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Southern Ocean frontal system changes precede Antarctic ice sheet growth during the middle Miocene

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ABSTRACT

The middle Miocene climate approximately 14 Ma ago was characterized by the glaciation of Antarctica, deep-ocean cooling and variations in the global carbon cycle. Although the Southern Ocean underwent significant oceanographic changes, there is limited information on their spatial extent and timing. However, such knowledge is crucial for understanding the role of the Southern Ocean and the Antarctic Circumpolar Current (ACC) for Antarctic glaciation and the coupling between the ocean and continental climate. We have reconstructed surface temperatures and seawater oxygen isotopes at Ocean Drilling Program (ODP) Site 1092 in the Polar Frontal Zone of the Atlantic sector of the Southern Ocean from foraminiferal oxygen isotopes ($\delta^{18}O$) and magnesium to calcium ratios (Mg/Ca). Sea surface cooling by ~4 °C and freshening indicated by the ~1‰ reduction of seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) at 14.2 Ma precede the major step in Antarctic ice sheet growth at 13.8–13.9 Ma. This pattern qualitatively mirrors previous findings from the Pacific sector, and we interpret the surface hydrographic changes to reflect the circum-Antarctic northward shift of the Southern Ocean fronts and specifically at Site 1092 the passage of the Subantarctic Front. The magnitude of change in reconstructed $\delta^{18}O_{sw}$ requires a $\delta^{18}O_{sw}$: salinity gradient significantly higher than the modern value (~0.52‰) and it possibly exceeded 1.1‰. This implies the Polar Frontal Zone was influenced by freshwater derived from Antarctica, which in turn confirms higher than modern continental precipitation. The latter has previously been suggested to have contributed to Antarctic glaciation.

1. Introduction

1.1. Middle Miocene climate change

The middle Miocene climate transition (MMCT) about 14 Ma ago has been recognized as one of the most prominent shifts in Cenozoic climate. The global stepwise increase of marine carbonate oxygen isotope ratios reflects the expansion of the East Antarctic Ice Sheet and deep water cooling (Woodruff and Savin, 1991; Flower and Kennett, 1994; Zachos et al., 2001). Much of the climatic change took place in the relatively short time period from about 14.4 until 13.5 Ma. Within this interval the major step occurred at about 13.8 Ma (MI 3 or MI 3b event), a precursor at 14.2 Ma (MI 3a event) has been identified in some records (Miller et al., 1996). The climatic transition was accompanied by successive changes in the composition and sources of deep-water masses in the Pacific (Flower and Kennett, 1995; Shevenell and Kennett, 2004) and Atlantic (Wright et al., 1992; Wright and Miller, 1996).

The reason for the climate change is still a matter of debate. Miocene anomalies in marine carbon isotope ratios ("Monterey excursion") have been interpreted to reflect phases of CO_2 downdraw (Vincent and Berger, 1985; Raymo, 1994). However, levels of this greenhouse gas were low throughout the Neogene (Pagani et al., 1999). From the discrepancy between sea surface temperatures (SST) and pCO_2 Shevenell et al. (2004) concluded that other mechanisms were responsible and identified orbital forcing as the key driver for middle Miocene climate changes. Holbourn et al. (2005) noted the climatic transition took place when orbital forcing changed from obliquity- to eccentricity-dominated and suggested that reduced summer insolation at a time of low pCO_2 facilitated ice sheet expansion. Modelling studies confirm this view where ice sheet growth is triggered by orbital forcing at low pCO_2 (DeConto et al., 2007). Heat provided by the upwelling of warm deep-water masses (whose origin is a matter of debate) increased the atmospheric moisture supply necessary for the initial continental ice build-up before the major cooling step (Schnitker, 1980; Shevenell et al., 2008).

1.2. Southern Ocean

An important factor in the Southern Ocean hydrography is the Antarctic circumpolar current (ACC). The associated ocean frontal system (Fig. 1) determines the boundaries of the subantarctic water masses (Fig. 2). To the north of the ACC upper ocean density is primarily based on temperature, whereas to the south salinity plays a

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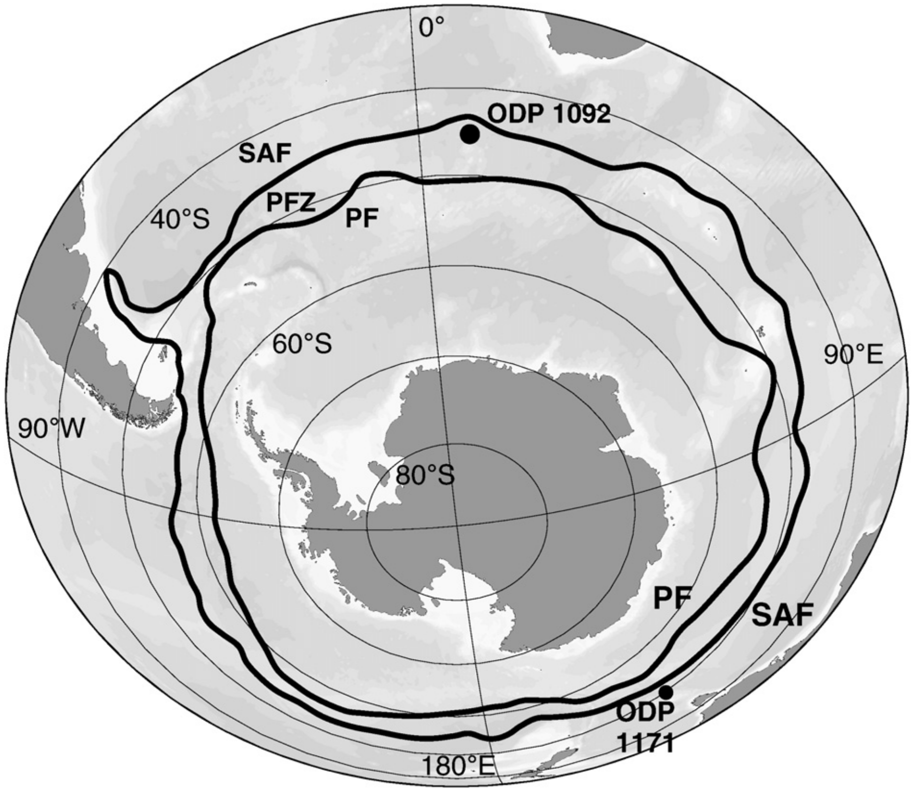

