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Lithogenic Particle Transport Trajectories on the Northwest Atlantic Margin

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Key Points:

- Detrital Nd isotopes were used to constrain trajectories of sediment dispersal on the northwest Atlantic margin
- Spatial gradients in surface sediment $\varepsilon_{\text{Nd-detrital}}$ imply contrasting provenance, and across- and along-margin sediment transport
- Sinking particle $\varepsilon_{\text{Nd-detrital}}$ values at three depths on the lower slope imply particle transport via intermediate and bottom nepheloid layers

Supporting Information:

- Supporting Information S1

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Abstract The neodymium isotopic composition of the detrital (lithogenic) fraction ($\varepsilon_{\text{Nd-detrital}}$) of surface sediments and sinking particles was examined to constrain transport trajectories associated with hemipelagic sedimentation on the northwest Atlantic margin. The provenance of resuspended sediments and modes of lateral transport in the water column were of particular interest given the energetic hydrodynamic regime that sustains bottom and intermediate nepheloid layers over the margin. A large across-margin gradient of ~5 ε_{Nd} units was observed for surface sediments, implying strong contrasts in sediment provenance, with $\varepsilon_{\text{Nd-detrital}}$ values on the lower slope similar to those of "upstream regions" (Scotian margin) under the influence of the Deep Western Boundary Current (DWBC). Sinking particles collected at three depths at a site (total water depth, ~3,000 m) on the New England margin within the core of the DWBC exhibited a similarly large range in $\varepsilon_{\text{Nd-detrital}}$ values. The $\varepsilon_{\text{Nd-detrital}}$ values of particles intercepted at intermediate water depths (1,000 and 2,000 m) were similar to each other but significantly higher than those at 3,000 m (~50 m above the seafloor). These observations suggest that lithogenic material accumulating in the upper two traps was primarily advected in intermediate nepheloid layers emanating from the adjacent shelf, while that at 3,000 m is strongly influenced by sediment resuspension and along-margin, southward lateral transport within the bottom nepheloid layer via entrainment in the DWBC. Our results highlight the importance of both along- and across-margin sediment transport as vectors for lithogenic material and associated organic carbon transport.

Plain Language Summary The New England slope on the northwest Atlantic margin is a region of high kinetic energy stemming from the interplay between two major current systems: The Gulf Stream and the Deep Western Boundary Current (DWBC). Clay and silt-sized detrital particles comprising hemipelagic sediments are laterally advected and dispersed over this margin, and the provenance of resuspended sediments and modes of lateral transport in the water column are of particular interest. Neodymium isotopic compositions (^{143}Nd/^{144}Nd) of sedimentary detrital phases can be used as a tracer of the provenance of lithogenic particles in the ocean since detrital sediments eroded from the continents reflect that of host rocks from which they emanate. We examined the Nd isotopic composition of the detrital fraction of surface sediments and sinking particles to constrain particle transport trajectories. The spatial gradients in the Nd isotopic composition of sediments reflect both the provenance of lithogenic inputs and sediment dispersal over the continental margin and into the interior northwest Atlantic basin. Based on Nd isotopic measurements of sinking particle samples from sediment traps deployed on the lower slope, we identify two primary modes of detrital particle delivery: across-margin transport and along-slope transport within the DWBC.

1. Introduction

Continental margins are characterized by high sedimentation rates and hydrodynamic energy. High surface ocean primary productivity on the margin promotes rapid vertical settling of biogenic particles to the seafloor, while clay and silt-sized detrital particles comprising hemipelagic sediments may be laterally advected and dispersed over the margin. Lateral transport of resuspended sediment particles is demonstrated by the existence of nepheloid layers—layers of elevated particle concentrations. Intermediate nepheloid

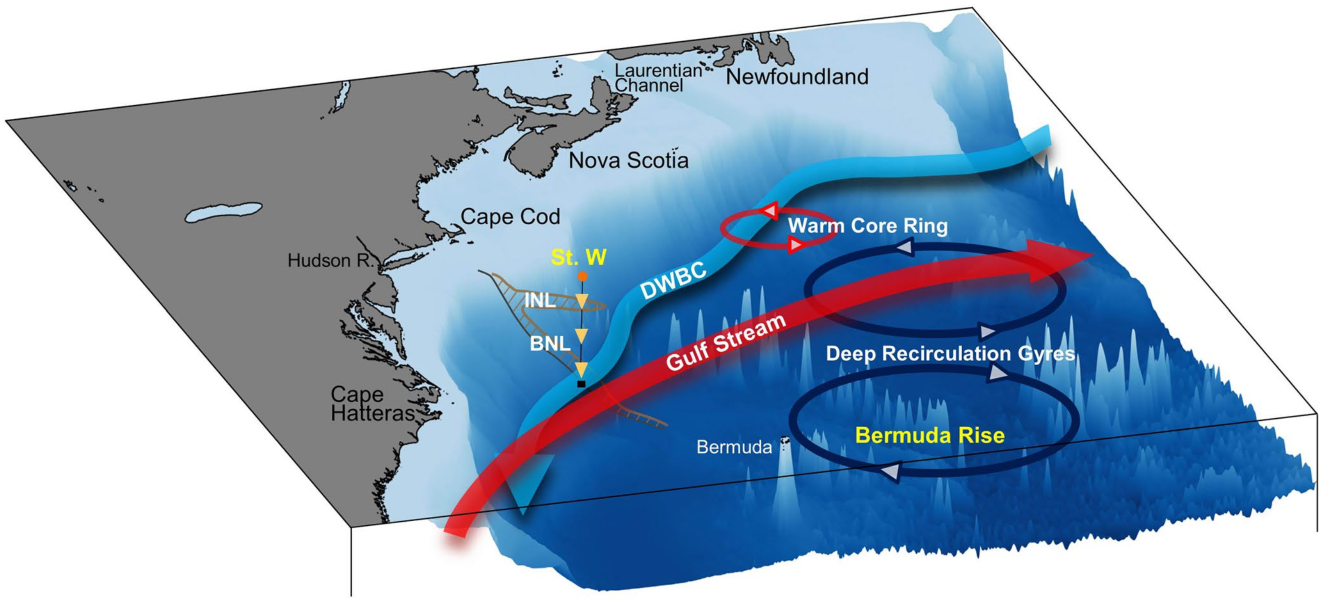

Figure 1. A schematic showing key features of the northwest Atlantic margin. Approximate location and feature of the sediment trap mooring (St. W) is also shown. INL and BNL respectively stand for intermediate and bottom/benthic nepheloid layers. BNL, bottom nepheloid layer; DWBC, Deep Western Boundary Current; INL, intermediate nepheloid layer.

