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Nd isotopic constraints on the origin of suspended particles in the Atlantic Sector of the Southern Ocean

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[1] In the nutrient-rich Southern Ocean, Fe is a vital constituent controlling the growth of phytoplankton. Despite much effort, the origin and transport of Fe to the oceans are not well understood. In this study we address the issue with geochemical data and Nd isotopic compositions of suspended particle samples collected from 1997 to 1999 in the South Atlantic Sector of the Southern Ocean. Al, Th, and rare earth element (REE) concentrations as well as $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios in acetic acid-leached particle samples representing the lithogenic fraction delineate three major sources: (1) Patagonia and the Antarctic Peninsula provide material with $\epsilon_{\text{Nd}} > -4$ that is transported toward the east with the polar and subpolar front jets, (2) the south African shelf, although its influence is limited by the circumpolar circulation and wind direction, can account for material with ϵ_{Nd} of -12 to -14 adjacent to South Africa, and (3) East Antarctica provides material with ϵ_{Nd} of -10 to -15 to the eastern Weddell Sea and adjacent Antarctic Circumpolar Current. For this region we interpret the Nd isotopic evidence in combination with oceanographic/atmospheric constraints as evidence for supply of significant amounts of terrigenous detritus by icebergs.

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1. Introduction

[2] In the remote Atlantic Sector of the Southern Ocean, low Fe concentrations inhibit the growth of phytoplankton [De Baar *et al.*, 1995; Löscher *et al.*, 1997]. Nevertheless, sporadic and vigorous phytoplankton blooms [Tynan, 1998] indicate Fe-fertilization to an extent that the bioavailable Fe concentrations exceed the critical threshold. It has been recognized that phytoplankton blooms operate as efficient sinks for atmospheric CO₂ [Blain *et al.*, 2007; Coale *et al.*, 2004; De Baar *et al.*, 1995]. The origin of the limiting nutrient Fe is still unresolved. Some authors have argued that aeolian dust is the predominant source of Fe in the oceans [Duce and Tindale, 1991; Fung *et al.*, 2000; Jickells *et al.*, 2005; Jickells and Spokes, 2001]. Wells *et al.* [1999] and Lacan and Jeandel [2001] suggested that the Fe stimulating the primary production in the Central Pacific originated at the Papua New Guinea margin. Their observations are consistent with the hypotheses of Westerlund and Öhman [1991], De Baar *et al.* [1995], and Löscher *et al.* [1997], who considered the continental shelves as potential sources of dissolved Fe. Dissolution of suspended particles advected from the continental shelf into the ocean may also represent a significant source of Fe. Similarly, Laës *et al.* [2003] explained the high Fe content in intermediate waters of the Atlantic Ocean as due to exchange of water with the continental margin. In this context, Elrod *et al.* [2004] estimated that the continental margins supply about 10 times more Fe to the oceans than aeolian dust. This assessment has recently been confirmed by Lam *et al.* [2006]. Another important source of Fe may be upwelling deep waters [De Baar *et al.*, 1995; Löscher *et al.*, 1997; Watson *et al.*, 2000]. Icebergs, known to distribute terrigenous detritus in the oceans, have been identified as an additional, although subordinate source of Fe [De Baar *et al.*, 1990, 1995; Löscher *et al.*, 1997]. To address the sources of Fe, measuring its concentrations in seawater alone is not providing compelling evidence. One of the goals of the EU Programme CARUSO was to better constrain the sources of suspended particles and Fe for the Atlantic Sector of the Southern Ocean. The goal was pursued with lithogenic tracers such as the rare earth elements (REE), Nd isotopes, and Al concentrations.

[3] Al has been interpreted as a conservative lithogenic tracer and the ¹⁴³Nd/¹⁴⁴Nd isotopic ratio in the lithogenic fraction of suspended particles as evidence for the provenance of terrigenous detritus

[Grousset and Biscaye, 2005; Grousset *et al.*, 1988, 1998; Henry *et al.*, 1994; Tachikawa *et al.*, 1997]. These proxy data have been used to decipher the origin and delineate the distribution of sediment in the recent Holocene as well as in the oceans of the past [Grousset *et al.*, 1998; Walter *et al.*, 2000]. Several studies have shown that the Nd isotopic composition of the authigenic fraction, that is the component of the suspended particle that formed in the water column and comprising biogenic components or oxy-hydroxide precipitates, can provide the Nd isotopic composition of the seawater surrounding the particle [Bayon *et al.*, 2004; Jeandel *et al.*, 1995; Tachikawa *et al.*, 1999b].

[4] In this paper we explore the Nd isotopic composition and Al, Th, and REE concentrations in suspended particles from the South Atlantic Sector of the Southern Ocean. The goals are to decipher the provenance of the lithogenic fraction or terrigenous component in the particles, their transport, and ultimately the sources of dissolved elements, including that of Fe. Our study is complementary to others dealing with the supply and transport of terrigenous detritus as recorded in the distribution of clay minerals [e.g., Petschik *et al.*, 1996] and the Nd and Sr isotopic compositions of bulk sediments and grain-size fractions [Walter *et al.*, 2000; Rutberg *et al.*, 2005; Franzese *et al.*, 2006]. A common trait of sedimentary studies is the mixed signal of material transport in surface- and deep-water currents. In contrast, the Nd isotopic compositions reported in this paper are the first data for the South Atlantic pertaining only to surface water and dust transport.

2. Samples and Methods

[5] The samples were collected from 1997 to 1999 during three cruises of the research vessel *Polarstern* (cruise ANT XV/2 from 9 November 1997 to 11 January 1998, cruise ANT XV/3 from 13 January to 25 March 1998, and cruise ANT XVI/3 from 18 March to 10 May 1999). The samples were collected along N-S transects across the Antarctic Circumpolar Current (ACC) in the central and eastern South Atlantic, transects across the Weddell Sea, and a W-E transect along the Weddell-Scotia confluence between the Antarctic Peninsula and the South Shetland Islands (SSI). Additional samples were collected near the Antarctic Peninsula, East Antarctica, southern South America, and South Africa (Figure 1 and Table 1).

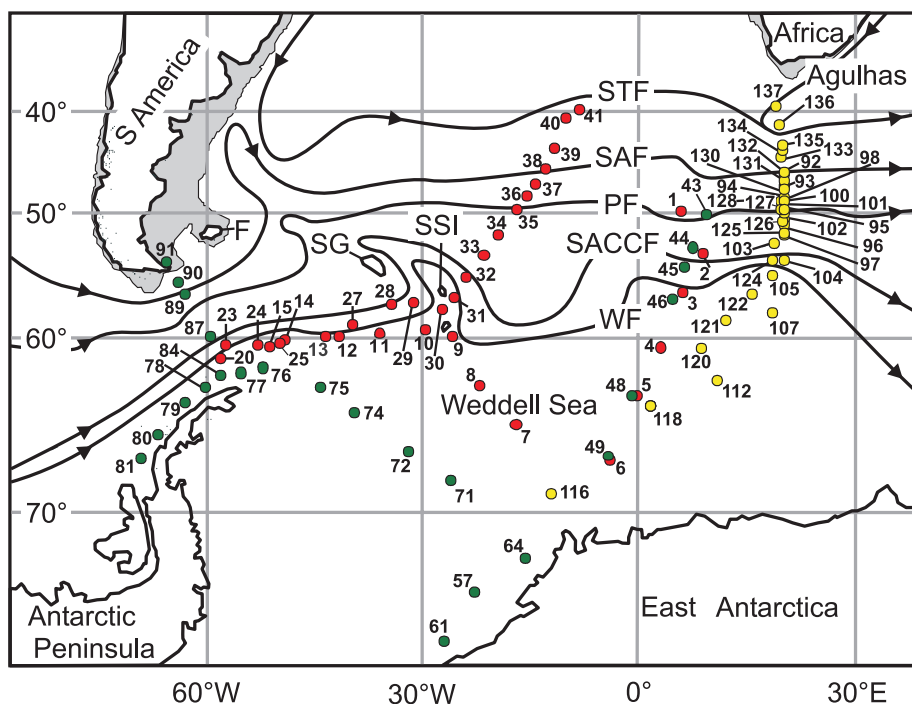


Figure 1. Map of the South Atlantic Sector of the Southern Ocean showing sample localities, major oceanic fronts, and the flow directions of surface waters [Orsi *et al.*, 1995]. STF, Subtropical Front; SAF, Subantarctic Front; PF, Polar Front; SACCF, Southern Antarctic Circumpolar Current Front; WF, Weddell Front. Shaded areas outline the continental shelves with water depths <200 m. SSI, South Sandwich Islands; SG, South Georgia; F, Falkland Islands. The sampling parameters are listed in Table 1.

