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## Ocean surface water response to short-term climate changes revealed by coccolithophores from the Gulf of Cadiz (NE Atlantic) and Alboran Sea (W Mediterranean)

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### Abstract

The response of coccolithophore assemblages to short-term millennial and centennial climatic changes over the last 50 kyr is studied in core M39029-7 from the Gulf of Cadiz (Atlantic Ocean) and core MD95-2043 from the Alboran Sea (Western Mediterranean Sea). The nannoplankton data are compared with oxygen isotopes,  $U_{37}^k$ -SST and other biogeochemical and sedimentological proxies to obtain a new perspective of the paleoceanography and paleoecology of the area during these short-term climatic changes. Coccolithophores indicate that Heinrich events (HE) were characterised by the presence of cold, low salinity and turbid water masses on both sides of the Strait of Gibraltar. High abundances of the Lower Photic Zone (LPZ) species *Florisphaera profunda* in the Gulf of Cadiz synchronous with HE are interpreted as being an evidence of upper water-column stratification on the Atlantic side. These episodes coincided with input of terrigenous material, especially during H2. Surface waters during Dansgaard-Oeschger (DO) Stadials were also cold and turbid, while most of DO Interstadials were characterised by warm-water flora. The increase in small placoliths (small *Gephyrocapsa* and *Emiliania huxleyi* (<4 μm)) reveals a higher coccolithophore production during DO Interstadials and the Holocene. Conversely, HE and most of DO Stadials show peaks of *E. huxleyi* (>4 μm), which is considered here as a cold-water indicator. The sharp decrease in large specimens of *E. huxleyi* related to the warming trend in the last deglaciation can be used as a biostratigraphic reference level that marks—at least approximately—the deglaciation and the beginning of the Holocene. Peaks of *F. profunda* are observed during Termination 1 (T1) in the Alboran Sea. They are isochronous with the “Organic-Rich Layer 1” recognised in the Western Mediterranean. In this interval, the water column of the region was stratified as a consequence of the global increase in the sea level following the deglaciation. Quantitative analyses of the coccolithophore assemblage allow us to interpret that coccolithophore production has been higher in the Alboran Sea than in the Gulf of Cadiz during the Holocene.

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## 1. Introduction

The Gulf of Cadiz (Atlantic Ocean) and the Alboran Sea (Western Mediterranean Sea) are situated at both sides of the Strait of Gibraltar (Fig. 1). This narrow pass is the only connection of the Mediterranean Sea with the Atlantic Ocean. At both the Atlantic and Western Mediterranean sides, the water column is composed by low-salinity Atlantic surface waters and dense, highly saline Mediterranean deep waters. These masses interact together, giving rise to a specific hydrodynamic regime in the area (e.g. Ambar and Howe, 1979a,b; Parrilla, 1984; Heburn and La Violette, 1990; Perkins et al., 1990), following an antiestuarine model (Bormans et al., 1986).

Both sides of the Gibraltar Strait have been studied in depth. Alkenone ( $U_{37}^k$ -SST) and planktonic foraminifer (Modern Analog Techniques—MAT) sea-surface temperature reconstructions (Cacho et al., 1999, 2001; Pérez-Folgado et al., 2003), and palynological (Targarona et al., 1997; Sánchez-Goñi et al., 2002) and paleoproductivity records (Abrantes, 1988; Sierra et al., 1998; Bárcena et al., 2001) have been documented. Several micropaleontological studies based

on coccolithophore assemblages have also been performed (Weaver and Pujol, 1988; Beaufort et al., 1996; Flores et al., 1997).

Coccolithophores are one of the major components of the phytoplankton in present-day waters in the area and they are well represented in Mediterranean sediments (Knappertsbusch, 1993). The variations of the different species are assumed to reflect changes in the paleoceanography, paleoproductivity and paleoecology of the area (Weaver and Pujol, 1988; Beaufort et al., 1996; Bouldoire et al., 1996; Flores et al., 1997; Sierra et al., 1999). Some of the taxa can be used for biostratigraphic and paleotemperature approaches (Sbaffi et al., 2001). Quantitative records of coccolithophores offer the possibility of monitoring the paleoceanographic changes that have occurred in this area since the last glacial period. In this work, we attempt to use the coccolithophore assemblages of cores M39029-7 and MD95-2043 to (1) obtain the qualitative and quantitative coccolithophore distributions for the area during the last 50 kyr; (2) compare the coccolithophore records with other geochemical and sedimentological proxies; (3) improve the coccolithophore biostratigraphy in the region for the last 50 kyr; and (4) provide

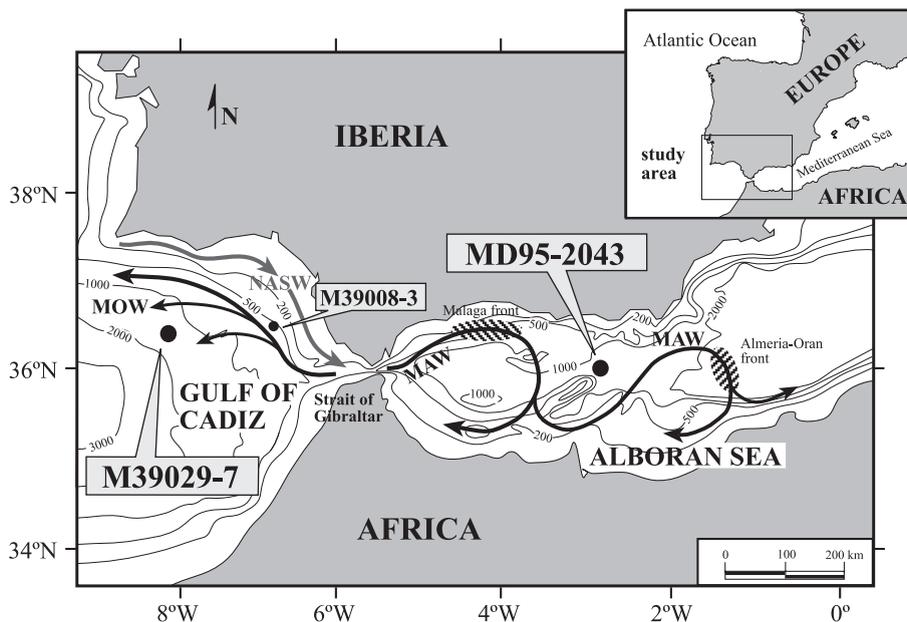


Fig. 1. Location of cores M39029-7 and MD95-2043 and regional water mass circulation. Shaded areas indicate the position of high-productivity cells at present. The position of core M39008-3 is also shown.

paleoenvironmental information for the interpretation of recorded short-term climatic events.

## 2. Oceanographic setting

In the semi-enclosed Mediterranean Sea, excessive evaporation causes the sinking of saline and dense water masses in several locations along the basin (Bormans et al., 1986; Rohling et al., 1998; Rohling and De Rijk, 1999). The exchange of water with the open ocean takes place through the Strait of Gibraltar, with a flow intensity that is controlled by a wide range of seasonal and non-seasonal factors (Parrilla, 1984; Bormans et al., 1986; La Violette, 1990; Manzella and La Violette, 1990).

This study is focused on sediments from both sides of the Strait of Gibraltar, where the exchange of Atlantic and Mediterranean waters operate (Fig. 1). At the location of core M39029-7, the water column is dominated by the cold North Atlantic Intermediate Water (NAIW) and North Atlantic Surface Water (NASW) currents, which flow southwards along the Iberian Margin following the Subtropical North Atlantic Gyre (Baraza et al., 1999). The main core of the Mediterranean Outflow Waters (MOW), characterised by higher temperatures and salinities (Ambar and Howe, 1979a,b), is found at this location between 1000 and 1100 m water depth (Schott et al., 1999), flowing westwards as a separate current and progressively mixing with the NAIW. The NASW follows the Atlantic Iberian shelf and enters the Alboran Sea through the Strait of Gibraltar, forming a low-salinity surface current (Modified Atlantic Water—MAW) (Bormans et al., 1986; Manzella and La Violette, 1990). This current describes two major anticyclonic gyres and forms several upwelling cells in the Alboran Sea before flowing farther into the Mediterranean along the Algerian coast (Parrilla and Kinder, 1987; Heburn and La Violette, 1990). Core MD95-2043 is located in the middle path of those gyres and is under their direct influence. In a deeper position in the water column of the Alboran Sea, dense and highly saline Levantine Intermediate Waters (LIW) and Western Mediterranean Deep Waters (WMDW) flow westwards, forming the MOW as they leave the Mediterranean Sea through the Strait of Gibraltar (Bormans et al., 1986).

