. 1997). Therefore, the $\delta^{15}N$ values of aquatic organisms such as fish (often >12‰) are usually high relative to that of primary terrestrial consumers such as cattle (c. 4-6‰) (DeNiro 1985; Bocherens et al. 1991; Dufour et al. 1999); Katzenber and Weber, 1999). To investigate the effect of a variety of dietary sources upon isotopic composition we analysed a domestic pig (*Sus* sp.) bone from one of the sites in Mývatnssveit (Hrísheimar). This species is omnivorous and may have been fed on a diet that included food scraps containing marine and freshwater material. If this were so, the mixed diet should be reflected in the stable isotopic composition of the bone and in a ^{14}C age with some evidence of a reservoir age.

METHODOLOGY

Samples were taken from two archaeological sites in Mývatnssveit: Hofstaðir (65^0 61' N, -17^0 16' W) and Hrísheimar (65^0 52' N, -17^0 10' W), and one site on the North

Icelandic coast: Gásir (65^0 78' N, -18^0 16' W) (see Fig. 1). Extensive excavations have shown that Hofstaðir was a large, high-status farm; Hrísheimar a smaller farmstead involved in specialised iron working and Gásir a later coastal trading centre. From tephrochronology and previous ^{14}C measurements, Hofstaðir and Hrísheimar are estimated to have been occupied between the 9th-12th centuries AD and Gásir between the 12th-15th centuries AD (McGovern et al. 2006). At each site the MRE or FRE was calculated using ^{14}C measurements of multiple samples of domestic material discarded during occupation within a single, sealed archaeological midden deposit, associated with a single archaeological phase. The *Mytilus edulis* specimens used for calculation of the MRE at Hofstaðir and Hrísheimar appear to have been brought to the inland sites via the transportation of seaweed, whilst the *Mya* sp. shells at Gásir were deliberately harvested and discarded into the midden.

The FRE of Lake Mývatn was assessed at Hrísheimar, using Arctic char (*Salvelinus alpinus*) bones. This material was also obtained from the same deposit as the samples used to assess the MRE. Due to the small size of individual Arctic char bones, single entities from demonstrably different individuals could not be dated and a bulk sample of bones, split into four sub-samples, was used for measurement. The two further samples measured were the harbour seal (*Phoca vitulina)* bone from Gásir and the domestic pig (*Sus* sp.) bone from Hrísheimar.

Pre-treatment of the bone samples followed a modified Longin (1971) procedure to extract collagen for ^{14}C measurement, while pre-treatment of the mollusc shells involved a 20% removal of the outer shell surface by etching in 1M HCl (Ascough et al. 2005). CO_2 was obtained from the bone collagen samples by combustion in sealed quartz tubes (Vandeputte et al. 1996). For marine mollusc shell samples, a secondary pre-treatment, consisting of a further 20% removal of the shell surface was performed in a pre-cleaned Pyrex hydrolysis unit. Finally, CO_2 was evolved by acid hydrolysis of the shell under vacuum. A 2 ml sub-sample of CO_2 was converted to graphite by the method of Slota et al. (1987). AMS measurements were made using the SUERC 5 MV terminal voltage spectrometer. $\delta^{13}C$ measurements were made using a VG SIRA 10 isotope ratio mass spectrometer with NBS 22 (oil) and NBS 19 (marble) employed as standards. $\delta^{15}N$ measurements were made by continuous flow isotope ratio mass spectrometry (CF-IRMS) using a Thermo Electron Delta XP Plus isotope ratio mass spectrometer interfaced with a Costech ECS 4010 elemental analyser. Gelatin was used as the primary internal standard, alanine as the secondary and tryptophan for the C/N ratio. Approximately 0.8 mg of collagen was required for analysis. $\delta^{13}C$ measurements were also generated by this technique, although of lower precision than the Sira 10 measurements. These were used only as a confirmation of the Sira 10 measurements and are not presented here.

