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Key Points:
- Sedimentary archives indicate alteration of local bottom water Nd isotope signatures in the Northwest Atlantic by nepheloid layers
- New high-resolution Nd isotope depth transect from the Blake Bahama Outer Ridge constrains deglacial millennial-scale water mass changes
- An increased contribution of southern sourced water is confirmed for all cold periods of the past 30 ka

Supporting Information:
- Supporting Information S1
- Table S1

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Influence of Ocean Circulation and Benthic Exchange on Deep Northwest Atlantic Nd Isotope Records During the Past 30,000 Years

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Abstract Neodymium (Nd) isotopes extracted from authigenic sediment phases are increasingly used as a proxy for past variations in water mass provenance. To better constrain the controls of water mass provenance and nonconservative effects on the archived Nd isotope signal, we present a new depth transect of Nd isotope reconstructions from the Blake Bahama Outer Ridge along the North American continental margin covering the past 30 ka. We investigated five sediment cores that lie directly within the main flow path of the Deep Western Boundary Current, a major advection route of North Atlantic Deep Water. We found offsets between core tops and seawater Nd isotopic compositions that are observed elsewhere in the Northwest Atlantic. A possible explanation for this is the earlier suggested redistribution of sediment by nepheloid layers at intermediate as well as abyssal depths, transporting material downslope and along the continental margin. These processes potentially contributed to Nd isotope excursions recorded in Northwest Atlantic sediment cores during the Bølling-Allerød and early Holocene. An Atlantic-wide comparison of Nd isotope records shows that the early Holocene excursions had an additional contribution from conservative advection of unradiogenic dissolved Nd. Nevertheless, the trends of the Nd isotope records are in general agreement with previous reconstructions of water mass provenance from the entire Atlantic and also reveal millennial-scale changes during the last deglaciation in temporal high resolution, which have rarely been reported before. Further, the new records confirm that during cold periods the Northwest Atlantic was bathed by an increased contribution of southern sourced water.

Plain Language Summary The Atlantic Meridional Overturning Circulation is of great importance for the climate system since it distributes heat to the northern high latitudes, where the only deep water of the Northern Hemisphere is formed. Here, we investigate how this North Atlantic Deep Water propagated southward in response to deglacial climatic trends during the transition from the last ice age to modern day. However, we found differences between the archived modern signal and modern seawater measurements that might hinder the interpretation of past water mass provenance. We attribute this effect to influences from suspended material altering the local bottom waters. This process was likely most prominent during the invigoration of northern deep water formation during the Bølling-Allerød and early Holocene but less pronounced to absent during cold time periods. Nevertheless, the findings of this study confirm that North Atlantic Deep Water was partly replaced in the deep Northwest Atlantic basin by southern sourced water during cold intervals.

1. Introduction

Recent efforts in seawater sampling as well as improvements in measurement techniques and intercalibration have facilitated the geochemical identification of water masses on a regional to local scale (e.g., GEOTRACES program, Schlitzer et al., 2018). The reconstruction of paleo water masses, however, is more difficult, because proxy-based reconstructions are indirect and limited in their spatial and temporal coverage. The North Atlantic is of particular interest for water mass reconstructions since it hosts the only major deep water mass formed in the Northern Hemisphere. Warm southern sourced surface water cools in the