layers (INLs) are formed by lateral transport of resuspended particles emanating from the shelf break and upper slope along isopycnal surfaces (e.g., McCave et al., 2001 and references therein) and from submarine canyon systems (Gardner, 1989). Benthic nepheloid layers (BNLs, hereafter bottom nepheloid layer and benthic nepheloid layer are used without distinction) are well developed in regions of high surface eddy kinetic energy (Gardner et al., 2017, 2018). Thick and strong (>20 μgl^{-1} in particle concentration) BNLs are commonly associated with continental margin systems, for example, the northwest Atlantic margin, northeastern Atlantic margin off Ireland, south of Aleutian Islands and Kamchatka Peninsula, and southeastern Pacific margin off Chile (Gardner et al., 2017, 2018). Lateral transport of sediment particles has been shown to be an important vector for not only lithogenic material but also associated organic carbon (Hwang et al., 2010; Kim et al. 2020 and references therein). For example, Inthorn et al. (2006) demonstrated the importance of lateral particle transport in the BNLs in organic carbon burial in the highly productive Benguela upwelling system. As an extreme case, laterally transported particles accounted for >85% of sinking particle and 45%–69% of the particulate organic carbon (POC) flux in the seasonally ice-covered Canada Basin, western Arctic Ocean (Hwang et al., 2015).

The New England slope on the northwest Atlantic margin is a region of high kinetic energy (Dixon et al., 2011; Gardner et al., 2017, 2018) stemming from the interplay between two major current systems: the Gulf Stream and the deep western boundary current (DWBC; Figure 1). Processes associated with high abyssal kinetic energy on the Nova Scotian margin, in the upstream region of the DWBC, were the subject of intensive study during project HEBBLE (High Energy Benthic Boundary Layer Experiment; Hollister & Nowell, 1991). Energetic conditions promote sediment resuspension and subsequent current-driven transport that create thick BNLs (Gardner et al., 2017). Sediment resuspension in shallow waters, induced by coastal currents as well as wave and tidal energy (Gardner et al., 2017), can advect particulate matter via detachment of INLs from the shelf break, injecting it into the open ocean. These processes were a focus of the SEEP-I (Shelf Edge Exchange Processes) program on the NW Atlantic margin (Biscaye et al., 1988).

Previously, we have examined the dynamics of POC and associated fluxes of biogenic and lithogenic material in the vicinity of Station W (39.5 °N, 68.3 °W, ~3,000 m) on the New England continental margin. This location has been the subject of sustained physical oceanographic investigations designed to better understand dynamics of the DWBC, a key component of North Atlantic Deep Water (NADW) transport (Andres et al., 2016; https://dods.ndbc.noaa.gov/thredds/catalog/data/oceansites/DATA/LINE-W/catalog.html). Pronounced BNLs and INLs were found to be a persistent feature in CTD-transmissometry hydrocasts conducted as part of repeat hydrographic surveys along Line W (Figure S1). The BNLs were 50–400 m in thickness on the New England slope based on enhanced beam attenuation (Hwang et al., 2009b, Figure S1). Analyses of sinking particles intercepted by bottom-tethered time-series sediment traps (Hwang et al., 2009a, 2014, 2017) and suspended particles collected by large-volume *in situ* filtration (Hwang et al., 2009b) revealed substantial fractions of lithogenic material and associated aged organic carbon in both sinking and suspended particles, as indicated by high Al fluxes and low radiocarbon isotope ratios (expressed as $\Delta^{14}C$ values). Based on these observations, two modes of lateral particle supply were suggested: INLs emanating from the shelf break and BNLs propagating along the slope. The degree of unsaturation (U^{K}_{37}, Ohkouchi et al., 2002) and hydrogen isotopic compositions (δD values, Englebrecht & Sachs, 2005) of alkenones—molecular proxies of surface ocean temperature and salinity, respectively—have been measured in surficial sediments on the Bermuda Rise, underlying the adjacent northern Sargasso Sea. These proxy signals suggest resuspension and long-range transport of sediment emanating from cooler, fresher waters to the north and west, likely via entrainment in BNLs. Alkenone proxy measurements on sinking particles at Station W are consistent with these processes (Hwang et al., 2014), but the provenance of detrital sediments subject to lateral transport and redistribution remains poorly constrained.

Neodymium isotopic compositions ($^{143}Nd/^{144}Nd$, expressed as ε_{Nd}) of continental rocks can vary markedly depending on their lithology and formation age (S. L. Goldstein and Hemming, 2003). These isotopic signatures are transferred to the ocean via weathering and erosion, imparting regional isotopic gradients in adjacent waters and sediments. The isotopic composition of dissolved Nd has been used as a tracer of water mass movement (e.g., Lacan & Jeandel, 2005; van de Flierdt et al., 2016), while Nd associated with oxyhydroxide and biogenic carbonate phases provides a window into past ocean circulation (e.g., Roberts et al., 2010). The Nd isotopic composition of sedimentary detrital phases has been used as a tracer of the provenance of lithogenic particles in the ocean (e.g., Behrens et al., 2018; Jeandel et al., 2007) since detrital sediments eroded from the continents reflect that of host rocks from which they emanate. A few prior studies have used detrital Nd isotopic signatures of suspended and sinking particles to trace the provenance of lithogenic material in ocean waters (Grousset et al., 1990; Hegner et al., 2007; Stichel et al., 2020). Correspondingly, the Nd isotopic composition of the detrital fraction of sediment cores has been used for reconstruction of past lithogenic material transport and ocean currents (e.g., Fagel et al., 2004; Revel et al., 1996). Nd isotopic compositions are reliable indicators of lithogenic material provenance as they are unaffected by the mineralogical sorting and grain size variations (e.g., Garcon et al., 2014; Jonell et al., 2018), and serve as an effective tracer where putative sources have distinctive $\varepsilon_{Nd\text{-}detrital}$ values.