Multiple samples of each type of material were measured from each site in order to assess the likely range of ^{14}C ages represented in a single deposit. This is indicative of the duration of accumulation of a deposit, as well as the potential for post-depositional mixing of material. Several samples of one material type with indistinguishable ^{14}C ages raise the likelihood that all material in a deposit was included over a short time interval. The contemporaneity of a group of terrestrial, marine or freshwater sample ^{14}C ages was statistically assessed using a χ^2 test (Ward and Wilson 1978), where the test statistic (T) was compared with the critical value for 95% significance ($\chi^2_{:0.05}$) for the number of samples (N). This determined whether the internal variability of a measurement group was consistent with the errors on the individual determinations. Outliers were removed from the measurement group and the remaining terrestrial and marine ages were used to calculate ΔR values.

The ΔR calculation followed the procedure described in Ascough *et al*. (2006), where a terrestrial ^{14}C age ± 1σ was converted to an upper and lower global average modelled marine age using an interpolation of the INTCAL04 and MARINE04 ^{14}C calibration datasets (Reimar et al 2004, Hughen et al 2004). ΔR was then the difference between the midpoint of the modelled age range and the measured ^{14}C age of the corresponding marine sample. A value was calculated for each possible pairing of terrestrial and marine ^{14}C ages and the distribution was summarised by the weighted mean and standard error.

The age range of the archaeological context was calculated using the weighted mean value of the terrestrial measurements that were indistinguishable on the basis of the χ^2 tests. The weighted mean terrestrial age BP was converted to a calibrated age range using the INTCAL04 atmospheric dataset (Reimer et al. 2004) and the OxCal v3.10 calibration program (Bronk Ramsey 1995, 2001, 2005).

RESULTS

The average $\delta^{13}C$ values for the cattle bones are –21.1‰, -21.6‰ and –22.0‰ for Hofstaðir, Hrísheimar and Gásir, respectively. These are comparable to the –22‰ value predicted for herbivores consuming a 100% C_3 plant diet (van der Merwe 1989) and confirm that the ^{14}C measurements of these samples do not reflect any component other than the terrestrial biosphere. With one exception (SUERC-8629; 7.3‰, which requires re-analysis for confirmation), the $\delta^{15}N$ values of the cattle bones show a total variability of 3.2‰, around an average of 1.2‰. The specific $\delta^{15}N$ of an animal reflects general interactions between soil, vegetation and climate as well as its trophic level, and these influences produce geographic variations between organisms at similar trophic levels from different regions (Richards and Hedges 1999). The $\delta^{15}N$ values for the cattle bones therefore should reflect that of primary herbivorous consumers in Mývatnssveit during the Norse and Medieval periods. The low values for these $\delta^{15}N$ measurements may reflect lower values for Icelandic plants than in other regions. Low $\delta^{15}N$ values in terrestrial plants have been observed in various locations as a result of interactions between specific plant physiological and environmental variables (Erskine et al. 1998; McKee et al. 2002; Tozer et al. 2005). In a study of stable isotopic measurements of Icelandic plants and lichens, including material from sites in the North of Iceland, Wang and Wooller (2006) found a series of low $\delta^{15}N$ values, with an overall range down to -12‰ for terrestrial plants. Such low $\delta^{15}N$ values may then be transferred to the bones of grazing herbivores. In contrast, the pig bone (SUERC-8355) $\delta^{15}N$ is measured at 7.4‰, and $\delta^{13}C$ at -16.9‰, indicating consumption of material from a higher trophic level than that of the cattle, and that the carbon originated in reservoirs other than the terrestrial biosphere. The ^{14}C age of the pig is 1103 ± 44 ^{14}C yr older than the weighted mean age (1147 ± 27 ^{14}C yr) of four statistically indistinguishable (T= 6.78; ($\chi 2$:0.05 = 7.81)) cattle bones from the same, sealed context, which is therefore likely to be the result of a diet that included material influenced by a ^{14}C reservoir effect. The $\delta^{13}C$ of the seal bone falls within the range of –12.3 ± 1.3‰ for average bone collagen values for seals from various global locations (Richards and Hedges 1999).

