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Sea surface dynamics and coccolithophore behaviour during sapropel deposition of Marine Isotope Stages 7, 6 and 5 in Western Adriatic sea

Áurea Narciso[1], José-Abel Flores[2], Mário Cachão[1,3], Francisco Javier Sierro[2], Elena Colmenero-Hidalgo[2], Andrea Piva[4] and Alessandra Asioli[5]

[1] Centre Geology University of Lisbon, 1749-016 Lisboa, Portugal. acnarciso@fc.ul.pt
[2] Departament of Geology, University of Salamanca, 37008 Salamanca, Spain
[3] Department of Geology, Fac. Sciences, University of Lisbon, 1749-016 Lisboa, Portugal
[4] ISMAR, Consiglio Nazionale delle Ricerche, Via Gobetti 101, 40129 Bologna, Italy
[5] IGG, Consiglio Nazionale delle Ricerche, Via Giotto 1, 35100 Padova, Italy

Resumen

Se presenta un análisis detallado de los nanofósiles calcáreos registrados en el testigo PRD1-2, recuperado durante la campaña PROMESS 1 con el objetivo de estudiar las variaciones en las asociaciones durante los MIS (Estadios Isotópicos Marinos) 7, 6 y 5, que integran capas equivalentes a los sapropeles S_8eq.–S_3eq.. Los datos reflejan un descenso en la productividad de cocolitóforos, marcada por *Gephyrocapsa* spp., durante los MIS 7 y 6 en la capa equivalente al sapropel S_5eq. Por el contrario, *Florispharea profunda* muestra picos en su abundancia en esos intervalos, reflejando una posición relativamente profunda de la nutriclina. En las dos capas equivalentes a sapropeles del MIS 5 (S_4eq. y S_3eq.) se observa lo opuesto. La sedimentación de esos sapropeles atípicos son concomitantes con la producción de agua profunda del Adriático y una subsecuente mezcla, como consecuencia de la actividad del viento Bora (noreste), favoreciendo la eclosión de especies de zona fótica superior en relación a las de zona fótica inferior. Por otra parte, se ponen de manifiesto modelos de distribución similar entre especímenes retrabajados (Cretácico-Terciario), *Coccolithus pelagicus* y *Helicosphaera carter*i, con incremento importante en las capas equivalentes a sapropeles de los MIS 7 y 6 y durante la parte final del MIS 6, el más frío y seco. Debido al amplio rango de distribución de *C. pelagicus* (Paleoceno temprano-Reciente) y *H. carteri* (Mioceno-Reciente) los ejemplares procedentes del continente y vertidos a la cuenca Adriática, o redistribuidos por Corrientes de fondo, son de particular importancia en cientos intervalos (210-200, 145, 135, 110 y 85 ka). *Syracosphaera* spp., *Rhabdosphaera clavigeraaa* y *Calciosolenia* spp., normalmente relacionadas con aguas cálidas y oligotróficas, no muestran relación con el registro isotópico. Sin embargo, su importante incremento hacia la parte superior o sobre la terminación de algunas capas equivalentes a sapropeles es coherente con el final de las condiciones secas y con el subsecuente de una situación oligotrófica y una redistribución de los nutrientes. Al mismo tiempo, el incremento de *Braarudosphaera bigelowii* coincidiría con una reducción en la salinidad durante S_8eq. y S_6eq., aunque su presencia puede corresponder también a aportes continentales, dado su amplio rango estratigráfico (Cretácico-Reciente).

Palabras clave: Nanofósiles calcareous, Cocolitóforos, Pleistoceno, Sapropeles, Adriático, Paleoceanografía, Paleoecología

Abstract

A detailed calcareous nannofossil analysis was performed in the core PRAD1-2, recovered in the Mid-Adriatic Deep during the PROMESS 1 Cruise, in order to show fluctuations of several species during the Marine Isotope Stages 7, 6 and 5, crossing the S_8eq.–S_3eq. sapropel-equivalent layers. This study reports a decrease in the coccolithophore productivity, given by *Gephyrocapsa* spp. abundance decreases, during the deposition of MIS 7 and MIS 6 sapropel-equivalent layers and also during S_5eq. *Florisphaera profunda*, on the contrary, shows abundance peaks within these intervals, reflecting a deeper position of the nutricline. Within the two last sapropel-equivalent layers of MIS 5 (S_4eq. and S_3eq.) the opposite can be observed. The deposition of these atypical sapropels may have been concomitant with some Adriatic Deep Water production and subsequent some water column mixing, in result of the activity of the north-easterly Bora wind, favouring the development of the upper photic zone species in relation to the lower photic zone inhabitant *F. profunda*. Similar general abundance patterns are evidenced by reworked specimens (Cretaceous-Tertiary), *Coccolithus pelagicus* and *Helicosphaera carteri*, with important increases during the sapropel-equivalent layers of MIS 7 and MIS 6 and during the latest part of the glacial stage 6, the coldest and the driest one. Due to the extended fossil record of *C. pelagicus* (Early Paleocene-Recent) and *H. carteri* (Miocene-Recent), reworked placoliths and helicoliths from a continental source, by precipitation and runoff into the Adriatic basin, or from redistribution by bottom currents, are of particular importance at certain moments (210-200, 145, 135, 110 and 85 kyr). *Syracosphaera* spp., *Rhabdosphaera clavigeraa* and *Calciosolenia* spp., usually related to warm and oligotrophic water masses, do not show a clear correlation with the isotope record. However, their important increases at the top or above the termination of some sapropel-equivalent layers is consistent with the end of dryer conditions that feature the sapropel deposition, and with the subsequent reestablishment of the general oligotrophic state of the surface water with a nutrient redistribution. At the same time a salinity reduction should occur due to the simultaneous presence of *Braarudosphaera bigelowii*. During S_8eq. and S_6eq. the presence of *B. bigelowii* coupled with its stratigraphic range (Cretaceous-Recent), may also indicate a continental source for some pentaliths.

