



## Temporal stability of the neodymium isotope signature of the Holocene to glacial North Atlantic

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[1] The neodymium isotopic composition of marine precipitates is increasingly recognized as a powerful tool for identifying changes in ocean circulation and mixing on million year to millennial timescales. Unlike nutrient proxies such as  $\delta^{13}\text{C}$  or Cd/Ca, Nd isotopes are not thought to be altered in any significant way by biological processes, and thus they can serve as a quasi-conservative water mass tracer. However, the application of Nd isotopes in understanding the role of thermohaline circulation in rapid climate change is currently hindered by the lack of direct constraints on the signature of the North Atlantic end-member through time. Here we present the first results of Nd isotopes measured in U-Th-dated deep-sea corals from the New England seamounts in the northwest Atlantic Ocean. Our data are consistent with the conclusion that the Nd isotopic composition of North Atlantic deep and intermediate water has remained nearly constant through the last glacial cycle. The results address long-standing concerns that there may have been significant changes in the Nd isotopic composition of the North Atlantic end-member during this interval and substantiate the applicability of this novel tracer on millennial timescales for paleoceanography research.

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### 1. Introduction

[2] The water masses of the ocean display distinct Nd isotopic values that are ultimately derived from the continents and are delivered to the ocean through weathering, erosion, and particle-seawater interaction [Piepgras *et al.*, 1979; Goldstein and O'Nions, 1981; Frank, 2002; Goldstein and Hemming, 2003; Lacan and Jeandel, 2005b]. The  $^{143}\text{Nd}$  is produced by radioactive decay of  $^{147}\text{Sm}$ , and the  $^{143}\text{Nd}/^{144}\text{Nd}$  (expressed as  $\epsilon_{\text{Nd}}$ , which is the fractional deviation from the “bulk Earth” value of 0.512638 in parts per  $10^4$  [Jacobsen and Wasserburg, 1980]) in seawater is primarily a function of the age of the continental source rocks. In the global oceans the two main end-members for dissolved Nd are North Atlantic Deep Water (NADW) ( $\epsilon_{\text{Nd}} = -13.5 \pm 0.5$  [Piepgras and Wasserburg, 1987]), with low values reflecting the old continental crust surrounding the North Atlantic, and deep water in the North Pacific ( $\epsilon_{\text{Nd}} = -2$  to  $-3$ ; for a recent summary see van de Flierdt *et al.* [2004]), with higher values reflecting contributions from circum-Pacific volcanics. The covariance of Nd isotopes with both salinity and

dissolved silicate in Atlantic waters provide key evidence for the validity of Nd isotopes as a water mass tracer in the modern ocean [von Blanckenburg, 1999; Goldstein and Hemming, 2003]. Because Nd isotopes are not known to be affected by biological activity, or physical processes such as temperature and salinity, they can be used to assess ocean circulation changes that are independent of nutrient and carbon cycling [Frank, 2002; Goldstein and Hemming, 2003; Vance *et al.*, 2004; Martin and Scher, 2004].

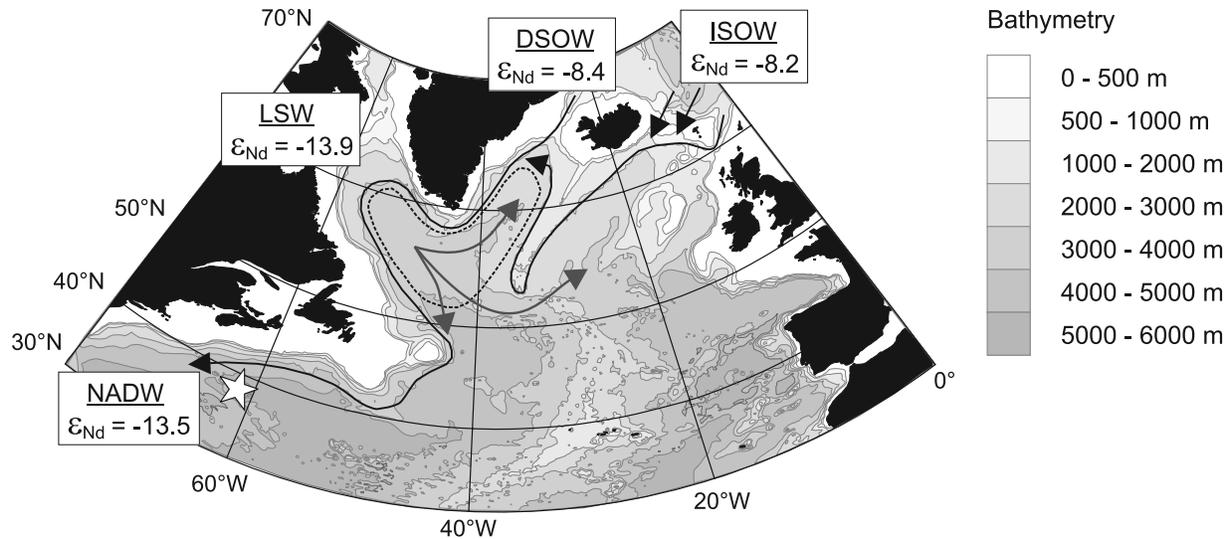
[3] Recently, Piotrowski *et al.* [2004, 2005] produced the first high-resolution seawater Nd isotope record over the last  $\sim 100$  thousand years, based on Nd leached from the dispersed ferromanganese fraction of sediments from the Cape Basin in the South Atlantic. They interpreted the record to indicate greater NADW export during warm intervals on glacial-interglacial to millennial scales, including major interstadial events in the Greenland ice record. Focusing on the deglaciation, Piotrowski *et al.* [2004] concluded the “baseline” level of NADW export strength gradually intensified over the period between  $\sim 18$  and 9 thousand years ago before present (kyr B.P.), with superimposed millennial variability.

