Radiogenic isotope fingerprint of Wilkes Land–Adélie Coast Bottom Water in the circum-Antarctic Ocean

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1 Wilkes Land–Adélie Coast Bottom Water encompasses the bottom waters formed around the coast of East Antarctica in the area east of Prydz Bay and west of the Ross Sea (90°E–150°E). Here we show that these bottom waters have not only characteristic physical properties, but also carry a distinct radiogenic isotope signal that traces their dispersal. The Nd, Hf and Pb isotopic compositions of Circum-Antarctic ferromanganese nodules record the isotopic composition of ambient seawater. Those with the lowest Nd and Hf isotopic ratios and the highest Pb isotopic ratios are from the deep Australian-Antarctic Basin, and they fingerprint Wilkes Land–Adélie Coast Bottom Water. The data illustrate the potential value of these isotope systems as tracers of present and past deep and bottom waters in the Circum-Antarctic realm and elsewhere.


1. Introduction

The Southern Ocean plays a crucial role in the present-day global ocean current system. The connection among the major ocean basins provided by the Antarctic Circumpolar Current (ACC) not only permits efficient global water-mass exchange, but also dominates transport of heat, fresh water, and other properties that influence climate. Furthermore, it is the Southern Ocean where the densest waters in the global thermohaline circulation system are formed. Its estimated production rate of 8–21 Sv is equal to, or even greater than, the production of North Atlantic Deep Water (NADW: 13–18 Sv; 1Sv = 10⁶ m³s⁻¹ [e.g., Broecker et al., 1998; Orsi et al., 1999; Ganachaud and Wunsch, 2000; Jacobs, 2004]). While most monitoring studies have been focused on the Weddell Sea, it has become increasingly clear that bottom water is formed at many sites around Antarctica, including the Weddell Sea, the Enderby Land–Amery Shelf - Prydz Bay area, the Wilkes Land–Adélie Coast area, and the Ross Sea (see Figure 1 and recent summaries by Orsi et al. [1999], Rintoul et al. [2001], and Jacobs [2004]). Bottom waters formed around Antarctica, together with (well-characterized) NADW, are exported to the global ocean, and hence their composition is of major interest for understanding global deep water circulation patterns.

2. Radiogenic Isotope Fingerprint of Southern Ocean Water Masses

In the absence of radiogenic isotope tracer information of Southern Ocean seawater (with the exception of the Drake Passage [Piepgrass and Wasserburg, 1982]), ferromanganese nodules have been shown to be very useful and reliable recorders of ambient seawater signals, for Nd, Hf, and Pb isotopes [Frank, 2002]. These isotope systems may have slightly different sources and cycling behavior in the ocean, but share the characteristic that newly formed water masses carry a distinct signature [Frank, 2002; Goldstein and Hemming, 2003, and references therein]. This signature predominantly originates from weathering and erosion of continental material (Nd and Hf [e.g., van de Flierdt et al., 2004]), but Pb may also involve significant hydrothermal inputs [e.g., Vlastélic et al., 2001]. Another important difference between the globally coupled Nd and Hf isotope signal in seawater [Albarède et al., 1998] and dissolved Pb, is the shorter residence time of Pb in seawater (50–200 yrs) compared with Nd and Hf (500–2000 yrs) [Frank, 2002; Goldstein and Hemming, 2003, and references therein].

Previous studies on surface scrapings of ferromanganese nodules from the Southern Ocean for their Nd and Pb isotopic compositions revealed a strong geographic control on the seawater signal, suggesting a strong imprint of NADW on the eastern Atlantic and Indian Ocean sectors of the Southern Ocean [Abouchami and Goldstein, 1995; Albarède et al., 1997]. Reinvestigation of some of the nodules led Vlastélic et al. [2001] to suggest a Ross Sea or Weddell Sea bottom water influence in the Indian Ocean sector. Here we report new Hf isotope data on many of the same circum-Antarctic nodules. In the context of the new data we argue that a large fraction of the bottom seawater signal in the Indian Ocean sector of the Southern Ocean is derived from local bottom water sources around the Wilkes Land–Adélie Coast area.

