

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

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**ABSTRACT.** This paper examines 2 potential sources of the radiocarbon offset between human and terrestrial mammal (horse) bones recovered from Norse (~AD 870–1000) pagan graves in Mývatnssveit, north Iceland. These are the marine and freshwater  $^{14}\text{C}$  reservoir effects that may be incorporated into human bones from dietary sources. The size of the marine  $^{14}\text{C}$  reservoir effect (MRE) during the Norse period was investigated by measurement of multiple paired samples (terrestrial mammal and marine mollusk shell) at 2 archaeological sites in Mývatnssveit and 1 site on the north Icelandic coast. These produced 3 new  $\Delta\text{R}$  values for the north coast of Iceland, indicating a  $\Delta\text{R}$  of  $106 \pm 10$   $^{14}\text{C}$  yr at AD 868–985, and of  $144 \pm 28$   $^{14}\text{C}$  yr at AD 1280–1400. These values are statistically comparable and give an overall weighted mean  $\Delta\text{R}$  of  $111 \pm 10$   $^{14}\text{C}$  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  $^{14}\text{C}$  yr, where the fish are depleted in  $^{14}\text{C}$  relative to the terrestrial mammals. This is attributed to the input of geothermally derived  $\text{CO}_2$  into the groundwater and subsequently into Lake Mývatn. We conclude the following: 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  $^{14}\text{C}$  activity of samples influenced by groundwater at Icelandic archaeological sites.

### 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, 2005), dated to  $\text{AD } 871 \pm 2$  (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, e.g. the series of cooling episodes from AD 1200 that culminated in the “Little Ice Age” interval (Mann et al. 1999; Bond et al. 2001). 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 paleoenvironmental resources. One of these is Lake Mývatn, a highland lake basin in the interior of north Iceland (see Figure 1). Investigations of the surrounding area (Mývatnssveit) have revealed over 1200 archaeological sites demonstrating excellent organic preservation (McGovern et al. 2007), and a wide range of paleoenvironmental records providing detailed landscape reconstruction (Lawson et al. 2007). These

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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 landnám 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 centers, 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.

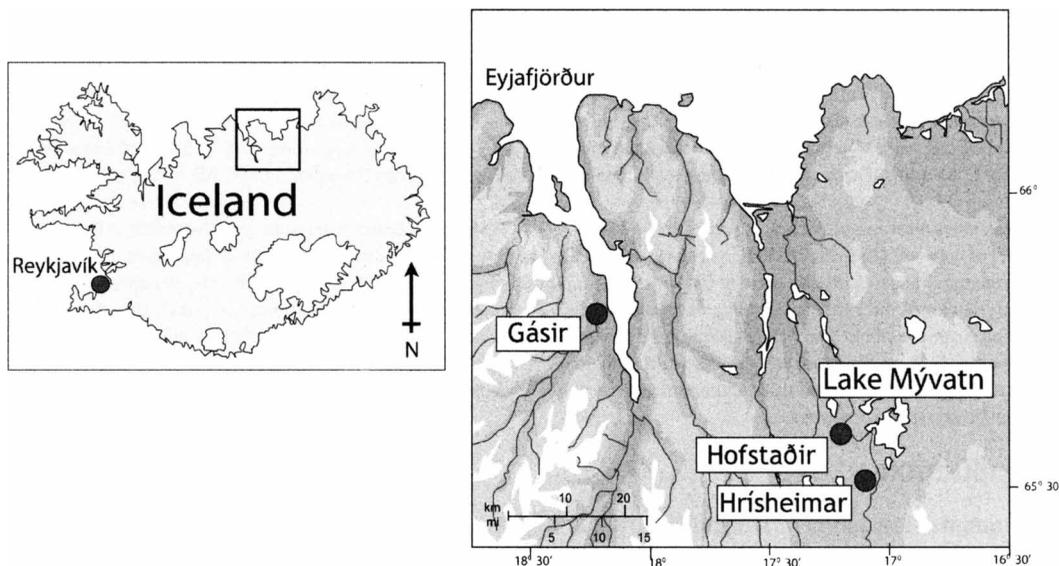


Figure 1 Location map showing the positions of sampled archaeological sites

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 radiocarbon 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 mollusks—transported inland via extensive trade and exchange networks (McGovern et al. 2006, 2007). The dating program indicated a possible influence of  $^{14}\text{C}$  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, e.g. by  $\sim 200$   $^{14}\text{C}$  yr at Ytri-Neslönd (McGovern et al. 2006) (see Table 1). In this example, the human burial was also stratigraphically above the landnám tephra fall; therefore, the  $^{14}\text{C}$  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  $^{14}\text{C}$  depleted.

