# Incursions of southern-sourced water into the deep North Atlantic during Late Pliocene glacial intensification

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**The circulation and internal structure of the oceans exert a strong influence on Earth's climate because they control latitudinal heat transport and the segregation of carbon between the atmosphere and the abyss[1]. Circulation change, particularly in the Atlantic Ocean, is widely suggested[2-5] to have been instrumental in the intensification of northern hemisphere glaciation when large ice-sheets first developed on North America and Eurasia during the Late Pliocene, ~2.7 million years ago[6]. Yet the mechanistic link and cause/effect relationship between ocean circulation and glaciation are debated. Here we present new records of North Atlantic Ocean structure using the carbon and neodymium isotopic composition of deep waters for both the Last Glacial to Holocene (35-5 thousand years ago) and the Late Pliocene to earliest Pleistocene (3.3 to 2.4 million years ago). Our data show no secular change. Instead we document major southern-sourced water incursions into the deep North Atlantic during prominent glacials from 2.7 million years ago. Our results suggest that Atlantic circulation acts as a positive feedback rather than as an underlying cause of Late Pliocene northern hemisphere glaciation. We propose that, once surface Southern Ocean stratification[7] and/or extensive sea-ice cover[5] was established, cold-stage expansions of southern-sourced water such as those documented here enhanced carbon dioxide storage in the deep ocean, helping to increase the amplitude of glacial cycles.**

During the Last Glacial Maximum (LGM, ~26-19.5 thousand years ago, ka) nutrient (carbon)-poor North Atlantic Deep Water (NADW), or northern component waters (NCW) were replaced at depth in the western North Atlantic by nutrient (carbon)-enriched southern-component waters (SCW)[8], although the precise relationship between this orbitally paced change in ocean structure and Atlantic Meridional Overturning Circulation (AMOC) is uncertain[8,9]. Ocean circulation change is also suggested[2-5] to have played an important role in driving Earth's last major transition in secular climate state, the intensification of northern hemisphere glaciation (NHG) (~3.6-2.4 million years ago, Ma[10]). Here we test this hypothesis by constructing new records of water mass mixing in the deep North Atlantic Ocean using two proxies: carbon isotopes ($\delta^{13}C$) in benthic foraminiferal calcite and the neodymium (Nd) isotope composition ($\varepsilon_{Nd}$) of fish debris. Our records come from the benchmark site for monitoring the water mass structure of the deep Plio-Pleistocene North Atlantic, Deep Sea Drilling Project (DSDP) Site 607[11-15] and its reoccupation[16], Integrated Ocean Drilling Program (IODP) Site U1313 (~41°N and 3427 m depth) situated in the core of modern NADW.

The first reconstructions of water mass mixing during the intensification of NHG used $\delta^{13}C$ from Site 607[11,12] and concluded that prominent glaciations from ~2.5 Ma were associated with suppression of NCW in the deep North Atlantic, but that NCW production was always greater during NHG intensification than during the Late Pleistocene glaciations. Subsequent $\delta^{13}C$-based investigations[3,13-15] concluded, however, that NHG intensification was not associated with any major reorganization of North Atlantic circulation, but was instead characterized by the persistence of NCW in the deep Atlantic and of SCW in the deep South Atlantic throughout this time. That interpretation is at odds with suggestions that either a major spin-up[2] or a slow down[5] in AMOC played a key role in driving NHG intensification.

Our ability to reconstruct water mass mixing using benthic $\delta^{13}C$ is complicated by the potential for biological modification of this signal[14] and published estimates of the relative abundance of NCW (versus SCW) bathing the deep North Atlantic (%NCW) during NHG intensification are compromised by use of low resolution $\delta^{13}C$ data and unsuitable end-member records (see S1 in supplementary information). To address these issues we present two new independent estimates of %NCW over the past 3.3 Myr based on: (i) published benthic $\delta^{13}C$ from Site 607 (for <2.4 Ma[11,12]) and Site U1313 for 3.3 to 2.4 Ma[16] (which has twice the temporal resolution of the record from Site 607 for the NHG intensification interval; Fig. 1); and (ii) new records of the $\varepsilon_{Nd}$ of fish debris at Site U1313 for both the Last Glacial to Holocene (35–5 ka) and the Late Pliocene to earliest Pleistocene (1 sample every 6 kyr, 3.3–2.4 Ma; Fig. 2). Fish debris flourapatite acquires a bottom water $\varepsilon_{Nd}$ signature during early stage diagenesis that is retained on geological timescales under widely divergent preservation conditions[17]. Ocean $\varepsilon_{Nd}$ acts as a quasi-conservative water-mass tracer because the ocean residence time of Nd (400–700 years[17]) is short relative to the whole ocean mixing time (~1500 years) allowing water masses originating in different ocean basins to bear distinct $\varepsilon_{Nd}$ signatures (reflecting spatial heterogeneity in the age and lithology of material added to surface oceans and ocean continental-margin sediment boundary exchange processes[17]). The unradiogenic present day composition of NCW (modern NADW, $\varepsilon_{Nd} \sim -13.5$, Ref. 17) reflects the ancient continental crust surrounding sites of North Atlantic Deep-Water formation, while Pacific Deep Water (typically $\varepsilon_{Nd} \sim -3$ to $-6$, Ref. 17) and SCW end-members (modern Antarctic Bottom Water and Antarctic Intermediate Water, $\varepsilon_{Nd} \sim -7$ to $-9$, Ref. 17) bear more radiogenic values. Bottom water $\varepsilon_{Nd}$ can be modified through 'boundary exchange' with ocean sediments[18] but, unlike $\delta^{13}C$, $\varepsilon_{Nd}$ is independent of the carbon cycle[17], which underwent major change during NHG intensification[19]. Thus, application of two proxies with different controls provides a way to improve our understanding of NCW history during this time.

