

**A major change in  
North Atlantic deep  
water circulation  
1.6 Ma**

N. Khélifi and M. Frank

# A major change in North Atlantic deep water circulation during the Early Pleistocene transition 1.6 million years ago

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## Abstract

The global ocean-climate system has been highly sensitive to the formation and advection of deep water in the North Atlantic but its evolution over the Pliocene–Pleistocene global cooling is not fully understood. In particular, changes in the sources and mixing of prevailing deep waters are not well constrained. Here we present new records of the bottom-water radiogenic neodymium isotope ( $\epsilon_{Nd}$ ) variability obtained from three DSDP/ODP sites at water depths between 2100 and 5000 m in the Northeast Atlantic to reconstruct changes in deep water circulation over the past 4 million years. Prior to 1.6 million years ago (Ma), we find  $\epsilon_{Nd}$  values primarily oscillating between  $-9$  and  $-11$  at all sites, consistent with enhanced vertical mixing of water masses. At 1.6 Ma, the  $\epsilon_{Nd}$  signatures synchronously shifted to less radiogenic values around  $-12$  at different water depths and water mass signatures gradually became more distinct. Since then values and amplitudes of “glacial/interglacial”  $\epsilon_{Nd}$  oscillations have been similar to the Late Quaternary at each site. This change 1.6 Ma reflects a major reorganization of deep water circulation in the Northeast Atlantic towards a more stratified water column with distinct water masses accompanying the enhanced response of climate to the Earth’s obliquity forcing during the Early Pleistocene transition.

## 1 Introduction

The reconstruction of past changes in ocean circulation enables the assessment of the role of the ocean in the development of the global climate system. In particular, changes in the cold, dense overflow from the Greenland-Iceland-Norwegian (GIN) Seas into the deep North Atlantic and the compensating northward flow of warm, saline surface waters as part of the Gulf Stream/North Atlantic Current (NAC) system have had a significant impact on the Atlantic meridional overturning circulation (AMOC). It is therefore crucial to constrain past changes of this conveyor belt system and to evaluate its role in North Atlantic circulation and climate, especially over the Plio–Pleistocene global

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cooling, during which the modern feedbacks and mechanisms driving the global climate system developed.

Here, we trace changes in deep-water formation and water mass mixing in the deep Northeast Atlantic using the radiogenic neodymium (Nd) isotope composition of past seawater extracted from the authigenic ferromanganese (Fe–Mn) coatings of deep sea sediment particles and of foraminiferal shells at three core sites near the GIN Seas overflow over the last 4 million years. In their source areas water masses are imprinted with the Nd isotope signature of the rocks of the adjacent landmasses through weathering processes. The Nd isotope signatures are expressed as  $\epsilon_{\text{Nd}}$  values corresponding to the deviation of the measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of a sample from that of the chondritic uniform reservoir (CHUR = 0.512638), multiplied by 10 000 (Jacobsen and Wasserburg, 1980). Old continental rocks contribute much lower  $\epsilon_{\text{Nd}}$  values than younger mantle-derived material (e.g. Goldstein and O’Nions, 1981). Given that Nd has an average global oceanic residence time of  $\sim 400\text{--}700$  yr (Rempfer et al., 2011) and differences in  $\epsilon_{\text{Nd}}$  between water masses are large enough to be detectable (cf. Frank, 2002), Nd isotopes have been used as a quasi-conservative tracer to infer changes in past deep-water sources and their mixing within the North Atlantic basin on different time scales (e.g. O’Nions et al., 1998; Burton et al., 1999; Roberts et al., 2010; Crocket et al., 2011; Piotrowski et al., 2012).

## 2 Study area

Modern circulation patterns in the North Atlantic result in an  $\epsilon_{\text{Nd}}$  value near  $-13$  for the northward flow of NAC, whereas  $\epsilon_{\text{Nd}}$  values of  $-9$  or above characterize the deep southward return overflow from the GIN Seas that contribute to the formation of lower North Atlantic Deep Water (NADW; Lacan and Jeandel, 2004a, b, 2005; Figs. 1 and 2). The easternmost part of the GIN Seas overflow occurs through the Faroe–Shetland Channel across the Wyville–Thomson Ridge into the Rockall Trough with a typical  $\epsilon_{\text{Nd}}$

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signature of  $-10.3$  (Crocket et al., 2011) as a consequence of the entrainment of the overlying NAC (Sherwin et al., 2008; Figs. 1 and 2).