Key words: Calcareous nannofossils, Coccolithophores, Pleistocene, Sapropels, Adriatic, Paleoceanography, Paleoecology.

1. INTRODUCTION

Several studies have been performed on sapropel layers, a characteristic organic rich matter deposit commonly occurring in the Mediterranean Sea. Using sedimentological (Kroon *et al.*, 1998; Capozzi and Picotti, 2003; among others), geochemical (Bouloubassi *et al.*, 1999; Arnaboldi and Meyers, 2003; Gogou *et al.*, 2007; among others) and micropaleontological (Castradori, 1993; Rio *et al.*, 1997; Giunta *et al.*, 2003; Principato *et al.*, 2006; Marino *et al.*, 2007; Triantaphyllou *et al.*, 2009a, b, c; among others) techniques, most of these studies refer that sapropels are dark-coloured organic-rich layers interbedded in the normal pelagic (or hemipelagic) sediments of the Mediterranean Sea, related to climatic or oceanographic variations. The sapropel generation is associated to orbital scale oscillations under conditions of maximum summer insolation, corresponding to a minimum of the precession component of Earth's orbital with a periodicity of 21 kyr (Hilgen, 1991; Lourens *et al.*, 1996; Hilgen *et al.,* 1997; Sierro *et al.*, 1999). The maximum summer insolation is reflected by an increase in precipitation and runoff in the Mediterranean basin, responsible for an increased stratification of surface waters, while its reduction leads to a dry and cold climate, with the mixing of the bottom waters and, consequently, the reduction of organic matter (Hilgen, 1991; Sierro *et al.*, 1999, Flores *et al.*, 2005).

During the PROMESS 1 project several cores were recovered in the Adriatic Sea. The good quality record of the sapropels in some sectors, as well as the moderately high sedimentation rates (20 cm/kyr) observed after the preliminary analyses, allowed the achievement of new material for study (Piva *et al.*, 2008).

Calcareous nannofossils, in which the Coccolithophore group is included, are an important component of sapropels and have been used mainly for biostratigraphic correlations and also for paleoceanographic reconstructions (Müller, 1985; de Kaenel and Villa, 1996; Negri *et al.*, 1999a, b; Negri and Villa, 2000; Flores *et al.*, 2005; Principato *et al.*, 2006; Triantaphyllou *et al.*, 2009a, b, c) by the knowledge of some parameters such as temperature, salinity, productivity, turbidity, depth, among others.

The present study addresses a time series that crosses several sapropel layers (S_3, S_4, S_5, S_6, S_7 and S_8) included in Marine Isotope Stages (MIS) 7, 6 and 5, between 199 and 81 kyr. Our sapropel layers are referred as sapropel-equivalent (e.g. S_3eq.) because this numeric sequence was not specifically defined for the Adriatic ones, but for the sapropels of the Mediterranean in general (Piva *et al.*, 2008). They correspond to dark seldom laminated sediments bearing distinctive micropaleontological, geochemical and paleomagnetic parameters, indicating low oxygen conditions (Piva *et al.*, 2008). Based on micropaleontological content, this study allows to recognize the response of coccolithophore assemblages to climate variation during interglacial/glacial stages, and also to infer changes on several (paleo)ceanographic variables during the mentioned interval.

2. MATERIAL AND METHODS

2.1 Location of the studied area and material

For the present study, a borehole referred as PRAD1-2 was collected in the Mid-Adriatic Deep (LAT 42º40'34.7826"N; LONG 14º46'13.5565"E) in 185.5 m water depth (Figure 1). The coring device on board R/V Bavenit in the PROMESS1 Cruise provided a continuous sediment core of 71.2 m, with a recovery of 99.96 % (Piva *et al.*, 2008).

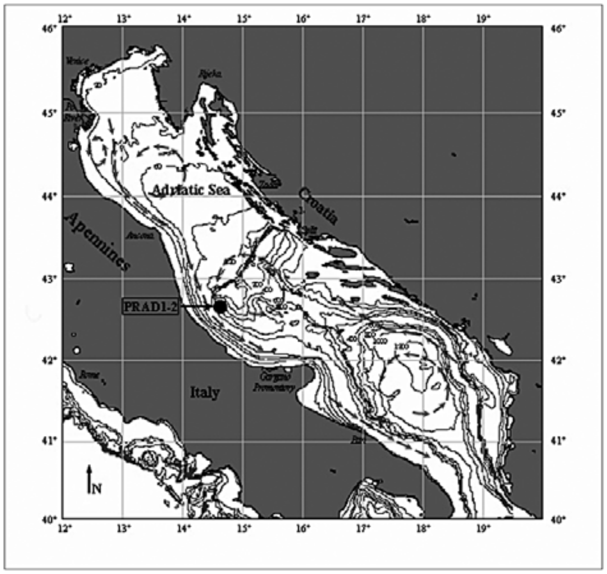

Figure 1. Map location of the borehole PRAD1-2 with coastline, topography and surface circulation (represented by arrows; based on Artegiani *et al.* (1997) and Cattaneo *et al.* (2003)).

A total of 234 samples, with an interval of 10 cm between contiguous samples, were analysed in what concerns the abundances of coccolithophore assemblages. The sequence selected for this study ranges between 21 to 43.7 mbsf (metres below surface), and includes the Marine Isotope Stages 7, 6 and 5 (Piva *et al.*, 2008).

2.2 Techniques

The study of coccolithophores involved the preview preparation of 234 slides according to Flores and Sierro (1997) decantation technique, followed by its observation under an optical polarizing microscope at 1250x magnification. In random fields of view up to 400 small coccoliths were counted, additionally with an independent counting of the larger coccoliths (> 5µm). When was not possible to find 400 small specimens, the counting was extended to a 24 random fields of view. The analysis based on absolute abundances (liths/g) was applied at first, however the related curves were indicative of clear dilution, revealing low significance. Therefore, the results are presented in percentage abundances (Figure 2).

