Variability in North Atlantic marine radiocarbon reservoir effects at c.1000 AD

Ascough, P. L.[1,2*], Cook, G. T.[2], Church, M. J.[1], Dugmore, A. J.[1], Arge, S. V.[3] and McGovern, T. H.[4]

[1]Institute of Geography, School of GeoScience, University of Edinburgh, Edinburgh EH8 9XP, UK.

[2]Scottish Universities Environmental Research Centre, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 OQF, UK.

[3]Føroya Fornminnissavn, Tórshavn, The Faroe Islands

[4]Hunter Bioarchaeology Laboratory, Hunter College CUNY, NYC 10021 USA

[*]Author for correspondence (email: s9742453@sms.ed.ac.uk, tel: 01355 2233322).

Abstract

^{14}C age measurements made on samples from three archaeological sites located on North Atlantic coasts were used to investigate the marine reservoir effect (MRE) at c.1000 AD. This is an important period within human cultural and paleoenvironmental research as it is a time when Norse expansion to the North Atlantic islands occurred, during what appears to be a period of ameliorating climatic conditions. This makes improved chronological precision and accuracy at this time highly desirable. The data indicate a potential latitudinal variation in MRE at c.1000 AD from a ΔR of –142 ± 16 ^{14}C yr at Omey Island (53^{0} 32' N) to 64 ± 13 ^{14}C yr at Undir Junkarinsfløtti (61^{0} 51' N). The results are compared with modern assessments of MRE values within the context of oceanographic and climatic regimes that provide a possible driving mechanism for spatial and temporal variation in MRE.

Keywords: North Atlantic, radiocarbon, marine reservoir effect, ΔR, Norse archaeology

Introduction

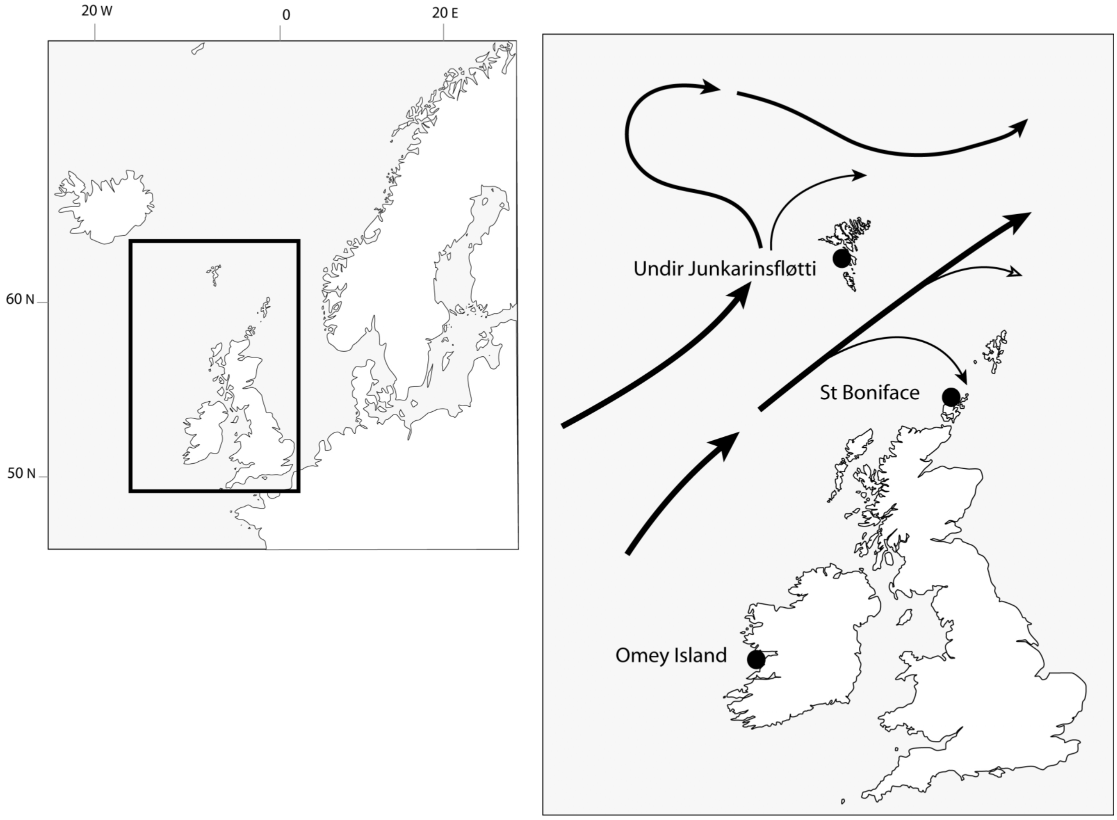
The North Atlantic is a key region in paleoenvironmental studies as it contains oceanographic and climatic systems that are globally significant and that vary in rate and intensity on extended timescales (Broecker *et al.,* 1985; Bond *et al.,* 1997). During the Holocene, the region is also very important for the study of interactions between human communities and the environment. Human-environment interactions in the North Atlantic islands have been subject to especially detailed examination during the period of Norse settlement in the pristine landscapes of Faroes, Iceland, Greenland and Labrador between c.850 and1100 AD (Edwards *et al*., 2004; Dugmore *et al*., 2005).