3. Methods and Samples

To characterize the Hf isotopic composition of deep and bottom waters in the Southern Ocean, we analyzed 26 surface scrapings from ferromanganese nodules (Table S1) previously characterized for their Pb and Nd isotopic compositions by Abouchami and Goldstein [1995] and Albarède et al. [1997]. Most samples are located north of...
65°S and south of 49°S within the eastward flowing ACC (Figure 1) and at depths below 3000 m. 50–100 mg of powdered nodule material was leached for 15 minutes in a mixture of 6 M HCl and trace HF and the separation of Hf was carried out with a fluorite precipitation step followed by anion and Ln Spec ion exchange chromatography [e.g., van de Flierdt et al., 2004]. All samples were analyzed on the Axiom MC-ICP-MS at Lamont and details are in the electronic supplement.1

4. Results

A striking observation is that the overall variation of authigenic Hf isotopes in the Southern Ocean ferromanganese nodules is small (Figures 2 and 3 and Table S1). The mean Hf isotopic composition of the 26 samples is ε\textsubscript{Hf} = 4.2 ± 1.4 (2σ) (Table S1 and Figures 2 and 3). Nodule IO-TC1578-14A from the NE corner of the Weddell Sea (Table S1 and Figure 1) is not included in this average value, because its ε\textsubscript{Hf} of −12.1 together with its unradiogenic ε\textsubscript{Nd} of −11.3 [Albarède and Goldstein, 1997] defines a position in Nd-Hf isotope space that indicates a detrital rather than an authigenic origin (Figure 2). We therefore eliminate this sample from further discussion. For the rest of the data the average seawater Hf isotopic composition in the Indian sector (30°E to 149°E; ε\textsubscript{Hf} = 3.5) is slightly lower than the Atlantic (67°W to 30°E; ε\textsubscript{Hf} = 4.5) and Pacific (149°E to 67°W; ε\textsubscript{Hf} = 4.4) sectors (Figures 2 and 3). The five Indian sector nodules with the lowest ε\textsubscript{Hf} values are derived from the Antarctic-Antarctic Basin, and these also show elevated 206\textsuperscript{Pb}/204\textsuperscript{Pb}, 207\textsuperscript{Pb}/204\textsuperscript{Pb}, and 208\textsuperscript{Pb}/204\textsuperscript{Pb} ratios [Abouchami and Goldstein, 1995] (Figure 3). Three out of these 5 nodules exhibit some of the lowest ε\textsubscript{Nd} values (ε\textsubscript{Nd} = −8.8 to −9.3 [Albarède et al., 1997]) and the highest 206\textsuperscript{Pb}/204\textsuperscript{Pb} ratios (206\textsuperscript{Pb}/204\textsuperscript{Pb} = 39.32 to 39.40 [Abouchami and Goldstein, 1995; Vlastelíc et al., 2001]) observed in the Southern Ocean (Figures 2 and 3). These three nodules grew from bottom waters which have present day temperatures below 0°C (Figure 4).

5. Bottom Water Sources Around East Antarctica

[7] Physical and chemical properties of bottom waters around East Antarctica suggest the existence of multiple source areas beyond the Weddell Sea and the Ross Sea [e.g., Orsi et al., 1999; Rintoul et al., 2001; Jacobs, 2004]. Due to strong topographic control on pathways, most newly formed bottom waters are restricted to individual basins. For example, Weddell Sea Bottom Water (WSBW) is restricted to the Weddell-Enderby Basin west of 20°E and is only recorded by nodule IO-PC1277-14 (ε\textsubscript{Hf} = 4.5, ε\textsubscript{Nd} = −7.9; Table S1 and Figure 4). Weddell Sea Deep Water (WSDW), on the other hand, which is recorded by nodule IO-TC1277-36 (ε\textsubscript{Hf} = 4.2, ε\textsubscript{Nd} = −8.8; Table S1 and Figure 4) is exported to the north and to the east, but does not enter the Antarctic-Antarctic Basin directly, since there is a pronounced westward flow of waters south of the Kerguelen Plateau (Figure 1) [Rintoul, 1998]. The westward flowing part of Ross Sea Bottom Water (RSBW) is recorded by nodules TC42-6 and E38-8; ε\textsubscript{Hf} = 3.9 to 3.9, ε\textsubscript{Nd} = −7.2 to −7.9; Table S1 and Figure 4) enters the eastern part of the Antarctic (67°W to 30°E; ε\textsubscript{Hf} = 4.5) and Pacific (149°E to 67°W; ε\textsubscript{Hf} = 4.4) sectors (Figures 2 and 3). The five Indian sector nodules with the lowest ε\textsubscript{Hf} values are derived from the Antarctic-Antarctic Basin, and these also show elevated 206\textsuperscript{Pb}/204\textsuperscript{Pb}, 207\textsuperscript{Pb}/204\textsuperscript{Pb}, and 208\textsuperscript{Pb}/204\textsuperscript{Pb} ratios [Abouchami and Goldstein, 1995] (Figure 3). Three out of these 5 nodules exhibit some of the lowest ε\textsubscript{Nd} values (ε\textsubscript{Nd} = −8.8 to −9.3 [Albarède et al., 1997]) and the highest 206\textsuperscript{Pb}/204\textsuperscript{Pb} ratios (206\textsuperscript{Pb}/204\textsuperscript{Pb} = 39.32 to 39.40 [Abouchami and Goldstein, 1995; Vlastelíc et al., 2001]) observed in the Southern Ocean (Figures 2 and 3). These three nodules grew from bottom waters which have present day temperatures below 0°C (Figure 4).

of the Australian-Antarctic Basin but is overprinted west of 143°E.

