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Neodymium isotopic composition and rare earth element concentrations in the deep and intermediate Nordic Seas: Constraints on the Iceland Scotland Overflow Water signature

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[1] Neodymium isotopic composition and rare earth element concentrations were measured in seawater samples from eleven stations in the Nordic Seas. These data allow us to study how the Iceland Scotland Overflow Water (ISOW) acquires its neodymium signature in the modern ocean. The waters overflowing the Faroe Shetland channel are characterized by $\varepsilon_{Nd} = -8.2 \pm 0.6$, in good agreement with the only other data point, published 19 years ago. In the Greenland and Iceland Seas the water masses leading to the formation of the ISOW display lower neodymium isotopic composition, with ε_{Nd} around -11 and -9, respectively. Since no water masses in the Nordic Seas are characterized by $\varepsilon_{Nd} > -8$, the radiogenic signature of the ISOW likely reflects inputs from the highly radiogenic Norwegian Basin basaltic margins (Jan-Mayen, Iceland, Faroe, with $\varepsilon_{Nd} \approx +7$). In addition to the neodymium isotopic composition, the rare earth element patterns suggest that these inputs occur via the remobilization (which includes resuspension and dissolution) of sediments deposited on the margins. Whereas the neodymium isotopic composition behaves conservatively in the oceans in the absence of lithogenic inputs, and can be used as a water mass tracer, these results emphasize the role of interactions, between sediments deposited on margins and seawater, in the acquisition of the neodymium isotopic composition of water masses. These results should allow a better use of this parameter to trace the present and the past circulation in the North Atlantic.

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Keywords: Iceland Scotland Overflow Water; neodymium isotopic composition; Nordic Seas; North Atlantic; rare earth; sediment water mass interactions.

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1. Introduction

[2] The Iceland Scotland Overflow Water (ISOW) is a dense water mass playing a significant role in the formation of the North Atlantic Deep Water (NADW) [*McCartney*, 1992; *Read*, 2001]. The flux of ISOW is therefore a significant parameter of the global thermohaline circulation. The ISOW neodymium isotopic composition (Nd IC, defined below) is very different from that of the other water masses found downstream of the Iceland-Scotland ridge [*Piepgras and Wasserburg*, 1987; *Lacan and Jeandel*, 2004b; this work]. This contrasting signature recorded in marine sediments can therefore be used to reconstruct the past variability of this overflow [e.g., *Fagel et al.*, 2004]. However, the processes leading to the present ISOW Nd signature have been unknown so far (a single measurement in this water mass was available [*Piepgras and Wasserburg*, 1987]) which limited the scope of such paleo applications. The aim of this study is to understand how the ISOW acquires its Nd IC.

[3] The Nd IC is expressed as

$$\varepsilon_{Nd} = \left(\frac{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{Sample}}{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{CHUR}} - 1 \right) \times 10^4, \qquad (1)$$

where CHUR stands for Chondritic Uniform Reservoir and represents a present-day average earth value; $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ [*Jacobsen and Wasserburg*, 1980]. The Nd IC of the continents is heterogeneous, varying from −45 in old granitic cratons to +12 in recent mid-oceanic ridge basalts [*Goldstein and Hemming*, 2003] and references therein. In the ocean, Nd is a trace element (concentrations of the order of 1 ppt; 1 ppt = 1×10^{-12} g g^{-1}), predominantly found in the dissolved form (90 to 95% [*Jeandel et al.*, 1995]). Its residence time is around 500 to 1000 years [*Tachikawa et al.*, 2003]. Through lithogenic inputs, different water masses acquire different Nd IC. ε_{Nd} is therefore used to quantify dissolved/particulate fluxes, notably along continental margins or close to the bottom, when highly energetic currents are in contact with the oceanic floor [*Lacan and Jeandel*, 2001; *Lacan and Jeandel*, 2004a]. Away from those inputs, ε_{Nd} behaves conservatively in the ocean and is used as a water mass tracer [*Piepgras and Wasserburg*, 1987; *Piepgras and Jacobsen*, 1988; *Jeandel*, 1993; *Lacan and Jeandel*, 2001; *Goldstein and Hemming*, 2003; *Amakawa et al.*, 2004; *Lacan and Jeandel*, 2004b].

[4] Nd belongs to the geochemical group of the Rare Earth Elements (REE). In the ocean, particle scavenging and cerium oxidation cause a heavy versus light REE enrichment and a negative Ce anomaly respectively, relative to the lithogenic sources [*Elderfield*, 1988]. These fractionations are quantified by normalizing the oceanic concentrations to a lithogenic reference material; in this work the Post-Archean Australian Sedimentary Shales (PAAS) [*Taylor and McLennan*, 1985]. They can be expressed by the La_n/Yb_n ratio and the Ce anomaly, Ce/Ce*, $Ce/Ce^* = Ce_n/[(La_n + Pr_n)/2]$, where the subscript "n" indicates that the concentrations are normalized (e.g., $X_n = X_{sample}/X_{PAAS}$). These parameters are a useful tool for studying dissolved/particulate interactions in seawater and notably for identifying recent lithogenic inputs [*Elderfield*, 1988; *Tachikawa et al.*, 1999]. The closer to 1 these parameters are, the smaller the anomalies are, i.e., the closer to a lithogenic sample the seawater sample is. Conversely, values closer to 0 characterize a "marine" REE pattern, indicating that the REE fractionation processes described above were significant.