On the basis of the χ^2 test, the groups of marine and terrestrial measurements from Hofstaðir and Hrísheimar are internally consistent (Table 3), while at Gásir one terrestrial measurement (SUERC-8635), and one marine measurement (SUERC-8639) were significantly different from the remainder of the respective measurement groups. Repeat measurements of the terrestrial samples confirmed the original ages (Table 4). Interestingly, the measurement of seal bone accorded with the three consistent shell measurements, where the test statistic for this group of four samples was T = 2.63; (χ^2:0.05 = 7.81). To check this, the measurement of the seal bone was repeated and the repeat and original measurements were indistinguishable (Table 4). If the seal bone was deposited at the same time as the group of marine shells that have consistent ^{14}C ages, it appears that the food consumed by the seal may have had a homogeneous ΔR value that was representative of the North Icelandic surface ocean ΔR for this time period. However, as this can only be confirmed by further reproducible measurements, the value of ΔR for Gásir in this paper is based on the two statistically indistinguishable terrestrial measurements and three statistically indistinguishable marine (mollusc shell) measurements.

The consistency of multiple ^{14}C measurements from deposits at Hofstaðir and Hrísheimar gives confidence to the fact that these are reliable assessments of the surface ocean ^{14}C during this period. The calibrated age range for the terrestrial radiocarbon dates from Hrísheimar was modelled using the terrestrial weighted mean in combination with the Landnám tephra that pre-dated the archaeological remains. using the methodology outlined by Church et al. (this volume). The higher variability in measurements at Gásir, identified in the χ^2 test represents actual variation in the ages of the samples within the context, rather than any analytical problem, and is indicative of incorporation of material into the deposit over an extended time period or of intrusive material. These outliers can be explained by the large horizontal extent of the midden sampled at Gásir, which had the potential for incorporation of older material from lower levels. The use of a greater number of consistent ages in this instance gave an estimate of ΔR that had an improved likelihood of accuracy (see Table 5). The calibrated age range for Hofstaðir (95 years at 2σ) overlaps with that of Hrísheimar (100 years at 2σ). Together, the material from Hofstaðir and Hrísheimar relates to the period following Norse *landnám* settlement in Iceland. These age ranges are separated by 317 calibrated years from that of Gásir, where the deposit from which material was obtained for ^{14}C measurement relates to the medieval period. The ΔR values calculated for the three sites are comparable (T= 2.31; (χ2:0.05 = 5.99)), and give an overall weighted mean ΔR of +111 ± 10 ^{14}C yr.

The ^{14}C ages of the freshwater Arctic char were much older than the terrestrial material from the same Norse deposits (see Table 2) and were highly variable within the sample group (ages ranging between 2505 and 2950 yr BP). Based on these assessments, the FRE represented in the freshwater fish bone is therefore much greater than the MRE for the North coast of Iceland during the Norse period, as the offset varies from 1285 ± 53 to 1830 ± 49 ^{14}C years. The $\delta^{13}C$ values of the samples ranged between -15.0 and -15.5‰. The $\delta^{15}N$ values varied between 5.6 and 6.0‰ and are indicative of the char feeding at a relatively low trophic level.

DISCUSSION

The measurement results show that marine and freshwater ^{14}C reservoir effects affect some archaeological sample types found in Mývatnssveit, and provide an assessment of ΔR values for the Norse period on the North Icelandic coast. Depending upon the resources consumed, both types of reservoir effect may contribute to offsets observed in measurements of individual terrestrial organisms, including humans. Changes in resource use through time would potentially alter the relative contribution of the MRE and FRE to the ^{14}C depletion in different individuals from a site in different phases. For example, Figure 2 shows that while the relative proportions of marine and freshwater fish bones at Hofstaðir are approximately constant through time, a larger proportion of freshwater fish were found in a later phase at Hrísheimar.

The MARINE04 curve (Hughen et al. 2004) and an appropriate ΔR must be used for calibration of marine samples, such as are found at sites in Mývatnssveit. As noted above, there is a wide variation in currently available (pre-bomb) assessments of ΔR for Iceland. The additional uncertainty that is introduced over the most appropriate ΔR correction means that the most reliable archaeological and palaeoenvironmental chronologies in Mývatnssveit will be based on material that reflects only the terrestrial ^{14}C reservoir. In some instances however, it may not be possible to avoid measurement of samples that have been influenced by the MRE and/or the FRE if this is the only suitable material for dating within a deposit of interest. In this case, the data presented in this paper may be used for calibration, where a weighted mean of the two values for periods 868-985 AD (Hofstaðir and Hrísheimar: ΔR= 106 ± 10 ^{14}C yr) and the value for 1280-1400 AD (Gásir: ΔR= 144 ± 28 ^{14}C yr) gives an overall weighted mean ΔR of +111 ± 10 ^{14}C yr for these time periods. This value is very similar to the value obtained from a weighted mean of all measurements for Icelandic modern surface waters <3 m depth from the online marine reservoir correction database (Reimer and Reimer 2001), where $\Delta R = 106 \pm 89$ ^{14}C yr.