An understanding of the correlations between paleoenvironmental and archaeological processes within the North Atlantic, at times of significant change, such as the Norse colonizations, requires chronological data with a high level of precision and accuracy. This has led to the use of extensive radiocarbon (^{14}C) age measurements to form North Atlantic chronological frameworks. However, when samples for ^{14}C analysis contain marine derived carbon, the calculated ^{14}C age must be corrected for the marine reservoir effect (MRE). The high density of material containing marine derived carbon at archaeological and paleoenvironmental sites has introduced the need to understand and quantify the MRE (Ascough *et al*., 2004). The MRE is the ^{14}C age offset at any point in time between samples formed in the terrestrial biosphere (which is in equilibrium with the atmosphere) and the oceans (Stuiver *et al*., 1986). This variable offset exists because of the extended mean residence time of ^{14}C once transferred to the oceans, and in particular to the deep oceans. During this time, radioactive decay of ^{14}C atoms means that the deep oceans are depleted in ^{14}C relative to the coeval atmosphere and therefore, following the eventual return of deep waters to the surface, the surface oceans are also depleted, although to a lesser extent. ΔR is the offset of the ^{14}C age of the surface ocean at a particular geographic location from the global average MRE value (obtained by modelling ocean response to atmospheric ^{14}C variations), and is dependant upon specific oceanographic and climatic variables, which may also change through time (Stuiver *et al.*, 1986). ΔR is established by empirical measurement of relevant local samples, and a range of current assessments of ΔR exist for the North Atlantic region from a variety of studies (Stuiver *et al.,* 1998b; Stuiver and Braziunas, 1993; Reimer and Reimer, 2005).

At present, the available data suggest a significant geographic variability in North Atlantic ΔR, reflecting the distribution of water masses with varying ^{14}C content, however, there is a lack of comprehensive or standardised studies of spatial variability to address this phenomenon. A second consideration is the potential for temporal change in ΔR values, particularly at times of known cultural and environmental change when there is a particular requirement for high levels of chronological accuracy. This paper presents the results of ΔR assessments derived from comparisons of ^{14}C ages on marine and terrestrial archaeological material from three sites in the Faroe Islands, Orkney and Ireland (Figure 1).

Methodological approach

Figure 1



The three archaeological sites are located on island coastlines: Omey Island, off the west coast of Ireland (53^0 32' N Omey Island: O'Keeffe, 1994); Papa Westray in the Orkney Isles (59^0 21' N; St. Boniface: Lowe, 1999) and Sandoy in the Faroe Islands (61^0 51' N; Undir Junkarinsfløtti: Arge, 2001; Church *et al.*, forthcoming). These sites are situated within a zone that is highly sensitive to fluctuations in the surrounding climate and oceanography, therefore, the ^{14}C ages represented in marine organisms are likely to reflect significant changes in these factors. All three sites are exposed to the open North Atlantic Ocean, making them highly suitable for this study because marine material grown at each site will represent a ^{14}C activity that is not dictated by local carbon sources. These sources, found in enclosed or sheltered marine environments such as fjords, can potentially influence the extent to which calculated ΔR values at different sites are comparable. In these locations, the ^{14}C content of local surface waters is often significantly modified from that of open coastal locations due to a large scale (terrestrial) freshwater input that contains carbon derived from carbonate rocks (*eg*. limestone) or terrestrial organic detritus (Heier-Neilsen *et al*., 1995).

For each site, MRE and ΔR values were obtained using the paired sample approach (Ascough *et al*., 2004) in which ^{14}C measurements were made on coeval marine and terrestrial material from a single stratigraphic layer at recently excavated archaeological sites. At each of the three sites, samples were obtained from a midden layer that had been produced by successive dumping of domestic refuse by the site inhabitants. A selection protocol (cf. Ascough *et al*., 2004) was applied during sample selection to maximize the likelihood of contemporaneity of the sample groups. The suite of samples from each site consisted of four individual carbonised barley grains (*Hordeum sp.*) and four individual marine mollusc shells. The species of mollusc selected for measurement was the common limpet (*Patella sp.*), which has a typical lifespan of 5-10 years. Eight separate ^{14}C measurements were therefore produced for each site at the SUERC AMS facility. The measurements were normalised for natural isotopic fractionation to $\delta^{13}C = -25‰$ with respect to VPDB. Within each group of four terrestrial or four marine samples the coherence of the marine and terrestrial sample ages was established using a χ^2 test (cf. Ward and Wilson, 1978). The test assesses whether the internal variability of a group of measurements is consistent with the errors on the individual determinations. The test statistic (T) was compared with the critical value for 95% significance ($\chi^2_{:0.05}$) for the appropriate number of samples (N) in a tested group to determine whether the variability within the measurement groups exceeded what could occur by chance. The T statistic for a group of ^{14}C ages is calculated by:

$$T = \sum \frac{(t_i - t)^2}{\sigma_i^2}$$

Where: t = the weighted mean of the ^{14}C age group

t_i = the individual ^{14}C measurement

σ = the error on the individual measurement

Once it had been established that the ages of each group of samples were statistically indistinguishable at 95% confidence using the χ^2 test, MRE and ΔR values were determined for each site using all possible combinations of terrestrial and marine ages (16 values in total). Thereafter, weighted mean MRE and ΔR values were calculated for each site. The MRE is the age difference between the marine and terrestrial ^{14}C age. The associated error was calculated from the combination of the errors on both ages. ΔR was determined by converting the terrestrial ^{14}C ages ± 1σ to upper and lower 1σ modelled marine ^{14}C age bounds, using a linear interpolation of the Intcal98 atmospheric calibration data and Marine98 modelled marine ^{14}C ages (Stuiver *et al.*, 1993). ΔR was then the difference between the midpoint of the modelled marine ^{14}C age bounds and the measured marine ^{14}C age, with an associated error derived from the model age bounds and the error on the measured marine age (Reimer *et al.*, 2002). A calibrated age range for the samples at each site was obtained using the weighted mean terrestrial ^{14}C age and Calib 4.4 with the Intcal98 atmospheric calibration dataset (Stuiver and Reimer, 1993; Stuiver *et al.,* 1998).

Results

All ^{14}C age measurements and δ^{13}C results are presented in Table I. The terrestrial ages at each site are very similar (approx 1000 y BP), however, the marine ages vary between about 1230 y BP (Omey Island) and 1440 y BP (Undir Junkarinsfløtti). The δ^{13}C values for all samples agree well with published ranges for terrestrial plants and marine carbonates (cf. Aitken, 1990).

The critical value of T' (for 95% significance ($\chi^2_{:0.05}$)) for all groups of marine and terrestrial samples is 7.81. The results in Table II indicate that all T values were <7.81 and demonstrate that the ^{14}C measurements within each group can be legitimately combined in subsequent determination of MRE and ΔR. The terrestrial samples from all three sites lie within the same calibrated 2σ AD range (although we cannot comment on whether they are absolutely contemporary) showing that the MRE and ΔR values obtained using these samples apply to the period from c.990 - 1150 AD, which is consistent with the period of Norse cultural influence within the region (Barrett *et al.*, 2000). However, there is significant variation in the calculated MRE values (T'=87.79; $\chi^2_{:0.05}$ = 5.99) and ΔR values (T'=116.89; $\chi^2_{2:0.05}$ = 5.99), between the three sites, indicating that a single MRE offset did not apply across the study area during this period.

Site	Sample ID	Material	Age BP ± 1σ	d 13C ‰
Omey Island	SUERC-3226	Hordeum sp.	970 ± 35	-24.3
	SUERC-1073		945 ± 45	-23.6
	SUERC-1074		1050 ± 35	-22.5
	SUERC-1075		980 ± 45	-24.6
	SUERC-1076	Patella vulgata	1225 ± 35	0.8
	SUERC-1077		1220 ± 40	1.9
	SUERC-1078		1285 ± 35	1.2
	SUERC-1079		1170 ± 50	0.9
St Boniface	SUERC-129	Hordeum sp.	965 ± 40	-25.0
	SUERC-130		995 ± 40	-23.9
	SUERC-131		935 ± 40	-24.8
	SUERC-132		935 ± 40	-23.5
	SUERC-133	Patella vulgata	1240 ± 40	0.3
	SUERC-134		1270 ± 40	1.2
	SUERC-135		1260 ± 40	0.7
	SUERC-136		1250 ± 40	0.4
Undir Junkarinsfløtti	SUERC-3400	Hordeum sp.	1000 ± 40	-23.9
	SUERC-3401		980 ± 40	-26.8
	SUERC-3402		940 ± 45	-26.3
	SUERC-3403		995 ± 35	-24.0
	SUERC-3404	Patella vulgata	1410 ± 35	1.5
	SUERC-3407		1460 ± 40	1.6
	SUERC-3408		1445 ± 35	1.4
	SUERC-3409		1440 ± 35	1.3

Table I: ^{14}C ages and δ^{13}C results for marine and terrestrial samples from the 3 sites under study