[6] The particle samples were collected at a water depth of ~ 7 m using a continuous flow centrifuge [Schüßler and Kremling, 1993] processing 400 to 900 liters of seawater per hour. The volume of filtered seawater per particle sample ranges from 2,000 to 7,000 liters collected over distances of ~ 30 to 160 km. Some samples were taken at stationary sites. The particle samples represent the $\geq 1 \mu\text{m}$ grain-size fraction and consist of a predominantly biogenic component such as phytoplankton, zooplankton made up of opal, carbonate, organic carbon, and a subordinate amount of aluminosilicate minerals of continental origin. After collecting, the particle samples were freeze-dried and homogenized. The concentration of the particles was determined after correcting the sample weight for a salt content ranging from ~ 35 to 75 wt.%.

[7] During the three cruises we collected over 130 samples and for this study we selected 92 samples. For these we report biogenic SiO_2 and Al, Th, REE, and Nd isotopic compositions (Table 1). The biogenic SiO_2 and NaCl concentrations were determined at the Alfred-Wegener-Institut in

Bremerhaven (AWI). The Al, Th, and REE concentrations in bulk samples were measured with an Elan 6000 ICP-MS using Indium as internal standard at the Observatoire Midi-Pyrénées (Toulouse). The analytical procedures are described by Tachikawa *et al.* [1999a]. The analytical uncertainties as inferred from measurements of the international basalt standard BE-N and the river water standard SLRS3 (distributed by the Institute of Environmental Chemistry, Ottawa, Canada) are $<5\%$ (2σ) for Al, and 2–15% (2σ) for Th and the REE, the largest uncertainties relating to the less abundant heavy REE.

[8] The $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios of 53 residue- and bulk-particle samples as well as 29 acetic acid-leachate samples (Table 1) were determined at Universität München using a MAT 261 in static data acquisition mode. Due to the very low Nd concentrations of <30 ng in 16 bulk-particle samples, we analyzed them as bulk without prior acid-leaching. The wet chemical and mass spectrometric procedures are described by Hegner *et al.* [1995]. The $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios were corrected for a machine bias so that they correspond to 0.511850



Table 1 (Representative Sample). Sampling Parameters, Major and Trace Element Concentrations, and Nd Isotopic Composition in Residue, Bulk, and Leachate Samples of Suspended Particles From the South Atlantic Sector of the Southern Ocean [The full Table 1 is available in the HTML version of this article at <http://www.g-cubed.org>]

Sample (z)	Cruise "Antarktis" (ANT)	Sampling Date	Lat. (Mean)	Long. (Mean)	Volume of Centrifuged Seawater, m ³	Sampling Distance, km	Particle Conc., mg/L	Biogenic SiO ₂ , wt.%	Al, nmol/L	Th, fmol/L	Nd, pmol/L
1	XV/2	14.11.97	-49.75	5.87	1.80	95	0.24	29	5.09	122	1.15
2	XV/2	15.11.97	-53.47	9.00	2.96	145	0.14	42	2.72	60.2	0.41
3	XV/2	16.11.97	-56.60	6.09	2.74	139	0.15	46	1.22	27.5	0.25
4	XV/2	17.11.97	-60.58	3.00	1.64	69	0.14	17	23.4	661	4.64
5	XV/2	18.11.97	-63.63	-0.31	1.71	68	0.15	8	15.7	309	4.03
6	XV/2	19.11.97	-67.27	-3.93	2.17	157	0.13	9	4.87	111	1.17
7	XV/2	01.12.97	-65.34	-17.06	2.09	3	0.09	14	n.d.	n.d.	n.d.
8	XV/2	02.12.97	-63.01	-22.03	2.23	65	0.17	11	8.40	180	2.06
9	XV/2	03.12.97	-59.82	-26.03	2.77	32	0.12	22	2.12	26.7	0.54
11	XV/2	05.12.97	-59.61	-36.04	2.95	55	0.15	23	0.95	21.7	0.36
13	XV/2	06.12.97	-59.80	-43.54	3.52	67	0.22	19	3.52	90.3	0.66
14	XV/2	07.12.97	-60.08	-49.21	2.88	91	0.26	12	4.51	84.5	0.72
15	XV/2	07.12.97	-60.45	-51.46	3.40	79	0.14	18	20.0	205	1.31
24	XV/2	22.12.97	-60.36	-52.98	3.03	61	0.33	6	11.1	146	0.84
25	XV/2	22.12.97	-60.33	-50.05	2.93	61	0.25	10	3.54	44.3	0.46
27	XV/2	24.12.97	-58.94	-39.93	2.50	82	0.26	35	1.78	37.1	0.41
28	XV/2	25.12.97	-57.48	-34.39	2.78	62	0.23	39	0.60	16.1	0.29
31	XV/2	01.01.98	-56.93	-25.73	2.12	57	1.35	48	2.30	48.7	0.54
34	XV/2	03.01.98	-51.93	-19.58	3.57	99	0.62	47	1.62	26.5	0.59
35	XV/2	04.01.98	-49.73	-17.02	3.21	87	0.45	33	1.68	32.3	0.52
36	XV/2	04.01.98	-48.41	-15.52	2.22	21	0.40	37	1.27	26.4	0.42
38	XV/2	05.01.98	-45.79	-13.05	3.01	94	0.38	31	0.68	21.9	0.69
43	XV/3	17.01.98	-50.08	9.37	1.43	38	0.41	41	0.70	19.0	0.81
44	XV/3	18.01.98	-53.00	7.43	1.69	48	0.20	70	0.19	5.9	0.20
45	XV/3	18.01.98	-54.62	6.32	2.74	52	0.13	40	0.10	6.8	0.28
46	XV/3	19.01.98	-57.04	4.63	1.16	17	0.11	43	0.37	5.0	0.22
48	XV/3	21.01.98	-63.58	-0.86	1.70	28	1.19	61	0.54	29.0	0.68
57	XV/3	04.02.98	-73.45	-22.82	4.83	-	0.18	37	n.d.	n.d.	n.d.
61	XV/3	12.02.98	-75.28	-26.98	4.55	-	0.64	n.d.	n.d.	n.d.	n.d.
64	XV/3	21.02.98	-72.01	-15.90	3.32	63	0.47	42	6.53	122	1.31
72	XV/3	05.03.98	-66.81	-32.00	2.88	55	0.79	47	0.14	8.5	0.16
75	XV/3	07.03.98	-63.03	-44.17	3.76	58	0.15	37	1.62	117	0.68
78	XV/3	09.03.98	-63.04	-60.30	3.23	79	0.22	n.d.	40.4	363	1.85
89	XV/3	23.03.98	-56.68	-63.21	3.81	84	0.05	29	1.03	10.1	0.14
90	XV/3	23.03.98	-55.73	-64.23	3.95	80	0.07	15	1.25	11.3	0.19
91	XV/3	24.03.98	-54.12	-65.73	3.38	57	0.11	12	n.d.	n.d.	n.d.
92	XVI/3	22.03.99	-46.36	20.00	2.42	31	0.09	n.d.	0.55	11.3	0.08
93	XVI/3	22.03.99	-47.47	20.00	2.54	33	0.10	n.d.	0.46	15.7	0.16
94	XVI/3	23.03.98	-48.67	20.00	3.00	34	0.08	n.d.	7.16	117	0.79
95	XVI/3	23.03.98	-49.66	20.00	1.65	28	0.38	n.d.	2.67	42.8	0.27
98	XVI/3	27.03.99	-48.83	19.97	6.00	-	0.05	n.d.	0.18	5.1	0.12
100	XVI/3	31.03.99	-48.97	19.90	5.50	-	0.06	n.d.	n.d.	n.d.	n.d.
112	XVI/3	10.04.99	-62.59	10.85	6.00	125	0.03	n.d.	n.d.	n.d.	n.d.
116	XVI/3	12.04.99	-69.19	-5.85	3.36	88	0.13	n.d.	6.66	138	2.35
118	XVI/3	22.04.99	-64.21	1.69	5.00	81	0.05	n.d.	n.d.	n.d.	n.d.
121	XVI/3	24.04.99	-58.72	12.18	5.02	122	0.04	n.d.	n.d.	n.d.	n.d.
124	XVI/3	25.04.99	-54.02	19.97	4.80	-	0.21	n.d.	0.79	15.3	0.10
125	XVI/3	26.04.99	-51.97	20.00	4.51	84	0.26	n.d.	0.55	13.0	0.13
131	XVI/3	05.05.99	-47.00	20.00	4.65	-	0.10	n.d.	0.46	12.0	0.24
132	XVI/3	05.05.99	-46.15	19.94	4.22	96	0.10	n.d.	0.68	23.4	0.29
135	XVI/3	07.05.99	-43.48	19.82	3.70	51	0.05	n.d.	0.38	10.3	0.09
136	XVI/3	08.05.99	-41.55	19.25	5.37	120	0.16	n.d.	1.06	43.5	0.74
137	XVI/3	08.05.99	-39.53	18.84	5.34	101	0.08	n.d.	1.92	45.4	0.44

^aBulk sample.