## 3. Core location, materials and methods

Gravity core M39029-7 (36°2′ 5 N, 8°13′ 8 W; 1917 m water depth, 5.02 m length) was recovered in 1997 by the R/V Meteor (cruise M-39) in the outer Gulf of Cadiz (Schott et al., 1999). Calypso piston core MD95-2043 (36°8′ 6 N, 2°37′ 2 W; 1841 m water depth, total length 36 m) was recovered by the R/V Marion Dufresne during the 1995 IMAGES I cruise (Cacho et al., 1999) (Fig. 1). The sediment successions of both cores are mainly composed of calcareous oozes and clays (Schott et al., 1999; Plaza, 2001).

Samples used for nannoflora studies were prepared following the methodology of Flores and Sierro (1997). With this technique, both the area over which the sediment is uniformly distributed and the surface observed with the microscope are known. This allows accurate comparisons among samples and the possibility of estimating absolute abundances. Nannoflora counts were performed using polarised-light microscopes at 1250× magnification. Between 450 and 500 coccoliths were counted per slide in a variable number of visual fields. According to Dennison and Hay (1967), this number of specimens would provide precision at 99% level, meaning that all species whose abundance is higher than 1% should have been noticed and counted. Reworked specimens of nannofossils were counted separately in the same visual fields. The relative and absolute abundances of coccoliths were considered in this study.

For diatom analyses, samples were prepared according to the random distribution method of Bárcena and Abrantes (1998). A detailed description of the preparation and counting techniques can be found in Bárcena et al. (2001).

## 4. Results

### 4.1. Stratigraphy and age model

The stratigraphic framework of core MD95-2043 has been established by Cacho et al. (1999). Of the two age models proposed there, the first one—performed by the combination of 17 AMS <sup>14</sup>C ages and oxygen isotope stratigraphy—was chosen for this

study, since we consider that radiocarbon ages and isotopic correlations provide independent and reliable age sources.

The age model for core M39029-7 has been established by correlation of the  $\delta^{18}\text{O}$  *Globigerina bulloides* record of this core (Löwemark, 2001) and the equivalent records from nearby cores M39008-3 (Cacho et al., 2001) and MD95-2043 (Cacho et al., 1999) (Fig. 1). Age points for core M39029-7 were obtained by locating possible matches with the  $^{14}\text{C}$  dated points of these two cores (Table 1, Fig. 2). Additional control points (Younger-Dryas (YD) and Heinrich events (HE)) were identified and added to the core M39029-7 age model with the ages proposed for core M39008-3 (Cacho et al., 2001) and core MD95-2043 (Cacho et al., 1999). H1, H2 and H4 were identified in core M39029-7 by the peak abundances of coarse-grained ice-rafted debris (IRD), which coincide with occurrences of the sub-polar planktonic foraminifer *Neogloboquadrina pachyderma* sin. (Reguera, 2001). H3 does not have an associated IRD layer in core M39029-7; this is a common feature with other cores from the Western Iberian Margin (Baas et al., 1997; Zahn et al., 1997; Bard et al., 2000). Nevertheless, the correlation of its isotopic curve with that of core MD95-2043 and the synchronous maximum abundance of *N. pachyderma* sin., similar to those at H1, H2 and H4, allow us to locate with confidence this HE in core M39029-7.

#### 4.2. Coccolithophore assemblages: preservation and taxonomy

The preservation of coccoliths in cores M39029-7 and MD95-2043 is good to moderate. Partial dissolution of some elements on the distal shield and central area of placoliths is frequent but does not hamper identification. Easily dissolved coccoliths such as *Syracosphaera* spp. and very small placoliths are common in all the samples studied, confirming the good preservation of the materials.

The coccolithophore assemblages of both cores essentially comprise the same taxa and are very similar to those reported in previous studies in the area (Weaver and Pujol, 1988; Kleijne, 1993; Knap-pertsbusch, 1993; Flores et al., 1997; Esposito, 1999; Sierro et al., 1999; Scaffi et al., 2001). However, there are substantial differences in the response of certain taxa and in the absolute abundances of coccoliths in some intervals between the two cores.

Small placoliths are the main group of coccoliths in both cores, especially in the top sections (Fig. 3). This group is composed by two species of the genus *Gephyrocapsa* smaller than 3  $\mu\text{m}$  (*Gephyrocapsa aperta* and *Gephyrocapsa ericsonii*, commonly grouped together as small *Gephyrocapsa*), and *Emiliania huxleyi* (<4  $\mu\text{m}$ ). *Gephyrocapsa* larger than 3  $\mu\text{m}$  (*Gephyrocapsa muelleriae* and *Gephyrocapsa oceanica*) and *E. huxleyi* (>4  $\mu\text{m}$ ) are also frequent. Other common taxa are *Calcidiscus leptoporus*, *Ooli-*

Table 1

Age points for core M39029-7 (Gulf of Cadiz)

Depth in core (cm)	Age source	Dated species	AMS $^{14}\text{C}$ age (years)	Cal. BP age (years)
60	corr. with Cacho et al. (2001) (a)	<i>G. ruber</i>	8755	9238
87	corr. with Cacho et al. (2001) (a)	<i>G. ruber</i>	9860	10,610
112	corr. with Cacho et al. (2001) (b)			12,400
117	corr. with Bard et al. (1987) (c)		11,080	12,626
140	corr. with Bard et al. (1987) (c)		13,980	16,143
154.5	corr. with Cacho et al. (2001) (b)			16,500
178	corr. with Cacho et al. (2001) (a)	<i>G. ruber</i>	15,800	18,285
222	corr. with Cacho et al. (2001) (a)	<i>G. ruber</i>	18,370	21,243
276.5	corr. with Cacho et al. (1999) (d)			23,800
345	corr. with Cacho et al. (1999) (d)			30,600
496	corr. with Cacho et al. (1999) (d)			39,200

(a)  $^{14}\text{C}$ -AMS data obtained in core M39008-3 by Cacho et al. (2001).

(b) Calendar ages obtained by direct correlation with M39008-3 isotopic curve.

(c) Data from Cacho et al. (2001). No correction for reservoir effect.

(d) Calendar ages obtained by direct correlation with MD95-2043 isotopic curve.

