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Neodymium isotopic characterization of Ross Sea Bottom Water and its advection through the southern South Pacific

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A B S T R A C T

Since the inception of the international GEOTRACES program, studies investigating the distribution of trace elements and their isotopes in the global ocean have significantly increased. In spite of this large-scale effort, the distribution of neodymium isotopes ($^{143}Nd/^{144}Nd$, ε_{Nd}) and concentrations ([Nd]) in the high latitude South Pacific is still understudied, specifically north of the Antarctic Polar Front (APF). Here we report dissolved Nd isotopes and concentrations from 11 vertical water column profiles from the South Pacific between South America and New Zealand and across the Antarctic frontal system. Results confirm that Ross Sea Bottom Water (RSBW) is represented by an ε_{Nd} value of ~ -7, and for the first time show that these Nd characteristics can be traced into the Southeast Pacific until progressive mixing with ambient Lower Circumpolar Deep Water (LCDW) dilutes this signal north of the APF. That is, ε_{Nd} behaves conservatively in RSBW, opening a path for studies of past RSBW behavior.

Neodymium concentrations show low surface concentrations and a linear increase with depth north of the APF. South of the APF, surface [Nd] is high and increases with depth but remains almost constant below $\sim$1000 m. This vertical and spatial [Nd] pattern follows the southward shoaling density surfaces of the Southern Ocean and hence suggests supply of Nd to the upper ocean through upwelling of Nd-rich deep water. Low particle abundance due to reduced opal production and seasonal sea ice cover likely contributes to the maintenance of the high upper ocean [Nd] south of the APF. This suggests a dominant lateral transport component on [Nd] and a reduced vertical control on Nd concentrations in the South Pacific south of the APF.

1. Introduction

Preferential retention of Sm vs. Nd within the mantle creates different initial Sm/Nd ratios between mantle derived rocks and continental crustal material. Since ^{147}Sm decays to produce ^{143}Nd (at a very slow rate), rocks with different petrogenetic history develop characteristic $^{143}Nd/^{144}Nd$ ratios ($^{143}Nd/^{144}Nd$ expressed as $\varepsilon_{Nd} = [(^{143}Nd/^{144}Nd)_{measured}/(^{143}Nd/^{144}Nd)_{CHUR}] - 1 * 10^4$; CHUR = Chondritic Uniform Reservoir with $^{143}Nd/^{144}Nd$ = 0.512638, Jacobsen and Wasserburg, 1980). The heterogeneous $^{143}Nd/^{144}Nd$ distribution in rocks reaches the oceans via mechanical and chemical weathering of continental rocks and subsequent transport of the particulate and dissolved material by rivers, chemical exchange between continental margins and seawater (i.e., boundary exchange), and dust input (Frank, 2002; Goldstein and Hemming, 2003; Lacan and Jeandel, 2001, 2005; Rickli et al., 2009). Once a water mass is tagged with the characteristic ε_{Nd} signatures of its formation region, Nd isotopes can be used as a water mass tracer due to the intermediate average residence time of Nd between 300 and 1000 years in the ocean (Tachikawa et al., 2003; Arsouze et al., 2009; Rempfer et al., 2011), which is shorter than the whole ocean mixing time of $\sim$1500 years (Broecker and Peng, 1982). While Nd isotopes are considered a quasi-conservative water mass tracer in the open ocean, water masses close to continental margins can be overprinted by interactions between seawater and continental sediments, either through partial dissolution of particles or a mechanism known as 'boundary exchange' (Lacan and Jeandel, 2001, 2005).

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In the modern ocean, North Atlantic Deep Water (NADW, $\varepsilon_{Nd} = -13.5$; Piepgras and Wasserburg, 1987) and North Pacific Deep Water (NPDW, $\varepsilon_{Nd} = -4$ to -6; Piepgras and Jacobsen, 1988; Amakawa et al., 2009) represent the two major deep water ε_{Nd} endmembers, which is a consequence of weathering inputs from older cratonic rocks in the North Atlantic and young volcanic rocks in the North Pacific. Simple mixing of these waters in the Southern Ocean are thought to dominantly determine the isotopic composition of Circumpolar Deep Water (CDW) with an intermediate ε_{Nd} value of -8 to -9 (Goldstein and Hemming, 2003; Stichel et al., 2012; Garcia-Solsona et al., 2014) but weathering contributions from Antarctica to the Southern Ocean ε_{Nd} have also recently been reported to play some role (Carter et al., 2012; Stichel et al., 2012; Rickli et al., 2014). In contrast to the Nd isotope distributions in the ocean, which appear to be dominated by advection and mixing of water masses, Nd concentrations generally show a nutrient-like behavior with increasing [Nd] with water depth, indicating a dominant vertical control (Elderfield and Greaves, 1982).

The circulation of the Southern Ocean is dominated by the westerly wind driven eastward moving Antarctic Circumpolar Current (ACC), which reaches abyssal depths and connects all major ocean basins (Talley et al., 2011 and references therein). The Southern Ocean is further characterized by the circum-Antarctic frontal system, which consists of the upward shoaling of density surfaces towards the south that create bands of steep meridional hydrographic gradients at the surface (Nowlin et al., 1977; Orsi et al., 1999). The South Pacific, which represents the largest sector of the Southern Ocean, hosts areas of major intermediate and bottom water formation (Tsuchiya and Talley, 1996; Orsi and Wiederwohl, 2009), thus making it a key area for better understanding present and past deep ocean circulation. The latitudinal location of the Pacific Subantarctic Front (SAF) reaches its southernmost position in the eastern South Pacific (Orsi et al., 1995; Talley et al., 2011). South of the SAF, the APF is represented by a strong eastward flow and upwelling of deep waters south of it. Similar to the rest of the Southern Ocean, these frontal systems in the South Pacific are associated with steep meridional gradients in surface hydrographic properties and upwelling of deep waters south of the APF. Very little is known about the behavior of dissolved Nd isotopes and concentrations in the South Pacific and their distribution in relation to the Antarctic fronts.

