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Western versus eastern Mediterranean paleoceanographic response to astronomical forcing: a high-resolution microplankton study of precession-controlled sedimentary cycles during the Messinian

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Abstract

Planktic foraminifera and stable isotopes were analyzed in samples from four precession-controlled sedimentary cycles from southeastern Spain and the island of Gavdos (Greece) to reconstruct the paleobiologic and paleoceanographic response of the western and eastern Mediterranean to astronomically driven climate variability during the Messinian. Although the lithological succession in the western Mediterranean cycles (sapropel–homogeneous marl–diatomite–homogeneous marl) is different from that in the eastern Mediterranean (sapropel–diatomite–homogeneous marl), the pelagic biological succession is similar. Four stages were recognized in both environments, characterized by the dominance of warm-oligotrophic foraminifera (stage 1), Neogloboquadrinids and Globorotaliids (stage 2), *Globigerina bulloides* (stage 3) and *Globigerinita glutinata* (stage 4). The first stage occurs during deposition of the upper part of the sapropels in Spain, and the sapropels and part of the diatomites on Gavdos. This stage is inferred to relate to high summer insolation and strong surface water stratification with winter temperatures not high enough to allow eutrophic foraminifera growth. Stage 2 occurs during the deposition of the lower homogeneous marls in Spain and the middle–upper part of the diatomites in Greece, most likely indicating stratification, with colder winter temperatures and a nutricline above the euphotic layer. The end of surface water stratification is indicated during stage 3 by the replacement of the Neogloboquadrinids by *G. bulloides*, which occurs at the base of the diatomites in Spain and near the top of the diatomites in Greece. We link this event to the appearance of dryer climates in the Mediterranean at times of relatively low summer insolation in the Northern Hemisphere which would result in higher surface salinities, deep water convection, and deep water ventilation. Stage 4, defined by the dominance of *G. glutinata* and low concentrations of planktic foraminifera, appears linked to the base of the sapropels both in the western and eastern Mediterranean. The onset of sapropel deposition occurred at a time of relatively high surface water salinities, as suggested by the heavy $\delta^{18}O$ in *Orbulina universa*, and prior to the

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development of surface water stratification evident in the subsequent increase in warm-oligotrophic foraminifera. Gavdos diatomites were deposited under anoxic conditions, whereas Sorbas diatomites were formed in an oxygenated environment. The difference between western and eastern Mediterranean diatomites would be due to differences in hydrographic conditions between the two studied settings.
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1. Introduction

Since the discovery of the first sapropels (Kullenberg, 1952) in deep sea sediments from the eastern Mediterranean, anoxic and laminated sediments have been recognized in different climatic, oceanographic and tectonic settings in the western and eastern Mediterranean, from the Miocene to the Holocene (see for review, Kidd et al., 1978; Hilgen, 1991; Comas et al., 1996; Emeis et al., 1996; Cramp and O'Sullivan, 1999). The sequence of sapropelitic beds interbedded within homogeneous marls represents the most common response to orbitally driven climatic variability and has been used to construct astronomical time scales (Hilgen, 1991; Hilgen et al., 1995; Krijgsman et al., 1999). Sapropels were deposited during times of precession minima (insolation maxima), when higher precipitation and runoff over Mediterranean regions could produce bottom water stagnation, and hence, anoxia, which in turn could force organic-rich sediments deposition. As precession increased (insolation decreases), the climate became dryer and colder, increasing sea surface evaporation. This could favor water mixing and re-oxygenation of bottom waters, which could have prevented sapropel formation (Rossignol-Strick, 1985; Hilgen, 1991; Sierro et al., 1999). However, the lithological composition of the astronomically forced, sedimentary cycles is variable and does not always contain sapropels. Couplets of sapropels and homogeneous marl beds are frequent in Late Miocene sections from the eastern Mediterranean (e.g. in Sicily, Gavdos; Hilgen et al., 1995; Sprovieri et al., 1996; Krijgsman et al., 1995; Schenau et al., 1999). However, during the Messinian, at ca. 6.7–6.8 Ma, a wide shift in lithologies in the western and eastern Mediterranean took place. In the Sorbas basin, this time marks the onset of sapropel deposition (Sierro et al., 1999, 2001), whereas in the eastern Mediterranean, sapropels became siliceous and were replaced by the diatomites of the Tripoli Formation (Pedley and Grasso, 1993; Suc et al., 1995; Sprovieri et al., 1996; Hilgen and Krijgsman, 1999). These changes occurred about 100 ka prior to our interval of study, and could presumably be related to changes in basin-wide circulation patterns. Diatom-rich beds sometimes occur in Pliocene and Pleistocene sapropels (Kemp et al., 2000). However, the presence of cyclical diatomites seems to be related to pre-evaporite environments, either during the Messinian (Hilgen and Krijgsman, 1999; Sierro et al., 2001) or the Late Tortonian (Krijgsman et al., 2000).