2. Sampling and Methods

[5] Samples were collected during the Signature/GINS cruise, on board R/V *Marion Dufresne* (Institut Paul Emile Victor), in August 1999. Eleven stations were occupied in the Nordic Seas (Figure 1). Unfiltered samples were analyzed for Nd IC and REE concentrations following the procedure described by *Lacan and Jeandel* [2001] and *Lacan and Jeandel* [2004b]. Briefly, for the Nd IC analysis, the Nd is extracted from a 10 L sample by ion exchange chromatography. For the REE concentrations analysis, the REE are extracted from a 500 mL sample by iron oxide coprecipitation. Nd IC was measured on a Finnigan MAT 261 Thermo Ionization Mass Spectrometer (TIMS; at the Observatoire Midi Pyrénées, Toulouse, France), in static mode; Nd was analyzed as Nd^+. Internal precision was 0.2 to 0.3 ε_{Nd} units ($2\sigma_m$). The national Rennes Nd standard gave $^{143}Nd/^{144}Nd = 0.511964 \pm 16$ (2σ, 30 runs), which corresponds to a La Jolla value of 0.511851 [*Chauvel and Blichert-Toft*, 2001]. No corrections were applied to measured isotopic ratios. The reproducibility of the Nd IC measurement was 0.4 ε_{Nd} unit, blank values were 700 pg (3.5% of the most depleted sample and 2% on average). REE concentrations were measured with a Perkin-Elmer Elan 6000 Inductively Coupled Plasma Mass

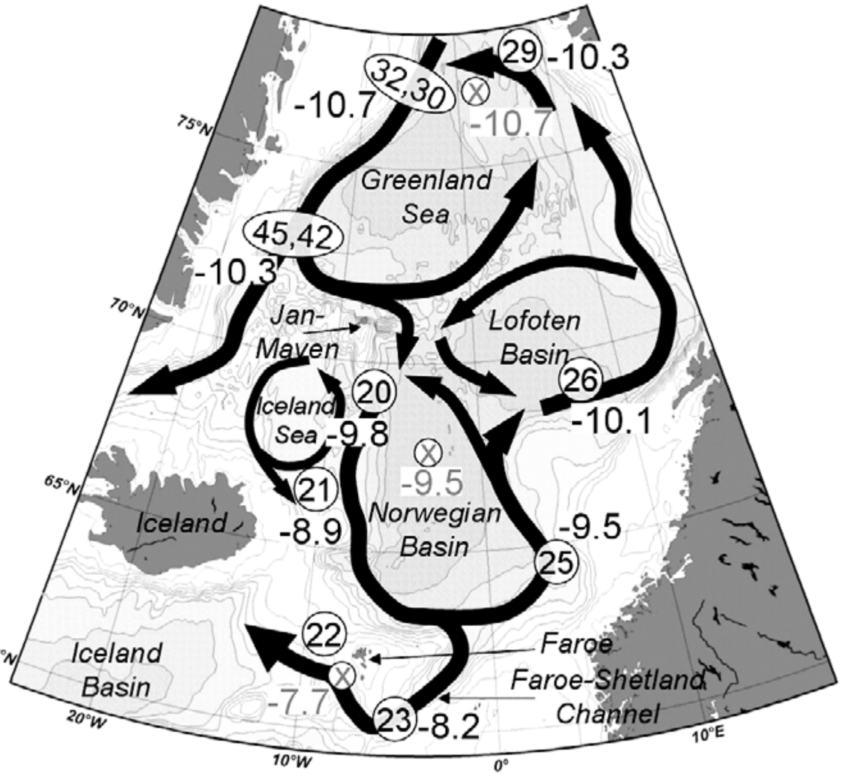

Figure 1. Large-scale intermediate and deep circulation in the Nordic Seas. Circled numbers indicate station locations and numbers. The other black numbers indicate the mean Nd IC of samples with $\sigma_\theta \geq 28.05$ kg m^{-3} (in some cases these are averages of two significantly different numbers), at each station (or at a couple of stations). Gray numbers display the Nd IC reported by *Piepgras and Wasserburg* [1987] for three samples taken in dense waters at the location indicated by the gray crosses.

Spectrometer (ICPMS, in the same laboratory). Nd and Yb concentrations were measured by isotopic dilution. Reproducibility of the REE concentration measurements was better than 10% for all REE and better than 5% for Nd, blanks values were better than 8% for all REE and better than 3% for Nd. Internal precision (2σ) was better than 10% for all REE and lower than 0.2 ppt for Nd.

3. Hydrology and Geological Setting

[6] The topography and the large-scale intermediate and deep circulation in the Nordic Seas are represented in Figure 1. This circulation is mainly composed of cyclonic gyres in each of the basins [*Smethie et al.*, 1988; *Nøst and Isachsen*, 2003].

[7] Dense waters overflow the Iceland-Scotland gap from the Norwegian Basin toward the Iceland Basin. This occurs in two places. About 1 Sv ($1\ \mathrm{Sv} = 1 \times 10^6\ \mathrm{m^3.s^{-1}}$) flows over the Iceland-Faroe ridge and 1.5 Sv through the Faroe-Shetland Channel. Since the Iceland-Faroe ridge overflow was not detected in the present study, we will not describe its hydrology. The Faroe-Sheltand overflow is mainly constituted of 1) Norwegian Sea Arctic Intermediate Water (NSAIW, characterized approximately by $-0.5°\mathrm{C} < \theta < 0.5°\mathrm{C}$ and $34.85 < S < 34.89$), originating from both the Greenland and Iceland Seas, as Greenland Sea Arctic Intermediate Water (GSAIW) and Iceland Sea Arctic Intermediate Water (ISAIW), and 2) Norwegian Sea Deep Water (NSDW, characterized approximately by $-1.2°\mathrm{C} < \theta < -0.5°\mathrm{C}$ and $34.90 < S < 34.91$), originating from the Greenland Sea, mainly as Greenland Sea Deep Water (GSDW) and Eurasian Basin Deep Water (EBDW) [*Swift and Koltermann*, 1988; *Blindheim*, 1990; *Hansen and Østerhus*, 2000; *Fogelqvista et al.*, 2003]. The θ-S ranges of both water masses found in the Faroe-Shetland overflow are reported in Figure 2.