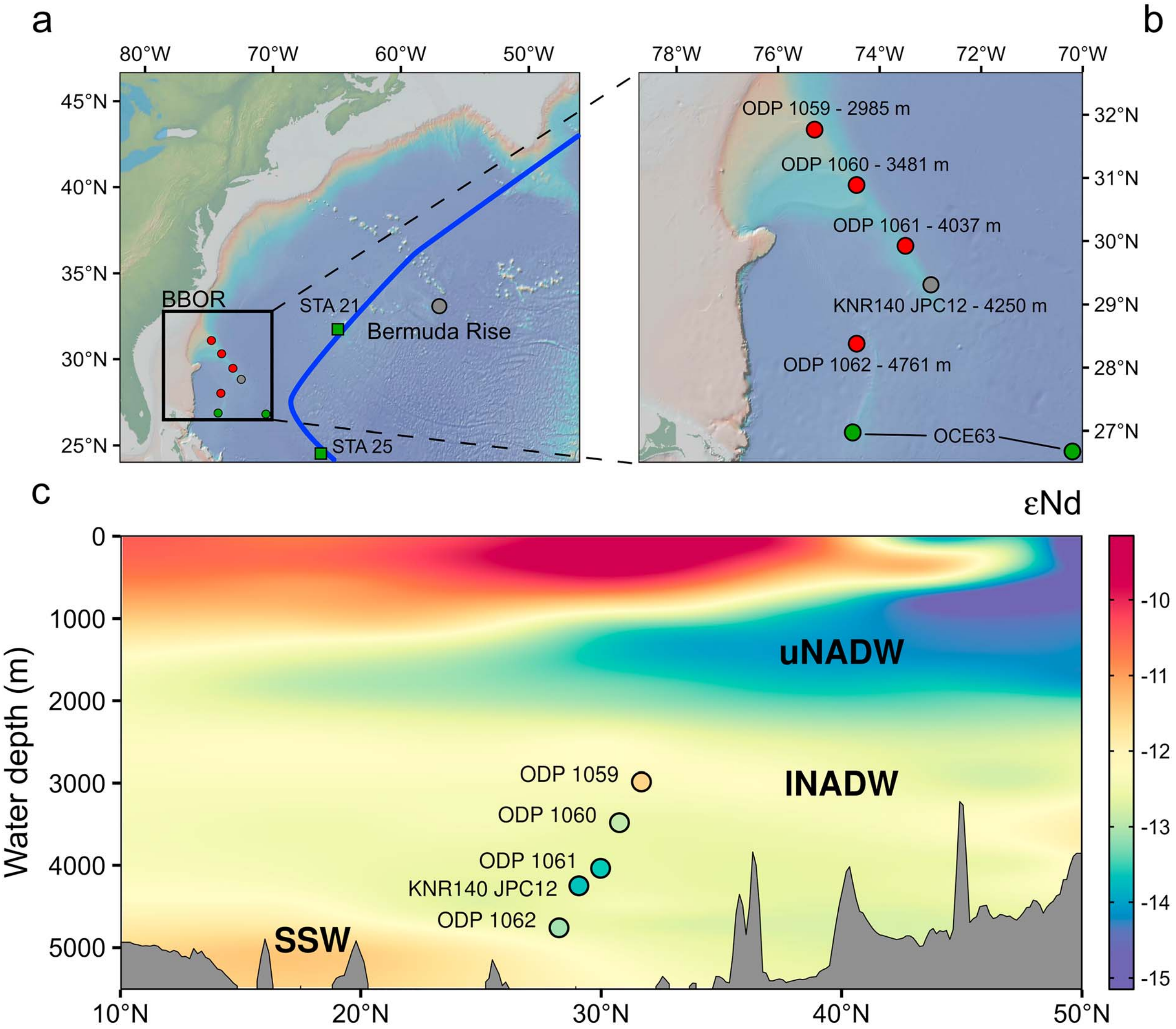

Figure 1. (a) Overview map of the Northwest Atlantic with locations from the BBOR (KNR140 JPC12, this study, and Gutjahr et al., 2008) and previously published εNd records from the Bermuda Rise (Böhm et al., 2015; Gutjahr & Lippold, 2011; Roberts et al., 2010) as red and gray circles. The blue line indicates the transect of the section in panel (c). Nearby εNd seawater stations for comparison are depicted as green squares (Lambelet et al., 2016) and green circles (Piepgras & Wasserburg, 1987). (b) Zoom into the BBOR with core locations of Sites 1059–1062 as well as KNR140 JPC12. (c) Section plot of seawater εNd through the Northwest Atlantic from 10–50°N (Lambelet et al., 2016). uNADW and lNADW, and SSW (as defined in the text) are indicated. Symbol colors of the investigated sites correspond to the core top εNd value on the same scale as the background. BBOR = Blake Bahama Outer Ridge; SSW = southern sourced water; uNADW = upper North Atlantic Deep Water; lNADW = lower North Atlantic Deep Water; ODP = Ocean Drilling Program.

marginal seas of the North Atlantic (Labrador and Nordic Seas) and increases in density, forming the tributaries of North Atlantic Deep Water (NADW). Deep water formed in the Labrador Sea is less dense than the water masses formed in the Nordic Seas and can be identified in the North Atlantic as upper NADW (uNADW, Figure 1). The overflow waters from the Nordic Seas, on the other hand, form the lower subcomponent of NADW (lNADW). In general, the main flow paths of uNADW and lNADW are along the North American continental margin as Deep Western Boundary Current (DWBC, Lambelet et al., 2016; Rhein et al., 2015). Below NADW a contribution of a more dense southern sourced deep water mass can be identified in the North Atlantic, commonly referred to as Antarctic Bottom Water (AABW, up to 20% below 4,000-m water depth, e.g., Lambelet et al., 2016; Jenkins et al., 2015). Ultimately, the part of AABW entering the Atlantic is formed in the Weddell Sea, but this bottom water mass is substantially diluted on its northward path with Circumpolar Deep Water (Foster & Carmack, 1976). To avoid the ambiguity with AABW and its modifications, we refer to the deep water mass entering the Atlantic from the Southern Ocean as Southern Sourced Water (SSW). The identification of these different deep water masses in the Atlantic is possible not only by properties like density, temperature, or salinity but also with geochemical tracers such as the neodymium (Nd) isotopic composition of seawater (e.g., Frank, 2002; van de Flierdt et al., 2016) that behave quasi-conservatively in the oceans away from ocean margins. Here we focus on the Nd isotopic composition that is denoted as εNd which is ^{143}Nd/^{144}Nd normalized to the *Chondritic Uniform Reservoir* in parts per ten thousand. In the modern South Atlantic SSW has a Nd signature of −8.5 ± 0.3 (Stichel et al., 2012) and in the North Atlantic uNADW and lNADW have signatures of −13.2 ± 0.6 and −12.6 ± 0.4, respectively (Figure 1c, Lambelet et al., 2016).

While NADW is mostly confined to depths between 1,500 and 4,500 m in the modern Northwest Atlantic Ocean, it is thought that its glacial counterpart was located much shallower at depths between 1,000 and 3,000 m (e.g., Boyle & Keigwin, 1987; Curry & Oppo, 2005; Evans & Hall, 2008; Sarnthein et al., 1994). A growing body of evidence suggests that extensive freshwater input, for example, during major Heinrich Stadials (HS 11, 2 or 1) or the Younger Dryas (YD) significantly weakened the deep water formation around the North Atlantic, resulting in decreased strength of the Atlantic Meridional Overturning Circulation (AMOC) and the shoaling of NADW (Böhm et al., 2015; Bradtmiller et al., 2014; McManus et al., 2004). In contrast to these cold events a recent study based on Nd isotopes proposed that a large part of the North Atlantic was still dominated by Northern Sourced Water (NSW) during the Last Glacial Maximum (LGM, Howe, Piotrowski, Noble, et al., 2016).

However, the interpretation of downcore Nd isotope records directly in terms of water mass mixing is complicated by two processes. First, past εNd end members are not well constrained and presumably changed over time (e.g., Gutjahr et al., 2008; Skinner et al., 2013). And second, the extracted authigenic Nd isotope signal could have been altered at the sediment-bottom water interface or during early diagenesis, thus not necessarily representing the local bottom water (Blaser et al., 2019; Lacan & Jeandel, 2005). The extent of these benthic exchange processes most likely depends on the reactivity and surface area of the deposited material (Howe, Piotrowski, & Rennie, 2016). While the reactivity strongly depends on the source, the effective surface area can be increased by nepheloid layers (Gardner et al., 2018) that can either increase the dissolved Nd concentration and shift the isotopic composition by particle dissolution (van de Flierdt et al., 2016) or contrary reduce the dissolved Nd concentration by increased scavenging (Morrison et al., 2019). Especially the Northwest Atlantic is a region with thick and dense benthic nepheloid layers that are presumably generated by the high surface eddy kinetic energy of the Gulf Stream (Gardner et al., 2018). Nevertheless, sediment core top calibrations to seawater data yield generally good agreements (e.g., Lippold et al., 2016; Piotrowski et al., 2008; Tachikawa et al., 2014), but small discrepancies were also reported especially around Iceland and in parts of the abyssal Northwest Atlantic (Elmore et al., 2011; Pöppelmeier et al., 2018; Roberts et al., 2010), both are areas where potentially reactive material and benthic nepheloid layers are observed (Gardner et al., 2018; Morrison et al., 2019). Here, we first investigate possible mechanisms for the core top-seawater offsets in the Northwest Atlantic and then discuss the temporal evolution thereof. We facilitate this with five new high-resolution records of authigenic Nd isotopes from the Blake Bahama Outer Ridge (BBOR) located directly in the flow path of the DWBC (Figure 1). The sites form a depth transect from 2,985- to 4,760-m water depth along the crest of the BBOR sediment drift site (Keigwin et al., 1998), extending an earlier Nd-based study (Gutjahr et al., 2008). After assessing potential influences by local sediment dynamics (Gutjahr et al., 2008) and the local benthic nepheloid layer of the North American Basin (Gardner et al., 2018), we further employ the authigenic Nd isotopic signal in these sediments for a semiquantitative assessment of bottom water provenance. The new Nd isotope records allow us to investigate the nature of the potential alteration of local bottom water in the Northwest Atlantic and provide constraints on the water mass geometry during the past 30 ka.