[4] However, deglacial changes in the Nd isotopic composition of northern component waters could strongly affect this interpretation. Their assumption that it has remained nearly constant is based on data from surfaces of slow growing North Atlantic ferromanganese crusts and nodules, which generally show Nd isotope ratios similar to present-day NADW [Rutberg *et al.*, 2000]. Short-timescale changes can be hidden because each crust and nodule sample represents an average of several glacial cycles.

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**Figure 1.** Bathymetric map with key features of the deep circulation of the North Atlantic. Solid arrows highlight the highly simplified deep ocean circulation pattern in the North Atlantic, with the stippled line indicating the major recirculation pathway in the subpolar North Atlantic [Schmitz and McCartney, 1993; Dickson and Brown, 1994]. Shaded arrows mark the flow of Labrador Seawater. Additionally, inflow of Southern Ocean water (Lower Deep Water) takes place in the western and eastern basins, and waters communicate between both basins through the Charlie Gibbs Fracture Zone at 52°N. Extensive recirculation also takes place in the eastern North Atlantic and along the Deep Western Boundary Current off North America (not shown) [Schmitz and McCartney, 1993]. Star marks the sampling location of deep-sea corals on the New England seamount chain. Boxes refer to water masses originating from the two main areas of convection in the North Atlantic, which are the Labrador Sea (Labrador Seawater (LSW)) and the Nordic Seas (Denmark Strait Overflow Water (DSOW) and Iceland-Scotland Overflow Water (ISOW)). Numbers denote the Nd isotopic compositions of waters formed in these areas, respectively [Piepgras and Wasserburg, 1987; Lacan and Jeandel, 2004a, 2004b, 2005a]. Mature North Atlantic Deep Water (NADW) carries a signature of  $-13.5 \pm 0.5$  [Piepgras and Wasserburg, 1987].