[8] As these dense waters overflow the Iceland Scotland gap and sink into the Iceland Basin depths, they entrain the overlying Atlantic waters and Labrador Seawater. The so-formed water mass is called Iceland Scotland Overflow Water (ISOW)

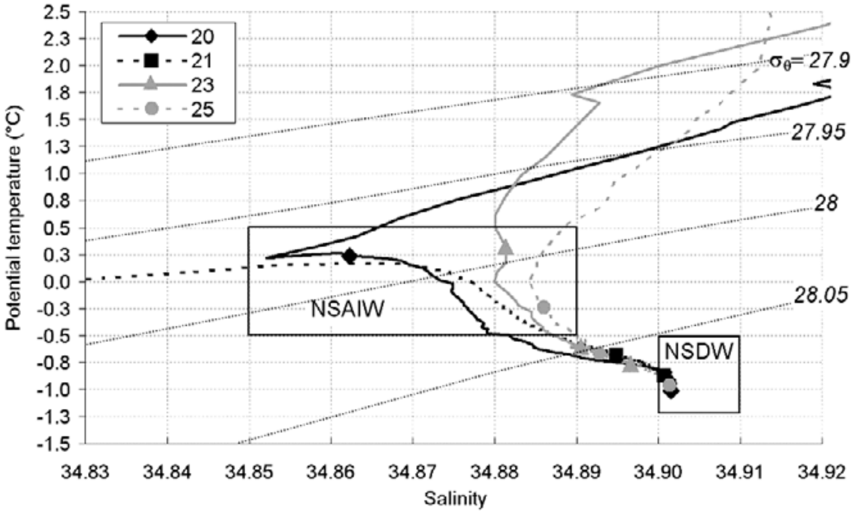

Figure 2. Potential temperature versus salinity diagram for the four stations in the Norwegian Basin (the other stations are not represented for clarity purposes), where dense waters occur (potential density is also indicated). Norwegian Sea Arctic Intermediate Water (NSAIW) and Norwegian Sea Deep Water (NSDW) typical hydrological boundaries are reported. Sample localizations are indicated by markers.

and is characterized by $\sigma_\theta < 27.8$ kg m^{-3}, $S > 34.94$ and $\theta < 3°C$. In the following, we will use the name "pure ISOW" (pISOW) to clearly distinguish the overflowing waters before the above mentioned entrainments, from the ISOW.

[9] Due to the cyclonic circulation in the Norwegian Basin, precursors of the pISOW likely flowed along the western and south boundaries of this basin. These margins are primarily composed of basalt, and include the Jan-Mayen Plateau and Ridge, the Iceland margin, the Iceland-Faroe Ridge and the Faroe slope. These are characterized by radiogenic Nd signatures (i.e., with high Nd IC), with typical ε_{Nd} values of +6 to +8 [*Mertz et al.*, 1991; *Hémond et al.*, 1993; *Holm et al.*, 2001], contrasting with the much less radiogenic signature of the surrounding water masses, of the order of $\varepsilon_{Nd} = -10$ [*Lacan*, 2002; this work].

4. Results

[10] Hydrological parameters, Nd IC and REE concentrations are reported in Table 1.

[11] At station 22, located above the sill of the Iceland-Faroe ridge, the following properties are found at all depths: $S > 35.1$, $\theta > 5.7°C$ and $\sigma_\theta < 27.7$ kg m^{-3}. These values clearly identify Atlantic water and the absence of overflow, at this location at the time of the sampling. This observation confirms the known intermittent nature of this overflow [*Hansen and Østerhus*, 2000].

[12] On the other hand, overflowing waters are found at station 23: NSAIW, around 600 m depth, with $S \approx 34.88$, $\theta \approx 0°C$ and $\sigma_\theta \approx 28.0$ kg m^{-3}, and NSDW at the bottom, around 990 m depth, with $S = 34.90$, $\theta = -0.77°C$ and $\sigma_\theta = 28.06$ kg m^{-3} (see Table 1 and Figure 2). Considering the 3 samples of these water masses (station 23: 599, 800 and 988 m depth), pISOW is characterized by $\varepsilon_{Nd} = -8.2 \pm 0.6$ (mean deviation) and $[Nd] = 3.1 \pm 0.3$ ppt. These values confirm the unique data obtained 19 years ago in the Faroe-Bank Channel (located just downstream of station 23; see Figure 1): $\varepsilon_{Nd} = -7.7 \pm 0.6$ (2σ) and $[Nd] = 3.1$ ppt [*Piepgras and Wasserburg*, 1987]. These values are much more radiogenic than the waters entering the Nordic Seas either from the Atlantic, with ε_{Nd} around -13 (see shallow samples at stations 22 and 23, Figure 1 and Table 1), or through Fram Strait, with ε_{Nd} around -11 (see stations 30 and 32).