In Figure 2 we present new $\varepsilon_{Nd}$ records from Site U1313 for the Last Glacial through mid-Holocene and for NHG intensification from the deep North Atlantic and compare them to other $\varepsilon_{Nd}$ data sets and the $\delta^{13}C$ records from Figure 1. Our $\varepsilon_{Nd}$ record for the Last Glacial shows the same isotopic composition and closely follows published records from the deep western North Atlantic ($\varepsilon_{Nd}$ LGM > Holocene by ~3.5 ε-units)[8,18,20], demonstrating a clear incursion of radiogenic SCW into the deep North Atlantic during the LGM. Based on the age model of Ref. 21, and our new records of coarse lithic deposition at Site U1313 (Fig. 2c), changes in bottom water $\varepsilon_{Nd}$ suggest that the return of NADW during the last deglacial may occur at our study site during Heinrich (H)-event 1, ~18 ka, ~3 kyrs earlier than at deeper (>4500 m) and more southerly sites (Fig. 2a). This finding may be attributable to the more proximal location of Site U1313 to the Labrador Sea compared to Bermuda Rise, or alternatively, bottom water $\varepsilon_{Nd}$ at Site U1313 may be influenced by unradiogenic-labeling of deepwaters by massive episodes of ice-rafted detrital-carbonate deposition upstream of our study site during H1[22] (see supplementary information, S4). Regardless, our records show that, outside of H-events, $\varepsilon_{Nd}$ data from Site U1313 track the pattern of Last Glacial SCW incursion into the deep North Atlantic well documented by other proxy records[9].

Our new Nd isotope record for NHG intensification exhibits a range of $\varepsilon_{Nd}$ values (-9.6 to -13.1 = 3.5 ε-units) similar to the amplitude of change (-11 to -14.5 = 3.5 ε-units) documented for the Last Glacial transition (Fig. 2e,f). During the mid-Piacenzian Warm Period (~3.3-3 Ma), Site U1313 is characterized by unradiogenic values (Fig. 2b) similar to those observed for NCW as observed in contemporaneous Fe-Mn crust records precipitated in the shallow North Atlantic (1.9-2.65 km). In contrast in a number of cold stages during NHG intensification (MIS M2, G16, G6, 100 and 96) and one interglacial (MIS K1), our Nd record shows prominent radiogenic excursions that must reflect either significant changes in NCW $\varepsilon_{Nd}$ or times of increased influence of SCW on bottom waters at Site U1313 (see S2-4 in supplementary information). Analogy to our Last Glacial record strongly supports the latter explanation, thus providing the first evidence for a number of LGM-magnitude incursions of SCW into the deep North Atlantic during NHG intensification. To explore these events further we employ simple binary mixing equations (see methods, and supplementary information, S1-2) to both the $\varepsilon_{Nd}$ and $\delta^{13}C$ records from Site 607/U1313.