2. Materials and Methods

2.1. Sediment Cores and Age Models

Four of the five sediment cores investigated in this study were retrieved from the BBOR during Ocean Drilling Program (ODP) Leg 172, covering water depths between 2,985 and 4,761 m (Sites 1059–1062, Table S1 in the supporting information; Keigwin et al., 1998). The fifth core KNR140 JPC12 (hereafter JPC12) was retrieved from 4,250-m water depth during a survey cruise for ODP Leg 172 (Keigwin, 2004).

The main water mass bathing all sites in the modern ocean is lNADW with a small contribution of SSW reaching only the deepest site (Lambelet et al., 2016; Figure 1c). The original chronology of the ODP cores is based on astronomical tuning of color reflectance derived calcium carbonate from Grützner et al. (2002). The age models are further improved by 14 new ^{14}C Accelerator Mass Spectrometry dates (12 for ODP 1060 and 2 for ODP 1062; Tables S2 and S3) as well as 4 recalibrated ^{14}C ages for ODP 1059 (Hagen & Keigwin, 2002). New dates were produced at NOSAMS, Woods Hole Oceanographic Institution and at the LARA laboratory of the University of Bern, Switzerland (Gottschalk et al., 2018). All ^{14}C ages were calibrated with the CALIB 7.1 online tool tied to the Marine13 curve (Reimer et al., 2013), with the standard 400-year reservoir age correction. Further, $CaCO_3$ content of Sites 1059 and 1062 were correlated to well-dated neighboring cores KNR140 GGC39 (11 ^{14}C dates, Keigwin & Schlegel, 2002) and KNR31 GPC-9 (Figure S1, 11 ^{14}C dates, Keigwin & Jones, 1994), respectively. In addition, all BBOR cores were correlated to each other on the basis of the $CaCO_3$ percentages and magnetic susceptibility (Keigwin et al., 1998) to ensure a common age scale (Table S2 and Figure S2). The age model of JPC12 was updated by combining new ^{14}C dates from Keigwin and Swift (2017) with previously published ones (Gutjahr et al., 2014; Keigwin, 2004; Robinson et al., 2005).

2.2. Analytical Procedures

Neodymium isotopes were extracted from the authigenic phase of bulk sediment following the procedure described by Blaser et al. (2016), with a slight modification for the leaching solution that was buffered with ammonia instead of NaOH to introduce less Na (Blaser et al., 2019; Pöppelmeier et al., 2018). Separation of rare earth elements and ultimately Nd followed the protocols of Cohen et al. (1988) and Pin et al. (1994) using a two-step column chromatography. Measurements of the Nd isotopic composition were carried out on two Neptune Plus multicollector inductively coupled plasma mass spectrometry at the Institute of Environmental Physics, Heidelberg University, and GEOMAR, Kiel. Instrumental fractionation on isotopic ratios was corrected for by normalization of $^{146}Nd/^{144}Nd$ to 0.7219. Samples were bracketed by concentration matched JNdi-1 standard solutions normalized to the accepted value of $^{143}Nd/^{144}Nd = 0.512115$ (Tanaka et al., 2000). The external reproducibility (double standard deviation) was determined for each session by repeated measurements of secondary in-house standards to 0.15–0.25 ε-units. Full procedure blanks were all below 100 pg and are thus negligible.

3. Results

3.1. Nd isotope Records

The core top εNd values from the BBOR sites vary considerably with depth (Figures 1c and 2). The shallowest Site 1059 has the most radiogenic core top value (-11.6 ± 0.2) that is about 0.75 ε-units more radiogenic than the modern seawater value of the nearest stations (Stations 21 and 25 in Lambelet et al., 2016). Site 1060 at 3,500-m water depth has a core top Nd isotopic signature of -12.9 ± 0.2, in agreement with local seawater measurements. At 4,000- to 4,250-m Sites 1061 and JPC12 have the least radiogenic core top values of the depth transect that are offset from local seawater by about 1 ε-unit toward less radiogenic values. Foraminiferal data (cleaned and uncleaned, Roberts et al., 2010) of Site 1061 agree well with these leachate data and thus exhibit the same offset toward seawater. The deepest Site 1062 at 4,760-m water depth displays a slightly more radiogenic core top value (-13.0 ± 0.2) than the next two shallower sites, and is offset from local bottom water by less than 0.5 ε-units toward less radiogenic values (Lambelet et al., 2016).

The downcore records from all five sites are rather stable from 24 ka BP until the end of HS1 at around 15 ka BP, exhibiting Nd isotopic signatures between −11 and −12 (Figure 2). Prior to HS2 Sites 1060 and 1061 show a trend of 2 ε-units toward more radiogenic values that seemed to be less pronounced at Site 1059 and 1062. Sites 1060 and 1061 are also the only sites that recorded a drop of ~1 ε-unit during HS2. During the Bølling-Allerød (B/A) deglacial warm period all εNd records display an abrupt change toward less radiogenic values that is reversed during the second half of the B/A and YD. Site JPC12 does not exhibit the reversal toward more radiogenic values during the YD, displaying only a small plateau. The least radiogenic Nd isotopic signatures of the past 30 ka were recorded at all sites during the early Holocene, ranging from −13.0 at Site 1059 to −15.2 at Site 1061. The middle to late Holocene is then marked by a steady increase toward more radiogenic values.