Table 1 Duplicate  $^{14}\text{C}$  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).

| Lab code   | Material | $\delta^{13}\text{C}$ (‰) | $\delta^{15}\text{N}$ (‰) | $^{14}\text{C}$ age (yr BP) |
|------------|----------|---------------------------|---------------------------|-----------------------------|
| SUERC-2016 | Human    | -18.9                     | 9.7                       | 1395 $\pm$ 35               |
| SUERC-2660 | Human    | -19.3                     | 8.7                       | 1405 $\pm$ 35               |
| SUERC-2017 | Horse    | -21.8                     | 2.7                       | 1175 $\pm$ 35               |
| SUERC-2661 | Horse    | -21.7                     | 2.0                       | 1200 $\pm$ 35               |

The evidence for consumption of marine and freshwater resources in Mývatnssveit, together with the  $^{14}\text{C}$  measurement results discussed above, mean that it is important to examine the nature and size of  $^{14}\text{C}$  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  $^{14}\text{C}$  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  $^{14}\text{C}$  activity in a reservoir, relative to the atmosphere, at any point in time. The  $^{14}\text{C}$  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  $^{14}\text{C}$  activities of the local freshwater and marine systems with the contemporaneous atmosphere.

The MRE is a result of the extended residence time of  $^{14}\text{C}$  in the global ocean (up to 1000 yr; Mangerud 1972) relative to that of the atmosphere (approximately 5 yr; Levin and Hesshaimer 2000). A time-dependent 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  $\Delta\text{R}$  (Stuiver et al. 1986), and modern (pre-bomb)  $\Delta\text{R}$  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  $\Delta\text{R}$ ); however, there is a wide range of measured values, from  $\Delta\text{R} = -56 \pm 85$   $^{14}\text{C}$  yr (Olsson 1980) to  $\Delta\text{R} = 225 \pm 51$   $^{14}\text{C}$  yr (Broecker and Olson 1961). The weighted mean of these values gives  $\Delta\text{R} = 106 \pm 89$   $^{14}\text{C}$  yr, while a weighted mean of all values (including waters >3 m depth) yields  $\Delta\text{R} = 52 \pm 53$   $^{14}\text{C}$  yr. This variability makes it difficult to define a modern  $\Delta\text{R}$  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  $^{14}\text{C}$  content than Atlantic Current waters, which undergo gaseous exchange with contemporary atmospheric  $\text{CO}_2$  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 about 450 yr) include measurements of ~950 yr at ~25,000 cal yr BP; ~2240 yr at ~18,000 cal yr BP; between ~630 and ~1160 yr at 14,600–18,100 cal yr BP (Voelker et al. 1998); and 750–800 yr at ~12,000 cal yr BP (Haflidason et al. 2000). Variations have also been observed during the Holocene, with an MRE of 730 yr at ~9000  $^{14}\text{C}$  yr BP off the north Icelandic coast (Haflidason et al. 2000). Fluctuations over the past 4600 cal yr include lower MRE values (~400  $^{14}\text{C}$  yr) associated with dominance of the Irminger Current, while an increase in MRE to 530  $^{14}\text{C}$  yr is linked to increasing influence of the East Icelandic Current in the area (Eiriksson et al. 2000, 2004).

In addition to marine  $^{14}\text{C}$  offsets, processes within freshwater systems (rivers and lakes) can result in a freshwater reservoir effect (FRE). This is then apparent in  $^{14}\text{C}$  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, dependent upon the specific local causes of the offset. The principle sources of  $^{14}\text{C}$  in freshwater systems are gaseous exchange with atmospheric  $\text{CO}_2$  and incorporation of dissolved inorganic carbon from groundwater entering the system (Geyh et al. 1998). It is the latter that often results in depleted  $^{14}\text{C}$  levels in freshwater relative to the coeval atmosphere. Groundwater and runoff can contain quantities of  $^{14}\text{C}$ -free carbon in the form of bicarbonate ions ( $\text{HCO}_3^-$ ) 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  $^{14}\text{C}$  activities in modern Icelandic groundwater have been attributed (Sveinbjörnsdóttir et al. 2000). As a result of geothermal processes, low  $^{14}\text{C}$ -activity  $\text{CO}_2$  is leached from the underlying bedrock, sediments, and soils into groundwater in a series of interactions, resulting in high apparent groundwater  $^{14}\text{C}$  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  $^{14}\text{C}$  measurements of the water in Lake Mývatn are not available; however, it is very likely that the influence of  $^{14}\text{C}$ -depleted groundwater input to the lake has resulted in a high FRE.