^bErrors are 2σ mean.

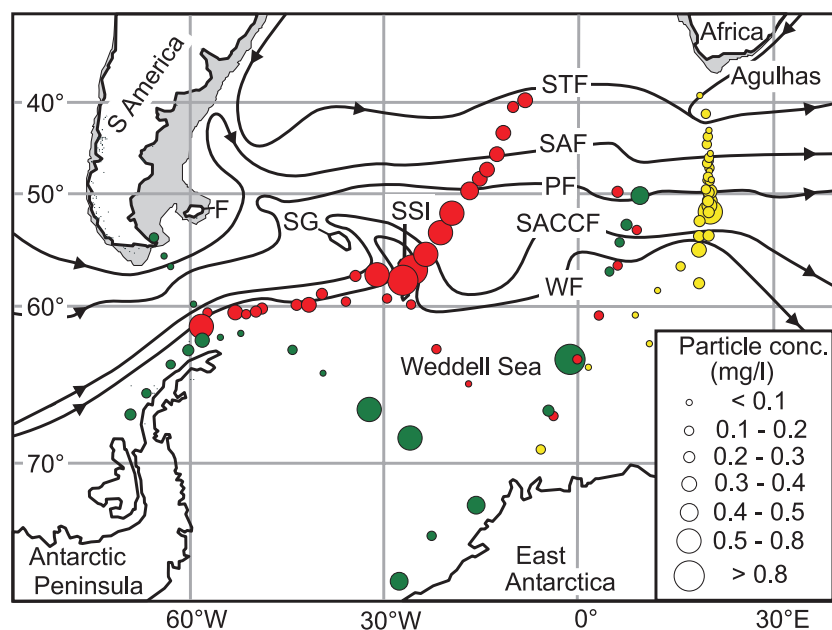


Figure 2. Particle concentrations in surface waters of the South Atlantic Sector of the Southern Ocean. High particle concentrations >0.5 mg/L indicate major blooms of phytoplankton. Color code: red, cruise ANTXV/2, austral spring and early summer, 9 November 1997 to 11 January 1998; green, cruise ANTXV/3, austral summer, 3 January to 25 March 1998; yellow, cruise ANTXVI/3, austral autumn, 18 March to 10 May 1999.

in the La Jolla Nd standard. Thermal mass fractionation was corrected with $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The typical external precision of the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios as determined from measurements of an Ames metal Nd-solution is $\sim 1.3 \times 10^{-5}$ (± 0.25 ϵ -units, 2σ , $N = 45$). The total procedural blank of ~ 40 pg amounts to $<0.3\%$ of the Nd in the particle samples and is not significant for the residue samples. As the isotopic composition of the laboratory blank is similar to the prevalent seawater value in the study area, we are confident that the procedure blank did not affect the leachate composition. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are reported as ϵ_{Nd} values, which is the deviation of the measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio in the sample from the value in Bulk Earth (BE, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$) in parts per 10^4 , e.g., $\epsilon_{\text{Nd}} = ((^{143}\text{Nd}/^{144}\text{Nd})_{\text{Sample}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{BE}} - 1) \times 10^4$.

[9] For the purpose of separating the Nd scavenged by the suspended particles from seawater, the dried particle samples weighing ~ 0.05 to 1 g were leached three times with 25% acetic acid at 50–60°C for 2 hours using the procedure outlined by *Tachikawa et al.* [1997]. The residue obtained after leaching the bulk sample is interpreted as the silicate fraction or lithogenic sample fraction com-

prising the Nd of terrigenous origin. The efficiency of the leaching procedure is corroborated by the results for two particle samples collected at the Antarctic Peninsula (samples 15 and 24, Table 1). After leaching the bulk samples, the residues yielded ϵ_{Nd} values of -1.4 and -2.4 similar to those in shelf sediment from the Antarctic Peninsula [*Walter et al.*, 2000]. In contrast, the leachate samples yielded much lower ϵ_{Nd} values of -7.5 to -8.8 , not much different from the ϵ_{Nd} values of -8 to -9 in seawater entering the South Atlantic via the Drake Passage [*Piepgras and Wasserburg*, 1982; M Frank, personal communication, 2007]. Although the seawater samples of *Piepgras and Wasserburg* [1982] were collected at ~ 50 m and deeper below sea level, considering the strong vertical mixing of water in this area and the new data for surface water of M Frank (personal communication, 2007), justifies a comparison of the ϵ_{Nd} values. The results of our acetic acid-leaching procedure apparently confirm the efficient separation of Nd scavenged from seawater from the silicate residue as was documented by *Tachikawa et al.* [1997]. However, we cannot rule out that some of the leachate signals are biased by a contribution from the residue. In the following we adopt the working hypothesis that the Nd

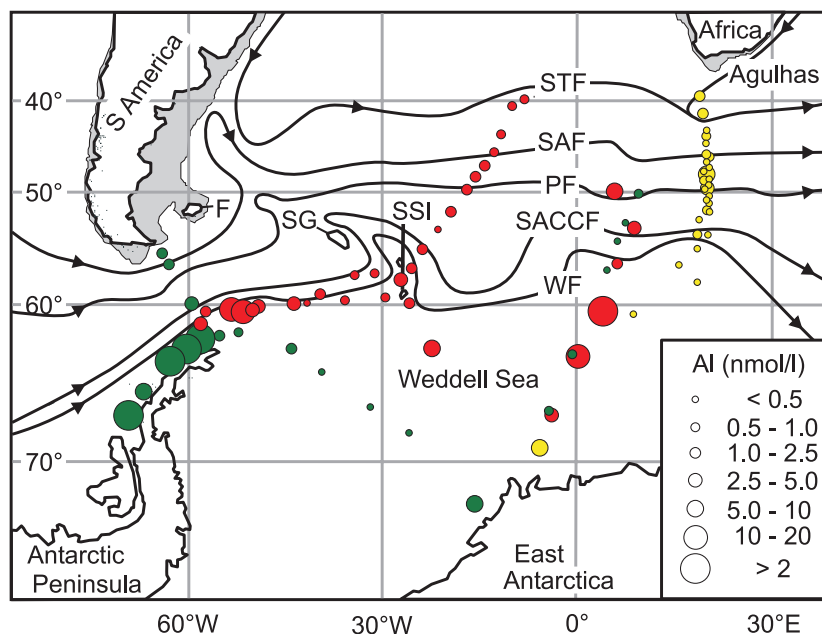


Figure 3. Aluminum concentrations in bulk-particle samples from South Atlantic surface waters.

isotopic composition of the leachate samples reflects the dissolved Nd in the surface waters.

3. Results

3.1. Particle Concentrations in the South Atlantic Sector of the Southern Ocean

[10] The concentration of the particles in the surface waters are shown in Figure 2. High particle concentrations >0.5 mg/L can be found in the Weddell Sea, near the tip of the Antarctic Peninsula, the region surrounding the South Shetland Islands (SSI), and north of East Antarctica between the Polar Front (PF) and the Southern Antarctic Circumpolar Front (SACCF). Very high particle concentrations >0.8 mg/L were encountered during the austral spring and summer near the SSI and in the Weddell Sea. The magnitude of the particle concentrations are evidence for major phytoplankton blooms and by inference significant fertilization of surface waters with the limiting nutrient Fe. Independent evidence for major phytoplankton blooms in the northern Weddell Sea, where our data indicate high particle concentrations, is provided by SeaWiFS satellite images obtained for January 1998 (SeaWiFS Project, NASA Goddard Space Flight Center and ORBIMAGE; <http://oceancolor.gsfc.nasa.gov/SeaWiFS/>).

