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Late Miocene through early Pleistocene nutrient utilization and export production in the Antarctic Zone of the Southern Ocean

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ABSTRACT

We use bulk sediment $\delta^{15}N$ values and opal and carbon mass accumulation rates (MAR) to reconstruct nutrient utilization and export productivity at Ocean Drilling Program Site 745 (Antarctic Zone of the Southern Ocean) spanning the late Miocene through early Pleistocene (~6.5–1.4 Ma). We investigate whether early Pliocene climatic warmth and subsequent cooling can be related to changes in high latitude productivity. Results indicate that $\delta^{15}N$ values increase to above late Holocene levels from the late Miocene through the late Pliocene (6.5 to 2 Ma). Opal and carbon MARs are low during the early Pliocene. Relatively high $\delta^{15}N$ together with low export production is consistent with a more southerly position of the Polar Frontal Zone (PFZ) allowing the expansion of nitrate depleted, low nutrient upper waters south toward Site 745. The interpretation is supported by a relatively small $\delta^{15}N$ gradient between Site 745 and a site in the Subantarctic Zone of the Southern Ocean (Site 1090). There are no unique changes in the Site 745 $\delta^{15}N$ values or export productivity at 2.7 Ma. During the late Pliocene to early Pleistocene climate transition (between ~2.1 and at 1.7 Ma), $\delta^{15}N$ values display large variations approaching those observed during the last glacial to interglacial transition in this latitude band. Opal and carbon MARs also show large fluctuations, but in the opposite sense with maxima corresponding to minima in the $\delta^{15}N$ record and vice versa. The pattern of high $\delta^{15}N$ values associated with low export production may reflect changes in nutrient utilization in response to changes in water column stratification once the PFZ has moved north of the location of Site 745. Our results provide a mechanism for enhancing early Pliocene CO_2 concentrations via reduced uptake of CO_2 due to low productivity in the Southern Ocean. Once the PFZ has moved north, the region may have become sensitive to changes in water column stratification, potentially contributing to fluctuations in CO_2.

1. Introduction

Because of the direct link between export productivity and atmospheric CO_2 levels, much research effort has been directed at reconstructing aspects of the carbon cycle during the past. The Antarctic Zone of the Southern Ocean may be a significant variable in regulating atmospheric CO_2 levels as it is a vast region where CO_2 (and nutrient)-rich deep waters upwell to the surface. The interplay between the rate of CO_2 removal during phyotoplankton photosynthesis and the rate of CO_2 and nutrient delivery from the deep affects the amount of CO_2 escaping to the atmosphere thereby contributing to global climate change (Toggweiler and Sarmiento, 1985; Watson and Garabato, 2006).

In the Antarctic Zone of the Southern Ocean, the region south of the Polar Frontal Zone, an important factor in determining the direction of the CO_2 flux with respect to the air–sea interface is the degree of upper water column stratification (Francois et al., 1997; Sigman et al., 2004; Watson and Garabato, 2006). Weak polar ocean stratification favors upwelling and hence venting of CO_2 into the atmosphere while a well-stratified water column limits upwelling and thus the amount of CO_2 brought to the sea surface. Changes in water column stratification arise essentially from two factors: changes in the Ekman pull of the westerly winds and buoyancy fluxes related to both mixing with dense bottom water currents and air–sea heat exchange (Watson and Garabato, 2006).

Water column stratification has been inferred from the degree to which nutrients such as nitrate are consumed by phytoplankton (Francois et al., 1992; Altabet and Francois, 1994; Francois et al., 1997; Sigman et al., 1999; Horn et al., 2011). For example, enhanced water column stratification limits the amount of upwelling of deeper and nutrient-laden waters to the photic zone. Thus, by reconstructing the amount of nutrients in the upper water column, or the degree of nutrient utilization, it is possible to track temporal changes in water column stratification on geologic time scales.

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The nitrogen isotopic composition ($\delta^{15}N$ values) of bulk sediment reflects nitrate utilization, and it has been used to assess changes in water column stratification through time. Similar to the carbon isotopic composition of organic matter, $\delta^{15}N$ values are low in the organic phase with respect to dissolved inorganic source (i.e. NO_3^-) because biological assimilation discriminates against the heavier isotope (^{15}N). However, the degree of discrimination decreases as dissolved inorganic nitrogen concentrations decrease and become increasingly limiting. As a result, with increasing NO_3^- depletion, or nitrate utilization, $\delta^{15}N$ values will increase in the biomass (e.g., Mariotti et al., 1981; Montoya and McCarthy, 1995; Wu et al., 1997). Therefore, there is an inverse relationship between nitrate concentrations in surface water and the $\delta^{15}N$ of nitrate and algal nitrogen, which is reflected in the $\delta^{15}N$ of sedimentary nitrogen (Francois and Altabet, 1992; Wu et al., 1997; Sigman et al., 1999). For example, water column stratification in the Antarctic Zone has been invoked to explain higher bulk sediment $\delta^{15}N$ values coupled with lower opal accumulation rates during the Last Glacial Maximum with respect to the late Holocene (Francois and Altabet, 1992; Altabet and Francois, 1994; Francois et al., 1997; Sigman et al., 1999; Horn et al., 2011).

