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Antarctic Intermediate Water penetration into the Northern Indian Ocean during the last deglaciation

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ABSTRACT

The two-stage increase in atmospheric carbon dioxide (CO_2), and the associated decrease in radiocarbon (^{14}C) during the last deglaciation, are thought to have been linked to enhanced Southern Ocean upwelling and the rapid release of sequestered ^{14}C-depleted CO_2. Antarctic Intermediate Water (AAIW), originating from the Southern Ocean, reflects variations in the Southern Ocean and, crucially, mirrors the chemical signature of upwelling deep water. However, the penetration of AAIW into the Northern Indian Ocean and its relationship with deglacial climate changes have not been thoroughly elucidated to date. Here, we present the neodymium isotopic composition (ε_{Nd}) of mixed planktonic foraminifera from core MD77-176 from an intermediate depth in the Northern Indian Ocean to reconstruct the past evolution of intermediate water during deglaciation. The ε_{Nd} record in the Northern Indian Ocean displays two pulse-like shifts towards more radiogenic Southern Ocean values during the deglaciation, and these shifts coincide with excursions in $\Delta^{14}C$ and ε_{Nd} records in the Pacific and Atlantic Oceans. These results suggest invasion of AAIW into the Northern Hemisphere oceans associated with enhanced Southern Ocean ventilation during deglaciation. Our new ε_{Nd} record strongly supports the close linkage of AAIW propagation and atmospheric CO_2 rise through Southern Ocean ventilation during deglaciation.

1. Introduction

During deglaciation (~18–10 kyr BP), atmospheric carbon dioxide (CO_2) increased from 180 to 265 parts per million (ppm); meanwhile, its radiocarbon content (^{14}C) decreased by ~35‰. These changes occurred in two steps during the periods ~18 to 14.7 kyr BP and ~12.8 to 11.7 kyr BP (Monnin and Barnola, 2001). A mechanism of enhanced Southern Ocean ventilation and release of excess ^{14}C-depleted CO_2 by upwelled deep water has been invoked to explain this extraordinary phenomenon (Anderson et al., 2009; Bryan et al., 2010; Marchitto et al., 2007; Skinner et al., 2014). This explanation is based on the fact that the deep ocean is the largest and relatively most ^{14}C-depleted carbon reservoir that can interact with the atmosphere on a millennial timescale (Sigman and Boyle, 2000). However, the specific processes involved in Southern Ocean ventilation and/or atmospheric CO_2 leakage during the deglaciation remain unclear (Anderson et al., 2009; Burke and Robinson, 2012; Jaccard et al., 2016; Skinner et al., 2014). More evidence is needed to clarify the role of Southern Ocean variations and their influence on global thermohaline circulation. The formation and advection of AAIW, which is highly sensitive to the perturbation of the Southern Ocean and westerly wind stress (Ribbe, 2001), is therefore key for understanding the deglacial variations in the Southern Ocean. The propagation of Antarctic Intermediate Water (AAIW) is also important for regulating heat and freshwater distribution, and for ventilation associated with intermediate thermohaline circulation of the ocean (Lynch-Stieglitz et al., 1994; Ribbe, 2001).

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A reconstruction of intermediate water $\Delta^{14}C$ values near Baja California in the Pacific Ocean shows two oscillations associated with old ^{14}C-depleted waters during Heinrich Stadial 1 (HS1) and the Younger Dryas (YD), consistent with the timing of atmospheric CO_2 rise during the deglaciation (Marchitto et al., 2007). These observations have also been confirmed by the Nd isotopic compositions (reported as ε_{Nd}) of fish teeth/debris from the same core, which indicated a shift in the ε_{Nd} values towards Southern Ocean values at the beginning of the deglaciation (Basak et al., 2010). Both studies suggest that this intermediate water observed near Baja California was sourced from the Southern Ocean, and was advected to the Northern Pacific Ocean via AAIW (Basak et al., 2010; Marchitto et al., 2007). Direct evidence of strong Southern Ocean upwelling has been reported based on ^{14}C (Skinner et al., 2010) and opal flux records (Anderson et al., 2009) in the Southern Ocean during the deglaciation, and the existence of strong upwelling also suggests strong production and advection of the AAIW at this time. In contrast, a $\Delta^{14}C$ reconstruction of the AAIW signature off the coast of Chile showed no impact of old abyssal carbon during deglaciation (De Pol-Holz et al., 2010). Furthermore, a modelling study was also not able to achieve the observed mid-depth ^{14}C anomalies, even with a totally ^{14}C-free deep reservoir (Hain et al., 2011), suggesting that the linkage between Southern Ocean overturning and ^{14}C-depleted AAIW penetration is complicated.