To quantify a MRE or FRE requires knowledge of the  $^{14}\text{C}$  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  $^{14}\text{C}$  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. These animals have a terrestrial ( $\text{C}_3$ ) plant diet; this is confirmed by the stable isotope (i.e.  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) analyses of the bone collagen (Table 2). The material used to represent the marine  $^{14}\text{C}$  reservoir was marine mollusk 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 Polyak 1997) and have limited mobility, making them a good record of surface water  $^{14}\text{C}$  for a specific area.  $^{14}\text{C}$  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  $^{14}\text{C}$  ages (Dumond and Griffin 2002) as their diet may include food from a variety of ocean areas and water depths. If these areas have a variety of different  $\Delta R$  values, the  $^{14}\text{C}$  age of the bone will reflect an averaging of these values and would be unsuitable for determining a  $\Delta R$  value for a specific ocean area. To test whether we could identify a difference between the MRE represented in marine mammal bone and the marine mollusk shells, we measured the bone of a harbor seal (*Phoca vitulina*) from one of the sites included in the study (Gásir).

The  $\delta^{13}\text{C}$  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, e.g. a 2‰ increase between herbivores and carnivores (van der Merwe 1992). In addition, there are distinct differences in  $\delta^{13}\text{C}$  signatures within different ecosystems, e.g. the primary producers (phytoplankton) in the marine environment are enriched in  $^{13}\text{C}$  relative to the primary producing  $\text{C}_3$  plants of the terrestrial biosphere. This allows identification of marine vs. terrestrial dietary sources, as the marine  $\delta^{13}\text{C}$  enrichment is transferred to organisms formed in the marine reservoir. This also applies

Table 2 Measurement results for terrestrial, marine, and freshwater samples from 3 north Icelandic sites.

| Site       | Sample ID  | Material                                  | $^{14}\text{C}$ age<br>(yr BP $\pm 1 \sigma$ ) | $\delta^{13}\text{C}$<br>(‰) | $\delta^{15}\text{N}$<br>(‰) |
|------------|------------|---|--|------------------------------|------------------------------|
| Hofstaðir  | SUERC-8618 | Cow ( <i>Bos</i> sp.)                     | 1110 $\pm$ 40                                  | -21.0                        | 1.4                          |
| Hofstaðir  | SUERC-8619 | Cow ( <i>Bos</i> sp.)                     | 1110 $\pm$ 30                                  | -20.9                        | 2.6                          |
| Hofstaðir  | SUERC-8623 | Cow ( <i>Bos</i> sp.)                     | 1130 $\pm$ 35                                  | -21.1                        | 0.1                          |
| Hofstaðir  | SUERC-8624 | Cow ( <i>Bos</i> sp.)                     | 1080 $\pm$ 35                                  | -21.2                        | -0.2                         |
| Hofstaðir  | SUERC-8625 | Marine shell ( <i>Mytilus edulis</i> )    | 1555 $\pm$ 35                                  | 1.9                          | —                            |
| Hofstaðir  | SUERC-8626 | Marine shell ( <i>Mytilus edulis</i> )    | 1585 $\pm$ 45                                  | 1.4                          | —                            |
| Hofstaðir  | SUERC-8627 | Marine shell ( <i>Mytilus edulis</i> )    | 1610 $\pm$ 35                                  | 1.8                          | —                            |
| Hofstaðir  | SUERC-8628 | Marine shell ( <i>Mytilus edulis</i> )    | 1600 $\pm$ 35                                  | 0.2                          | —                            |
| Hofstaðir  | SUERC-8355 | Pig ( <i>Sus</i> sp.)                     | 2250 $\pm$ 35                                  | -16.9                        | 7.4                          |
| Hrísheimar | SUERC-6431 | Cow ( <i>Bos</i> sp.)                     | 1220 $\pm$ 35                                  | -21.5                        | -0.4                         |
| Hrísheimar | SUERC-6432 | Cow ( <i>Bos</i> sp.)                     | 1200 $\pm$ 35                                  | -21.4                        | 1.5                          |
| Hrísheimar | SUERC-6433 | Cow ( <i>Bos</i> sp.)                     | 1120 $\pm$ 35                                  | -21.7                        | 0.0                          |
| Hrísheimar | SUERC-6437 | Cow ( <i>Bos</i> sp.)                     | 1120 $\pm$ 35                                  | -21.6                        | 1.8                          |
| Hrísheimar | SUERC-6438 | Marine shell ( <i>Mytilus edulis</i> )    | 1650 $\pm$ 40                                  | 0.8                          | —                            |
| Hrísheimar | SUERC-6439 | Marine shell ( <i>Mytilus edulis</i> )    | 1610 $\pm$ 35                                  | -0.3                         | —                            |
| Hrísheimar | SUERC-6440 | Marine shell ( <i>Mytilus edulis</i> )    | 1595 $\pm$ 35                                  | 0.3                          | —                            |
| Hrísheimar | SUERC-6441 | Marine shell ( <i>Mytilus edulis</i> )    | 1615 $\pm$ 35                                  | 0.6                          | —                            |
| Hrísheimar | SUERC-9045 | Arctic char ( <i>Salvelinus alpinus</i> ) | 2625 $\pm$ 40                                  | -15.2                        | 6.0                          |
| Hrísheimar | SUERC-9049 | Arctic char ( <i>Salvelinus alpinus</i> ) | 2505 $\pm$ 40                                  | -15.5                        | 5.7                          |
| Hrísheimar | SUERC-9050 | Arctic char ( <i>Salvelinus alpinus</i> ) | 2950 $\pm$ 35                                  | -15.0                        | 5.6                          |
| Hrísheimar | SUERC-9051 | Arctic char ( <i>Salvelinus alpinus</i> ) | 2670 $\pm$ 35                                  | -15.3                        | 5.8                          |
| Gásir      | SUERC-8629 | Cow ( <i>Bos</i> sp.)                     | 645 $\pm$ 40                                   | -21.8                        | 7.3                          |
| Gásir      | SUERC-8634 | Cow ( <i>Bos</i> sp.)                     | 595 $\pm$ 35                                   | -22.1                        | 2.2                          |
| Gásir      | SUERC-8635 | Cow ( <i>Bos</i> sp.)                     | 795 $\pm$ 35                                   | -22.1                        | 2.8                          |
| Gásir      | SUERC-8636 | Marine shell ( <i>Mya</i> sp.)            | 1200 $\pm$ 35                                  | 2.8                          | —                            |
| Gásir      | SUERC-8637 | Marine shell ( <i>Mya</i> sp.)            | 1175 $\pm$ 35                                  | 2.5                          | —                            |
| Gásir      | SUERC-8638 | Marine shell ( <i>Mya</i> sp.)            | 1165 $\pm$ 35                                  | 0.5                          | —                            |
| Gásir      | SUERC-8639 | Marine shell ( <i>Mya</i> sp.)            | 1305 $\pm$ 35                                  | 1.9                          | —                            |
| Gásir      | SUERC-8633 | Seal ( <i>Phoca vitulina</i> )            | 1115 $\pm$ 40                                  | -12.7                        | 14.4                         |