Site	Omey Island	St Boniface	Undir Junkarinsfløtti
T-statistic for terrestrial samples	4.3; $x^2:_{0.05} = 7.81$	1.55; $x^2:_{0.05} = 7.81$	1.21; $x^2:_{0.05} = 7.81$
Weighted mean terrestrial age (± 1σ)	992± 23	958± 20	982± 20
Calc. 2σ range	AD 993-1156	AD 1020-1158	AD 1000-1156
T-statistic for marine samples	3.95; $x^2:_{0.05} = 7.81$	0.31; $x^2:_{0.05} = 7.81$	0.98; $x^2:_{0.05} = 7.81$
Weighted mean marine age (± 1σ)	1234± 32	1255± 20	1437± 18
MRE (± 1σ)	252± 29	298± 14	457± 13
ΔR (± 1σ)	-142± 16	-96± 16	+64± 13

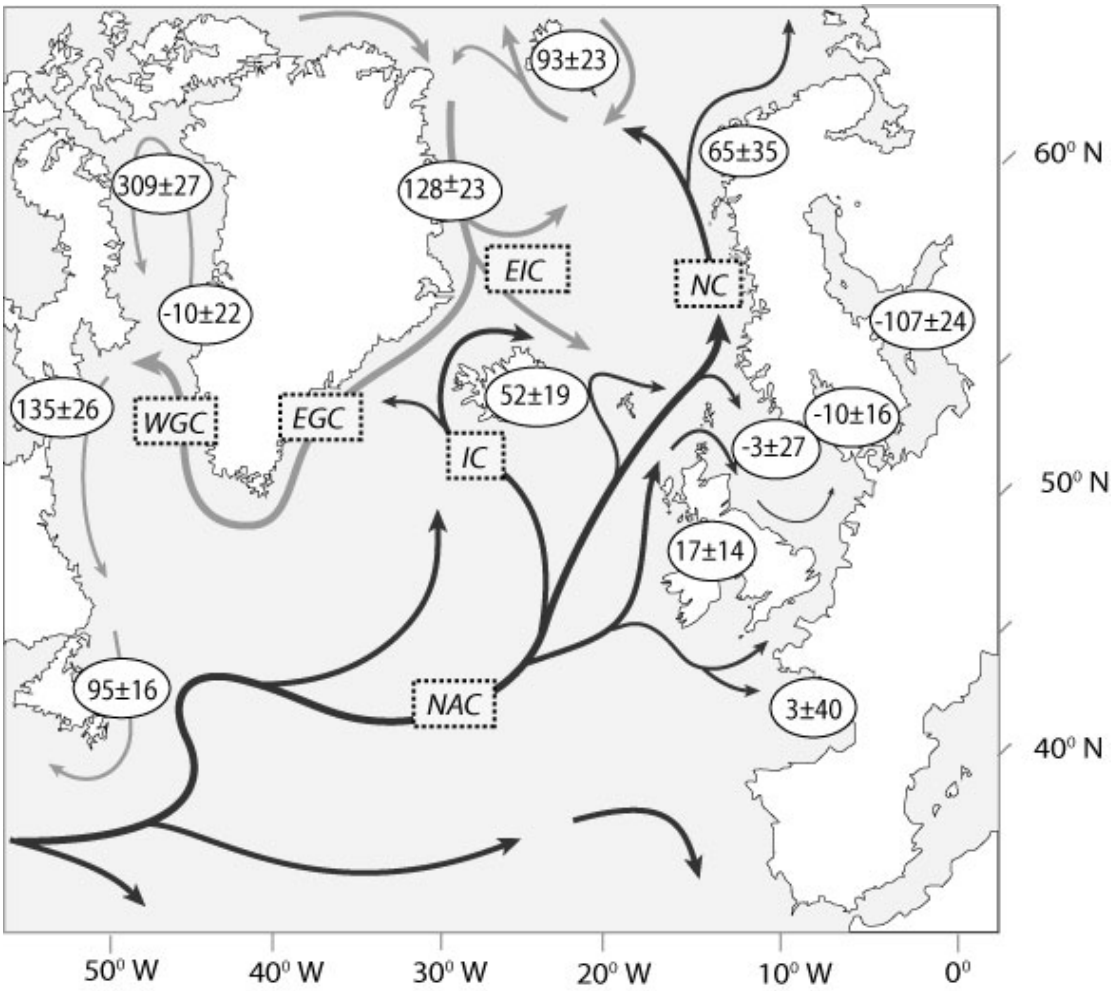
Table II: *T*-statistics, weighted mean terrestrial and marine ^{14}C ages and derived MRE and ΔR values for each site