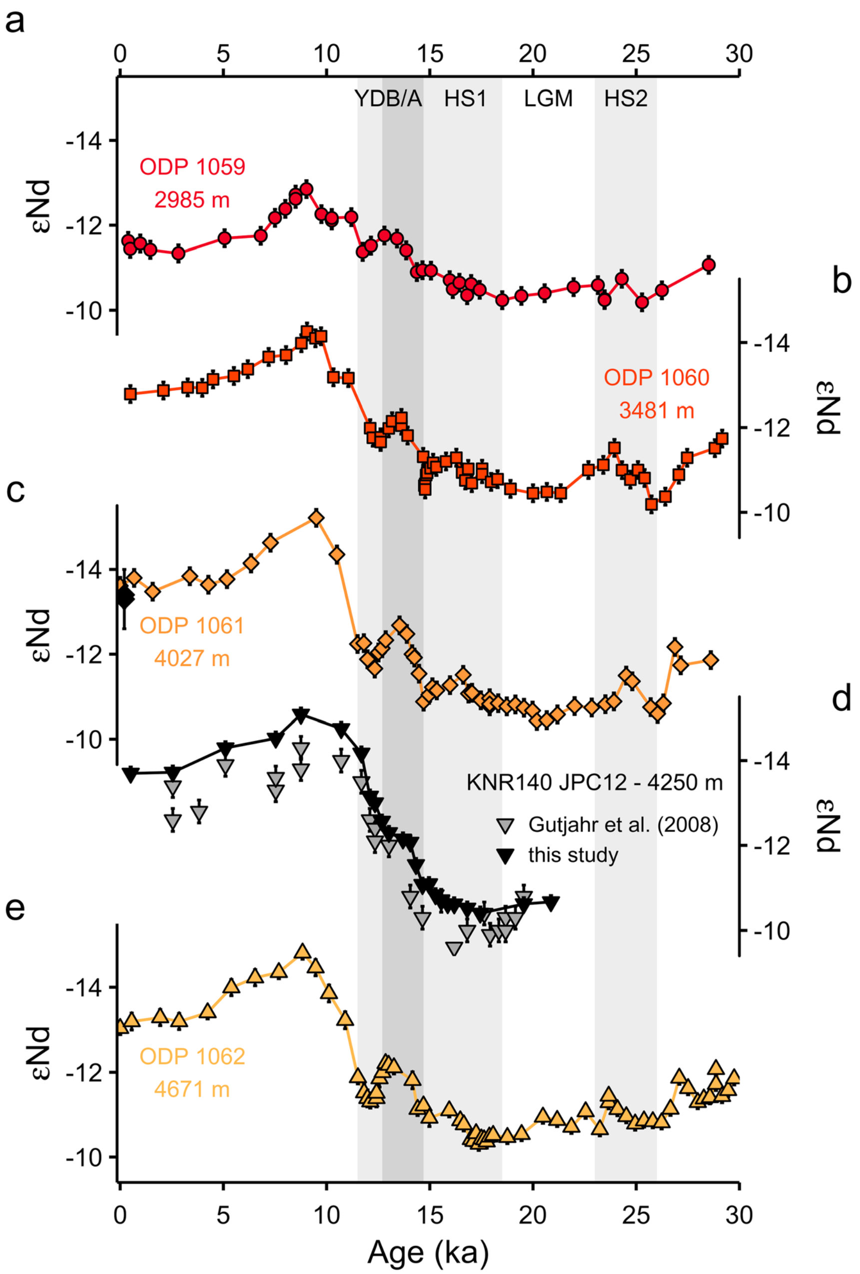

Figure 2. (a–e) Blake Bahama Outer Ridge εNd records of ODP 1059–1062 and KNR 140 JPC12 (this study). Core top εNd values measured on foraminifera (Roberts et al., 2010) are depicted in panel (c) as black diamonds. For comparison panel (d) also shows the data of JPC12 from Gutjahr et al. (2008; gray triangles). Light and dark gray shaded bars indicate the time ranges of HS2, HS1, and YD and B/A, respectively. Double standard deviations are partly smaller than symbol sizes. Note the reversed *y* axes. B/A = Bølling-Allerød; HS = Heinrich Stadials.

3.2. Comparison of Different Leaching Methods

Gutjahr et al. (2008) previously investigated the authigenic Nd isotopic signatures of site JPC12 that we reinvestigated here. The authors used a 10 times stronger leaching solution than was used for this study in addition to a prior decarbonation step. The εNd data from Gutjahr et al. (2008) and this study extracted with two different methods are generally similar, but the new data produced after Blaser et al. (2016) yielded partly less radiogenic values that are also less variable (Figure 2d). Further, the new εNd data of JPC12 produced in this study are in slightly better agreement with the data from neighboring Site 1061 than the ones from Gutjahr et al. (2008); Figure S3).

4. Discussion

4.1. Significance of the Authigenic Nd Isotopic Signatures at BBOR

The comparison of new and old JPC12 data shows that (while the trends seen in the new and old records are in agreement) the earlier Nd isotope data set is partly more radiogenic, especially during the Holocene section. An important difference between the leaching methods of Gutjahr et al. (2007) and Blaser et al. (2016) is the carbonate removal step in the former. During the leaching process carbonate plays an important role acting as a buffer and increasing the pH (Blaser et al., 2016). In combination with the dilution by a factor of 10, the leaching solution after Blaser et al. (2016) is thus less likely to partially dissolve detrital phases. To test for detrital contaminations, Gutjahr et al. (2008) dissolved the bulk detrital sediment and found εNd values between −13 (LGM) and −16 (Holocene). These detrital values are less radiogenic than the data from Gutjahr et al. (2008) as well as this study. This suggests that the difference between both methods is not due to the partial dissolution of the bulk detritus but rather a specific more susceptible detrital phase that is more radiogenic than the bulk material and preferentially leached (Blaser et al., 2016; Howe, Piotrowski, Oppo, et al., 2016; Wilson et al., 2013). This effect might have caused the more radiogenic values of Gutjahr et al. (2008) and we therefore exclude these data from the following discussion.

Only two out of the five core top Nd isotopic signatures are in agreement with modern seawater measurements from the nearest stations. Since foraminiferal and leachate data agree with each other, we exclude laboratory leaching artifacts as a source for the observed offsets. Surprisingly, the core top-seawater mismatches are inconsistent and partly toward both radiogenic and unradiogenic values. Gutjahr et al. (2008) previously suggested that preformed authigenic phases from the Florida Strait get transported downslope and thus contribute to the extracted Nd from shallow to mid depth BBOR sites. As the only regional source that transports material with highly radiogenic εNd, we attribute the radiogenic offset of Site 1059 to sediment redistribution caused by the vigorous Gulf Stream resuspending shelf sediments and transporting these into the open North Atlantic in an intermediate depth nepheloid layer (e.g., Gardner et al., 2017; Stahr & Sanford, 1999). Gutjahr et al. (2008) further investigated the temporal evolution of the intermediate nepheloid layer by analyzing changes in sediment focusing. They found reduced focusing at intermediate depth sites hinting to reduced shelf-derived sediment redistribution before the Holocene. It has been suggested that nepheloid layers are produced by upper ocean dynamics of surface eddy kinetic energy propagating downward (Gardner et al., 2018; McCave, 1986). The reduced Gulf Stream and DWBC strength as well as the reduced shelf contact area due to lower sea level before the Holocene (McGee et al., 2010), thus, should have led to a smaller intermediate depth nepheloid layer that would have also reduced the sediment redistribution at the upper BBOR. This might thus facilitate paleoceanographic interpretations of the Nd isotope record of Site 1059 for the last glacial and deglaciation.

The core top-seawater offsets from the deeper sites are unlikely caused by downslope sediment redistribution since the offsets are in the opposite direction toward less radiogenic values. A possible contribution to this mismatch might be attributed to seawater sampling and processing as suggested by Pöppelmeier et al. (2018). For instance, a recent study investigating the seawater Nd isotopic composition of the Northwest Atlantic used filtered samples (Lambelet et al., 2016) yielding different results for lNADW εNd than a study from over three decades ago that used unfiltered seawater (Piepgras & Wasserburg, 1987). Interestingly, the core top-seawater mismatch at the deep BBOR seems to be partly independent of water depth. Site 1062 at 4,760-m water depth is slightly more radiogenic than the two next shallower Sites 1061 and JPC12. However, Site 1062 is situated further south in the open ocean and not part of the sediment drift forming the Blake Outer Ridge. A comparison to sites further north, upstream of the DWBC, shows that the core top-seawater offsets correlate with the proximity to the Labrador Sea and the particulate matter concentration and thickness of the benthic nepheloid layer of the North American basin (Figure 3 and S4; Gardner et al., 2018). A possible explanation of the core top-seawater mismatch could therefore be associated with the particle load and reactivity of this benthic nepheloid layer. The benthic nepheloid layer could contribute to the core top-seawater offset by two mechanisms. First, it might release unradiogenic Nd into the local bottom water at BBOR during dissolution of particles that originated from the Labrador Sea (van de Flierdt

