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# The last 100,000 years in the western Mediterranean: sea surface water and frontal dynamics as revealed by coccolithophores

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## Abstract

A quantitative analysis was carried out on coccolith assemblages from two Pleistocene cores (K1 and K10) from the western Mediterranean. The distribution of selected coccolithophore species provides new paleoclimatic and paleoceanographic data. A continuous sequence from the top of Isotope Stage 5 to the Holocene was recorded. The reversal in dominance between *Gephyrocapsa muellerae* and *Emiliania huxleyi* was dated in both cores at ca. 73 ka. At about 47 ka, *E. huxleyi* shows a regular increase, whereas *G. muellerae* progressively decreases in abundance. During interglacial periods, high concentrations of coccoliths are observed, whereas in glacial times, coccoliths are more diluted and the percentage of reworked forms increases as a consequence of the higher terrigenous input. After taking careful account of the dilution factor, we conclude that the production of coccolithophores was higher during warm periods. Maxima in coccolith concentrations coincide with highstand episodes, probably as a result of the intensification of the Atlantic flux into the Mediterranean across the Gibraltar Strait. This intensification could have produced an increase in nutrient content in the surface Mediterranean waters. During cold periods, the western Mediterranean front underwent a reduction in activity, probably due to an increase in the saline and/or thermal gradients between the superficial waters, and intermediate waters in the Liguro Provençal basin.

**Keywords:** coccolithophores; stratigraphy; paleoceanography; Mediterranean; Pleistocene

## 1. Introduction

Study of coccolithophores in cores K1 and K10 provides the opportunity to reconstruct the characteristics of the surface water masses in the western Mediterranean during the latest Pleistocene.

The Mediterranean is a semi-enclosed basin, connected to the ocean by the Gibraltar Strait (with an anti-estuarine regime). The positive evaporation–pre-

cipitation (EP) budget is the main factor controlling its oceanographic dynamics. In addition fresh-water river input and regional topography influencing hydrological peculiarities, such as the definition of frontal systems or local upwellings.

The most significant changes that have occurred in the Mediterranean during the last 100,000 yr, as shown in the carbon and oxygen isotopic records (Vergnaud-Grazzini et al., 1977), comprise a response to northern ice-sheet fluctuations (Shackleton and Opdyke, 1976). However, as a semi-confined

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basin, the Mediterranean yields an isotopic record with some differences from open ocean sequences (Vergnaud-Grazzini et al., 1986; Vázquez et al., 1991). Ice volume determines the amplitude of sea-level changes, which in turn control the water flux between the Atlantic and Mediterranean gateway.

Using the assemblages of coccolithophores together with other sedimentological and biogeochemical parameters, we attempt: (1) to show the qualitative and quantitative development of the coccolithophore assemblages during the last 100 ka and to compare the variations observed with other sedimentary data; (2) to identify and date coccolithophore events with stratigraphic significance; (3) to provide additional information for better interpretation of the paleoclimatic curve; (4) to compare the area studied with the adjacent Mediterranean and Atlantic regions for the same time interval; and (5) to study the paleoceanographic characteristics of the western Mediterranean and its evolution during the last 100 ka.

## 2. Material and techniques

Two piston cores, K1 and K10, were recovered from the slope of the Southwestern Balearic Margin (Fig. 1), and archived at the Instituto de Ciencias del Mar in Barcelona. Core K1 (470 cm long; 38°57.0'N; 0°50.0'E) and core K10 (440 cm long; 38°03.0'N; 1°00.9'E) were recovered from 750 m and 1957 m water depth, respectively. Core K1 is located in the Catalanian–Balearic Sea, while core K10 is from the Algero–Balearic Sea; both cores are close to the western Mediterranean front. Periplatform sediments are dominant in both cores; sand and silt particles are scarce and the carbonate-free fraction generally consists of clay minerals. Core K1 is composed entirely of homogeneous green-gray hemipelagic oozes. The carbonate content, derived from coccoliths and planktic foraminifers, averages 43%. Core K10 comprises hemipelagic oozes, with colors ranging from gray to light brown. Calcium carbonate contents, mainly due

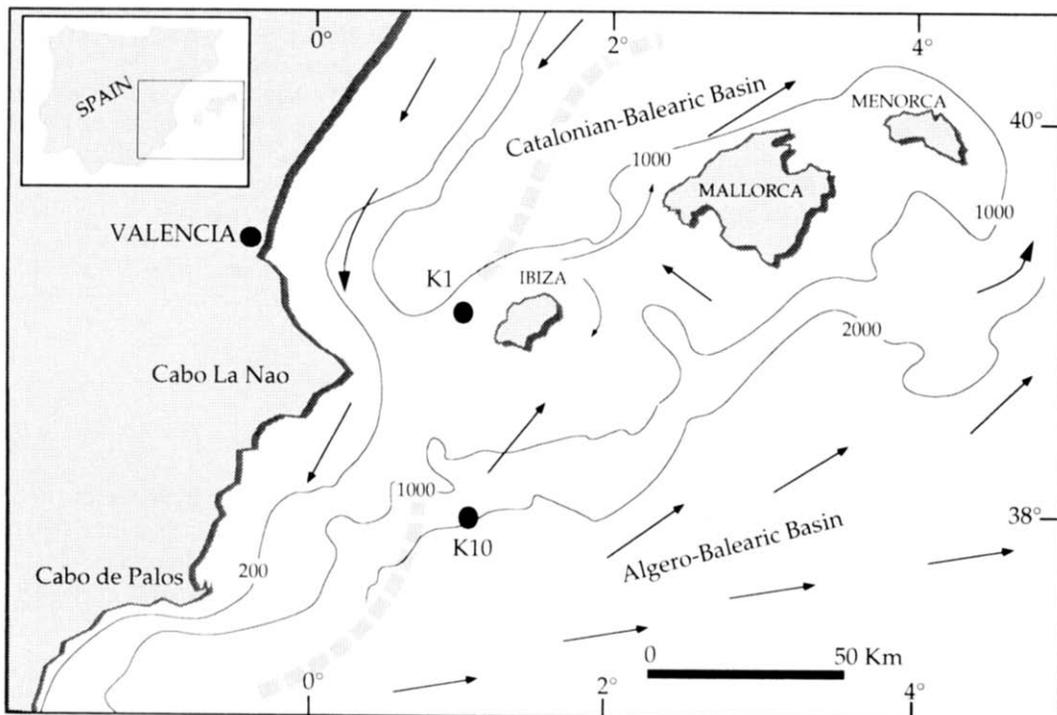


Fig. 1. Location of the cores studied (K1 and K10), and generalized pattern of the surface currents in the present western Mediterranean (modified from Lacombe and Tchernia, 1972; Millot, 1987). The dotted line represents the Mediterranean front (after Estrada and Margalef, 1988).

to coccoliths, planktic foraminifers and pteropods, average 47%.