Fig. 1. Map of the positions of Ocean Drilling Program (ODP) sites discussed in this study and modern oceanographic setting. Sea floor is shaded in steps of 500 m. Map based on Ocean Data View (Schlitzer, 2007). SAF: Subantarctic Front; PFZ: Polar Frontal Zone; PF: Polar Front. Positions of the fronts are simplified after Orsi et al. (1995), Belkin and Gordon (1996), and Moore et al. (1999).

larger role in stratification. The sensitivity of the frontal system to climate change has been demonstrated by the northward movement of the Subtropical Front during Pleistocene glacials (Cortese et al., 2007; Sikes et al., 2009).

Although the ACC was already present during the Oligocene (Kennett, 1977; Scher and Martin, 2006) the major strengthening occurred in the Miocene. The erosion of deep-sea sediments and lowered sedimentation rates in the Southern Ocean indicate early (Lyle et al., 2007) and middle Miocene (Mackensen et al., 1992; Diekmann et al., 2003) timings. Foraminiferal stable oxygen isotopes ($\delta^{18}O$) and magnesium to calcium ratios (Mg/Ca) from the Subantarctic Zone in the Pacific sector indicate surface cooling and freshening between 14.2 and 13.8 Ma, caused by the intensification of the ACC and the rising influence of subantarctic surface waters (Shevenell et al., 2004).

Miocene Southern Ocean fronts were generally close to their modern positions in the Atlantic sector, as evidenced by calcareous microfossils (Cooke et al., 2002) and radiolarian assemblages and the spatial distribution of different sediment types (Lazarus and Caulet, 1993). However, the middle Miocene strengthening of the ACC was accompanied by the northward migration of the Polar Frontal Zone, reconstructed from alkenone and stable isotope data from the Southwest Atlantic (Pagani et al., 2000). The position of the Polar Front in the Atlantic sector has been close to 50°S since the Oligocene, but a minor northward shift is indicated between the middle and late Miocene (Lazarus and Caulet, 1993).

In summary, several studies suggest that during the middle Miocene cooling the ACC strengthened and moved northwards. However, this general picture suffers from the scarcity of salinity data and the relatively low temporal resolution of many existing records. It is therefore unclear whether the changes in Southern Ocean hydrography were truly synchronous between sites and with the evolution of the Antarctic ice sheet. Shevenell et al. (2004) have shown that surface hydrographic changes lead the ice sheet expansion by 60 ka, but this may well represent a regionally restricted signal. Clarifying the spatial extent is crucial for identifying the role of the ocean during the middle Miocene climate change.

1.3. Mg/Ca proxy in foraminifera

Mg/Ca in foraminiferal calcite is an established proxy of ocean temperatures (Nürnberg et al., 1996; Mashiotta et al., 1999; Martin et al., 2005). Since foraminiferal $\delta^{18}O$ reflects both temperature and $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$), paired measurements of Mg/Ca and $\delta^{18}O$ allow the reconstruction of $^{18}O_{sw}$, an indicator of salinity.

Seawater pH (and thus carbonate ion saturation) and salinity may act as secondary modifiers for Mg/Ca. For pH the effect is considerable only at temperatures below ~4 °C, where Mg/Ca increases with decreasing pH (Russell et al., 2004). The sensitivity of foraminiferal Mg/Ca to salinity is low (4–10% per salinity unit; Nürnberg et al., 1996; Lea et al., 1999), and no noticeable effect occurs when salinity changes are less than 3 units (Nürnberg et al., 1996). Steeper gradients (>15%) have only been reported from high-salinity regions (Ferguson et al., 2008).

One problem when using Mg/Ca on pre-Quaternary times is the limited knowledge on the past ocean water composition. Estimates of the middle Miocene ocean Mg to Ca molar ratio usually vary between 3 and 4.5 (Wilkinson and Algeo, 1989; Stanley and Hardie, 1998; Horita et al., 2002), compared to the modern value of 5.3 (Broecker and Peng, 1982). The residence times in the ocean for Mg and Ca are $\geq 10^6$ years (Broecker and Peng, 1982), which means that changes in foraminiferal Mg/Ca reflect temperature variability on time scales of several hundred ka and shorter. Relative temperature changes reconstructed from foraminiferal Mg/Ca are correct, but absolute temperatures may systematically deviate.