Both of our %NCW records (Figs. 1b, 2g-h) show significant excursions towards SCW values during NHG intensification (with reductions in %NCW down to 60%) consistent with published reconstructions[11,12], albeit not as clearly expressed in the lower resolution Site 607 $\delta^{13}C$ record (Fig. S4e). Comparison of our $\%NCW_{\delta 13C}$ and $\%NCW\varepsilon_{Nd}$ records shows that the significant radiogenic excursions in $\varepsilon_{Nd}$ at Site U1313 during MIS M2, 3.3 Ma, and MIS K1, ~3.07 Ma, (Fig. 2b,h) are not supported by our $\delta^{13}C$-based record (Fig. 2h,j). Similarly, a number of cold stages between ~3 and 2.75 Ma show $\%NCW_{\delta 13C}$ reductions that are not evident in $\%NCW\varepsilon_{Nd}$. Our understanding of the history of %NCW prior to ~2.72 Ma will improve when our knowledge of NCW and SCW end-member compositions is refined. Meanwhile, the good correspondence between our two records from ~2.72 Ma onwards strongly suggests that SCW incursions during MIS G6, 100 and 96 were comparable to the LGM. This inference is supported by LGM-magnitude cooling of bottom water temperatures at Site 607 during these three glacials, presumably reflecting the arrival of cold SCW in the deep North Atlantic (Fig. 3a, b). We also note that these events correlate with pronounced cooling of mid-latitude and/or Arctic surface temperatures (Fig. 3a-c).

Our evidence for Southern Ocean incursions into the deep North Atlantic provides fresh insight into the relationship between North Atlantic circulation and NHG intensification (Fig 3). Numerical models of ocean circulation suggest that any substantial secular slowdown in overturning of the NCW cell during NHG intensification would be registered by shoaling of its lower boundary[23] and hence a change in $\varepsilon_{Nd}$ at Site U1313 on a corresponding timescale. Instead the most prominent feature of our records is that they exhibit enhanced excursions during cold-stages rather than any long-term secular change (Fig. 2). We also observe the development of a lag in $\varepsilon_{Nd}$ relative to changes in benthic $\delta^{18}O$ at Site U1313 from ~2.9 Ma (typically of 4-9 kyr, Fig. S11), analogous to the Late Pleistocene (e.g., Ref. 8). These observations suggest a response of Atlantic circulation to, rather than secular forcing of glaciation.

Long-term expansion of the Antarctic Ice Sheet and coastal sea-ice between ~3.3 and 2.6 Ma[4,5,24], bi-polar surface water stratification from ~2.7 Ma[7] and increased heat transport from the northern hemisphere to the deep Pacific from this time[4] during warm but not cold stages (this study) helped to precondition the northern hemisphere for significant continental glaciation by cooling the Arctic and by enhancing storage of carbon dioxide in the abyss. We suggest that, once these preconditions were met (Fig. 3g-h), incursions of SCW into the deep North Atlantic acted as a positive feedback to amplify glacial cycles from ~2.72 Ma through increased sequestration of carbon in the deep Atlantic[1], contributing to the observed[4,5] tighter coupling of inter-hemisphere climate on orbital timescales from this time (Fig. 3). One prediction of this hypothesis is that further improvements to the proxy record of atmospheric $CO_2$ levels[19] will reveal an amplified signal at the obliquity scale from ~2.7 Ma.

It is debated whether Southern Ocean water incursions into the deep Atlantic during the Last Glacial Cycle were driven by southern polar ocean conditions, notably deepwater densification through increased sea-ice formation (a proposed driver of LGM NADW shoaling[25]) or by reductions in NCW formation during the LGM because of sensitivity to freshwater forcing[8] in the North Atlantic and/or sea ice expansion in the Nordic Seas. For NHG intensification, the close association between major SCW incursions at Site U1313 and evidence for the onset of major ice-rafted debris (IRD) deposition across both the Nordic Seas[26] and North Atlantic[6] from ~2.72 Ma onwards (Fig. 3f) suggests that SCW incursions into the deep North Atlantic were perhaps driven by northern forcing agents. On the other hand, step-wise expansion of the Antarctic Ice Sheet ~3.3 Ma is thought[5] to have triggered the initiation of quasi-permanent Antarctic sea ice formation (Fig 3g,h). Hence, if as suggested by our $\varepsilon_{Nd}$ record, major incursions of SCW into the deep Atlantic date to MIS M2 (i.e., well before the onset of major NHG[6,27,28]; Fig. 3e) then a southern hemisphere forcing mechanism is implied.

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**Author contributions**

IB and PAW designed the study. DCL picked, prepared and analysed fish debris for their Nd isotope compositions with guidance from MG. IB generated the Last Glacial-Holocene IRD record. DCL made initial interpretations of the data. IB and PAW wrote the main text with input from GLF and MG. TBC and GLF performed Monte Carlo simulations and statistical analyses. All authors discussed the results.

**Competing financial interests**

The authors declare no competing financial interests.

