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Reconstructing Deglacial Circulation Changes in the Northern North Atlantic and Nordic Seas: $\Delta^{14}C$, $\delta^{13}C$, Temperature and $\delta^{18}OSW$ Evidence

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With 1 Figure

Ice-core records have revealed that atmospheric CO_2 has varied during glacial-interglacial by ~90 ppm, with rapid increases in atmospheric CO_2 occurring during deglaciations. It is widely accepted that changes in the amount of carbon stored in the deep ocean play a leading role in explaining these cycles, primarily because of the size of the deep ocean carbon reservoir (~60 times that of the atmosphere) and the millennial timescales on which it interacts with the atmosphere (Sigman et al. 2010). To gain an understanding of how changes in deep ocean carbon storage may have controlled past variations in atmospheric CO_2, we ideally require robust and detailed proxy records of the properties and ventilation pathways of the deep ocean across glacial-interglacial transitions. The deep ocean is ventilated in the high latitudes, where dense isopycnals outcrop at the sea surface. Therefore to help understand deep ocean-atmosphere exchange we require reconstructions of past hydrographic changes at these high latitude ventilation sites. Furthermore, constraints on the timing and phasing of deglacial changes in these regions enable us to evaluate hypotheses regarding the underlying mechanisms of the glacial termination.

I will present a suite of multiproxy deglacial records from one of the regions of deep ocean ventilations: the high latitude North Atlantic and Nordic Seas. These data enable the reconstruction of past ventilation rates as well as the physical properties of the surface and deep ocean. There are several lines of enquiry that will be addressed through these new datasets: (*i*) What was the cause and mechanism(s) involved in the appearance of a highly ^{14}C-depleted water mass in the mid-depth northern North Atlantic during deglaciation? (*ii*) To what extent can this water mass explain changes in mid-depth ocean properties further south, in the subtropical North Atlantic and South Atlantic? (*iii*) What was the timing and nature of ocean reorganizations within the northern North Atlantic during Heinrich stadial 1 and what role, if any, did this play in the early deglacial rise of atmospheric CO_2?

(*i*). New benthic radiocarbon reconstructions from a site at 2.7 km depth in the Norwegian Sea reveal the formation of an aged deep water mass within the glacial Arctic Mediterranean (AM), with a ventilation age of up to 10,000 years. Despite such an old ventilation age, $\delta^{13}C$ and nutrient reconstructions do not suggest substantial remineralization of organic matter occurred, likely owing to low surface productivity and export of AM waters at shallow and intermediate depths. A simple box model exercise confirms the feasibility of obtaining such old ventilation ages within the AM, as long as rates of deep water renewal remained less than ~0.1 Sv for the glacial and deglaciation. It is hypothesized that gradual filling of the AM with a dense water mass occurred throughout MIS2, resulting in aging of the water column and a sharp radiocarbon front developing between well ventilated intermediate waters and the underlying aged deeper waters. Ultimately, overflow of this aged water over the Iceland-Scotland Ridge occurred during HS1 and throughout the deglaciation, influencing the northern North Atlantic. The chemical properties of this deep AM water mass, alongside those of the open deep Atlantic can explain the deglacial Δ^{14}C-δ^{13}C signals reconstructed south of Iceland (Thornalley et al. 2011). Further supporting evidence for the filling and overflow of this aged water from the Nordic Seas during HS1 has been observed at an intermediate depth core in the Faroe-Shetland Channel region (Rasmussen et al., AGU Fall 2014 Meeting, and personal communication).

New multi-proxy temperature reconstructions (benthic foram Mg/Ca and clumped isotopes) from the deep Norwegian Sea also reveal glacial temperatures that were 2–3 °C warmer than modern. This is consistent with the absence of deep convection, which today cools the deep Nordic Seas to temperatures below –1 °C. The warmer deep Norwegian Sea may have been caused by either a deep inflow of warm Atlantic water and/or by geothermal heating. The shift from a warm to cold deep Nordic Seas began during HS1 and the timing of the deep ocean heat release and surface records indicating input of substantial meltwater are consistent with a role for this deep ocean heat release in melting of sea-ice and surrounding ice sheets.

