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Pronounced mid-Pleistocene southward shift of the Polar Front in the Atlantic sector of the Southern Ocean

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Abstract

Ocean Drilling Program (ODP) Site 1094, situated in the Atlantic sector of the Antarctic region below the Polar Front (PF), is dominated by silica-rich sediments during the Pleistocene, but does contain occasional calcium carbonate-rich intervals. The analysis of the coccolithophore assemblages of one of these intervals in the mid-Pleistocene allows us to interpret a prominent southward displacement of the PF. An age model constructed using paleomagnetic and biostratigraphic information places this event around 1 Ma (close to the Jaramillo subchron) in an interval of strong eccentricity and high amplitude in the insolation record.

We distinguish five intervals based on coccolithophore assemblage and abundances. According to the age model used, this calcium carbonate-rich period should include Marine Isotope Stage 31, the most significant interglacial period recorded at this time; however, this model cannot decipher if adjacent isotope stages are partially represented. Interval V (the oldest) is interpreted as an episode with progressive abundance of coccolithophores with a characteristic assemblage from the Polar Front Zone (PFZ) but with dominance of siliceous micro-organisms. Interval IV contains the maximum abundance of coccolithophores with an assemblage characteristic of the Subantarctic Zone (SAZ), with peaks in abundance of *Calcidiscus leptoporus*, *Coccolithus pelagicus*, *Helicosphaera carteri* and *Syracosphaera* spp. related with the proximity of the Subantarctic Front (SAF). The southward displacement of the frontal system, linked to an increase in sea-surface temperature produced increases in diversity and in productivity. Conversely, we consider that the presence of some coccolithophore taxa, linked in other environments with anomalies in salinity, could reflect a pulse in the melting of West Antarctic Ice Sheet, as suggested previously for this interval. Interval III is characterized by a PFZ assemblage reflecting again a northward shift of the PF. Interval II is considered in this context as another southward pulse, but less important than Interval IV and with the absence of SAF and/or melting-related taxa. Interval I is considered a transition from a situation similar to the present-day PFZ to the Antarctic Zone conditions as consequence of a northward displacement of PF and Weddell Gyre/Antarctic Circumpolar Current boundary.

Keywords: Southern Ocean; Atlantic sector; Pleistocene; Paleoceanography; Micropaleontology; Coccolithophores

1. Introduction

The Ocean Drilling Program (ODP) Leg 177 recovered an unprecedented example of sedimentary record in the deep-ocean in the Subantarctic and

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Antarctic regions. Especially important was the Pleistocene record, where a broad N–S transect is combined with an excellent micropaleontological, sedimentological, and geochemical records at various sites with high to relatively high sedimentation rates. ODP Site 1094 is one of these locations, situated in the present day in the Circum-Antarctic Opal belt, below the Polar Front (PF) (DeMaster, 1981; Lisitzin, 1985). Although during the Pleistocene biogenic siliceous sediment is the dominant lithology, some calcium carbonate ($CaCO_3$)-rich episodes are of interest because these dramatic changes in the sedimentation pattern can be linked to environmental changes in response to ocean and continental ice dynamics (Shipboard Scientific Party, 1999). One of these peculiar episodes occurs around 1.0 Ma, close to the base of the Jaramillo subchron (Shackleton et al., 1990; Lisiecki and Raymo, 2005) in the so called mid-Pleistocene Transition, including the prominent interglacial Marine Isotope Stage (MIS) 31 (Shackleton et al., 1984; Raymo, 1994; Tiedemann et al., 1994; Mudelsee and Stattegger, 1997).

The identification and understanding of "extreme" interglacial episodes in recent ocean history, such as MIS 5 or MIS 11 (Howard, 1997; Droxler and Farrell, 2000; Berger and Loutre, 2002; Scherer et al., 1998; Scherer, 2003), is crucial to elucidating Earth system processes and reconstructing scenarios in environmental situations that are perhaps indicative of future climate responses. The extension of the sea-ice cover in the ocean plays a fundamental role in oceanic and climatic processes in this region, because of influences on the deep- and bottom-water formation, albedo (and relationship with the atmosphere–ocean energy budget), as well as other aspects such as the biological productivity and CO_2 concentration. An earlier extreme interglacial, MIS 31, close to the base of Jaramillo subchron, has not received much attention, but is perhaps much more predictive of future Antarctic ice responses (Scherer et al., 2003). The MIS 31 is also important because it is included in the so-called "Mid-Pleistocene Transition" (MPT) when a change in the dominance of 41–100 ka takes place (Ruddiman et al., 1989; Berger and Jansen, 1994; Raymo and Nisancioglu, 2003; Raymo et al., 2004). At this time the Eastern Antarctic Ice Sheet dynamics was controlled by ablation margin, although progressively influenced by a long-term cooling that gradually extended its margin seaward (Raymo et al., 2006). Any information about this interval can contribute to better understand the event.