Available compilations of Nd isotope data for rock outcrops on the continents and ocean margin sediments highlight those regions for which pronounced gradients in $\varepsilon_{Nd\text{-}detrital}$ exist (Jeandel et al., 2007). The northwest Atlantic margin, extending from Cape Hatteras to Greenland is one region that is characterized by sharp contrasts in Nd isotopic signatures of continental rocks (Stichel et al., 2020). These isotopic signatures also manifest themselves in fluvial signals draining into the Atlantic from eastern North America (S. J. Goldstein and Jacobsen, 1988), although only limited data currently exists for continental margin surface sediments in this region.

In this study, we examine the Nd isotopic composition of the detrital fraction ($\varepsilon_{Nd\text{-}detrital}$) of a suite of surface sediments from the northwest Atlantic margin and compare these signatures to those of sinking particles at a well-studied site (Station W) on the New England slope. The goal of the present study was to use Nd isotopic signatures to elucidate the trajectories of lithogenic material transport in this dynamic region.

2. Methods

2.1. Sample Collection

Details of sinking particle collection can be found in Hwang et al. (2009a) and in Table S1. Briefly, conical sediment traps (McLane Mark-7) were deployed at three depths: 968, 1,976, and 2,938 m (50 m above the bottom) in the vicinity of Station W on the continental slope south of Cape Cod (39.4667 °N, 68.3667 °W, total water depth ~2,988 m). Samples were collected from June 27, 2004 to April 27, 2005. Thirteen samples were collected with an interval of 23.4 days for 968 m trap and 21 samples with an interval of 14.5 days for each 1976 and 2,938 m trap. Samples were also collected by two more year-long trap deployments. For these

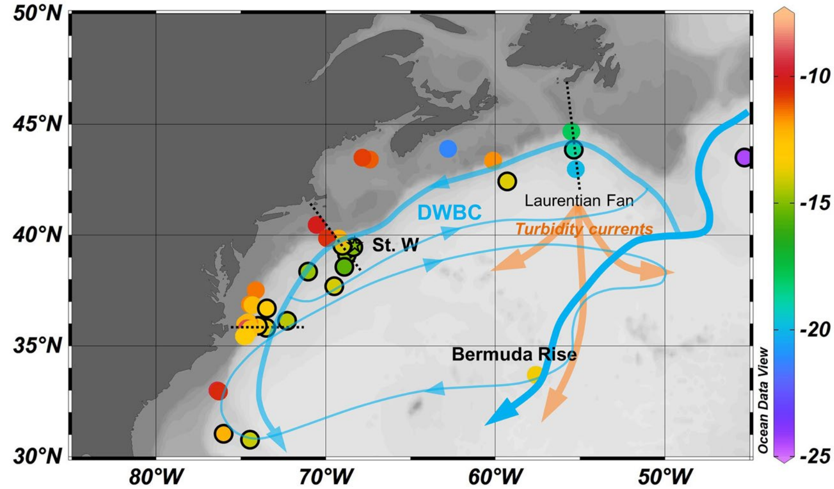

Figure 2. Detrital Nd isotope compositions (expressed as ε_{Nd} values) of core-top (0–1 cm) sediments in the northwest Atlantic Ocean. Relatively low values were observed at greater water depths on the continental slope. Considerably lower values were observed in the upstream region of the deep western boundary current (DWBC). The sediment trap mooring site at Station W is indicated by a star. The three across-margin transects for which $\varepsilon_{Nd\text{-detrital}}$ values are shown in Figure 3a are indicated by dotted lines. Symbols with black rims are the results used for the along-margin transect in Figure 3b. In addition to our new results, data from McLennan et al. (1990) is also shown (the easternmost site). Deep-ocean flows (blue lines) and turbidity currents (orange lines) are adopted from McCave (2002).

periods, only two samples for the ~1,000 m trap, and three samples for each ~2000 and ~3,000 m traps were analyzed per deployment (see Table S1 for details; hereafter, we use nominal trap depths of 1,000, 2,000, and 3,000 m).

Core-top sediment samples were collected from the northwest Atlantic margin during several cruises (KNR140, KNR178, EN407, OCE326, OCE400, OCE422, OCE426, and AT16-1) using a multicorer, boxcorer, or a gravity corer (Figure 2 and Table S2). Downcore samples (from the surface to 23 cm depth) were collected using a boxcorer from the Bermuda Rise in 1998 (OCE326 BC9C; 33.6933 °N, 57.6117 °W).

2.2. Sample Analysis

We examined Nd isotopic composition of the detrital fraction of sinking particles and sediments, representing the lithogenic material. For this purpose, a detrital fraction was separated following sequential extraction procedures described in Bayon et al. (2002). Leaching of the samples to isolate detrital fraction of Nd may have removed some labile detrital phases as well. Therefore, the concentration data may need to be used with caution. After leaching, between 5 and 60 mg of detrital fraction was spiked with Nd enriched in ^{150}Nd and dissolved in a 4:1 mixture of hydrofluoric acid and perchloric acid. One-step Nd column chemistry (Scher & Delaney, 2010) utilizing LN (Eichrom) resin was used, and isotope ratios were measured with a Thermo Finnigan NEPTUNE multicollector inductively coupled plasma-mass spectrometer (MC-ICP-MS). The internal precision for ^{143}Nd/^{144}Nd measurements is 5–15 $\times$ 10^{-6} (2σ, equivalent to 0.1–0.3 in epsilon units). The external precision, determined by multiple analyses of La Jolla Nd standard, is approximately 15 $\times$ 10^{-6} (equivalent to ~0.29 in epsilon units) after correction to values for La Jolla standards (0.511847). Neodymium isotopic composition is reported as ε_{Nd}, which is the part per 10,000 deviation of a measured ^{143}Nd/^{144}Nd ratio from that of CHUR (Chondritic Uniform Reservoir, ^{143}Nd/^{144}Nd = 0.512638; Jacobsen & Wasserburg, 1980). Neodymium content was determined by isotope dilution with a precision of ~0.5%.