(*ii*) Temperature, δ^{18}Osw and radiocarbon reconstructions from south of Iceland reveal a complex pattern of hydrographic change during the deglacial, and most notably during HS1. The signature of the aged deep water from the Nordic Seas can be detected south of Iceland during HS1 in multiple proxies. Yet HS1 also contains prominent intervals of better ventilation. One such event (~15–15.5 ka) is also associated with a warming from ~0–1 °C to 4–5 °C at 1.2 km depth. Given that identical physical and chemical properties are reconstructed in both planktic and benthic foraminifera at this time, we hypothesize that this interval represents a period of regional intermediate-deep water formation that also entrained aged water from the Nordic Seas. I will compare the timing and changing hydrography of this event to assess the extent to which it may explain hydrographic changes reconstructed further south in the Atlantic.

A brief interval of particularly strong ventilation occurred ~16–16.5 ka, which is also detected in the deep Nordic Seas. This benthic radiocarbon event has importance for constraining the timing of benthic δ^{18}O and δ^{13}C changes in the subpolar North Atlantic because it occurs at the onset of major shifts in benthic and planktic δ^{18}O and δ^{13}C within the same cores. Traditionally, constraining the age of the HS1 benthic δ^{18}O and δ^{13}C isotope change in this region has been hampered by uncertainty in the planktic ^{14}C reservoir age. Notwithstanding the possibility that this event is an artefact of bioturbation (although replication in two cores and other lines of evidence suggest this is unlikely), the young benthic radiocarbon ages at 16–16.5 ka provide an upper (i.e. oldest) age constraint on the timing of the major isotopic shift during HS1 in these cores. Supporting evidence for a relatively young age (<17 ka) of the timing of the HS1 benthic isotope event in the northern North Atlantic is also provided by new planktic radiocarbon dates in additional cores. In light of these suggestions on the timing of regional isotopic events in the northern North Atlantic, I will explore the relative timing of HS1 benthic isotopic events throughout the North and South Atlantic.

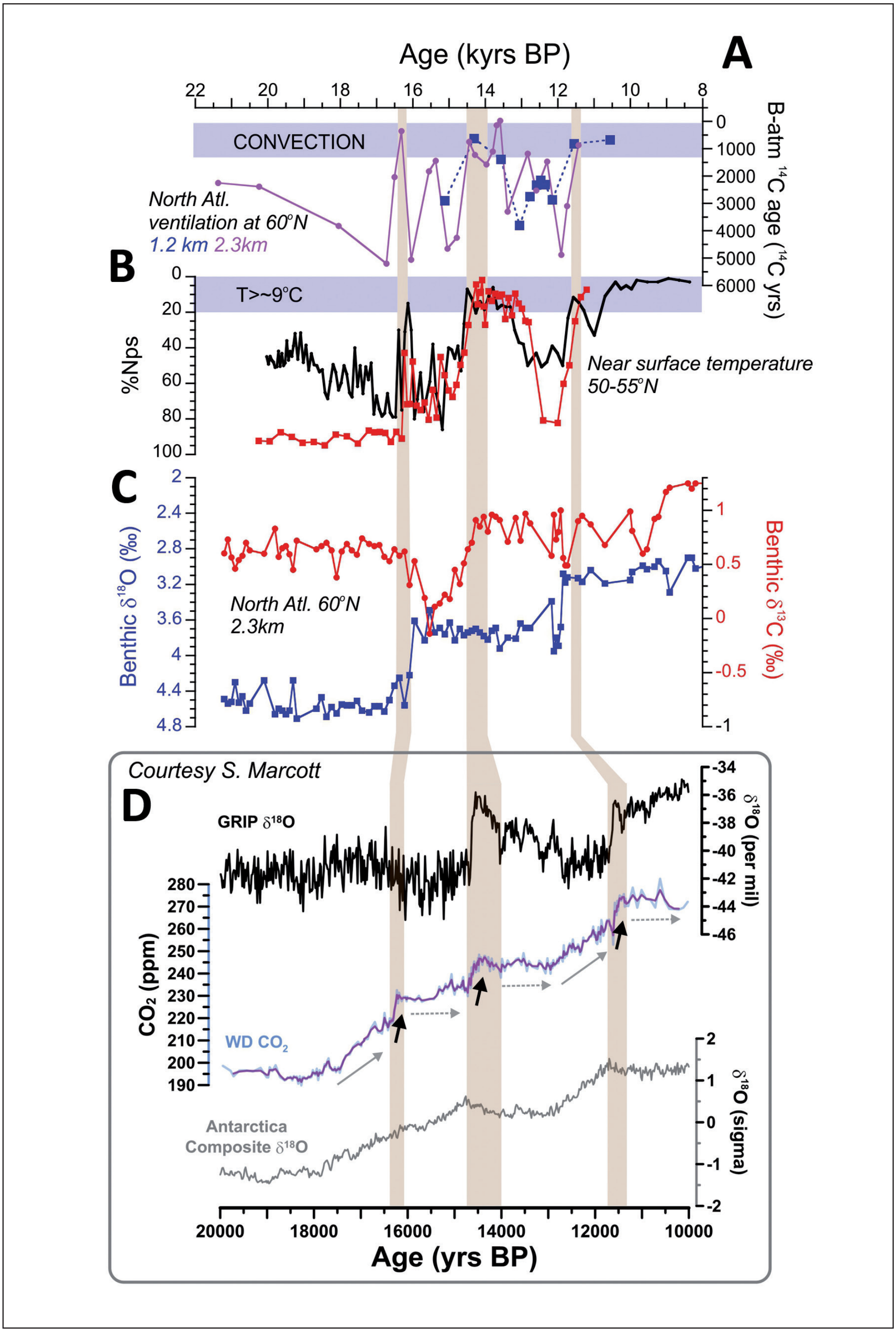
Finally, the data from south of Iceland and the Nordic Seas suggests that intermediate and deep water formation may have been highly variable during HS1. This apparent variability would undermine the rationale behind producing single time-slice composites of HS1, e.g.