Coccolithophores are autotrophic planktonic organisms that can develop a carbonate cover around their cell, whose assemblages are sensitive to environmental variations such as temperature, salinity, nutrient content, etc., and consequently a potential proxy for paleoenvironment (McIntyre, 1967; Winter and Siesser, 1994; Thierstein and Young, 2004). Coccolithophores are distributed between approximately 65°N and S, and display a latitudinal zonation (McIntyre and Bé, 1967; Ziveri et al., 2004), with a clear reduction in diversity toward high latitudes, where temperature and seasonally light are the most important controlling factor (Winter and Siesser, 1994). The objective of this study is to analyze how coccolithophore assemblages varied during the middle Pleistocene. This information is used to reconstruct surface water characteristics and water-mass distributions in this region, with the goal of examining the relationships between surface-water masses, frontal systems, and sea-ice cover changes during the critical MIS 31. Although Site 1094 is situated today in a sector where coccolithophores are almost absent and the dominant planktonic components are diatoms and other siliceous organisms (Fig. 1), this certainly was not the case at ~1 Ma, when

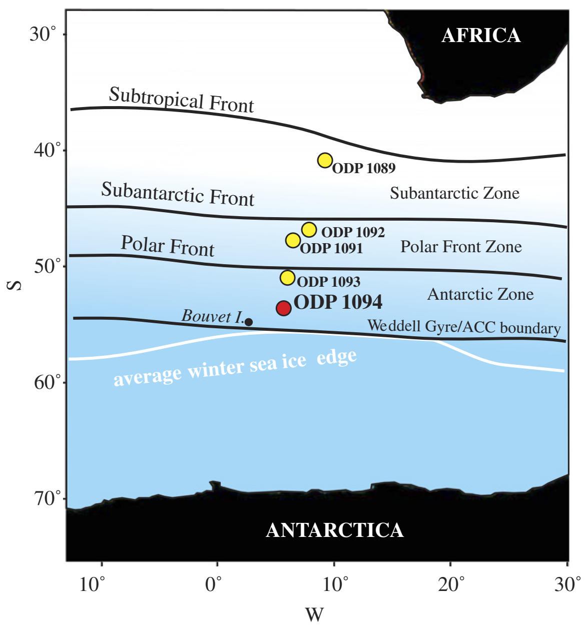

Fig. 1. Location of ODP Site 1094 and other adjacent sites recovered during ODP Leg 177 in the South Atlantic, and pattern of the most significant oceanographic features in the present day.

isolated intervals of coccolithophore-rich sediment may provide clues to extreme variations in climate and surface oceanography. The exceptional concentration in $CaCO_3$ in this interval is noteworthy both in the smear slide report and in the OSU-SCAT reflectance data (Shipboard Scientific Party, 1999). On the other hand, studies carried out in ODP sites 1090 and 1092, north of Site 1094, show the lower values in the $\delta^{18}O$ record (Venz and Hodell, 2002) and the highest temperatures for the MPT interval (Becquey and Gersonde, 2002).

2. Material and methods

2.1. Site location

The site was located at 53°S and 5°E, 2807 m water depth, close to Bouvet Island, in the middle of the ice-free Antarctic Zone. This location is south of the PF and north of the Weddell Gyre (ACC—Antarctic Circumpolar Current-boundary), within the biogenic silica belt (Fig. 1) (Gloerson et al., 1993). The site is presently north of the winter sea-ice edge, but the presence of sea-ice diagnostic diatoms indicates that Site 1094 was covered by sea ice during the last Ice Age (Zielinski and Gersonde, 2002). The investigated sediments sampled from core 1094D-12H mainly consist of gray carbonate-bearing diatom ooze, with varying amounts of foraminifera and nannofossils (between 20% and 45%) (Shipboard Scientific Party, 1999) (Fig. 2).

2.2. Stratigraphy

A combination of geomagnetic and biostratigraphic data is used here to construct an age-model (Table 1) after data of Shipboard Scientific Party (1999), Channell and Stoner (2002), and Flores and Marino (2002) (Table 1). A linear interpolation based on data in Table 1 indicates an approximate age between 1.02 and 1.12 Ma, for 125 and 132 mcd (meters of composite depth), respectively. These data are fully consistent with the presence in all the analyzed samples of *Reticulofenestra asanoi* (Wei, 1993; Flores and Marino, 2002), although sampling resolution and dissolution in the silica-rich material does not permit an accurate calibration, especially the first common occurrence of this species requiring quantitative analyses to be interpreted. For the same reason the age assignments must be considered approximate (Fig. 3).