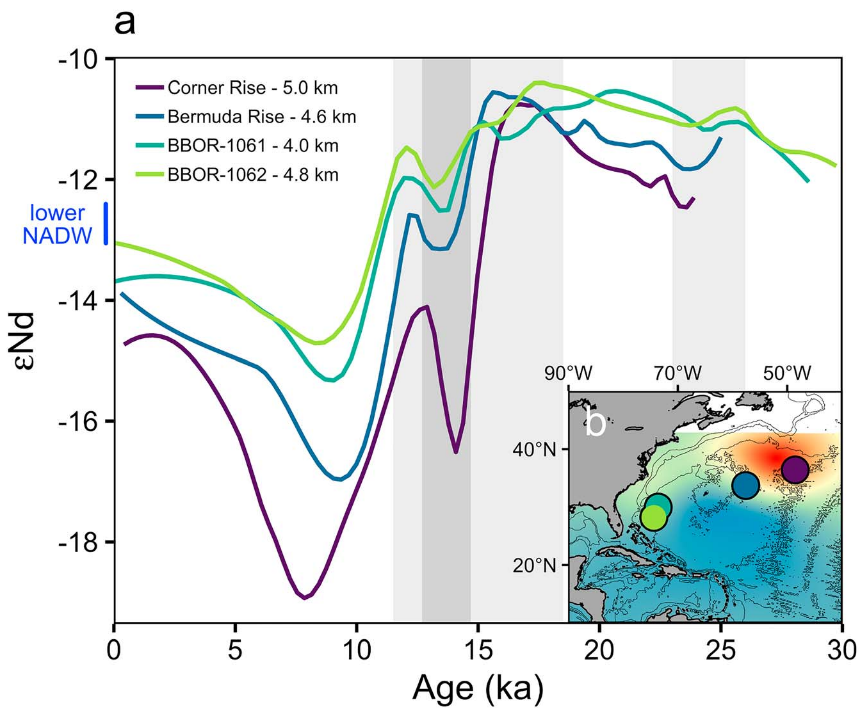

Figure 3. (a) εNd records of Corner Rise (36°24′N, 48°32′W, 5,010 m; Pöppelmeier et al., 2018), Bermuda Rise (33°41′N, 57°37′W, 4,580 m, Böhm et al., 2015; Gutjahr & Lippold, 2011; Roberts et al., 2010), and BBOR Sites 1061 and 1062 (this study) in comparison. Lines represent local polynomial regressions of measured data. Modern seawater Nd isotopic composition at around 4,500-m water depth (Lambelet et al., 2016) is indicated by the blue bar. Light and dark gray shaded bars indicate the time ranges of HS2, HS1, and Younger Dryas and B/A, respectively. (b) Map inset shows the core sites in the Northwest Atlantic. Map color scale corresponds to the particle beam attenuation of the deepest 10 m, indicating the presence of a benthic nepheloid layer in the northern North American basin transported with the Deep Western Boundary Current (Gardner et al., 2018). Red indicates thick and blue no benthic nepheloid layer, respectively. BBOR = Blake Bahama Outer Ridge; NADW = North Atlantic Deep Water.

et al., 2016). We suggest that this process contributed to the elevated dissolved Nd concentrations and unradiogenic εNd offsets from conservative end member mixing of the local bottom water observed at seawater stations slightly upstream of BBOR (Hartman, 2015). A similar process was also observed at the Mauritanian Margin where a benthic nepheloid layer changed the local bottom water Nd isotopic composition by about 1 ε-unit (Stichel et al., 2015). Second, a benthic nepheloid layer can also transport preformed authigenic phases, which are extracted during sample treatment in addition to the locally formed authigenic phases. Generally, such processes associated with benthic nepheloid layers can be assumed to be part of the term "boundary exchange" which describes various exchange processes at the sediment-bottom water interface (Jeandel, 2016; Lacan & Jeandel, 2005).

Potential influences on the Nd release from the benthic nepheloid layer of the North American Basin are the amount and reactivity of sediments deposited into the Labrador Sea. On the other hand, the bottom water current strength tends to be of lesser impact for the formation of benthic nepheloid layers but is important for transporting the resuspended material along the continental margin (Gardner et al., 2018). Substantial variations in the amount and reactivity of the sediment occurred during past glacial-interglacial transitions related to the exposure of poorly chemically weathered material in particular during intervals of ice sheet retreat (Howe, Piotrowski, & Rennie, 2016). Therefore, deep Northwest Atlantic Nd isotope records should be interpreted carefully especially during such times, for example, the B/A and the early Holocene.

4.2. (De)glacial Changes in Authigenic Nd Isotopes and Water Mass Provenance

It is important to evaluate possible influences from the nepheloid layers, as observed in the modern North American Basin, in the past before interpreting the Nd isotope records in terms of deep water mass provenance. This, however, constitutes a major challenge since the influence of benthic nepheloid layers on Nd