Coccolithophore associations could reflect the nutrient content and its position in the water column, due to their ecological preferences. The relationship between small coccoliths and *F. profunda* (*N* ratio), which occur in the upper and in the lower photic zone, respectively, can be used to monitor the nutricline (and thermocline) fluctuations and, consequently, be used as a productivity proxy (Flores *et al.*, 2000). *N* ratio oscillates between 0 and 1, being the higher values indicative of higher productivity in the upper photic zone while the opposite is indicate by lower values.

Due to the high probability that certain coccoliths may be driven to the Adriatic basin reworked from surrounding onshore Cenozoic formations, a simple statistical parameter named DELTA (Cachão, 1996) was computed as the standard difference between certain taxonomic groups, in this case the standardized abundance of the total of non-Quaternary coccoliths and nannoliths against the standardized abundance of two common Tertiary species: *Coccolithus pelagicus* and *Helicosphaera carteri*. The purpose is to statistically determine intervals when one variable prevails (has independent behaviour) over other (in the present case, reworking) that is recognized to strongly and directly influence most of the time the former (Figure 3).

2.3 Chronostratigraphic framework

The chronostratigraphic framework for PRAD1-2 is based on stable oxygen isotope stratigraphy, magnetostratigraphy, radiocarbon dates and bioevents (Piva *et al.*, 2008). The combination with additional control points corresponding to the ages of Termination midpoints (Lisiecki and Raymo, 2005) and to dated sub-stages relative maxima/minima values (Martinson *et al.*, 1987; Bassinot *et al.*, 1994) were also used. Concerning isotope oxygen stratigraphy, the $d^{18}O$ records were performed from the plank-

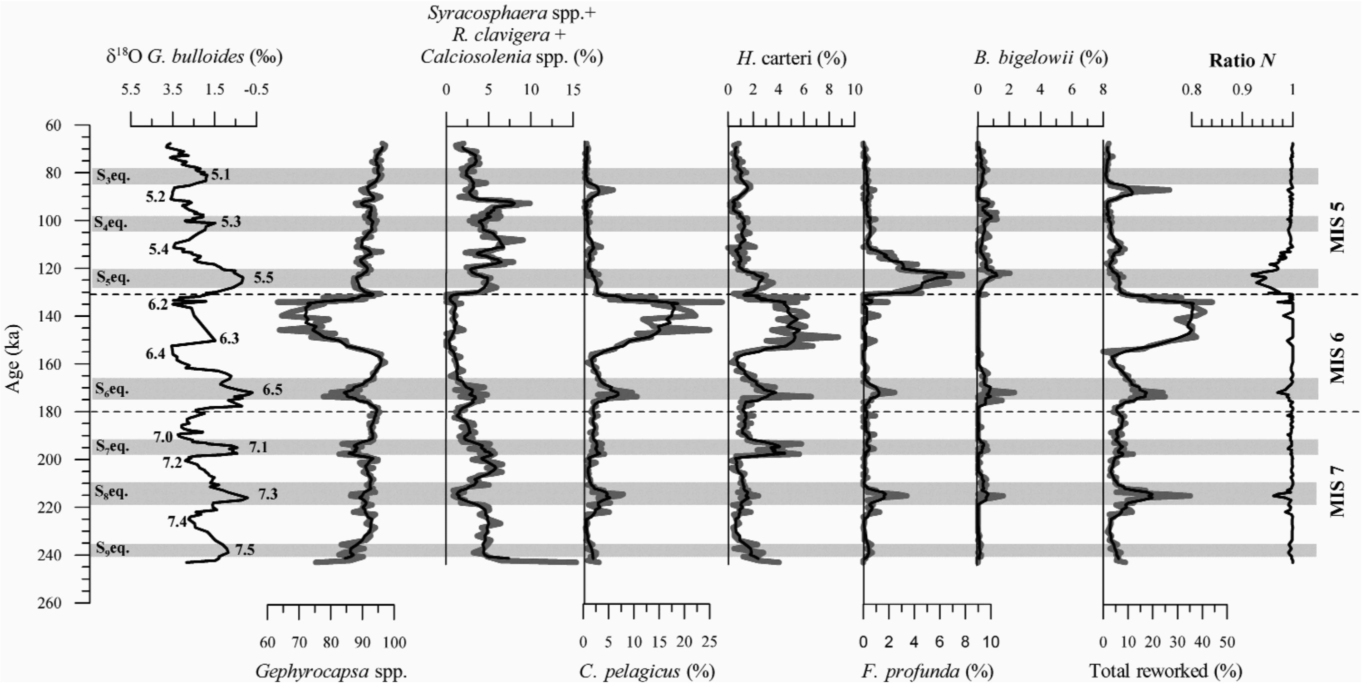

Figure 2. Relative abundances (percentages) of several coccolithophores and reworked specimens analysed in the borehole PRAD1-2, as well as the isotope curve based on *Globigerina bulloides* and the *N* ratio. A smooth line was applied to the abundance curves. Sapropel layers, isotopic stages and sub-stages are indicated. S_3eq.- Sapropel 3 equivalent; MIS-Marine Isotope Stage.

tic foraminifer *Globigerina bulloides*, which curve is illustrated in our results, and from the benthic foraminifer *Bulimina marginata*. The ages ascribed to sapropels in the mentioned borehole refer to the sapropel-based astronomical timescale for the last 1.1 Ma established in the Ionian Sea, eastern Mediterranean (Lourens, 2004). The sapropel layers can be detected by the decrease in reflectance index, by the oxygen isotope shift to lower values (Lourens, 2004), by the Oxygen Deficiency Stress curve, which reflects severe low-oxygen stress of the seafloor before totally azoic conditions (Rohling *et al.*, 1997), and by the quasi-absence in benthic foraminifera concentration (in Piva *et al.*, 2008).

The obtained age control points for the analysed core section are summarized in Table 1, concur in producing a refined age model (Figure 4).

