Consistently large marine reservoir ages in the Norwegian Sea during the Last Deglaciation

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Abstract

With the exception of the GS-1/Younger Dryas cold period marine reservoir ages for the Last Deglaciation in the North Atlantic–Norwegian Sea are generally assumed to have been around 400–500 radiocarbon years in magnitude (Earth Planet. Sci. Lett. 126 (1994) 275; Radiocarbon 37 (1995) 53; Quat. Res. 52 (1999) 104; Nature 412 (2001) 724). By comparing the climate records obtained from the GRIP ice-core (Nature 359 (1992) 311; J. Quat. Sci. 13(4) (1998) 283) and from North Atlantic/Norwegian Sea cores (Quat. Res. 52 (1999) 104; Geology 23 (12) (1995) 1059; Nature 356 (1991) 757; Nature 356 (1992) 757; Paleoceanography 3(1) (1988) 1; Nature 343 (1990) 612; Earth Planet. Sci. Lett. 126 (1994) 275), with radiocarbon-dated European continental records, we show that marine reservoir ages in the Norwegian Sea were of the order of 1000 ¹⁴C yr, including large uncertainties. This approach rests on the reasonable assumption that climate changes throughout the NE Atlantic and Europe were more or less synchronous at the centennial scale. Fairly large variations in reservoir ages over time may have been caused by changing atmospheric ¹⁴C content. The results indicate that detailed land-sea correlations for the North Atlantic during the Last Deglaciation are not feasible using radiocarbon dating alone.

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1. Introduction

Detailed comparisons between marine, ice core and terrestrial records of the Last Deglaciation in the N. Atlantic region, and estimates of the leads and lags between them are hampered by major chronology uncertainties affecting the marine records in particular. Possibly the most important sources of uncertainty are related to temporal and spatial changes in the marine reservoir effect, which remain poorly understood. Nevertheless, precise correlations between various marine proxy records and the Greenland Summit ice cores have frequently been proposed (e.g. Bond et al., 1993; Hafliðason et al., 1995).

It has recently been shown, however, that three North Atlantic marine records from sites north of 40°N indicate that apparent surface-water ages (the so-called marine reservoir age) at 15,000 cal. yr BP exceed modern

reservoir values by 1200–1900 ¹⁴C yr (Waelbroeck et al., 2001) and by 800–1000 ¹⁴C yr at 12,000 cal. yr BP. Higher reservoir ages during the GS-1/Younger Dryas have also been suggested by earlier studies (Bard et al., 1994; Austin et al., 1995). By contrast, it is generally assumed that the magnitude of the regional marine reservoir age during the intervening warm period, the Bølling–Allerød interval or Greenland interstadial 1 (GI-1), approximated that of modern reservoir ages (Bond et al., 1999; Waelbroeck et al., 2001).

2. Material and methods of correlation

Radiocarbon dating of time-parallel marker horizons, such as tephra layers that are common to marine and continental sequences, are required to test any temporal and spatial changes in reservoir ages. However, there are few tephra layers within the Last Deglaciation interval, and the marine tephra stratigraphy is particularly problematic (Bond et al., 2001). The only method available, therefore, is to make detailed comparisons

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between paleoceanographic and terrestrial records using the event stratigraphy approach (Björck, et al., 1998; Walker et al., 1999). Regional climatostratigraphic boundaries can be used as more or less synchronous marker events, and thus temporal and spatial variations of reservoir ages can be estimated for the North Atlantic for the period between 15,000 and 11,000 cal. yr BP.