Large parts of the Australian-Antarctic Basin are filled with Adélie Land Bottom Water, a water mass with lower salinity, higher oxygen content, and lower potential temperature compared to RSBW. This water mass is thought to form predominantly in the Adélie depression between 142.5°E and 145.5°E [Rintoul, 1998, and references therein]. Bottom water at the location of four out of the five nodules from the Australian-Antarctic Basin has a temperature of less than 0.3°C (Figure 4), and the three nodules with the lowest Nd and Hf isotopic compositions and the highest Pb isotope ratios (E-PhC 54-1, E-PhC 54-3, and E-TC 45-42; Table S1) are derived from waters below 3950 m with temperatures less than 0°C (LEVITUS and WOA01 databases), consistent with Adélie Land Bottom Water. However, we label this water mass here as Wilkes Land–Adélie Coast Bottom Water, as the entire shelf between these two locations on East Antarctica may be its source region. The notion of a local water mass filling the abyssal part of the Australian-Antarctic Basin is also supported by high CFC contents [Orsi et al., 1999], as well as by provenance studies suggesting rapid dispersal of Antarctic-derived marine sediment to the Australian-Antarctic Basin by bottom waters below 3500 m [e.g., Dezileau et al., 2000].

6. Previous Interpretations of the Nd-Pb Isotope Signal in the Australian-Antarctic Basin

[8] Abouchami and Goldstein [1995] and Albarède et al. [1997] inferred inflow of NADW to the Southern Ocean as a source for lower Nd and higher Pb isotope signal in the Indian sector, and this would be consistent with the slightly lower Hf isotope ratios. It was noted by Vlastélic et al. [2001] however that for Pb the NADW signal can be traced to the eastern Atlantic sector but not further east in the Indian Ocean. Indeed, when NADW intrudes the northern rim of the ACC, the salinity maximum associated with it gradually fades eastward and shoals southward [e.g., Orsi et al., 1999]. It is intriguing that the water depths of the samples with the least radiogenic Nd and Hf isotope ratios, as well as the most radiogenic Pb isotopes (Table S1 and Figures 2 and 3) are between 3950 and 4620 m, and therefore much deeper than the entrainment level of NADW at 2500 to 3000 m. Furthermore, these samples are found far to the east of the Atlantic sector, in the Australian-Antarctic Basin in the Indian Ocean sector (Figure 1).

[10] Vlastélic et al. [2001] therefore concluded that the radiogenic Pb isotope signal in the Indian Ocean sector must be derived from Antarctica and suggested WSBW and RSBW as sources. This is however an unlikely explanation as these water masses do not enter the central and western part of the Australian-Antarctic Basin, as outlined above. Instead the signal is much more simply attributable to Wilkes Land - Adélie Coast Bottom Water.

7. New Interpretation of the Nd-Hf-Pb Isotope Signal in the Australian-Antarctic Basin

[11] All Southern Ocean nodules fall on the global “seawater array” between the Atlantic and Pacific end-members. Thus a simple mixture of Atlantic and Pacific sources can explain a large portion of the overall Nd-Hf and Pb isotopic variability in the Southern Ocean (Abouchami and Goldstein [1995], Albarède et al. [1997], and this study). However, such a mixture fails to explain the geographical detail of the data in the Indian Ocean sector, calling for a local source affecting the radiogenic isotope signature of bottom waters. Here we suggest that the slight offset of the data in the Australian-Antarctic Basin compared to the rest of the Southern Ocean data is due to local inputs from glacially weathered old continental crust.

[12] Indeed, large parts of East Antarctica are characterized by old basement ages as evidenced from a survey of the

Figure 3. 208Pb/204Pb ratios versus Hf isotopic compositions of Circum-Antarctic ferromanganese nodules. Lead data are from Abouchami and Goldstein [1995]. Symbols are the same as in Figure 2.