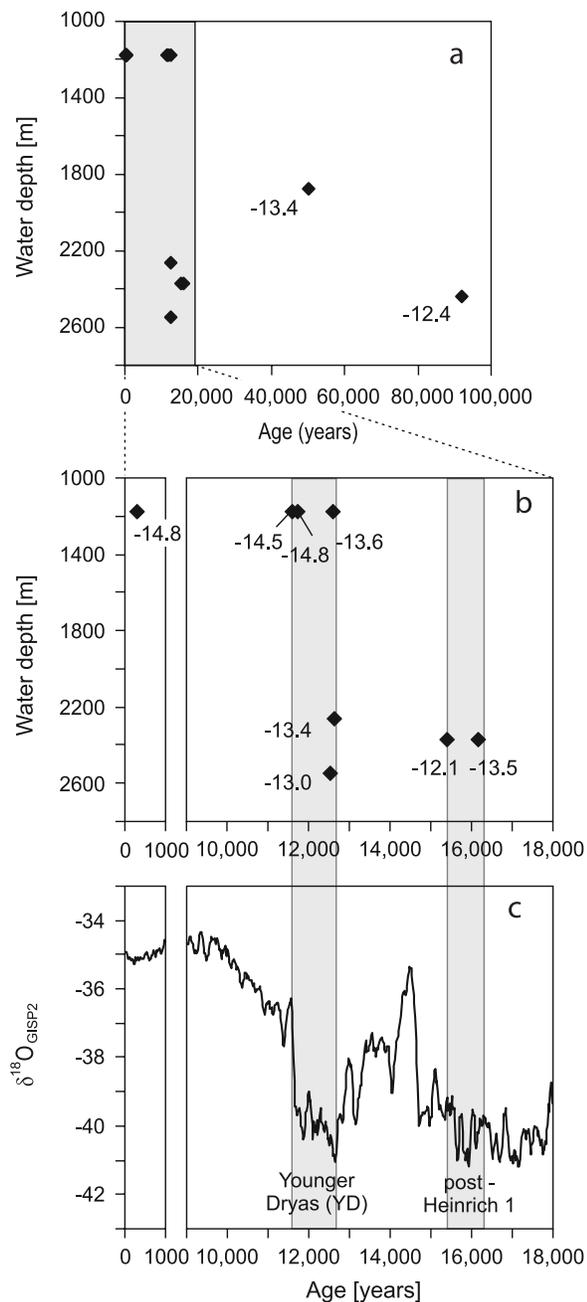
[5] There are distinct mechanisms through which the Nd isotopic signature of northern component waters may be altered on millennial to orbital timescales. First, the dominant fraction of modern NADW is formed by convection in the Labrador and Nordic Seas, where NADW source waters display a large range of Nd isotopic compositions ( $\epsilon_{Nd}$  of Labrador Seawater:  $-13.9 \pm 0.4$ ; Denmark Strait Overflow Water:  $-8.2 \pm 0.6$ ; Iceland-Scotland Overflow Water:  $-8.4 \pm 1.4$  [Lacan and Jeandel, 2004a, 2004b, 2005a]; Figure 1). A change in either the rate or place of formation of these key water masses could have a pronounced effect on the Nd isotopic composition of northern component waters. Secondly, changes in the style of weathering, the provenance of material, or the flux of material from the continents may significantly impact seawater Nd isotopic compositions [e.g., Burton et al., 1999; von Blanckenburg and O’Nions, 1999; Vance and Burton, 1999; Reynolds et al., 2004]. For example, a shift in continental weathering conditions (e.g., physical versus chemical) may cause incongruent release of Nd from different minerals leading to changes in the Nd isotopic composition of northern component source waters on short timescales [Öhlander et al., 2000; Andersson et al., 2001; von Blanckenburg and Nägler, 2001].

[6] In order to address the question of possible North Atlantic end-member changes we use deep-sea corals to

constrain the Nd isotopic composition of paleo-North Atlantic deep and intermediate waters. Our data indicate that there were no major changes in the Nd isotopic composition of the North Atlantic end-member over the last glacial cycle.

## 2. Samples, Methods, and Results

[7] We investigated 10 solitary corals (eight *Desmophyllum dianthus* and two *Caryophyllia*), collected from the New England Seamounts from water depths between 1100 and 2500 m below sea level (mbsl) (Figure 2). Corals settle and grow on hard substrates, mainly in areas of swift ocean currents and low sedimentation, and fossil samples exposed to seawater typically acquire a black coating of ferromanganese oxides and oxyhydroxides (“crusts”). In order to remove this coating, each coral was subjected to a rigorous physical and chemical cleaning. Cleaned samples of 230–830 mg of carbonate were dissolved, passed through ion exchange chemistry, and precisely dated by U-Th disequilibrium by MC-ICP-MS [Edwards et al., 1986; Cheng et al., 2000; Robinson et al., 2002, 2005]. *D. dianthus* live for decades to  $\sim 100$  years [Adkins et al., 2004] and each sample measured in this study integrates about 10 years of growth. Multiple measurements made along a single skeleton would allow decadal resolution



**Figure 2.** Neodymium isotope results for 10 solitary corals. Samples were recovered from the New England seamounts at 1100–2500 mbsl water depth. Ages on the  $x$  axis are derived from U-Th dating (Table S1 in auxiliary material). Numbers are Nd isotopic compositions of the individual samples, shown as diamonds. (a) Overview of all samples analyzed (to ages of  $\sim 100,000$  years). (b) Deglacial samples. (c) GISP2 oxygen isotopes. Shaded bar in Figure 2a marks the time interval shown in the blowups in Figures 2b and 2c. Shaded bars in Figures 2b and 2c highlight the times of growth of seven of the investigated deep-sea corals, which are during the Younger Dryas and post-Heinrich 1.

climate records to be generated from an individual coral. All corals of this study recorded a marine initial  $\delta^{234}U$ , indicating that they are free of diagenetic effects, and U series ages range from  $\sim 0.3$  to  $\sim 90$  ka (Table S1 in auxiliary material).<sup>1</sup> We make the assumption that our cleaning procedure, designed to remove Th associated with ferromanganese coating, will also remove Nd, so that the remaining rare earth element (REE) abundances and Nd isotopic compositions reflect ambient seawater. Neodymium was extracted from the same sample as used for U-Th analyses (Table S2 in auxiliary material) and details on the method can be found in Table S2. Measurements were carried out on a VG Sector 54–30 thermal ionization mass spectrometer at Lamont.