Strontium was separated and purified from the samples using Sr-Spec (Eichrom) resin. Sr isotopic measurements were performed on the same MC-ICP-MS. Isobaric interferences of ^{87}Rb on ^{87}Sr and ^{86}Kr on ^{86}Sr were corrected for by monitoring ^{82}Kr, ^{83}Kr and ^{85}Rb and applying a mass bias correction using an exponential relationship (Jackson & Hart, 2006). The internal precision for Sr isotopic measurements was 8 – 15 $\times$ 10^{-6} (2σ). All Sr results are corrected with standard SRM987 (^{87}Sr/^{86}Sr = 0.710214). Repeated measurement of a NBS987 standard yielded precision estimates of 25 $\times$ 10^{-6} (2σ). Strontium isotopic compositions measured

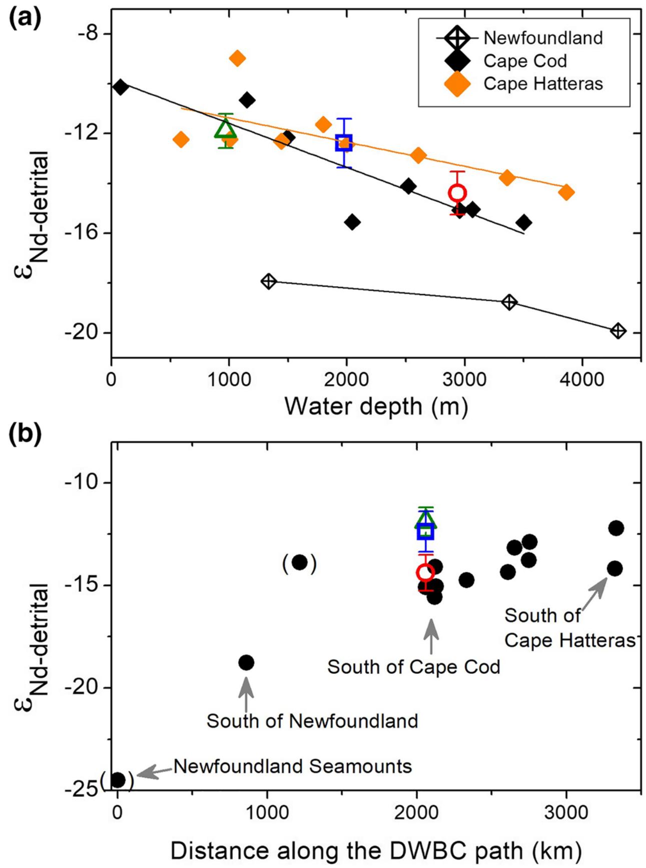

Figure 3. (a) Variation of $\varepsilon_{Nd\text{-}detrital}$ values of surface sediments along transects across the margins south of Newfoundland, approximately along the Line W transect south of Cape Cod, and near the Cape Hatteras. Best-fit lines are shown for the Cape Cod and Cape Hatteras transects. (b) Variation in $\varepsilon_{Nd\text{-}detrital}$ values of surface sediments as a function of along-slope distance from the Newfoundland Seamounts site (McLennan et al., 1990). Only results from sites located within the core of the DWBC (i.e., depth range between ca. 2,500 m and 4,000 m except for the symbols in parentheses whose depths are ~4,400 m; symbols with black rims in Figure 2) are shown. The measurement uncertainty (2σ) is similar to the symbol size and not indicated. Flux-weighted mean values of the sinking particles for three sediment traps deployed at Station W (total water depth, 2,988 m) at nominal depths of 1,000 m (open triangles), 2,000 m (open squares), and 3,000 m (open circles) are also shown (NB. the vertical error bars represent the temporal variability and not the analytical uncertainty; see Figure 5 for full data).

as part of this investigation are included in the Supplemental Information (Table S2). Although we report the results for future reference, we decided not to consider $^{87}Sr/^{86}Sr$ ratios in our discussion because of limited data coverage and potential influences of mineral sorting (Garcon et al., 2014) and grain size distribution (e.g. Meyer et al., 2011) on Sr isotope ratios.

3. Results

3.1. Nd Content and Isotopic Composition of Sediments

Detrital Nd contents of core-top sediments ranged between 16 and 41 ppm with an average of 29.7 ± 5.1 ppm (n = 20; arithmetic mean is reported throughout the paper unless mentioned otherwise). Slightly higher values were observed on the shelf and upper slope than at greater water depths (Figure S2)

$\varepsilon_{Nd\text{-}detrital}$ values of the core-top sediments ranged between −9.0 and −21.3 (Figure 2). Higher (more radiogenic) values were observed in the Gulf of Maine and in general at sites proximal to land. One exception is the Emerald Basin, on the Nova Scotian shelf ($\varepsilon_{Nd\text{-}detrital}$ −21.3; Figure 2). Measured values were consistently higher than that reported for southeast of Newfoundland (−24.5; McLennan et al., 1990). When across-margin transects approximately normal to isobaths are considered, a trend of decreasing (less radiogenic) $\varepsilon_{Nd\text{-}detrital}$ values with increasing water depth was apparent, with the exception of the region south of Newfoundland, where consistently low values were observed (Figure 3a).

Neodymium isotopic compositions of box core sediment samples from the Bermuda Rise ranged within ~ 2 epsilon units (Figure 4). In general, $\varepsilon_{Nd\text{-}detrital}$ decreased from the surface to 3–4 cm layer, below which the values decreased slightly or remained uniform. Neodymium content varied with depth in the same fashion as $\varepsilon_{Nd\text{-}detrital}$. One exception is the Nd content in the 0–1 cm layer, which is significantly lower than the values for deeper layers.

3.2. Neodymium Content and Isotopic Composition of Sinking Particles

The flux of sinking particulate matter (<1 mm) over the 2004–2005 sediment trap mooring deployment period is described in detail in Hwang et al. (2009a). Briefly, the mass flux at 1,000 m was bimodal with the highest value in October/November (Figure 5), while corresponding fluxes at 2000 and 3,000 m were more variable, exhibiting sporadic peaks that typically lasted for a single sampling interval. With the exception of an April maximum, these peaks were temporally decoupled from one another. Average particle flux was lowest at 2000 m. Lithogenic material fluxes based on aluminum concentration data (Al flux × 12.15, Taylor & McLennan, 1985) at 1,000 and 2,000 m were similar to each other in both magnitude and temporal variation but different from that at 3,000 m (Hwang et al., 2009a). Lithogenic material flux was highest at 3,000 m (95 mg $m^{-2}d^{-1}$), with intermediate flux at 1,000 m (57 mg$m^{-2}d^{-1}$), and the lowest flux at 2000 m (46 mg$m^{-2}d^{-1}$).