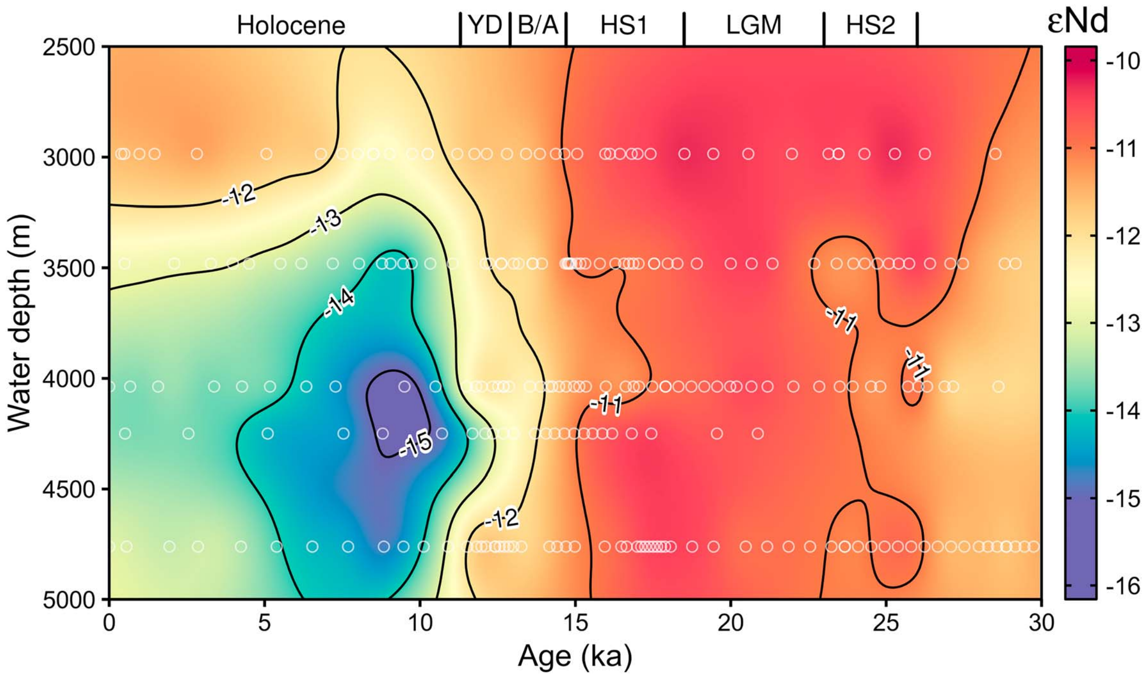

Figure 4. Hovmöller diagram of the Blake Bahama Outer Ridge authigenic εNd records for the past 30 ka. Data points are marked with white circles (ODP 1059 = 2,985 m, ODP 1060 = 3,481 m, ODP 1061 = 4,037 m, JPC12 = 4,250 m, and ODP 1062 = 4,761 m). B/A = Bølling-Allerød; HS = Heinrich Stadials; LGM = Last Glacial Maximum; YD = Younger Dryas.

isotopes is not well understood even for the modern ocean (Haley et al., 2017; van de Flierdt et al., 2016). Due to this caveat, we first estimate the potential influence of nepheloid layers in the past and then assess changes in past water mass provenance in a semiquantitative way.

As discussed in section 4.1 there is evidence that the intermediate nepheloid layer was less pronounced during the last glacial (Gutjahr et al., 2008). We therefore assume that the observed authigenic εNd values are not significantly offset toward more radiogenic signatures in comparison to past seawater. Comparison to Sites SU90-03 and U1313 at similar depth but further north (~40°N) and not influenced by nepheloid layers corroborate this assumption, since both more northern sites exhibited the same εNd values as Site 1059 during the LGM (Howe, Piotrowski, & Rennie, 2016). Whether the deep benthic nepheloid layer also lost its influence is unclear but most of the unradiogenic material of North America and Greenland was closed off under the Laurentian Ice Sheet. Thus, compared with the Holocene, rather, mature material, substantially less reactive, may have been transported by the benthic nepheloid layer and the DWBC during the LGM and in turn would have produced considerably smaller offsets of the authigenic sediment phase from past seawater. This is supported by the fact that the deep BBOR sites recorded the most radiogenic values during the LGM and HS1 hinting toward minimal influence of the benthic nepheloid layer during these times (Figure S5).

A common feature present at all water depths investigated here are the radiogenic Nd isotopic signatures of about −10.5 that prevailed during glacial times (Figures 4 and 5). Such values, more than 2 ε-units more radiogenic than today, are commonly interpreted as a strong increase in the contribution of SSW (Lippold et al., 2016; Roberts et al., 2010). However, a Nd isotope record from the South Atlantic (45°S) reported glacial values of −5 to −6 interpreted to represent the glacial SSW εNd end member (Skinner et al., 2013). Values around −10.5 with such a radiogenic SSW end member suggest a larger contribution of glacial NADW to the water mass mixing of the Northwest Atlantic than previously assumed but in agreement with a recent Atlantic-wide study also based on Nd isotopes (Howe, Piotrowski, Oppo, et al., 2016). This conclusion contradicts the interpretation of stable carbon isotope data (Curry & Oppo, 2005; Evans & Hall, 2008; Keigwin, 2004) but low δ^{13}C values, indicative of SSW, might be partly caused by the underestimated effect of remineralization of organic matter (Gebbie, 2014). A better assessment of the discrepancy of εNd and δ^{13}C

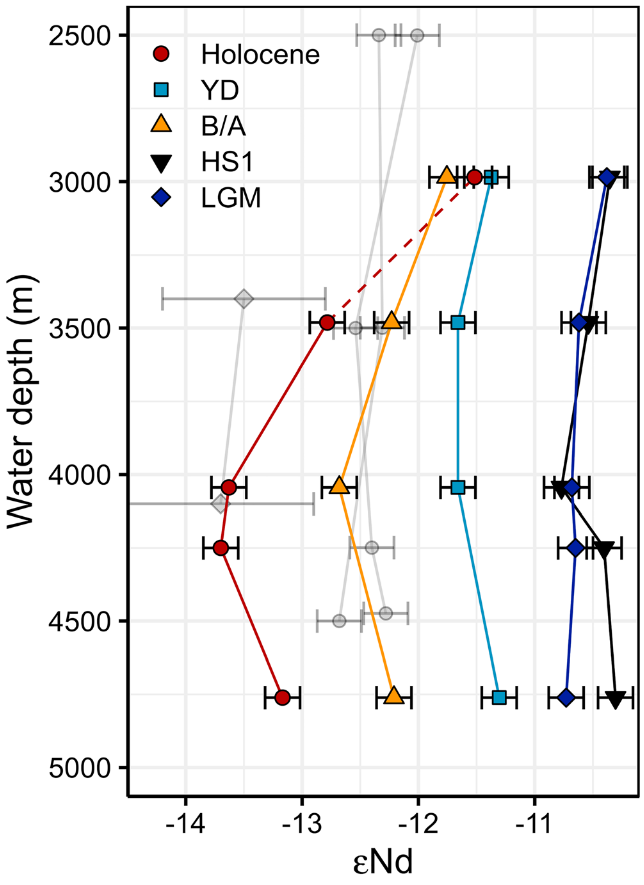

Figure 5. εNd Blake Bahama Outer Ridge depth transects of the Holocene, YD, B/A, HS1, and LGM. The Holocene and LGM values are averaged over 0–2 and 19–23 ka BP, respectively. YD, B/A, and HS1 data points show peak excursions of the respective time periods. Data from JPC12 are excluded for the YD and B/A as discussed in the text. Seawater data of Stations 21 and 25 (Lambelet et al., 2016) as well as older and more proximate data from OCE63 (Piepgras & Wasserburg, 1987) are depicted as gray circles and diamonds, respectively. B/A = Bølling-Allerød; HS = Heinrich Stadials; LGM = Last Glacial Maximum; YD = Younger Dryas.

needs to take the whole Atlantic into account as well as secondary processes altering the extracted signal of both proxies. That is, however, beyond the scope of this study.

Before HS2, Sites 1060 and 1061 (and to a lesser extent 1062) display an abrupt shift of about 1 ε-unit toward more radiogenic values. At the proximate Bermuda Rise a similar shift was interpreted as an early arrival of SSW to the glacial Northwest Atlantic basin preceding HS2 (Gutjahr & Lippold, 2011), but changes in the weathering regime around the Labrador Sea affecting the benthic nepheloid layer cannot be excluded as the cause for these excursions. In contrast to HS2, HS1 is virtually indistinguishable from the LGM in terms of εNd (Figure 4,5a). Thus, no significant changes in abyssal water mass sourcing at the beginning of the last deglaciation is indicated, even under consideration of the slight southern end member shift observed by Skinner et al. (2013; Figure 6c). Comparison to other records from the abyssal NW Atlantic shows convergence during HS1 (Figures 3 and S7), suggesting a more homogeneous water mass distribution with slightly more SSW reaching up to 40°N during this time (Pöppelmeier et al., 2018).