[8] Modern calibration of a 315 year old coral from the Gregg Seamount ( $39^{\circ}0'N$ ,  $61^{\circ}0'W$ ; 1176 mbsl) yielded  $\epsilon_{Nd} = -14.8 \pm 0.4$ , within error of the modern value of  $\epsilon_{Nd} = -14.0 \pm 0.4$  of nearby seawater ( $36^{\circ}15'38''N$ ,  $61^{\circ}58'27''W$ , 1100 mbsl [Piepgras and Wasserburg, 1987]). Further studies are required to show that deep-sea corals capture the full range of modern seawater Nd isotopic compositions, but preliminary data on *D. dianthus* corals from the Drake Passage and the southwest Pacific indicate that deep-sea corals reflect the true Nd isotopic composition of surrounding seawater (T. van de Flierdt et al., unpublished data, 2006). The observation that REE are incorporated into the aragonitic lattice of shallow water corals approximately in proportion to their seawater concentrations [Sholkovitz and Shen, 1995] lends further support to the integrity of the marine Nd isotope signal in aragonitic coral skeletons.

[9] The Nd isotope data for nine fossil corals from intermediate and deep waters over the past 91 kyr span a range of  $\epsilon_{Nd} = -12.1$  to  $-14.8$ , while those from only the intermediate depths show a narrower range of  $\epsilon_{Nd} = -13.4$  to  $-14.8$  (Figure 2). Seven of the measured samples are from the deglacial interval, and the Younger Dryas (YD) time interval is especially well represented with five deep-sea coral ages from 11.6 to 12.6 kyr cal. B.P. (Figures 2b and 2c). Two more deglacial samples are from the time interval immediately following the Heinrich 1 event (H1) but preceding the Bølling warming (15.4 and 16.2 kyr cal. B.P.) (Figure 2b). The remaining two fossil samples are from marine isotope stages (MIS) 3 and 5, respectively (Figure 2a).

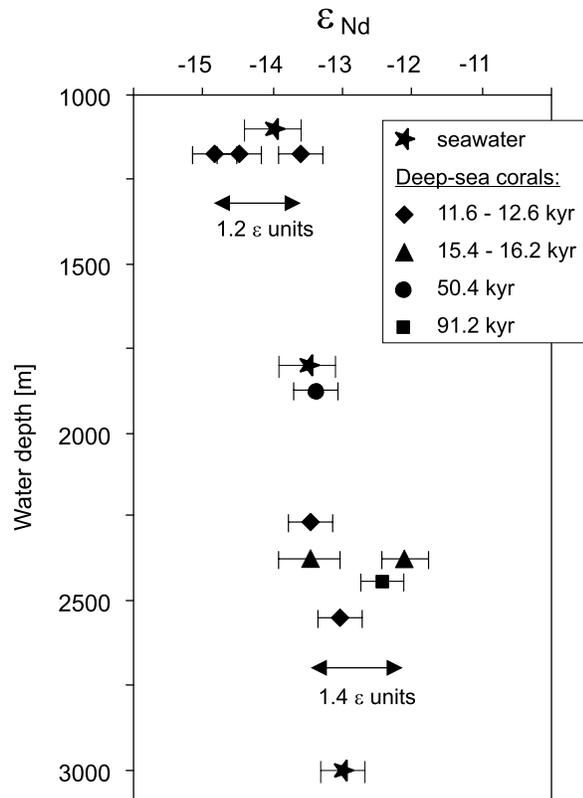
### 3. Discussion

[10] Overall the deep-sea coral results indicate that there were no major changes in the Nd isotopic composition of the North Atlantic end-member over the last glacial cycle. As most of our samples are of deglacial age, we will focus our discussion on these samples.

#### 3.1. Deglacial Nd Isotopic Composition in the Northwest Atlantic

[11] The recently published Nd isotope record from the Cape Basin [Piotrowski et al., 2004] shows large deglacial

<sup>1</sup>Auxiliary materials are available at <ftp://ftp.agu.org/apend/pa/2006pa001294>.