3.2. Al, ^{232}Th , and Nd Concentrations in Bulk-Particle Samples

[11] Al and ^{232}Th are both enriched in the continental crust [Taylor and McLennan, 1985] and may therefore be used to constrain terrigenous detritus in the suspended particles. The Al and ^{232}Th concentrations in the bulk-particle samples covary as seen in Figures 3 and 4 (Table 1) where samples with high Al concentrations also exhibit high ^{232}Th concentrations. This observation supports the notion that the concentrations of both elements are controlled by the amount of terrigenous detritus in the samples. In addition, the Al and ^{232}Th concentrations indicate large regional differences. For example, the samples collected NW of the Antarctic Peninsula reveal very high amounts of terrigenous detritus when compared to those from the central Atlantic Ocean (e.g., Al concentrations of 11 to 40 nmol/L versus <1 nmol/L, Figure 3). Near the Antarctic Peninsula, the amount of terrigenous detritus rapidly decreases along the Weddell-Scotia confluence and its evidence ceases at $\sim 40^\circ\text{W}$, where samples yielded Al concentrations as low as 1.8 nmol/L. Other areas of remarkably high Al concentrations are the central and eastern Weddell Sea where the samples 8, 4 and 5 yielded concentrations of 8, 16, and 23 nmol/L, respectively (Figure 3 and Table 1). High abundances of terrigenous detritus occur also to the west of the

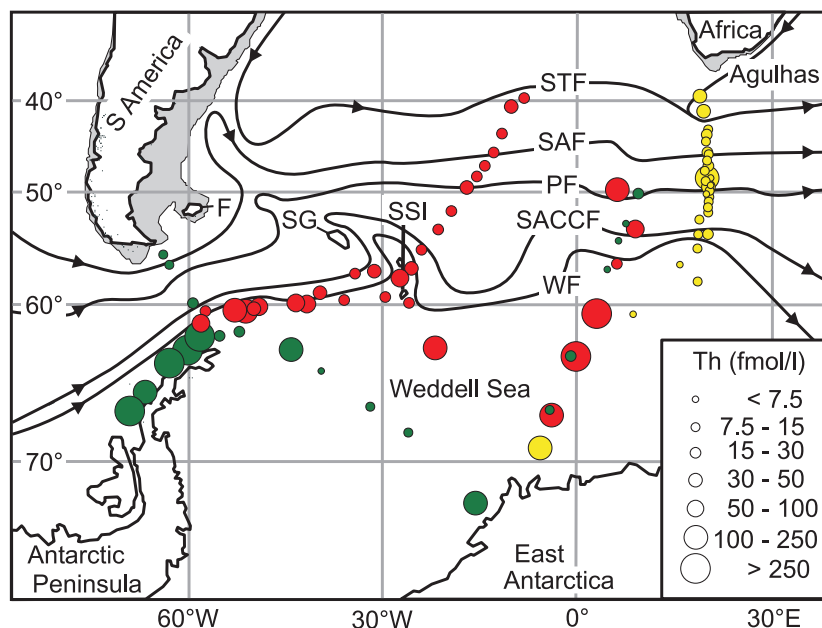


Figure 4. Thorium concentrations in bulk-particle samples from South Atlantic surface waters.

SSI (Al \sim 5.5 nmol/L) and near the Polar Front in the SE Atlantic (Al = 5–7 nmol/L).

[12] Although Al and Th are highly particle-reactive, a small amount of these elements is dissolved in surface waters. Al and Th may be scavenged by biogenic material [Bennekorn *et al.*, 1991; Beusekom *et al.*, 1997; Coale and Bruland, 1985] and it is conceivable that the observed maxima in Al, ^{232}Th , and particle concentrations may be due to phytoplankton growth and subsequent adsorption of these elements. However, the known amounts of dissolved Al and ^{232}Th are not sufficient to support this possibility. Dissolved Al concentrations in surface waters from the South Atlantic (south of \sim 40°S) and in the Weddell Sea are on the order of 1–5 nmol/L [Helmert and Rutgers van der Loeff, 1993; Moran *et al.*, 1992]. The low Al concentrations imply that even efficient removal of all dissolved Al after a strong phytoplankton bloom cannot explain the Al concentrations observed in the samples. Few data of dissolved ^{232}Th in surface waters of the Southern Ocean are available. Coppola *et al.* [2006] found 25–70 pg/L (90–300 fmo/L) ^{232}Th in the Indian Sector of the Southern Ocean between 42° and 47°. Rutgers van der Loeff *et al.* [1997] showed that even during bloom periods near the southern Polar Front the amount of ^{234}Th adsorbed on particles did not exceed 32%. Hence we can assume that not more than about half of the dissolved ^{232}Th will be

adsorbed on bloom particles. We conclude that the high particulate Al and Th concentrations cannot be explained with adsorption from the dissolved state but must indeed reflect the presence of high amounts and recently supplied terrigenous detritus. This conclusion corroborates the notion that Al and Th are important conservative tracers for the lithogenic fraction in suspended particles.

[13] Samples 31 and 48 exhibit outstanding bloom characteristics as shown by suspended loads exceeding 1 mg/L and high opal contents of 48% and 61%, respectively. These values are among the highest observed in all of the samples (Table 1). Their low particulate Al (2.3 and 0.5 nmol/L) and Th concentrations (49 and 29 fmo/L) confirm the view that high Al and Th concentrations are not necessarily related to bloom situations.

[14] The Nd concentrations of the particle samples mimic the behavior of Al and Th (compare Figure 5 with Figures 3 and 4). This finding implies that the Nd isotopic composition and Nd concentration also should reflect the characteristics of recently supplied terrigenous detritus. When attempting to place constraints on the magnitude of the terrigenous component in the bulk-particle samples, it is important to keep in mind that Nd is less particle reactive than Th and Al. This behavior is apparent by its one-order-of-magnitude higher oceanic residence time [Tachikawa *et al.*, 1999a] than for Al

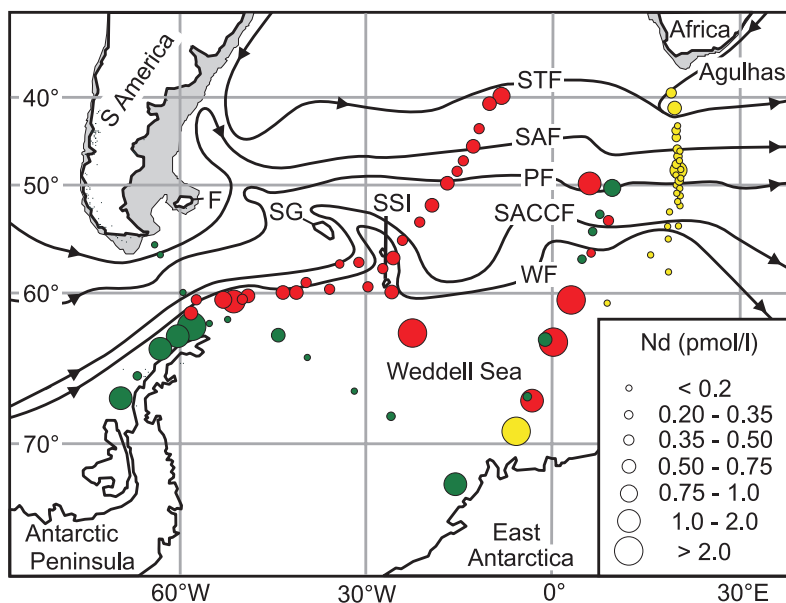


Figure 5. Neodymium concentrations in bulk-particle samples from South Atlantic surface waters.

and Th. Furthermore, it is noteworthy that the concentrations of dissolved Nd of $\sim 8\text{--}10$ pmol/L in surface waters of the South Atlantic [Jeandel, 1993] are much higher than those in the particle samples showing in most cases < 1 pmol/L (Table 1). If, e.g., only 5% of the dissolved Nd would have been adsorbed by the particles, the Nd

concentrations resulting from scavenging of dissolved Nd would amount to $0.4\text{--}0.5$ pmol/L, a value similar to that in many of our samples. It follows that, when interpreting Nd data alone, an unambiguous terrigenous signal can only be assigned to those bulk-particle samples with very high Nd concentrations.