Here we use a bulk sediment $\delta^{15}N$ record together with opal and organic carbon mass accumulation rates (MAR) from the Antarctic Zone of the Southern Ocean (Ocean Drilling Program, ODP, Site 745) to assess potential changes in nitrate utilization and export production from the late Miocene through early Pleistocene. The early Pliocene (~5–3.5 Ma) is one of the most recent intervals of time characterized by prolonged relative global warmth (e.g., Ravelo et al., 2007) and higher CO_2 levels with respect to pre-anthropogenic times (Pagani et al., 2010). Global cooling followed with the expansion of Northern Hemisphere glaciers between 3.5 and 2.5 Ma (Mudelsee and Raymo, 2005) and decreasing atmospheric pCO_2 (Pagani et al., 2010). We hypothesize that the Southern Ocean nutrient utilization and export production may have played a key role in the long-term decrease in atmospheric CO_2 levels and climatic cooling during this interval of time.

2. Regional setting

Site 745 (59°37′S, 85°52′E) is located in the Australian–Antarctic Basin in the Indian Ocean sector of the Southern Ocean in a water depth of 4082 m (Fig. 1). This region lies within the Antarctic Zone where nutrient and CO_2 rich deeper waters rise to the surface (Pickard and Emery, 1990). The region is just 1.5° south of the Permanently Open Ocean Zone (Pondaven et al., 2000) with partial sea ice cover only during the winter (Cavalieri and Parkinson, 2008). As this is the time when primary productivity, because of low light levels, is already low (Bianchi et al., 1997) nutrient utilization and export production should be minimally affected by regional changes in sea ice cover. Thus, we surmise that this region reflects primarily open ocean processes such as the position of the Polar Frontal Zone and the strength of the Antarctic Divergence.

Primary productivity in the Antarctic Zone of the modern Southern Ocean is low despite relatively high nitrate concentrations (Boyd et al., 2000) (e.g., Fig. 1B). This is because Fe limits productivity in this region today. During glacial intervals, however, increases in aeolian input of Fe resulted in enhanced nitrate consumption as recorded by higher bulk sediment $\delta^{15}N$ values (Brzezinski et al., 2002). However, in this region, opal export fluxes decreased during the LGM suggesting that nitrate limited productivity at that time (Kumar et al., 1995; Francois et al., 1997; Brzezinski et al., 2002). Francois et al. (1997) argue that both reduced export production and high sedimentary bulk $\delta^{15}N$ values can be explained by enhanced water column stratification limiting the amount of nutrients upwelled into the photic zone and hence primary and export productivity.

Site 745 is unique because it is located south of the Polar Front, yet north of the region significantly affected by seasonal sea-ice cover, and also contains a complete late Miocene through Pleistocene sedimentary sequence. Although not multiply cored, recovery rate was near 100%, and shipboard biostratigraphy as well as magnetostratigraphy do not show the presence of significant gaps in the sedimentary record (Barron and Larsen et al., 1989). Late Miocene through early

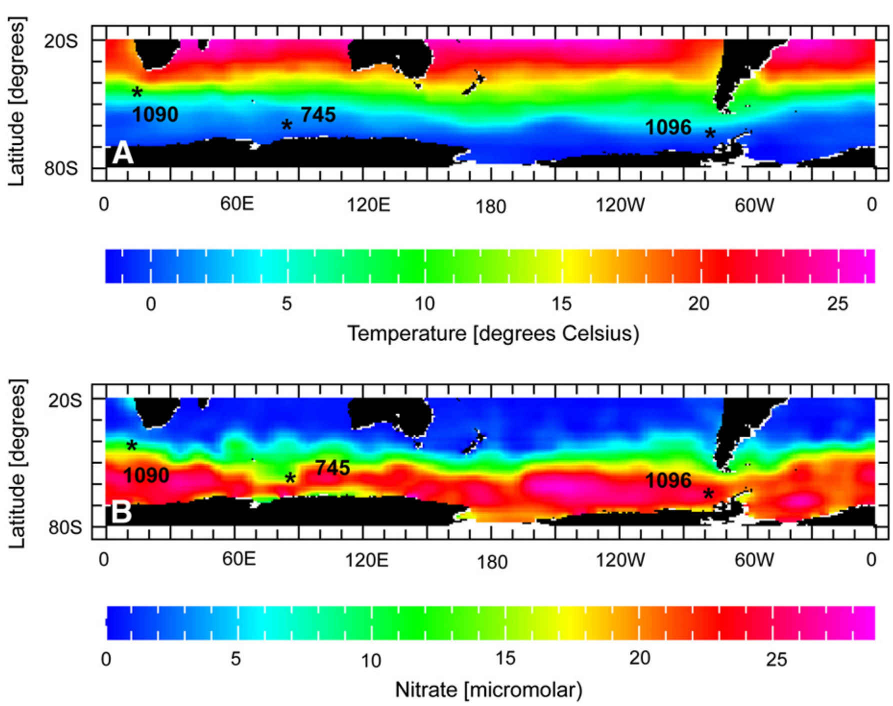

Fig. 1. Location of Ocean Drilling Program Leg 119 Site 745 (59°35.71′S, 85°51.60′E, 4082 m water depth) in the Antarctic Zone of the Southern Ocean with respect to mean annual sea surface temperatures (A) and nitrate (B) (Levitus and Boyer, 1994; Conkright et al., 1994, respectively). Also shown are Sites 1090 (43°S, 20°E, Etourneau et al., 2009) and 1096 (66.5°S, 77°W, Sigman et al., 1999) for which published $\delta^{15}N$ records exists that at least partially span the study interval. Site 745 lies to the south of the modern day Polar Front in this region and to the north of dense winter sea ice extent. The graph was generated using the interactive climate data library of the Lamont Doherty Earth Observatory.