**Figure 3.** History of intermediate and deep water in the North Atlantic over the past glacial cycle. Neodymium isotopic results for deep-sea corals from the New England Seamounts versus water depth are shown. Different symbols characterize different age groups of the corals: diamonds, Younger Dryas; triangles, post-Heinrich 1; circle,  $\sim 50$  kyr cal. B.P. (marine isotope stage (MIS) 3); and square,  $\sim 90$  kyr cal. B.P. (MIS 5). Stars represent the present-day Nd isotopic composition of seawater as derived from a nearby modern water column profile [Piepgras and Wasserburg, 1987]. Error bars for our data points are external  $2\sigma$  standard deviation; for the Piepgras and Wasserburg [1987] data they are internal  $2\sigma$  deviations of the mean. The boundary between intermediate and deep waters in the deglacial ocean was most likely located between 2000 and 2500 mbsl.

variability ( $\sim 4 \epsilon$  units), covering the entire amplitude of changes observed on glacial to interglacial timescales [Piotrowski et al., 2005]. Cape Basin Nd isotopic composition during the Younger Dryas and the time following H1 were higher (by 2–3  $\epsilon$  units) than Holocene seawater, indicating a lower contribution of northern component waters as compared to today. Therefore the deglacial in the North Atlantic is a good period in which to evaluate whether the northern component end-member changed on glacial-interglacial timescales.

[12] Neodymium isotopes of deglacial deep-sea coral samples at intermediate water depth span a range of only 1.2  $\epsilon$  units during the Younger Dryas, and the average value of  $-14.3$ , as well as each individual datum point, is

consistent with the modern local seawater value of  $\epsilon_{Nd} = -14.0 \pm 0.4$  (Figures 2 and 3). Although the dominant water mass in the modern northwest Atlantic is NADW, during the YD the northwest Atlantic water column was similar to the Last Glacial Maximum (LGM), where modern NADW shoaled and transformed to its glacial analogue, Glacial North Atlantic Intermediate Water (GNAIW) [Boyle and Keigwin, 1987; Curry et al., 1988; Duplessy et al., 1988; Oppo and Lehman, 1993; Keigwin and Lehman, 1994; Sarnthein et al., 1994; Marchitto et al., 1998; Keigwin, 2004; Curry and Oppo, 2005]. GNAIW was most likely formed by convection south of Iceland [Duplessy et al., 1988; Oppo and Lehman, 1993; Sarnthein et al., 1994], and therefore south of the present-day convection in the Nordic Seas, and is thought to have filled the glacial North Atlantic down to depths of  $\sim 2000$  m. Deeper waters in the glacial North Atlantic were derived from the Southern Hemisphere [Boyle and Keigwin, 1987; Curry et al., 1988; Duplessy et al., 1988; Marchitto et al., 2002; Keigwin, 2004; Curry and Oppo, 2005], and probably had higher Nd isotopic compositions. Our results show that GNAIW during the YD had the same Nd isotopic composition as modern NADW. Because of our limited data set we cannot exclude the possibility of Nd isotope changes of the North Atlantic end-member at other times during the deglaciation, but we consider such changes unlikely as our samples are from times of abrupt climate change (e.g., the Younger Dryas). Our results confirm the value of Nd isotopes as a water mass and circulation tracer through time because they eliminate the long-standing concern that the Nd isotopic composition of the North Atlantic end-member has undergone substantial variability.

### 3.2. Acquisition of the NADW and GNAIW Nd Isotope Signal

[13] The results also have important implications for the manner in which GNAIW and NADW acquire their Nd isotopic compositions. In the present day, proto-NADW is formed downstream of the formation regions of Labrador Seawater (LSW), Iceland-Scotland Overflow Water, and Denmark Strait Overflow Water, through mixing in the subpolar gyre (Figure 1). LSW ( $\epsilon_{Nd} = -13.9$ ), Northeast Atlantic Deep Water (NEADW:  $\epsilon_{Nd} = -11.3$ ), and Northwest Atlantic Bottom Water (NWABW:  $\epsilon_{Nd} = -10.9$ ) are the direct precursors of NADW [Schmitz, 1996; Lacan and Jeandel, 2005a] and simple ternary mixing of these three water masses results in a predicted Nd isotope ratio of  $\epsilon_{Nd} = -11.7$  (calculation details are in auxiliary material). This value is outside of error of the mature NADW signature of  $\epsilon_{Nd} = -13.5$  and boundary exchange of deep waters with low  $\epsilon_{Nd}$  shelf sediments from the Greenland slope and the Labrador Sea has been suggested as a mechanism to obtain the Nd isotopic composition of NADW [Innocent et al., 1997; Lacan and Jeandel, 2005a].