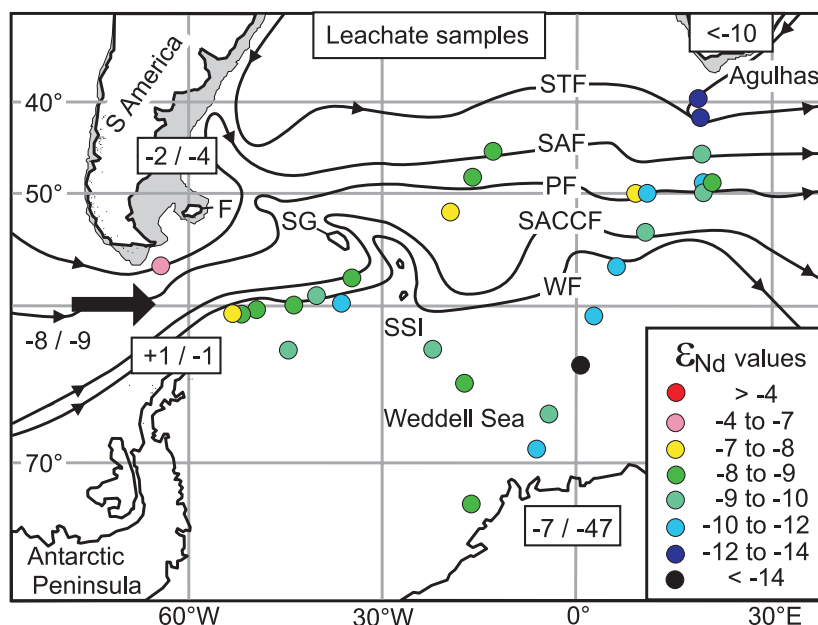


Figure 6. Values of ϵ_{Nd} for acetic acid-leachate samples of suspended particles from South Atlantic surface waters.

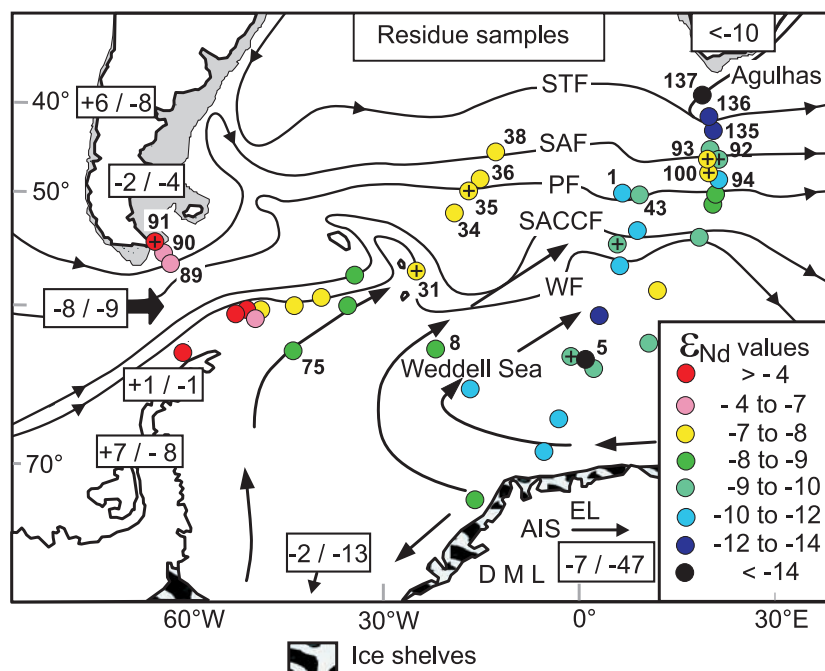


Figure 7. Values of ϵ_{Nd} for residue- and bulk-particle samples (indicated by plus signs) from South Atlantic surface waters. Samples discussed in the text are indicated by bold numbers; other sample numbers are shown in Figure 1. Values of ϵ_{Nd} for continents from Möller *et al.* [1998] and Basile *et al.* [1997]; seawater values for the Drake Passage from Piepgras and Wasserburg [1982]. Only those bulk samples (5 altogether) showing ϵ_{Nd} values distinct from -8 to -9 as inferred to be typical of surface water in the study area are shown. Bold arrows show drift trajectories of icebergs [Tchernia and Jeannin, 1983; Reid and Anderson, 1990]. DML, Dronning Maud Land; EL, Enderby Land; AIS, Amery Ice Shelf.

3.3. Nd Isotopic Composition of Bulk, Residue, and Leachate Samples

[15] The bulk-particle samples with high Nd concentrations were leached with acetic acid in order to obtain a leachate sample providing the $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratio of the ambient seawater, and a residue sample providing the $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratio of the terrigenous detritus (lithogenic fraction) in the particles [e.g., Basile *et al.*, 1997; Goldstein *et al.*, 1984; Jeandel *et al.*, 1995; Tachikawa *et al.*, 1999a]. The data for leachate and residue samples are listed in Table 1 and plotted in Figures 6 and 7, respectively.

3.3.1. Leachate Samples

[16] The 29 leachate samples show a very large range of ϵ_{Nd} values of ~ -6 to -19 with ~ 20 samples yielding ϵ_{Nd} values of ~ -8 to -10 (Table 1 and Figure 6). The ϵ_{Nd} values of ~ -8 to -10 are similar to those reported for sub-surface and surface seawater from the Drake Passage [Piepgras and Wasserburg, 1982; M Frank, personal communication, 2007], and the eastern South Atlantic [Jeandel, 1993]. Their predominance suggests an

overall uniform isotopic composition of large areas of surface water in the Atlantic Sector of the Southern Ocean. However, leachate samples with very low ϵ_{Nd} values of -13 to -19 indicate heterogeneities in the surface waters characterized by Nd from very old continental sources. On the other hand, leachate sample 89 collected south of South America with an ϵ_{Nd} value of -5.6 suggests more radiogenic Nd isotopic composition of the surface water than commonly observed. The large analytical error of ± 2.7 ϵ -units, however, limits the significance of the ϵ_{Nd} value. It is noteworthy that the number of isotopic data for dissolved Nd includes only four samples from the Drake Passage [Piepgras and Wasserburg, 1982; M Frank, personal communication, 2007] and one sample from the Scotia Sea [Jeandel, 1993]. Only the two samples of M Frank (unpublished data, 2007) pertain to Nd dissolved in surface waters.

3.3.2. Residue Samples

[17] The ϵ_{Nd} values for the 37 residue samples show a very large range of -0.8 to -15.3 and indicate material from continental regions with

mean crustal residence times of ~ 0.7 to 1.9 Ga (Figure 7). The ϵ_{Nd} values of approximately -3 to -10 in sixteen bulk-particle samples (Table 1) corroborate the evidence provided by the residue samples.

[18] An ϵ_{Nd} value of -0.8 in residue sample 78 collected NW of the tip of the Antarctic Peninsula clearly reflects material from the young magmatic arc in this region [Walter *et al.*, 2000]. Most samples from west of the Antarctic Peninsula show very high amounts of terrigenous detritus as indicated by particulate Al concentrations of 11 to 40 nmol/L (Figure 3). In the NE Drake Passage near the Patagonian shelf, contributions from the young Andean magmatic arc can be inferred from the high ϵ_{Nd} values of -4 to -5 in samples 89 and 90 (Figure 7). The Al and Th concentrations in these samples indicate moderate abundances of terrigenous detritus. A similarly high ϵ_{Nd} value of -3.5 was measured in bulk sample 91 collected in surface waters of the Patagonian shelf.

[19] The residue samples 34, 36, and 38 from a $\sim 1,000$ km long N-S traverse at 46° – 52° S in the central South Atlantic Ocean reveal remarkably uniform ϵ_{Nd} values of -7.3 to -7.6 . These values are supported by the ϵ_{Nd} values of -7.3 and -7.4 for bulk samples 31 and 35 from the same traverse. Note that in Figure 7 only these bulk-particle samples are plotted that show ϵ_{Nd} values *different* from the inferred seawater value of -8 to -9 .

[20] Near the South Shetland Islands, bulk-particle sample 31, collected in austral summer in the midst of a phytoplankton bloom, yielded an ϵ_{Nd} value of -7.4 indistinguishable from the values for samples from farther north, whereas bulk sample 9 (not plotted in Figure 7), collected during spring in a no-bloom environment, yielded an ϵ_{Nd} value of -8.6 that is indistinguishable from seawater in the Drake Passage.