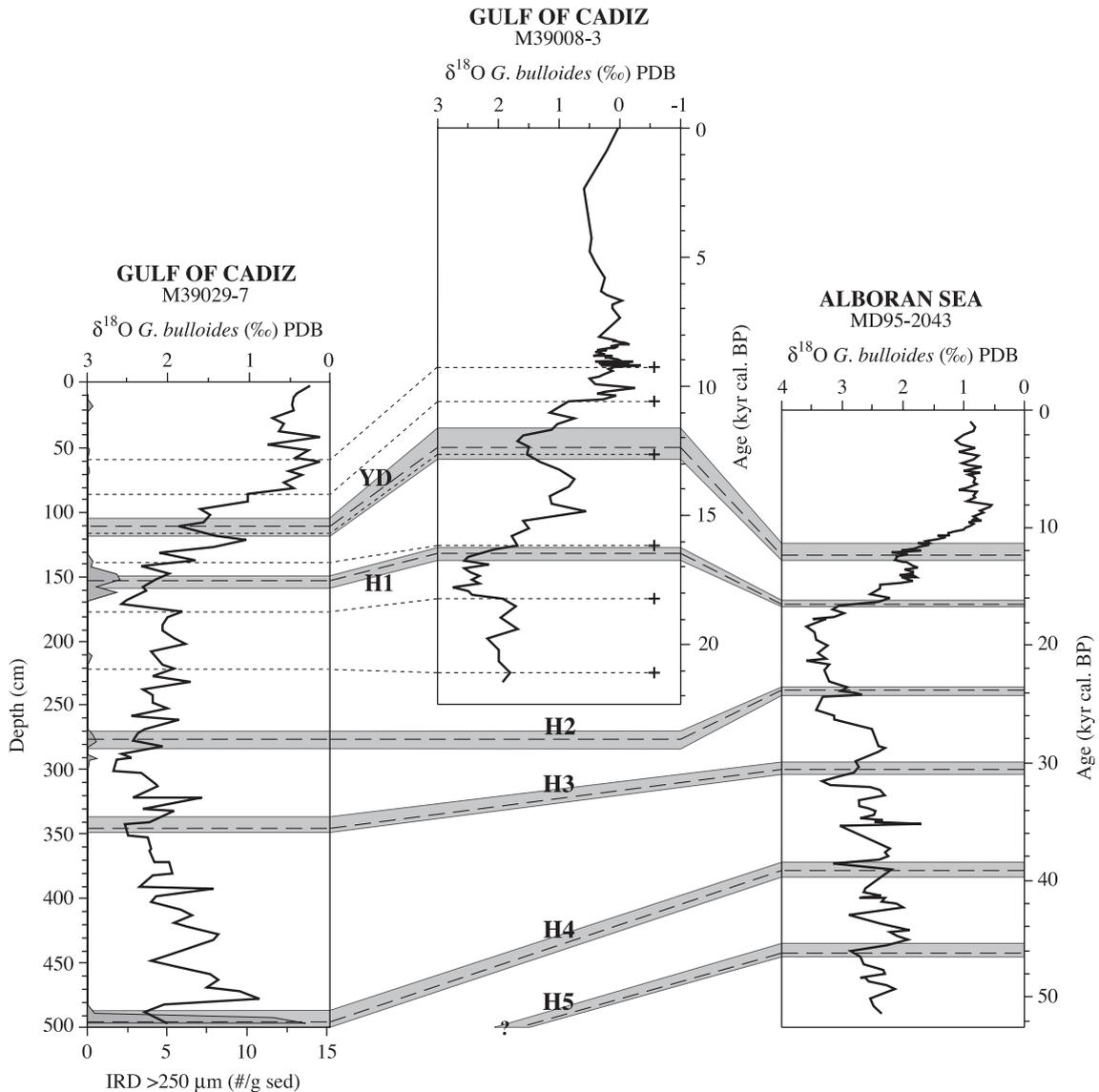


Fig. 2. Oxygen isotope records and correlation of cores M39029-7, M39008-3 (Cacho et al., 2001) and MD95-2043 (Cacho et al., 1999). The IRD record of core M39029-7 is also shown. Short dashed lines and black crosses correspond to AMS  $^{14}\text{C}$  age points from core M39008-3 (Cacho et al., 2001). Grey bands mark cold events correlated in all cores; long dashed lines in them indicate exact points of correlation. See text for explanation. Exact data of age points for core M39029-7 are given in Table 1.

*thothus fragilis*, *Umbellosphaera* spp., *Umbilicosphaera* spp., *Helicosphaera carteri*, *Syracosphaera* spp., *Coccolithus pelagicus* and *Florisphaera profunda*. Taxa such as *Braadurosphaera bigelowii*, *Pontosphaera* spp., *Rhabdosphaera clavigera*, *Calciosolenia murrayi* and *Gephyrocapsa caribbeanica* are only present in very small quantities at specific

depths. Reworked coccoliths—mainly Cretaceous taxa—may constitute more than 4% of the total assemblage in certain intervals.

*E. huxleyi* was divided into forms larger and smaller than 4  $\mu\text{m}$ , which were counted separately. Similar proportions of these two forms were recorded in the glacial stages (Fig. 3). In both cores, a sharp

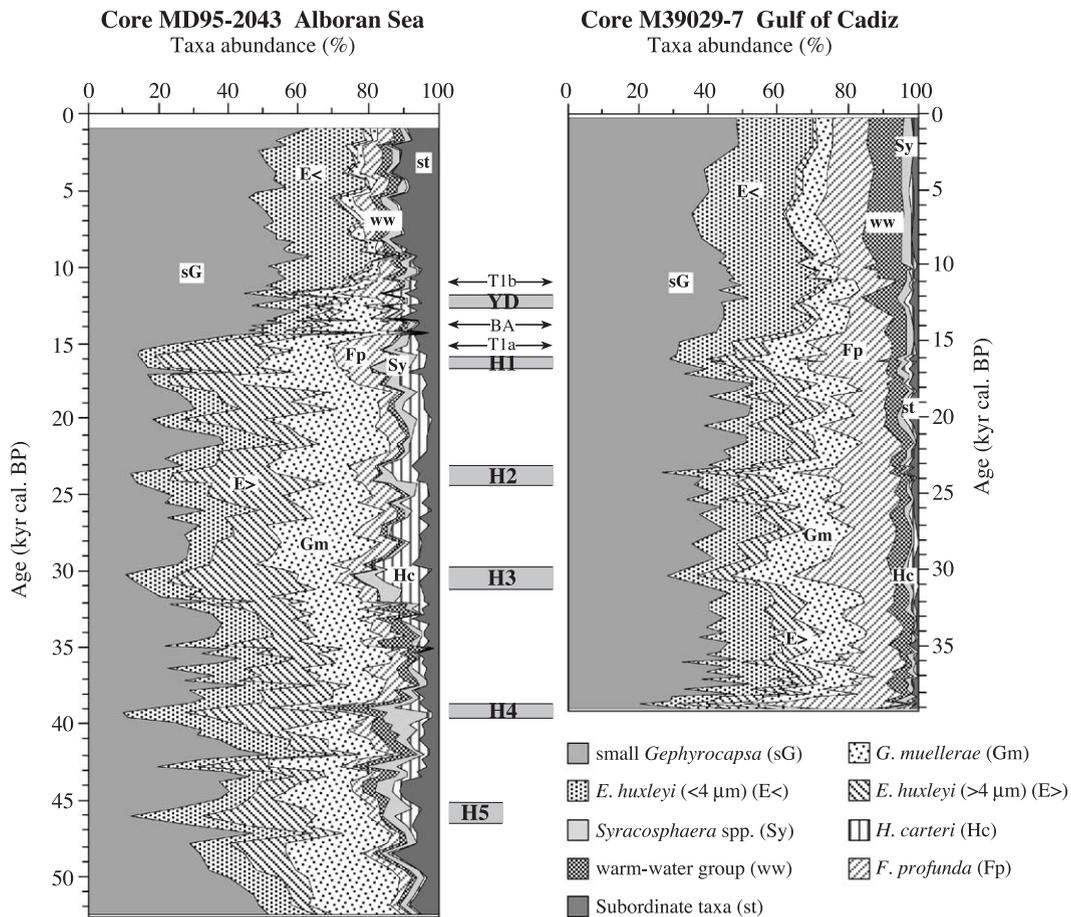


Fig. 3. Stratigraphic variations in the nannoflora abundances observed in cores M39029-7 and MD95-2043.

decrease in the abundances of *E. huxleyi* (>4 μm) occurred during the deglaciation, and in the Holocene the assemblages were characterised by unimodal populations of *E. huxleyi* (<4 μm) (Colmenero-Hidalgo et al., 2002). This occurrence of two differently sized *E. huxleyi* in the glacial period together with the decrease in larger ones at the end of this time have also been documented in the North Atlantic Ocean (Pujos-Lamy, 1977) and in the Western Mediterranean (Flores et al., 1993, 1997; Esposito, 1999). Verbeek (1990) even proposed a new species—*Emiliania pujoseae*—for forms larger than 3.5 μm and this latter classification was also used by Weaver et al. (1999). Nevertheless, a single species of *E. huxleyi* with at least two differently sized forms was considered here, as stated by Colmenero-Hidalgo et al. (2002). For the genus *Gephyrocapsa*, the proposal of Flores et al.

(1999) was followed (Flores et al., 1999, Table 3 and Appendix A).

Because light microscopy was used in this study, separate counts of the different species of *Syracosphaera* spp. were not performed. The different species of this genus are usually characterised by very thin structures, which are hard to distinguish with optical methods. *Syracosphaera* spp. is integrated by more than 20 species (McIntyre and Bé, 1967; Okada and McIntyre, 1977; Kleijne, 1993). Among them, *S. pulchra* is the most common species in sediment traps, cores, and recent sediments of the area (Knap-pertsbusch, 1993; Flores et al., 1997; Cros, 2001) and it is probably the main species in our cores.

*C. leptoporus*, *Umblicosphaera* spp., *O. fragilis* and *Umbellosphaera* spp. have been described as characteristic of tropical to subtropical oligotrophic

warm-water masses and of the Upper and Middle Photic Zones (McIntyre and Bé, 1967; McIntyre et al., 1970; Okada and Honjo, 1973; Kleijne, 1993; Winter et al., 1994). Here, all these four taxa have been lumped together as a warm water group.

The relationship between small placoliths and *F. profunda* (N Ratio) can be used as a primary productivity proxy (Beaufort et al., 1997, 2001; Flores et al., 2000). Small placoliths live mainly in the Upper Photic Zone (UPZ) and their abundance is generally interpreted as an indicator of upwelling intensity and medium to high productivity (Wells and Okada, 1997; Okada and Wells, 1997; Beaufort et al., 1997). On the other hand, *F. profunda* is a typical Lower Photic Zone (LPZ) inhabitant in medium and low latitudes (Okada and Honjo, 1973), and has been used as an indicator of the depth of the nutricline (Molfino and McIntyre, 1990a,b; Ahagon et al., 1993; McIntyre and Molfino, 1996; Beaufort et al., 1997). The N Ratio was calculated following the formula proposed by Flores et al. (2000), in which higher values imply higher primary productivity while low values are a signal of low productivity in the UPZ (Fig. 4).