[14] The similarity of the Nd isotopic signature of present-day NADW and GNAIW, as inferred from intermediate water depth YD deep-sea corals, implies that either (1) locations and/or processes associated with the acquisition of the Nd isotopic signature of GNAIW and NADW have been constant during glacial and interglacial climate

regimes, or (2) competing shifts in processes and/or locations lead to the same net result. Because convection in the NE Atlantic likely shifted from the Nordic Seas to the open North Atlantic south of Iceland during the LGM [Duplessy et al., 1988; Oppo and Lehman, 1993; Sarnthein et al., 1994], and glacial sea ice cover probably prevented vigorous convection in the Labrador Sea [Hillaire-Marcel et al., 2001], it is unlikely that GNAIW formed at the same locations as NADW does today. One possible mechanism to explain the similar Nd isotopic compositions is that convection or exchange of seawater with sediments south of Iceland (high  $\epsilon_{Nd}$ ) and on the Greenland shelf (low  $\epsilon_{Nd}$ ) imprinted a Nd isotopic signature to GNAIW resembling the modern contributions from the Nordic and Labrador Seas, respectively.

### 3.3. Influence of Southern Ocean Water

[15] Constraints on the water mass distribution in the glacial and deglacial North Atlantic are derived from various tracer data on benthic foraminifera ( $\delta^{13}C$ , Cd/Ca, radiocarbon) and indicate a water mass boundary between GNAIW and Southern Ocean waters at around 2000 to 2500 mbsl [Boyle and Keigwin, 1987; Curry et al., 1988; Duplessy et al., 1988; Marchitto et al., 2002; Keigwin, 2004; Curry and Oppo, 2005; Robinson et al., 2005]. Neodymium isotope ratios of four deglacial deep-sea coral samples from ~2500 mbsl water depth cover a range of 1.4  $\epsilon$  units ( $\epsilon_{Nd} = -12.1$  to  $-13.5$ ). These values are slightly higher (average  $\epsilon_{Nd} = -12.8$ ) than modern NADW ( $\epsilon_{Nd} = -13.5 \pm 0.5$  [Piepgras and Wasserburg, 1987]) and GNAIW ( $\epsilon_{Nd} = -14.3$ ), pointing to a mixture of GNAIW with Southern Ocean-derived waters. However, before we can determine quantitative mixing proportions of GNAIW and southern component water masses in the deep North

Atlantic, we need better constraints on the composition of the southern end-member on glacial-interglacial timescales.

## 4. Conclusions

[16] We analyzed 10 deep-sea corals from the New England seamounts in the northwest Atlantic ranging in age from modern to 91 kyr cal. B.P. for their Nd isotopic compositions. The results provide direct evidence that GNAIW in the western North Atlantic had the same Nd isotopic composition as modern NADW. This conclusion is based on deep-sea corals that grew during the Younger Dryas, and is also confirmed by one sample from MIS 3. Stability of the North Atlantic end-member composition on glacial-interglacial timescales considerably simplifies interpretation of Nd isotope variability through time in other locations as a tracer of water mass mixing and ocean circulation.

[17] Future analyses of deep-sea corals will put tighter constraints on the glacial-interglacial Nd isotopic composition of both the northern and the southern end-member, and on their mixing ratio in the deep Atlantic over time. Additionally, since deep-sea corals are faithful archives for the radiocarbon contents of the past ocean [Robinson et al., 2005] coupled radiocarbon and Nd isotope analyses on deep-sea corals may open a new avenue of research in rapid climate change by providing a proxy to derive water mass fingerprinting and rates of overturning from the same, absolutely dated archive.