Discussion

The dataset presented in this paper is indicative of spatial variability in the ^{14}C content of North Atlantic surface waters at c.1000 AD that is significant with respect to the precision of the ^{14}C method. While little other MRE data are available for that period, assessments of modern (pre-bomb) MRE data are available for the North Atlantic, based upon a large number of studies that measured the ^{14}C age of known-age, pre-nuclear marine samples. Regional mean ΔR values have been calculated from these data (Reimer and Reimer, 2005) and presently available assessments of the MRE for the study area include values for the UK that are based upon known-age marine shells from the English and Scottish coasts (Harkness, 1983). These data demonstrate a regional MRE of 405 ^{14}C yrs and a pre-industrial ΔR value of 17 ± 14 ^{14}C yrs (Reimer and Reimer, 2005). Available results from the Faroe Isles are limited to an MRE value of 370 ± 99 ^{14}C yrs and ΔR of 19 ± 99 ^{14}C yrs, based upon measurement of known age mussel shells (*Mytilus edulis*) from Sörvåg (Krog and Tauber, 1974). This is included in the calculation of a regional mean ΔR value for the Faroes and Iceland for modern pre-bomb samples of 52 ± 19 ^{14}C yrs (Reimer and Reimer, 2005).

The distribution of ^{14}C in surface waters is related to the relative strength and flow pattern of various water masses, meaning oceanographic variables significantly influence the North Atlantic MRE. Modern surface circulation within the North Atlantic is characterised by the northward flow of warm, saline North Atlantic Current (NAC) waters, and the southward flow of cold Arctic waters (Figure 2). Due to extended periods of gaseous exchange with atmospheric CO_2 during northward transport, NAC waters have relatively high ^{14}C content (Campin *et al.,* 1999). To the south of Iceland, a branch of the NAC forms the Irminger Current (IC), which flows in a clockwise direction around Iceland. Further to the east, the NAC branches around the western coast of the British Isles. Ocean salinities off the west coast of Ireland indicate a mainly Atlantic water origin (OSPAR, 2000), and this coastal water then flows up the west coast of Scotland, reinforced by lower-salinity water from the major west coast Firths (McKay *et al.*, 1996). A further branch of the NAC flows around the Faroe Isles, and to the east the NAC forms the Norwegian current (NC), which flows northwards up the Norwegian coast. After passing the UK and Faroe Isles the surface waters of the NAC are cooled in the Nordic Seas, west of Norway and north of Iceland. Here, surface salinity (already elevated by evaporation during northward transport), is increased by brine rejection as sea ice forms at high latitudes. These effects mean that the density of surface waters is increased, and surface NAC waters sink to form North Atlantic deep water (NADW), which then flows southwards at depth. The formation of NADW releases a large amount of latent heat that plays a major role in regulation of both North Atlantic and global climates (Broecker *et al.,* 1985; Lehman and Keigwin, 1992; Humlum, 1998). Southward flowing surface waters in the North Atlantic are dominated by the East Greenland Current (EGC), which flows down from the Arctic. The East Iceland Current (EIC) is formed from components of the EGC water, and flows eastwards along the north Icelandic coast. Upon leaving the coast the EIC forms the Iceland-Faeroe Front as it flows eastward along the Iceland-Faroe Ridge (Pistek and Johnson 1992).

The availability of modern (pre-bomb) data for the wider North Atlantic region enables an examination of spatial variation in MRE and ΔR values that may be correlated with the known oceanographic variables discussed above. The offset between atmospheric and surface ocean ^{14}C content appears to show a general northward increase (Figure 2). Lower values of MRE (and therefore of ΔR) are recorded in surface ocean areas that are more strongly influenced by the North Atlantic Current (NAC), due to the higher ^{14}C content of surface waters. This contrasts with areas under the influence of Arctic-derived surface water masses such as the east coast of Greenland, where higher MRE values are associated with the Arctic-dominated waters of the EGC (Hjort *et al.*, 1973). This results in a gradient of apparent surface-water ages across the interface between Atlantic and Arctic water known as the Polar Front that reflects climatic and oceanographic gradients (Eiríksson *et al.*, 2004). The northward trend of increasing MRE is reflected in modern ΔR values along the Norwegian coast, with a regional mean ΔR of -3 ± 27 ^{14}C yr for South Norway and the North Sea that increases to ΔR = 65 ± 35 ^{14}C yr for northern Norwegian waters (Mangerud and Gulliksen, 1975; Olsson, 1980; Reimer and Reimer, 2005). Further north, the increasing influence of Arctic water is also apparent in the west Spitsbergen coastal water (a mix of Arctic and Atlantic water) that displays a MRE of 510 ± 30 ^{14}C yr (Mangerud and Gulliksen, 1975) and a ΔR of 93 ± 23 ^{14}C yr (Reimer, and Reimer, 2005).