to terrestrial organisms consuming marine resources. For example, Neolithic sheep from the Orkney Isles in Scotland that fed on seaweed give bioapatite  $\delta^{13}\text{C}$  values as high as  $-5.7\text{‰}$  (Balasse et al. 2005), reflecting the  $\delta^{13}\text{C}$  of the seaweed consumed, which was measured at  $-18.5$  to  $-13.1\text{‰}$ . These values for seaweed are significantly heavier than terrestrial ( $\text{C}_3$ ) plants, which have a mean value of  $-27\text{‰}$  (Raven et al. 2002). The  $\delta^{15}\text{N}$  value of bone collagen increases with each successive trophic level above that of the primary producer by  $1.3$ – $5.3\text{‰}$ , 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  $\delta^{15}\text{N}$  of bone collagen from terrestrial animals consuming these resources is often enriched (Schoeninger and DeNiro 1984; Bonsall et al. 1997). Therefore, the  $\delta^{15}\text{N}$  values of aquatic organisms such as fish (often  $>12\text{‰}$ ) are usually high relative to that of primary terrestrial consumers such as cattle (about  $4$ – $6\text{‰}$ ) (DeNiro 1985; Bocherens et al. 1991; Dufour et al. 1999; Katzenberg and Weber 1999). To investigate the effect of a variety of dietary sources upon isotopic composition, we analy-

zed a domestic pig (*Sus* sp.) bone from one of the sites in Mývatnssveit (Hofstaðir). This species is omnivorous and may have been fed on a diet that included food scraps containing marine and fresh-water material. If this were so, the mixed diet should be reflected in the stable isotopic composition of the bone and in a  $^{14}\text{C}$  age with some evidence of a reservoir age.

## METHODOLOGY

Samples were taken from 2 archaeological sites in Mývatnssveit, Hofstaðir ( $65^{\circ}61'N$ ,  $-17^{\circ}16'W$ ) and Hrísheimar ( $65^{\circ}52'N$ ,  $-17^{\circ}10'W$ ), and 1 site on the north Icelandic coast, Gásir ( $65^{\circ}78'N$ ,  $-18^{\circ}16'W$ ) (see Figure 1). Extensive excavations have shown that Hofstaðir was a large, high-status farm; Hrísheimar was a smaller farmstead involved in specialized iron working; and Gásir a later coastal trading center. From tephrochronology and previous  $^{14}\text{C}$  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  $^{14}\text{C}$  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, while 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 4 subsamples, was used for measurement. The 2 further samples measured were the harbor seal (*Phoca vitulina*) bone from Gásir and the domestic pig (*Sus* sp.) bone from Hrísheimar.