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## References

- Adkins, J. F., G. M. Henderson, S.-L. Wang, S. O'Shea, and F. Mokadem (2004), Growth rates of the deep-sea scleractinia *Desmophyl- lum cristagalli* and *Enallopsammia rostrata*, *Earth Planet. Sci. Lett.*, *227*, 481–490.
- Andersson, P. S., R. Dahlqvist, J. Ingri, and Ö. Gustafsson (2001), The isotopic composition of Nd in a boreal river: A reflection of selective weathering and colloidal transport, *Geochim. Cosmochim. Acta*, *65*, 521–527.
- Boyle, E. A., and L. D. Keigwin (1987), North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature, *Nature*, *330*, 35–40.
- Burton, K. W., D.-C. Lee, J. N. Christensen, A. N. Halliday, and J. R. Hein (1999), Actual timing of neodymium isotopic variations recorded by Fe-Mn crusts in the western North Atlantic, *Earth Planet. Sci. Lett.*, *171*, 149–156.
- Cheng, H., J. F. Adkins, R. L. Edwards, and E. A. Boyle (2000), U-Th dating of deep-sea corals, *Geochim. Cosmochim. Acta*, *64*, 2401–2416.
- Curry, W. B., and D. W. Oppo (2005), Glacial water mass geometry and the distribution of  $\delta^{13}C$  of  $\Sigma CO_2$  in the western Atlantic Ocean, *Paleoceanography*, *20*, PA1017, doi:10.1029/2004PA001021.
- Curry, W. B., J. C. Duplessy, L. Labeyrie, and N. J. Shackleton (1988), Changes in the distribution of  $\delta^{13}C$  of deep water  $\Sigma CO_2$  between the last glaciation and the Holocene, *Paleoceanography*, *3*, 317–341.
- Dickson, R. R., and J. Brown (1994), The production of North Atlantic Deep Water: Sources, rates, and pathways, *J. Geophys. Res.*, *99*, 12,319–12,341.
- Duplessy, J. C., N. J. Shackleton, R. G. Fairbanks, L. Labeyrie, D. W. Oppo, and N. Kallel (1988), Deepwater source variations during the last climatic cycle and their impact on the global deep-water circulation, *Paleoceanography*, *3*, 343–360.
- Edwards, R. L., J. H. Chen, and G. J. Wasserburg (1986),  $^{238}U$ - $^{234}U$ - $^{230}Th$ - $^{232}Th$  systematics and the precise measurement of time over the past 500,000 years, *Earth Planet. Sci. Lett.*, *81*, 175–192.
- Frank, M. (2002), Radiogenic isotopes: Tracers of past ocean circulation and erosional input, *Rev. Geophys.*, *40*(1), 1001, doi:10.1029/2000RG000094.
- Goldstein, S. L., and S. R. Hemming (2003), Long-lived isotopic tracers in oceanography, paleoceanography, and ice-sheet dynamics, in *Treatise on Geochemistry*, vol. 6, edited by H. Elderfield, pp. 453–489, Elsevier, New York.
- Goldstein, S. L., and R. K. O'Nions (1981), Nd and Sr isotopic relationships in pelagic clays and ferromanganese deposits, *Nature*, *292*, 324–327.
- Hillaire-Marcel, C., A. de Vernal, G. Bilodeau, and A. J. Weaver (2001), Absence of deep-water formation in the Labrador Sea during the last interglacial period, *Nature*, *410*, 1073–1077.
- Innocent, C., N. Fagel, R. K. Stevenson, and C. Hillaire-Marcel (1997), Sm-Nd signature of modern and late Quaternary sediments from the northwest North Atlantic: Implications for deep current changes since the Last Glacial Maximum, *Earth Planet. Sci. Lett.*, *146*, 607–625.
- Jacobsen, S. B., and G. J. Wasserburg (1980), Sm-Nd isotopic evolution of chondrites, *Earth Planet. Sci. Lett.*, *50*, 139–155.
- Keigwin, L. D. (2004), Radiocarbon and stable isotope constraints on Last Glacial Maximum and Younger Dryas ventilation in the western