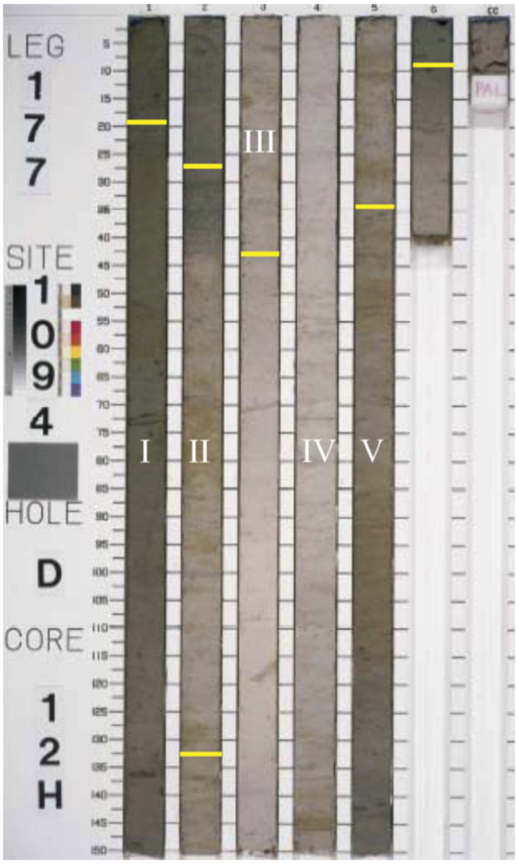

Fig. 2. Core photo of the studied interval and identification of the five intervals defined in this study (courtesy of ODP). For definition and characterization of these intervals see text.

Table 1
Reference point used for the age-model in ODP Site 1094

Event	mcd	Age (Ma)
C1n (Brunhes)[a]	98.5	0.78
LO *R. asanoi* [b]	110.62	0.88
C1r.1n (Jaramillo top)[a]	122.5	0.99
C1r.1n (Jaramillo)[a]	128.5	1.07
LO *Gephyrocapsa* $>5\,\mu m$[b]	141.56	1.24

mcd = meters of composite depth (Shipboard Scientific Party, 1999).
[a]Channell and Stoner (2002).
[b]Flores and Marino (2002).

The lack of a stable isotope curve does not permit us to confirm if this period represents only one interglacial; according to the geomagnetic pattern, the studied interval includes MIS 31, but other intervals, such as MIS 30 and 29, cannot be ruled out.

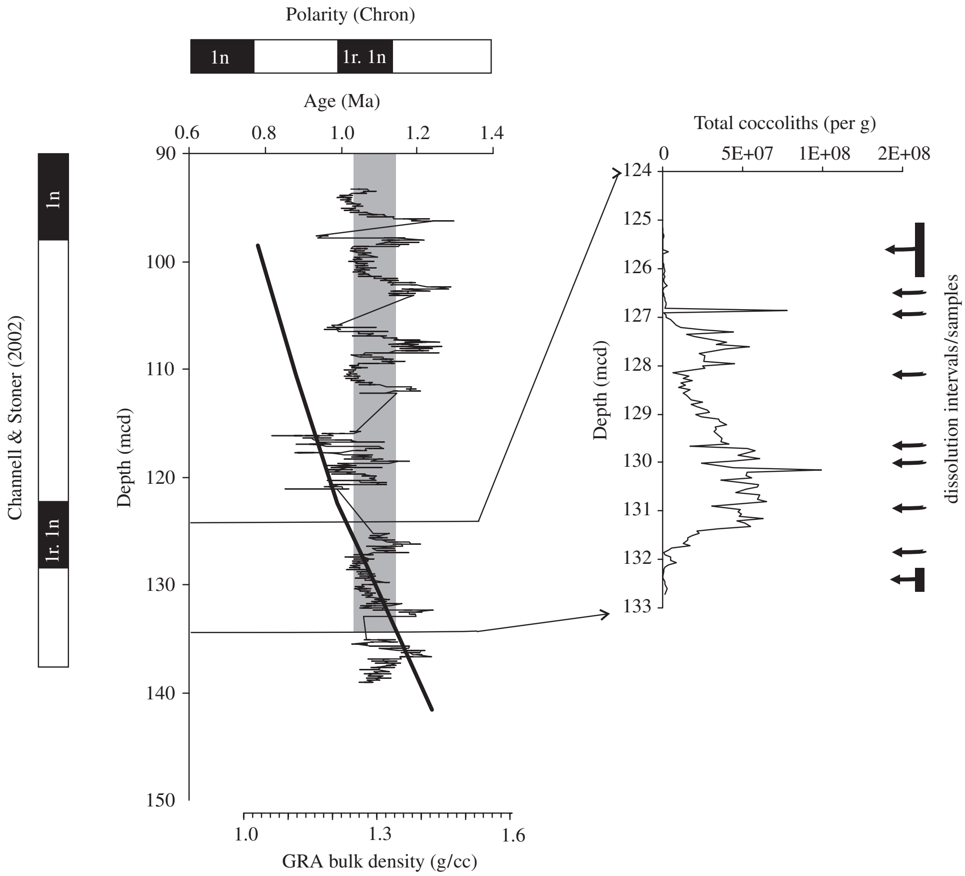

Fig. 3. Age–depth plot showing the geomagnetic scale and reference points used in this study and the gamma ray attenuation (GRA) record (Shipboard Scientific Party, 1999), total abundance of coccoliths, and intervals of extreme or significant dissolution (shown by arrows on the right).