Pretreatment of the bone samples followed a modified Longin (1971) procedure to extract collagen for  $^{14}\text{C}$  measurement, while pretreatment of the mollusk shells involved a 20% removal of the outer shell surface by etching in 1M HCl (Ascough et al. 2005).  $\text{CO}_2$  was obtained from the bone collagen samples by combustion in sealed quartz tubes (Vandeputte et al. 1996). For marine mollusk shell samples, a secondary pretreatment consisting of a further 20% removal of the shell surface was performed in a precleaned Pyrex<sup>®</sup> hydrolysis unit. Finally,  $\text{CO}_2$  was evolved by acid hydrolysis of the shell under vacuum. A 2-mL subsample of  $\text{CO}_2$  was converted to graphite by the method of Slota et al. (1987). Accelerator mass spectrometry (AMS) measurements were made using the SUERC 5MV terminal voltage spectrometer.  $\delta^{13}\text{C}$  measurements were made using a VG SIRA 10 isotope ratio mass spectrometer with NBS 22 (oil) and NBS 19 (marble) employed as standards.  $\delta^{15}\text{N}$  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 analyzer. 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.  $\delta^{13}\text{C}$  measurements were also generated by this technique, although of lower precision than the VG 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  $^{14}\text{C}$  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 1 material type with indistinguishable  $^{14}\text{C}$  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 fresh-

water sample  $^{14}\text{C}$  ages was statistically assessed using a  $\chi^2$  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  $\Delta\text{R}$  values.

The  $\Delta\text{R}$  calculation followed the procedure described in Ascough et al. (2006), where a terrestrial  $^{14}\text{C}$  age  $\pm 1\sigma$  was converted to an upper and lower global average modeled marine age using an interpolation of the IntCal04 and Marine04  $^{14}\text{C}$  calibration data sets (Reimer et al. 2004; Hughen et al. 2004).  $\Delta\text{R}$  was then the difference between the midpoint of the modeled age range and the measured  $^{14}\text{C}$  age of the corresponding marine sample. A value was calculated for each possible pairing of terrestrial and marine  $^{14}\text{C}$  ages and the distribution was summarized 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  $\chi^2$  tests. The weighted mean terrestrial age BP was converted to a calibrated age range using the IntCal04 atmospheric data set (Reimer et al. 2004) and the OxCal v 3.10 calibration program (Bronk Ramsey 1995, 2001).

## RESULTS

The average  $\delta^{13}\text{C}$  values for the cattle bones are  $-21.1\text{‰}$ ,  $-21.6\text{‰}$ , and  $-22.0\text{‰}$  for Hofstaðir, Hrísheimar, and Gásir, respectively. These are comparable to the  $-22\text{‰}$  value predicted for herbivores consuming a 100%  $\text{C}_3$  plant diet (van der Merwe 1989) and confirm that the  $^{14}\text{C}$  measurements of these samples do not reflect any component other than the terrestrial biosphere. With 1 exception (SUERC-8629;  $7.3\text{‰}$ , which requires re-analysis for confirmation), the  $\delta^{15}\text{N}$  values of the cattle bones show a total variability of  $3.2\text{‰}$ , around an average of  $1.2\text{‰}$ . The specific  $\delta^{15}\text{N}$  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  $\delta^{15}\text{N}$  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  $\delta^{15}\text{N}$  measurements may reflect lower values for Icelandic plants than in other regions. Low  $\delta^{15}\text{N}$  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  $\delta^{15}\text{N}$  values, with an overall range down to  $-12\text{‰}$  for terrestrial plants. Such low  $\delta^{15}\text{N}$  values may then be transferred to the bones of grazing herbivores. In contrast, the pig bone (SUERC-8355)  $\delta^{15}\text{N}$  is measured at  $7.4\text{‰}$  and  $\delta^{13}\text{C}$  at  $-16.9\text{‰}$ , 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  $^{14}\text{C}$  age of the pig is  $1142 \pm 39$   $^{14}\text{C}$  yr older than the weighted mean age ( $1108 \pm 17$   $^{14}\text{C}$  yr) of 4 statistically indistinguishable ( $T = 1.04$ ; [ $\chi^2_{:0.05} = 7.81$ ]) cattle bones from the same, sealed context, which is therefore likely to be the result of a diet that included material influenced by a  $^{14}\text{C}$  reservoir effect. The  $\delta^{13}\text{C}$  of the seal bone falls within the range of  $-12.3 \pm 1.3\text{‰}$  for average bone collagen values for seals from various global locations (Richards and Hedges 1999).