[13] The goal of this work is therefore to understand how the pISOW acquires its radiogenic signature, by tracking upstream the evolution of the Nd IC of the water masses constituting this overflow.

[14] The NSDW precursors are mainly GSDW and EBDW. The mean Nd IC of these water masses (characterized by $\sigma_\theta \geq 28.05$ kg m^{-3}, Table 1) at each station are reported in Figure 1. In the Greenland Sea these waters are characterized by $\varepsilon_{Nd} \approx -10.4$. Just downstream of Jan-Mayen (station 20), NSDW has $\varepsilon_{Nd} \approx -9.8$. Its Nd IC is

Table 1. Hydrological Parameters, Nd IC, and REE Concentrations in Unfiltered Seawater Samples in the Nordic Seas[a]

R/V *Marion Dufresne*, Cruise FI3519992, IPEV		Hydrological Data				Nd Isotopic Composition			Concentration (10^{-12} g g^{-1})															
Station (Number, Location, Date, Depth)	Depth, m	θ, °C	S	σ_θ	O_2, mg/L	$^{143}Nd/^{144}Nd$	ε_{Nd}	$2\sigma_m$	La	Ce	Pr	**Nd**	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ce/Ce*	La_n/Yb_n
Station 20	331	0.22	34.86	27.98	10.44	0.512207	**−8.4**	0.2	3.62	2.26	0.67	**2.87**	0.57	0.16	0.82	0.14	0.99	0.26	0.89	0.13	0.80	0.14	**0.33**	**0.33**
69.21°N, −6.85°E	2491	−1.02	34.90	28.07	9.63	0.512136	**−9.8**	0.2	2.54	1.17	0.55	**2.69**	0.52	0.14	0.72	0.13	0.92	0.24	0.83	0.12	0.78	0.14	**0.23**	**0.24**
02/08/1999, 2502 m																								
Station 21	20	7.94	34.65	27.00	10.15	0.512230	**−8.0**	0.2	2.85	1.18	0.46	**2.13**	0.45	0.13	0.63	0.11	0.81	0.22	0.75	0.10	0.65	0.11	**0.24**	**0.33**
66.55°N, −10.11°E	101	−0.26	34.75	27.92	11.74	0.512164	**−9.2**	0.2	2.68	1.10	0.48	**2.25**	0.46	0.12	0.68	0.12	0.90	0.24	0.85	0.11	0.75	0.13	**0.22**	**0.26**
03/08/1999	1000	−0.68	34.89	28.05	9.68	0.512134	**−9.8**	0.2	2.34	1.01	0.52	**2.20**	0.48	0.13	0.69	0.12	0.85	0.22	0.75	0.10	0.63	0.10	**0.21**	**0.28**
1450 m	1431	−0.87	34.90	28.07	9.43	0.512231	**−7.9**	0.2	3.59	2.06	0.66	**2.96**	0.62	0.16	0.82	0.13	0.99	0.24	0.84	0.13	0.80	0.14	**0.31**	**0.33**
Station 22	20	10.96	35.24	26.97	9.22	0.511963	**−13.2**	0.2	2.44	0.86	0.42	**1.83**	0.36	0.10	0.56	0.10	0.73	0.21	0.70	0.10	0.60	0.10	**0.20**	**0.30**
62.75°N, −9.01°E	50	9.19	35.29	27.32	9.04	0.511960	**−13.2**	0.2	3.32	1.10	0.59	**2.52**	0.51	0.13	0.72	0.12	0.91	0.24	0.80	0.12	0.72	0.12	**0.18**	**0.34**
04/08/1999	200	8.18	35.26	27.45	9.03	0.511929	**−13.8**	0.2	-	-	-	**2.55**	-	-	-	-	-	-	-	-	-	-	-	-
490 m	411	7.41	35.21	27.53	8.40	0.512029	**−11.9**	0.2	1.95	0.84	0.46	**2.01**	0.48	0.13	0.75	0.13	0.99	0.25	0.88	0.12	0.75	0.11	**0.20**	**0.19**
	483	5.71	35.13	27.70	8.82	0.512436	**−3.9**	0.2	4.34	3.58	0.90	**4.04**	0.90	0.25	1.16	0.20	1.37	0.32	1.09	0.15	0.91	0.16	**0.42**	**0.35**