Ascough *et al.* fig. 2

Figure 2

The Polar Front is one of a series of frontal systems in the North Atlantic that mark strong ocean and atmosphere gradients and result in sensitive oceanographic boundaries that respond to shifts in climatic conditions. The Polar Front is presently located north of Iceland, and its relative position over time is strongly correlated with records of climatic and oceanographic changes (Ruddiman and McIntyre, 1981; Dansgaard *et. al.,* 1993; Haflidason *et. al.,* 1995). Significant shifts in oceanographic and climatic variables have been identified within both the wider North Atlantic and the study area during the Holocene, including the location and intensity of surface and deep-water currents. During colder phases, features such as increased sea-ice cover may surround areas including the Faroes as a body of cold polar waters extends from the East Iceland Current towards the Faroes from the north (Moros *et al.,* 1997; Humlum, 1998; Kuijpers *et al.,* 1998; 2002). Variability in the relative influence of Atlantic and Arctic waters around Iceland has also been identified over short timescales (Knudsen *et al*., 2004), and a relationship has been identified between variability in the influence of Arctic and Atlantic water masses and MRE values on the North Iceland shelf over the past c.4000 years (Knudsen and Eiríksson, 2002; Larsen *et al*., 2002; Eiríksson *et al*., 2004). Here, higher MRE values are associated with periods of increased influence of Arctic waters (Larsen *et al*., 2002), whereas the period between c. 750 and c. 1150 cal AD is characterised by dominance of Atlantic waters and a lower offset between atmospheric and ocean surface apparent ages.

The data presented in this paper indicate that a spatial trend in MRE was also present at c.1000 AD, with an overall increase of c.200 ^{14}C years in ΔR between the west coast of Ireland and the Faroe Islands. Such a trend could imply that the relative differences in oceanic and climatic regimes between the geographic locations are comparable to those that operate today. This interpretation has important implications for the study of past climate and oceanographic variables in the North Atlantic, during the phase of Norse expansion within the region. The cultural developments at this time are often linked with a set of favourable environmental conditions that permitted the settlement and exploitation of a wide range of North Atlantic settings, including the initial settlement in the Faroes, Iceland and Greenland (cf. Jones, 1986). It is possible that these conditions were comparable to the present climatic situation, and that the subsequent retraction of settlements, such as the termination of the Greenland and Labrador settlements, was linked to deterioration in environmental conditions (cf. Davis *et al*., 1988; McGovern, 1991).

In light of this, an assessment of any spatial trends in North Atlantic MRE is desirable. Values for the modern North Atlantic are not the result of a standardized study but of individual investigations over an extended time period, and are mostly based upon ^{14}C measurements of marine material for which the calendar time of death is known. The temporal period for which such material is available is restricted and there is a limited range of data currently available that examines characteristics of the North Atlantic MRE over Holocene timescales. Previous investigation of temporal variation in MRE for the study area includes assessments of $\Delta R = -79 \pm 17$ ^{14}C yr for the Outer Hebrides of Scotland between c.400 BC – 100 AD (Ascough *et al.*, 2004). This result is comparable to the assessment of -71 ± 58 ^{14}C yr made for the Orkney Isles at c.1000 AD, and may represent a deviation in both periods from values derived from modern samples. The lack of available data make it difficult to assign confidently any temporal trends in MRE values across the area, however, it is hoped that future data will enhance the understanding of how variable both spatially and temporally the North Atlantic MRE is over longer timescales.

A greater understanding of the MRE enables an improved level of accuracy for ^{14}C measurements using sample material that contains marine-derived carbon, and the incorporation of such data within chronological frameworks. This is of particular importance in the North Atlantic during the Norse period because of the extensive occupation of coastal settlements during a period of economic change. These changes often involved an increased dependence upon marine resources, both for subsistence and commercial trade (Barrett *et al.* 2000; McGovern *et al.*, 2001; Perdikaris and McGovern, in press). In addition, precise ^{14}C dating of sites from this temporal period is often hindered by the existence of a plateau in the atmospheric calibration curve that limits the calendrical precision that can be attained with measurements of terrestrial material (Hannon *et al.*, 2001). One possibility is that measurement of marine material may provide the opportunity to achieve higher levels of precision on calibrated ages. This is due to the smoothed nature of the marine calibration curve, and shortened plateau length for a specific calendar interval. However this effect would only be of use if a high level of accuracy and precision could be achieved upon ^{14}C measurement of marine material by the application of a relevant and precise ΔR value, prior to calibration.

Conclusion

A new dataset for the MRE in the North Atlantic at c.1000 AD is presented that is indicative of significant spatial variation in values at this time. The dataset has been produced using a standardised methodology and multiple samples to achieve a high level of precision and accuracy. The spatial trend in MRE shows consistency with known modern variations in relative oceanographic regime across the area and has implications for both archaeological and paleoenvironmental chronologies in the North Atlantic c.1000 AD.

Acknowledgments

The data were produced with funding from Historic Scotland, the Leverhulme Trust ('Landscapes circum landnám' grant), the Moray Endowment fund and the Carnegie

Trust. The authors gratefully acknowledge Patrick Ashmore for many useful discussions, Dr. Christoper Lowe for providing sample material from St. Boniface, Dr. Emily Murray for material from Omey Island, and Paula Reimer for ΔR data and FORTRAN coding. We gratefully acknowledge the invaluable help and support of the staff of the SUERC AMS laboratory for ^{14}C measurements, and also the helpful and constructive comments of two reviewers, Dr. W. Austin and Prof. C. Caseldine.