Although reservoir effects create considerable problems for accurate comparison of ^{14}C ages of samples from different reservoirs, they can provide valuable information on climatic and oceanic regimes, for example, ocean ventilation rates (Broecker et al. 2004). The ΔR values presented in this paper can therefore be considered in the context of other assessments for the Norse period. A value of $\Delta R = 64 \pm 13$ ^{14}C yr is available for the Faroe Isles (61^0 51' N) for the period AD 1000 – 1156 (Ascough et al. 2006). This value is lower than the North Icelandic values presented in this paper, where for the four ΔR values (Icelandic and Faroes) $T = 11.02$ (χ^2:0.05 = 7.81). Further south in the North Atlantic, during a similar period to the Faroes assessment, ΔR values are lower than the North Icelandic values by c.200-240 ^{14}C yr. Here, values for the Western Isles of Scotland (59^0 21' N) at 1020-1158 AD and the west coast of Ireland (53^0 32' N) at 993-1156 AD are $\Delta R = -96 \pm 16$ ^{14}C yr and $\Delta R = -142 \pm 16$ ^{14}C yr, respectively (Ascough et al. 2006). These data show a developing picture of MRE values within the North Atlantic for the Norse period that indicates a spatial gradient in surface ocean ^{14}C activity with higher ΔR values in the northwest (i.e. the North of Iceland) than the southeast (i.e. the British Isles). The higher values for the North Icelandic coast relative to those at more southerly latitudes may reflect the influence of the East Icelandic current in this region. As noted above, these waters are derived from the East Greenland Current, which is depleted in ^{14}C relative to the Atlantic current.

While an appropriate ΔR allows calibration of 100% marine samples, calibration of measurements of terrestrial mammals from Mývatnssveit that appear to be affected by the MRE is more complex for two reasons. Firstly, it is necessary to know both the appropriate MRE correction, and the fraction of diet that came from marine sources (Arneborg et al. 1999). Secondly, in this ecosystem, other dietary components may result in depletion of ^{14}C in bone collagen, namely freshwater resources. The measurement made on pig bone highlights the problem. The apparent age of the pig bone (2250 ± 35 yr BP) is significantly older than the cattle bone from the same context and also gives an age offset from the cattle bone that is larger than the offset between the terrestrial and marine samples in the same deposit. The ^{14}C depletion between pig and cow bone, equivalent to c.1100 ^{14}C yr, could not therefore be produced even if the pig had consumed a diet of 100% marine material. The pig $\delta^{13}C$ value (-16.9‰) is enriched relative to animals existing solely within the terrestrial food web ($\delta^{13}C$ = c. -22‰), and the higher $\delta^{15}N$ value (7.4‰) indicates a mixed diet. Both the ^{14}C and stable isotopic measurements therefore show that the pig consumed material from a carbon reservoir other than the atmospheric and marine reservoirs that was strongly depleted in ^{14}C.

The high apparent age of the pig can be explained by the FRE calculated in Arctic char from Mývatnssveit. The results of these measurements show that the ^{14}C activity in the Mývatnssveit freshwater ecosystem is strongly depleted, as a result of the low ^{14}C content of the groundwater entering the lake. This depletion is transferred to primary producers (e.g. plants, algae) within the lake, and then throughout higher trophic levels, including the char. The $\delta^{13}C$ of the char reflects a range of food sources that have comparable stable isotopic compositions within the freshwater ecosystem.