2.1. Synchronous changes

The notion that climate changes in the North Atlantic region during the Last Deglaciation were more or less synchronous has become widely accepted during the last few years. The deep Greenland ice cores have been adapted as palaeoclimatic templates and, with the aid of tephra stratigraphy (Hafliðason et al., 1995) and matching of ^{14}C data-sets (Björck et al., 1996), it has been concluded that Norwegian Sea records, European lake records and tree-ring variations are synchronous with ^{18}O variations in the ice-cores. Furthermore, a common sequence of events during the interval 15,000–11,000 cal. yr BP has convincingly been demonstrated for a diversity of proxy records obtained from sites throughout the North Atlantic region (Björck, et al., 1998; Walker et al., 1999), as well as for records obtained from the Caribbean Sea (Hughen et al., 1998) and the Santa Barbara basin (Kennett and Ingram, 1995). If similar North Atlantic marine ^{14}C dated paleoclimatic sequences are found, then it should be possible to estimate the magnitude of regional marine reservoir variations during the Last Deglaciation, where these exceed the uncertainties in the dating and correlation methods employed.

2.2. Four marine records

Because of the many uncertainties that affect marine ^{14}C dates, reliable estimates of reservoir ages require robust marine ^{14}C data-sets. Here we present palaeoceanographic records and associated ^{14}C data-sets from four marine cores. Three are located in the Norwegian Sea and one in the North Atlantic, west of Ireland (Fig. 1). A record of August SSTs based on transfer function inferences of diatom assemblage data has been obtained from core HM79-6/4 (Koç Karpuz and Jansen, 1992; water depth = 983 m), while records of the polar planktonic foraminifera *Neogloboquadrina pachyderma* (s.) have been obtained from cores Troll 8903 (Hafliðason et al., 1995, water depth = 300 m), Troll 3.1 (Lehman et al., 1991; Lehman and Keigwin, 1992, water depth = 322 m), and V23-81 (Broecker et al., 1988; Jansen and Veum, 1990; Bard et al., 1994, water depth = 2393 m). These four records match well the pattern of ^{18}O variations in the GRIP ice-core record (Fig. 2). Since it is highly unlikely that North Atlantic and Norwegian Sea surface temperatures were in anti-

Fig. 1. Map showing the region between NW Europe and Greenland, including the location of the four marine cores, where Troll is the location of two. The dotted line over Scandinavia shows the extent of the Fennoscandian ice-sheet at the Younger Dryas/Preboreal transition at 11,500 cal. yr BP.

phase with air temperature variations in Greenland and in western and central Europe during the Last Deglaciation, any time lags between the ice-core and marine records must be shorter than the duration of the short-lived climate events identified in the records, i.e. <150 ice yr. This is also within the 1-sigma dating errors of most of the marine ^{14}C dates used here. Furthermore, the onset of major warming in Greenland at the GS-2/GI-1 transition (14,700 ice yr BP) may have been slightly lagged compared with warming of the near-by ocean and continents, but a significant time-lag between the Norwegian Sea/North Atlantic records and those of northwest Europe is highly unlikely. With the exception of the V23-81 core, the marine cores discussed here have high sedimentation rates, and are thus suitable for detailed correlations with the high-resolution ice-core records. Reasonably detailed series of ^{14}C dates are available for all 4 records (Table 1), while the well-dated Vedde Ash has been found in three of them (Fig. 2).

2.3. Dating uncertainties

For a direct comparison of marine ^{14}C chronologies with reliable terrestrial ones, using the GRIP event stratigraphy scheme as a template, the ^{14}C chronology of the GRIP event horizons needs to be established. For this purpose we have evaluated well-dated terrestrial sequences, which show at least some of the key events of the GRIP record. We have tried to use at least two different ^{14}C dated data-sets for each defined event boundary (Table 1). Because of fluctuations in

Fig. 2. The $\delta^{18}\text{O}$ curve from the GRIP ice core (Johnsen et al., 1992) with its ice year based chronology (ss08c) correlated to the four marine proxy records with the aid of the event stratigraphy (Björck et al., 1998). Note that the Vedde Ash is indicated in four of the records by a grey bar.