Most of the samples studied here have been used by Vázquez et al. (1991), and Vázquez and Zamareño (1993) for sedimentological and isotope analysis, with an average sampling interval of about 10 cm.

The slides used to inventory the coccolith assemblages were prepared using the methodology of Flores et al. (1995), which allows for homogeneous and comparable data analysis among different samples. For the preparation of these slides the weight of sediment, as well as the surface over which the sediment is homogeneously extended and the observed surface, are controlled, allowing estimation of the number of coccolith per surface area (coccoliths per mm<sup>2</sup>). These slides are archived in the Micropaleontological Collection of the University of Salamanca. For quantitative analysis, about 300 coccoliths larger than 3 μm were counted per slide in a variable number of fields of view. Coccoliths smaller than 3 μm, and 'manifestly' reworked specimens, as well as species recorded in low proportions in the previous counting, were counted separately analysing additional fields of view.

For the stratigraphic work, the relative abundances (percentages of the most abundant taxa) of selected species were used in order to avoid dilution effects and to compare our data with those previously published (see Section 4 and Fig. 2). In Fig. 3 we plot the most abundant coccolithophore species in terms of coccoliths per mm<sup>2</sup>. Pujos (1992) highlights the value of converting coccoliths into the number of coccospheres in paleoecological studies, in order to give a more accurate representation of the abundance in the biocenosis. Since most of the identified taxa are extant and the number of coccoliths per coccosphere of each species used in this study has been estimated (Knappertsbusch, 1993), we also calculated the total number of coccospheres per mm<sup>2</sup> (Fig. 4).

### 3. Present and glacial geographic pattern

The Mediterranean is a semi-enclosed evaporative sea formed by a complex system of interconnected and interacting basins. The general circulation has a thermohaline origin, due to the excess of evaporation

over precipitation, and is controlled by the exchange of water through the Strait of Gibraltar (Lacombe and Tchernia, 1972). There are no significant tides in certain areas and wind action is the only major governing effect (Abrantes, 1988; Font, 1990).

The western Mediterranean can be considered as a two-layer system of intermediate and deep saline Mediterranean waters and lighter Atlantic surface water (Gascard and Richez, 1985). The western basins are also characterized by a marked seasonal variability: with summer water stratification due to the intense solar heating, and cooling and mixing during winter (Pérez et al., 1985; La Violette, 1994).

The oceanographic circulation patterns in the Catalanian–Balearic and the Algero–Balearic basins are complex and differ considerably. A southwestward surface water flow dominates the Catalanian–Balearic area and is linked to the existence of density fronts between the low-salinity shelf-water and the offshore water (Font et al., 1988) (Fig. 1), whereas the Algero–Balearic basin is directly influenced by Atlantic waters entering through the Gibraltar Strait (Millot, 1987). The instability of the incoming jet of Atlantic water leads to the creation of anticyclonic eddies which are responsible for some upwellings near the continental slope, and for intense mesoscale variability in the contact areas between the inflowing Atlantic waters and the Mediterranean surface water (Millot, 1987; Perkins and Pistek, 1990). The exchange of waters through the island straits has also been documented (Perkins and Pistek, 1990). The Balearic Islands form a key transition region between the north and south circulation regimes (López et al., 1994).

The dynamics of intermediate and deep waters are driven by the EP balance and are greatly influenced by local topography, especially the morphology of the continental slope morphology and the sill formed by the Balearic arc (Miller, 1983; Font, 1986; La Violette et al., 1990). These cold-water masses arise especially during winter in the Gulf of Lyon and their circulation remains obscure, although they mainly occur along the slope.

The biological productivity of the Mediterranean Sea is known to be among the lowest in the world (Sournia, 1973). However, the western Mediterranean is far from uniformly oligotrophic. The concentration of nutrients in the less-dense Atlantic