Figure 4. Nd isotope data set for all surface scraping of ferromanganese nodules from the Southern Ocean south of 49°S and below 2500 m water depth (Albarède et al. [1997], Frank et al. [2002], and this study) versus temperature of the water mass the nodules grew in (WOA01 database). All groupings are primarily based on the physical properties of the water masses the samples were recovered from. Symbols are the same as in Figure 2.
Nd and Hf isotopic compositions of the detrital fraction of marine core top sediments in direct proximity to Antarctica. Erosional products from Dronning Maud Land, Prydz Bay, and Wilkes Land display a very unradiogenic Nd and Hf isotopic composition (εNd = −11 to −23, εHf = −5 to −30) in contrast to the more radiogenic Nd and Hf isotope composition (εNd = +1 to −5, εHf = +4 to −5) found around West Antarctica. Core top sediments from the Ross and Weddell Seas show intermediate values (εNd = −3 to −9, εHf = −3 to −8; sediment results: unpublished data from M. Roy and T. van de Flierdt, 2004).

8. Potential Mechanisms for the Acquisition of the Radiogenic Isotope Fingerprint of Wilkes Land–Adélie Coast Bottom Water

[13] Sanudo-Wilhelmy et al. [2002] investigated the importance of coastal sources for dissolved trace metal levels in the Weddell Sea and attributed elevated coastal concentrations to benthic remobilization, including particle resuspension and diffusive fluxes, and continental weathering, including shelf ice erosion. Taking the sum of these processes, we may explain the observed Nd-Hf-Pb isotope signal of Wilkes Land - Adélie Coast Bottom Water.

[14] The low Hf isotope signature of Wilkes Land - Adélie Coast bottom water, compared to WSBW, RSBW and Circumpolar Deep Water (CDW), may be explained by a weathering signal derived from the old continental crust of East Antarctica, which gets imprinted on local bottom waters. It has been suggested by van de Flierdt et al. [2002] that glacial grinding of old zircons has the potential to release an unradiogenic Hf isotope signal to the ocean. In addition to destruction of zircons, enhanced alteration of other less resistant unradiogenic phases such as biotites or K-feldspars could also contribute to lowering the seawater Hf isotopic composition [Bayon et al., 2006]. Incongruent weathering on the Antarctic continent may also play an important role in creating the radiogenic Pb isotope signal in the Southern Ocean from 0º to 149ºE [Vlastèlic et al., 2001]. Weathering of fresh granitic rock initially releases radiogenic Pb consistent with a correlation of Pb isotope ratios with water depth in the Indian Ocean sector of the Southern Ocean [Vlastèlic et al., 2001].

[15] In contrast, the Nd isotopic composition of seawater more directly reflects the bulk composition of continental sources. Along the perimeter of East Antarctica the continental Nd isotope signal is likely to assert some influence on the seawater signal through exchange of Nd along the margin with newly forming bottom waters [e.g., Lacan and Jeandel, 2005]. Figure 4 includes all available authigenic Nd isotope data south of 49ºS and below 2500 m water depth (Albarède et al. [1997]; Frank et al. [2002], and this study), and nicely illustrates that the main controls on the Nd isotopic composition of the Southern Ocean are geography and water depth. The lowest values are found in bottom waters of the Indian and Atlantic sectors of the Southern Ocean where the formation regions are characterized by old continental rocks (Enderby Land, Prydz Bay, Wilkes Land, Adélie Coast). In comparison to Wilkes Land–Adélie Coast Bottom Water, WSBW and RSBW appear to have a slightly more radiogenic Nd isotope signature, overlapping with CDW. CDW becomes predominant above ~3700 m, and has a much more variable isotopic composition due to entrainment of NADW, return flow of Indian and Pacific deep waters, and mixing with regional bottom waters and overlying subsurface water masses.

9. Conclusions

[16] Water mass characteristics in the deep Australian-Antarctic Basin indicate a strong bottom water source in the region of Adélie Coast and Wilkes Land. By combining new and previously published results on surface scrapings of authigenic ferromanganese nodules from the Southern Ocean, we show that bottom waters in the Australian-Antarctic basin have the lowest Hf and Nd isotopic compositions and the highest Pb isotopic compositions yet observed in the Southern Ocean. We suggest that this signature is the distinct radiogenic isotope fingerprint of Wilkes Land–Adélie Coast Bottom Water, a water mass formed in vicinity to the old, glacially weathered continental crust of East Antarctica.

[17] In contrast to physical water mass properties, a radiogenic isotope signature can be traced back in time. Thus, one important implication of our finding is that, given the availability of suitable archives, radiogenic isotopes can provide valuable insights into formation and spreading of Antarctic Bottom Waters in the past ocean.

References


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