The depletion represented in the char is c.1300-1700 ^{14}C yr, and this variability may reflect differences in feeding behaviour and habitat within the lake among different individual char represented in the bulk sample. Arctic char are opportunistic feeders taking advantage of a range of vertebrate and invertebrates, and a range of morphologies is displayed within the species. These are related to behavioural differences including feeding, and whether a particular individual char feeds predominantly in the benthic or pelagic zone is related to its particular morphological form (Andersson and Persson 2005). Different char food resources within the lake may therefore have variable levels of ^{14}C activity, depending on factors such as the transfer of atmospheric CO_2 to the lake surface and the incorporation of organisms that obtain some carbon from atmospheric sources, such as terrestrial insects, into the aquatic food web. Significantly more work is required to identify the variability in ^{14}C age of individual specimens in relation to variations in their stable isotope values.

The large FRE in Mývatnssveit may result in ^{14}C ages that are too old, by potentially >1000 ^{14}C yr in certain terrestrial mammals (including humans) relative to the coeval atmosphere. In previous studies, it has been possible to correct the ^{14}C age of mammals existing on a mixed diet, by using bone collagen stable isotopic composition to determine the proportions of marine or freshwater-derived material dietary resources and to apply a proportional reservoir correction (Arneborg et al. 1999; Cook et al. 2001). The situation in Mývatnssveit is more complex however, because of the use of both marine and freshwater material within the same economic system. Where an individual has consumed a significant amount of freshwater resources, this should be evident in a high apparent ^{14}C age, for example, of the order of 2000 yr BP for samples from Norse deposits. However, identifying the source of a

^{14}C-depletion may be more difficult where smaller amounts of freshwater resources, or a high ratio of marine to freshwater resources have been consumed.

If relative proportions of dietary components could be identified, there still remains the problem of identifying a FRE correction for Lake Mývatn that is both accurate and precise. At present, the measurements made on Arctic char show a range of c.400 ^{14}C yr in FRE, and it is not known whether this variation is typical of all fish (both char and other species) within Lake Mývatn, or whether a similar FRE is represented in other freshwater resources used by the inhabitants of Mývatnssveit, including other fish species and waterfowl. Previous determinations of FREs in other locations have indicated a wide potential range in the size of the effect, for example from 3600 to c.18,000 ^{14}C yr in Antarctic lakes (Hall and Henderson, 2001), and of 340 ± 20 ^{14}C yr in lakes in the Buena Vista Basin, California (Culleton, 2006). In addition, it is also necessary to identify whether the FRE in Lake Mývatn has remained constant through time. Geyh et al. (1998) found that FREs in lakes are not necessarily constant through time and may exhibit considerable variation due to changes in physical lake parameters (i.e. surface area and water depth). It is also reasonable to assume that such variability would also result from fluctuations in the ^{14}C activity of source waters to the lake. Seasonal variations have been identified in the temperature and chemical composition of groundwater in the Lake Mývatn area (Ármannsson et al, 2000), however it is not clear to what extent these affect the water ^{14}C activity.

The data presented in this paper have important implications for the use of ^{14}C measurements to construct chronologies for North Icelandic Norse settlements. The extensive use of resources by the Norse settlers means that both a MRE and a FRE can result in high apparent ^{14}C ages of archaeological samples. While a correction is available for calibration of 100% marine samples, the variability in FRE values calculated from Arctic char make it impossible to assign a single correction based upon these data. This means that it is difficult to reliably calibrate not only the ^{14}C ages of freshwater organisms, but of terrestrial mammals that are affected by the FRE via consumption of freshwater resources. The use of stable isotopic measurements is recommended to identify consumption of a mixed diet, however, enrichment in $\delta^{13}C$ in terrestrial mammal bone collagen may result from the consumption of either marine or freshwater material, or from a combination of both these foods. Further study is therefore required to determine whether it is possible to separate the relative contribution of marine and freshwater resources in terrestrial mammals that appear to be affected. In addition, further work is needed to determine whether it is possible to more precisely determine the FRE in Mývatnssveit in different freshwater resources. If the variability in FRE in the samples discussed here is representative of the range in ^{14}C ages of contemporaneous freshwater samples from Mývatnssveit, it may not be possible to accurately correct measurements of terrestrial mammals affected by the FRE. At present therefore, we recommend the use of stable isotopic measurements on bone collagen of terrestrial mammals to identify individuals that have consumed a purely terrestrial diet. It is these samples that should be used to construct archaeological and palaeoenvironmental chronologies in Mývatnssveit.