Station 23	51	10.13	35.34	27.20	8.92	0.511970	**−13.0**	0.2	3.16	1.22	0.58	**2.44**	0.50	0.13	0.74	0.12	0.92	0.24	0.81	0.11	0.69	0.12	**0.21**	**0.34**
60.50°N, −5.00°E	99	9.20	35.33	27.35	8.93	0.511982	**−12.8**	0.2	3.12	1.27	0.57	**2.64**	0.51	0.14	0.76	0.13	0.95	0.25	0.85	0.12	0.77	0.13	**0.22**	**0.30**
06/08/1999	280	7.72	35.24	27.50	9.16	0.511984	**−12.8**	0.2	2.70	1.14	0.50	**2.38**	0.47	0.13	0.68	0.12	0.89	0.23	0.85	0.11	0.75	0.13	**0.23**	**0.26**
1000 m	500	2.41	34.92	27.88	10.50	0.512172	**−9.1**	0.2	3.12	1.78	0.58	**2.76**	0.55	0.15	0.77	0.13	0.95	0.24	0.90	0.12	0.82	0.14	**0.31**	**0.28**
	599	0.33	34.88	27.99	10.37	0.512221	**−8.1**	0.2	2.68	1.65	0.67	**2.89**	0.59	0.16	0.85	0.14	0.99	0.26	0.89	0.12	0.72	0.10	**0.29**	**0.27**
	800	−0.60	34.89	28.05	10.09	0.512170	**−9.1**	0.2	3.34	1.60	0.62	**2.87**	0.56	0.16	0.81	0.14	1.01	0.26	0.90	0.12	0.84	0.15	**0.26**	**0.29**
	988	−0.77	34.90	28.06	9.97	0.512266	**−7.3**	0.2	4.04	2.77	0.82	**3.54**	0.72	0.21	0.97	0.17	1.16	0.29	0.98	0.13	0.88	0.15	**0.35**	**0.34**
Station 25	21	12.23	35.04	26.57	9.36	0.511961	**−13.2**	0.2	3.22	1.67	0.52	**2.24**	0.42	0.12	0.64	0.11	0.85	0.24	0.78	0.11	0.67	0.12	**0.29**	**0.36**
64.65°N, 4.18°E	101	8.11	35.27	27.47	8.86	0.511968	**−13.1**	0.2	-	-	-	**3.44**	-	-	-	-	-	-	-	-	-	-	-	-
11/08/1999	401	2.88	34.92	27.83	10.13	0.512160	**−9.3**	0.2	-	-	-	**2.76**	-	-	-	-	-	-	-	-	-	-	-	-
1400 m	600	−0.24	34.89	28.03	10.12	0.512121	**−10.1**	0.2	-	-	-	**2.52**	-	-	-	-	-	-	-	-	-	-	-	-
	800	−0.67	34.89	28.05	9.99	0.512128	**−9.9**	0.2	1.95	1.11	0.57	**2.54**	0.55	0.14	0.77	0.13	0.92	0.24	0.80	0.11	0.70	0.10	**0.24**	**0.21**
	1385	−0.96	34.90	28.07	9.74	0.512172	**−9.1**	0.2	4.04	2.78	0.78	**3.29**	0.66	0.19	0.89	0.15	1.07	0.28	0.93	0.14	0.83	0.15	**0.36**	**0.36**
Station 26	43	8.29	35.19	27.38	9.64	0.512011	**−12.2**	0.2	-	-	-	**1.30**	-	-	-	-	-	-	-	-	-	-	-	-
69.03°N, 7.95°E	74	7.27	35.22	27.55	9.28	0.512016	**−12.1**	0.2	4.02	2.77	0.70	**2.94**	0.59	0.16	0.80	0.12	0.99	0.24	0.86	0.12	0.77	0.14	**0.38**	**0.39**
14/08/1999	351	4.84	35.10	27.77	9.80	0.512017	**−12.1**	0.2	-	-	-	**2.25**	-	-	-	-	-	-	-	-	-	-	-	-
3060 m	801	0.93	34.89	27.96	10.19	0.512115	**−10.2**	0.2	4.39	2.29	0.75	**3.16**	0.64	0.18	0.92	0.15	1.12	0.28	1.00	0.14	0.88	0.15	**0.29**	**0.37**
	1001	−0.21	34.88	28.02	10.07	0.512130	**−9.9**	0.2	-	-	-	**2.32**	-	-	-	-	-	-	-	-	-	-	-	-
	1700	−0.82	34.90	28.07	9.75	0.512108	**−10.3**	0.2	2.06	1.04	0.60	**2.49**	0.55	0.15	0.79	0.13	0.96	0.25	0.88	0.12	0.70	0.11	**0.21**	**0.22**
	2972	−1.01	34.90	28.08	9.79	0.512135	**−9.8**	0.2	6.28	4.76	0.96	**3.93**	0.68	0.17	0.88	0.15	1.03	0.28	0.91	0.14	0.88	0.15	**0.44**	**0.53**