3. SETTING

The Adriatic Sea is an elongated NW/SE orientated basin, located in the centre of the Mediterranean basin. The bathymetric features allow three subdivisions: a very shallow northern section, a central part in which water depth moderately increases, to reach at a depth of 1250 m in the south. Finally, the basin is limited by a sill, the Otranto strait, with a water depth of about 800 m (Ciabatti *et al.*, 1987) (Figure 1).

There are three principal water masses in the Adriatic Sea: the Adriatic Surface Water (0-30 m), the Levantine Intermediate Water (30-130 m) and the Adriatic Deep Water (> 130 m). The general circulation is cyclonic, driven by thermohaline currents, with a flow towards the northwest along the eastern side and a return flow towards the southeast along the western side. Into the three sub-basins the circulation is dominated by local cyclonic gyres, which are seasonally modulated (Orlic *et al.*, 1992; Artegiani *et al.*, 1997). The cold and dense Adriatic Deep Water is produced in the winter by the action of the cold and dry north-easterly Bora wind, which leads to deep water flow to the Mediterranean via the southern Adriatic Basin (Artegiani *et al.*, 1989).

The Adriatic Sea occupies the foreland of the Apennine and Dinaric thrust belts, originated by the collision of the African and the European plates (Geiss, 1987). The main clastic sources of the northern and central Adriatic appear

mbsf	Event	Age (ka B.P.)	Source
23.059	S3	81	*Lourens* [2004]
24.094	MIS 5.2	91	*Martinson et al.* [1987]
27.3	S4	101	*Lourens* [2004]
28	MIS 5.4	111	*Martinson et al.* [1987]
30.6	S5	124	*Lourens* [2004]
30.95	T II	130	*Lisiecki and Raymo* [2005]
32.5	MIS 6.2	135	*Martinson et al.* [1987]
33.581	MIS 6.4	152.5	*Martinson et al.* [1987]
35.3	S6	172	*Lourens* [2004]
37.32	IBE	188	*Laj et al.* [2006]
37.7	MIS 7.0	189.5	*Martinson et al.* [1987]
38.4	S7	195	*Lourens* [2004]
39.5	MIS 7.2	200.5	*Martinson et al.* [1987]
41.5	S8	216	*Lourens* [2004]
42.4	MIS 7.4	225	*Martinson et al.* [1987]
43.2	S9	239	*Lourens* [2004]

Table 1. Control points concurring in the definition of the age-depth model calculated for PRAD1-2 core (in Piva *et al.*, 2008). S_3- Sapropel 3; MIS-Marine Isotope Stage; TII- Termination II; IBE- Iceland Basin Excursion.Figure 2. Relative abundances (percentages) of several coccolithophores and reworked specimens analysed in the borehole PRAD1-2, as well as the isotope curve based on *Globigerina bulloides* and the *N* ratio. A smooth line was applied to the abundance curves. Sapropel layers, isotopic stages and sub-stages are indicated. S_3eq.- Sapropel 3 equivalent; MIS-Marine Isotope Stage.

located along its western side, being the catchment areas of this part of the Adriatic Sea associated to the drainage areas of the eastern Alpine rivers, the Po river catchment, and the eastern Apennine catchments north and south of the Gargano promontory (Cattaneo *et al.*, 2003).

4. RESULTS

4.1 Coccolithophore assemblage description

The coccolithophore assemblage in the studied core is generally well preserved and abundant. 'Small' *Gephyrocapsa*, with the long axis < 3.5 mm according to Rio *et al.* (1990), and *Gephyrocapsa muellerae* dominate the assemblages. *Gephyrocapsa oceanica* is also present in the studied core, but only during MIS 5/7 and in too low concentrations, while *Gephyrocapsa caribbeanica* is almost absent in the analysed samples. The large and subordinate taxa, by decreasing abundance order are: *Syracosphaera* spp. (dominated by *Syracosphaera pulchra*; with absolute abundances about 1.3x10^{10} liths/g in the total of samples), *Coccolithus pelagicus*, *Helicosphaera carteri*, *Rhabdosphaera clavigeraa*, *Florisphaera profunda* (dominated by *Forisphaera profunda* var. *profunda*; rare nanoliths of *Florisphaera profunda* var. *elongata*) *Calciosolenia* spp., *Braarudosphaera bigelowii*, *Calcidiscus leptoporus*, *Umbilicosphaera* spp., *Pontosphaera* spp. and *Umbellosphaera tenuis*. Due to the lower absolute abundances experienced by the last four taxa (< 1.4x10^9 liths/g in the total of samples), they were not presented graphically. The abundances of *Syracosphaera* spp., *Rhabdosphaera clavigeraa* and *Calciosolenia* spp. were plotted together due to the similarity between their ecological preferences. 'Small' *Gephyrocapsa* and *G. muellerae* are also presented together because are both indicative of productivity (moderate to high) in the upper photic zone (Bollmann, 1997; Wells and Okada, 1997; Flores *et al.*, 2003; Boeckel *et al.*, 2006). Cretaceous and Tertiary reworked specimens are always present, particularly during MIS 6. A complete list of the autochthonous taxa is given in the Appendix, including the less abundant species not mentioned above.

The results are presented in percentage abundances (Figure 2; the respective data matrix can be consulted in http://mcprojectos.fc.ul.pt/papers/adriatic/Appendix1.pdf).