References

Arge, S. V. 2001: Forn búsetning heima á Sandi. *FRØÐI* 2, 5-13.

Ascough, P. L., Cook, G. T., Dugmore, A. J., Barber, J., Higney, E. and **Scott, E. M**. 2004: Holocene variations in the Scottish marine radiocarbon reservoir effect. *Radiocarbon* 46, 611-620.

Ascough, P., Cook, G., and Dugmore, A. (in press): Methodological approaches to determining the marine radiocarbon reservoir effect. *Progress in Physical Geography*

Aitken, M. J. 1990. Science-based dating in archaeology. Longman Archaeology series. Longman Group

Barrett, J. H., Beukens, R. P. and **Brothwell, D. R**. 2000: Radiocarbon dating and marine reservoir correction of Viking Age Christian burials from Orkney, *Antiquity* 74, 537-43

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P, deMenocal, P., Priore, P., Cullen, H., Hajdas., and **Bonani, G**. 1997: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science*, 278

Broecker, W.S., D.M. Peteet, and D. Rind 1985: Does the ocean-atmosphere system have more than one stable mode of operation? *Nature* 315, 21-26.

Campin, J.-M., Fichefet, T., and Duplessy, J.-C. 1999: Problems with using radiocarbon to infer ocean ventilation rates for past and present climates. *Earth and Planetary Science Letters* 165, 17-24.

Church, M. J., Arge, S. V., Brewington, S., McGovern, T. H., Woollett, J., Perdikaris, S., Lawson. I. T., Gook, G. T. Amundsen, C., Harrison, R., and Krivogorskaya, K and **Dunbar, E.** (forthcoming): Puffins, Pigs, Cod, and Barley: Palaeoeconomy at Undir Junkarinsfløtti, Sandoy, Faroe Islands. *Environmental Archaeology*.

Davis, A.M., J.H. McAndrews, and B. Wallace. 1988: Paleoenvironment and the archaeological record at the L'Anse aux Meadows site. *Geoarchaeology* 3: 53-64.

Dugmore, A. J., Buckland, P. C., Church, M. J., Edwards, K. J., Lawson, I., McGovern, T. H., Panagiotakopulu, E., Simpson, I. A., Skidmore, P. and **Sveinbjarnardóttir, G.** 2005: The Norse *landnám* on the North Atlantic islands: an environmental impact assessment. *Polar Record* 41 (216), 21-37.

Edwards, K.J., Buckland, P.C., Dugmore, A.J., McGovern, T.H., Simpson, I.A. and **G. Sveinbjarnardóttir**. 2004: Landscapes circum-Landnám: Viking settlement in the North Atlantic and its human and ecological consequences - a major new research programme. In: Housley, R.A. and Coles, G., editors, *Atlantic connections and adaptations: economies, environments and subsistence in lands bordering the North Atlantic*. Oxford: Oxbow Books, 260-271.

Eiríksson, J., Larsen, G., Knudsen, K. L., Heinemeier, J., and Símonarson, L. A. 2004. Marine reservoir age variability and water mass distribution in the Iceland Sea. *Quaternary Science Reviews* 23, 2247-2268.

Hannon, G. E., Wastegård, S., Bradshaw, E., and **Bradshaw, R. H. W.** 2001: Human impact and landscape degradation on the Faroe Islands. *Biology and Environment: Proceedings of the Royal Irish Academy* 101B, 129-139.

Harkness, D. D. 1983: The extent of natural ^{14}C deficiency in the coastal environment of the United Kingdom. *PACT, Journal of the European Study Group on Physical, Chemical and Mathematical Techniques Applied to Archaeology* 8 (IV.9), 351-364.

Heier-Neilsen, S., Heinemeier, J., Nielsen, H. L. and **Rud, N.** 1995: Recent reservoir ages for Danish Fjords and marine waters: *Radiocarbon* 37 (3), 875-882.

Hjort, C. 1973: A sea correction for East Greenland, *Geolgiska Foreningens i Stockhom Forhandlingar* 95,132-134.

Humlum, O. 1998: Rock glaciers on the Faeroe Islands, the North Atlantic, *Journal of Quaternary Science*, 13, 293-308.

Jones, G. 1986: *The Norse Atlantic Saga: Being the Norse Voyages of Discovery and Settlement to Iceland, Greenland and North America*. Oxford: University Press.

Knudsen, K.L., and Eiríksson, J. 2002. Application of tephrochronology to the timing and correlation of palaeoceanographic events in Holocene and Lateglacial shelf sediments off North Iceland. *Marine Geology* 191, 165-188.

Knudsen, K. L., Eiríksson, J., Jansen, E., Jiang, H., Rytter, F., and Gudmundsdóttir, E. R. 2004: Paleoceanographic changes off North Iceland through the last 1200 years: foraminifera, stable isotopes, diatoms and ice rafted debris. *Quaternary Science* Reviews, 23, 2231-2246.