[21] The residue samples from the Weddell Sea west of 20° W all yielded ϵ_{Nd} values of -8 to -9 . Samples 8 and 75 have ϵ_{Nd} values of -9.2 ± 0.2 and -9.1 ± 0.2 , respectively, whereas the bulk sample 72 (not plotted) yielded an ϵ_{Nd} value of -8 ± 0.8 . In contrast, samples from the Weddell Sea east of 20° W yielded highly variable ϵ_{Nd} values ranging from -8 to -15 . The very low ϵ_{Nd} values indicate supply of considerably older terrigenous detritus than in the central and western Weddell Sea.

[22] Among the samples from a N-S transect across the ACC (cruise ANT XVI/3), all showing uni-

formly low terrigenous Al signals, except for sample 94 (Table 1), bulk-particle samples 93 and 100 yielded ϵ_{Nd} values of -7.7 and -7.4 , slightly higher than those assumed to be typical for surface waters of the ACC. Although the terrigenous signal is weak in these samples, the Nd isotopes suggest the presence of material from “young” continental source such as the Andean magmatic arc in South America.

[23] In the Agulhas Current at the northernmost ACC and near the tip of South Africa, samples 137 and 136 reveal moderately strong terrigenous signals (Al = 1–2 nmol/L) and very low ϵ_{Nd} values of -13 to -14 . Very low ϵ_{Nd} values also characterize the leachate fraction of these samples. In addition, sample 135 from south of the Agulhas retroflexion area in the northernmost ACC at about 43.5° S yielded a very low ϵ_{Nd} value of -13 coupled with a very small terrigenous signal (Al = 0.38 nmol/L). At this locality, a water temperature of up to 17° C and a salinity of 35.5 permil (ANT XVI/3 cruise report [Bathmann *et al.*, 2000]) are similar to those of the Agulhas Current. The agreement of water data suggests that the sample was collected in an eddy that separated from the Agulhas Current [Boebel *et al.*, 2003].

[24] Samples revealing clear evidence for an origin in phytoplankton blooms, as can be inferred from their high concentration of particles, high biogenic opal content, and low Al content, show a limited range of intermediate ϵ_{Nd} values similar to those reported for seawater (Figures 8a and 8b). This observation is well documented in sample 43, collected during austral summer at ~ 1 – 2° north of the Polar Front (Figure 7). It exhibits a very low terrigenous Al signal and a seawater-like Nd isotopic composition of $\epsilon_{Nd} = -9.2$. On the other hand, samples 1 and 94 collected in the same area during austral spring and fall, respectively, show large amounts of terrigenous detritus (Al > 5 nmol/L) and low ϵ_{Nd} values of approximately -11 .

4. Discussion

4.1. Provenance and Transport of Terrigenous Detritus

[25] In the following we will infer potential sources and modes of transport of the terrigenous detritus in the suspended particles. This will be done by comparing the Nd isotopic compositions of the residue samples with those of the continents bordering the South Atlantic Sector of the Southern

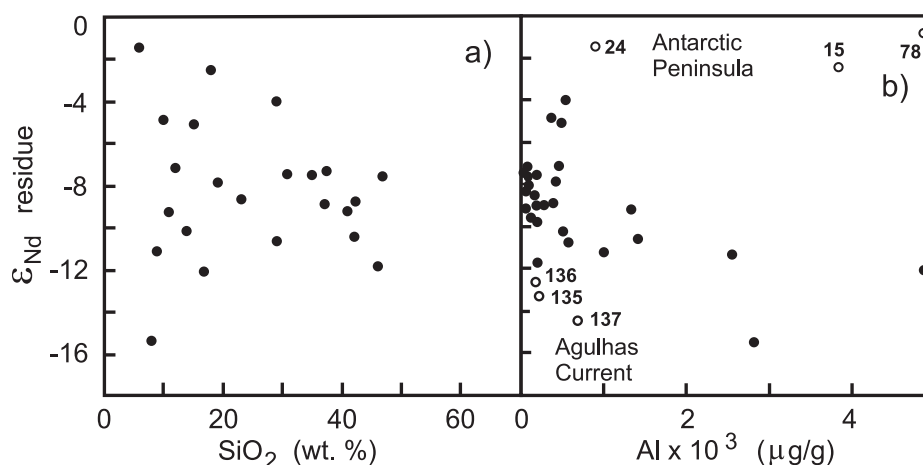


Figure 8. Values of ϵ_{Nd} for residue samples as a function of particle composition. Samples with the most obvious bloom characteristics, e.g., those with high biogenic SiO_2 content (Figure 8a) and low Al content (Figure 8b), show intermediate ϵ_{Nd} values of -7.5 to -10 , rather than extreme Nd isotopic compositions. The samples collected near the Antarctic Peninsula and the Agulhas Current are indicated.

Ocean. The hydrographic and atmospheric circulation regimes will be used as additional constraints. The frontal structure of the ACC is an effective barrier for latitudinal exchange of surface water components whereas atmospheric circulation does allow this transport. Although the general atmospheric circulation in the latitude of the ACC is characterized by the westerlies [Kottmeier and Fay, 1998], it is also known that dust from Patagonia may reach the Antarctic continent via a southeasterly pathway [Basile *et al.*, 1997]. In the case when dust of African origin is transported south, it will also follow a southeasterly route [Piketh *et al.*, 2000]. Dust of African and Australian origin is less likely to be carried as far south, because these territories are located in the subtropical high-pressure belt [Iriando, 2000].

4.1.1. Drake Passage: Signals in the Wake of the Antarctic Peninsula

[26] To the NW of the Antarctic Peninsula, the terrigenous detritus obviously originated from the Antarctic Peninsula and its transport occurred in suspension to the NE along the Weddell-Scotia confluence. The evidence of this terrigenous input decreases rapidly to the east and disappears at $\sim 40^\circ W$. As the frontal structure of the ACC prevents transport of particles to the north, the radiogenic material found in the NE Drake Passage must have been supplied from South America. The data array formed by the ϵ_{Nd} values and Al/Nd ratios in samples collected west of $30^\circ W$ (Figure 9a) suggests that the silicate component in these suspended particles is a mixture of

(1) detritus derived from continental crust containing a large amount of juvenile material (e.g., with $\epsilon_{Nd} > 0$) with (2) much older material with an average ϵ_{Nd} value of -8 to -10 found as dissolved Nd in seawater of the Drake Passage. High ϵ_{Nd} values and high Al/Nd ratios may be assigned to clay-rich detritus from the overall andesitic arcs of South America and the Antarctic Peninsula [Hickey *et al.*, 1986; Hole *et al.*, 1993; Roy *et al.*, 2007]. The older mixing member with low Al/Nd may represent quartz-rich material from evolved granitoid crust possibly transported from the Weddell Sea through the frontal jet of the ACC (see below).

4.1.2. Central South Atlantic Ocean–South Sandwich Islands: Evidence for Dust?

[27] In the central South Atlantic Ocean at 46° – $52^\circ S$, three residue samples and two bulk-particle samples reveal uniform ϵ_{Nd} values of -7.3 to -7.6 over a distance of almost 1,000 km and across oceanic fronts (Figure 7). The Al concentrations of 0.7 to 1.7 nmol/L indicate the presence of moderate amounts of terrigenous detritus. Icebergs from the Antarctic Peninsula could provide material with $\epsilon_{Nd} > -8$, although it is unlikely that they would drift that far north beyond the Polar Front (see below). In addition, iceberg loads would be expected to produce a scattered terrigenous signal. It is also unlikely that coastal erosion, which is thought to be the major pathway of material from South America to sediment deposits in the northern Scotia Sea [Walter *et al.*, 2000], can explain the homogeneous Nd isotopic composition across the oceanic fronts. Alternatively, the homogeneous Nd