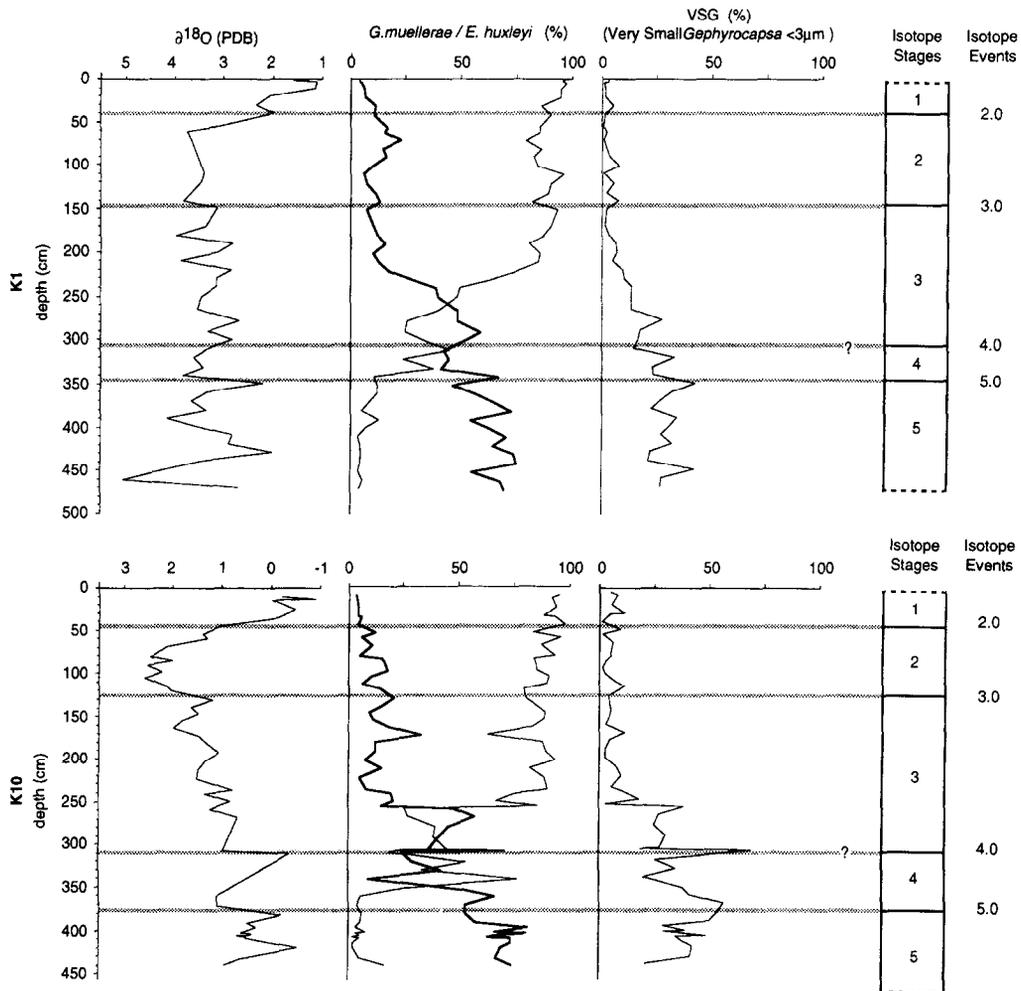


Fig. 2. Oxygen isotope signal and placement of the most significant isotope events vs. the percentage of *E. huxleyi*, *G. muelleriae* (thick line) and *Gephyrocapsa* <3  $\mu\text{m}$ , in cores K1 and K10. The oxygen isotope curve in core K1 from Vázquez et al. (1991).

inflow is low, but higher than in the surface Mediterranean water (Salat and Cruzado, 1981; Millot, 1987). These differences should result in variations in plankton productivity between the two basins in the study area (Estrada et al., 1985; Vázquez and Zamarreño, 1993). Additionally, Estrada, 1985 and Estrada and Margalef (1988) have documented the presence of a front between Iberia and the Balearic Islands. This front is defined as a isopicnal ridge that seasonally upwells denser and more saline waters. The dynamics of this front seem to be defined and controlled by surface water currents (Font et al., 1988). This feature is the main supplier of nutrients in the area (Estrada and Margalef, 1988).

It has been suggested that during the Last Glacial Maximum (LGM) the sea level would have fallen about 100–120 m (Fairbanks, 1989) and in the western Mediterranean the water temperature would have decreased about 4–6°C (CLIMAP, 1981), salinity increasing by 1.7‰ (Bethoux, 1984). At the same time, the north-northwest trade-winds would have tended to become westerlies (Pèrés, 1985). The drop in sea level did not interrupt the connection between the Atlantic and the Mediterranean across the Gibraltar Strait or the fluxes through the Strait of Sicily. Nevertheless, these connections were restricted and the fluxes through the two straits strongly influenced the general thermohaline circulation in the Mediter-

ranean (Bigg, 1994). The observation of a change to a general increase in aridity and salinity led Zahn and Sarnthein (1986), Poutiers (1987), and Abrantes (1988) to conclude that the outflowing waters would have increased during Marine Isotope Stages (MIS) 3 and 2.

#### 4. Stratigraphy

The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  ‰(PDB) isotopic records of core K1 have been studied by Vázquez et al. (1991) using the planktic foraminifers *Globigerina bulloides* (Figs. 2 and 4). For core K10 *Globigerinoides ruber* was analysed. In both cores, MIS 4 and 5 could not be accurately located due to uncertainties resulting from the low sampling resolution (Vázquez and Zammaréño, 1993). However, similar  $\delta^{18}\text{O}$  records were observed in both cores. Amplification of the isotope signal, compared with open ocean records, was reported by Vergnaud-Grazzini (1983) and Vergnaud-Grazzini et al. (1986), and is probably related to variations in the salinity of a confined-basin such as the Mediterranean (Vázquez et al., 1991). Here, a more accurate location of isotope stage boundaries is inferred by means of coccolithophore stratigraphy, and paleoclimatic proxies such as the proportion of warm-water coccolithophore species, detrital supply, and  $\text{CaCO}_3$  contents.

The *Emiliania huxleyi* Acme and *E. huxleyi* Zones (Gartner, 1977) can be identified in both cores. However, the position of the base of the *E. huxleyi* Acme Zone is ambiguous because a progressive increase in the abundance of this species is observed from the base of the cores (Fig. 2). Thierstein et al. (1977) recorded the “dominance reversal of *Gephyrocapsa caribbeanica*-*Emiliania huxleyi*” in transitional waters from the North Atlantic towards the bottom of MIS 4 (73 ka), but this event is diachronous (Thierstein et al., 1977; Ahagon et al., 1993; Jordan et al., 1996). *Gephyrocapsa muelleriae* Bréhéret is a medium-sized placolith abundant in Pleistocene sediments and often identified in the literature as *G. caribbeanica* Boudreaux and Hay (Jordan and Kleijne, 1994). Thus, the reversal in abundance of *G. muelleriae*-*Emiliania huxleyi* is equivalent to the dominance reversal of *G. caribbeanica*-*E. huxleyi* of Thierstein et al. (1977). This event was identified in cores K1 and K10, at 340 and 360 cm, respectively.

Table 1

Adopted taxonomy for *Gephyrocapsa* and *Emiliania* coccoliths, main morphological features, and systematic equivalences

Isotope event	Age (ka)	K1 (cm)	K10 (cm)
2.0	12.05	40	45
3.0	24.11	145	125
4.0	58.96	305	310
5.0	73.91	345	365
5.3	99.38	428	419

As shown in Fig. 5, in cores K1 and K10 this event is dated at 70–73 ka, above Isotope Event (IE) 5.0, dated at 74 ka by Martinson et al. (1987). The abundance reversal has been located in the North Atlantic at the same age (J. Grimalt and J. Villanueva, pers. commun., 1995), and is also coincident with the bottom the *G. muelleriae* Acme Zone reported by Jordan et al. (1996) at ODP Site 658. This timing is not in agreement with Violanti et al. (1987) who studied cores from the Tyrrhenian Sea, and dated the above-mentioned event at ~85 ka. A reduction in the abundance of warm-water foraminifers (*Globigerinoides* spp.) occurs at this level in both cores (M. Gonera, pers. comm., 1995), interpreted as a cold period.

In cores K1 and K10 the *G. muelleriae* Acme Zone is characterized by alternation in the dominance of *G. muelleriae* and *E. huxleyi*, and peaks of the Very Small *Gephyrocapsa* group (VSG, <3  $\mu\text{m}$ ). The top of the *G. muelleriae* Acme Zone, characterized by a dramatic and continuous reduction of *G. muelleriae*, is dated at about 47 ka (Figs. 2 and 5).

The age-model we adopt here is based on the age proposed by Martinson et al. (1987) for isotope events (Table 1). The average sedimentation rates are calculated for the intervals between isotope events and are plotted in Fig. 5. The estimated sedimentation rates for the cores range between 2.5 and 8.5 cm/ka.