Table 1

Estimated radiocarbon ages of the GRIP event stratigraphy (Johnsen et al., 1992; Björck, et al., 1998; Walker et al., 1999) and other defined events

GRIP events, event boundaries and other defined events	Estimated terrestrial ^{14}C age (yr BP)	Geographic region and reference
Saksunarvatn Ash	9000	Faroe Islands (Mangerud et al., 1986), Norway (Gulliksen et al., 1998)
GH-11.2	9800–9600	SW Sweden (Björck et al., 1996), Holland (van Geel et al., 1989; Wagner et al., 1999)
Early Preboreal	10,000–9800	SW Sweden (Björck et al., 1996), Switzerland (Ammann and Lotter, 1989)
GS-1/Holocene	10,000	SW Sweden (Björck et al., 1996), Norway (Gulliksen et al., 1998)
Vedde Ash	10,300–10,350	W Norway (Mangerud et al., 1984), S Sweden (Wastegård et al., 1998)
GI-1a/GS-1	10,800–10,600	S Sweden (Björck, 1984, 1996), Switzerland (Ammann and Lotter, 1989)
GI-1b/GI-1a	11,200–11,000	Denmark (Andresen et al., 2000), Switzerland (Ammann and Lotter, 1989; Lotter et al., 1992)
GI-1c/GI-1b	11,300	Denmark (Andresen et al., 2000), Switzerland (Ammann and Lotter, 1989; Lotter et al., 1992)
GI-1d/GI-1c	11,900–12,000	SE Sweden (Björck, 1984), Switzerland (Welten, 1982; Ammann and Lotter, 1989), Holland (van Geel et al., 1989)
GI-1e/GI-1d	12,100	SE Sweden (Björck, 1984), Switzerland (Welten, 1982; Ammann and Lotter, 1989), Holland (van Geel et al., 1989)
GS-2/GI-1e	12,500–12,700	Switzerland (Ammann and Lotter, 1989), Holland (van Geel et al., 1989), SW Sweden (Hammarlund, 1999)

All dates are from lake sediments, peat or cover sand where either terrestrial macrofossils or aquatic mosses in softwater lakes have been dated.

atmospheric ^{14}C content, the radiocarbon time scale is distorted, such that long periods in calendar time have almost constant radiocarbon ages, the so-called ^{14}C

plateaus, while some short periods are characterized by abruptly decreasing ^{14}C age. During periods with more or less constant atmospheric ^{14}C content, radiocarbon

age steadily decreases. Where an event boundary coincides with a ^{14}C plateau, it has a well-defined radiocarbon age. We can confidentially define radiocarbon ages for such boundaries, or for short distinct events, e.g. the Vedde Ash, within an uncertainty range of ± 100 ^{14}C yr (Table 2). For example, the Pleistocene–Holocene boundary, which corresponds to the GS-1/Holocene boundary in the GRIP scheme, falls within the 700 cal. yr long plateau of near-constant ^{14}C ages of 10,100–9900 ^{14}C yr BP (Stuiver et al., 1998) and is thus assigned an age of 10,000 ^{14}C yr BP. On the other hand, where an event boundary coincides with a period of rapidly decreasing ^{14}C ages, the radiocarbon age becomes less well defined. For radiocarbon ages around such periods we assume uncertainties of ca ± 150 –200 ^{14}C yr. The same uncertainty is estimated for ^{14}C ages of horizons that fall between event boundaries, while uncertainties of ± 200 –300 ^{14}C yr are assumed for ^{14}C ages that are regarded older or younger than the GI-1 and GS-1 events. The estimation of the calendar year (GRIP ice year) age, and its uncertainty, for each marine ^{14}C dated level is based on stratigraphic interpolations with the assumption of constant accumulation rate between each event boundary. For ^{14}C dated levels around boundaries or in the middle of short events we have estimated GRIP ice chronology uncertainties to vary between ± 50 and 100 yr, while uncertainties for the remaining levels are estimated to ± 100 –200 yr. Finally, as each marine ^{14}C dated level was assigned an ice-layer age and a terrestrial ^{14}C age, the latter could then be calibrated by using INTCAL98 (Stuiver et al., 1998). This exercise results in that only one of the estimated GRIP ages (including the uncertainty error) falls slightly outside the calibrated age range (Table 2). This may be a further indication that there are no significant time lags between GRIP and the terrestrial records.