Sediments obtained from two core sites close to the GIN Seas overflow serve to reconstruct its variability through time (Figs. 1 and 2). Ocean Drilling Program (ODP) Site 980/981 ( $55^{\circ}29' N$ ,  $14^{\circ}42' W$ ; 2170 m water depth) is located at the southernmost edge of the tongue of Wyville–Thomson Ridge Overflow Water (WTROW; Johnson et al., 2010). This location is therefore ideally suited to sensitively monitor past changes in the flow of WTROW into Rockall Trough. Deep Sea Drilling Project (DSDP) Site 610 ( $53^{\circ}13' N$ ,  $18^{\circ}53' W$ ; 2420 m w.d.) is located at the lowermost limit of the core of WTROW. Underneath deep-water masses prevail that consist of Labrador Sea Water (LSW) and (old) lower NADW, which is mixed with relatively cold and less saline Southern Ocean Water (SOW), a transformed derivative of Antarctic Bottom Water (AABW; e.g. Tarakanov et al., 2013). This lower NADW fills most of the Northeast Atlantic below 2500 m today (McCartney, 1992). We thus also included deep ODP Site 900 ( $46^{\circ}40' N$ ,  $11^{\circ}36' W$ ; 5050 m w.d.) to reconstruct potential changes in the abyssal circulation of the lower NADW and SOW. With  $\epsilon_{Nd}$  values of SOW around  $-8.5$  at its source (Jeandel, 1993; Stichel et al., 2012) Site 900 should be sensitive to changes in the relative influence of northern vs. southern source waters, as has been demonstrated for other sites further south on glacial/interglacial time scales of the latest Quaternary (e.g. Roberts et al., 2010).

### 3 Methods

The bottom water Nd isotope composition was extracted from the ferromanganese coatings of  $\sim 2$  g of dried bulk sediment by leaching following the analytical protocol of Gutjahr et al. (2007). The Nd in the leach solutions was chemically treated and purified following the protocol of Cohen et al. (1988). Nd isotope compositions were measured on a Nu instruments multi collector–inductively coupled plasma mass spectrometer at GEOMAR Kiel. All Nd isotope ratios presented were normalized to the accepted value

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for the standard JNdi-1 of 0.512115 (Tanaka et al., 2000). External reproducibility was assessed by repeated measurements of the JNdi-standard yielding  $2\sigma$  uncertainties of  $\pm 0.2$  to  $\pm 0.4$   $\epsilon_{\text{Nd}}$  units during the different measurement sessions.

In order to overcome potential problems of contamination with highly radiogenic Nd leached from basaltic glasses or ash at Site 610 we used Fe–Mn oxide coatings on shells of mixed species of planktonic foraminifera to extract the  $\epsilon_{\text{Nd}}$  signature of bottom waters following the cleaning procedure of Roberts et al. (2010). Between 30 and 80 mg of the shells were picked from the  $> 250$   $\mu\text{m}$  fraction and weighed. Samples were split into 1/3 of the samples for analysis as “unclean” foraminifera (not reductively cleaned) and the remaining 2/3 of the sample underwent oxidative-reductive cleaning. The  $\epsilon_{\text{Nd}}$  signature of cleaned and “uncleaned” foraminifera were always indistinguishable within analytical uncertainty although external reproducibility was  $\pm 0.9$   $\epsilon_{\text{Nd}}$  units for these data due to smaller amounts of Nd present in the samples. Moreover,  $\epsilon_{\text{Nd}}$  data of both mixed planktonic foraminifera and bulk sediment leaches were generally indistinguishable and showed the same trends of the downcore records. We thus did not generate an additional foraminiferal  $\epsilon_{\text{Nd}}$  record for nearby Site 980/981. At Site 900, planktonic foraminifera are not sufficiently abundant to generate an  $\epsilon_{\text{Nd}}$  record, which is why we base our reconstructions only on the bulk sediment leaches. The results demonstrate that the authigenic ferromanganese coatings of both mixed planktonic foraminifera and of bulk sediment preserved a reliable bottom water  $\epsilon_{\text{Nd}}$  signature at the investigated sites in the North Atlantic. The extraction of pure seawater  $\epsilon_{\text{Nd}}$  signals by the applied leaching procedure is also supported by measurements of the Sr isotope composition of selected leachate solutions, which all are very close to the contemporaneous seawater values (see Table S1 in the Supplement).