Following HS1 the warm B/A was a time for which kinematic proxies and model results suggest an invigorated AMOC (McManus et al., 2004; Ng et al., 2018; Weaver et al., 2003). In terms of Nd isotopic signatures we document a rapid change by up to 2 ε-units toward less radiogenic values at the onset of the B/A (Figure 5). Sites to the north from Bermuda and Corner Rise, display a similar abrupt shift in εNd (Pöppelmeier et al., 2018; Roberts et al., 2010), but with larger amplitudes of 3 and 6 ε-units, respectively (Figure 3). Laurentian ice sheet retreat during the B/A could have delivered poorly weathered material to the Labrador Sea for the first time in the past 30 ka. Consequently, similar to today, reactive unradiogenic material was most likely transported downstream in a benthic nepheloid layer altering the local bottom waters. The spatial distribution of the amplitude suggests that the benthic nepheloid layer reached the Sohm Abyssal Plain strongly influencing the Corner Rise but considerably less the sites at the Bermuda Rise and BBOR further south. Nevertheless, the presence of the unradiogenic signal in the B/A interval of the BBOR cores implies southward transport of NADW (recorded either as a water mass signal or indirectly through a benthic nepheloid layer) at least toward 28°N during the B/A, in agreement with the invigorated AMOC. Direct comparison of the new εNd reconstructions from BBOR to εNd records from the equatorial Atlantic shows that the latter did not record an abrupt unradiogenic excursion during the B/A (Figure 6d, Howe, Piotrowski, & Rennie, 2016; Howe & Piotrowski, 2017), but rather resemble the South Atlantic record from Skinner et al. (2013). This hints to a strong attenuation of the signal either by the lack of the benthic nepheloid layer or mixing with other water masses on its path further southward. Thus, from the Northwest Atlantic sites alone it is impossible to determine how much of the B/A excursion amplitude is due to water mass transport or local alteration by the benthic nepheloid layer. For this separation further research on sites carefully chosen and outside the influence of benthic nepheloid layers is required.

The Nd isotope records of the ODP sites indicate a return to more radiogenic values during the onset of the YD (Figure 2). This reversal is missing in JPC12 with only a small plateau evident in the εNd data during this time interval. The origin of this discrepancy between neighboring sites is unclear, but the nonexistence seems to be a rather localized feature, since radiogenic εNd excursions are also documented in the other locations of the NW Atlantic (Pöppelmeier et al., 2018; Roberts et al., 2010). Possible explanations include sediment winnowing during the reinvigoration of the deep circulation during the early Holocene removing the YD section and overprinting due to sediment redistribution at site JPC12. The very dynamic sediment

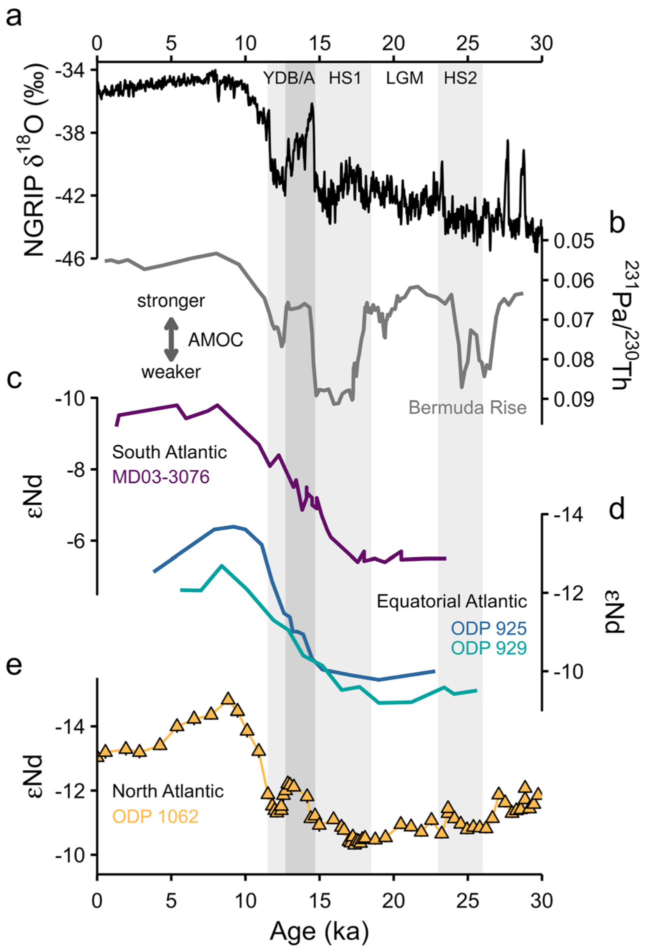

Figure 6. (a) Oxygen isotope record of the NGRIP ice core (Andersen et al., 2006). (b) ^{231}Pa/^{230}Th from Bermuda Rise (three-point running mean, Lippold et al., 2009; McManus et al., 2004). (c) εNd record from the South Atlantic (44°S) core MD03-3076Q (3,770 m; Skinner et al., 2013) (d) εNd records from the deep equatorial Atlantic (ODP 925 = 3,040 m, blue, and ODP 929 = 4,360 m, turquoise; Howe, Piotrowski, & Rennie, 2016, 2017). (e) εNd record of ODP Site 1062. Error bars of the double standard deviations are smaller than symbols. Light and dark gray shaded bars indicate the time ranges of HS2, HS1, and YD and B/A, respectively. Note the reversed *y* axes in panels (b)–(e) as well as the different εNd *y* scales in panels (c)–(e). B/A = Bølling-Allerød; HS = Heinrich Stadials; LGM = Last Glacial Maximum.

dynamics of the BBOR drift site could have facilitated this without affecting the nearby Site 1061. Since no conclusive explanation can be given here, we exclude the YD part of the JPC12 εNd record from further discussions.

The reversal in εNd during the YD indicates a weakening of North Atlantic deep water export. It is thought that the YD was, similar to HS, caused by freshwater input into the marginal seas of the North Atlantic (Keigwin et al., 2018; McManus et al., 2004). The new εNd data indicate a return to a more glacial-like water mass distribution with an increased contribution of SSW during the YD, in agreement with stable carbon isotope data (Evans & Hall, 2008; Keigwin, 2004). We exclude the possibility of an end member change as the cause for the εNd changes at BBOR, since Sites SU90-03 and U1313 further north do not exhibit a YD reversal which corroborates the interpretation of the BBOR εNd records in terms of water mass mixing. Thus, ambient YD-aged Nd isotopic compositions at BBOR indeed reflect local bottom water, the depth transect indicates that a significant contribution of SSW bathed the BBOR rather homogeneously at all depths below 3,000 m during the YD, similar to HS1.

