A Pleistocene warming event at 1 Ma in Prydz Bay, East Antarctica: Evidence from ODP Site 1165

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Summary Magneto-stratigraphic and nannofossil assemblage data from ODP Site 1165 evidence an anomalous warming event of the surface waters in and around Prydz Bay during the Early Pleistocene. This results from an increase in the abundance of nannofossils at Site 1165, that occurred at 1 Ma. High-resolution sampling permits a new bio-magnetostratigraphic interpretation for ODP Site 1165. A decrease in $\delta^{18}O$ values at Sites 1165 and 1167 also occurs at this time, supporting the presence of warming conditions in the Prydz Bay area. A return to colder surface waters, indicated by the absence or rare occurrence of nannofossils in the upper cores from Site 1165, suggests that more stable glacial conditions existed in the Prydz Bay basin for the last 900 ka. These new evidences call for a re-evaluation of the notion that the East Antarctic Ice Sheet has experienced stable conditions similar to today since the late Neogene.

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Introduction

The Antarctic Ice-Sheet and the surrounding Southern Ocean are key components of the global climate regime and distribution of biota, from the early Cenozoic to the present day. The Antarctic continent is presumed to have been under stable polar conditions for many millions of years (Kennett and Barker, 1990; Barrett, 2003). Recently, a debate over stable versus more dynamic Antarctic climate has arisen based on evidence of partial collapses of the Western Antarctic Ice-Sheet (WAIS) (Scherer et al., 1998; 2002), as well as on the temporal stability of the Eastern Antarctic Ice-Sheet (EAIS). The stable glacial state hypothesis suggests that the EAIS became stable in the middle Miocene and has changed little since (e.g. Kennett and Hodell, 1995; Lear et al., 2000; Zachos et al., 2001). On the other hand, other evidence (e.g. Hambrey and McKelvey, 2000) suggests that the EAIS was subject to major fluctuations up to Pliocene time implying considerable climate variation extending from the late Miocene through the Pliocene–Pleistocene (Escutia et al., 2003).

One means to test the idea of a more dynamic climate in the high southern latitudes is the study of calcareous microfossils, such as foraminifers and nannofossils. However, a few studies examine the distribution and abundance of calcareous nannofossils of the Antarctic region at latitude south of 65°S for the younger part of the geological record. One of the reasons is that today, the coccolithophorid distribution are confined at latitudes lower than the Antarctic Divergence (at about latitude 65°S) (Findlay and Giraudeau, 2000). Recent studies have reported calcareous nannofossils in sediment drifts off the Antarctic Peninsula (Villa et al., 2003), and from several piston cores recovered in the Weddell Sea, Ross Sea, Maud Rise, Bellingshausen Sea (Villa et al., 2005). Though discontinuous and rare, the occurrence of calcareous nannofossils in upper Pliocene-Pleistocene deposits near the Antarctic margin may indicate that, different from present-day conditions, the environment was at times favorable to nannoplankton productivity. The environmental conditions that caused their paucity are generally associated with the thermal isolation of the Southern Ocean, low sea surface-water temperatures, sea-ice extension, nutrient availability, and sea-water bottom conditions that influence nannofossil preservation in sediments (Villa et al., 2003; 2005).

Site location and analytical methods

ODP Leg 188 consists of a transect of three sites (1165, 1166 and 1167) drilled across Prydz Bay along the Antarctic continental margin, between 68°E and 78°E (O'Brien et al., 2001; Cooper and O'Brien, 2004). Sediment samples used in this study were obtained from ODP Site 1165 Hole B, drilled in a water depth of 3,537 m on the continental rise offshore from Prydz Bay (64°22' S; 67°13' E). It recovered a mix of pelagic and hemipelagic sediments of the central Wild Drift, which was formed by the interaction of sediment supplied from the shelf and westward-flowing currents on the continental rise.

The upper 50 m from Core 1 to 5 were analysed for calcareous nannofossils. Samples were collected at 15 cm intervals and 142 smear slides were prepared following standard techniques. Smear slides were examined using a polarizing light microscope (LM) at a magnification of 1,250x. For each sample, all the nannofossil specimens in 400 fields of view were counted.

Results

Biostratigraphy

Calcareous nannofossils are unevenly distributed throughout the succession, as also reported by Pospichal (2003). They occur discontinuously only in Cores 1 and 2 with variable total abundance, whereas Cores 3, 4 and 5 are barren. Sediments of the upper 6.55 m display scattered low abundances and low-diversity assemblages; from 6.55 mbsf to 15.74 mbsf, the preservation is moderate and the total abundance increases slightly.

Despite the discontinuous occurrence of calcareous nannofossils, key bioevents have been detected using species abundance data. However, the position of the biostratigraphic events must be considered with some caution, because of the strong variability observed in the assemblage abundance.

Six calcareous nannofossil biohorizons are detected in the uppermost 15.74 mbsf of the section. Some of these bioevents have been previously included in the standard biostratigraphic schemes of Martini (1971), Okada and Bukry (1980), or discussed as biohorizons (i.e Wei, 1993; Raffi et al., 1993; Raffi et al., 2007).