#### 5. Coccolithophore assemblage

The general composition of the coccolithophore assemblages observed in cores K1 and K10 is similar to those reported in studies of Pleistocene and Holocene sediments in the western Mediterranean (Bartolini, 1970; Duplessy et al., 1975; Pujos-Lamy, 1977; Blechschmidt et al., 1982; Violanti et al., 1987; Weaver and Pujol, 1988; Kleijne, 1993; Knap-

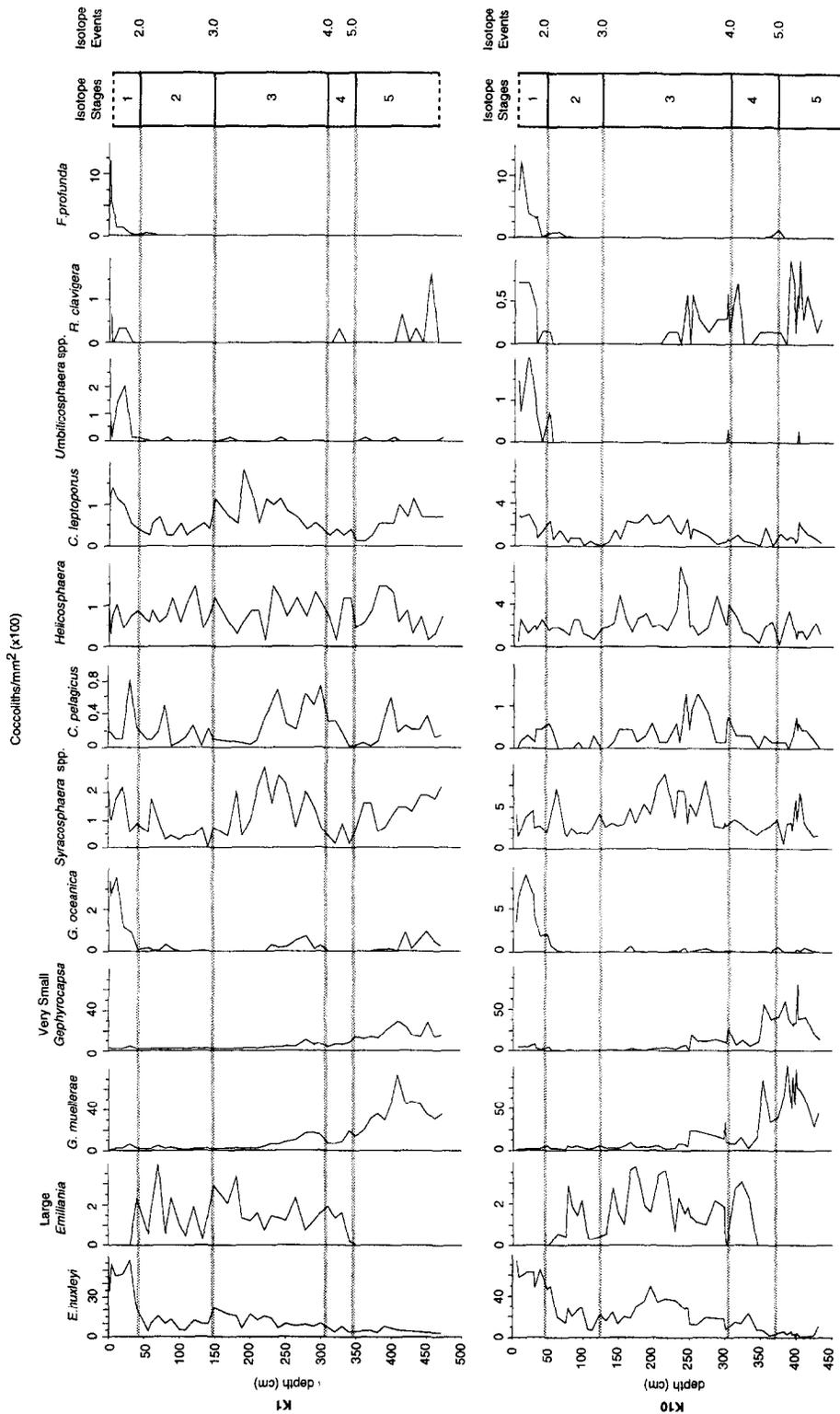


Fig. 3. Abundance distribution of the most significant coccolithophore species per mm<sup>2</sup> in cores K1 and K10. For the isotope stages and events see Fig. 2