Detrital Nd content of sinking particulate matter varied between 10 and 25 ppm (Figure 5). The Nd content of particles intercepted at 3,000 m was higher than those at 1,000 and 2,000 m, which were similar to each other. Average Nd content was 14.5 ± 3.0, 14.0 ± 3.3, and 19.0 ± 3.5 ppm at 1,000, 2,000, and 3,000 m, respectively (note that the ± values are standard deviations of the time-series data around the average, not

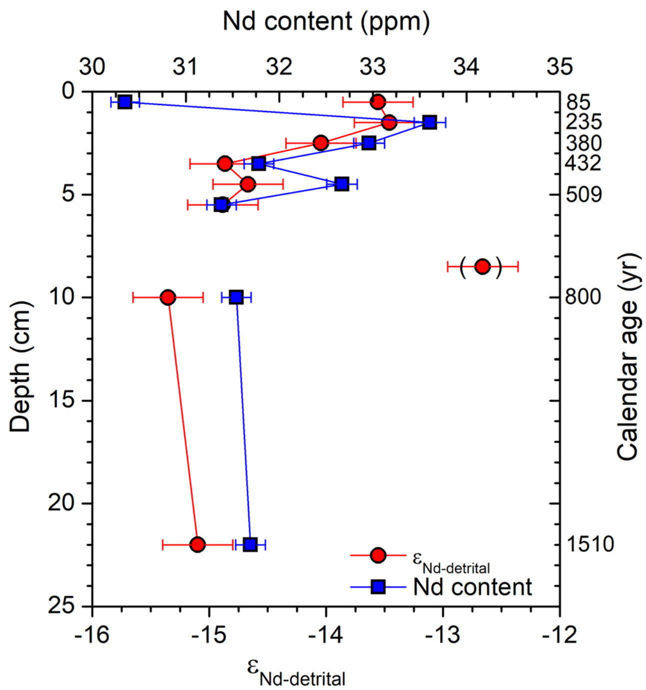

Figure 4. Downcore variability in detrital Nd content and isotopic composition ($\varepsilon_{\text{Nd-detrital}}$ values) in a sediment core from the Bermuda Rise. Calendar age on the right axis is adopted from Ohkouchi et al. (2002).

the measurement uncertainties). Detrital Nd fluxes ranged up to 9.5 μg-m^{-2}d^{-1} (Figure 5). In general, Nd flux was highest at 3,000 m and lowest at 2000 m, with average Nd fluxes of 3.4 ± 1.4, 1.9 ± 1.1, and 4.1 ± 2.1 μg-m^{-2}d^{-1} at 1,000, 2,000, and 3,000 m, respectively. Temporal variability in Nd flux at 3,000 m has some resemblance to that of overall particle flux. Nd flux echoed that of Al flux (and hence, lithogenic material flux) since Nd and Al contents have a strong linear positive correlation (R^2 = 0.96; Figure S3).

The $\varepsilon_{\text{Nd-detrital}}$ values of sinking particles ranged between −10 and −16 (Figure 5). In general, $\varepsilon_{\text{Nd-detrital}}$ values were lower (less radiogenic) at 3,000 m than at the shallower depths, with average $\varepsilon_{\text{Nd-detrital}}$ values of −11.9 ± 0.7 (n = 11), −12.6 ± 1.0 (n = 20), and −14.2 ± 0.9 (n = 27) at 1,000, 2000, and 3,000 m, respectively. There was no clear relationship between $\varepsilon_{\text{Nd-detrital}}$ and Nd flux at specific depths (Figure S4), and flux-weighted mean values (−11.9, −12.4, and −14.4 at 1,000, 2,000, and 3,000 m, respectively) were similar to the arithmetic mean values. The mean $\varepsilon_{\text{Nd-detrital}}$ value at 3,000 m was close to, but slightly higher than that of core-top sediment at the mooring site (−15.1).

4. Discussion

4.1. Neodymium Isotopic Gradients in Surface Sediments and Provenance of Lithogenic Material

The relatively high $\varepsilon_{\text{Nd-detrital}}$ values observed in shelf sediments between Cape Hatteras and the Gulf of Maine echo those of lithological units outcropping on the adjacent continent (Figure S5; Jeandel et al., 2007). The shelf sediment values are similar to those of suspended sediment from the Hudson River (−11.3; S. L. Goldstein et al., 1984) and bracketed by the $\varepsilon_{\text{Nd-detrital}}$ between −5 and −13 of Appalachian Mountain lithologies that supply sediment to this and other rivers draining the eastern USA (Patchett et al., 1999). The strong (~5 epsilon units) across-margin gradients in $\varepsilon_{\text{Nd-detrital}}$ observed along the quasi shelf-perpendicular transects near Cape Hatteras and south of Cape Cod (Figure 3a) indicate that hemipelagic sedimentation on the slope is governed by at least two processes: (*i*) export of lithogenic material with high $\varepsilon_{\text{Nd-detrital}}$ values (up to −9) from the shelf or upper slope, and (*ii*) entrainment of resuspended particles from distal locations where detrital sediment is characterized by low $\varepsilon_{\text{Nd-detrital}}$ values.

With respect to (*i*), lithogenic materials emanating from the shelf and upper slope are likely mobilized by coastal currents and storms, and advected offshore. This may occur via several mechanisms, including impingement of the Gulf Stream (Gawarkiewicz et al., 2012), or Warm Core Rings that it sheds on the continental margin (Bishop & Joyce, 1986), cyclonic eddies (Garvine et al., 1988), entrainment in INLs detaching from the shelf-slope break and advecting basinward along isopycnal surfaces (Biscaye et al., 1988; Figure S1), funneling down submarine canyons that may serve as conduits for focused shelf-slope sediment transfer (Biscaye et al., 1988; Puig et al., 2014). Topographic Rossby Waves prevalent in this area (Thompson & Luyten, 1976) and deep cyclogenesis associated with Gulf Stream meandering and eddy formation (Andres et al., 2016) can boost bottom current speeds to promote sediment resuspension.