(Tessin and Lund 2012), and invalidate interpretations based on a single mode of circulation during HS1.

(*iii*) The brief interval of particularly strong ventilation at ~16–16.5 ka also coincides with surface warming events recorded further south in the subpolar North Atlantic (Fig. 1). It is therefore plausible that there was a brief reinvigoration of deep water formation in the Northeast Atlantic at ~16–16.5 ka. This observation may have implications for our understanding of the mechanisms of deglacial atmospheric CO_2 rise.

During the deglaciation, proxy and modelling studies have established the simplified paradigm (Rahmstorf 2002) that the North Atlantic ocean switched between a relatively deep, modern-like, mode of NADW formation during warm intervals (the Holocene, 0–11.7 ka and Bølling Allerød, BA, 13–14.7 ka), to a shallower 'cold' mode, in which Antarctic Bottom Water (AABW) replaced water of northern origin below ~2–2.5 km (e. g., the Last Glacial Maximum, LGM, ~19–23 ka). In addition, during intervals of intense ice-rafting and freshwater input such as Heinrich stadial 1 (HS1, ~14.7–19 ka) and the Younger Dryas (YD, 11.7–13 ka), it is hypothesized that convection in the North Atlantic further shoaled and weakened in response to freshwater input to the North Atlantic ('Off mode'; Fig. 1). Changes in the relative proportions of NADW *vs.* AABW affects the amount of carbon stored in the deep ocean, because of their varying preformed [DIC] and physical properties. For example, it is thought that the glacial Atlantic Ocean contained a larger volume of high [DIC], cold AABW, enabling greater carbon storage in the deep ocean, helping lower atmospheric CO_2 (Brovkin et al. 2012).

Another important deep ocean control on atmospheric CO_2 is the amount of CO_2 that 'leaks' out of the deep ocean through upwelling in the Southern Ocean. It is hypothesized that ventilation of the deep Southern Ocean was reduced during the LGM through a range of physical and biogeochemical processes, thereby decreasing the Southern Ocean CO_2 'leak'. This enabled greater storage of carbon in the deep ocean, thus helping lower atmospheric CO_2 concentration (Sigman et al. 2010). Employing this mechanism, numerous studies have suggested that the deglacial rise in atmospheric CO_2 occurred *via* enhanced upwelling in the Southern Ocean e.g. (Anderson et al. 2009). Previous ice-core reconstructions of atmospheric CO_2 suggested that the deglacial increase occurred predominantly through two gradual rises, during HS1 and the YD, likely in response to North Atlantic ice-rafting and freshwater events altering the overturning circulation (Denton et al. 2010). However, the new higher resolution atmospheric CO_2 reconstruction from the WD ice core (Fig. 1*D*; courtesy of Marcott and Brook, OSU)) reveals an alternate picture of the deglacial rise in atmospheric CO_2: in addition to a gradual rise in CO_2 during early HS1 and the YD (18–16.5 ka; 13–11.7 ka; solid grey arrows), there were three abrupt 'jumps' in CO_2 of ~10–15 ppm (black arrows), followed by millennial-scale plateaus (dashed grey arrows), resulting in a more step-like curve, in which up to ~40ppm of the ~90ppm deglacial rise in atmospheric CO_2 occurred as abrupt 'jumps'. The 'jumps' occur at the onset of the BA and Holocene, as well as at ~16.3 ka. The onset of the BA and Holocene are widely accepted as intervals of reinvigoration of NADW (Rahmstorf 2002), begging the question, was the jump at 16.3 ka also associated with an (albeit brief) interval of strong convection in the North Atlantic? I hypothesize that the onset of deep convection led to a rapid replacement of the previously poorly ventilated, DIC-rich deep Atlantic ocean, by low [DIC], warm and salty NADW, that caused the observed abrupt increases in atmospheric CO_2. Recharging of deep Atlantic CO_2 storage likely occurred during subsequent intervals of reduced NADW formation, resulting in the atmos-