The main biohorizons recorded in the studied cores are: Lowest occurrence (LOw) of *Emiliania huxleyi*, Highest occurrence (HO) of *Pseudoemiliania lacunosa,* HO of *Reticulofenestra asanoi,* LOw of *Reticulofenestra asanoi,* LOw of *Gephyrocapsa oceanica* > 4 µm, LOw of *Gephyrocapsa caribbeanica* > 4 µm.

At Site 1165, calcareous nannofossils are more abundant in the Lower Pleistocene interval, whereas in the middle-upper Pleistocene their abundance decreases drastically. In particular, the uppermost 6 m of sediments contain mainly poorly diversified assemblages, and the microfossil associations are dominated by diatoms. From 6 to 15 mbsf, low diversified but frequent to abundant calcareous nannofossils co-occur with *Thoracosphaera* spp. and less abundant diatoms and silicoflagellates. *Coccolithus pelagicus* dominates the assemblage and represents 60-100% of the nannoflora.

Biomagnetostratigraphy and chronostratigraphy

The magnetostratigraphic interpretation for the upper part of Hole 1165B was obtained by Florindo et al. (2003), aided by diatom and radiolarian biostratigraphy. The obtained nannofossil biostratigraphic resolution, more detailed than that provided by diatoms (Whitehead and Bohaty, 2003), permits a revision of the previous magneto-biochronological interpretation.

Our interpretation, based on the correlation with the geomagnetic polarity time scale of Lourens et al. (2004), is discussed below.

- A normal polarity interval from 0 to 5.37 mbsf is referred to the Brunhes Chron based on the LOw of *Emiliania huxleyi* and the HO of *Pseudoemiliania lacunosa*.
- A reversed polarity interval extending from 5.37 to 6.97 mbsf is assigned to Subchron C1r.1r (0.780 - 0.990 Ma), based on the HO of *Reticulofenestra asanoi* at 7.05 mbsf.
- A normal polarity interval from 6.97 to 14.10 mbsf correlates with the Jaramillo Subchron (C1r.1n, 0.990 - 1.070 Ma) based on the absence of the large *Gephyrocapsa* (Raffi et al., 1993; Wei, 1993; Raffi et al., 2007) and the presence of *R. asanoi.* In Florindo et al. (2003) this thick interval of normal polarity was correlated to at least a portion of the Olduvai Subchron (C2n, 1.770 - 1.950 Ma).
- A reversed polarity interval from 14.10 to 14.66 mbsf is associated with the LOw of *R. asanoi* and the absence of large *Gephyrocapsa*, and is correlated to Subchron C1r.2r (1.070 - 1.201 Ma).
- A normal polarity interval is recognised from 14.66 to the base of the studied section and may represent a least a portion of the Olduvai Subchron (C2n, 1.770-1.950 Ma). The presence of *G. caribbeanica* > 4 µm at 14.99 mbsf allows correlation of the uppermost portion of this normal polarity interval with the Cobb Mountain Subchron (C1r.2n, 1.201 - 1.211 Ma). The reverse polarity C1r.3r Subchron (1.211 - 1.770 Ma) is inferred to be missing. This is further supported by the absence of *Calcidiscus macintyrei*. Below 15.00 mbsf the species recorded are not exclusively of Pleistocene age.

Although the Pliocene/Pleistocene boundary cannot be identified at Site 1165B using calcareous nannofossil events, according to the geomagnetic polarity time scale it is placed close to the upper limit of the Olduvai Subchron, therefore in this section it is probably missing due to the supposed unconformity described above.

Florindo et al. (2003) suggested the occurrence of several hiatuses in the two upper cores in order to explain the thinness of the Matuyama (C1r, 0.780-2.581 Ma) and Brunhes Chrons. The only hiatus that is discernible biostratigraphically on the basis of our data is located below the Cobb Mountain Subchron.

Magnetic susceptibility record

The magnetic susceptibility (κ) includes contributions from all minerals present in a sediment in proportion to their abundance. It is mostly used as a relative proxy indicator for changes in sediment composition that can be linked to palaeoclimate-controlled depositional processes. In this record, downcore variations of κ are associated with similar changes in other bulk magnetic parameters such as the artificial remanence intensities (namely, ARM and IRM), which suggest that these fluctuations are controlled by changes in magnetite concentrations (Florindo et al., 2003; Richter et al., 2003; Warnke et al., 2004).

The κ record shows various large- and small-scale cycles and may reflect temporal variations in terrigenous input, which are likely caused by changes in sea level and erosion of the continental shelf in the region of Prydz Bay. This may indicate a more heterogeneous sediment composition during a cooling trend, starting from 900 ka, possibly associated to the presence of more floating debris-charged icebergs at this site.

Discussion

Evidence for an early Pleistocene warming

The observed higher abundances of nannofossils during the early Pleistocene suggest that more favourable conditions developed leading to improvement in productivity and preservation such as: (1) high nannofloral productivity in surface waters around Prydz Bay, possibly associated with warmer intervals; (2) periodic downward fluctuations in the calcium carbonate compensation depth (CCD), permitting carbonate preservation; (3) rapid transport and burial downslope; or (4) minor dissolution and overgrowth during diagenesis that can control nannofloral assemblage compositions and relative proportions.