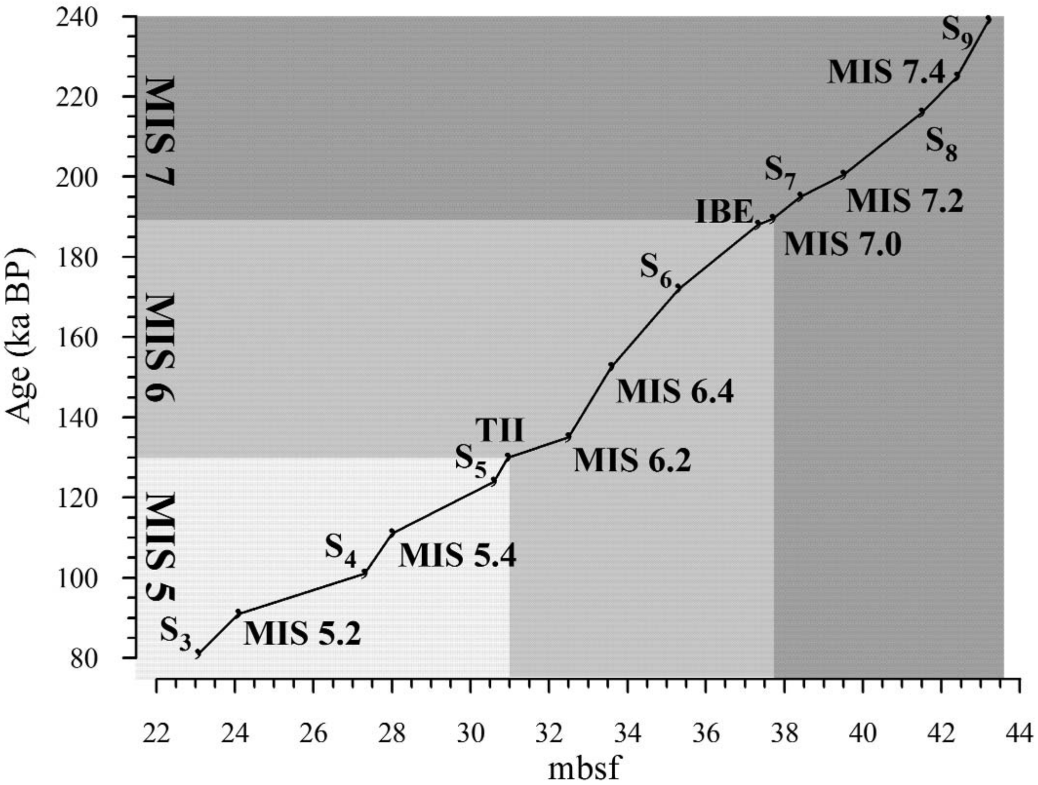

Figure 3. Age-depth model calculated for PRAD1-2 core (based on Piva *et al.*, 2008). Sapropel layers, isotopic stages and sub-stages are indicated. S_3- Sapropel 3; MIS-Marine Isotope Stage; TII- Termination II; IBE- Iceland Basin Excursion.

The analysis based on absolute abundances (liths/g) was applied at first, however, the related curves were indicative of clear dilution, revealing low significance.

The percentage abundance of *Gephyrocapsa* spp. ('small' *Gephyrocapsa* and *Gephyrocapsa muellerae*) exhibits clear decreases during the sapropel layers of MIS 7 (S_9eq.-S_7eq.) and MIS 6 (S_6eq.). However, the lowest abundances of these taxa are registered during the interval situated in the second half of the glacial stage, between the cold events 6.4 and 6.2. During MIS 5 these species decrease within S_5eq. and slightly increase within both S_4eq. and S_3eq. (Figure 2).

The abundance record of *Syracosphaera* spp., *Rhabdosphaera clavigeraa* and *Calciosolenia* spp. presents a decreasing trend from the base of MIS 7 until the top of MIS 6, recovering during the interglacial MIS 5 with moderate values. The comparison between the curves and the sapropel layers shows general decreases during the two first sapropel layers of MIS 7 (S_9eq. and S_8eq.) and the last two of MIS 5 (S_4eq. and S_3eq.). During S_7eq., S_6eq. and S_5eq. abundance increases are observed. Peaks of these taxa are also registered at the top or above the MIS 5 sapropel layers (Figure 2).

A very close pattern is observed between *C. pelagicus* and reworked specimens, with abundance increases during the sapropel layers of MIS 7 (S_9eq. – S_7eq.; more pronounced within S_8eq.) and MIS 6 (S_6eq.), and a very slight increase during S_5eq. The highest abundances are observed, however, during the second half of the glacial stage, between the cold events 6.4 and 6.2. A similar pattern is also observed between the last two forms (*C. pelagicus* and reworked specimens) and *Helicosphaera carteri*, which present increases coincident with the sapropel layers of MIS 7 (S_9eq. – S_7eq.; more pronounced within S_7eq.), MIS 6 (S_6eq.)., and the highest abundances during the second half of MIS 6, between the cold events 6.4 and 6.2. During MIS 5, the *H. carteri* abundance increases are essentially within the sapropel layers S_5eq. and S_4eq. (Figure 2).

The abundance peaks of *Florisphaera profunda* show clear association with almost all sapropel layers that cross the isotope stages 7 (S_9eq. – S_7eq.), 6 (S_6eq.), and 5 (S_5eq.), being its record particularly important during S_5eq. (Figure 2).

Braarudosphaera bigelowii (Figure 2) record is more significant during MIS 5, with higher abundances mostly indicative of the end of sapropel deposition, and also within the sapropel layer of MIS 6 (S_6eq.).

The *N* ratio presents lower values during several sapropel layers, reflected by higher abundances of *F. profunda* and lower abundances of *Gephyrocapsa* spp. during their deposition.

4.2 The DELTA parameter

The relatively high proportion of reworked forms recommended the use of the statistical parameter DELTA to determine their influence in the abundance pattern of specific taxa, *C. pelagicus* and *H. carteri* in this case. Figure 3 shows that during most of the time interval the DELTA parameter varies close to 0, indicating that the two variables in analysis have similar behaviour, either co-variante or both less represented. However, there are discrete moments where reworked forms are statistically much more significant than the two species: 210-200, 145, 135, 110 and 85 kyr. These moments do not have a direct relation to the sapropel equivalent intervals, except for S_8eq. *C. pelagicus* displays four prominent maxima in the second half of MIS 6, none directly related to sapropel layers. *H. carteri* discloses five preferential moments of development: at the base, just before S_9eq.; during S_7eq.; at the beginning of S_6eq.; at around 150 kyr (MIS 6); and during S_5eq.