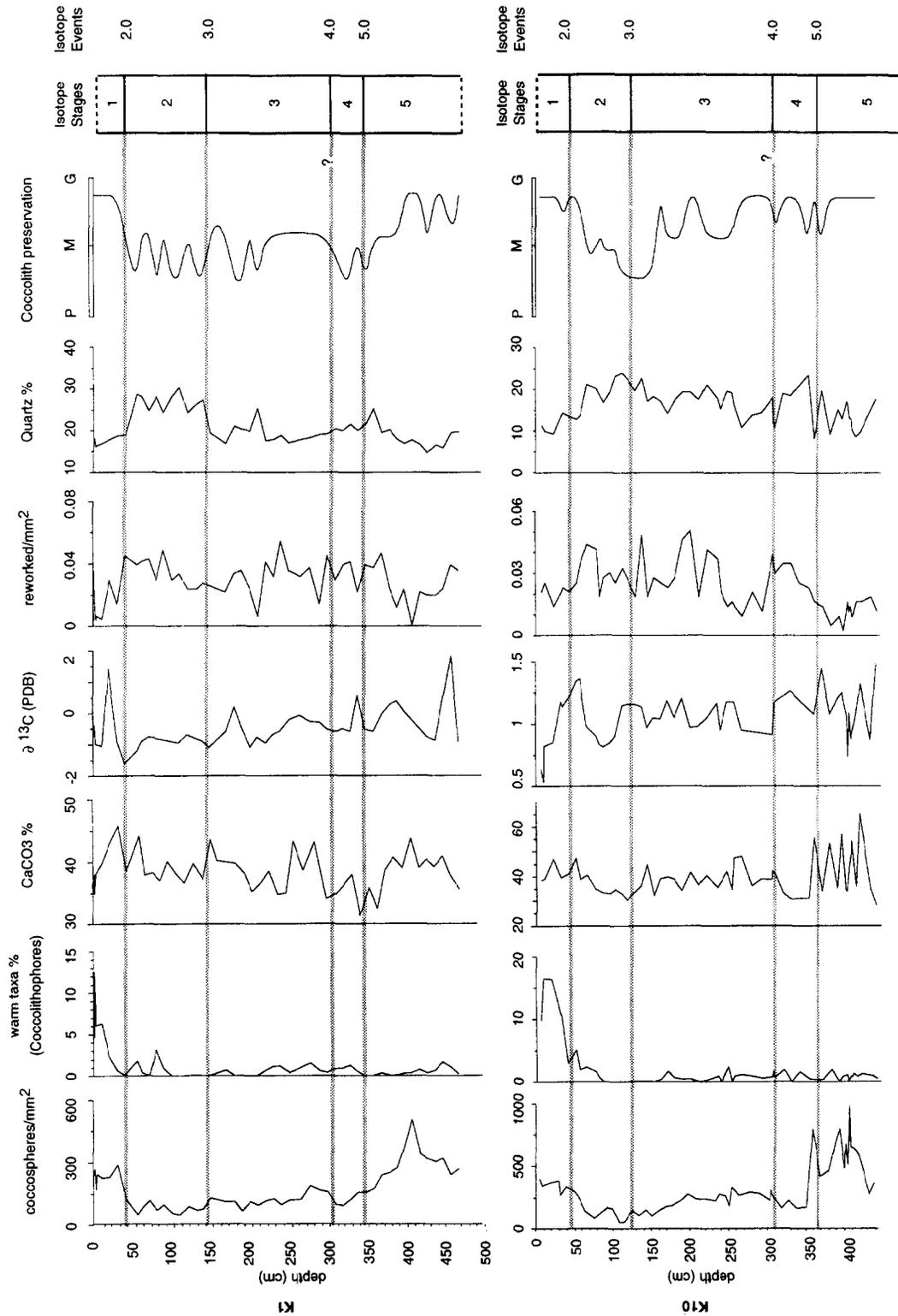


Fig. 4. Distribution of some coccolithophorid, sedimentological, biogeochemical signals and estimated coccolith preservation in cores K1 and K10. For the isotope stages and events see Fig. 2. Coccolith preservation: P = poor; M = moderate; and G = good.

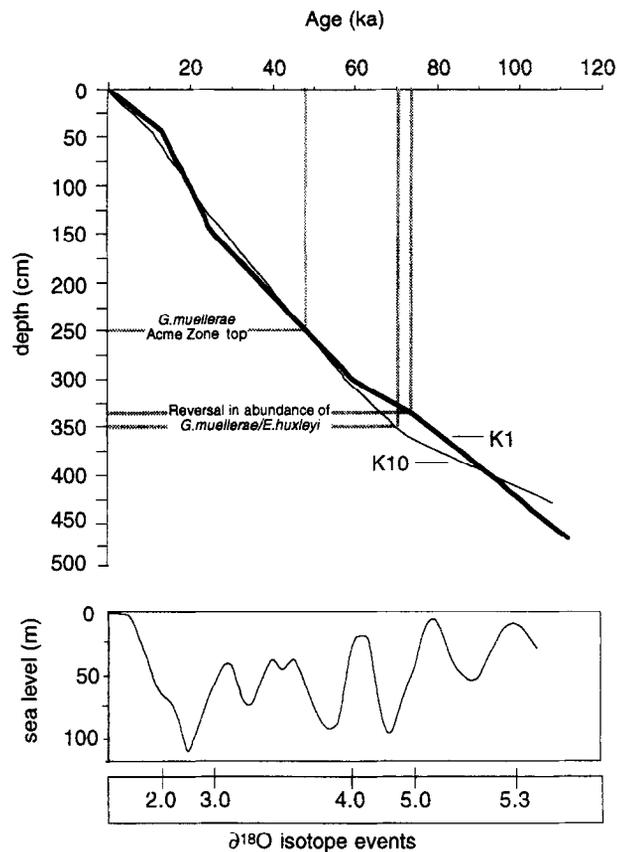


Fig. 5. Estimated sedimentation rates for the age model presented in Table 2, and its correspondence with some coccolithophore events and the eustatic curve.

pertsbusch, 1993). However, there are significant differences in the total abundance of coccoliths in the sediments and of the relative abundance of specific taxa or groups observed in our material.

The coccolithophore assemblage mainly consists of placoliths smaller than  $5 \mu\text{m}$ . In cores K1 and K10, *Gephyrocapsa* spp. is the most abundant taxa below 320 and 256 cm, respectively, whereas *Emiliana huxleyi* (Lohman) Hay and Mohler dominates in the upper part of the section (Fig. 3). Different authors have studied the taxonomy of representatives of the genus *Gephyrocapsa* (Pujos-Lamy, 1977; Br  h  ret, 1978; Samtleben, 1980). Their small size and morphological variability has resulted in the proliferation of nomenclatural terms, from which terminological confusion has arisen (Raffi et al., 1993). In this study we primarily used the optical microscope for identification, and so adopted simple biometric criteria to avoid systematic mistakes es-

entially derived from the small size and taphonomic features, such as dissolution and overgrowth. These observations were completed with scanning electron microscope analysis of selected samples. In general terms, our *Gephyrocapsa* morphotypes can be identified following the taxonomic frameworks of Br  h  ret (1978) and Samtleben (1980). For the genus *Emiliana*, the studies of Young and Westbroek (1991) and Verbeek (1990) were followed. The adopted nomenclature and its systematic equivalence are shown in Table 2.

Other commonly identified taxa are: *Coccolithus pelagicus* (Wallich) Schiller, *Helicosphaera carteri* (Wallich) Kamptner, *Helicosphaera hyalina* Gaarder, *Calcidiscus leptoporus* (Murray and Blackman) Loeblich and Tappan, *Syracosphaera* spp. (mainly *S. pulchra* Lohmann), *Rhabdosphaera clavigera* Murray and Blackman, *Calciosolenia* spp., *Umbilicosphaera* spp., *Umbellosphaera* spp.,

Table 2

Stable isotope events and their position in cores K1 and K10 (ages based on Martinson et al., 1987)

Adopted terminology	Maximum diameter ( $\mu\text{m}$ )	Systematic equivalence	Authors
<i>Gephyrocapsa</i> <3 $\mu\text{m}$	< 3	<i>G. aperta</i> ; <i>G. ericsonii</i>	Bréhéret (1978) and Samtleben (1980)
<i>G. muellerae</i>	3–5	<i>G. muellerae</i>	Bréhéret (1978) and Samtleben (1980)
<i>G. oceanica</i>	>5	<i>G. oceanica</i>	Bréhéret (1978) and Samtleben (1980)
<i>E. huxleyi</i>	< 5	<i>E. huxleyi</i> types A and B	Young and Westbroek (1991)
Large <i>Emiliana</i>	>5	<i>E. huxleyi</i> var. 3 <i>E. pujoseae</i>	Bréhéret (1978) (part.); Verbeek (1990) (part.)

*G.* = *Gephyrocapsa*.*E.* = *Emiliana*.

