Supplementary Materials for

North Atlantic ocean circulation and abrupt climate change during the last glaciation

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Other Supplementary Materials for this manuscript includes the following:

- Databases S1 as zipped archives: [paste data table titles in a list]
Materials and Methods

Digestion of marine sediments was followed by column chromatography to separate U and Th from Pa isotopes. Uranium series nuclides were measured by isotope dilution on a Thermo-Scientific Element XR ICPMS at the Lamont-Doherty Earth Observatory. Carbon and oxygen isotopic measurements on benthic and planktonic foraminifera, as well as the XRF scan for CDH19 were made at the Woods Hole Oceanographic Institution. Figure 1 was produced with Ocean data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2015.) from 783 previously published Pa/Th core top measurements, the data for which can be found in the supplemental data file.

Supplementary Text

Background for our study site/core and age model

Core CDH19 was retrieved from the Bermuda Rise (33˚ 41.443’ N; 57˚ 34.559’ W, 4541m water depth). This 38.83m core allows us the possibility of resolving fine stratigraphic events, and producing a record that spans the last glacial cycle. Benthic δ18O reveals that the core extends from the recent interglacial interval, marine isotope stage 1 (MIS 1), into the penultimate glaciation of MIS 6 (Fig. S4). Water mass reconstructions derived from δ13C measurements on the benthic foraminifera Cibicidoides wuellerstorfi and Nuttallides umbonifera (Fig. S4) indicate the core site on the Bermuda Rise was bathed in the southern-sourced waters during the Last Glacial Maximum (1). Over the interval encompassing MIS 3, the sedimentation rates range from approximately 20-40cm/kyr. Samples spaced at 4 cm intervals therefore represent between 100 and 200 years.

The Bermuda Rise study site sampled by core CDH19 fits well within a compilation of previously published core top Pa/Th (Fig. 1). Values in the oligotrophic regions of the subtropical gyres show a deficit of 231Paxs. Active advective export by ocean currents and diffusive transport along isopycnal delivers 231Pa to regions of higher particle flux where elevated particle flux removes it from the water column (2). High particle fluxes along the margins of Asia and the Americas, and within the Arabian Sea, sequester 231Pa in excess of the production ratio, contributing to the deficits found in the subtropical gyres of the Pacific and Indian Oceans. In the Atlantic Ocean, export by NADW delivers 231Pa to the Southern Ocean opal belt, outweighing the contribution of scavenging by particle fluxes along the bounding margins (3-5).

A compilation of carbonate and carbonate proxy records (Fig. S1) taken from the Bermuda Rise demonstrates the coherent expression of millennial events across the region, allowing for direct comparison of data from one core to another. Taking advantage of this relationship, spectral reflectance data from core MD95-2036 were tuned to x-ray fluorescence (XRF) calcium scans of core CDH19 with a correlation optimization algorithm. CDH19 XRF calcium was calibrated with coulometric CaCO3 content data ($r^2 = 0.91, n = 190$, Fig. S1). Cores MD95-2036 and CDH19 should have nearly identical CaCO3 content fluctuations (correlation coefficient 0.72) as they were taken 20m apart and within 11m of the same depth. Sea-surface temperature (SST) estimates from core MD95-2036 were converted to their equivalent influence on
foraminifera δ¹⁸O using a calibration informed by modern observations and subtracted from our well-resolved CDH19 G.ruber δ¹⁸O record to generate δ¹⁸O_sw (Fig. S2).

During the late glacial, the core is dated using calibrated radiocarbon dates on planktonic foraminifera (6), and during MIS 3 by correlating the alkenone SST from MD95-2036 to the North Greenland Ice Core Project core’s (NGRIP) [75.1°N, 42.32°W, 2917m ice thickness], GICC05 chronology, and then by correlating spectral reflectance, a proxy for %CaCO₃, in MD95-2036 to XRF Ca, another proxy for %CaCO₃ in core CDH19. Both associations were developed with an automated correlation maximization algorithm. The penultimate deglaciation, Termination 2, was aligned with the δ¹⁸O transition in the Hulu cave, constrained by three high-precision U/Th dates (7). Although evidence does exist for remobilization of alkenone-bearing coccolithophores during the last deglaciation, and not during the Holocene, multi-millennial deviations from the two age models developed in study are rejected based on the correlation optimization of multiple proxy records produced within core CDH19 (8).