On the basis of the  $\chi^2$  test, the groups of marine and terrestrial measurements from Hofstaðir and Hrísheimar are internally consistent (Table 3), while at Gásir, 1 terrestrial measurement (SUERC-

8635) and 1 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 agreed with the 3 consistent shell measurements, where the test statistic for this group of 4 samples was  $T = 2.63$ ; ( $\chi^2_{:0.05} = 7.81$ ). 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  $^{14}\text{C}$  ages, it appears that the food consumed by the seal may have had a homogeneous  $\Delta\text{R}$  value that was representative of the north Icelandic surface ocean  $\Delta\text{R}$  for this time period. However, as this can only be confirmed by further reproducible measurements, the value of  $\Delta\text{R}$  for Gásir in this paper is based on the 2 statistically indistinguishable terrestrial measurements and 3 statistically indistinguishable marine (mollusk shell) measurements.

Table 3  $\chi^2$  test statistics for terrestrial and marine sample measurements.

| Site       | Terrestrial sample $\chi^2$ test statistic | Marine sample $\chi^2$ test statistic     |
|------------|--|---|
| Hofstaðir  | $T = 1.04$ ; ( $\chi^2_{:0.05} = 7.81$ )   | $T = 1.41$ ; ( $\chi^2_{:0.05} = 7.81$ )  |
| Hrísheimar | $T = 6.78$ ; ( $\chi^2_{:0.05} = 7.81$ )   | $T = 1.11$ ; ( $\chi^2_{:0.05} = 7.81$ )  |
| Gásir      | $T = 17.46$ ; ( $\chi^2_{:0.05} = 7.81$ )  | $T = 10.10$ ; ( $\chi^2_{:0.05} = 7.81$ ) |

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

| Original measurement |                                   |                       | Repeat measurement |                                   |                       |               |
|----------------------|-----------------------------------|-----------------------|--------------------|-----------------------------------|-----------------------|---------------|
| Sample ID            | $^{14}\text{C}$ age (1 $\sigma$ ) | $\delta^{13}\text{C}$ | Sample ID          | $^{14}\text{C}$ age (1 $\sigma$ ) | $\delta^{13}\text{C}$ | Weighted mean |
| SUERC-8629           | 645 $\pm$ 40                      | -21.8                 | SUERC-9042         | 645 $\pm$ 35                      | -21.9                 | 645 $\pm$ 26  |
| SUERC-8634           | 595 $\pm$ 35                      | -22.1                 | SUERC-9064         | 590 $\pm$ 40                      | -21.4                 | 593 $\pm$ 26  |
| SUERC-8635           | 795 $\pm$ 35                      | -22.1                 | SUERC-9065         | 790 $\pm$ 35                      | -22.3                 | 793 $\pm$ 25  |
| SUERC-8633           | 1115 $\pm$ 40 <sup>a</sup>        | -12.7                 | SUERC-9043         | 1145 $\pm$ 35                     | -12.7                 | 1132 $\pm$ 26 |

<sup>a</sup>Seal bone.

The consistency of multiple  $^{14}\text{C}$  measurements from deposits at Hofstaðir and Hrísheimar gives confidence to the fact that these are reliable assessments of the surface ocean  $^{14}\text{C}$  during this period. The calibrated age range for the terrestrial  $^{14}\text{C}$  dates from Hrísheimar was modeled using the terrestrial weighted mean in combination with the landnám tephra that predated the archaeological remains using the methodology outlined by Church et al. (these proceedings). The higher variability in measurements at Gásir, identified in the  $\chi^2$  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  $\Delta\text{R}$  that had an improved likelihood of accuracy (see Table 5). The calibrated age range for Hofstaðir (95 yr at 2  $\sigma$ ) overlaps with that of Hrísheimar (100 yr at 2  $\sigma$ ). 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 yr from that of Gásir, where the deposit from which material was obtained for  $^{14}\text{C}$  measurement relates to the Medieval period. The  $\Delta\text{R}$  values calculated for the 3 sites are comparable ( $T = 2.31$ ; [ $\chi^2_{:0.05} = 5.99$ ]), and give an overall weighted mean  $\Delta\text{R}$  of  $111 \pm 10^{14}\text{C}$  yr.

Table 5 Terrestrial ages and  $\Delta\text{R}$  values based upon measurements of samples from 3 north Icelandic sites.

| Site   | Hofstaðir     | Hrísheimar    | Gásir        |
|--|---------------|---------------|--------------|
| Terrestrial weighted mean $^{14}\text{C}$ age        | 1108 $\pm$ 17 | 1165 $\pm$ 26 | 645 $\pm$ 26 |
| Calibrated age range AD                              | 890–985       | 868–968       | 1280–1400    |
| Calculated $\Delta\text{R}$ ( $^{14}\text{C}$ yr BP) | 114 $\pm$ 14  | 97 $\pm$ 15   | 144 $\pm$ 28 |