#### 4.3. Stratigraphic distribution

##### 4.3.1. Glacial stages

The glacial period (MIS 2 and part of 3) is characterised by moderate to high proportions of small placoliths (between 20% and 70%) in both cores. *E. huxleyi* (>4 µm) and *G. muelleriae* constitute about 10–15% of the assemblage, while *G. oceanica* represents less than 5% in the Alboran Sea. The warm-water group is present in low quantities in the Alboran Sea, whereas its proportion in the Gulf of Cadiz is slightly higher; however, this group reaches more than 7.5% of the total assemblage in the Alboran Sea during MIS 3 (Figs. 3 and 5).

Several taxa show abundance peaks at specific short intervals of the glacial period; this is evident in the data from the Alboran Sea (Fig. 3). *H. carteri*, *Syracosphaera* spp. and reworked coccoliths show maximum peaks centred at about 16–17, 23–24, 29–30, 38.5–40 and 44.5–45.5 kyr cal. BP (Figs. 3, 6 and 7). *F. profunda* also increases—even up to 40%—in the above intervals in the Gulf of Cadiz, while in the Alboran Sea its proportion ranges around 5% (Fig. 3). *E. huxleyi* (>4 µm) increases its propor-

tion up to 30–50% during these intervals and in some other minor ones (identified as Dansgaard-Oeschger (DO) Stadials), showing a moderate inverse correlation with the  $U_{37}^k$ -SST profile of core MD95-2043 (Cacho et al., 1999) (Fig. 5). By contrast, small placoliths decrease in those periods, especially in the Alboran Sea (Figs. 3 and 8). In the Gulf of Cadiz, the IRD record allows these intervals to be identified as HE (Fig. 2), as stated above. To date, no IRD have been found in core MD95-2043 or in other cores from the Alboran Sea (Plaza, 2001).

In the glacial stages, the values of absolute abundances are similar in both cores, decreasing in HE and showing changes associated with DO oscillations (Figs. 4 and 8). The variations are more pronounced from 30 kyr cal. BP to the core bottoms; this is usually the period of stronger DO cycles, as seen in the  $U_{37}^k$  and GISP2 ice core records (Meese et al., 1997; Cacho et al., 1999).

##### 4.3.2. The deglaciation

In the deglaciation, coccolithophore assemblages were dominated by small placoliths. This period is characterised by a general decrease in larger placoliths (Fig. 3). A sharp increase in the proportions of *F. profunda* can be observed in both cores, with a maximum peak during Termination 1 (T1). This change is greater in core MD95-2043.

Increases in absolute abundances are observed at Termination 1a (T1a) in both cores (Fig. 4). The values during the Bølling-Allerød (BA) warm period are two-fold higher in the Alboran Sea. In core MD95-2043, abundances decrease slowly during YD and show an abrupt minimum peak at the end of this cold interval. In the Gulf of Cadiz, the YD is not well developed and absolute abundances are constant from BA to T1b.

##### 4.3.3. The Holocene

In the Holocene small placoliths represent around 75% of the total assemblage (Fig. 3). The warm-water group is also common, although it only exceeds 5% in the Gulf of Cadiz (Figs. 3 and 5). *H. carteri*, *Syracosphaera* spp. and reworked coccoliths do not exceed proportions higher than 5% or even 4% in both cores. *F. profunda* constitutes about 10% of the total assemblage in the Gulf of Cadiz and about 5% in the Alboran Sea.

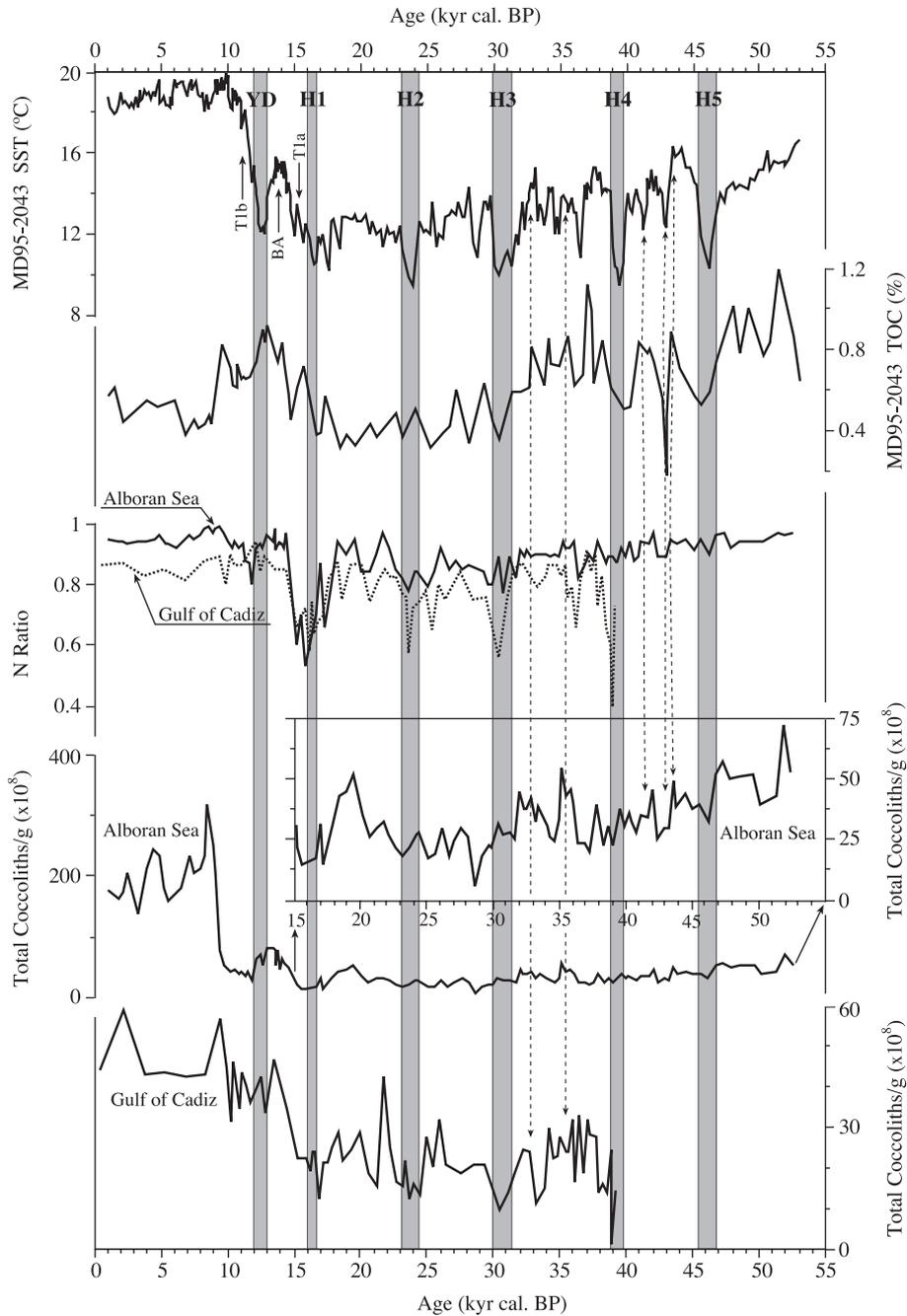


Fig. 4. Plots of absolute abundances and *N* Ratio (relationship between small placoliths and *F. profunda*) from cores M39029-7 and MD95-2043. The SST and TOC profiles from core MD95-2043 (Sierro et al., 1998; Cacho et al., 1999; Cacho et al., 2000) are plotted as reference. Total absolute abundances in the glacial interval of core MD95-2043 are enlarged in the small outlined box. HE and YD are marked by grey bands, while T1a, T1b and BA are indicated by black arrows. Dashed arrows join the horizons of better DO cyclicity correlation between signals.