During a period of MIS 3 when SST variations were of lower magnitude and less easily correlated to Greenland, between 40-43ka, ²³⁰Thxs-normalized fluxes are utilized instead to refine the chronology.

Abrupt events during the glacial

Abrupt glacial climate change was first detected in ice cores taken from the Greenland ice sheet more than two decades ago (9). The Greenland summit undergoes seasonal storm cycles that allow visual confirmation of annual layers for several tens of thousands of years. Though Antarctic ice core records offer no such visual check, their respective chronologies can be tied to Greenland ice cores through correlating spikes in trace gases trapped in ice cores’ air bubbles (10). Recently, careful work has been done to tie δ¹⁸O to the U/Th dated Hulu cave record. These efforts, with careful correction of gas age/ice age offsets, and high-resolution methane-synchronization, have revealed a lead of 200 years of Greenland climate over that of Antarctica(11).

Mechanisms and Interpretations

The stadial to interstadial transitions are ideal for analyzing the sequence of events that give rise to Dansgaard-Oeschger (DO) events for the following reasons: the stadial to interstadial Pa/Th transition relies only on the rate at which dissolved ²³¹Pa xs may be flushed from the North Atlantic basin, and does not rely on ²³¹Pa xs or ²³⁰Th xs to be produced through radioactive decay; the stadial to interstadial transitions shifts dwarf the proxies’ associated uncertainties; thirdly, the transitions in the NGRIP (12) and other Greenland ice cores are known to occur over subcentennial timescales.

Water mass properties

As the world transitioned from glacial to interglacial climate, approximately four hundred gigatons of carbon were released from the abyssal ocean to the atmosphere and terrestrial biosphere, resulting in a whole-ocean δ¹³C_BF shift of 0.34‰, as C3 plants incorporated ¹³C-depleted carbon into biomass(1, 13-15).

While there exists broad agreement on the oceanic source of CO₂ release during deglaciation, the mechanism sequestering this carbon is debated; two mechanisms for which there exists strong experimental evidence are iron fertilization(16, 17) and
stratification revealed by nutrient proxies in the Southern Ocean\(^{(18)}\). While P\(_{CO2}\) data recovered from an Antarctic ice core suggest variations in the load of atmospheric CO\(_2\) \(^{(19)}\), and associated changes in the net primary productivity of the planet via the Dole Effect \(^{(20)}\) across abrupt glacial climate change events\(^{(21)}\), the magnitude of these changes across MIS3 is small compared to glacial to interglacial shifts. This suggests that at our oligotrophic North Atlantic core site, shifts in relative proportion of water masses drive differences in \(\delta^{13}C_{BF}\).

In a sediment core taken from the Iberian margin, Shackleton and Hall were able to generate two intriguing oxygen isotope records. The planktic \(G.\) bulloides oxygen isotope record reflected the changes seen in Greenland’s NGRIP ice core, while the \(\delta^{18}O_{BF}\) isotope record, generated from \(C.\) wuellerstorfi and \(Globobulimina\) affins, bore a striking resemblance to the changes seen in the Antarctic Vostok ice core \(^{(22)}\). This suggests that the bottom water masses change with temperature over Antarctica, while the upper water column is in equilibrium with local North Atlantic atmospheric temperature. Evidence from SST reconstructions support the interpretation that temperatures of the upper water column broadly across the North Atlantic, and specifically overriding the Bermuda Rise, vary in step with temperatures reconstructions from oxygen isotopes measured in ice from the summit of Greenland \(^{(23)}\).

Interestingly, the phase of Pa/Th does not appear to be stationary with respect to the other proxies, but lags when the ratio is increasing and northern temperature is declining, and decreases essentially in phase with warming SST and Greenland temperature (S.3). This likely reflects the century-scale time required for seawater Pa to grow into a steady state profile \(^{(24)}\) when lateral export by AMOC diminishes, and the more immediate response when export increases.