*Pontosphaera* spp., *Scyphosphaera* spp., *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, *Florisphaera profunda* Okada and Honjo, and *Ceratolithus cristatus* Kamptner. In general, these taxa constitute less than 5% of the total assemblage. The variation in abundance of many of these taxa, expressed in coccoliths per  $\text{mm}^2$ , is very similar in the two cores, as shown in Fig. 3.

MIS 5 is characterized by the dominance of the VSG and *G. muellerae*. Above MIS 5, these coccolithophores are progressively replaced by *E. huxleyi*. Peaks of *Pontosphaera* spp. *R. clavigera*, *C. pelagicus* and *Syracosphaera* spp. are also observed in MIS 5.

The boundary between MIS 5 and 4 (IE 5.0) marks the first record of large *Emiliana*, whose placoliths have a maximum diameter larger than 5  $\mu\text{m}$ . These specimens disappear after IE 2.0 (Fig. 3).

Within MIS 4, low proportions of *Syracosphaera* spp. and *C. pelagicus* are detected. The abundance of these taxa increase after IE 4.0. MIS 3 is characterized by increases in *E. huxleyi*, *C. pelagicus*, *Syracosphaera* spp., *R. clavigera* and *Pontosphaera* spp. All these forms are generally very scarce within MIS 2.

After IE 2.0, a clear dominance of *E. huxleyi* is observed together with an increased abundance of the most common taxa in Holocene Mediterranean sediments *G. oceanica*, *Umbilicosphaera* spp., *R. clavigera* and *F. profunda* (Fig. 3).

## 6. Coccolithophore preservation, carbonate record and reworking

The state of preservation was estimated based on the criteria of Flores (1985) and Raffi and

Flores (1995) modified after Roth and Thierstein (1972).

Dissolution is the main feature of preservation. The rim of some placoliths, such as *G. muellerae* and *Emiliana* morphotypes, or the central area of *Syracosphaera* spp. and *Pontosphaera* spp., are significantly dissolved in some levels. These differences in preservation do not hamper the identification of taxa. It is also of note that in all the samples studied easily dissolved specimens (e.g. very small placoliths, cancoliths, holococcoliths, etc.) are present. It is difficult to determine whether dissolution occurred in the water column (Samtleben and Schröder, 1992; Knappertsbusch, 1993) or was the consequence of diagenetic processes (Vázquez and Zamarréño, 1993). Overgrowth is less significant than etching and is only observed in the central area of several specimens of *C. pelagicus* and large *Gephyrocapsa*.

Preservation was analyzed in both cores and is plotted in Fig. 4. It varies from good to moderate. The general trends of preservation can be compared with the biogeochemical signal in Figs. 2 and 4. In general a high correlation is observed between good preservation, lower  $\delta^{18}\text{O}$  values, a high carbonate content, and low quartz (detrital) proportions. The higher values of  $\delta^{18}\text{O}$  occur in the worst preserved intervals.

Since the basins studied are mainly affected by drainage from eastern Spain and the Balearic Islands (Vita-Finzi, 1972; Miller, 1983), Cretaceous to Pliocene reworked nannofossils are frequent. The reworked nannoliths parameter (per  $\text{mm}^2$ ) is compared with the proportion of quartz. Similar trends are observed in the two parameters and hence reworked nannolith abundance is suggested here to be a good proxy for the input of continental elements (Fig. 4).

## 7. Discussion

### 7.1. *Coccolithophore production versus dilution*

Coccolithophore abundance in sediments may be interpreted in terms of fluctuations in production due to the different hydrodynamic conditions or to dilution caused by the variable terrigenous input. However, it is difficult to distinguish between these two factors. The increase in coccoliths should reflect an increase in productivity. In modern upwelling areas, an increase of coccolithophores is observed in waters with high nutrient contents, although the highest abundances of coccolithophores occur in mature upwelled waters following diatom blooms (Margalef, 1974, 1978, 1983; Mitchell-Innes and Winter, 1987; Giraudeau et al., 1993; Kleijne, 1993). In the modern western Mediterranean, the highest production of coccolithophores occurs after the maximum mixing episodes, when nutrients are partially depleted by diatoms (M. Estrada, pers. commun., 1993), although the coccolithophore behavior is not well understood. In general, a correlation between paleoproductivity and carbonate production by coccoliths can be inferred (Brummer and Van Eijden, 1992; Farrell et al., 1995), although dilution by terrigenous material and dissolution may mask this correlation.

The number of coccospheres per  $\text{mm}^2$  reaches a maximum in MIS 5 and 1 (Fig. 4). In the Mediterranean higher clastic sedimentation rates are believed to be related to glacial stages, as a result of lowered sea levels, shelf erosion and by-pass processes (Stanley and Maldonado, 1977; Weaver and Pujol, 1988; Abrantes, 1988). According to our data, higher sedimentation rates occur in MIS 4 and 2. These stages also show an important increase in detrital quartz (Vázquez and Zamarreño, 1993) and pulses of enhanced reworked nanofossils (Fig. 4). All these parameters follow the same trend as the eustatic curve, reflecting episodes of major terrigenous input from the Iberian and Balearic areas (Fig. 5) over the last 100 ka (Stanley and Maldonado, 1977; Moore, 1982; Kendall and Lerche, 1988). The minimum value of coccospheres per  $\text{mm}^2$  observed in MIS 2 coincides with a maximum input of detrital material and an increase in the sedimentation rate (Figs. 4 and 5). Since sediment density data are not available, it is only possible to make an approximation to coccolithophore fluxes (Backman and Pestiaux, 1987; Flores et al., 1995). However, since the density of cores K1 and K10 is quite uniform (Vázquez et al., 1991), and since the differences in sedimentation rates are not very high, we infer that maxima in the abundance of coccolithophores are equivalent to maxima in fluxes. Even in the LGM, where the sedimentation rate is highest, the total number of coccospheres per  $\text{mm}^2$  is too low to compensate the recorded values in interglacial periods. Therefore, coccolithophore fluxes are the main factor controlling the sedimentation rate, since changes in sediment density are very slight in cores K1 and K10. Although the sedimentation rate in MIS 2 is higher than in other intervals, the extremely low concentration of coccolithophores suggests low coccolithophore fluxes in this period. It can therefore be proposed that the Interglacial intervals in the Catalanian and Algero–Balearic Seas would have seen a greater coccolithophore production than cold periods.

The water flux between the Atlantic and Mediterranean during the LGM, as compared to the interglacial (or present day) episodes, has been discussed by different authors. Abrantes (1988) infers a maximum outflow in MIS 2 that caused an upwelling in the Alboran Sea. The isotope data from Vergnaud-Grazzini et al. (1986) supports the idea of an intensification of vertical mixing in the northern part of the Mediterranean as a consequence of the southward displacement of the polar front during glacial periods. Béthoux (1984) estimates that during the LGM water exchange would have decreased by about 40%, as a consequence of the temperature drop and an increase in salinity following a sea-level drop of about 100 m and the subsequent reduction in width and depth of the Gibraltar Strait.