- North Atlantic, *Paleoceanography*, 19, PA4012, doi:10.1029/2004PA001029.
- Keigwin, L. D., and S. J. Lehman (1994), Deep circulation change linked to Heinrich event 1 and Younger Dryas in a middepth North Atlantic core, *Paleoceanography*, 9, 185–194.
- Lacan, F., and C. Jeandel (2004a), Denmark Strait water circulation traced by heterogeneity in neodymium isotopic compositions, *Deep Sea Res., Part I*, 51, 71–82.
- Lacan, F., and C. Jeandel (2004b), Neodymium isotopic composition and rare earth element concentrations in the deep and intermediate Nordic Seas: Constraints on the Iceland Scotland Overflow Water signature, *Geochem. Geophys. Geosyst.*, 5, Q11006, doi:10.1029/2004GC000742.
- Lacan, F., and C. Jeandel (2005a), Acquisition of the neodymium isotopic composition of the North Atlantic Deep Water, *Geochem. Geophys. Geosyst.*, 6, Q12008, doi:10.1029/2005GC000956.
- Lacan, F., and C. Jeandel (2005b), Neodymium isotopes as a new tool for quantifying exchange fluxes at the continent-ocean interface, *Earth Planet. Sci. Lett.*, 232, 245–257.
- Marchitto, T. M., Jr., W. B. Curry, and D. W. Oppo (1998), Millennial-scale change in North Atlantic circulation since the last glaciation, *Nature*, 393, 557–561.
- Marchitto, T. M., Jr., D. W. Oppo, and W. B. Curry (2002), Paired benthic foraminiferal Cd/Ca and Zn/Ca evidence for a greatly increased presence of Southern Ocean water in the glacial North Atlantic, *Paleoceanography*, 17(3), 1038, doi:10.1029/2000PA000598.
- Martin, E. E., and H. D. Scher (2004), Preservation of seawater Sr and Nd isotopes in fossil fish teeth: Bad news and good news, *Earth Planet. Sci. Lett.*, 220, 25–39.
- Öhlander, B., J. Ingri, M. Land, and H. Schöberg (2000), Change of Sm-Nd composition during weathering of till, *Geochim. Cosmochim. Acta*, 64, 813–820.
- Oppo, D. W., and S. J. Lehman (1993), Mid-depth circulation of the subpolar North Atlantic during the Last Glacial Maximum, *Science*, 259, 1148–1151.
- Piegras, D. J., and G. J. Wasserburg (1987), Rare earth element transport in the western North Atlantic inferred from Nd isotopic observations, *Geochim. Cosmochim. Acta*, 51, 1257–1271.
- Piegras, D. J., G. J. Wasserburg, and E. J. Dasch (1979), The isotopic composition of Nd in different ocean masses, *Earth Planet. Sci. Lett.*, 45, 223–236.
- Piotrowski, A. M., S. L. Goldstein, S. R. Hemming, and R. G. Fairbanks (2004), Intensification and variability of ocean thermohaline circulation through the last deglaciation, *Earth Planet. Sci. Lett.*, 225, 205–220.
- Piotrowski, A. M., S. L. Goldstein, S. R. Hemming, and R. G. Fairbanks (2005), Temporal relationships of carbon cycling and ocean circulation at glacial boundaries, *Science*, 307, 1933–1938.
- Reynolds, B. C., S. C. Sherlock, S. P. Kelley, and K. W. Burton (2004), Radiogenic isotope records of Quaternary glaciations: Changes in the erosional source and weathering processes, *Geology*, 32, 861–864.
- Robinson, L. F., G. M. Henderson, and N. C. Slowey (2002), U-Th dating of marine isotope stage 7 in Bahamas slope sediments, *Earth Planet. Sci. Lett.*, 196, 175–187.
- Robinson, L. F., J. F. Adkins, L. D. Keigwin, J. Southon, D. P. Fernandez, S.-L. Wang, and D. Scheirer (2005), Radiocarbon variability in the western North Atlantic during the last deglaciation, *Science*, 310, 1469–1473.
- Rutberg, R. L., S. R. Hemming, and S. L. Goldstein (2000), Reduced North Atlantic Deep Water flux to the glacial Southern Ocean inferred from neodymium isotope ratios, *Nature*, 405, 935–938.
- Sarnthein, M., K. Winn, S. J. A. Jung, J.-C. Duplessy, L. Labeyrie, H. Erlenkeuser, and G. Ganssen (1994), Changes in east Atlantic deepwater circulation over the last 30,000 years: Eight time slice reconstructions, *Paleoceanography*, 9, 209–267.
- Schmitz, W. J. J. (1996), On the world ocean circulation: Volume I, some global features/North Atlantic circulation, *WHOI Tech. Rep. WHOI-96-03*, 150 pp., Woods Hole Oceanogr. Inst., Woods Hole, Mass.
- Schmitz, W. J. J., and M. S. McCartney (1993), On the North Atlantic circulation, *Rev. Geophys.*, 31, 29–49.
- Sholkovitz, E., and G. T. Shen (1995), The incorporation of rare earth elements in modern coral, *Geochim. Cosmochim. Acta*, 59, 2749–2756.
- Vance, D., and K. W. Burton (1999), Neodymium isotopes in planktonic foraminifera: A record of the response of continental weathering and ocean circulation rates to climate change, *Earth Planet. Sci. Lett.*, 173, 365–379.
- Vance, D., A. E. Scrivner, P. Beney, M. Staubwasser, G. M. Henderson, and N. C. Slowey (2004), The use of foraminifera as a record of the past neodymium isotope composition of seawater, *Paleoceanography*, 19, PA2009, doi:10.1029/2003PA000957.
- van de Flierdt, T., M. Frank, D.-C. Lee, A. N. Halliday, B. C. Reynolds, and J. R. Hein (2004), New constraints on the sources and behavior of neodymium and hafnium in seawater from Pacific Ocean ferromanganese crusts, *Geochim. Cosmochim. Acta*, 68, 3827–3843.
- von Blanckenburg, F. (1999), Tracing past ocean circulation, *Science*, 286, 1862–1863.
- von Blanckenburg, F., and T. F. Nägler (2001), Weathering versus circulation-controlled changes in radiogenic isotope tracer composition of Labrador Sea and Northern Atlantic Deep Water, *Paleoceanography*, 16, 424–434.
- von Blanckenburg, F., and R. K. O’Nions (1999), Response of beryllium and radiogenic isotope ratios in Northern Atlantic Deep Water to the onset of Northern Hemisphere glaciation, *Earth Planet. Sci. Lett.*, 167, 175–182.

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