3. Results and discussion

The estimated reservoir ages (Fig. 3) are calculated as the difference between each ^{14}C age obtained from the marine cores and the corresponding ^{14}C age estimate for the same event stratigraphic level in the terrestrial records. Our comparison shows that the ^{14}C ages in the North Atlantic core V23-81 display an enormous variation (Fig. 3); the calculated magnitude of reservoir ages varies between +1300 ^{14}C yr and –1100 ^{14}C yr, with a mean of 346 yr and a weighted mean of 404 yr. The spread of ages within 1σ is ± 538 ^{14}C yr, a degree of variation that renders this data-set unsuitable for estimating likely marine reservoir off-sets. With the exception of expected reservoir age values in the Holocene, no clear temporal trend can be distinguished. Furthermore, ca 25% of the dates are clearly too young, though the ^{14}C dates for samples of *N. pachyderma* (s)

seem less prone to this problem, which suggests the influence of a bioturbation bias on the other dated samples consisting of planktonic foraminifera.

However, the three cores from the Norwegian Sea with their 25 ^{14}C dates (Table 1), show much less age variation for the study period (Fig. 3). The magnitude for the reservoir ages in the Norwegian Sea (RANS) varies between 400 and 1300 ^{14}C yr, but 60% of the age estimates suggest a RANS exceeding 1000 ^{14}C yr. The mean RANS is 1035 ^{14}C yr, while the weighted mean is 1043 yr, and the ages have a 1σ spread of ± 252 ^{14}C yr. Furthermore, the data do not show any obvious decreasing or increasing trend (Fig. 3) throughout the 4000 cal. yr long period. This is inconsistent with the assumption that the North Atlantic, including the Iceland and Norwegian Sea, experienced a doubling of the marine reservoir effect during the GS-1, as a consequence of reduced advection of surface waters and increased abundance of sea ice (Bard et al., 1994; Bondevik et al., 1999). The occurrence of the Vedde Ash in three of the marine cores, and dated to ca 10,350 ^{14}C yr BP (Mangerud et al., 1984; Wastegård et al., 1998) in the middle of GS-1, gives us an additional opportunity to compare marine and terrestrial ^{14}C dates; the five ^{14}C dates situated at, slightly above or slightly below, the Vedde Ash in these cores give a mean ^{14}C age of 11,360 yr BP, which is consistent with a RANS of ca 1000 ^{14}C yr.

There is, however, a quasi-cyclic pattern in the Norwegian Sea data, and fitting a polynomial function suggests two maxima in RANS at 12,300 and 13,600 cal. yr BP, and three minima at 11,500, 13,000 and 14,500 cal. yr BP. Such fluctuations do not necessarily indicate changes in ocean ventilation, but could reflect delayed responses to variations in atmospheric ^{14}C content, which will be damped by the vertical diffusive exchange, but still show up in the marine ^{14}C record. Because of this effect, it can be calculated from published data (Stuiver et al., 1998), for example, that the tropical ocean reservoir age fluctuated between 300 and 800 ^{14}C yr during the early Holocene, a period of significant $\Delta^{14}\text{C}$ changes.

4. Conclusions

The comparisons outlined above show that RANS was much higher than is usually assumed during the period 15,000–11,000 cal. yr BP. This conclusion poses serious questions about how marine ^{14}C chronologies have been used to construct regional chronologies. Since there is a fairly high consistency in the results, indicating that relative ^{14}C ages in this marine realm may be reliable, we suggest a RANS of ca 1000 yr (± 250 yr) for this period. The real degree of uncertainty is, difficult to quantify because of many different uncertainties. The Norwegian Sea data indicate that RANS varied during

Table 2

Uncorrected ^{14}C dates from the four marine cores in Fig. 2^a with dated foraminiferal species^b, estimated corresponding age in the GRIP ice core (ss08c) with our error estimates, the assumed terrestrial ^{14}C age of the corresponding event stratigraphic level with our error estimates, and the calibrated age (Stuiver et al., 1998) of the assumed terrestrial ^{14}C age. Empty space means the same value as above