The age model for Site 610 has been adopted from De Schepper and Head (2008) and for Site 980/981 from Lisiecki and Raymo (2005). The age model for Site 900 integrates evidence from shipboard biostratigraphy and magnetostratigraphy of ODP Leg 173 (Zhao et al., 2001). In order to better constrain the ages for selected samples at

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Site 900 we sampled only within the intervals of biostratigraphic and magnetostratigraphic age control points.

All data presented in this study are available in the Supplement (Table S1).

## 4 Results and discussion

5 Modern and Holocene bottom water  $\epsilon_{\text{Nd}}$  signatures of four samples of shallower Site 980/981 extracted from ferromanganese coatings of bulk sediments yield an average value of  $-10.6 \pm 0.2$ , similar to estimated values for WTROW at the same site for the late Holocene (Crocket et al., 2011; Fig. 3). The late Holocene  $\epsilon_{\text{Nd}}$  signature at Site 610 is  $-11.5 \pm 0.2$  which is within error identical to the bottom water signature extracted from ferromanganese coatings precipitated on mixed (cleaned) planktonic foraminifera of the same sample (Fig. 3; Table S1 in the Supplement). These values are also within the  $\epsilon_{\text{Nd}}$  range of modern bottom water at nearby locations (Lacan and Jeandel, 2004a, b, 2005; Rickli et al., 2009). For Site 900, the  $\epsilon_{\text{Nd}}$  signature of the youngest sediments is  $-9 \pm 0.2$  which is  $\sim 2\epsilon_{\text{Nd}}$  units more positive than the water column signature of a  $\sim 400$  m shallower water mass in the Bay of Biscay (Rickli et al., 2009) and is also slightly more positive than the modern  $\epsilon_{\text{Nd}}$  signature of AABW-derived deep water further south near Cape Verde ( $\epsilon_{\text{Nd}} = -9.6$ ; Godfrey et al., 2009). This would indicate that water masses with more positive  $\epsilon_{\text{Nd}}$  signatures were admixed to the bottom waters of deep Site 900, which most likely overflowed from the GIN Seas as part of the Iceland Scotland Overflow Water (ISOW;  $\epsilon_{\text{Nd}} = -8$ ; Lacan and Jeandel, 2005) and then were advected across the Iceland Scotland gap into the recirculation gyre south of the Iceland Basin (McCartney, 1992; Figs. 1 and 2). However, a similarly radiogenic  $\epsilon_{\text{Nd}}$  signature of  $-8$  was also recorded for the last glacial at nearby core site BOFS 8K south of Rockall Plateau at 4045 m depth located under the same influence of the re-circulation gyre (Piotrowski et al., 2012; Figs. 1 and 2), most likely as a response to intermittent contributions from GIN Seas overflow. This suggests that the more radiogenic  $\epsilon_{\text{Nd}}$  signature extracted from the bulk surface sediment Fe–Mn coatings at Site

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900, most likely due to erosion of the Holocene sediments, rather represents a glacial signature and is not a consequence of potential contamination of the leachate samples with basaltic material.

The downcore  $\epsilon_{\text{Nd}}$  records of Sites 980/981 and 610 show broadly similar oscillations  $\sim 1\epsilon_{\text{Nd}}$  unit higher than today around average levels of  $-9.5 \pm 0.4$  and  $-10.5 \pm 0.3$ , respectively, over the time interval 3.90–1.65 Ma (Fig. 3). However, unlike Site 610, the record of Site 980/981, which is more proximal to the GIN Seas overflow (Fig. 2), is intersected by distinct positive excursions of  $\sim 2\epsilon_{\text{Nd}}$  units reaching the modern level of the Nordic Seas overflow at  $-8$  to  $-9$  (Lacan and Jeandel, 2004a, b, 2005) during glacial marine isotope stages (MIS) G20 (3.02 Ma), 98 (2.48 Ma), and 70 (1.86 Ma). Only during cold MIS M2 near 3.3 Ma both records display a major positive excursion reaching  $-9$ . At glacial MIS 58 (1.65 Ma) a marked decrease by  $3\epsilon_{\text{Nd}}$  units occurred to reach  $-11.5$  at Site 980/981 and  $-13$  at Site 610 near 1.4 Ma. This major  $\epsilon_{\text{Nd}}$  shift primarily represents interglacial intervals and was followed by pronounced “glacial/interglacial” oscillations of  $\sim 3\epsilon_{\text{Nd}}$  units at Sites 610 and 980/981 (Figs. 3 and 4), which are similar to the Last Glacial Maximum/Holocene range for nearby deeper core BOFS 8K ( $\sim 4\epsilon_{\text{Nd}}$  units; Piotrowski et al., 2012). This prominent shift is corroborated by  $\epsilon_{\text{Nd}}$  measurements of cleaned and “uncleaned” planktonic foraminifera at Site 610, further supporting the reliability of our bottom water  $\epsilon_{\text{Nd}}$  reconstruction from bulk sediment leachates.