Over the last few years, the international GEOTRACES program has generated high-resolution data for many ocean basins to improve our understanding of the "biogeochemical cycles and large-scale distributions of trace elements and their isotopes in the marine environment" (Henderson et al., 2007). Only a limited number of dissolved Nd isotope data is available from the South Pacific sector of the Southern Ocean; these are located around the southern boundary of the ACC and one station immediately north of the APF (Carter et al., 2012; Rickli et al., 2014), leaving data gaps across the high latitude South Pacific that have so far prevented a comprehensive understanding of the ε_{Nd} and [Nd] behavior in this region. Carter et al. (2012) reported that Nd isotopes in the middle of the water column behave conservatively at open ocean stations. Closer to the Antarctic continent, CDW signatures are modified to more radiogenic values due to exchange with the margins (Carter et al., 2012). The same mechanism was inferred for the isotopic signature of Antarctic Bottom Water (AABW) formed in the Ross Sea (Rickli et al., 2014). At depth, AABW actively forms along the Antarctic shelf in the Weddell Sea, Ross Sea, Adélie Coast, and Prydz Bay (Orsi et al., 1999). Continental Antarctica consists of diverse types of bedrock of different ages with a wide range of ε_{Nd} values (Roy et al., 2007), which can be hypothesized to tag the deep water formed in different regions with different ε_{Nd} signatures. The study presented here adds new dissolved Nd isotope data to test whether the RSBW ε_{Nd} signature in the Ross Sea can be traced along the flow path of RSBW into the Southeast Pacific.

Here we report dissolved Nd isotope and Nd concentrations from 11 vertical profiles from across the South Pacific between South America and New Zealand and between 46° S and 69° S (Fig. 1). The samples cover different water masses (Fig. 2) east and west of the Pacific-Antarctic Ridge and across the circum-Antarctic fronts, allowing insight into mixing processes of different water masses and their origins. The [Nd] distribution across the circum-Antarctic frontal system is interpreted in the context of deep-water upwelling and productivity. The Nd isotope distribution enables the tracing of AABW formed in the Ross Sea into the Southeast Pacific.

2. General hydrography

Volumetrically speaking, the most important water mass of the deep ACC is CDW. Deep waters of North Atlantic (NADW), North Pacific (NPDW), and Indian Ocean (Indian Ocean Deep Water (IDW)) origin enter the Southern Ocean and mix to form the main body of the CDW (Talley et al., 2011). It can be subdivided into the oxygen-depleted and nutrient-rich Upper CDW (UCDW) and the more saline Lower CDW (LCDW) (Reid and Lynn, 1971; Orsi et al., 1995; Talley et al., 2011). The UCDW, which acquires its oxygen minimum from IDW and NPDW, is defined by a density range of 27.55 $kg/m^3 < \gamma^n < 28$ kg/m^3. The oxygen minimum of UCDW is most prominent at 1500 m water depth immediately north of the SAF (Talley et al., 2011). The LCDW is defined by a neutral density range of 28.00 $kg/m^3 < \gamma^n < 28.27$ kg/m^3 and a salinity maximum that is inherited from NADW (Reid and Lynn, 1971; Reid, 1994; Orsi et al., 1995; Whitworth et al., 1998). Lower CDW occupies the deep South Pacific north of the SAF and progressively shoals to 700–400 m water depth in the Antarctic Zone (AZ) south of the APF (Talley et al., 2011). At several locations, the upwelled LCDW reaches Antarctic continental shelves, mixes with dense shelf waters and sinks to the abyss, forming AABW (Foster and Carmack, 1976; Jacobs et al., 1970; Orsi et al., 1999). North of the SAF, Antarctic Intermediate Water (AAIW; 27.13 $kg/m^3 < \gamma^n < 27.55$ kg/m^3) found between 500–1500 m water depth within the eastern South Pacific is characterized by low salinity and a high oxygen content (Talley, 1996; Whitworth and Nowlin, 1987). North Pacific Deep Water (NPDW), unlike NADW, is composed of recycled deep water from the Southern Hemisphere. The NPDW flows south at 1500–3500 m water depth as a low-oxygen water mass and enters the South Pacific between the East Pacific Rise and South America (Kawabe and Fujio, 2010; Molina-Kescher et al., 2014).

The Ross Sea is one of the major sites of AABW formation (Orsi and Wiederwohl, 2009). Sea-ice production and associated brine rejection transforms the near freezing Antarctic Surface Water into dense Shelf Water, which continuously interacts with the overlying modified CDW to produce dense transitional waters known as Modified Shelf Water (MSW). Once this highly dense MSW has sunk into the adjacent Antarctic basins, it is generally recognized as AABW (Orsi et al., 1999; Orsi and Wiederwohl, 2009). The AABW formed in the Ross Sea (Ross Sea Bottom Water, RSBW) is the coldest ($-0.3°$ to 0 °C) and saltiest (34.7–34.72) bottom water in the Southern Ocean with a neutral density >28.27 kg/m^3 (Jacobs et al., 1970; Orsi and Wiederwohl, 2009). Through mixing with overlying LCDW, the hydrographic properties of AABW are quickly eroded along its northward flow path.

3. Materials and methods

South Pacific seawater samples were collected during expedition ANT-XXVI/2 (November 2009–January, 2010) aboard *F/S Po-*