5. DISCUSSION

The analysis of the coccolith records for the entire core shows discrepancies between the marine isotope stages 7, 6 and 5. As shown in Figure 2, the overall reduction of *Gephyrocapsa* spp. (*Gephyrocapsa muellerae* and 'small' *Gephyrocapsa*) across the sapropel layers of MIS 7 and MIS 6 reproduces the relative abundance pattern of the total autochthonous calcareous nannofossils, since its percentages are always above 60 %. During MIS 5, the record of *Gephyrocapsa* spp. is a little bit different, with an abundance decrease within S_5eq. and slight increases within S_4eq. and S_3eq. The calcareous nannofossil reduction at the beginning of sapropel layers had already been detected by other authors (Negri *et al.*, 1999a, b; Negri and Villa, 2000; Negri and Giunta, 2001; Negri *et al.,* 2003), who also speculated that the general decrease could be a consequence of an increase of the primary siliceous productivity (r-strategist species), which in turn would not be preserved in sediment because of the high silica unsaturation of the Mediterranean waters. The slight abundance increases observed during the deposition of S_4eq. and S_3eq., may reflect different depositional conditions that feature the marine isotope stage 5 when compared to the previous stages.

The comparison of *Florisphaera profunda* and *Gephyrocapsa* spp. curves shows opposite trends between these two taxa, although two exceptions can be observed, in S_4eq. and S_3eq. again. *F. profunda* is a lower photic layer inhabitant of tropical and subtropical waters in the present day ocean (Okada and McIntyre, 1977; Molfino and McIntyre, 1990). Considering the ecological preferences of *F. profunda* and *Gephyrocapsa* spp., opposite trends between their records should be expected. If we imagine a mechanism which favours the water column stratification, the consequent deeper position of the nutricline would lead to a productivity drop in the upper photic zone, given by *Gephyrocapsa* spp. decreases, and to a productivity raise in the lower photic zone, given by *F. profunda* increases. *N* ratio, constructed through the relationship between the upper and lower productivity layer species reflects exactly that. The *N* curve shows negative peaks, which reproduce the dominance of *F. profunda*, coincident with the sapropel layers of MIS 7 (although during S_7eq. this is not so evident), MIS 6, and with S_5eq. Other authors had already reported this positive correlation between *F. profunda* abundances and sapropel layers (Negri *et al.*, 1999a; Negri and Giunta, 2001; Principato *et al.*, 2006; Thomson *et al.,* 2004), considering the increase of this taxon also an excellent tool to indicate the Deep Chorophyll Maximum (Castradori, 1993) and to infer paleonutricline dynamics (Molfino and McIntyre, 1990; Castradori, 1993; Marino *et al.*, 2008).

The variation in the intensity of the cold and dry north-easterly Bora wind, responsible for the production of the Adriatic Deep Water (ADW) during winter (Artegiani *et al.*, 1989), may trigger or not the generation of sapropels. When there is a tendency for normal winter conditions the continuous production of the ADW is expected and the subsequent mixing of the water column, which in turn leads to the oxidation of the organic matter in the deep sea sediments. Under these conditions no sapropels are formed in the Adriatic Sea. However, when there is a tendency for a reduction in the intensity of the Bora wind, the less deep water production leads to the stagnation of deep waters and the subsequent preservation of organic matter and sapropel generation. The gradual decrease of *F. profunda* above S_5eq. and until the event 5.4 reflects the gradual fresh water input and water column mixing in response to the Bora wind activity. At the beginning of S_4eq., and also of S_3eq., a reduction in the Bora wind intensity occurred changing the main paleoceanographic conditions. However, characteristics of these two last sapropels of MIS 5 that are not observed in the others, like the slight abundance increase of *Gephyrocapsa* spp. and the scarce presence of *F. profunda*, may reflect a rise in coccolithophore productivity synchronous with the sapropel deposition due to a shallower nutricline. In this way, during the deposition of these atypical sapropel layers at the present site, the reduction of the winter north-easterly Bora wind has not been so intense, allowing some deep water formation that prevented the total stratification of the water column and bottom stagnation.

The similarity between the records of *C. pelagicus*, *H. carteri* and reworked specimens has already been mentioned. If on the one hand the record of *C. pelagicus* could be useful, providing us information about eutrophication and sea surface temperature, if we are referring to small morphotype (Geisen *et al.*, 2002), or about turbulence and nutrient availability, if we are referring to intermediate morphotype (Cachão and Moita, 2000), on the other hand the similarity between the records of the total *C. pelagicus* and reworked specimens can not guarantee an autochthonous origin for the *C. pelagicus* placoliths. In addition, since reworked specimens recognized in this work range from Cretaceous to Tertiary (Piva *et al.*, 2008) and *C. pelagicus* is known in the geological record since Early Palaeocene (Perch-Nielsen, 1985), there is a strong probability that a significant proportion of their placoliths has been transported into the Adriatic basin. The high correlation between *C. pelagicus* and reworked specimens is confirmed by a correlation coefficient of 0.94, for the entire data set. DELTA parameter, however, discloses a sequence of short term preferential developments of this species towards the end of MIS 6, with no direct relation to sapropel equivalent time intervals. This possibly could indicate time slices of a productivity increase in the basin at the end of the cold period.