2.3. *Coccolith preparation and estimation of absolute abundance*

Coccolith slides were prepared using the technique of Flores and Sierro (1997). For each slide, a predetermined mass of sediment was taken and spread on a fixed surface. This procedure allows calculation of the number of coccoliths per gram of sediment. A total of 142 samples were analyzed with a sample interval of approximately 5 cm yielding an average age resolution of 0.5 ka. Coccolithophore analyses were made at 1000 × magnification using a polarized light microscope. About 500 coccoliths were counted per slide in a varying number of fields of view. Rare species were counted in additional fields of view (depending of abundance these can be from 10 to 100). Coccolith counts were performed in random visual fields on slides on which the coccoliths were homogeneously distributed. In addition, relative coccolith abundances (percentages) of some species also were calculated and compared with fluctuations in total abundance. Additionally, routine scanning electron microscope analyses were performed to evaluate the preservation of coccoliths in selected samples.

2.4. *Preservation*

Although we generally find an inverse relationship between the concentrations of siliceous microfossils and calcareous nannoplankton, the analyzed interval is characterized by a good to moderate preservation of coccoliths, with the exception of some samples that are coccolith-barren (Fig. 3). It is especially interesting that some intervals with high concentration of *Coccolithus pelagicus* occur together with small placoliths. Typically, high proportions of the robust *C. pelagicus* can be interpreted as the result of dissolution of smaller forms, but in most samples the presence of relatively easily dissolved forms, such as small-sized *Gephyrocapsa* (<3 μm) (Roth, 1994; Flores et al., 2003) with almost no evidence of corrosion, allows us conclude that the assemblage is not significantly modified. Intervals and/or samples with intense dissolution are marked with arrows in Fig. 3.

3. Results

Absolute and relative abundances of coccolithophores analyzed are plotted in Figs. 4 and 5. Maximum abundance in coccolithophores is observed in the lower-half portion. The coccolithophore assemblage is dominated by the species *C. pelagicus*, with maximum diameters close to 10 μm or smaller, representing sometimes 90%; variable amounts of Noelaerhabdaceae (*Pseudoemiliania lacunosa, Gephyrocapsa* spp. and *Reticulofenestra* spp.) as well as *Calcidiscus leptoporus*, complete main taxa of the assemblage.

Five intervals can be defined in the study interval with maxima abundance of coccoliths based on total abundances (coccoliths per g; Fig. 4) and changes in the assemblage composition (Figs. 4 and 5).

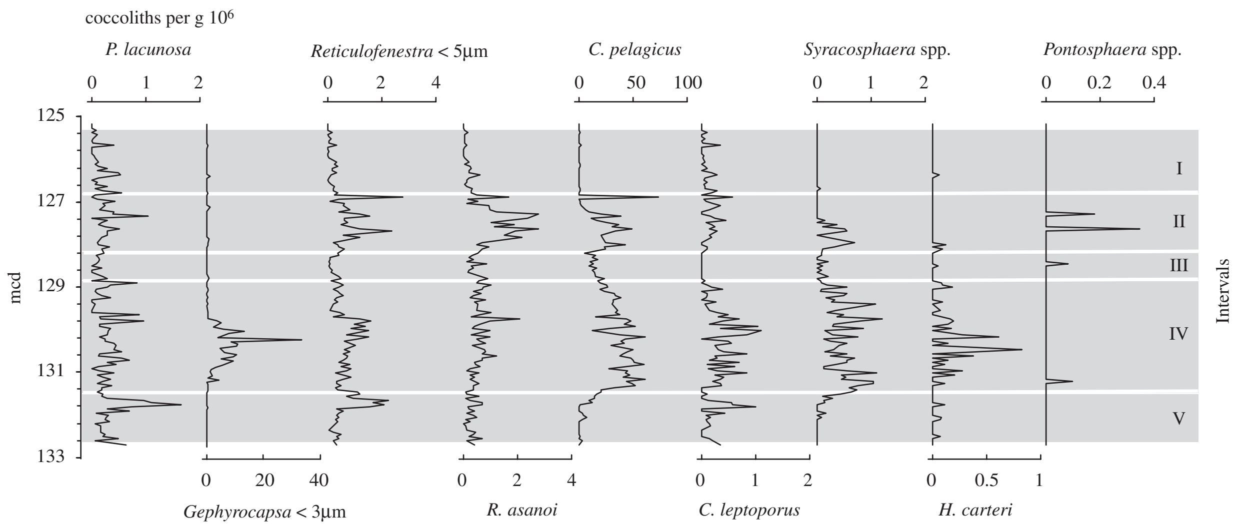

Fig. 4. Total abundance vs. composite depth (mcd) of the most significant taxa and/or groups of coccolithophores in ODP Site 1094. I–V are coccolithophore assemblage intervals defined in this study (see text for details).