Age (kyrs BP)
A
22
20
18
16
14
12
10
8
0
1000
2000
3000
4000
5000
6000
B-atm ¹⁴C age (¹⁴C yrs)
CONVECTION
North Atl.
ventilation at 60°N
1.2 km 2.3km
B
0
20
40
60
80
100
%Nps
T>~9°C
Near surface temperature
50-55°N
C
2
2.4
2.8
3.2
3.6
4
4.4
4.8
Benthic δ¹⁸O (‰)
1
0.5
0
-0.5
-1
Benthic δ¹³C (‰)
North Atl. 60°N
2.3km
Courtesy S. Marcott
D
GRIP δ¹⁸O
-34
-36
-38
-40
-42
-44
-46
δ¹⁸O (per mil)
280
270
260
250
240
230
220
210
200
190
CO₂ (ppm)
WD CO₂
Antarctica
Composite δ¹⁸O
2
1
0
-1
-2
δ¹⁸O (sigma)
20000
18000
16000
14000
12000
10000
Age (yrs BP)

pheric CO_2 plateaus. A similar mechanism has been invoked to explain transient increases in atmospheric CO_2 during the onset of the Dansgaard-Oeshger warm events of Marine Isotope Stage 3 (30–60 ka) (Bereiter et al. 2012). Although a wide range of behaviour is displayed by different models, several previous studies have suggested that, by itself, the replacement of SSW by NADW can cause a rise in atmospheric CO_2 of up to ~10–30 ppm e.g. (Schulz et al. 2001, Brovkin et al. 2012). Initial constraints on North Atlantic deep convection, from south of Iceland and the Nordic Seas (Fig 1*A*, *B*), support this hypothesis, but to gain confidence that this is a robust feature, further measurements are required.

To trace the extent of the 16–16.5 ka convection event in the subpolar Northeast Atlantic, I have analysed benthic $\delta^{13}C$ and benthic-planktic ^{14}C ages in the high sedimentation rate core OCE-326-GGC14, from 3.5 km depth in the Northwest Atlantic, during HS1. These data do not suggest that the deep North Atlantic was subject to a strong ventilation event from 16–16.5 ka, in line with other existing proxy data. It is therefore likely that ventilation was restricted to the mid-depth ocean, weakening the supporting case for this event playing a role in the atmospheric CO_2 jump at 16.3 ka. Yet it remains intriguing that there were clearly important hydrographic reorganizations occurring within the subpolar North Atlantic at this time, warranting continued investigation into the cause of the Northeast Atlantic ventilation and surface warming signals and any possible link to atmospheric CO_2 change.

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Fig. 1 Open ocean deep convection produces waters that have a small ^{14}C offset from the contemporaneous atmosphere, allowing past intervals of convection to be identified. Existing data from the high latitude North Atlantic is shown in (*A*) (Thornalley et al. 2011), suggesting a deep convection occurred at ~16–16.5 ka, during the early BA (~14.5–14.0 ka), and the Holocene (11.7–0 ka). (*B*) The convection event at 16–16.5 ka also coincides with near-surface warming in the subpolar North Atlantic (Peck et al. 2006, Lagerklint and Wright 1999); (*C*) as well as marking the onset the major benthic $\delta^{13}C$ and $\delta^{18}O$ in the mid-depth subpolar North Atlantic (data from RAPiD-17-5P). (*D*) WD ice-core atmospheric CO_2 reconstruction (purple), with Greenland (GRIP) and Antarctic $\delta^{18}O$ shown for reference – figure courtesy of S. Marcott (OSU).

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