At the end of the deglaciation (~12 ka BP) authigenic Nd isotopes at the BBOR shifted toward less radiogenic values until about 8 ka BP. The following middle to late Holocene was then characterized again by a steady increase toward the modern seawater data. These unradiogenic εNd excursions during the early Holocene are unlikely associated with large changes in water mass mixing since other proxies indicate a rather stable Holocene circulation (Keigwin & Boyle, 2000; McManus et al., 2004). The early Holocene was similar to the B/A a time of extensive ice sheet retreat (Clark et al., 2012), which exposed chemically poorly weathered material (Howe, Piotrowski, & Rennie, 2016). Similar to the proposed process producing the seawater-core top offsets as well as affecting the B/A, this reactive unradiogenic material probably contributed to the benthic nepheloid layer of the North American Basin altering the bottom water εNd. The distribution of the early Holocene excursion amplitude is remarkably similar to the B/A (Figure 3), suggesting the same spatial extension potentially forced by the invigorated AMOC (McManus et al., 2004). However, contrasting to the B/A, an early Holocene excursion is documented not only in the North American Basin but Atlantic-wide (Figure 6; Howe, Piotrowski, & Rennie, 2016, 2017; Piotrowski et al., 2004; Skinner et al., 2013). This hints to an advected water mass signal that is not exclusively associated with a local benthic nepheloid layer. Howe, Piotrowski, and Rennie (2016) proposed that the reactive unradiogenic material partly dissolved in the Labrador Sea imprinting its signal into the local deep water that was then advected southward as a conservative water mass signal. The differences between the minimum early Holocene (7–10 ka BP) εNd and the modern seawater values of the Northwest to equatorial Atlantic decrease with increasing distance from the Labrador Sea (Figure 7). An exponential fit of this decrease approaches a value of −1.4 ± 0.4 ε-units at large distance, which reflects the shift in the water mass end member signal conservatively transported southward. At BBOR this conservative part contributes to about 50% to the −2.8 ε-units early Holocene εNd excursion. The other half was caused by nonconservative effects most likely associated with local alteration by a benthic nepheloid layer. Closer to the Labrador Sea, the local alteration by a benthic nepheloid layer dominated the recorded early Holocene εNd minimum while outside the North American basin the end member change of lNADW can be assumed to be the cause for the εNd shift. Thus, the early Holocene unradiogenic εNd excursions of the Atlantic were most likely produced by two different mechanisms. The alteration of local bottom water by a benthic nepheloid layer in the

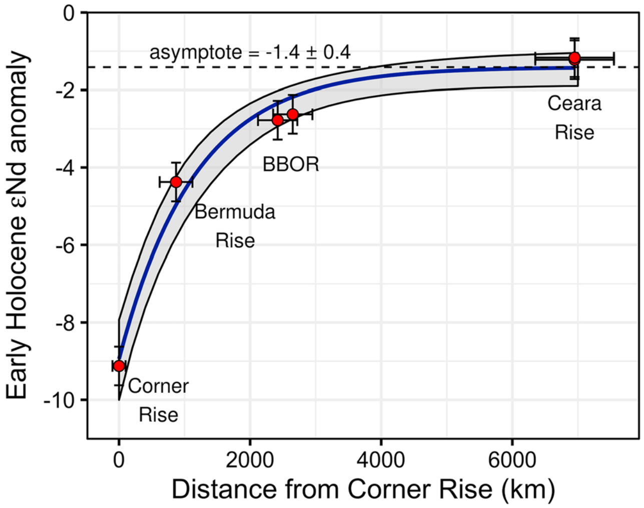

Figure 7. Early Holocene εNd anomaly (calculated as the difference between nearest seawater (Lambelet et al., 2016) and the minimum εNd value during the early Holocene) versus the distance along the margins of the sites from the location of Corner Rise. Data are from Corner Rise (Pöppelmeier et al., 2018), Bermuda Rise (Roberts et al., 2010), Blake Bahama Outer Ridge (BBOR, Sites 1061 and 1062, this study), and Ceara Rise (Ocean Drilling Program Sites 925 and 929; Howe, Piotrowski, & Rennie, 2016, 2017). All data points are scaled with the % North Atlantic Deep Water contribution (Jenkins et al., 2015). The exponential fit depicted as blue line approaches a value of -1.4 ± 0.4 (1σ) ε-units with a half-distance of 800 ± 170 (1σ) km. Gray ribbon indicates the 1σ fit uncertainty.

Northwest Atlantic and the alteration of deep water εNd in the Labrador Sea essentially producing an end member change of lNADW. Both processes are not associated with changes in water mass mixing but are probably mechanistically linked with each other. These features are therefore specific to the Nd isotope proxy and need to be carefully considered during the interpretation of εNd data.

5. Conclusions

The new εNd depth transect from BBOR recorded various paleoceanographic changes over the past 30 ka that are in general agreement with Atlantic-wide reconstructions. Due to the high temporal resolution of the records, the deglacial time periods of the YD and B/A are well resolved within the depth transect. Comparison between seawater and core top εNd values reveals offsets that are most likely attributed to local sediment dynamics of nepheloid layers. At BBOR sites shallower than 3,000-m water depths seem to be influenced by an intermediate depth nepheloid layer redistributing sediment from the Florida Shelf downslope as suggested earlier. The strength of this process presumably varied over glacial-interglacial timescales due to changes in shelf exposure and current strength and routing, resulting in a smaller effect during glacials. On the other hand, the εNd records of the deeper BBOR sites seem to be influenced by a benthic nepheloid layer that is transported by the DWBC and carries material sourced from the Labrador Sea. The reactivity and density of this benthic nepheloid layer appear to be dependent on sediment input into the Labrador Sea. As suggested earlier, after ice sheet retreat during the last deglaciation and early Holocene large amounts of chemically poorly weathered material entered the Labrador Sea probably releasing unradiogenic Nd to the local deep water and further contributed to the benthic nepheloid layer of the North American Basin. This led to an εNd end member change of -1.4 ± 0.4 ε-units during the early Holocene and further produced offsets between past seawater and archived Nd isotope signals in the entire Northwest Atlantic during the early Holocene and B/A. Thus, the nonconservative process associated with the benthic nepheloid layer most probably exaggerated the εNd B/A excursion observed at various Northwest Atlantic sites.

While apparently altered in amplitude of change, the water mass reconstructions indicate a strengthened northern deep water formation during the onset of the B/A, producing NSW which reached at least as far south as 28°N at a depth of 4,760 m. Comparison to other available εNd records from the equatorial and South Atlantic show that these records do not resolve the B/A-YD transition in the same way as in the NW Atlantic, hinting to an attenuation of the NW Atlantic NSW onset signal further southward. During the cold periods of the YD and HS1 the contribution of NSW was reduced in the whole lower water column below 3,000 m, which agrees with circulation strength reconstructions of a weakened AMOC.

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