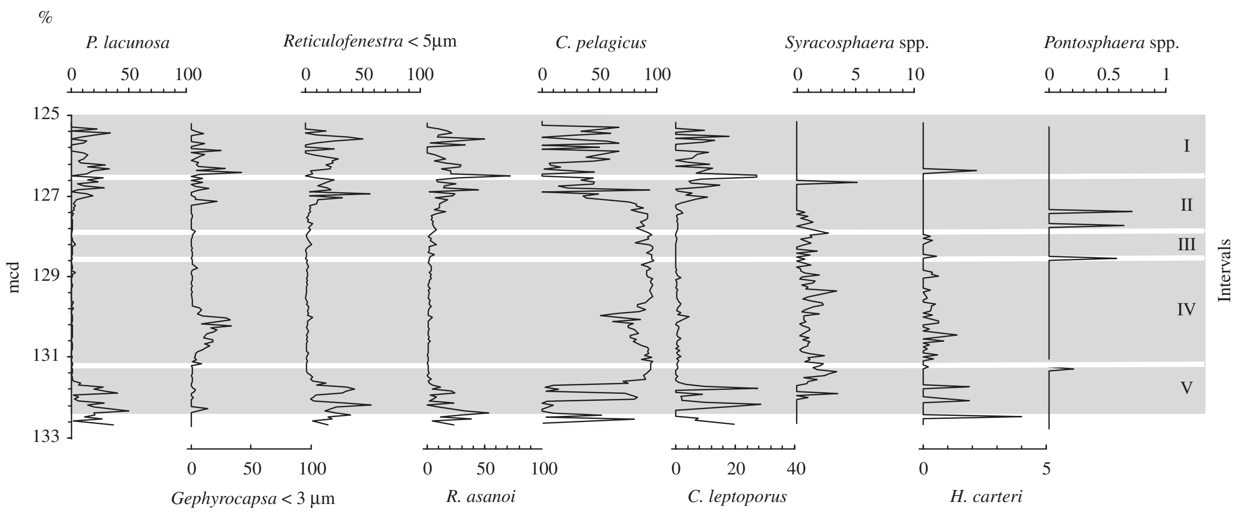

Fig. 5. Relative abundance (percentages) vs. composite depth (mcd) of the most significant taxa and/or groups of coccolithophores in ODP Site 1094. I–V are coccolithophore assemblage intervals defined in this study (see text for details).

4.1. Interval I (~125.00–126.75 mcd)

Transitional from the upper silica-dominant sediments to a progressive increase in coccoliths. Although *C. pelagicus* is the most abundant taxon, Reticulofenestrids and *C. leptoporus* are also well represented in this interval. In terms of total abundance the interval is characterized by low values, sometimes due to intense dissolution.

4.2. Interval II (~126.75–128.50 mcd)

This interval is characterized by an increase of *C. pelagicus* (dominant) but also with increases of small Reticulofenestrids and, especially, *R. asanoi. C. leptoporus* and *Syracosphaera* spp. also show peaks in their total abundances.

4.3. Interval III (~128.50–128.90 mcd)

We observe here the low values in total abundance of coccolithophores. The assemblage is characterized by a decrease in the abundance of *R. asanoi*, *Reticulofenestra* spp. ($<5\,\mu m$) and *C. leptoporus* (almost absent).

4.4. Interval IV (~128.90–131.50 mcd)

Coincident with the lightest-colored interval (maximum in $CaCO_3$; Shipboard Scientific Party, 1999) (Fig. 2), we note the highest values in total abundance of coccoliths (Fig. 4). *C. pelagicus* shows maximum values, accompanied by peaks in the *C. leptoporus* and Noelaerhabdaceae. Especially significant is the record of *Gephyrocapsa* ($<3\,\mu m$) in the middle part of this interval together with increases of other subordinate taxa in the core such as *Helicosphaera carteri* and *Syracosphaera* spp.

4.5. Interval V (~131.50–132.75 mcd)

In terms of abundance, preservation and assemblage characteristics, this interval is similar to Interval I, and represents the transition to rich silica conditions of deeper sediment (Shipboard Scientific Party, 1999).