Holocene and Last Glacial oceanic circulation is characterized by a northeast flux of nutrient-rich Atlantic waters, with a relatively high coccolithophore production. The same pattern is observed in MIS 5 and 3. These periods seem to be related to a high entry of nutrient-rich Atlantic waters through the Gibraltar Strait. Core K10, which is directly affected by Atlantic waters (Fig. 1), shows more abundant coccospheres than the more nutrient-depleted waters of the Catalanian–Balearic basin (where core K1 is located). In this sense, MIS 5, with a similar sedimentation rate to that of the Holocene, is the

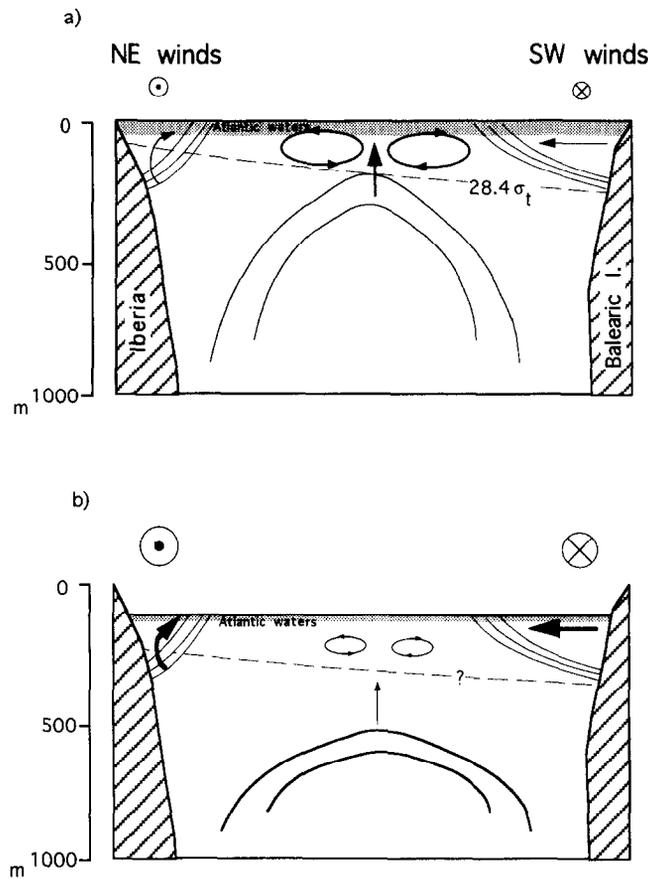


Fig. 6. Surface water, winds and frontal system dynamics scenario in the western Mediterranean: (a) present-day (interglacial) conditions (after Font et al., 1988; Estrada and Margalef, 1988), and (b) glacial conditions (for details see text).

interval with the highest coccolithophore production values. However, Estrada and Margalef (1988) estimated that only about 7% of the nutrients reaching the Algero–Balearic and Catalanian–Balearic Seas come from inflowing Atlantic superficial waters. According to these authors, most of the nutrients in the area studied are derived from a frontal system that seasonally upwells more saline and nutrient-rich waters. This front is mainly defined and controlled by surface dynamics: southward and northward currents in the Catalanian and Balearic margins (Fig. 1). Additionally, it is assumed that during glacial episodes, an intensification in front dynamics occurred in the Mediterranean as a consequence of wind intensification as well as of changes in sea levels (Béthoux, 1984; Abrantes, 1988; Targarona et al., 1995). In general, an intensification in the wind regime should produce an increase in mixing. In the Alboran region,

an increase in upwelling cells has been reported by Abrantes (1988). However, in the area studied here, MIS 2 coincides with a minimum in coccolithophore abundance. We interpret these data as pointing to a reduction in the intensity of the western Mediterranean front. The reduction in temperature and the increase in salinity argued by Béthoux (1984) for the last glacial period could have led to an increase in density gradients resulting from enhanced downwelling rates in the Liguro–Provençal region. The gradient increase could have reduced the activity of the front, even with more intense winds (Fig. 6).

Vergnaud-Grazzini et al. (1986) observed positive pulses in  $\delta^{13}\text{C}$  during the LGM in the highly productive area of the Alboran Sea (eastern and western Mediterranean). These authors interpreted this as reflecting an increase in photosynthesis, produced by

enhanced vertical mixing. However, in comparison with other open sea site data these data are anomalous. In our study (Fig. 4), values below the mean in the  $\delta^{13}\text{C}$  record are observed, following the global trend, but no special significant events can be described. It should be stressed that IE 5.0 and 2.0 coincide with peaks in the  $\delta^{13}\text{C}$  record. The  $\delta^{13}\text{C}$  record shown in Fig. 4 must be considered with caution because diagenesis could have had a significant effect in these sediments (Vázquez and Zamarreño, 1993).

## 7.2. Coccolithophore paleoceanographic indicators

The paleoclimatic meaning of Pleistocene coccolithophore taxa in the Mediterranean is controversial. Some of the characteristic open ocean indicators may have been influenced by non-climatic factors related to the semi-confined nature of the Mediterranean.

Weaver and Pujol (1988) have reported that *G. muelleriae* shows higher percentages in cold episodes prior to terminations Ia and Ib in the Alboran Sea; by contrast, *G. oceanica* is found in higher proportions during warmer periods, such as the Holocene and the Bølling/Allerød phases, and is absent in cold periods such as the Younger Dryas (YD) phase, in agreement with previous data by Bartolini (1970) and Geitzenauer et al. (1976). Knappertsbusch (1993), however, links the presence of *G. oceanica* in the Mediterranean to the low salinity Atlantic surface waters.