In contrast, regarding (*ii*), the observed spatial distribution of $\varepsilon_{\text{Nd-detrital}}$ values of surface sediments is consistent with sediment resuspension in upstream regions of the DWBC, i.e., Scotian margin and other regions draining the Canadian Shield, and entrainment and lateral transport by the DWBC, as suggested previously (e.g., Ohkouchi et al, 2002; Hwang et al., 2014, 2017). Giosan et al. (2002) also found evidence for sediment transport from the Gulf of St. Lawrence area to the southwest based on sediment color and the distribution of red lutites. Among our new as well as previously published data, the lowest $\varepsilon_{\text{Nd-detrital}}$ values were observed off Newfoundland and Nova Scotia, in the upstream region of the DWBC. While sediments east of Greenland had more radiogenic values (−8 ~ −9; Innocent et al., 1997), reflecting the influence of

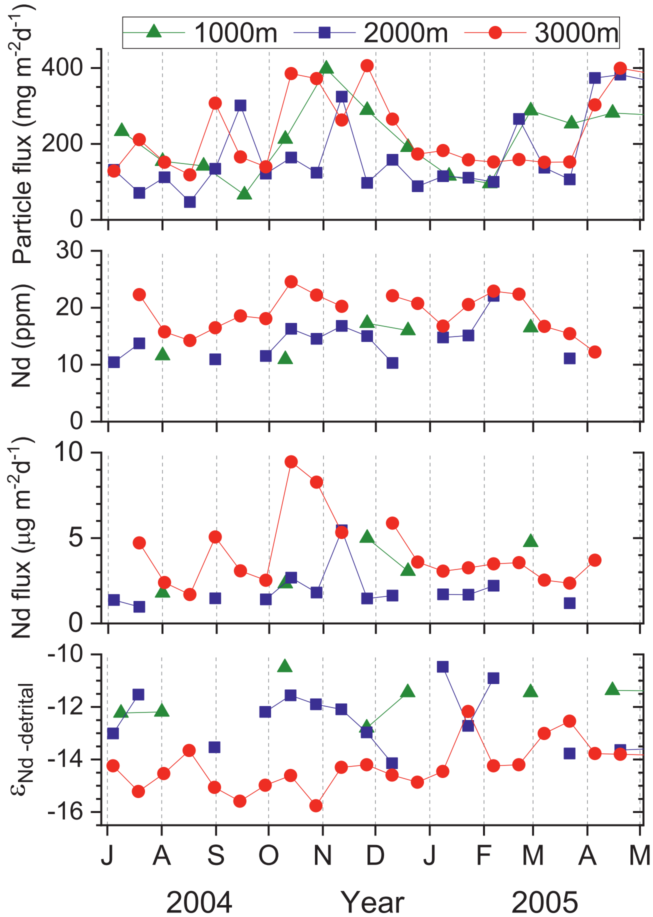

Figure 5. Temporal variation in particle flux (<1 mm), and detrital Nd content (in ppm), Nd flux (in μg $m^{-2}d^{-1}$), and detrital Nd isotopic composition (in ε_{Nd}) for three sediment traps deployed at Station W (total water depth, 2,988 m) at nominal depths of 1,000, 2,000, and 3,000 m (50 mab) from June 27, 2004 to April 27, 2005. Data from the two consecutive deployments are not shown here. Particle flux results are from Hwang et al. (2009a).

Icelandic volcanic sources (average $\varepsilon_{Nd\text{-detrital}} \sim +9$), $\varepsilon_{Nd\text{-detrital}}$ values on the east coast of Canada at ~55 °N and in the Labrador Basin were much lower (−23 ~ −28), reflecting lithogenic supply from unradiogenic Canadian Shield sources ($\varepsilon_{Nd\text{-detrital}}$, −24 ~ −36; Innocent et al., 1997). A low $\varepsilon_{Nd\text{-detrital}}$ value (−20) was also observed on Orphan Knoll, east of Newfoundland (Innocent et al., 1997). $\varepsilon_{Nd\text{-detrital}}$ values of surface sediments retrieved from water depths within the core of the DWBC (2,500 m–4,000 m) generally increased along its putative transport pathway (Figure 3b). Recently, Stichel et al. (2020) reported ε_{Nd} values of suspended particles along the north-south transect from the Irminger Basin with Icelandic influence, passing the Labrador Basin with Canadian Shield influence. These authors inferred the occurrence of significant lateral particle transport within the subpolar gyre based on the vertical heterogeneity of particulate ε_{Nd} values and large deviations from ambient seawater values (Stichel et al., 2020).

The north–south gradient in $\varepsilon_{Nd\text{-detrital}}$ along isobaths on the continental slope implies diminishing influence of lithogenic material originating from the Scotian margin and further north. Assuming a simple binary isotopic mixing, taking our highest $\varepsilon_{Nd\text{-detrital}}$ value observed on the shelf (−9) and the lowest reported value southeast of Newfoundland (−24.5; McLennan et al., 1990; the easternmost site in Figure 2), the proportion of DWBC-sourced sediment would decrease from ~60% (south of Newfoundland, $\varepsilon_{Nd\text{-detrital}}$ = −18.8) to 20%–30% (east of Cape Hatteras) for the samples along the ~2,300 km-long pathway of the DWBC (Figure 3b). Similarly, the core-top sediment at Station W (−15.1; water depth ~ 3,000 m) would approximately correspond to 40:60 mixture between the DWBC- and shelf-sourced end-members, respectively. Measured Nd content of core-top sediments varies within ~10% (Table S2), and thus this ratio can be considered as an approximate mixing ratio of sediment particles. Of course, these estimates are strongly affected by the assignment of the end-member $\varepsilon_{Nd\text{-detrital}}$ values, as well as Nd content of source materials.