4. Discussion

The record of several parameters related with physical properties such as magnetic susceptibility, gamma ray attenuation (density), and reflectance carried out on board during Leg 177 in Site 1094, combined with age models obtained by biogeochronological and geomagnetic data (Shipboard Scientific Party, 1999; Hodell et al., 2002, 2003; Kanfoush et al., 2002; Kleiven and Jansen, 2003), and alternating $CaCO_3$ content, allow us to interpret an orbital pattern along the Pleistocene. Kunz-Pirrung et al. (2002), Bianchi and Gersonde (2002), and Shemesh et al. (2002) using diatom-based data, concluded that over the most recent climatic cycles, sea ice covered Site 1094 during glacial periods; in contrast, pronounced interglacials, such as MIS 11, were characterized by a prominent southward displacement of the Polar Front. Although there are no available data concerning sea-ice dynamics or paleotemperatures for the interval around 1 Ma, a comparison with data from sites situated close allow us infer a the similar pattern concerning PF movements. Becquey and Gersonde (2002), for example, studying the planktonic foraminifera assemblages in Site 1090 (Fig. 1), observed a relevant peak in SSST (sea-surface summer temperature) during MIS 31, although below present-day mean values. Eynaud et al. (1999) observed the first coccolith in surface sediments at 57° N, south of the present-day position of PF, in agreement with the information reported from the core top samples recovered during Leg 177 (Shipboard Scientific Party, 1999; Flores and Marino, 2002).

In accordance with the terminology used in this study, intervals V and I represent the beginning and end, respectively, of a "warm" pulse. The Antarctic Zone (AZ-south of PF) coccolithophore assemblage is characterized today by only *Emiliania huxleyi*. Because this species had its first occurrence at 0.26 Ma (Thierstein et al., 1977), it is not present in our interval, however, its ecological niche was occupied by medium- and small-sized Noelaerhabdaceae (*Gephyrocapsa* and *Reticulofenestra*) that occur with other subordinate species such as *C. leptoporus*, *H. carter*i and *Syracosphaera* spp. According to Eynaud et al. (1999), working in the Atlantic sector, and Findlay and Giraudeau (2002) and Gravalosa et al. (2005), working in the Pacific sector, these taxa are present in low proportions in the Polar Front Zone (PFZ), increasing their abundances in the Subantarctic Zone (SAZ). Eynaud et al. (1999) in particular observed significant peaks of *H. carteri* and *C. pelagicus* close to the PF and Subantarctic Front (SAF). As such, Interval V can be correlated with a coccolithophore assemblage from the PFZ in transition from an

Antarctic Zone assemblage as observed today at this position (Fig. 6), and the coccolithophore assemblage described in Intervals IV is characteristic of the SAZ. Noteworthy in our record is the absence of subtropical taxa present although in low abundances in present-day assemblages (Winter et al., 1994; Wells and Okada, 1997; Eynaud et al., 1999; Findlay and Giraudeau, 2002; Flores and Marino, 2002). We can therefore interpret that during Interval IV the PF reached the southernmost position not far from the SAF. The increase of *Gephyrocapsa* (<3 μm) together *C. pelagicus* and *H. carteri* during Interval IV can be interpreted as an increase in coccolithophorid productivity (Findlay and Giraudeau, 2002; Cachão and Moita, 2000; Flores et al., 2003), due to the presence of the SAF. However, the peaks observed in *Syracosphaera* spp. as well as the mentioned *H. carteri* during this interval also can be considered in other terms (Fig. 6). Although in this study we are not be able to identify species corresponding with the genus *Syracosphaera*, since behavior of these taxa can be different (Kleijne, 1993), some authors have observed a relationship between the abundance of this genus and low salinities (Weaver and Pujol, 1988; Flores et al., 1997; Colmenero-Hidalgo et al., 2004, 2005) as well as with warm water pulses (Flores et al., 2000). *H. carteri* is a poorly-understood species, sometimes linked to shallow waters (Geitznauer et al., 1977), or high productivity (Giraudeau, 1992; Pujos, 1992), or warm surface waters (McIntyre, 1967; Geitznauer et al., 1977; Winter et al., 1979); little precise information exists about its characteristics in high latitudes. In the Mediterranean Sea, peaks in abundance of this species appears linked with riverine discharge (Colmenero-Hidalgo et al., 2004) or iceberg melting (Sierro et al., 2005). We cannot exclude the possibility that an increase of these organisms is only due to an increase in surface water temperatures as a consequence of the frontal migration, but perhaps also related to melting of the West Antarctic Ice Sheet (WAIS) environment and a reduction of salinity. This interpretation is consistent with a reduction of the ice cover/retreat of ice edge in Antarctica similar to that proposed by Scherer (1993). Conversely, Scherer et al. (2003) correlated these intervals as periods of minimal coastal ice, based on analysis from a drilling site situated in the Antarctic nearshore at 77°S (Cape Robert Project Site 1; Unit 3.2). In the North Atlantic, for the same interval, Kleiven et al. (2003) observed a reduction in the $\delta^{13}C$ in benthic fauna, interpreted as a possible consequence of increased melt waters. Collectively,