**Figure captions**

Fig. 1: Mixing history of northern- versus southern-sourced waters in the deep North Atlantic (~3400 m) for the past 3.3 Myr based on benthic foraminiferal carbon isotopes: (**a**) benthic $\delta^{13}C$ records from the shallow North Atlantic (ODP Site 982[14]), deep North Atlantic (composite of Chain 82-24-23PC[29], DSDP Site 607[11], and U1313[16]) and deep Pacific (ODP Site 849[30]) (**b**) %NCW estimated using records shown in (a) (purple line best estimate, shading 95% confidence interval, see methods); (**c**) benthic foraminiferal $\delta^{18}O$ data from Site U1313 (purple[31]) and global benthic $\delta^{18}O$ stack[10] (black).

Fig. 2: Mixing history of northern- versus southern-sourced waters in the deep North Atlantic, for 3.3-2.4 Ma and the Last Glacial-Holocene (35-5 ka): (**a** & **b**) fish debris $\varepsilon_{Nd}$ from IODP Site U1313 (purple; this study) and, in (a), $\varepsilon_{Nd}$ of uncleaned planktic foraminifera (brown[18]) and bulk sediment leachate (green[8,20]) from Bermuda Rise (error bars = 2σ uncertainty); (**c** & **d**) U1313 IRD concentration (40-5 ka, this study; NHG intensification[16,31]); $\varepsilon_{Nd}$ deviation from mean (35-5 ka) (**e**) and 3.3-2.4 Ma (**f**); (**g** & **h**) %NCW at U1313 using $\varepsilon_{Nd}$ (top) from (a & b, this figure) and $\delta^{13}C$ (bottom) from Fig. 1b; purple line best estimate, shading 95% confidence interval; (**i-l**) benthic foraminiferal $\delta^{13}C$, $\delta^{18}O$ and $\varepsilon_{Nd}$ from U1313[16]/82-24-23PC[29] and benthic $\delta^{18}O$ stack[10]. Sources of crust and Cape Basin $\varepsilon_{Nd}$ records used to define NCW and SCW $\varepsilon_{Nd}$ given in Tab. S3. Pink(blue) zones in (a) and (b) reflect $\varepsilon_{Nd}$ range of NCW(SCW) end-members used to estimate %NCW shown in (g) & (h) (see methods). Red bar in (a) = range of modern NADW $\varepsilon_{Nd}$[17].

Fig. 3: Incursions of southern-sourced water into the deep North Atlantic (~3400 m) and relation to NHG intensification: (**a**) %NCW$\varepsilon_{Nd}$ (purple line best estimate, shading 95% confidence interval); (**b**) alkenone-SST at Site U1313[32] and Mg/Ca bottom water temperature at Site 607[29]; (**c**) Air temperature in Arctic NE Russia[28] (**d**) age range and 2σ uncertainty for oldest advance of Laurentide Ice Sheet into Missouri[27]; (**e**) onset of major NHG[6,27,28]; (**f**) Ice-rafting to U1313[16,31], Site 611[6] (52.5˚N) and Site 907[26] (69˚N); (**g**) Antarctic sea-ice evolution based on Site 1096 opal mass accumulation[24] and on AND-1B diatom species[5]; (**h**) glacial regime of marine Antarctic Ice Sheet in Ross Embayment (AND-1B)[5]; (**i**) benthic $\delta^{18}O$ stack[10].

**Methods**

To reconstruct the provenance of bottom waters bathing Site U1313 during NHG intensification between 2.4 to 3.3 Ma (MIS MG1–95) we sampled on average every 30 cm (~6 kyr) from the shipboard primary splice (between 114.3 and 155.2 metres composite depth, mcd) used to generate the published benthic $\delta^{18}O$ (Ref. 31) and $\delta^{13}C$ (Ref. 16) stratigraphies for our study site. Fish debris from sediments deposited at Site U1313 during MIS 100, and from six samples on which detrital sediment $\varepsilon_{Nd}$ values were previously published[16], were hand-picked from samples taken from the secondary splice after placing the secondary splice onto the depth scale of the primary splice via manual graphical correlation of shipboard-derived sediment lightness records (L*, here driven by variability in the sediment calcium carbonate content[16], Fig. S10). The age model for our record is based on tuning[31] the Site U1313 benthic $\delta^{18}O$ stratigraphy to the LR04 stack[10]. To generate a Last Glacial to Holocene $\varepsilon_{Nd}$ record for Site U1313 we sampled Holes C and D of this site every 7 to 14 cm from 0.2–1.76 mcd, (n = 22, see also Fig. S9) corresponding to an average sampling resolution of ~1.3 kyr. The published age model[21] that we use for our Last Glacial record is based on correlation of H-layers in the Site U1313 stratigraphy (tracked by XRD dolomite/calcite ratio data) to X-ray fluorescence-based Ca/Sr elemental data that track the position of H-layers in the stratigraphy of northeast Atlantic Ocean IODP Site U1308 (~50°N), which has a benthic $\delta^{18}O$ stratigraphy on LR04 ages[33].