If Southern Ocean ventilation was accompanied by strong northward invasion of the AAIW during the deglaciation, the specific $\Delta^{14}C$ and ε_{Nd} signal should also be observed in intermediate-depth cores from other oceans. However, while such a possible invasion of AAIW during the deglaciation has been fully discussed in the Atlantic (Cao et al., 2005; Mangini et al., 2010; Pahnke et al., 2008), it is poorly established in the Indian Ocean. The only $\Delta^{14}C$ study from the northern Arabian Sea suggested that ^{14}C-depleted carbon from the deep Southern Ocean could have greatly influenced the intermediate water in the Arabian Sea during deglaciation (Bryan et al., 2010). However, there is a possibility that the $\Delta^{14}C$ record is contaminated with other upwelling ^{14}C-depleted water, such as local deep water and/or North Indian Intermediate Water (Basak et al., 2010; Bryan et al., 2010). In contrast, foraminiferal ε_{Nd} values have been widely used as a quasi-conservative tracer for past deep oceanic circulation (Frank, 2002; Piotrowski et al., 2012). Dissolved Nd in the ocean is characterized by a short residence time (from 360 to 700 yr) (Frank, 2002; Tachikawa et al., 2003), meaning different water masses carry distinct ε_{Nd} signatures that are generally altered only by mixing and/or local lithogenic Nd inputs from continents and marginal oceans.

In this study, we present the ε_{Nd} values of mixed planktonic foraminifera from core MD77-176 (Fig. 1), collected at an intermediate water depth in the Northern Indian Ocean to establish its intermediate water evolutionary history. Modern seawater ε_{Nd} in the Northern Indian Ocean can be used to discriminate between the relative contributions of Nd from the input of Himalayan rivers (mainly the Ganges–Brahmaputra river system) and water masses originating from the Southern Ocean (Yu et al., 2017a). Here, we constrain the relative contributions of lithogenic Nd inputs since the last glacial period and track deep- and intermediate-water masses originating from the Southern Ocean. In a broader context, the ε_{Nd} record reported in this study is compared with previous ^{14}C and ε_{Nd} records from Northern Hemisphere oceans in order to better understand the potential northward penetration of AAIW during deglaciation.

2. Materials and methods

2.1. Sediment core and age models

Cores MD77-176 (14°30′5″N–93°07′6″E, 1375 m water depth, Fig. 1) was collected in the northeastern Bay of Bengal (BoB) during cruise OSIRIS III of the R.V. Marion Dufresne in 1977. Core MD77-176 was extracted from a site located near the continental slope, 200 km away from the modern Irrawaddy River mouth. This core's lithology consists of intercalated olive grey terrigenous clay and silty clay layers with foraminifera- or nannofossil-bearing ooze. The age model was established using accelerator mass spectrometry (AMS) ^{14}C dates (31 monospecific planktonic foraminifera dates) and oxygen isotope measurements (correlating the $\delta^{18}O$ values of the MD77-176 core and the GISP2-Greenland ice core record) performed on planktonic foraminifera *Globigerinoides ruber* (Fig. 2) (Marzin et al., 2013). The Calib 4.1 program has been used to convert the ^{14}C ages into calendar ages over the last 20 kyr (Stuiver and Reimer, 1993; Stuiver et al., 1998) and includes a correction for the ocean surface reservoir age of 400 yr (Broecker and Peng, 1982). Ages older than 20 kyr ^{14}C BP were established using the Fairbanks et al. (2005) calibration model. The local $\delta^{18}O_{sw}$ values of MD77-176 display large millennial-scale oscillations, suggesting a correlation with the GISP2 record (Marzin et al., 2013). Using the Heinrich events as tie points, Marzin et al. (2013) developed a second age model for core MD77-176 by tuning the $\delta^{18}O_{sw}$ values of MD77-176 with respect to the GISP2 record. As evidenced by a comparison, these two age models are consistent (Marzin et al., 2013). The core MD77-176 thus provides a continuous record over the last 40 kyr BP, with an average sedimentation rate of approximately 25 cm/kyr and a sedimentation rate of up to 40 cm/kyr during the Holocene.

2.2. Analytical methods

Approximately 30 mg of mixed planktonic foraminifera species were picked from the size fraction ranging between 150 and 300 μm. The samples were gently crushed between glass slides under the microscope to ensure that all chambers were open, and ultrasonicated with MilliQ water. Samples were allowed to settle between ultrasonication steps before removing the supernatant. Each sample was rinsed thoroughly with MilliQ water until the solution was clear and free of clay. After the cleaning step, the foraminifera were dissolved using stepwise 100 μl nitric acid (0.5 M HNO_3) until the dissolution reaction was complete. The dissolved samples were centrifuged, and the supernatant was immediately transferred to Teflon beakers to prevent the leaching of any possible remaining phases.

Nd was separated from the carbonate matrix using Eichrom TRU and LN resins, following the analytical procedure described in detail by Copard et al. (2010). In brief, samples were loaded using 2 ml of 1 M HNO_3 on preconditioned TRU Spec columns (83 mg portion of TRU Spec). The unwanted cations were eluted using five aliquots of 0.5 ml of 1 M HNO_3. The TRU Spec columns were then placed over Ln Spec columns. The light REEs were then eluted from the upper (TRU Spec) column using seven aliquots of 0.1 ml of 0.05 M HNO_3. After decoupling from the TRU Spec columns, La, Ce, and most of the Pr were removed from the Ln Spec columns using 2.5 ml of 0.25 M HCl. Nd was then eluted with an additional 3.25 ml of 0.25 M HCl.

The $^{143}Nd/^{144}Nd$ ratios of all purified Nd fractions were analysed using a Thermo Fisher multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS Neptune ^{Plus}) at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) in Gif-sur-Yvette, France (Table 1). The mass-fractionation correction was