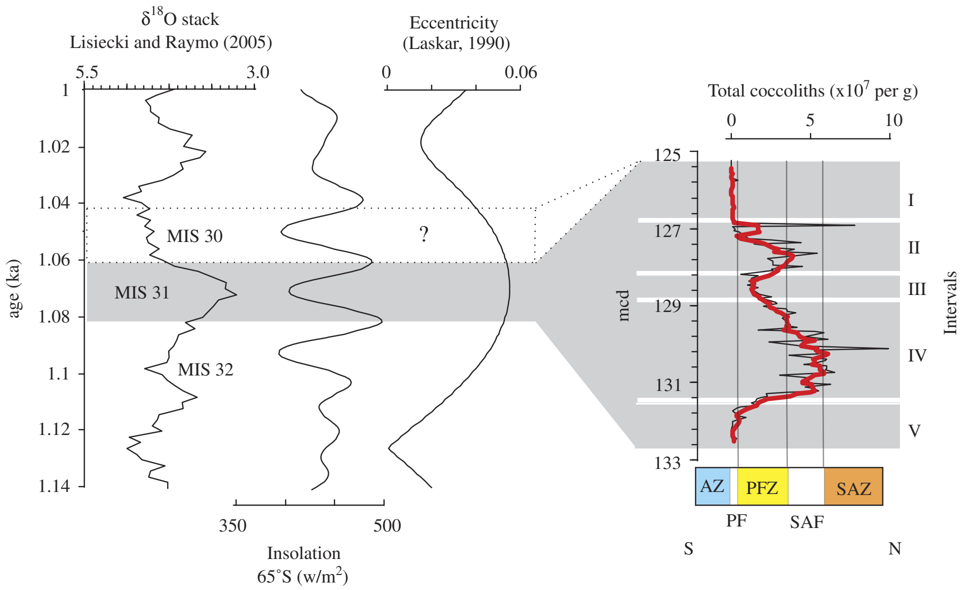

Fig. 6. Total abundance of coccolithophores in ODP Site 1094 *vr*. orbital eccentricity and insolation (Laskar, 1990) (Analyseries program-Paillard et al., 1996) and $\delta^{18}O$ stack standard curve (Lisiecki and Raymo, 2005). Intervals I–V are defined by the total abundance and taxa composition of coccolithophores. Shadowed interval represents MIS 31, and the white doted area an alternative correlation (see text). The smoothed curve in total abundance of coccoliths is correlated with the oceanographic zones and fronts in the region: AZ = Antarctic Zone; PF = Polar Front; PFZ = Polar Front Zone; SAF = Subantarctic Front; SAZ = Subantarctic Zone.