CONCLUSION

We have made the first assessment of marine and freshwater ^{14}C reservoir effects apparent in samples from Myvatnssveit, North Iceland, and have assessed the ΔR for the North Icelandic coast for the periods 868-985 AD and 1280-1400 AD. This has produced three new ΔR values that form part of a north-south gradient in surface ocean ^{14}C activity in the North Atlantic for the Norse period that appears similar to the present-day trend. The MRE affects marine samples found in Mývatnssveit, and the ΔR values presented here may be used for calibration of ^{14}C measurements made on such material. As well as purely marine derived samples however, the MRE also affects terrestrial mammals in Mývatnssveit, such as humans and pigs, which have consumed marine resources. Correction of this material is more complex, due to the additional depletion of ^{14}C activity of samples from this area attributable to a large freshwater reservoir effect (FRE). This has been identified in this paper using measurements of freshwater Arctic char in Norse middens, which give a FRE offset of at least c.1300 ^{14}C yr, however this varies up to c.1700 ^{14}C yr. The use of both marine and terrestrial material in the diet of the inhabitants of Mývatnssveit means that accurate correction values are required for terrestrial samples affected by varying quantities of both marine and freshwater material in the diet. Further work is needed to identify whether the relative amounts of marine and freshwater components can be distinguished using stable isotopic values. This work highlights that fact that the most reliable samples for construction of archaeological ^{14}C chronologies in Mývatnssveit and elsewhere is material containing solely terrestrial-derived carbon. This can be identified using stable isotopic analyses performed in conjunction with ^{14}C measurements.

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Figure captions:

Figure 1: Location map of Mývatnssveit showing the positions of sampled archaeological sites

Figure 2: Relative proportions of marine and freshwater fish from midden deposits during two different time periods at Hofstadir (HST) and Hrisheimar (HRH). Proportions remain approximately equal at (HST), while a higher proportion of freshwater fish were identified in the later phase at HRH (From McGovern *et al*., 2006).

Table captions:

Table 1: Duplicate ^{14}C and stable isotopic measurements of human and terrestrial mammal (horse) bone collagen from a pre-Christian grave at Ytri-Neslönd, Mývatnssveit (McGovern et al. 2006).

Table 2: Measurement results for terrestrial, marine and freshwater samples from three sites in Mývatnssveit.

Table 3: χ^2 test statistics for terrestrial and marine sample measurements

Table 4: Original and repeat measurements of terrestrial mammal and seal bone samples from Gásir

Table 5: Terrestrial ages and ΔR values based upon measurements of samples from three sites in Mývatnssveit

Tables:

Lab Code	**Material**	**δ^{13}C (‰)**	**δ^{15}N (‰)**	**^{14}C Age (yr BP)**
SUERC-2016	Human	-18.9	9.7	1395 ± 35
SUERC-2660	Human	-19.3	8.7	1405 ± 35
SUERC-2017	Horse	-21.8	2.7	1175 ± 35
SUERC-2661	Horse	-21.7	2.0	1200 ± 35