In cores K1 and K10, *G. muelleriae* has maxima values in MIS 5 when *G. oceanica* is sporadic. The same trend is seen in MIS 3. However, *G. muelleriae* became less abundant towards the Holocene, whereas a peak of *G. oceanica* is recorded after IE 2.0. This coincides with an increase in *Umbilicosphaera* spp. (mainly *U. sibogae*), *R. clavigera*, *Pontosphaera* spp., and *F. profunda*, which are considered to be relatively warm-water species (McIntyre and Bé, 1967; McIntyre et al., 1970; Okada and Honjo, 1973; Bukry, 1978; Gartner et al., 1979; Kleijne, 1993; Winter et al., 1994) and are therefore grouped under 'warm-water taxa' (Fig. 4). These species are very scarce prior to the Holocene, even in MIS 5, in which only *R. clavigera* (Fig. 3) and *Pontosphaera* show relatively high values. This trend is consistent with the relatively low tempera-

tures recorded for MIS 5 above IE 5.3 (e.g. Keigwin et al., 1994). It is also interesting to note that the interval corresponding to the YD, is characterised by low values of this group. The preference of *G. muelleriae* for cold-water conditions is not supported by our data because it is not abundant after IE 5.0

*C. pelagicus* is traditionally considered to be a cold water indicator in open ocean conditions (e.g. McIntyre, 1967; Bartolini, 1970; Ruddiman and McIntyre, 1976). As shown in Fig. 3, *C. pelagicus* is recorded at proportions below 1% in the total assemblage, and no clear relationship is observed with the isotope record or any other paleoclimatic indicator, with the exception of the Holocene, where a notable peak of this species is recognized, probably related to the YD. It seems that during the Holocene, *C. pelagicus* may have been controlled climatically, but below this interval other factors could have influenced its distribution. Cachão and Motta (1995) have found a relationship between the abundance of *C. pelagicus* and nutrient enrichment. In our cores, we have not found any correspondence between *C. pelagicus* and other records such as total of carbonate,  $\delta^{13}\text{C}$  or the total of coccospheres, occasionally used as paleoceanographic proxies.

Large *Emiliania*, is recorded from IE 5.0 to 2.0, the coldest period in the studied interval, and can therefore be interpreted as a cold water indicator. The reversal of *G. muelleriae*–*E. huxleyi* in the area studied and adjacent Atlantic occurred just after IE 5.0 (Figs. 2 and 5), coinciding with a drop in temperature. However, this diachronous event is older at lower latitudes (Thierstein et al., 1977; Ahagon et al., 1993), when it occurs within a warmer interval. Consequently, it does not seem to have any paleoclimatic significance.

*Syracosphaera* spp., mainly represented by *S. pulchra*, are commonly recorded, showing an interesting distribution that is very close to that of *C. pelagicus* but out of phase. This cosmopolitan genus (Okada and McIntyre, 1977), which generally inhabits the middle euphotic zone (cf. Jordan, in Weaver and Pujol, 1988), has been related to high terrigenous input during terminations Ib and Ia in the Alboran Sea (Weaver and Pujol, 1988). Bukry (1974) recorded specimens of *Syracosphaera* in the coccolith assemblage of the low-salinity Black Sea. This low-salinity relationship, however, is not yet well

documented. Pujos (1992) found no relationship between this genus and salinity changes in the tropical Atlantic. Additionally, Giraudeau et al. (1993) observed that upwelled waters favor the development of *Syracosphaera* populations in the Benguela area. In cores K1 and K10, *Syracosphaera* shows important peaks during MIS 5, 3 and immediately after IE 2.0. This pattern fits the expected superficial water paleotemperatures only partially (e.g. MIS 1 and 5). The high abundances of *S. pulchra* in relatively cold intervals suggest that other factors such as salinity or nutrient content, could have controlled the distribution of this species.

Maxima in the abundance of taxa such as *H. carteri* and *C. leptoporus* during interglacial periods seem to support the suggestion by Pujos (1992), Giraudeau (1992) and Flores et al. (1995) that these taxa may have occurred in higher proportions in relatively nutrient-rich waters.

### 7.3. Winnowing and sea-level changes

The calcium carbonate/quartz ratio and coccospheres per mm<sup>2</sup> curves generally show similar shapes. The intervals in which the values are out of phase are due to high concentrations of planktic foraminifers, which may be interpreted as a winnowing effect. At the same time, the main drops in sea level can be recognized by pulses of reworked nannoliths.

### 7.4. Preservation

In Atlantic sediments situated above the Carbonate Compensation Depth (CCD), cyclicity in calcium carbonate contents during the Late Pleistocene is well established. In glacial periods dissolution is more intense than in interglacial periods (Meyers and Diester-Haass, 1987; Diester-Haass and Rothe, 1987). In the western Mediterranean, Vázquez and Zamarreño (1993) observed a similar pattern, although this relationship is not clear in the eastern Mediterranean (Cita et al., 1982). The short residence time of Mediterranean Intermediate Waters (around 100 yr) and their response to climatic changes during the glacial–interglacial cycles in the region could have played an important role in the preservation of the coccolith assemblages in cores

K1 and K10 (Vázquez and Zamarreño, 1993). Morse and Mackenzie (1990) have commented that dissolution is favored by low-temperature conditions. However, the kinetic pattern is still not well known.

Core K1, with a rich terrigenous component, shows poorer preservation than core K10. Likewise, the dilution and increase in terrigenous input during glacial periods (Fig. 4) coincides with episodes of moderate preservation.

## 8. Conclusions

The use of coccolithophore proxies has allowed us to construct a continuous sequence that is compared with the isotopic record over the last five isotope stages, weakly defined in the  $\delta^{18}\text{O}$  curve of Vázquez et al. (1991).

The reversal in dominance between *G. muelleriae* and *E. huxleyi* occurs ca. 73 ka in the western Mediterranean; this event is isochronous in the North Atlantic. After an interval in which *G. muelleriae* and *E. huxleyi* show alternations in abundance, a progressive and regular reduction in *G. muelleriae*, together with a regular increase in *E. huxleyi* can be seen. This event is dated at ca. 47 ka.

The highest concentrations of coccolithophores are observed during the interglacial warm periods, while in the LGM the recorded coccoliths are more diluted due to the increase in terrigenous input. Such episodes of major terrigenous input are characterized by an increase in reworked nannofossils. Since higher terrigenous input is usually tied to drops in the sea level, the number of reworked nannofossils is proposed as a proxy to estimate sea-level fluctuations.

Coccolithophore production seems to have been controlled by changes in the fluxes of Atlantic–Mediterranean waters. The high concentration of coccoliths is correlated with high coccolithophore fluxes and lower terrigenous dilution. The maxima in coccolith production occurred during interglacial periods, coinciding with high stand episodes, and hence maximum influxes of relatively nutrient-rich Atlantic surface waters through the Gibraltar Strait as well as an intensification in the Catalanian–Balearic frontal system. During cold periods, even taking into account more intense detrital sedimentation, only a minor coccolithophore production is seen in the

western Mediterranean. We argue that a reduction in the intensity of the above frontal system occurred related to an increase in the saline and/or thermal gradient between the intermediate and superficial waters.

The slightly more intense dissolution observed during glacial periods could be linked to differences in porosity and/or to an increase in the residence time of the LIW (or other intermediate waters) in this area.

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