Concerning *H. carteri*, the interpretation of its record must also be carefully done, since the presence of *H. carteri* helicoliths may also result from the Apennine source. In fact, the stratigraphic range of this taxon (Early Miocene-Recent; in Perch-Nielsen, 1985) and the similar abundance pattern with reworked specimens (r = 0.73), especially during MIS 7 and 6, corroborates this assumption. However, the information provided by DELTA indicates abundance peaks of autochthonous *H. carteri* just before S_9eq., during S_7eq., at the beginning of S_6eq., during mid MIS 6 and during S_5eq. *H. carteri* is considered a coastal taxon, indicative of moderately elevated nutrient conditions and turbidity (Giraudeau, 1992; Ziveri *et al.*, 1995; Ziveri *et al.*, 2000; Colmenero-Hidalgo *et al.*, 2004; Malinverno *et al.*, 2009), and proliferates between 40 to 70 m water depth close to the chlorophyll maximum (Cros *et al.*, 2000; Cros, 2002). Other authors suggest that high frequencies of *H. carteri* indicate an increase in productivity and/or a decrease in salinity (Pujos, 1992; Flores *et al.*, 2005; Triantaphyllou *et al.*, 2009c). During S_7eq. our data suggest two hypotheses for the proliferation of *H. carteri*: a reduction in surface salinity due to enhanced continental runoff and higher nutrient availability in the middle part of the photic zone, since a nutrification in the lower part, inferred by *F. profunda*, and in the upper part of the photic zone, inferred by *Gephyrocapsa* spp., is not so evident.

During the latest part of the glacial stage 6, the coldest and the driest one (Bard *et al.*, 2002), the subsequent sea-level fall (Siddall *et al.*, 2006) with the shortening of the distance between the continental source and the depositional area was responsible for the terrigenous input increase and, consequently, for calcareous nannofossils assemblages strongly composed by reworked specimens. During most of the analysed time interval, reworked coccoliths, including *C. pelagicus* and *H. carteri*, were trans-

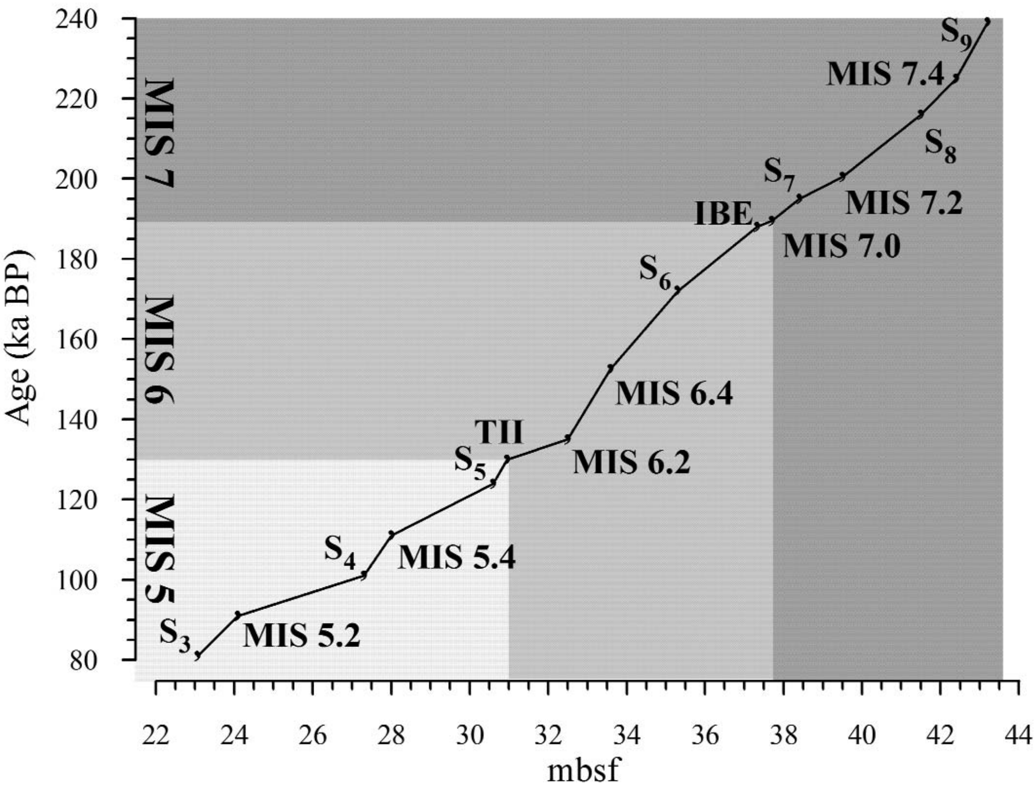

Figure 4. The parameter DELTA or the difference between the standardized abundance of the total non-Quaternary coccoliths and nanoliths, and the standardized abundance of two Tertiary species: *Coccolithus pelagicus and Helicosphaera carteri*. The light arrows indicate the most significant predominance of reworked specimens whereas the dark arrows indicate the most significant predominance of autochthonous *C. pelagicus* and *H. carteri*.

ported into the Adriatic Sea by rivers or/and re-distributed from material already deposited by bottom currents, and finally deposited together with autochthonous specimens in the studied site. However, at certain moments (see Figure 3), sediment delivery mainly from the Cretaceous areas led to a strong dominance of coccoliths from other species. These episodes occurred during MIS 7, at the onset of S_8eq., and also during MIS 6 or MIS 5, although without a relation to sapropels.

Syracosphaera spp. and *Rhabdosphaera clavigeraa* are upper-middle photic zone taxa preferring warmer and low nutrient environments (McIntyre *et al.*, 1972; Ziveri *et al.*, 2004; Maiorano *et al.*, 2008; Dimiza *et al.*, 2008; Malinverno *et al.*, 2009; among others). The same ecological preferences are assumed for *Calciosolenia* spp., which is plotted together with the last two taxa (Figure 2). Our data show that the record of these forms follows a complex pattern with general decreases during S_9eq., S_8eq., S_4eq. and S_3eq., and general increases during S_7eq., S_6eq. and S_5eq. Considering that the onset of sapropel deposition is driven by cold and mixed surface waters, also suggested by Negri *et al.* (2003), this first eutrophic phase would lead to nutrient depleted waters, favouring k-strategist species in a second phase. If on the one hand this fact is reflected in our data by the abundance increases during some sapropel layers, on the other hand another explanation is needed for the abundance decreases registered within the other sapropels. During S_8eq., for instance, the reduction of oligotrophic species occurs simultaneously with the most important increase of reworked specimens, which in turn may reflect climatic conditions probably more severe than in the other sapropel layers. In this way, the development of the k-strategist species should have been inhibited by the higher turbidity of the surface waters, in response to a more intensive runoff and higher terrigenous input during this time slice. The patterns observed during S_4eq. and S_3eq. are consistent with water masses still too productive for the predominant development of k-strategist species. This suggests, as already mentioned, a water mass stratification not very strong or not well marked during these time slices. A simple correlation between this oligotrophic cluster and the temperature inferred from the isotope record is difficult to establish, although the better development of these taxa is related to interglacial isotope stages.