The general similarity of the  $\epsilon_{\text{Nd}}$  records at Sites 980/981 and 610 over the 4-million-year-long interval suggests a largely persistent advection of the same northern source deep waters. The consistent offset of  $\sim 1\epsilon_{\text{Nd}}$  unit between the two records reflects the presence of a water mass with slightly lower  $\epsilon_{\text{Nd}}$  signature at  $\sim 250$  m deeper Site 610, most likely a result of persistent mixing with less radiogenic underlying LSW and/or lower NADW (present day  $\epsilon_{\text{Nd}} = -14$  and  $-13$ , respectively; Lacan and Jeandel, 2005). At the deepest Site 900,  $\epsilon_{\text{Nd}}$  values display a similar decrease by  $\sim 2\epsilon_{\text{Nd}}$  units from 1.65 to 1.35 Ma. However, in contrast to Sites 980/981 and 610, the  $\epsilon_{\text{Nd}}$  signatures at Site 900 evolved to significantly more radiogenic values thereafter. In addition, Site 900

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has experienced less pronounced oscillations, finally reaching last glacial  $\epsilon_{Nd}$  levels near  $-9$  (Fig. 3).

The concurrent shift in bottom water Nd composition at two sites close to the GIN Seas overflow at 1.65–1.40 Ma documents a key change in Nordic Seas overflow and climate occurring primarily during interglacial intervals (Fig. 4). During this period, surface waters in the study area experienced a major cooling (summarized in Lawrence et al., 2010) that was accompanied by frequent inputs of ice rafted debris (Mc Intyre et al., 1999). The cooling occurred during what appeared to be a time of relatively stable polar climate and glacial ice volumes (Lisiecki and Raymo, 2005; Fig. 3). Since pertinent records (e.g. Lawrence et al., 2009; Naafs et al., 2010) do not show any coeval decrease in poleward heat and salt transport within the NAC (present day  $\epsilon_{Nd} = -13$ ; Lacan and Jeandel, 2004a, b) which would have resulted in less advection of “unradiogenic” subsurface waters into the Nordic Seas, the cooling was most likely linked to an expansion of subpolar waters (present day  $\epsilon_{Nd} = -10$  to  $-8.5$ ; Lacan and Jeandel, 2004a, b). Recent findings by Martínez-García et al. (2010) show, in fact, that during that very time the sub-Arctic region underwent a substantial cooling associated with sea-ice expansion, which continued across the mid-Pleistocene transition (McClymont et al., 2008). This major sub-Arctic cooling led to the formation and advection of cold deep waters into the North Atlantic basin, which was recorded further south in the North Atlantic (ODP Site 607) by a long-term decrease in NADW temperature after  $\sim 1.55$  Ma (Sosdian and Rosenthal, 2009), coeval with major surface water cooling in the area (see comparison in Lawrence et al., 2010).

Assuming that the bottom water signature was derived primarily from the sinking of surface waters in the Nordic Seas similar to the modern conditions, we infer that the 1.65–1.40 Ma period reflects a major weakening of deep-water production at the Nordic Seas convection centers and consequently of Nordic Seas overflow. We propose that the major shift to less radiogenic signatures (especially during interglacial intervals; Fig. 4) was related to a change in overturning circulation after 1.6 Ma rather than changes in erosional inputs and continental weathering regime. The reduced