Based on the quantitative observations, as documented by the presence of dissolution-susceptible taxa with high surface/volume ratios, the assemblages are generally moderately well preserved. Therefore, low species diversity and low total abundance are probably related to the extreme environmental conditions, rather than dissolution. These results document that sea surface temperature (SST), sea-ice, and light conditions in Prydz Bay became favourable for coccolithophorid production during interglacial intervals of the early and middle Pleistocene, when SST maxima were warmer than today (Villa et al., 2005).

Relationship between nannofossil assemblage and palaeoceanographic setting

During the late Early Pleistocene (Jaramillo Subchron), the higher abundance of nannofossils in our cores suggests enhanced warm SST and open-marine conditions. This is supported by evidence from Site 1167, which contains a clayey interval enriched of calcareous plankton, dated at 900-1090 ka, which is interpreted by Theissen et al. (2003) as the response to warmer conditions and reduced ice-sheet volume. It is worth noting that in the shelly carbonate sequence recovered in the Cape Roberts Project (CRP-1) (Cape Roberts Science Team, 1998) with an age estimated of 1070 ka (Scherer et al., 2002), the unexpected presence of *Thoracosphaera* spp. for such high latitudes (Villa and Wise, 1998) was related, together with other palaeontological evidences (Bohaty et al., 1998; Taviani and Claps, 1998), to a warm interval in the midst of a Quaternary glacial period.

As discussed above, at Site 1165 higher calcareous nannofossil abundances, including the presence of *Thoracosphaera* spp., are recorded within the Jaramillo Subchron. Our biostratigraphic data support the hypothesis of an unconformity at the boundary Jaramillo/ C1r.1r and, therefore, the top of the Jaramillo may be missing. As a result, the warmer SST interval could correspond to the lower part of the Jaramillo subchron, as recorded at the CRP-1.

The presence of higher abundances of calcareous nannofossils also suggests that, in the Eastern Antarctic basins, a warmer interval occurred during the Quaternary dominated by a glacial climate regime. In fact, before this warmer interval, the absence of calcareous nannofossils, in our upper Pliocene samples, seems to indicate lower SST, which is in agreement with the global cooling trend that started at 3.2-2.5 Ma (Raymo et al., 1992, Baker and Camerlenghi, 2002).

The sharp decrease of nannofossils from the C1r.1r Subchron (ca. the last 900 ka) upward correlates with the trend of heavier δ^{18}O values (Warnke et al., 2004), which reflect an increase of ice volume and cooling for this upper interval, as indicated also by the magnetic susceptibility record. Since a minimum of 2°-3°C in surface-subsurface waters is necessary for coccolithophorid reproduction (Burckle and Pokras, 1991; Findlay and Giraudeau, 2000), we argue that since 900 ka, the SST in the Eastern Antarctic basins dropped below the aforementioned minimum value, and only sporadically exceeded it. Moreover, at the nearby Site 1167, Theissen et al. (2003) interpreted the increased oxygen isotope values as the response to a cooling trend beginning at 900 ka.

The results presented in this paper support the hypothesis of stable polar glacial conditions since 900 ka in the Prydz Bay region, which is part of the EIAS.

Conclusions

An increase in nannofossil abundances observed in core samples from ODP Site 1165 are consistent with an anomalous warming event in the surface waters in and around Prydz Bay during the early Pleistocene at ~1 Ma. Climate proxies from other studies around Antarctica (the oxygen isotope stratigraphy from Sites 1165 and 1167, the presence of a clay enriched of biogenic carbonate at Site 1167, and the CRP-1 shelly carbonate unit) also support a warming event during this time interval, suggesting that it extended around the Antarctic Continent. This anomalous warming event in the Southern Ocean surface waters is the only known warm event recorded in the Pleistocene for the Eastern Antarctic marginal basins to date. The warm interval during the Jaramillo Subchron, involving the EAIS and surrounding waters, indicates that these areas were climatically more dynamic than previously thought. We conclude that this warming event does not support the notion that Antarctica and the Southern Ocean have remained in a stable polar condition since the late Neogene.

Following this warm interval, during the last 900 ka, in Prydz Bay, Wilkes Land Basin (Busetti et al., 2003) and Bausan Bank (Villa et al., 2005), sea-surface conditions did not allow the growth and propagation of coccolithophores, suggesting a stable glacial condition for the EAIS. In contrast, nannofossil assemblages reported from the Ross Sea, Weddell Sea, Maud Rise (Villa et al., 2005), the Antarctic Peninsula (Villa et al., 2003) in the middle Pleistocene (presence of *Emiliania huxleyi* and *Pseudoemiliania lacunosa*), confirm that, at times, the Western Antarctic basins experienced conditions warmer than today, as also suggested by Scherer et al. (1998) who proposed at least a partial collapse of the WAIS from 750 ka, and specifically during Marine Isotope Stage 11-5.

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