Concerning *Braarudosphaera bigelowii*, although in low abundance across the entire core, it has some importance during MIS 5, being associated with the end of sapropel deposition and appearing sometimes above these terminations. This fact establishes a relation between this taxon development and low salinity waters in result of increased fluvial runoff, which in turn led to the reestablishment of the general oligotrophic state of the surface water. Although only few studies report the presence of this species in sapropels, our results show moderate abundances of *B. bigelowii* within S_8eq. (MIS 7) and S_6eq. (MIS 6), in which concomitant increases of reworked specimens are also registered. Since the First Occurrence of *B. bigelowii* is dated from Cretaceous (Perch-Nielsen, 1985), we can suggest that the identified specimens could correspond to reworked material from the Apennines, transported by fluvial runoff. However, the subsequent development of hyposaline and nutritive waters may also have promoted the autochthonous development of *B. bigelowii* during these same sapropel layers.

6. CONCLUSIONS

The results based on core PRAD1-2 allowed concluding the existence of fluctuations in the calcareous nannofossils content between the interglacial stages 7 and 5, and also between these and the glacial stage 6, revealing a transition between different paleoceanographic conditions across the analysed interval. The most similar features were observed among S_9eq., S_8eq., S_7eq. and S_6eq., and also between the last two sapropel layers of MIS 5, S_4eq. and S_3eq.

In particular our study is indicative that:

- There is a coccolithophore productivity decrease during the deposition of S_9eq., S_8eq., S_7eq., S_6eq. and S_5eq., given by the abundances of *Gephyrocapsa* spp. This productivity decrease, which occurs in the upper photic zone, is accompanied by an increase of *F. profunda* (extremely high within S_5eq.) in the lower photic zone, allowing to understand the nutricline dynamics for each moment. S_4eq and S_3eq. are atypical sapropel layers, in which slight abundance increases of *Gephyrocapsa* spp. and scarce abundances of *F. profunda* are observed;
- The sapropel layers of MIS 7 (S_9eq., S_8eq. and S_7eq.), MIS 6 (S_6eq.) and the first one of MIS 5 (S_5eq.) were formed during winters characterised by a reduction in the north-easterly Bora wind, which in turn limited the production of the Adriatic Deep Water. Thus, the subsequent strong stratification of the water column and the low oxygen content at the bottom, favoured the preservation of the organic matter. During the deposition of the last sapropel layers of MIS 5, S_4eq. and S_3eq., the reduction of the winter north-easterly Bora wind has not been so intense, allowing some ADW production and some subsequent mixing of the water column;
- The increase of reworked specimens abundance is another feature of MIS 7 and MIS 6 sapropel layers, indicating fluvial runoff events with terrigenous input synchronous with the sapropel deposition. However, the most important increases are observed during the latest part of MIS 6, which is associated with a remarkable sea-level fall, probably due to the action of bottom currents in material already deposited;
- The stratigraphic range of *C. pelagicus* and *H. carteri* and the similarity between their records and the record of reworked specimens, could reflect an Apennine source for the most part of *C. pelagicus* and *H. carteri* coccoliths by precipitation and runoff into the Adriatic basin. However, the information provided by DELTA indicates in situ developments of *C. pelagicus* during the second half of MIS 6, and in situ preferential developments of *H. carteri* just before S_9eq., during S_7eq., at the beginning of S_6eq., during mid of MIS 6 and during S_5eq.;
- There is not a clear relation between the cluster *Syracosphaera* spp., *R. clavigeraa* and *Calciosolenia* spp. and warm and oligotrophic waters. However, the de-

velopment of these taxa at the top or above the termination of some sapropel layers, is consistent with the end of dryer conditions that feature the sapropel deposition, and with the subsequent reestablishment of the general oligotrophic state of the surface water with a nutrient redistribution. At the same time a salinity reduction should occur due to the simultaneous presence of *B. bigelowii*. On the other hand, the presence of *B. bigelowii* within some sapropel layers of MIS 7 and MIS 6, together with its startigraphic range, may indicate also a continental source for some pentaliths.

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Taxonomic appendix

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Calcidiscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978

Calciosolenia murrayi Gran, 1912

Ceratolithus telesmus Norris, 1965

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930

Coccolithus pelagicus braarudii (Gaarder 1962a) Geisen *et al.* (2002)

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Florisphaera profunda var. *elongata* Okada and McIntyre, 1980

Florisphaera profunda var. *profunda* Okada and Honjo, 1973

Gephyrocapsa caribbeanica Boudreaux and Hay, 1967

Gephyrocapsa muellerae Bréhéret, 1978

Gephyrocapsa oceanica Kamptner, 1943

Gephyrocapsa ericsonii McIntyre and Bé, 1967

Gephyrocapsa aperta Kamptner, 1963

Helicosphaera carteri (Wallich, 1877) Kamptner, 1954

Helicosphaera carteri var. *carteri* (Wallich, 1877) Kamptner, 1954

Helicosphaera carteri var. *hyalina* (Gaarder, 1970) Jordan and Young, 1990

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Pontosphaera discopora Schiller, 1925

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Rhabdosphaera clavigeraa Murray and Blackman, 1898

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