Core ^a	Depth (cm)	^{14}C age, yr BP	^{14}C dated species ^b	GRIP age	Err. ($\pm$)	Terrestrial ^{14}C age	Err. ($\pm$)	Calibrated age, yr BP
HM	195	10,885 $\pm$ 135	N. p. (s)	11,250	50	9700	150	10,750–11,230
	250	11,675 $\pm$ 180	N. p. (s)	11,980	20	10,350	100	11,750–12,650
	270	11,635 $\pm$ 160	N. p. (s)	12,600	100	10,700	150	12,350–13,000
	284.5	11,665 $\pm$ 80	N. p. (s)	13,000	75	11,250	100	13,040–13,420
	289.5	12,080 $\pm$ 85	N. p. (s)	13,200	100	11,400	150	13,150–13,800
	305	12,765 $\pm$ 195	N. p. (s)	13,500	100	11,500	150	13,150–13,800
	335	12,820 $\pm$ 105	N. p. (s)	13,900	100	11,800	150	13,450–14,100
	365.5	12,995 $\pm$ 135	N. p. (s)	14,300	150	12,300	150	14,050–15,150
	390	13,605 $\pm$ 130	N. p. (s)	14,700	100	12,700	150	14,350–15,650
	430	14,540 $\pm$ 155	N. p. (s)	15,000	150	13,000	300	14,350–16,150
T3.1	407	10,950 $\pm$ 115	N.I.	11,500	50	10,000	100	11,230–11,690
	545	11,600 $\pm$ 120	N.I.	12,300	100	10,400	100	11,950–12,650
	825	12,170 $\pm$ 170	N.I.	13,100	75	11,250	100	13,040–13,420
	1158	12,850 $\pm$ 150	N.I.	13,700	100	11,600	200	13,200–13,850
	1454	13,025 $\pm$ 150	N.I.	14,000	100	12,000	100	13,650–14,300
	2060	13,885 $\pm$ 155	N.I.	14,800	150	12,800	150	14,350–15,750
T8	177	10,835 $\pm$ 115	Y. lent.	11,400	75	10,000	100	11,230–11,690
	266	11,100 $\pm$ 110	N.I.	11,980	20	10,300	100	11,750–12,600
	276	11,595 $\pm$ 90	N.I.	12,050	75	10,300	150	11,650–12,650
	320	11,665 $\pm$ 75	E. exc.	12,300	100	10,400	150	11,950–12,800
	390	11,785 $\pm$ 130	N.I. Cr	12,500	75	10,600	150	12,300–12,900
	460	12,305 $\pm$ 125	N.I.	12,950	100	11,200	150	13,010–13,390
	510	12,480 $\pm$ 145	N.I.	13,050	50	11,300	100	13,150–13,420
	1090	13,390 $\pm$ 85	Y. lent.	14,400	100	12,300	200	14,050–15,250
	1290	13,530 $\pm$ 75	E. exc.	14,800	150	12,800	200	14,350–15,850
V	135–136	9490 $\pm$ 200	G. infl.	10,350	200	9200	200	10,150–10,700
		9890 $\pm$ 160	G. bull.					
		9610 $\pm$ 150	G. glut.					
	141–143	10,940 $\pm$ 150	N. p. (s)	11,200	75	9600	150	10,740–11,170
	143–144	10,120 $\pm$ 180	N. p. (s)	11,300	50	9700	150	10,750–11,230
		10,450 $\pm$ 200	G. infl.					
	146–147	9600 $\pm$ 210	G. glut.	11,400	75	9900	100	11,180–11,560
	147–148	10,260 $\pm$ 190	G. infl.	11,500	50	10,000	100	11,230–11,690
	150–151	11,110 $\pm$ 140	N. p. (s)	11,600	50	10,000	100	11,230–11,690
	154–155	10,800 $\pm$ 170	N. p. (s)	11,800	150	10,200	200	11,350–12,350
	157–158	11,280 $\pm$ 90	N. p. (s)	12,100	100	10,400	100	11,950–12,650
		11,470 $\pm$ 140	N. p. (s)					
	160–161	11,380 $\pm$ 150	N. p. (s)	12,600	100	10,700	150	12,350–13,000
	164–165	11,500 $\pm$ 200	G. infl.	12,700	100	10,900	100	12,840–13,130
		11,500 $\pm$ 210	G. bull.					12,880–13,160
	171–172	10,530 $\pm$ 160	G. infl.	12,800	100	11,000	150	
		11,170 $\pm$ 180	G. bull.					
	172–173	11,980 $\pm$ 110	N. p. (s)	12,850	100	11,000	150	12,880–13,160
		10,960 $\pm$ 200	G. infl.					
		11,860 $\pm$ 170	G. bull.					
		11,140 $\pm$ 190	G. glut.					
	175–176	10,990 $\pm$ 190	N. p. (s)	12,950	100	11,100	100	12,950–13,180
		10,780 $\pm$ 190	N. p. (s)					
	180–181	12,240 $\pm$ 220	G. infl.	13,200	100	11,350	100	13,170–13,430
		11,990 $\pm$ 280	G. bull.					
	186–187	10,500 $\pm$ 230	G. infl.	13,500	150	11,600	150	13,390–13,830
		11,540 $\pm$ 210	G. bull.					
	188–190	11,850 $\pm$ 200	N. p. (s)	13,950	75	12,000	100	13,650–14,300
		11,330 $\pm$ 230	G. infl.					
		11,650 $\pm$ 210	G. bull.					
	194–195	12,660 $\pm$ 240	N. p. (s)	14,200	100	12,200	150	13,750–15,150
		11,940 $\pm$ 210	G. infl.					
		12,840 $\pm$ 230	G. bull.					