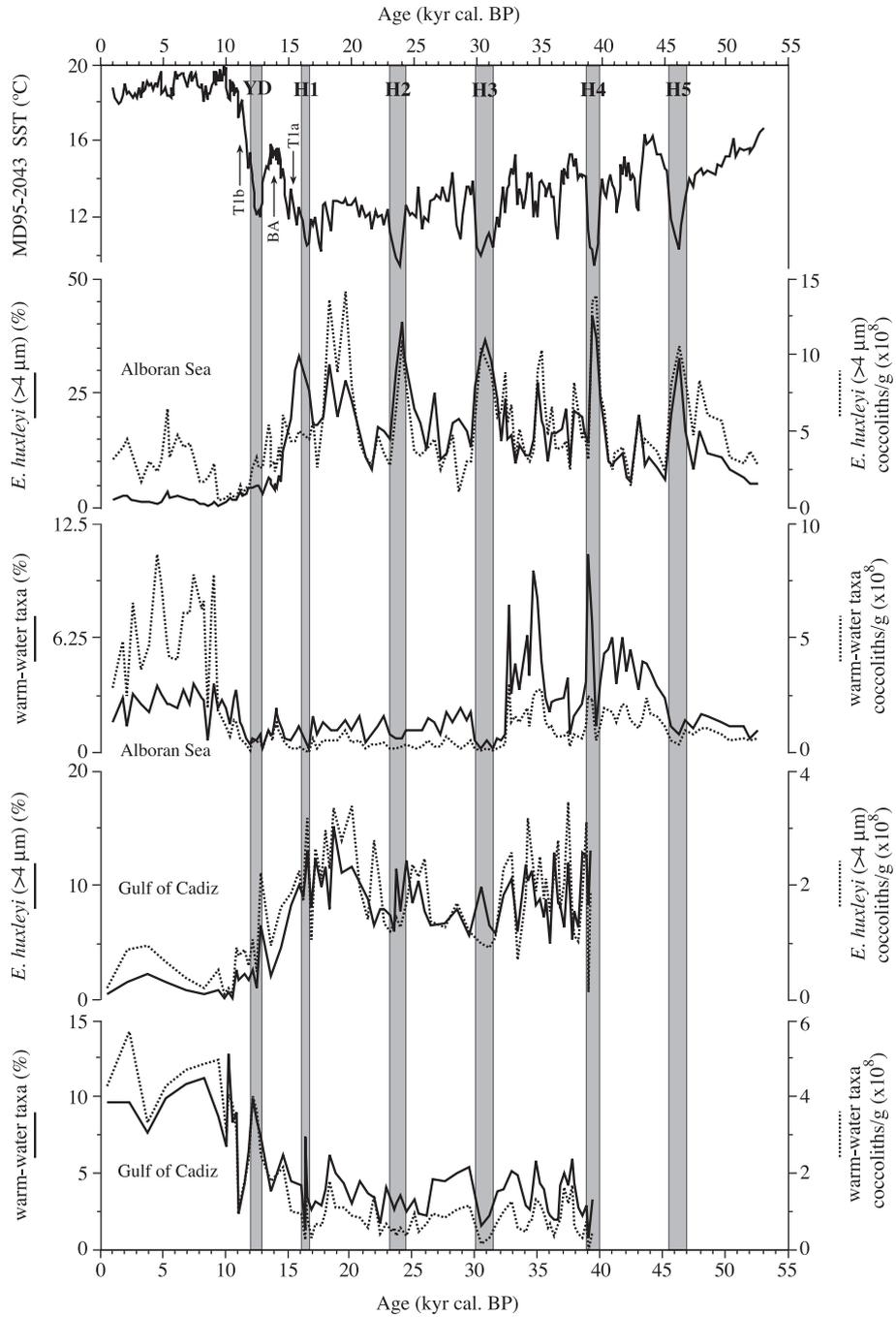


Fig. 5. Percentages (black lines) and absolute abundances (dotted lines) of the warm-water group and *E. huxleyi* (>4 μm) of cores M39029-7 and MD95-2043 in comparison to the SST record of core MD95-2043 (Cacho et al., 1999). HE and YD are marked by grey bands, while T1a, T1b and BA are indicated by arrows.

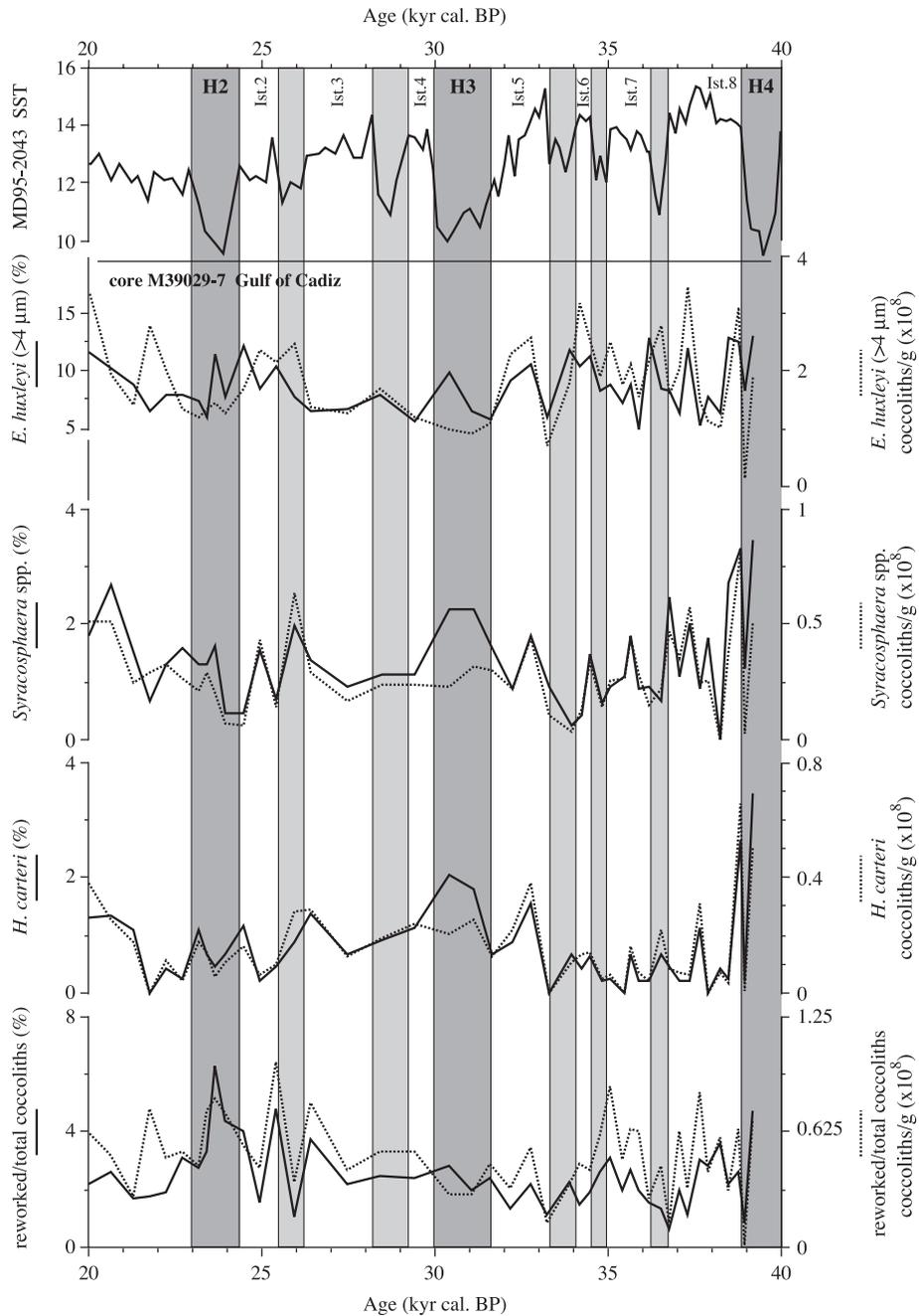


Fig. 6. Percentages (black lines) and absolute abundances (dotted lines) of several taxa from the lower section of core M39029-7. The SST record of core MD95-2043 (Cacho et al., 1999) has been plotted as a reference. HE and DO Stadials are marked with dark and light grey bands, respectively (Ist.: Interstadial).