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Nordic Seas overflow resulted in increased admixture of LSW and lower (old) NADW in the Northeast Atlantic. Our conclusion is supported by other more traditional paleoceanographic proxies such as stable carbon isotopes. There is indeed a clear evidence of such a change in North Atlantic deep water circulation after 1.6 Ma based on the analysis of stable carbon isotopes in benthic foraminifera at orbital-scale resolution in a series of cores located in the studied region as well as other areas of the Atlantic Ocean (e.g. Venz and Hodell, 2002; Hodell and Venz, 2006; Lawrence et al., 2010). These studies reported major changes in vertical, meridional and interbasinal benthic  $\delta^{13}\text{C}$  gradients occurring after  $\sim 1.55$  Ma, which have been interpreted to mark the development and intensification of a chemical divide in the Atlantic Ocean between well-ventilated intermediate water and poorly ventilated deep water (Hodell and Venz, 2006). This supports our findings on the major reorganization of deep water circulation in the North Atlantic. There, the  $\varepsilon_{\text{Nd}}$  shift towards less radiogenic values corresponded to a diminished production of well-ventilated deep waters from the Nordic Seas.

The major event near 1.65 Ma occurred at a point in time clearly preceding the main shift in amplitude and frequency of benthic  $\delta^{18}\text{O}$  (ice volume) record (Lisiecki and Raymo, 2005) and southward movement of the Arctic front (e.g. McClymont et al., 2008) during the mid-Pleistocene transition  $\sim 1.2$ – $0.8$  Ma (Fig. 3). Accordingly, it seems unlikely that the 1.65–1.4 Ma event can be only linked to changes in ice sheet dynamics. In contrast, for exactly this period of time an increase in the amplitude of the 41 kyr obliquity cycle (Laskar et al., 1993) and in the climatic response to obliquity forcing has been reported (Lisiecki and Raymo, 2007). This is supported by a change in southern high latitude climate which became more sensitive to (obliquity-driven) variations in Southern Hemisphere insolation forcing around 1.6 Ma (Naish et al., 2009). This most likely resulted in the observed cooling of the Nordic Seas and consequently in a reduction in deep convection and overflow of dense waters we propose here. However, this did not translate into advection of substantial volumes of southern source water. On the contrary, the  $\varepsilon_{\text{Nd}}$  values at deepest Site 900 gradually followed the shift towards more negative values indicating the dominant presence of northern source

waters in the abyssal North Atlantic. Consequently, we infer that the entire meridional overturning circulation in the northern North Atlantic decreased at 1.65–1.40 Ma and SOW did not reach as far North as during for example the last glacial (e.g. Crocket et al., 2011; Piotrowski et al., 2012), potentially as a consequence of the smaller size of West Antarctic ice sheet during that time (e.g. Naish et al., 2009).

After ~ 1.4 Ma, a long-term trend towards more radiogenic modern  $\epsilon_{Nd}$  signatures clearly marks that the deepest Site 900 gradually experienced the enhanced admixture of southern source waters and documents the establishment of modern type deep circulation in the North Atlantic. This reorganization was accompanied by an increase in the “glacial/interglacial” amplitude of the  $\epsilon_{Nd}$  time series at Sites 610 and 980/981 (Figs. 3 and 4). Predominantly “unradiogenic”  $\epsilon_{Nd}$  signatures during interglacial intervals at these sites indicate the enhanced injection of LSW and (old) NADW into intermediate and deep waters in the Northeast Atlantic. In contrast, the most radiogenic  $\epsilon_{Nd}$  values during glacial intervals may reflect decreased entrainment of NAC and increased admixture of southern source waters with intermittent GIN Seas overflow.

This major reorganization in the North Atlantic overturning circulation across the mid-Pleistocene transition is also evident from the significant increase in the glacial/interglacial amplitude of benthic  $\delta^{13}C$  signatures in the North Atlantic (e.g. Venz and Hodell, 2002; Hodell and Venz, 2006; Lawrence et al., 2010) indicating a change from being dominantly ventilated by NADW during interglacial periods to enhanced advection of SOW during glacial periods. Apparently, the expansion of West Antarctic ice sheet across the mid-Pleistocene transition promoted the production and export of AABW from the Southern Ocean (e.g. Naish et al., 2009; Lawrence et al., 2010). This major change suggests that after the mid-Pleistocene transition both Northern Hemisphere and Southern Hemisphere ice sheets started to exert more far-field influence on ocean circulation and climate linked to the onset of the more pronounced 100 kyr Late Quaternary style cyclicity of glacial/interglacial climates that still prevails today.