**Mechanics of \(\delta^{13}C_{BF}\), and \(G.\) ruber \(\delta^{18}O\)**

The carbon and oxygen isotopic composition of foraminifera reflect in part the water mass in which they calcified, as well as the kinetic, temperature-dependent steps of the calcification process. Variations in the \(\delta^{18}O\) of surface seawater are determined by hydrologic activity. In contrast gradations in \(\delta^{13}C_{BF}\) of seawater at depth track in part the residence time of waters at depth away from the surface ocean, with more negative carbon remineralized from the organic particles settling through the water column as water masses age. The contrast of younger North Atlantic Deep Water (NADW) and the older AABW allows changes in the water mass distributions to be reconstructed and attributed.

**Opal flux, differing lithology, authigenic uranium**

Because the opal belt in the South Atlantic would scavenge \(^{231}\)Pa from southern-sourced water mass, the increase of Pa/Th during stadials is unlikely to be a water mass artifact because that would tend to pull the ratio in the opposite direction. A subset of 55 thorium-230 normalized opal flux measurements were made throughout the record to test the hypothesis that the Pa/Th is sensitive to diatom blooms at the Bermuda Rise coring site. Opal fluxes were also reconstructed by differencing the carbonate wt% and thorium-232-based detrital contributions from bulk thorium normalized sediment fluxes. While there is some indication that opal fluxes increase during Heinrich stadials, there is no associated difference in opal flux by either method.
during stadial/interstadial events (Fig. S2). For that reason, we are confident that the return of the Pa/Th to the production ratio during DO stadials represents an increase in the residence time of waters of the North Atlantic basin. The $^{238}\text{U}/^{232}\text{Th}$ ratio of 0.56 +/- 0.12 (n=314) of previously published studies is consistent with our North Atlantic values within error, and therefore suggests that the source material should not alter our lithogenic corrections in any way that would change the conclusions of this study.
S1: X-ray fluorescence counts from scan of core CDH19 calibrated with coulometric measurements of %CaCO₃.
S2: Pa/Th on bulk sediment from core CDH19 plotted with $^{230}$Th$_{xs}$ normalized opal fluxes.
S3: Correlation of NGRIP with, respectively, entire Pa/Th record (black), Pa/Th only during periods when Pa/Th was decreasing and climate was warming (red), and Pa/Th only during periods when Pa/Th was increasing and climate was cooling (blue).
S4: NGRIP $\delta^{18}O_{\text{ice}}$ (blue), MD95-2036 SST C (dark red) (23), CDH19 CaCO$_3$ (%) based on x-ray fluorescence (XRF) Ca counts calibrated to discrete coulometric CaCO$_3$ analyses (red), CDH19 *G.ruber* $\delta^{18}O_{\text{calcite}}$ (blue) CDH19 *G.ruber* $\delta^{13}C_{\text{calcite}}$ (purple) CDH19 benthic $\delta^{18}O_{\text{BF}}$ (blue), and CDH19 mixed $\delta^{13}C_{\text{BF}}$ (purple).
Compilation of Bermuda Rise CaCO$_3$% records with NGRIP (blue), X-ray
fluorescence of core ODP1063 ln(Ti/Ca) (purple) (25), x-ray fluorescence (XRF) scans of core CDH19 ln(Ti/Ca) (pink), XRF scan of Ca counts (orange) calibrated to coulometric %CaCO$_3$ (black), spectral reflectance record (yellow) (26) of MD95-2036 calibrated with coulometric %CaCO$_3$ (in blue), GPC9 %CaCO$_3$ (light green), and GPC5 %CaCO$_3$ (dark green) (27).
S6: Benthic foraminifera species analyzed for this study, showing good correspondence in \( \delta^{13}C \) space, with a correlation of 0.75.
S7: While the range of values recorded for *C. wuellerstorfi* slightly exceed those recorded by *N. umbonifera*, their highly correlated values allow for interpretation of these species combined in a single time series of benthic $\delta^{13}C$. 
Bibliography