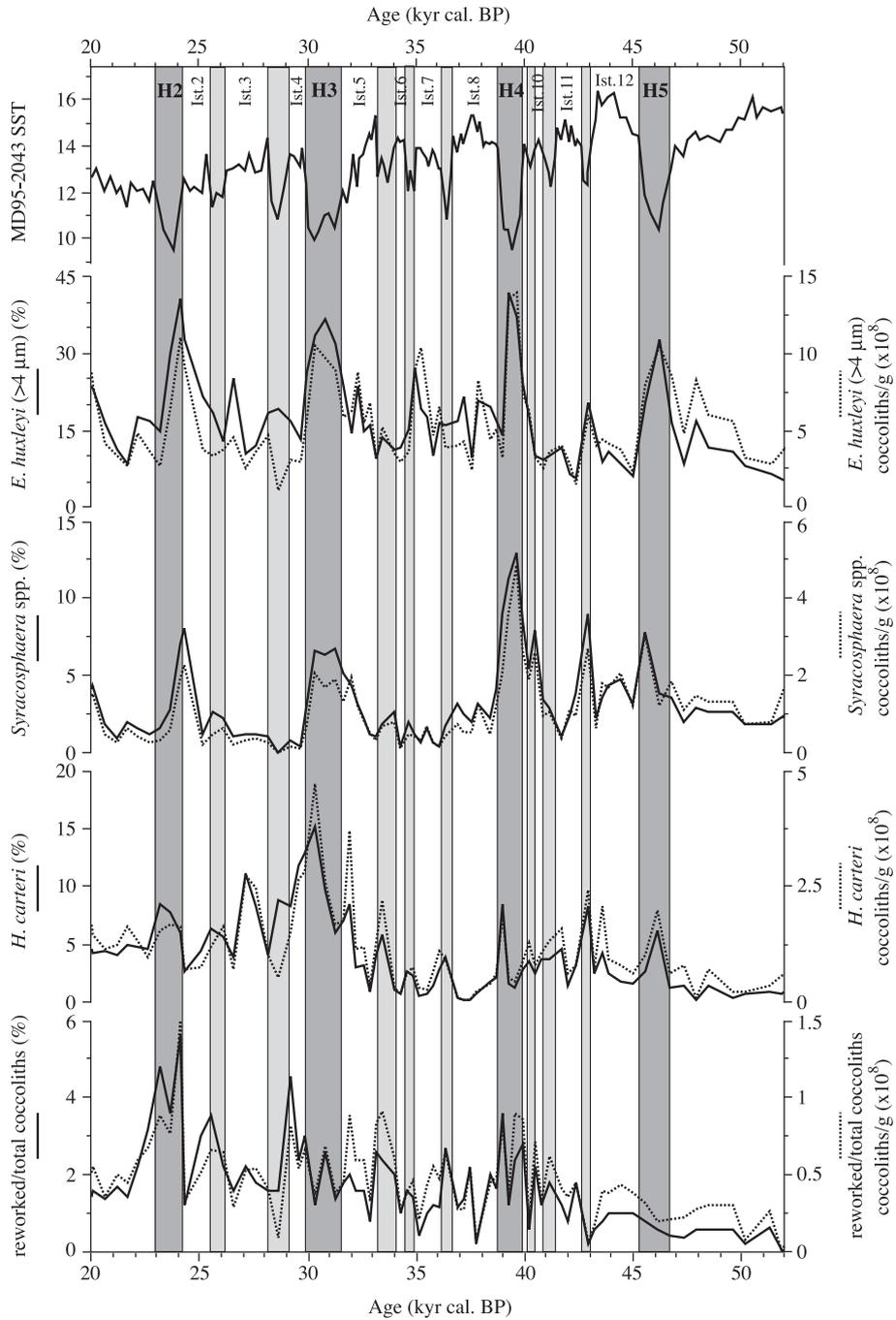


Fig. 7. Percentages (black lines) and absolute abundances (dotted lines) of selected taxa from the lower part of core MD95-2043. The SST record (Cacho et al., 1999) is used as a reference. HE and DO Stadials are marked with dark and light grey bands, respectively (Ist.: Interstadial).

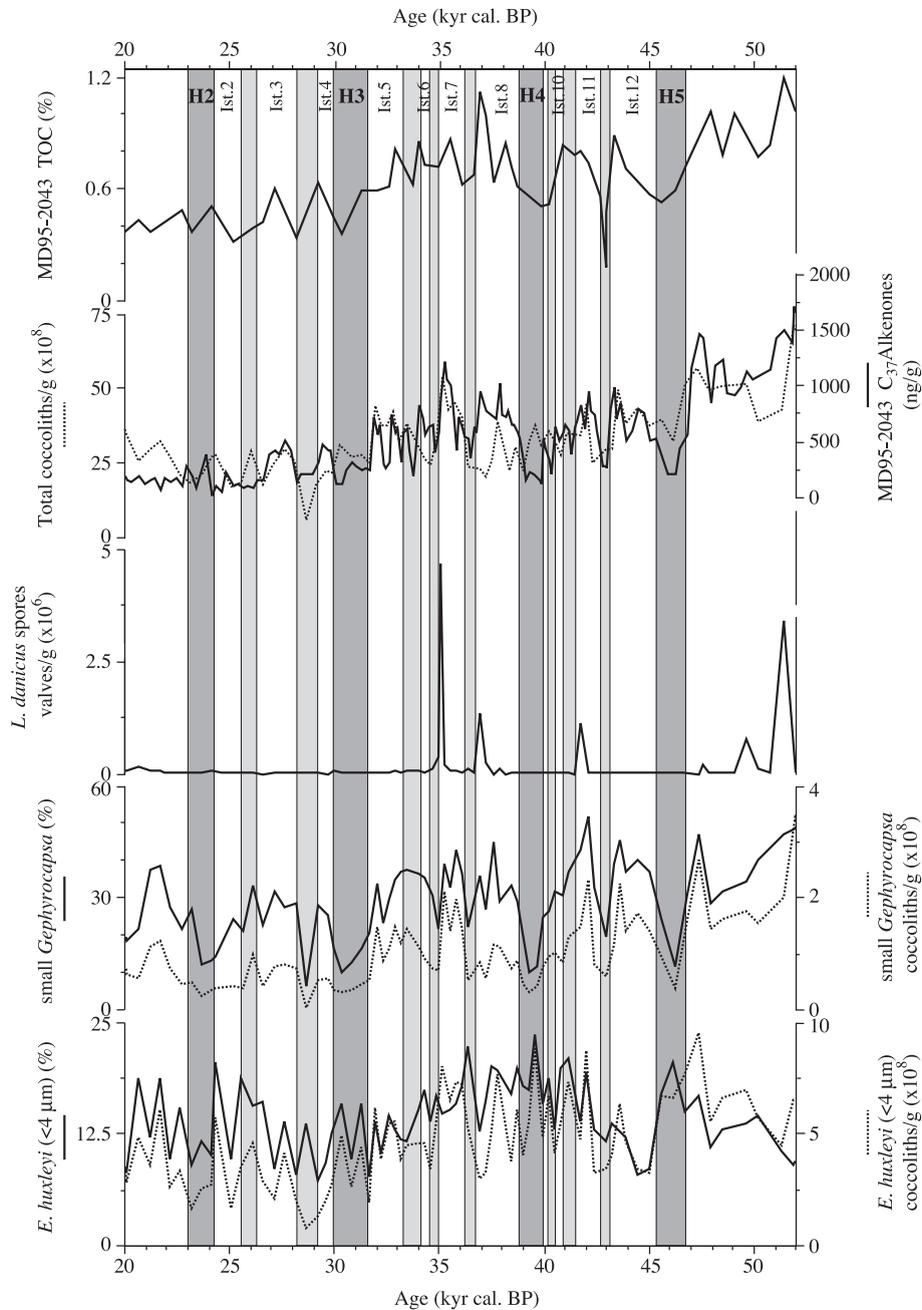


Fig. 8. Absolute abundances of coccoliths, *L. danicus* spores, and percentages (black lines) and absolute abundances (dotted lines) of small placoliths (small *Gephyrocapsa* and *E. huxleyi* (<4 μm)) of core MD95-2043 compared with TOC and C<sub>37</sub>-alkenone content (Cacho et al., 2000). Total absolute abundances of coccoliths (dashed line) are superimposed to C<sub>37</sub>-alkenone content (black line) for better comparison. HE and DO Stadials are marked with dark and light grey bands, respectively (Ist.: Interstadial).

In the Gulf of Cadiz, absolute abundances increase after 10 kyr cal. BP and show a maximum peak at around 9 kyr cal. BP. The highest abundances in the Alboran Sea are reached around 8 kyr cal. BP. The Holocene is the period with the highest absolute abundances, with values more than four times higher in the Alboran Sea ( $2 \times 10^{10}$  coccoliths/g) than in the Gulf of Cadiz ( $5 \times 10^9$  coccoliths/g) (Fig. 4).

## 5. Discussion

### 5.1. Coccolithophores and SST

The coccolithophore assemblages of cores M39029-7 and MD95-2043 consist of several taxa with very different ecological requirements and their variations can help to monitor the characteristics and evolution of the water masses of the area during the last glaciation and the present interglacial. The warm-water group seems to be controlled by SST in temperate waters. In our cores, they are scarce in the glacial stages and increase only in the deglaciation and Holocene (Fig. 5), following the reported increasing regional SST trend (Cacho et al., 1999, 2001; Bard et al., 2000; Pérez-Folgado et al., 2003). However, its higher abundance in the Gulf of Cadiz may be related to factors other than SST. Weaver and Pujol (1988) noted that these taxa never exceeded 2% in their cores from the Alboran Sea, and Knappertsbusch (1993) indicated that all but *Umbellosphaera* spp. were scarce in water and sediment samples from the whole Mediterranean. Therefore, the warm-water group seems to have been influenced by productivity in certain time intervals (as discussed below).