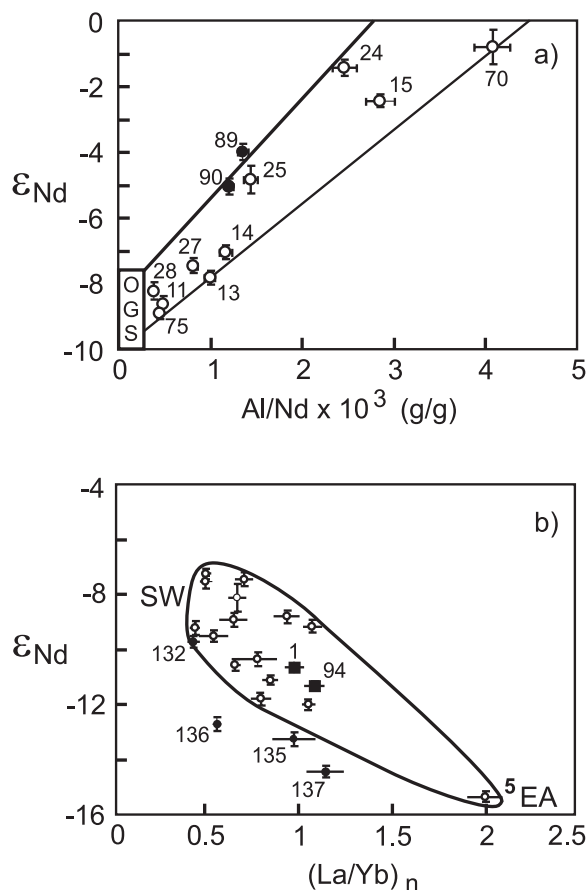


Figure 9. Values of ϵ_{Nd} for particle samples versus Al/Nd- and shale-normalized La/Yb ratios. (a) Values of ϵ_{Nd} versus Al/Nd ratios for samples collected west of $30^\circ W$. The data array suggests mixing of Nd from young South American magmatic arcs with high ϵ_{Nd} values and older granitic crustal sources (OGS) apparently dominating the Nd isotopic composition of seawater. Filled circles represent the samples from South America. (b) Values of ϵ_{Nd} versus shale-normalized La/Yb ratios for particle samples collected east of $30^\circ W$. Samples 135–137 from the Agulhas Current (filled circles) are distinct, while those from near the Polar Front (samples 1 and 94) follow the data trend of samples collected farther to the south. The data array suggests mixing of material with high La/Yb ratios from very old provenances such as East Antarctica (EA) with a seawater-like component (SW) showing a much lower La/Yb ratio and a higher ϵ_{Nd} value.

isotopic pattern could be due to a small amount of dust from Patagonia. As mentioned before, atmospheric circulation transports dust from Patagonia in a southeasterly direction as far as the Antarctic continent. Aeolian input of Patagonian origin in the central South Atlantic Ocean has often been invoked as a source of Fe for this area [Gaiero *et al.*, 2003; Löscher *et al.*, 1997]. It has also been

proposed that a Patagonian source was even more important in the last glacial [Grousset *et al.*, 1992; Kumar *et al.*, 1995; Martin, 1990].

[28] We note that the Nd isotopic signal in the residue samples of the central South Atlantic is similar to that in the leachate samples. This may suggest that the particles from this remote area were in contact for long enough time with the surrounding seawater to be overprinted by its isotopic composition. For the bulk samples 31 and 35 this possibility cannot be evaluated. In the case of the three residue samples 34, 36 and 38 we would need to invoke that the leaching procedure did not efficiently separate the terrigenous component from the coating in these samples. The ϵ_{Nd} values for the surface waters in this region are unknown. Yet, similar values of -7.8 , -8.1 , and -8.1 for the leachate samples suggest a higher ϵ_{Nd} value than measured in seawater of the Drake Passage, a possibility that needs to be further explored.

4.1.3. Southeast Atlantic Ocean: Major Contributions of Unradiogenic Nd From Africa and East Antarctica

[29] In the southeastern Atlantic Ocean, i.e., in the ACC east of $15^\circ W$ and in the central Weddell Sea, very low ϵ_{Nd} values in the residue- and bulk-particle samples indicate detritus from the Archean crust of South Africa and East Antarctica (Figure 7). There is the possibility that the $\epsilon_{Nd} > -10$ in a few samples are due to (atmospheric) sources in South America or the Antarctic Peninsula, yet these source regions cannot account for the unradiogenic Nd in the majority of the residue samples with $\epsilon_{Nd} < -10$. A large contribution of very old crustal detritus from East Antarctica to the eastern Weddell Sea is indicated by ϵ_{Nd} values as low as -15 in combination with high Al concentrations up to 23 nmol/L. These values were measured in sample 5 collected during the austral spring 1997 (Figure 7). An East Antarctic component can be traced in the ACC as far north as the PF where samples yielded ϵ_{Nd} values of -10 to -12 and moderately high Al concentrations up to 7.2 nmol/L. An African origin of the terrigenous detritus is unlikely because this interpretation would require transport of detritus across the Sub Antarctic Front although the Agulhas Current with the African signal retroflects north of the Subtropical Front [Park *et al.*, 2001]. However, there is evidence that cyclones formed near the Agulhas Current may drift in a SW direction [Boebel *et al.*,

2003]. An African source of terrigenous detritus cannot be precluded at the locality of sample 94, where satellite altimetry reveals a positive anomaly in the height of the sea surface. On the other hand, at the locality of sample 1, where satellite altimetry reveals a negative anomaly, a southern origin of the detritus appears more plausible. Furthermore, aeolian input from South Africa into the eastern Weddell Sea appears unlikely due to the prevailing westerly winds [Kottmeier and Fay, 1998] and the southeasterly direction of atmospheric transport [Piketh *et al.*, 2000].

4.1.4. REE Evidence

[30] The supply of terrigenous detritus in the SE Atlantic from different provenances is also supported by the REE concentrations of the bulk-particle samples (Table 1). Involvement of detritus from Archean tonalite-trondjemite-granodiorite (TTG) assemblages with high La/Yb ratios is suggested by the negative correlation between ϵ_{Nd} values and shale-normalized La/Yb ratios (Figure 9b). The diagram suggests that detritus from East Antarctica plots on a different data trend, with a higher ϵ_{Nd} value Nd for a given La/Yb ratio, than detritus from South Africa. If this finding can be substantiated in the future, the ϵ_{Nd} -La/Yb relationship may be helpful to distinguish terrigenous detritus of African and East Antarctic origin. Archean TTG are abundant rock types along the exposed coast of East Antarctica [Liu *et al.*, 2006; Stephenson, 2000; Zhao *et al.*, 1997] whereas similar rocks are not exposed in the southern part of South Africa. Nevertheless, Archean detritus ultimately derived from the Kaapvaal and Zimbabwe cratons control the sedimentary load of the Agulhas Current as indicated by the suspended particles of this study and sediments of the Cape Basin [Rutberg *et al.*, 2005; Franzese *et al.*, 2006].

[31] In Figure 9b, the samples collected in the Agulhas Current (samples 135, 136, 137 with La/Yb of ~ 0.6 to 1.2) plot below a mixing array formed by sample 5 of East Antarctic origin with La/Yb = 2.0 and the composition of seawater with much lower La/Yb and higher ϵ_{Nd} . Our REE data for the African samples are consistent with those from the Agulhas Current which also show overall flat REE patterns [Tachikawa *et al.*, 1999b]. The data in Figure 9b suggest an Antarctic rather than African origin for samples 1 and 94 from near the Polar Front. We suggest that the La/Yb ratio in combination with Nd isotopes in the particle samples may also be useful to trace the origin of old crustal detritus along the coast of East Antarctica.

4.1.5. Icebergs as Potential Vehicles for Terrigenous Detritus

[32] For the interpretation of the remarkably old terrigenous signals in the Weddell Sea we will investigate the role of icebergs and their trajectories as vehicles and pathways, respectively. In addition to accumulated dust, icebergs may also carry ice-rafted detritus (IRD). Icebergs calving from ice shelves (e.g., Dronning Maud Land, Filchner and Larsen ice shelves) lack sediment [Grobe *et al.*, 1993] but in those areas where calving takes place at the coastline (e.g., Enderby Land and on the Antarctic Peninsula) they contain IRD at their base. The distribution of IRD in the sediments from the floor of the Southern Ocean depicts the history of the pathways of sediment-laden icebergs [Diekmann and Kuhn, 1999; Grobe *et al.*, 1993]. At present, icebergs drift as far north as the Polar Front and farther north they undergo rapid melting in the warm surface waters [Keany *et al.*, 1976]. The present pathways of icebergs follow the Weddell Gyre (Figure 7) and coincide with the regions [Reid and Anderson, 1990; Schodlok *et al.*, 2006; Swithinbank *et al.*, 1977; Tchernia and Jeannin, 1983] where we found evidence for large amounts of terrigenous detritus. This observation strongly suggests that icebergs play a significant role in the transport of terrigenous detritus from East Antarctica to the open Southern Ocean. We expect the evidence for terrigenous input by icebergs to occur very patchy as ice-rafted particles comprise all grain sizes, and only the finest fractions will remain sufficiently long in suspension to allow some horizontal homogenization of the terrigenous signal.