We hand-picked fish debris (10 to 30 pieces of bones and teeth, depending on availability) from the >150μm fraction of disaggregated sediment. Samples were cleaned with two steps of ultrasonication in methanol, followed by three rinses in MilliQ $H_2O$. Organic material was removed by bathing each sample in an oxidising solution (1% $H_2O_2$ – 0.1M $NH_4OH$) at 80°C for 30 minutes, while sonicating for 30 seconds every 10 minutes. A weak-acid (0.001M $HNO_3$) leach was applied to ensure removal of any reabsorbed contaminants, before samples were dissolved in 0.1ml 1.75M HCl. Pure samples of Nd were separated following standard procedures[34,35]. Nd isotope ratios ($^{143}Nd/^{144}Nd$) were measured at the University of Southampton using a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, Thermo Scientific Neptune). Neodymium isotope compositions were obtained using the method of Ref. 36 through adjustment to a $^{146}Nd/^{144}Nd$ ratio of 0.7219 and a secondary normalization to $^{142}Nd/^{144}Nd$ = 1.141876 (Ref. 36). Total procedural blanks averaged 35 pg for fish debris. External reproducibility of the JNdi standard[37] was ±0.000006 (2 s.d.), corresponding to an external error of ±0.13 $\varepsilon_{Nd}$ (2 s.d.). In all cases we plot the external error, unless the internal error is larger than the external error when we plot a combined error calculated as $\sqrt{(\text{external error}^2 + \text{internal error}^2)}$. All Nd isotope ratios are reported in epsilon notation as:

$$\varepsilon_{Nd} = \left[ \frac{^{143}Nd/^{144}Nd_{sample}}{^{143}Nd/^{144}Nd_{CHUR}} - 1 \right] x10^4$$

Radiogenic ingrowth of $^{143}Nd$ is corrected using a typical $^{147}Sm/^{144}Nd$ of 0.125 (Ref. 38). Corrections are within analytical uncertainty (<0.06 $\varepsilon_{Nd}$ for our NHG intensification data, and negligible for Last Glacial–Holocene data), reflecting the young age of our samples relative to the half-life of $^{147}Sm$. We note that fish debris $^{147}Sm/^{144}Nd$ ratios typically vary within a narrow range and that our results are insensitive to the choice of this value.

A record of sand IRD abundance in sediments deposited at Site U1313 during NHG intensification already exists[16,31]. To assess the concentration of IRD in sediments for the Last Glacial at our study site we performed new coarse lithic counts on the >150 µm size fraction between 0.2-2.43 mcd. To generate a statistically significant record of sand IRD abundance in Site U1313 sediments (expressed as IRD per gram of dry sediment) we identified the composition of at least 300 coarse lithics or where 300 grains were not present we counted all grains in the sample (where there were typically only 1-30 total grains in Last Glacial sediments deposited outside of Heinrich-events). In each case, our counts differentiated between volcanics, cream coloured detrital limestone and other coarse lithics (predominantly quartz and feldspar, plus minor numbers of other rock clasts).

To estimate the relative contribution of NCW bathing Site 607/U1313 over the past 3.3 Ma using benthic $\delta^{13}C$ datasets we used the following binary mixing equation:

$$\%NCW_{\delta 13C} = 100 * \left( \frac{\delta 13C_{(607/U1313)} - \delta 13C_{(SCW)}}{\delta 13C_{(NCW)} - \delta 13C_{(SCW)}} \right)$$

Where $\%NCW_{\delta 13C}$ is the relative contribution of NCW to waters bathing the deep North Atlantic Ocean (%SCW = 100 - %NCW), $\delta^{13}C_{(607/U1313)}$ is the carbon isotope composition of benthic foraminiferal calcite (predominantly determined from the epifaunal benthic foraminifera *Cibicidoides wuellerstorfi*) from the deep North Atlantic (Site 607/U1313), and $\delta^{13}C_{(NCW)}$ and $\delta^{13}C_{(SCW)}$ are the equivalent carbon isotope signatures of NCW (ODP Site 982, Ref. 14) and SCW (ODP Site 849, Ref. 30), respectively (see supplementary information, S1, for further details).