The  $^{14}\text{C}$  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  $\pm$  53 to 1830  $\pm$  49  $^{14}\text{C}$  yr. The  $\delta^{13}\text{C}$  values of the samples ranged between  $-15.0$  and  $-15.5\%$ . The  $\delta^{15}\text{N}$  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  $^{14}\text{C}$  reservoir effects affect some archaeological sample types found in Mývatnssveit, and provide an assessment of  $\Delta\text{R}$  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  $^{14}\text{C}$  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  $\Delta\text{R}$  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  $\Delta\text{R}$  for Iceland. The additional uncertainty that is introduced over the most appropriate  $\Delta\text{R}$  correction means that the most reliable archaeological and paleoenvironmental chronologies in Mývatnssveit will be based on material that reflects only the terrestrial  $^{14}\text{C}$  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 2 values for periods AD 868–985 (Hofstaðir and Hrísheimar:  $\Delta\text{R} = 106 \pm 10$   $^{14}\text{C}$  yr) and the value for AD 1280–1400 (Gásir:  $\Delta\text{R} = 144 \pm 28$   $^{14}\text{C}$  yr) gives an overall weighted mean  $\Delta\text{R}$  of  $111 \pm 10$   $^{14}\text{C}$  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  $\Delta\text{R} = 106 \pm 89$   $^{14}\text{C}$  yr.

Although reservoir effects create considerable problems for accurate comparison of  $^{14}\text{C}$  ages of samples from different reservoirs, they can provide valuable information on climatic and oceanic regimes, e.g. ocean ventilation rates (Broecker et al. 2004). The  $\Delta\text{R}$  values presented in this paper can therefore be considered in the context of other assessments for the Norse period. A value of  $\Delta\text{R} = 64 \pm 13$   $^{14}\text{C}$  yr is available for the Faroe Isles (61°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 4  $\Delta\text{R}$  values (Icelandic and Faroes)  $T = 11.02$  ( $\chi^2_{:0.05} = 7.81$ ). Further south in the

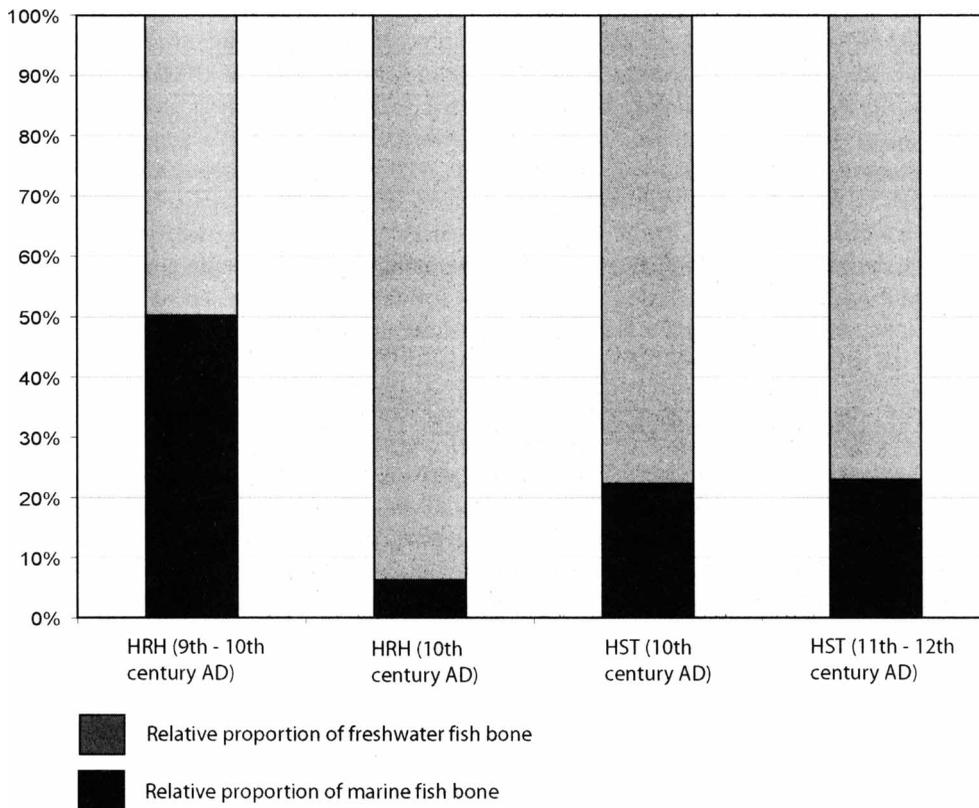


Figure 2 Relative proportions of marine and freshwater fish from midden deposits during 2 different time periods at Hofstaðir (HST) and Hrisheimar (HRH). Proportions remain approximately equal at (HST), while a higher proportion of freshwater fish were identified in the later phase at HRH (from McGovern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

North Atlantic, during a similar period to the Faroes assessment,  $\Delta R$  values are lower than the north Icelandic values by about 200–240  $^{14}\text{C}$  yr. Here, values for the Western Isles of Scotland ( $59^{\circ}21'\text{N}$ ) at AD 1020–1158 and the west coast of Ireland ( $53^{\circ}32'\text{N}$ ) at AD 993–1156 are  $\Delta R = -96 \pm 16$   $^{14}\text{C}$  yr and  $\Delta R = -142 \pm 16$   $^{14}\text{C}$  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  $^{14}\text{C}$  activity with higher  $\Delta R$  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  $^{14}\text{C}$  relative to the Atlantic Current.