Table 1. (continued)

R/V *Marion Dufresne*, Cruise FI3519992, IPEV		Hydrological Data				Nd Isotopic Composition			Concentration (10^{-12} g g^{-1})															
Station (Number, Location, Date, Depth)	Depth, m	θ, °C	S	σ_θ	O_2, mg/L	$^{143}Nd/^{144}Nd$	ε_{Nd}	$2\sigma_m$	La	Ce	Pr	**Nd**	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ce/Ce*	La_n/Yb_n
Station 29	604	0.37	34.88	27.99	10.63	0.512072	**−11.0**	0.2	3.16	1.33	0.57	**2.44**	0.54	0.15	0.78	0.13	0.98	0.26	0.90	0.12	0.76	0.14	**0.23**	**0.31**
77.67°N, 7.69°E	1513	−0.85	34.90	28.07	9.75	0.512120	**−10.1**	0.3	3.03	0.89	0.53	**2.41**	0.51	0.14	0.74	0.13	0.94	0.25	0.83	0.12	0.78	0.14	**0.16**	**0.29**
22/08/1999	2423	−1.00	34.90	28.08	9.80	0.512115	**−10.2**	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3320 m	3360	−0.99	34.91	28.08	9.88	0.512098	**−10.5**	0.2	3.27	1.47	0.60	**2.73**	0.57	0.15	0.79	0.13	0.96	0.26	0.87	0.13	0.80	0.14	**0.24**	**0.30**
Station 30	405	0.20	34.90	28.01	10.53	0.512065	**−11.2**	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
76.74°N, −2.33°E	505	0.00	34.89	28.02	10.64	0.512062	**−11.2**	0.2	3.03	1.04	0.52	**2.44**	0.48	0.14	0.76	0.13	0.94	0.26	0.86	0.12	0.77	0.14	**0.19**	**0.29**
22/08/1999	2016	−1.00	34.90	28.07	9.85	0.512099	**−10.5**	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2560 m	2512	−1.06	34.90	28.08	9.94	0.512083	**−10.8**	0.2	3.56	1.52	0.63	**2.83**	0.57	0.16	0.80	0.14	1.00	0.26	0.90	0.13	0.80	0.14	**0.23**	**0.33**
Station 32	608	0.61	34.88	27.98	9.78	0.512088	**−10.7**	0.2	3.05	1.17	0.55	**2.46**	0.55	0.15	0.77	0.13	1.01	0.26	0.89	0.12	0.82	0.14	**0.21**	**0.28**
77.03°N, −3.75°E	805	0.14	34.89	28.01	10.03	0.512066	**−11.2**	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23/08/1999, 1895 m	1840	−0.74	34.92	28.07	9.73	0.512087	**−10.7**	0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Station 42	707	−0.53	34.88	28.04	10.40	0.512079	**−10.9**	0.2	2.95	1.00	0.53	**2.36**	0.51	0.13	0.76	0.13	0.96	0.25	0.91	0.13	0.78	0.13	**0.18**	**0.28**
72.91°N, −12.97°E	2635[b]	−1.12	34.90	28.08	10.00	0.512113	**−10.2**	0.3	3.99	1.74	0.76	**3.15**	0.67	0.17	0.90	0.14	1.04	0.25	0.91	0.12	0.76	0.14	**0.23**	**0.39**
25/08/1999, 2690 m																								
Station 45	1521	−0.84	34.91	28.08	9.68	0.512102	**−10.5**	0.2	3.05	2.20	0.71	**3.11**	0.60	0.15	0.79	0.13	0.99	0.26	0.86	0.13	0.81	0.14	**0.35**	**0.28**
72.91°N, −15.85°E																								
25/08/1999, 2000 m																								
PAAS[c]									*38.20*	*79.58*	*8.83*	*33.90*	*5.55*	*1.08*	*4.65*	*0.78*	*4.68*	*0.99*	*2.84*	*0.41*	*2.82*	*0.44*		

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[a] Samples were taken during the Signature/GINS cruise in August 1999 (R/V *Marion Dufresne*, cruise FI3519992, Institut Paul Emile Victor). $2\sigma_m$ is the standard error of the mean (note that external precision is 0.3 ε_{Nd}). Ce/Ce* and La_n/Yb_n have been calculated using concentrations normalized to the Post-Archean Australian Sedimentary Shales (PAAS) [*Taylor and McLennan*, 1985] values reported in the table.

[b] Only this sample was filtered.

[c] PAAS REE concentrations in ppm (10^{-6} g g^{-1}).

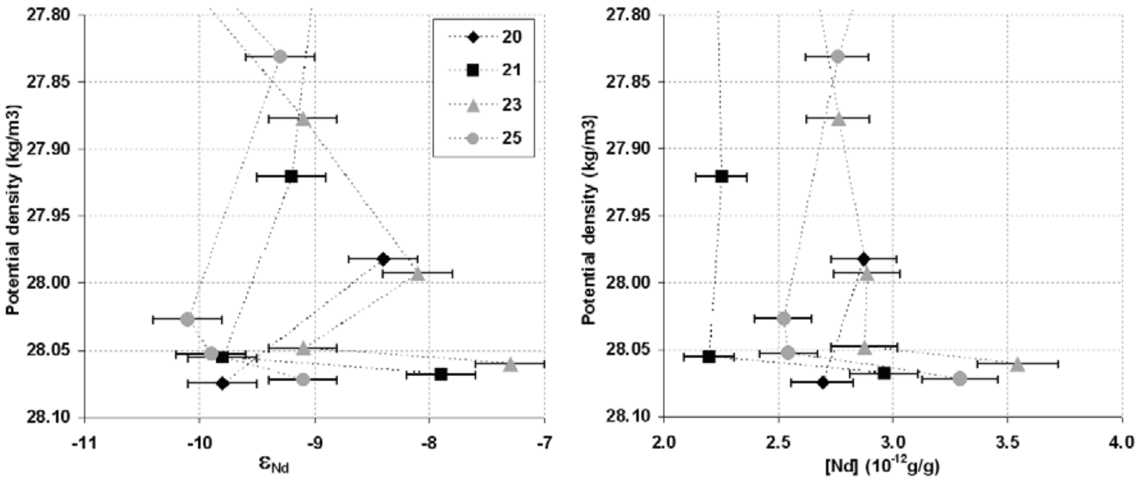

Figure 3. Neodymium isotopic composition (left panel) and concentration (right panel) profiles, in the lower part of the water column ($\sigma_\theta \geq 27.80$ kg m^{-3}), at the four stations in the Norwegian Basin, where dense waters occur. Error bars are 0.3 ε_{Nd} units and 5% of the measured concentrations (the external reproducibilities).

≈ -8.9 northeast of Iceland (station 21) and finally ≈ -8.2 in the Faroe-Shetland Channel. There is therefore a significant and progressive Nd IC increase as the NSDW leaves the Greenland Sea and flows around the Norwegian Basin. Considering the lack of waters with $\varepsilon_{Nd} > 8$ entering the Nordic Seas and the basaltic nature of the west and south margins of this Basin, this increase is likely due to the imprint of these margins along which the water mass flows. These interactions will be discussed below.