To estimate the relative contribution of NCW and SCW to waters bathing IODP Site U1313 during NHG intensification and the last deglacial using Nd isotopes we used the following binary mixing equation constrained by our current understanding of end-member compositions and their Nd concentrations:

$$\%NCW_{\varepsilon Nd} = \frac{\frac{fnCs}{fsCn}}{1+\frac{fnCs}{fsCn}} \times 100$$

Where $\%NCW_{\varepsilon Nd}$ is the relative contribution of NCW to waters bathing Site U1313 ($\%SCW = 100 - \%NCW_{\varepsilon Nd}$) and *Cs* = concentration of Nd in SCW, *Cn* = concentration of Nd in NCW. *fn* = fraction of Nd coming from the north, such that:

$$fn = \frac{\varepsilon_{NdU1313} - \varepsilon_{NdSCW}}{\varepsilon_{NdNCW} - \varepsilon_{NdSCW}}$$

where $\varepsilon_{NdU1313}$ is the Nd isotope value of fish debris from Site U1313, $\varepsilon_{NdSCW}$ is the southern end member isotope composition and $\varepsilon_{NdNCW}$ is the northern end member isotope composition; *fs* is then the fraction of Nd coming from the south which is equal to 1-*fn* in our binary mixing model (i.e. everything that is not from a northern source). To estimate the $\varepsilon_{Nd}$ of NCW and SCW during NHG intensification we took the average value of all published Fe-Mn crust $\varepsilon_{Nd}$ (and their 2s.d.) that span ~3.3-2.4 Ma (Fig. 2b and Tab. S3). For our Last Glacial-Holocene record, following Ref. 39, NCW $\varepsilon_{Nd}$ was defined as the average of our Holocene data (<14 ka; MIS 2/1 boundary as defined by Ref. 10) from Site U1313 (and their 2s.d.) (Fig. 2a and Tab. S3). We define SCW $\varepsilon_{Nd}$ for this time interval using a splice of Site RC11-83 &

TN057-21 $\varepsilon_{Nd}$; Ref. 39; Tab. S3), which we resampled onto the ages of our Site U1313 record (see S2 in supplementary information for further details). Confidence intervals (95%) for %NCW are estimated using a Monte Carlo simulation (n=10,000) performed in R[40], fully propagating analytical uncertainties, and uncertainties in the $\varepsilon_{Nd}$ of NCW and SCW and their Nd concentrations[41] (see S2 in supplementary information). To perform this exercise we make the following assumptions: (i) Nd isotopes exhibit conservative behaviour, which is an acceptable approximation in abyssal open ocean settings, (ii) mixing of NCW and SCW at Site U1313 is binary, and (iii) that the modern day end-member [Nd] has remained constant over the past ~3.3 Ma (see S2 in supplementary information).

To determine the lag-correlation of Site U1313 $\varepsilon_{Nd}$ (this study), benthic $\delta^{13}C$ (Ref. 16) and Site U1313 benthic $\delta^{18}O$ (Ref. 31) during NHG intensification (Fig. S11) we used an auto-correlation function in R[40] every 50 kyr using a 200 kyr window. Before analysing the data all records were resampled at a common 1 kyr resolution.