Krog, H and **Tauber, H**. 1974: C-14 chronology of late- and post-glacial marine deposits in north Jutland. *Danmarks geologiske Undersøgelse, Årbog*, 93-105.

Kuijpers, A., Troelstra, S. R., Wisse, M., Heier Nielsen, S., and **van Weering, T. C. E.** 1998: Norwegian Sea overflow variability and NE Atlantic surface hydrography during the past 150, 000 years. *Marine Geology* 152, 101-127.

Kuijpers, A., Hansen, B., Hühnerbach, V., Larsen, B., Nielsen, T., and **Werner, F.** 2002: Norwegian Sea overflow through the Faroe-Shetland gateway as documented by its bedforms. *Marine Geology* 188, 147-164.

Larsen, G., Eiríksson, J., Knudsen, K. L., and Heinemeier, J. 2002: Correlation of late Holocene terrestrial and marine markers, north Iceland: implications for reservoir age changes. *Polar Research* 21 (2), 283-290.

Lehman, S. J., and **L. D. Keigwin**. 1992: Sudden changes in North Atlantic circulation during the last deglaciation, *Nature*, 356, 757-762.

Lowe, C. 1999: *St. Boniface Church, Orkney: coastal erosion and archaeological assessment*. Stroud: Sutton Publishing.

Mangerud, J. and Gulliksen, S. 1975: Apparent Radiocarbon ages of recent marine shells from Norway, Spitsbergen and Arctic Canada. *Quaternary Review* 5, 263-273.

McGovern, T.H. 1991: Climate, correlation and causation in Norse Greenland. *Arctic Anthropology* 28: 77-100.

McGovern T. H., Perdikaris, S. and Tinsley, C. 2001: Economy of Landnám: the evidence of zooarchaeology, pp. 154-166 in Wawn, A and Sigurðardottir, T. (eds.), A*pproaches to Vinland* (Nordahl Institute Studies 4). Reykjavik: Nordahl Institute Studies.

McKay, W. A., Baxter, J. M., Ellett, D. J., and Meldrum, D. T. 1996: Radiocaesium and circulation patterns west of Scotland. *Journal of Environmental Radioactivity*, 4, 205-232.

Moros, M., Endler, R., Lackschewitz, K. S., Wallrabe-Adams, H.-J., Mienert, J., and **Lemke, W.** 1997: Physical properties of Reykjanes Ridge sediments and their linkage to high-resolution Greenland Ice Sheet project 2 ice core data. *Paleocenography* 12, 687-695.

O'Keeffe, T. 1994: Omey and the Sands of Time, *Archaeology Ireland* 8:2, 22-4.

Olsson, I. U. 1980: Content of ^{14}C in marine mammals from Northern Europe. *Radiocarbon* 22 (3), 515-544.

OSPAR Commission 2000: *Quality Status Report 2000*. OSPAR Commission London. 108 + vii pp.

Perdikaris, S., and McGovern, T. H. (in press). Cod Fish, Walrus, and Chieftains: Economic Intensification in the Norse N Atlantic. In Thurston, T. (ed.) *New Perspectives on Intensification*, Plenum Press, New York.

Pistek, P., and D.R. Johnson, 1992: A study of the Iceland-Faeroe Front using Geosat altimetry and current-following drifters. *Deep-Sea Research Part A*, **39**, 2029-2051.

Reimer PJ, McCormac FG, Moore J, McCormick F, and **Murray EV**. 2002. Marine radiocarbon reservoir corrections for the mid- to late Holocene in the eastern sub-polar North Atlantic. *The Holocene* 12, (2), 129-135.

Reimer, P., and **Reimer, R.** (2005): Marine Reservoir Correction database. http://www.qub.ac.uk/arcpal/marine/ Accessed 23/5/05.

Stuiver, M, Pearson, G W, and **Braziunas, T F**, 1986: Radiocarbon age calibration of marine samples back to 9000 cal yr BP. *Radiocarbon* 28:980-1021.

Stuiver, M and **Braziunas T. F**. 1993: Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. *Radiocarbon* 35,137-189.

Stuiver, M., and Reimer, P. J., 1993: Extended 14C database and revised CALIB radiocarbon calibration program, *Radiocarbon* 35, 215-230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v. d. Plicht, J., and **Spurk, M.** 1998a: INTCAL98 Radiocarbon age calibration 24,000 - 0 cal BP. *Radiocarbon* 4, :1041-1083.

Stuiver, M., Reimer, P.J., and **Braziunas, T. F.** 1998b: High-precision radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40, 1127-1151.

Ward, G. K. and **Wilson, S. R.** 1978: Procedures for comparing and combining radiocarbon age determinations: A critique. *Archaeometry* 20, 19-31.