[15] The NSAIW precursors are mainly ISAIW and GSAIW. The latter is characterized by $\varepsilon_{Nd} \approx -11.1$ in the Greenland Sea (Stations 29 to 45, $27.98 \geq \sigma_\theta \geq 28.04$ kg m^{-3}). ISAIW displays $\varepsilon_{Nd} \approx -8.8$ (stations 20 and 21). In the Faroe-Shetland Channel, NSAIW has $\varepsilon_{Nd} \approx -8.1$ (599 m depth). As for NSDW, there is an Nd IC increase between the NSAIW precursors and the NSAIW within the overflow. As for NSDW, this increase can be attributed to margin/seawater interactions as the waters flow along the west and south Norwegian Basin boundaries.

[16] In the following discussion, we will argue that the above mentioned increases can be attributed to margin/seawater interactions.

5. Discussion

[17] Figures 3 shows the Nd IC and concentration profiles in the Norwegian Basin. At stations 21 and 23, the bottom samples (1431 and 988 m depth, respectively) display sharp increases for both parameters in comparison with the overlying samples (1000 and 800 m depth, respectively). These suggest an Nd enrichment of the water mass from the radiogenic margin. Such enrichment is confirmed by the REE concentrations of these samples. At both stations, the cerium anomaly and light versus heavy REE fractionation are significantly smaller (i.e., values closer to 1) for the bottom samples than for the overlying ones (e.g., at station 21, Ce/Ce* is 0.31 and 0.21 at 1431 and 1000 m depth, respectively; see Figure 4 and Table 1). These indicate recent lithogenic inputs to the bottom samples in comparison with the overlying samples.

[18] At stations 21 and 23, assuming that before these inputs, the bottom waters had Nd characteristics similar to those of the overlying waters, we can calculate the Nd IC of the Nd added by this lithogenic "contamination," following equation (2):

$$\varepsilon_{Nd}^{final} \times [Nd]^{final} \times V = \varepsilon_{Nd}^{initial} \times [Nd]^{initial} \times V + \varepsilon_{Nd}^{input} \times \left([Nd]^{final} - [Nd]^{initial}\right) \times V, \qquad (2)$$

where initial and final refer to the water mass before and after the enrichment, respectively (here, the overlying and bottom samples). Input refers to the added matter and V to the volume of the water mass (V can be canceled in equation (2)).

[19] At stations 21 and 23, equation (2) leads to $\varepsilon_{Nd}^{input} = -2.5 \pm 3.1$ and $+0.8 \pm 4.7$, respectively (2σ; uncertainties were calculated by propagation of

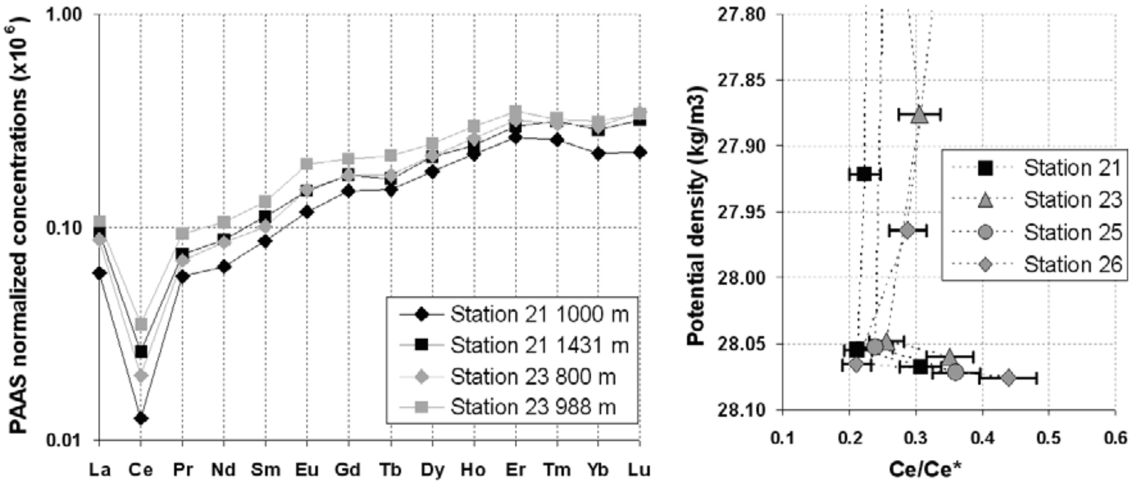

Figure 4. (left) REE patterns for the bottom and overlying samples at the two stations where sediment remobilization affecting the pISOW Nd signature is evidenced (displayed on a logarithm scale). REE concentrations were normalized to the Post-Archean Australian Sedimentary rocks (PAAS) [*Taylor and McLennan*, 1985] (see Table 1) and multiplied by 10^6. Note the Ce anomaly and heavy versus light REE enrichment, characteristic of marine samples. (right) Ce anomaly profiles, in the lower part of the water column ($\sigma_\theta \geq 27.80$ kg m^{-3}), at the four stations where sediment remobilization is evidenced.

those for ε_{Nd} and [Nd]: 0.4 ε_{Nd} units and 0.2 ppt). These data are in good agreement with each other. Their average value, $\varepsilon_{Nd} = -0.9$, is also similar to that reported for the radiogenic enrichment affecting the Denmark Strait Overflow Water (DSOW, $\varepsilon_{Nd} = -0.4$ [*Lacan and Jeandel*, 2004a]). As in that work, this value is less radiogenic than that of the surrounding basaltic formations ($\varepsilon_{Nd} \approx +7$), which probably reflects a small contribution of lithogenic matter from less radiogenic sources. Considering Nd IC and concentrations from the western Norwegian Caledonian margin for instance ($\varepsilon_{Nd} \approx -14$, [Nd] ≈ 30 ppm; 1 ppm = 1 × 10^{-6} g g^{-1} [*Bingen et al.*, 1996; *Boundy et al.*, 1997]) and those in Icelandic and Faroese basalts ($\varepsilon_{Nd} \approx +7$, [Nd] ≈ 8 ppm [*Hémond et al.*, 1993; *Holm et al.*, 2001]), the mean Nd IC of −0.9 calculated for the added matter suggest that the latter is composed of ≈85% basalts.