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## 5 Conclusions

Based on bottom-water radiogenic neodymium isotope ( $\epsilon_{Nd}$ ) variability our study suggests a major reorganization of deep circulation in the Northeast Atlantic after 1.65 Ma. The overflow of deep waters from the Nordic Seas strongly decreased, which had implications for the evolution of overturning in the North Atlantic. The enhanced climatic response to the Earth's obliquity forcing during the Early Pleistocene transition most likely ultimately triggered the reorganization of North Atlantic deep water circulation towards a more stratified water column and more distinct water masses after 1.4 Ma. This major change formed a marked step towards the onset of more pronounced Late Quaternary style cycles of glacial/interglacial climates after the mid-Pleistocene transition that still prevail today. Further evidence documenting, for example, past changes in  $pCO_2$  and ice sheet dynamics are required to better understand the cause of the Early Pleistocene climate transition.

**Supplementary material related to this article is available online at <http://www.clim-past-discuss.net/9/6495/2013/cpd-9-6495-2013-supplement.pdf>.**

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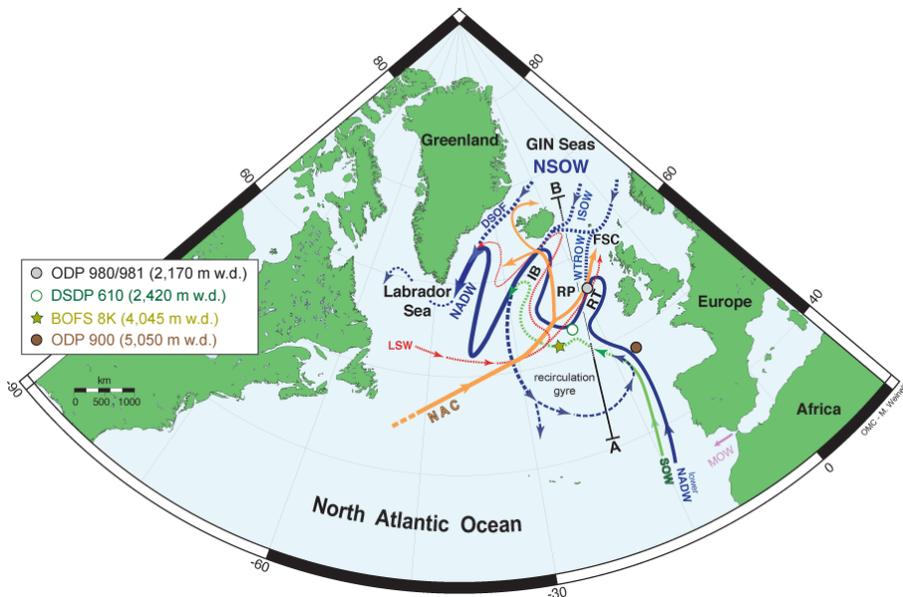
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**Fig. 1.** Circulation pattern in the modern North Atlantic with locations of study sites and core BOFS 8K (adopted from Manighetti and McCave, 1995). Nordic Seas Overflow Water (NSOW) consists of Iceland-Scotland, Denmark Strait, and Wyville-Thomson Ridge Overflow Water (ISOW, DSOW, and WTROW, respectively). Southern Ocean Water (SOW) and overlying lower (old) NADW mix with NSOW south of Iceland Basin (IB). A branch of this water mass flows back to form a cyclonic recirculation gyre south of the Rockall Plateau (RP). Dashed arrows indicate overflow pathways. NAC = North Atlantic Current. GIN = Greenland-Iceland-Norwegian. NADW = North Atlantic Deep Water. LSW = Labrador Sea Water. MOW = Mediterranean Overflow Water. Cross-section (A-B) shows water mass distribution in the modern Northeast Atlantic (see Fig. 2).