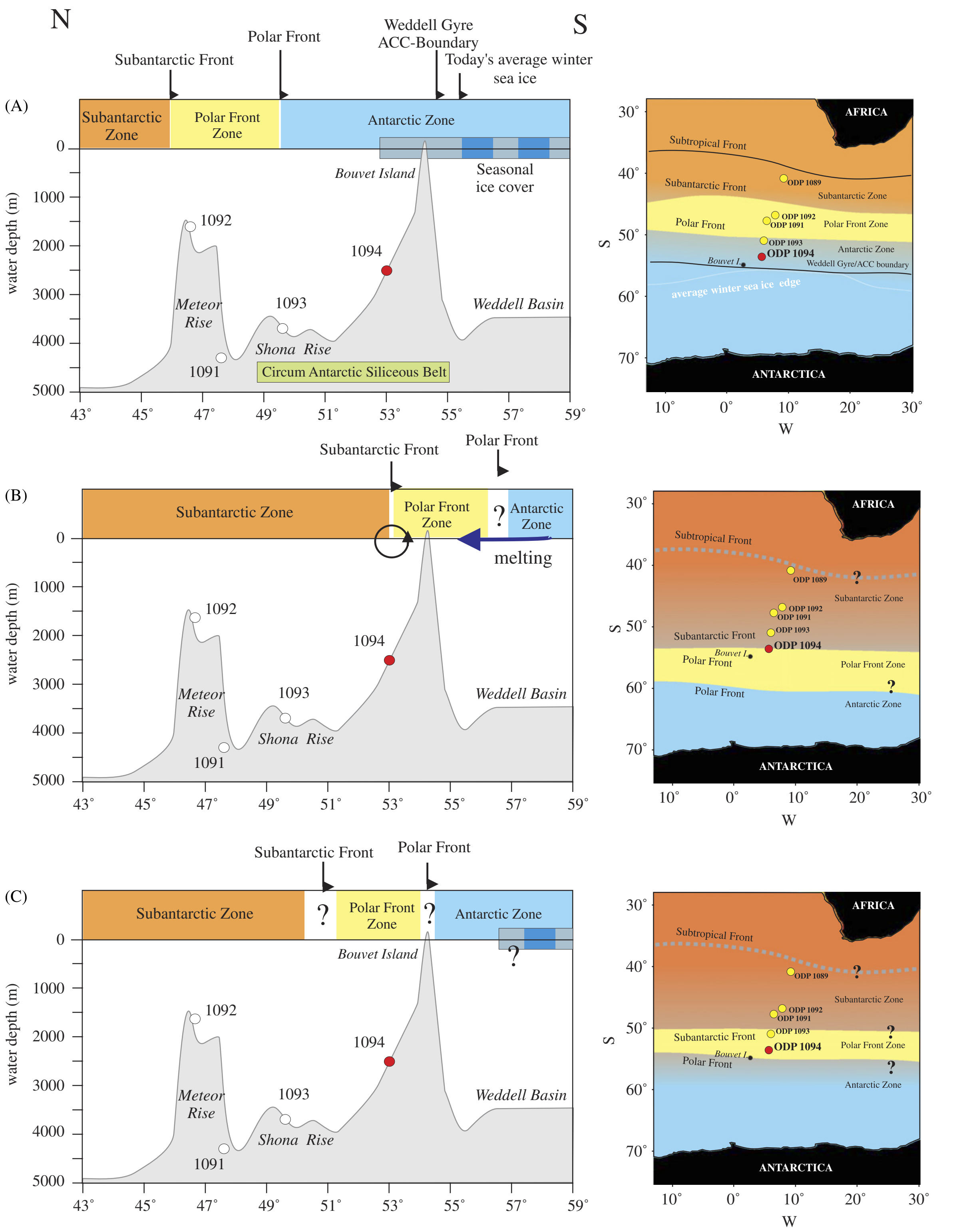

Fig. 7. Paleoceanographic scenarios in the surroundings of ODP Site 1094: (A) present-day and silica-dominant episodes, corresponding with Intervals V and I. (B) Maximum concentration of coccoliths interpreted as maximum displacement southward of the main oceanic frontal systems, corresponding with interval IV (and partially II). High productivity is linked with the proximity of the Subantarctic Front, as well as a probable fresh-water discharge form continental ice melting. (C) Moderate abundance of coccoliths characterizing a Polar Front Zone assemblage. Definition and coccolithophore assemblage for the mentioned intervals is explained in the text.

these results could indicate a strong inter-hemispheric response of polar environments during MIS 31.

During Interval III the production of coccolithophores was reduced and the coccolithophore assemblage close to those observed in Intervals V and I, indicating a northward displacement of the frontal system, although inside the PFZ.

Interval II may represent another southward pulse of the frontal system, although species indicative of warmer temperature or increased melting are not present in high abundance. Intervals III and II could represent different pulses of a significantly intense MIS 31, or simply a glacial and interglacial period (MIS 30 and 29?), respectively. Finally, Interval I is considered a transitional interval towards a situation close to present-day conditions in the Antarctic Zone (Fig. 6).

Accepting our age-model, the studied interval corresponds with a marked eccentricity cycle, with maxima amplitude in the insolation cycles at this location including the MIS 31 (Fig. 6), an unusual early Pleistocene interglacial that comes at a critical time with respect to Pleistocene climatic development, characterized by a strong precessional signal in the lead-up to the transition from 41 to 100 ka climate cycle dominance (Ruddiman et al., 1989; Raymo and Nisancioglu, 2003). Temporal resolution of our data does not allow us to distinguish whether this corbonate-rich interval represents only MIS 31, or includes other isotope cycles. For example, if we follow strictly the proposed age model, the maximum in abundance of coccolithophores occurs at the beginning of the cycle; however, we must consider that due to the low accurate age-model used, small inconsistencies are possible (Fig. 6). A direct correlation between abundance of total and some taxa with the insolation curve, cycle by cycle, is risky.

Independently of the geochronological framework, Fig. 7 attempts to synthesize the evolutionary scenarios in the 1.0 Ma interval, where the alternation of in warmer and colder periods (and their relationship with frontal dynamics) is the most significant feature. Pending a more decisive age model, Fig. 7 shows our interpretation of frontal zone displacements before, during, and after the maximum abundance of coccolithophores.

5. Conclusions

A quantitative analysis of the coccolithophore assemblage in sediments recovered in ODP Site 1094 allows us to interpret that a prominent southward displacement of the PF occurred during the mid-Pleistocene. According to our age-model, based in geomagnetic and biostratigraphic calibrated events, this period is dated at ~1.0 Ma, and corresponds to a marked eccentricity and high amplitude in the insolation signal during the interval of MIS 31.

Five intervals are identified, based on the absolute coccolithophore abundance and different nannofossil assemblage composition, which allow us to reconstruct the position of the PF and SAF in this region. Intervals V and I (oldest and youngest, respectively) characterizes episodes with low abundance of coccolithophores and with a dominance of siliceous plankton, related to the position of the site in the PPZ. Interval IV contains the maximum abundance in coccolithophores, with an assemblage characteristic of the SAZ, close or related to the SAF. From this interval some coccolithophore taxa suggest a reduction in salinity, perhaps in response to a pulse in the melting of WAIS. Interval III reflects a northward shift of the PF, reaching the PFZ. Interval II is considered in this context as another southward pulse, but less important than during Interval IV, with a characteristic PFZ assemblage and influence of the SAF, but with reduction in the species related with the frontal system and/or melting processes.

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