While an appropriate  $\Delta R$  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 2 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  $^{14}\text{C}$  in bone collagen, namely freshwater resources. The measurement made on pig bone highlights the problem. The apparent age of the pig bone ( $2250 \pm 35$  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 sam-

ples in the same deposit. The  $^{14}\text{C}$  depletion between pig and cow bone, equivalent to  $\sim 1100$   $^{14}\text{C}$  yr, could not therefore be produced even if the pig had consumed a diet of 100% marine material. The pig  $\delta^{13}\text{C}$  value ( $-16.9\text{‰}$ ) is enriched relative to animals existing solely within the terrestrial food web ( $\delta^{13}\text{C}$  = about  $-22\text{‰}$ ), and the higher  $\delta^{15}\text{N}$  value ( $7.4\text{‰}$ ) indicates a mixed diet. Both the  $^{14}\text{C}$  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  $^{14}\text{C}$ .

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  $^{14}\text{C}$  activity in the Mývatnssveit freshwater ecosystem is strongly depleted as a result of the low  $^{14}\text{C}$  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  $\delta^{13}\text{C}$  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 about 1300–1700  $^{14}\text{C}$  yr, and this variability may reflect differences in feeding behavior 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 behavioral differences including feeding, and whether a particular individual char feeds predominantly in the benthic or pelagic zone is related to its particular morphological form (Anderson and Persson 2005). Different char food resources within the lake may therefore have variable levels of  $^{14}\text{C}$  activity, depending on factors such as the transfer of atmospheric  $\text{CO}_2$  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  $^{14}\text{C}$  age of individual specimens in relation to variations in their stable isotope values.

The large FRE in Mývatnssveit may result in  $^{14}\text{C}$  ages that are too old, by potentially  $>1000$   $^{14}\text{C}$  yr in certain terrestrial mammals (including humans) relative to the coeval atmosphere. In previous studies, it has been possible to correct the  $^{14}\text{C}$  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  $^{14}\text{C}$  age, e.g. of the order of 2000 yr BP for samples from Norse deposits. However, identifying the source of a  $^{14}\text{C}$  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  $\sim 400$   $^{14}\text{C}$  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, e.g. from 3600 to  $\sim 18,000$   $^{14}\text{C}$  yr in Antarctic lakes (Hall and Henderson 2001), and of  $340 \pm 20$   $^{14}\text{C}$  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  $^{14}\text{C}$  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 (Ármansson et al. 2000); however, it is not clear to what extent these affect the water  $^{14}\text{C}$  activity.

The data presented in this paper have important implications for the use of  $^{14}\text{C}$  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  $^{14}\text{C}$  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  $^{14}\text{C}$  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  $\delta^{13}\text{C}$  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  $^{14}\text{C}$  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 paleoenvironmental chronologies in Mývatnssveit.

## CONCLUSION

We have made the first assessment of marine and freshwater  $^{14}\text{C}$  reservoir effects apparent in samples from Mývatnssveit, north Iceland, and have assessed the  $\Delta R$  for the north Icelandic coast for the periods AD 868–985 and AD 1280–1400. This has produced 3 new  $\Delta R$  values that form part of a north-south gradient in surface ocean  $^{14}\text{C}$  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  $\Delta R$  values presented here may be used for calibration of  $^{14}\text{C}$  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  $^{14}\text{C}$  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  $\sim 1300$   $^{14}\text{C}$  yr; however, this varies up to  $\sim 1700$   $^{14}\text{C}$  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 the fact that the most reliable samples for construction of archaeological  $^{14}\text{C}$  chronologies in Mývatnssveit and elsewhere is material containing solely terrestrial-derived carbon. This can be identified using stable isotopic analyses performed in conjunction with  $^{14}\text{C}$  measurements.

## ACKNOWLEDGMENTS

This work was supported by funding from the Leverhulme Trust ('Landscape circum landnám' Grant), the National Science Foundation of America, and the Royal Scottish Geographical Society. The authors gratefully acknowledge the excavators of the archaeological sites from which samples were obtained and the assistance of the SUERC Radiocarbon and AMS laboratory personnel.

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