**Methods References**


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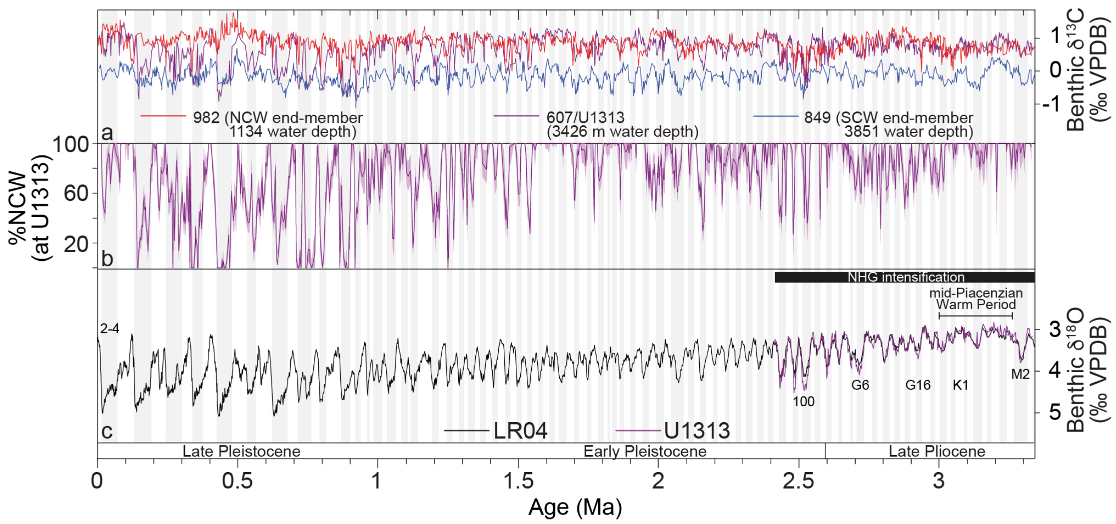
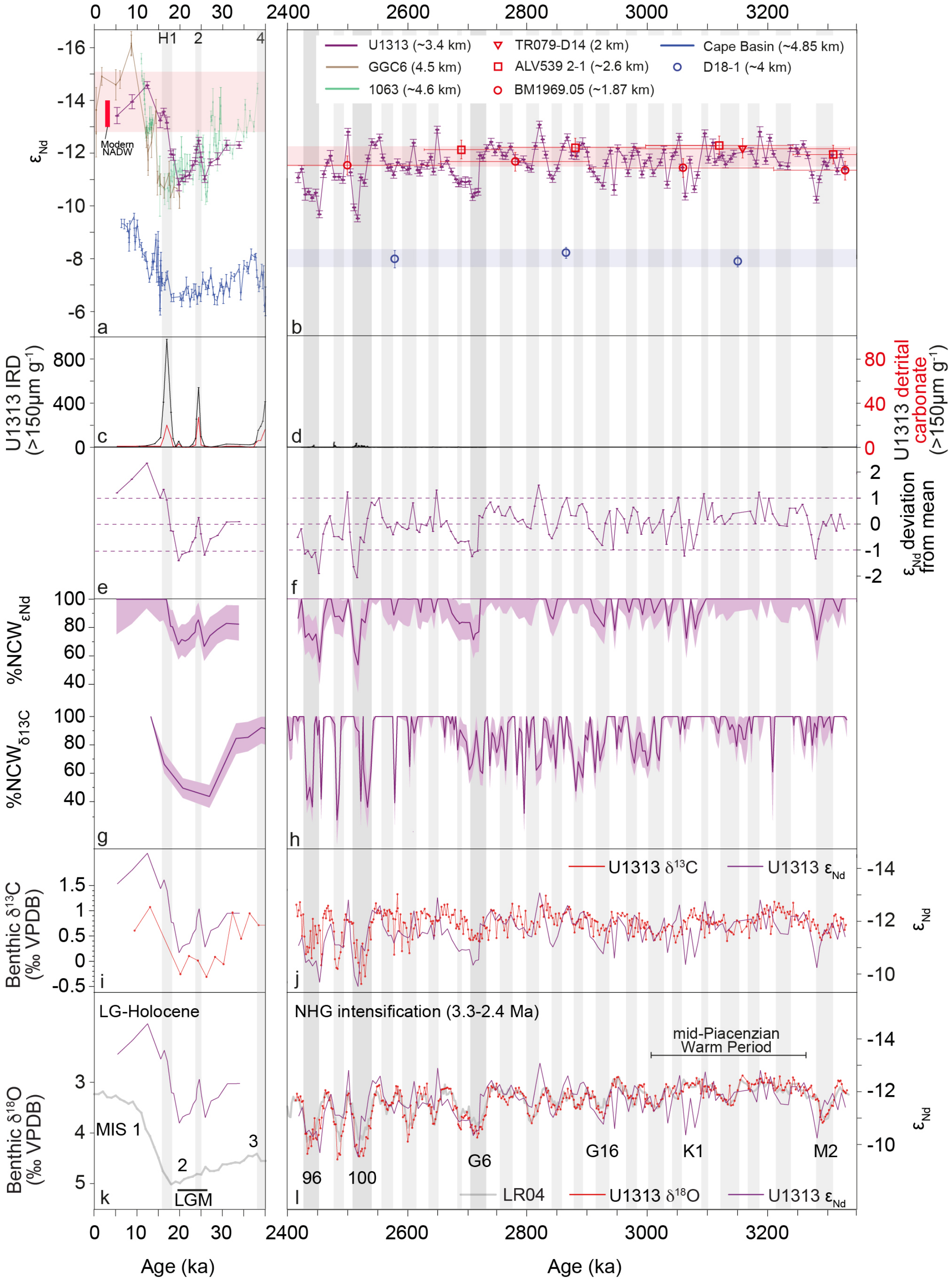