Table 2 (continued)

Core ^a	Depth (cm)	¹⁴ C age, yr BP	¹⁴ C dated species ^b	GRIP age	Err. (±)	Terrestrial ¹⁴ C age	Err. (±)	Calibrated age, yr BP
	198–199	12,720±220	N. p. (s)	14,400	150	12,400	200	14,100–15,050
		12,530±220	G. infl.					
		12,910±240	G. bull.					
	215–216	14,060±210	N. p. (s)	15,000	200	12,900	200	14,350–15,950

^a HM = HM79-6/4, T3.1 = Troll 3.1, T8 = Troll 8903, V = V23-81.

^b N. p. (s) = *Neoglobobulimina pachyderma* (sinistral), G. infl. = *Globobulimina inflata*, G. bull. = *Globobulimina bulloides*, G. glut. = *Globobulimina glutinata*, Y. lent. = *Yoldiella lenticula*, N.l. = *Nonionellina labradorica*, E. exc. = *Elphidium excavatum*, Cr = *Cassidulina reniforme*. All ages refer to AD 1950.

Fig. 3. The difference between the marine ¹⁴C ages and estimated terrestrial ¹⁴C ages, i.e. the marine reservoir age, related to the inferred GRIP age (ss08c). Reservoir ages for North Atlantic dates (filled symbols), Norwegian Sea dates (open symbols), dates on benthic foraminifera (diamonds), dates on *Neoglobobulimina pachyderma* (sinistral) foraminifera (triangles), and dates on other planktonic foraminifera (squares) are shown with different symbols. The weighted mean of our Norwegian Sea reservoir age is shown as a broken line, while the commonly used reservoir age of 440 yr before and after Younger Dryas, and the Younger Dryas reservoir age of ca 800 yr (Bard et al., 1994), is shown as a dotted line. The upper x-axis shows the chronologic position of the events and episodes in the GRIP ice core (Björck et al., 1998) according to the ss08c time-scale.

the Last Deglaciation, which suggests changing atmospheric ¹⁴C concentrations rather than changes in ocean ventilation. This conclusion is also supported by reconstructions of the limit of sea-ice throughout the Last Deglaciation (Koç et al., 1993), which suggest that the whole period was characterized by only a small ice-free corridor along the Norwegian coast. Under such a scenario, a fairly stable mode in thermohaline circulation, and hence quasi-constant marine reservoir ages, would be expected.

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