Conversely, the sharp decrease in *E. huxleyi* (>4  $\mu$ m) in the deglaciation and its scarce abundance in the Holocene is interpreted as a preference for cold waters (Fig. 5). A probably equivalent form (*E. huxleyi* type B of Young and Westbroek (1991)) is found in present-day waters of the North Sea (Van Bleijswijk et al., 1991). Maximum peaks of *E. huxleyi* (>4  $\mu$ m) occur during HE, which—according to the SST record (Cacho et al., 1999, 2001; Bard et al., 2000; Boessenkool et al., 2001; Pérez-Folgado et al., 2003)—are the coldest intervals in the area. The abundances of this taxon are higher in the Alboran Sea throughout the glacial period (and especially

during HE) (Fig. 5), suggesting that the Western Mediterranean was cooler than the Gulf of Cadiz during this entire time interval. This notion is supported by the higher proportions of cold-water planktonic foraminifers (*N. pachyderma* sin. and *Turborotalita quinqueloba*) in core MD95-2043 (Reguera, 2001; Pérez-Folgado et al., 2003), and by lower SST in the Alboran Sea during these cold events.  $U_{37}^k$ -SST profiles show that the water masses of the Gulf of Cadiz were around 4 °C warmer than Mediterranean ones in HE and that the differences were even larger during H1 (Cacho et al., 2001).

### 5.2. Coccolithophore production and paleoproductivity

Coccolithophores are among the most important primary producers in present-day oceans. Absolute abundances (Fig. 4) are in general agreement with the  $U_{37}^k$ -SST records and with previous research in the area (Flores et al., 1997; Cacho et al., 1999, 2001). Low values during HE and DO Stadials and their increase at T1a were probably forced by changes in SST. In the Gulf of Cadiz, the peak in abundance at 9 kyr cal. BP is synchronous with the maximum  $U_{37}^k$ -SST in the area (Cacho et al., 2001). In the Alboran Sea, maximum absolute abundances were reached later (around 8–9 kyr cal. BP), concomitant with a drop in SST related to the 8.2 kyr cal. BP event in the North Atlantic (Alley et al., 1997; Cacho et al., 2001). This peak has no equivalent in the Gulf of Cadiz and is synchronous with changes in the planktonic and benthic foraminifer assemblages in the area (Sierro et al., 1998; Pérez-Folgado et al., 2003). It can be interpreted as an increase in coccolithophore production due to the onset of the MAW gyres and the creation of upwelling cells in the Alboran Sea (Rohling et al., 1995; Pérez-Folgado et al., 2003). This dramatic hydrological change may account for large differences in the absolute abundances of coccolithophores between both cores during the Holocene. Higher proportions of oligotrophic warm-water taxa in core M39029-7 (Fig. 5) indicate that the Gulf of Cadiz was warmer and less productive than the Alboran Sea, where the development of a more eutrophic environment led to an increase in high-productivity taxa, such as small placoliths (mainly small *Gephyrocapsa*). This differ-

ence between areas has also been observed in the diatom record (Abrantes, 1988).

The N Ratio shows that, in general, both cores have high Upper Photoc Zone (UPZ) productivity values (Fig. 4). In the Gulf of Cadiz, HE and stronger DO Stadials are marked as drops in the N Ratio implying strong changes in the water column, while in core MD95-2043 the N Ratio gradually decreases following the SST trend during the glacial period and shows no strong changes. This suggests the existence of adverse conditions for the development of *F. profunda* in this area. Very low temperatures in the LPZ could have prevented this species from increasing, since its minimum temperature limit is around 10–12 °C (Okada and Honjo, 1973). Only between 18 and 15 and between 12 and 9 kyr cal. BP does the N Ratio seem to vary in the Alboran Sea, implying a decrease in small placoliths and an increase of *F. profunda*. This variation is synchronous in both cores, and it can be correlated with low coccolithophore absolute abundances. In core MD95-2043, this decrease is more abrupt and is related to the youngest “Organic-Rich Layer”, identified and interpreted by Sierro et al. (1998) as an interval in which the water column of the Western Mediterranean region was stratified due to the deglacial increase in sea level, higher productivity and/or increased rainfall. Total organic carbon (TOC) values of core MD95-2043 are high in this interval and have been interpreted as evidence of reduced bottom ventilation (Sierro et al., 1998; Bárcena et al., 2001). The higher TOC content could also indicate high UPZ productivity, although low coccolithophore abundances and the N Ratio are better explained by stratification, since the peak at H1 and T1a coincides with a low N Ratio and low absolute abundances in both cores. A smaller drop in the N Ratio is observed at the end of the YD and T1b, indicating that stratification was not as strong as during early T1a. The end of this episode is marked by a decreasing trend of the TOC at the end of T1b; at the same time, a higher N Ratio and peaks in absolute abundance values can be observed (Fig. 4).

### 5.3. Coccolithophores and Heinrich events

In the Gulf of Cadiz, *F. profunda* shows several peaks coinciding with HE, and it reaches 40% of the total assemblage during H4. This record is opposite to

that of small placoliths and such peaks are probably related to a decrease in productivity in the UPZ (Fig. 3). Two different, non-excluding hypotheses can be invoked to account for this:

- (1) high turbidity in the UPZ, with a decrease in the intensity of the light in the LPZ that forced *F. profunda* to migrate upwards (Ahagon et al., 1993)
- (2) stratification in the UPZ and a deepening of the nutricline, which increased abundance of *F. profunda* in the LPZ (Molfinio and McIntyre, 1990a,b).

Other evidence supports these two scenarios. For the first hypothesis, the increases in *H. carteri* and *Syracosphaera* spp. (Fig. 6) could indicate the presence of a turbid and fresher upper layer of water. *H. carteri* has commonly been cited as a coastal taxon and a marker of moderate nutrient levels and turbidity (Giraudeau, 1992; Ziveri et al., 1995). It has been recorded in the proximal Plio/Pleistocene sediments of the Nile delta (Lottaroli, 2000), and also in the Eastern Mediterranean Sapropel S1 sediments at 8 kyr cal. BP (Negri et al., 2000; Negri and Giunta, 2001). *Syracosphaera* spp. has been related to the input of terrigenous materials and a decrease in salinity in the Alboran Sea during T1 (Weaver and Pujol, 1988). Flores et al. (1997) indicated that variations in salinity and nutrient content could be the main factor controlling this genus, although SST could have controlled its increasing trend towards the Holocene in the Gulf of Cadiz (Sierro et al., 1999). Pollen analyses indicate that the Iberian climate during HE was cold and arid (Sánchez-Goñi et al., 2002); lower sea level periods in the zone were synchronous with HE (Hernández-Molina et al., 1994, 2000). These phenomena could have contributed to the formation of nepheloid currents from the continent. High abundances of reworked specimens are also recorded during most HE—with a maximum in H2—and this can be considered as a proxy of continental input (as in the Western Mediterranean; Flores et al., 1997), in agreement with the similar records of *H. carteri* and *Syracosphaera* spp.

In the second hypothesis, the presence of IRD in core M39029-7 (Löwemark, 2001) implies the arrival of cold and fresher North Atlantic waters carrying

icebergs in the area studied during HE (except H3). This, together with the presence of cold- (*E. huxleyi* (>4  $\mu\text{m}$ )) and warm-water taxa (*F. profunda*) at different depths, supports the existence of an inverse thermocline and water stratification. This model, proposed by Boudoire et al. (1996) for core MD95-2042 off SW Portugal, suggests that during HE cold North Atlantic waters were distributed only in the upper few meters of the water column and caused a decrease in coccolithophore productivity in the UPZ. In the same area, salinity could have decreased by about 1‰ or 2‰ during HE (Bard et al., 2000).

Both hypotheses can be unified within the same scenario for the Gulf of Cadiz area. A cold and fresher upper layer could have been originated by the southward flow of NASW following the Iberian margin and increasing terrigenous input from Iberia caused by lower sea level and aridity during HE. This combination could explain the maxima of *E. huxleyi* (>4  $\mu\text{m}$ ), *H. carteri*, *Syracosphaera* spp. and reworked coccoliths. This colder, fresher and probably more turbid upper layer would have produced a decrease in small placoliths (N Ratio minima—Fig. 4). At the same time, an inverse thermocline could have been formed due to the existence of warmer waters below the first meters. The presence of *F. profunda* indicates that the temperature of these waters was at least around 10–12 °C. The position of the nutricline is uncertain: either its deepening to the LPZ by stratification or the ascent of *F. profunda* to shallower depths due to a decrease in light could be invoked to explain the increase of this taxon.