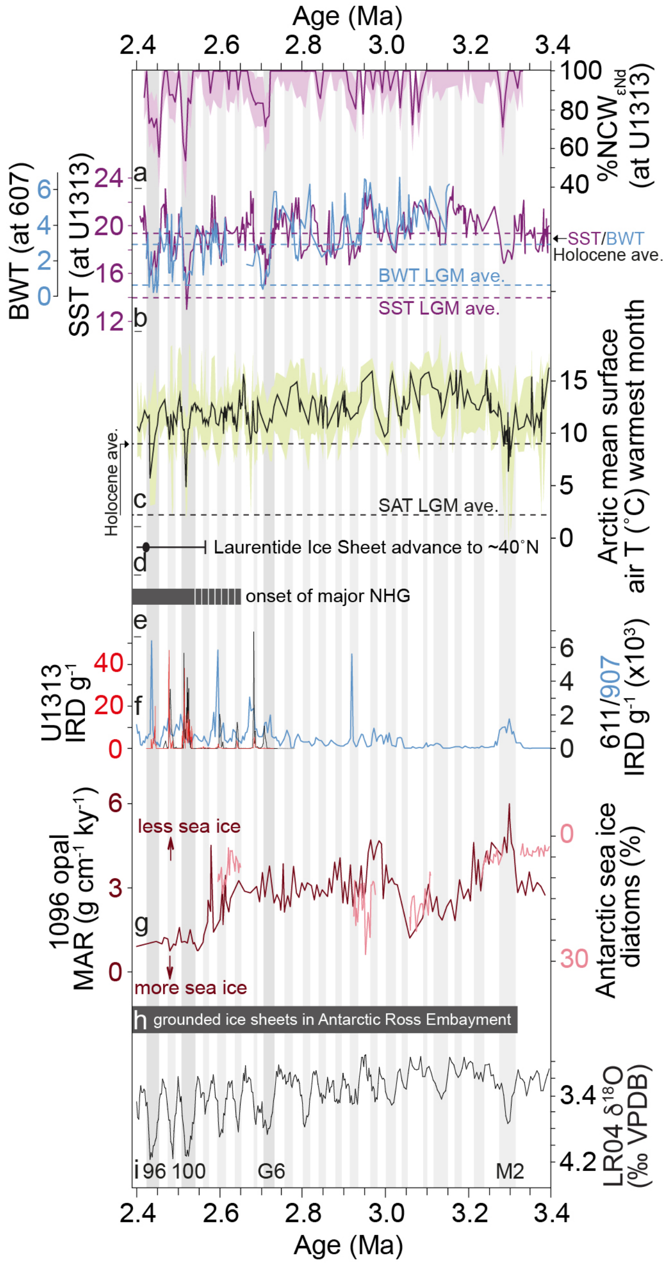
982 (NCW end-member
1134 water depth)
607/U1313
(3426 m water depth)
849 (SCW end-member
3851 water depth)
Benthic δ13C (‰ VPDB)
%NCW (at U1313)
NHG intensification
mid-Piacenzian Warm Period
2-4
100
G6
G16
K1
M2
LR04
U1313
Benthic δ18O (‰ VPDB)
Late Pleistocene
Early Pleistocene
Late Pliocene
Age (Ma)


Figure 1.



U1313 (~3.4 km)
GGC6 (4.5 km)
1063 (~4.6 km)
TR079-D14 (2 km)
ALV539 2-1 (~2.6 km)
BM1969.05 (~1.87 km)
Cape Basin (~4.85 km)
D18-1 (~4 km)
Modern NADW
H1
2
4
εNd
U1313 IRD (>150μm g-1)
U1313 detrital carbonate (>150μm g-1)
εNd deviation from mean
%NCWεNd
%NCWδ13C
Benthic δ13C (‰ VPDB)
U1313 δ13C
U1313 εNd
LG-Holocene
NHG intensification (3.3-2.4 Ma)
mid-Piacenzian Warm Period
Benthic δ18O (‰ VPDB)
MIS 1
LGM
3
96
100
G6
G16
K1
M2
LR04
U1313 δ18O
Age (ka)


Figure 2.



Age (Ma)
2.4
2.6
2.8
3.0
3.2
3.4
100
80
60
40
%NCW εNd (at U1313)
a
BWT (at 607)
SST (at U1313)
24
20
16
12
6
4
2
0
SST/BWT Holocene ave.
BWT LGM ave.
SST LGM ave.
b
15
10
5
0
Arctic mean surface air T (°C) warmest month
Holocene ave.
c
SAT LGM ave.
d
Laurentide Ice Sheet advance to ~40°N
onset of major NHG
e
U1313 IRD g-1
40
20
0
f
611/907 IRD g-1 (x10³)
6
4
2
0
1096 opal MAR (g cm-1 ky-1)
6
3
0
less sea ice
more sea ice
g
Antarctic sea ice diatoms (%)
0
30
h
grounded ice sheets in Antarctic Ross Embayment
3.4
4.2
LR04 δ18O (‰ VPDB)
i
96
100
G6
M2


Figure 3.