4.2. Depth and Dynamics of Lithogenic Particle Lateral Transport

The large range in $\varepsilon_{Nd\text{-detrital}}$ values both at a given trap depth (>2 epsilon units) and among the three trap depths (~5 epsilon units) clearly shows that lithogenic material in sinking particulate matter derives from more than one source, and that inputs vary both vertically and temporally. The range of $\varepsilon_{Nd\text{-detrital}}$ values in sinking particles was the same as observed for core-top sediments along the shelf-perpendicular transect on the New England margin (−10.1 ~ −15.6; 75 m ~ 3,506 m). Therefore, one plausible explanation for the spread in $\varepsilon_{Nd\text{-detrital}}$ values of sinking particles is varying contributions of shelf versus slope sediments to sinking particles intercepted by the sediment traps. In this scenario, the 1,000 and 2000 m traps predominantly collected lithogenic particles emanating from the adjacent shelf and upper slope, likely via detached INLs (McCave et al., 2001; Figure S1), whereas the 3,000 m trap intercepted particles resuspended from the lower slope. Hwang et al. (2017) offered a similar interpretation of the sources of sinking particles based on the vertical distribution of Al flux and POC $\Delta^{14}C$ values of sinking particles. Those authors observed that both POC $\Delta^{14}C$ values and Al fluxes were coherent at 1,000 and 2000 m, but differed from those at 3,000 m. The average Nd flux was higher at 1,000 m (3.4 μg$m^{-2}d^{-1}$) than at 2,000 m (1.9 μg$m^{-2}d^{-1}$), suggesting enhanced supply of lithogenic material via INLs to the shallower depth. In comparison, Nd flux was highest at 3,000 m (4.1 μg$m^{-2}d^{-1}$), indicating additional supply of lithogenic material near the seafloor.

Temporal variability in $\varepsilon_{Nd\text{-}detrital}$ at 3,000 m was small but included occasional excursions toward higher values (i.e., in mid-April, mid-January, and mid-March), when particle fluxes at 2000 and 3,000 m were low and similar to each other. Diminished supply of lower slope sediment to the 3,000 m trap was presumably responsible for these isotopic excursions. This temporal variability in $\varepsilon_{Nd\text{-}detrital}$ values is likely associated with surface and/or deep ocean hydrographic variations; however, the current time-series is too short to attribute this to specific physical phenomena.

The average, flux-weighted Nd isotopic composition of material accumulating in the 3,000 m trap ($\varepsilon_{Nd\text{-}detrital} = -14.4$) likely reflects a mixture of the particles intercepted by the 2000 m trap ($\varepsilon_{Nd\text{-}detrital} = -12.4$) and laterally supplied resuspended sediment mobilized from the lower slope and entrained in the BNL. The $\varepsilon_{Nd\text{-}detrital}$ value of the particles that are laterally supplied between the 2000 and 3,000 m was estimated based on the increase in Nd flux between the two depths (i.e., from 2.1 to 4.5 $\mu gm^{-2}d^{-1}$) and the observed isotopic contrast for the two depths (i.e., −12.4 and −14.4, respectively). The resulting estimated $\varepsilon_{Nd\text{-}detrital}$ value of the laterally supplied particles (−16.1), implies that it originates from further north, where surface sediment detrital $\varepsilon_{Nd\text{-}detrital}$ values were lower (Figure 2).

4.3. Long-Distance Particle "Teleconnections": Links to the Bermuda Rise?

The Nd isotopic composition of core-top sediment from the Bermuda Rise (−13.6) is similar to those of the sediments on the New England slope, more than 1,000 km to the northwest. The core-top $\varepsilon_{Nd\text{-}detrital}$ value is also similar to that of suspended particles collected at a depth of 2000 m at the BATS (Bermuda Atlantic Time-series Study) site (–14.2 ± 1.8, an average of five values determined on total digest or 0.6 N HCl leach; van de Flierdt et al., 2012). Although $\varepsilon_{Nd\text{-}detrital}$ values of aerosols/dust collected in Bermuda from both North American and Saharan sources were similar (–13.2 and –14.1, respectively; Jeandel et al., 1995), the atmospheric Nd deposition flux was only 20–80 $\mu gm^{-2}yr^{-1}$, of which ~40% is estimated to dissolve upon entering the seawater (Jeandel et al., 1995). Assuming similar atmospheric Nd input to the Bermuda Rise site, this flux corresponds to only ~1% of the annual accumulation in the sediment (3–10 $mgm^{-2}yr^{-1}$; this rate was estimated from a linear sedimentation rate of 12–24 $cmkyr^{-1}$ (Ohkouchi et al., 2002) and the measured Nd content), indicating that the majority must originate from lateral advection in the water column. Although a lack of data in the region between the continental slope and the Bermuda Rise site makes it difficult to delineate the origin of the lithogenic material accumulating on the Bermuda Rise, the $\varepsilon_{Nd\text{-}detrital}$ values suggest similar sources to those on the New England slope under the influence of the DWBC.

Ohkouchi et al. (2002) observed that the alkenone U^{K}_{37}' values in surficial (upper 3 cm) Bermuda Rise sediments corresponded to sea surface temperatures (SSTs) that were markedly (−7°C) colder than those of overlying Sargasso Sea waters. Based on this information, as well as markedly older alkenone and total organic carbon (TOC) ^{14}C ages than those of carbonate from coeval planktonic foraminifera, these authors concluded that at least part of the sedimentary organic matter was preaged and derived from productivity in cooler surface waters over the Canadian margin further north. Giosan et al. (2002) also suggested the Gulf of St. Lawrence region as a potential source of the red sediments found on the Bermuda Rise. The DWBC and associated deep recirculation gyres and eddies (Figures 1 and 2; Le Bras et al., 2018) represent a potential pathway for transport of lithogenic material and associated organic matter to the Bermuda Rise. Ohkouchi et al. (2002) suggested increased lateral particle supply from the Scotian margin over the past ~400 years (0–3 cm) than before (5–22 cm layer), based on colder alkenone temperatures, lower $CaCO_3$ contents (i.e., higher detrital mineral contents), and larger ^{14}C age offsets between foraminifera and other components such as TOC, alkenones, and fine-fraction (<63 μm) inorganic carbon in equivalent sediment layers. In contrast, higher $\varepsilon_{Nd\text{-}detrital}$ values in the 0–3 cm layer (Figure 4) imply either a shift in provenance or diminished supply of low $\varepsilon_{Nd\text{-}detrital}$ lithogenic material during the last ~400 years (chronology adopted from Ohkouchi et al., 2002). Downcore variations in Nd content and $\varepsilon_{Nd\text{-}detrital}$ are coupled, implying that when lithogenic material flux was higher the site was more strongly influenced by supply of more radiogenic sediments that may originate further to the north (e.g., off Iceland; cf. Innocent et al., 1997). Englebrecht and Sachs (2005) examined both alkenone unsaturation ratios and δD values of Bermuda Rise sediments and inferred that, in addition to the sediment from the Sargasso Sea and the Scotian margin, a third source of alkenones characterized by low U^{K}_{37}' values (i.e., cold sea surface temperatures) and high δD values (higher salinity) was