[20] The enrichments discussed above concern the NSDW. With regard to the NSAIW, we cannot conduct such a study because (1) the different NSAIW precursors have different Nd IC and geographical origins, which makes the problem more complex, and (2) samples of NSAIW and its precursor are too scarce. However, in addition to the Nd IC increase shown above, there are some indications of lithogenic inputs. First Nd concentrations of intermediate waters increase from ≈2.4 ppt in the Greenland Sea and ≈2.3 ppt in the Iceland Sea (station 21) to ≈2.9 ppt in the Norwegian Basin (station 20 and 23). Second, the relatively small REE fractionation at station 20 (331 m depth, Ce/Ce* = 0.33 and La_n/Yb_n = 0.34) indicates recent lithogenic inputs.

[21] Although not directly affecting the pISOW, it is worthwhile mentioning that bottom samples at stations 25 and 26 (eastern Norwegian and Lofoten Basins) are also subject to lithogenic inputs (indicated by Nd IC and concentration increases and small REE fractionations, in comparison with the overlying samples; see Figures 3 and 4). Here the calculated Nd IC of the added matter are −6.2 ± 2.6 and −8.9 ± 1.3, at stations 25 and 26, respectively. These values are much less radiogenic than those calculated above, which probably reflects the larger influence of the Norwegian Caledonian margin at these locations.

[22] Margin imprint on deep and intermediate water masses Nd signature has already been reported (North Indian Intermediate Water, Antarctic Intermediate Water, North Pacific Tropical Water, North West Atlantic Bottom Water and Denmark Strait Overflow Water [*Jeandel et al.*, 1998; *Amakawa et al.*, 2004; *Lacan and Jeandel*, 2004a; F. Lacan and C. Jeandel, Neodymium isotopes as a new tool for quantifying exchange fluxes at the continent-ocean interface, submitted to *Earth and Planetary Science Letters*, 2004 (hereinafter referred to as Lacan and Jeandel,

submitted manuscript, 2004)]). These interactions seem to play a significant role in the Nd IC global budget [*Tachikawa et al.*, 2003]. However, the detailed processes involved remain unknown. Considering the depth of these water masses and the magnitudes of the fluxes involved, sediment remobilization (including resuspension and dissolution) has been suggested as the best candidate (Lacan and Jeandel, submitted manuscript, 2004). The fact that all of theses observations were located in highly dynamic flows (boundary currents and straits) supports this hypothesis. In contrast, such enrichment were never observed along the seafloor in the middle of oceanic gyres [*Piepgras and Wasserburg*, 1987; *Piepgras and Jacobsen*, 1988; *Jeandel*, 1993]. Dissolved/particulate Nd exchange, already observed within the water column [*Jeandel et al.*, 1995; *Nozaki and Alibo*, 2003], could occur, enhanced by particle resuspension [*Tachikawa et al.*, 2003; *Amakawa et al.*, 2004; Lacan and Jeandel, submitted manuscript, 2004]. In particular, a recent work on REE concentrations in pore waters suggests that iron oxides reduction in marine sediments could be a significant source of dissolved Nd [*Haley et al.*, 2004]. However, addressing that issue in terms of isotopic composition will required the precise analysis of the dissolved and particulate phases in seawater, in addition to surface sediment analysis, in a region where margin/seawater interactions are suspected (pore water Nd IC analysis is not possible at present, considering the data published so far [*Haley et al.*, 2004] and references therein). This was not realized in any of the former studies. In particular, suspended particle Nd IC analysis would require the filtration of large sample volumes (typically 100 liters).

6. Conclusions

[23] The intermittent Iceland-Faroe overflow was not observed during the Signature/GINS cruise. On the other hand, the overflow through the Faroe-Shetland channel was observed, with $\varepsilon_{Nd} = -8.2 \pm 0.6$ (mean deviation) and [Nd] = 3.1 ± 0.3 ppt, in good agreement with one previously measured data.

[24] The radiogenic pISOW signature (in the Faroe-Shetland channel) can be explained by the imprint of mainly basaltic material, derived from the west and south Norwegian Basin margins, on the precursors of these waters, mainly GSDW, EBDW, ISAIW and GSAIW. Nd IC and concentration, and REE patterns show that significant enrichments affect the Norwegian Sea bottom samples. Those suggest that margin/seawater interactions occur, via the remobilization of surface sediments. Whereas the neodymium isotopic composition behaves conservatively in the oceans in the absence of lithogenic inputs and can be used as a water mass tracer, these results emphasize the role of interactions between sediments deposited on margins and seawater in controlling the acquisition of the neodymium isotopic composition of water masses. Although such interactions seem to play a significant role in the Nd IC global budget, the precise processes involved remain unknown. Joint analysis of sediments and particulate and dissolved seawater phases will be required to address this issue.

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