A similar scenario can be proposed for the Alboran Sea. Peaks of *H. carteri*, *Syracosphaera* spp. and reworked coccoliths simultaneous with HE suggest a fresher and turbid upper layer (Fig. 7). Peaks of reworked coccoliths and *Syracosphaera* spp. occurring in the same period as H1 have been reported previously (Weaver and Pujol, 1988). Pérez-Folgado et al. (2003) state that the HE in the Alboran Sea are characterised by increases in *N. pachyderma* sin. and *T. quinqueloba*; this latter planktonic foraminifer is better developed in cold, turbid and shallow water masses. Cold waters would have caused the sharp peaks of *E. huxleyi* (>4  $\mu\text{m}$ ), and all these factors probably led to the decline of small placoliths. Previous studies on core MD95-2043 have shown that during HE the adjacent

landmass was characterised by aridity (Sánchez-Goñi et al., 2002) and that aeolian terrigenous sediment input to the basin from the Sahara desert increased (Moreno, 2002). Some of the fine-grained material could have entered the Alboran Sea transported by the MAW (Weaver and Pujol, 1988), as has been noticed in the reworked diatom record from the Guadalquivir basin (Abrantes, 1988; Bárcena et al., 2001); this transport seemed to intensify at the end of MIS 2 (Grousset et al., 1988).

Nevertheless, *F. profunda* does not behave as in the Gulf of Cadiz and shows minor differences in abundance throughout the core, ranging around 5% except between 18 and 9 kyr cal. BP (Fig. 4). There may be several reasons for this difference between the two cores: first, *F. profunda* is not a common taxon in the Western Mediterranean Sea—even in the Holocene—with abundances always around 5% (Flores et al., 1997; Sbaifi et al., 2001). Second, LPZ temperatures during HE were too cold for the regular development of *F. profunda*. In fact, during H2 and H4 temperatures were lower than 10 °C, as inferred from  $U_{37}^k$ -SST and planktonic foraminiferal assemblages (Cacho et al., 1999; Pérez-Folgado et al., 2003). These cold waters probably represented a severe barrier for the development of *F. profunda*. Even in the case of the migration of this taxon to the UPZ due to a decrease in light levels, low SSTs were not favourable. Third, the circulation of MAW and MOW was intensified during these cold events (Cacho et al., 2000), while in the North Atlantic there was a general slowing down or even a shutdown of the thermohaline circulation. Increased water movement would have favoured an increase in some UPZ taxa as well as a decrease in the development of *F. profunda*.

The limiting effect of low SST and/or turbidity on the coccolithophore assemblage can be also inferred considering the decrease in small placoliths (Fig. 8) and in total absolute abundances (Fig. 4).

#### 5.4. Dansgaard-Oeschger cycles

DO cycles (Dansgaard et al., 1993; Meese et al., 1997) have been recorded in several profiles of the Western Mediterranean region (e.g. Allen et al., 1999; Cacho et al., 1999; Pérez-Folgado et al., 2003). The coccolithophore records of cores M39029-7 and MD95-2043 reveal short-term variations associated

with DO cycles, especially in core MD95-2043. These changes are of lower scale than those recorded during HE, showing that DO variability was not as strong (Figs. 6–8). In this area, DO cyclicity was driven by atmospheric teleconnection with higher latitudes instead of a coupled atmospheric–oceanic connection, as during DO cycles associated with HE (Cacho et al., 1999).

Higher values of the organic proxies (TOC, C<sub>37</sub> alkenones and the *n*-hexacosanol index) have been recorded during DO Interstadials in core MD95-2043 (Fig. 8), suggesting degradation due to enhanced bottom ventilation in DO Stadials (Cacho et al., 2000). Total absolute abundances and proportions of small placoliths—especially small *Gephyrocapsa*—follow the same trend as those records, pointing to a good correlation between organic and micropaleontological proxies. Accordingly, CO<sub>2</sub>-depleted, well-oxygenated bottom currents could have oxidised organic matter and, at the same time, enhanced the preservation of the carbonate fraction (including coccolithophores) during DO Stadials. Dilution by terrigenous input in these periods could also explain some of these changes (minima peaks) but this single effect cannot account for the decreasing trend of small placoliths: reworked specimens—though more abundant during DO Stadials—range between 1% and 5% of the assemblage and have low absolute abundances ( $5\text{--}15 \times 10^7$  coccoliths/g) as compared to those of small *Gephyrocapsa* ( $4\text{--}20 \times 10^8$  coccoliths/g) (Figs. 7 and 8).

Variations in total absolute abundances and in small *Gephyrocapsa* (the most abundant group) could also reflect changes in carbonate (coccolithophore) production. Higher SST during DO Interstadials could have led to increases in coccolithophore productivity and higher quantities of C<sub>37</sub> alkenones; during DO Stadials, lower SST would imply lower coccolithophore productivity and less C<sub>37</sub> alkenone production. Peaks of spores of *Leptocylindrus danicus* synchronous with most of the small *Gephyrocapsa* abundance peaks (e.g. DO Interstadials 7, 8, 11 and 14) (Fig. 8) are additional indications of higher primary productivity in those intervals. The high abundances of these diatom spores during YD and the LGM have been interpreted as the final interval of high diatom productivity periods, in association with nutrient depleted, fresher fluvial waters (Bárcena et al., 2001) and

higher rainfall during DO Interstadials, (as shown in the pollen record; Sánchez-Goñi et al., 2002).

Like HE, DO Stadials are characterised by increases in the abundance of *H. carteri*, *Syracosphaera* spp., reworked taxa and *E. huxleyi* (>4 μm), although the peaks are always lower than those seen within the HE and some of them are not clearly defined (Fig. 7). The abundances of these taxa are higher in the Alboran Sea than in the Gulf of Cadiz (Fig. 6), again showing that more severe conditions prevailed in the Alboran Sea. DO Stadials were dry and cold, with higher wind transport, as revealed by pollen and biogeochemical data (Cacho et al., 2000; Sánchez-Goñi et al., 2002). SST in the Alboran Sea ranged between 11 and 12.5 °C (Cacho et al., 1999), with a possible minimum land mean temperature in the coldest month of about –1 °C, as proposed by Sánchez-Goñi et al. (2002). *E. huxleyi* (>4 μm) was favoured by those SST. As in HE, an increase in terrigenous input, together with an enhanced MOW and MAW circulation (Cacho et al., 2000), could have led to higher surface water turbidity and therefore the flourishing of *H. carteri* and *Syracosphaera* spp. In this respect, the lower abundances of reworked specimens and of *H. carteri* and *Syracosphaera* spp. in the Gulf of Cadiz during DO Stadials would indicate that during these periods most of the Guadalquivir suspended material was deflected towards the Mediterranean Sea by a stronger NASW-MAW.

## 6. Conclusions

Long- and short-term climatic variability in the North Atlantic during the last 50,000 years is recorded in cores M39029-7 and MD95-2043, where HE and DO cycles have been observed and identified in the coccolithophore records. The “fingerprints” left by these events in the coccolithophore assemblages can be considered as useful biohorizons to improve the biostratigraphy of the region. The abundances of *E. huxleyi* (>4 μm) and of *Syracosphaera* spp. and *H. carteri* show peaks during HE and most DO Stadials. This, together with the sharp decline in the larger form of *E. huxleyi* during the deglaciation, indicates that this taxon is a cold-water indicator. *H. carteri* and *Syracosphaera* spp. were probably controlled by decreased salinity and higher turbidity levels.

Primary productivity during the Holocene was higher than in the glacial stages. This difference was several times higher in the Alboran Sea than in the Gulf of Cadiz, as indicated by the comparison of the total absolute abundances and proportions of warm/oligotrophic taxa. The onset of upwelling cells in the Alboran Sea in the early Holocene could explain these differences between the two areas.

HE and DO Stadials were characterised by colder and probably more turbid and fresher upper-water masses. An enhancement of the exchange of waters through the Strait of Gibraltar during these cold periods could be proposed on the basis of the higher abundances of some of the taxa in the Mediterranean core, which could have been transported from the Gulf of Cadiz. Stratification of the water column during HE probably led to an increase in the values of *F. profunda* in the Gulf of Cadiz, but in the Alboran Sea adverse paleoecological conditions (lower SST and enhanced circulation) probably prevented this taxon from occurring in higher abundances.

In both cores, warmer waters and higher coccolithophore productivity occurred during DO Interstadials. The abundances of small placoliths (in particular of small *Gephyrocapsa*) follow the same trend recorded in oxygen isotopes and SST measurements. The abundance of reworked specimens can be used as an indicator of terrigenous input; although it is higher during DO Stadials we consider that the quantity of inferred terrigenous input is insufficient to account for the decrease in small placoliths during those intervals. Therefore, small placoliths can be used as an index of decreased coccolithophore productivity in DO Stadials.

Quantitative differences in the coccolith signal between the two cores indicate that the Alboran Sea responded more strongly to climatic and oceanographic changes than the Gulf of Cadiz. This semi-enclosed basin seems to be more sensitive to changes despite the better connection of the Gulf of Cadiz to the open ocean.

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