Ascough *et al*., Table 1

Site	**Sample ID**	**Material**	**^{14}C age (yr BP ± 1σ)**	**δ^{13}C (‰)**	**δ^{15}N (‰)**
Hofstaðir	SUERC-8618	Cow (*Bos* sp.)	1110 ± 40	-21.0	+1.4
Hofstaðir	SUERC-8619	Cow (*Bos* sp.)	1110 ± 30	-20.9	+2.6
Hofstaðir	SUERC-8623	Cow (*Bos* sp.)	1130 ± 35	-21.1	+0.1
Hofstaðir	SUERC-8624	Cow (*Bos* sp.)	1080 ± 35	-21.2	-0.2
Hofstaðir	SUERC-8625	Marine shell (*Mytilus edulis*)	1555 ± 35	+1.9	-
Hofstaðir	SUERC-8626	Marine shell (*Mytilus edulis*)	1585 ± 45	+1.4	-
Hofstaðir	SUERC-8627	Marine shell (*Mytilus edulis*)	1610 ± 35	+1.8	-
Hofstaðir	SUERC-8628	Marine shell (*Mytilus edulis*)	1600 ± 35	+0.2	-
Hrísheimar	SUERC-6431	Cow (*Bos* sp.)	1220 ± 35	-21.5	-0.4
Hrísheimar	SUERC-6432	Cow (*Bos* sp.)	1200 ± 35	-21.4	+1.5
Hrísheimar	SUERC-6433	Cow (*Bos* sp.)	1120 ± 35	-21.7	0.0
Hrísheimar	SUERC-6437	Cow (*Bos* sp.)	1120 ± 35	-21.6	+1.8
Hrísheimar	SUERC-6438	Marine shell (*Mytilus edulis*)	1650 ± 40	+0.8	-
Hrísheimar	SUERC-6439	Marine shell (*Mytilus edulis*)	1610 ± 35	-0.3	-
Hrísheimar	SUERC-6440	Marine shell (*Mytilus edulis*)	1595 ± 35	+0.3	-
Hrísheimar	SUERC-6441	Marine shell (*Mytilus edulis*)	1615 ± 35	+0.6	-
Hrísheimar	SUERC-9045	Arctic char (*Salvelinus alpinus*)	2625 ± 40	-15.2	+6.0
Hrísheimar	SUERC-9049	Arctic char (*Salvelinus alpinus*)	2505 ± 40	-15.5	+5.7
Hrísheimar	SUERC-9050	Arctic char (*Salvelinus alpinus*)	2950 ± 35	-15.0	+5.6
Hrísheimar	SUERC-9051	Arctic char (*Salvelinus alpinus*)	2670 ± 35	-15.3	+5.8
Hrísheimar	SUERC-8355	Pig (*Sus* sp.)	2250 ± 35	-16.9	+7.4
Gásir	SUERC-8629	Cow (*Bos* sp.)	645 ± 40	-21.8	+7.3
Gásir	SUERC-8634	Cow (*Bos* sp.)	595 ± 35	-22.1	+2.2
Gásir	SUERC-8635	Cow (*Bos* sp.)	795 ± 35	-22.1	+2.8
Gásir	SUERC-8636	Marine shell (*Mya* sp.)	1200 ± 35	+2.8	-

Gásir	SUERC-8637	Marine shell (*Mya* sp.)	1175 ± 35	+2.5	-
Gásir	SUERC-8638	Marine shell (*Mya* sp.)	1165 ± 35	+0.5	-
Gásir	SUERC-8639	Marine shell (*Mya* sp.)	1305 ± 35	+1.9	-
Gásir	SUERC-8633	Seal (*Phoca vitulina*)	1115 ± 40	-12.7	+14.4

Ascough *et al*., Table 2

Site	**Terrestrial sample χ^2 test statistic**	**Marine sample χ^2 test statistic**
Hofstaðir	T= 1.04; (χ2:0.05 = 7.81)	T= 1.41; (χ2:0.05 = 7.81)
Hrísheimar	T= 6.78; (χ2:0.05 = 7.81)	T= 1.11; (χ2:0.05 = 7.81)
Gásir	T= 17.46; (χ2:0.05 = 7.81)	T= 10.10; (χ2:0.05 = 7.81)

Ascough *et al*., Table 3

Original measurement			**Repeat measurement**			
Sample ID	**^{14}C age (1 σ)**	**δ^{13}C**	**Sample ID**	**^{14}C age (1 σ)**	**δ^{13}C**	**Weighted mean**
SUERC-8629	645 ± 40	-21.8	SUERC-9042	645 ± 35	-21.9	645 ± 26
SUERC-8634	595 ± 35	-22.1	SUERC-9064	590 ± 40	-21.4	593 ± 26
SUERC-8635	795 ± 35	-22.1	SUERC-9065	790 ± 35	-22.3	793 ± 25
SUERC-8633	1115 ± 40*	-12.7	SUERC-9043	1145 ± 35	-12.7	1132 ± 26

* seal bone

Ascough *et al*., Table 4

Site	**Hofstaðir**	**Hrísheimar**	**Gásir**
Terrestrial weighted mean ^{14}C age	1104 ± 17	1165 ± 26	645 ± 26
Calibrated age range	890-985 AD	868-968 AD	1280-1400 AD
Calculated ΔR (^{14}C yr BP)	114 ± 14	97 ± 15	144 ± 28

Ascough *et al*., Table 5