4.2. Continental Shelves as Possible Sources of Terrigenous Signals

4.2.1. Southern South America and the Antarctic Peninsula

[33] Continental shelves are important sources of trace elements in the ocean, not only through riverine runoff, but also due to the dissolution and regeneration of particles in shelf and slope sediments. Sources of trace elements on the shelf have been identified by Kremling [1983] and the release of elements from coastal sediments has been determined by Westerlund *et al.* [1986] and Sundby *et al.* [1986]. Release of REE has been inferred from pore water analysis by Haley *et al.* [2004]. The release of Fe was shown by Johnson *et al.* [1999] who suggested that it is related to the resuspension of Fe-enriched particles in the benthic boundary layer.



Indeed, gradients of Fe concentrations in the Weddell Sea [Westerlund and Öhman, 1991] are consistent with its origin in the shelf of the Weddell Sea. It may therefore be postulated that the shelves of southern South America and Antarctica are important sources of dissolved elements as well as Fe for the remote South Atlantic Ocean [De Baar *et al.*, 1995; Löscher *et al.*, 1997].

[34] Previous studies [Amakawa *et al.*, 2000; Jeandel *et al.*, 1998; Lacan and Jeandel, 2001] have shown that Nd isotopes can be used for tracing the exchange of open ocean water masses with the continental shelves and slopes, a mechanism termed “boundary exchange”. This is feasible even in cases when the water masses are advected with currents into the remote ocean [Lacan and Jeandel, 2001]. The Antarctic Peninsula and southern South America are a priori ideal areas to study the efficiency of such a process, because the ϵ_{Nd} values of the shelf sediments are much higher than the seawater value in this region. If water exchange with the shelves and slopes is an important process, we would expect to find elevated ϵ_{Nd} values along the frontal jets. The frequent occurrence of plankton blooms in the wake of the Antarctic Peninsula has given rise to speculations on Fe input by this pathway. From the determination of the Nd isotopic signal in this area we expected a better understanding of the significance of the shelf and slopes as sources. As a matter of fact, the $\epsilon_{\text{Nd}} = -5.6$ in leachate sample 89 could reflect a seawater signature ($\epsilon_{\text{Nd}} = -8$ to -9) overprinted by the more radiogenic Nd ($\epsilon_{\text{Nd}} \sim -2$ to -4) in shelf sediments of the South American coast. However, the large uncertainty of the ϵ_{Nd} value of ± 2.7 ϵ -units, in combination with the limited knowledge of the dynamics and geochemical inventory of this region, are not conclusive and require additional data to support the notion of shelf influence. In contrast, the ϵ_{Nd} values for leachate samples from the Weddell-Scotia confluence apparently do not support the “boundary exchange” model. Their ϵ_{Nd} values including those samples collected close to the Antarctic Peninsula, where the strongest effects of “boundary exchange” would be expected, are indistinguishable from the value for seawater in the Drake Passage. These unexpected/surprising findings suggest that elemental release from the shelves and advective input into the remote South Atlantic Ocean is not an important process for elements like Nd, Al, and Th and, by inference, Fe. However, it also should be kept in mind that the Nd isotopic composition of the surface water in this region is not well known. To date, the Nd isotopic informa-

tion for seawater passing the Drake Passage [Piepgras and Wasserburg, 1982] stems from a sample collected at 50 m depth, 250 km northwest off the Peninsula ($62^{\circ}25\text{W}$, $61^{\circ}02\text{S}$) and two surface water samples analyzed by M Frank (personal communication, 2007). All samples yielded ϵ_{Nd} values of -8 to -9 . In addition, east of the Antarctic Peninsula, thorough mixing of Pacific waters with recirculating waters from the Weddell Gyre along the Weddell-Scotia confluence [Peterson and Stramma, 1991; Whitworth *et al.*, 1994] will likely result in a spectrum of Nd isotopic compositions. Our samples 11, 13, 14, 15, 24 were collected within this mixing zone.

[35] Seawater in the Weddell Gyre receives Nd not only from the Drake Passage inflow, but also from upwelling north Atlantic deep water (NADW) with ϵ_{Nd} of -12 to -13 [Jeandel, 1993], and probably from contact with the East Antarctic shelf. The ϵ_{Nd} values in our leachate samples from the Weddell Gyre are indeed all < -9 and obviously more negative than the Pacific inflow. The Nd isotopic signal of the Weddell Scotia confluence may therefore be a mixture of Nd from the Antarctic Peninsula and less radiogenic Nd from the Weddell Sea. Being aware of the possibility of isotopically heterogeneous surface waters in this type of coastal environment [Amakawa *et al.*, 2000] we conclude that evaluation of the role of the margins in modifying the Nd isotopic signature of the water masses awaits a larger data base than presented here.

[36] One may speculate if Nd is sufficiently reactive to cause the observed isotopic variation in the ACC. An isotopically heterogeneous ACC has previously been documented by Pb and Nd isotopic compositions in circum-Antarctic Mn nodules [Abouchami and Goldstein, 1995; Albarède *et al.*, 1997; Frank, 2002]. Blanckenburg and Igel [1999] explained the Nd isotopic heterogeneity with deep-water Nd residence times as short as 70 a. Isotopically heterogeneous water masses have also been observed in the Denmark Strait overflow [Lacan and Jeandel, 2004] where they were explained with the origin and history of different water masses. The isotopic data of this study extend the earlier findings for isotopically heterogeneous bottom water in the ACC to locally highly heterogeneous surface water, apparently in the vicinity of dissolving very old as well as young terrigenous detritus.

[37] Scavenging residence times in the surface ocean are much shorter than in the deep ocean.

For example for Pb, the residence time in productive surface waters is about 2 a, as opposed to 50–200 a in deep waters [Cochran, 1992]. Amakawa *et al.* [2000] suggested a similar residence time of 1.5 to 2.6 a for Nd in surface waters of the SE Indian Ocean. Thus it is not surprising to find a heterogeneous distribution of dissolved Nd with different ϵ_{Nd} values in the ACC, which is characterized by locally high productivity as well as strong oceanic fronts that prevent latitudinal mixing of water masses.

4.2.2. East Antarctica

[38] Input of terrigenous detritus from the shelves to the interior Weddell Sea can be particularly well investigated with ^{228}Ra . This tracer accumulates above the shelves along the East Antarctic coast and in the eastward flowing coastal current [Rutgers van der Loeff *et al.*, 1995]. However, a study using the sensitive ^{228}Th -ingrowth technique [Hanfland, 2002] has not provided any evidence for significant amounts of ^{228}Ra in the central Weddell Sea. The short half-life of 5.8 a for ^{228}Ra implies that on a timescale of 10 a ($\sim 70\%$ of the original activity will have decayed) there is no significant lateral advective transport of ^{228}Ra , and also other elements, from the shelves into the central Weddell Sea. The lack of shelf signals in the water masses of the central Weddell Sea also precludes significant lateral advective transport of terrigenous detritus in suspension. The material would have to reside in surface waters for more than ~ 10 a, for example longer than the timescale over which ^{228}Ra can trace shelf contact, which is not a realistic assumption. Aggregation in summer, triggered by blooms of variable extent, would always lead to a rapid removal of terrigenous detritus from surface waters.

5. Conclusions

[39] The first Nd isotopic composition of suspended particles from the South Atlantic Sector of the Southern Ocean combined with hydrographic data delineate Patagonia, the Antarctic Peninsula, South Africa, and East Antarctica as major provenances for terrigenous detritus.

[40] In the western study area the Nd isotopic signature of the Antarctic Peninsula disappears in the ACC at $\sim 40^\circ\text{W}$. The Nd isotopic composition of the leachate samples from south and northeast of the Drake Passage agree with the seawater values for the Drake Passage. A quantification of the Nd

exchange between the Antarctic Peninsula and its shelf with waters entering the Drake Passage awaits a comprehensive analysis of the distribution of ϵ_{Nd} in the dissolved phase.

[41] In the eastern study area, very old terrigenous detritus in samples collected to the south of the Polar Front can be assigned to sources in East Antarctica. The presence of old terrigenous detritus to the north of the Polar Front was probably transported by the Agulhas Current, an inference which is supported by the sediment data of Rutberg *et al.* [2005] and Franzese *et al.* [2006].

[42] REE patterns (e.g., La/Yb ratios) suggest differences between South African and East Antarctic detritus and may represent a potential tool to delineate provenances.

[43] The distribution of ϵ_{Nd} values in the residue samples from the eastern Weddell Sea and the adjacent ACC is consistent with icebergs as vehicle of East Antarctic detritus.

Acknowledgments

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