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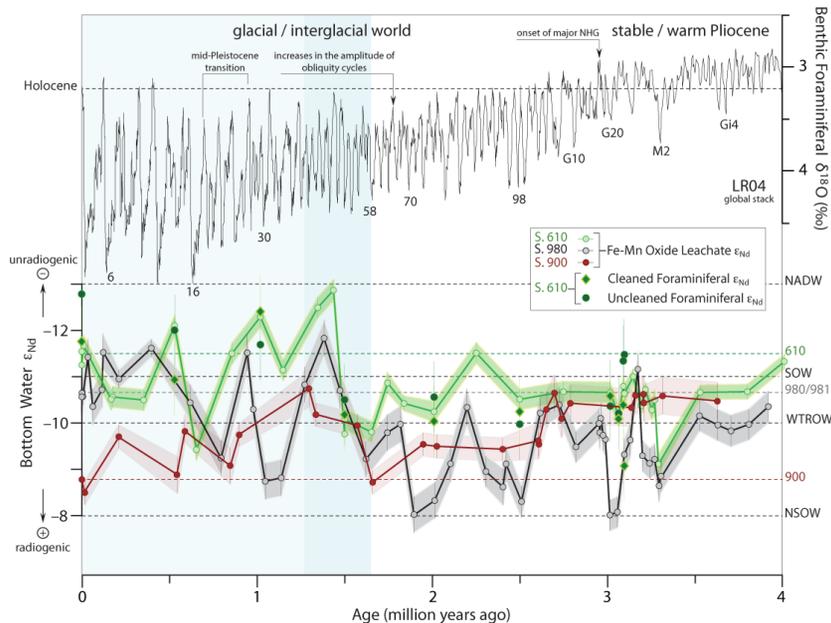
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**Fig. 3.** Changes in deep-water sources and water mass mixing in the Northeast Atlantic during the past 4 million years as reflected by bottom water  $\epsilon_{Nd}$  signatures at Site 980/981 (black; 2170 m water depth), Site 610 (green; 2420 m w.d.), and Site 900 (brown; 5050 m w.d.). Error bars and colored areas mark the  $2\sigma$  uncertainties of the measurements. Horizontal dashed lines mark inferred modern bottom water  $\epsilon_{Nd}$  signature at study sites and the Northeast Atlantic from proximally water column measurements (Lacan and Jeandel, 2004a, b, 2005; Rickli et al., 2009) and near-core top leachates and foraminifera (Crocket et al., 2011; Piotrowski et al., 2013; this study). The numbers on the global benthic foraminiferal  $\delta^{18}O$  stack LR04 of Lisiecki and Raymo (2005) correspond to the Marine Isotope Stage (MIS) of key glacials. NADW = North Atlantic Deep Water. SOW = Southern Ocean Water. WTROW = Wyville-Thomson Ridge Overflow Water. NSOW = Nordic Seas Overflow Water.

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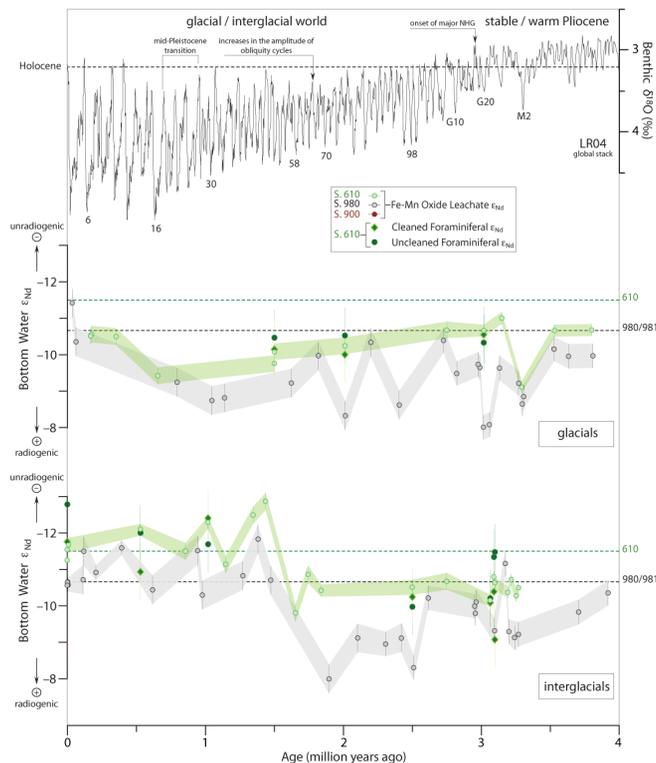
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**Fig. 4.** Comparison between changes in bottom water  $\epsilon_{Nd}$  signatures at Site 980/981 (black; 2170 m water depth) and Site 610 (green; 2420 m w.d.) during selected key glacial and interglacial periods as reflected in the global benthic foraminiferal  $\delta^{18}O$  stack LR04 of Lisiecki and Raymo (2005) for the last 4 million years. Error bars and colored areas mark the  $2\sigma$  uncertainties of the measurements. Horizontal dashed lines mark suggested modern bottom water  $\epsilon_{Nd}$  signature at study sites.

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