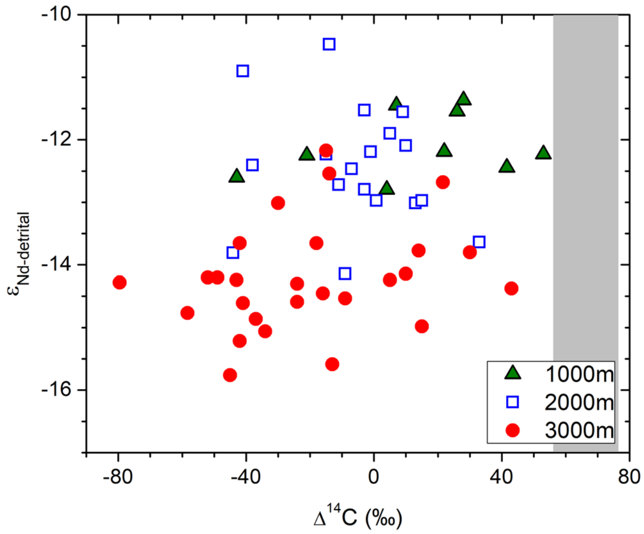

Figure 6. Cross-plot of detrital $\varepsilon_{Nd\text{-detrital}}$ versus $\Delta^{14}C_{POC}$ (‰) values of sinking particles. The gray box indicates the $\Delta^{14}C$ value of suspended POC in the surface water in 2005 (+67 ± 10 ‰; Hwang et al., 2009b). POC, particulate organic carbon.

necessary to explain observed signatures. These authors suggested the main branch of NADW from the Nordic Seas as a likely candidate. Our Bermuda Rise $\varepsilon_{Nd\text{-detrital}}$ data are consistent with this interpretation, although other potential factors, such as differential hydrodynamic particle sorting on Nd isotopic signatures (Bayon et al., 2015; Jeandel et al., 1995), potentially induced by varying bottom current strengths (e.g., McCave et al., 1995), should also be considered.

4.4. Biogeochemical Consequences of Lateral Transport

$\Delta^{14}C$ values of sinking POC at Station W were previously shown to decrease with increasing trap depth, i.e., as the contribution of resuspended, aged sedimentary organic carbon to total sinking POC increased (Hwang et al., 2009a). Although there was no strong relationship between detrital $\varepsilon_{Nd\text{-detrital}}$ values and $\Delta^{14}C$ values of sinking particles, there was a general trend where higher $\Delta^{14}C$ values were associated with higher $\varepsilon_{Nd\text{-detrital}}$ values and vice versa (Figure 6). Here, and also for the core-top sediments, the correlation between $\varepsilon_{Nd\text{-detrital}}$ and $\Delta^{14}C$ values of sinking particles likely reflects mixing between the shelf sediment of relatively high $\varepsilon_{Nd\text{-detrital}}$ and $\Delta^{14}C$ values, and the lower slope sediment of lower $\varepsilon_{Nd\text{-detrital}}$ and $\Delta^{14}C$ values. The large scatter on the $\varepsilon_{Nd\text{-detrital}} - \Delta^{14}C$ plot is not surprising given that the two properties are controlled by different processes: $\varepsilon_{Nd\text{-detrital}}$ is mainly controlled by mixing between lithogenic material sources of different $\varepsilon_{Nd\text{-detrital}}$ values (and Nd contents), whereas $\Delta^{14}C$ values of sinking POC are additionally influenced by a third and predominant source of fresh POC produced by primary production in overlying surface waters.

Overall, the variability in $\varepsilon_{Nd\text{-detrital}}$ signatures on the northwest Atlantic margin demonstrates that sedimentation on the slope is fed by long-distance, along-margin transport in addition to across-margin transport of shelf sediment. Lateral transport of resuspended sediment particles redistributes not only the lithogenic material but also organic carbon associated with resuspended particles. Resuspension and lateral transport of sediments will promote organic matter decomposition and aging (e.g., Bao et al., 2018; Inthorn et al., 2006). Long-range transport of particles may have implications on interpretation of authigenic Nd isotope records as the local Nd isotope signatures may reflect upstream conditions. Therefore, sediment resuspension and long-distance transport demands further study as one of the critical processes that affect the biogeochemical properties of inorganic and organic constituents of particulate matter, especially on energetic continental margins.

5. Summary and Conclusions

This study reveals marked spatial gradients in the detrital Nd isotopic composition of sinking particles and sediments on the northwest Atlantic margin. These gradients reflect both the provenance of lithogenic inputs as well as regional hydrography that entrains and disperses sediment over the continental margin and into the interior northwest Atlantic basin. Based on detrital Nd isotopic measurements of samples from time-series sediment traps deployed at three different depths at Station W, on the lower slope (~3,000 m isobath) of the New England margin, we identify two primary modes of detrital particle delivery: across-margin transport, likely via intermediate nepheloid layers, and along-slope transport within the DWBC. The latter supports a well-defined bottom nepheloid layer that entrains sediment from upstream regions to the north. Neodymium isotopic measurements provide further evidence for long-range sediment dispersal from temperate and subpolar regions of the NW Atlantic margin as well as to the Bermuda Rise underlying the subtropical North Atlantic gyre.

Overall, our results demonstrate the utility of detrital Nd isotopes for tracing the provenance, dynamics and trajectories of lithogenic particle dispersal on continental margins, and highlight the prevalence of lateral transport as a component of hemipelagic sedimentation over continental margins.

Data Availability Statement

Outcrop Nd isotope data were obtained from the GEOROC website (http://georoc.mpch-mainz.gwdg.de/georoc/). Tables S1 and S2 are also archived at the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI) web interface (https://accession.nodc.noaa.gov/0222212).

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