The Messinian pre-evaporite sedimentary cycles deposited in SE Spain (western Mediterranean) consist of a succession of four lithologies: a sapropel at the base, a homogeneous marl, a diatomite and a homogeneous marl on top (Sierro et al., 1999, 2001). By contrast, sedimentary cycles in the Tripoli Formation of the eastern Mediterranean (i.e. Sicily, Gavdos, Crete and Cyprus) are mainly tripartite and are composed of a sapropel at the base, followed by a prominent diatomite and a homogeneous layer on top (Sprovieri et al., 1996; Hilgen and Krijgsman, 1999; Krijgsman et al., 1999).

The purpose of this study is to analyze in detail the microfauna and microflora of four astronomically tuned, sedimentary cycles in the Sorbas basin (6.620–6.546 Ma, western Mediterranean), and in the Metochia section on the island of Gavdos (Greece, eastern Mediterranean). We used the cyclical changes of the microplankton populations to compare them with the lithological cycles in both basins, to constrain the mechanisms by

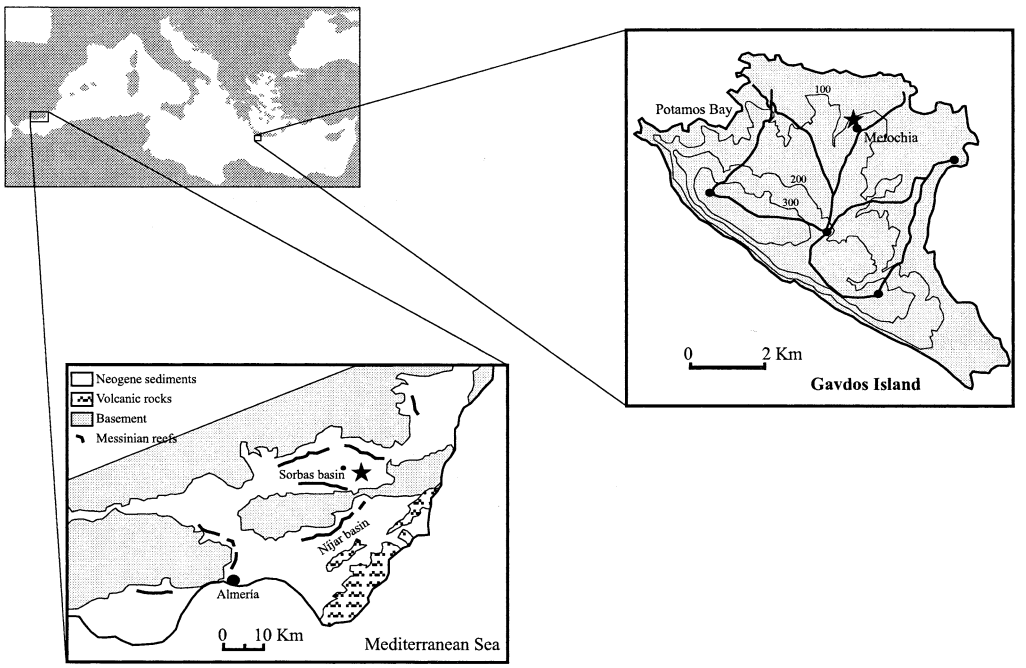


Fig. 1. Location maps of the Mediterranean Sea sections studied in this paper: west Mediterranean = southeast Spain; east Mediterranean = Gavdos Island (Greece). Sections are marked by stars.

which the same biological response led to different lithofacies in eastern and western Mediterranean.

2. Sedimentary cyclicity

The upper Abad marls were deposited in the central part of the Sorbas basin (SE Spain, Fig. 1) during the pre-evaporite Messinian. The rhythmic cyclostratigraphic patterns together with the biotic and geochemical cyclicity have been intensively studied over the past years (Sierro et al., 1999; Krijgsman et al., 1999; Vázquez et al., 2000) and the Abad composite, based on several sections from the Sorbas basin, was proposed as a standard reference section for the Late Messinian part of the Astronomical Polarity Time Scale (Sierro et al., 2001). In this study we will focus on high-resolution analysis of four precession-controlled cycles of the upper Abad (UA5 to UA8, after Sierro et al., 2001), ranging in age from 6.606 Ma (mid-point of sapropel UA5) to 6.544 Ma (mid-point of sapropel UA8). The same cycles were identified and sampled in Messinian marls exposed on the island of Gavdos (Metochia section, south of Crete, Greece). This identification was possible due to the cyclostratigraphic correlation between the Abad composite in southeastern Spain and the Metochia section on Gavdos (Krijgsman et al., 1999). Both sections were tuned to the 65°N summer insolation record (Laskar, 1990). The sedimentary cycles studied on Gavdos contain diatomite beds 6–9 and hence they were named MD6 to MD9 (Metochia diatomite 6–9). The sedimentation rate in the Sorbas basin was about four times higher than on Gavdos because the thicknesses of the same precession-controlled cycles measure around 10 m in Spain but only 2.3 m in Greece (Fig. 2). This resulted in an average sedimentation rate of 9.2 cm/kyr in the Sorbas basin and 2 cm/kyr on Gavdos.

Sedimentary cycles in Sorbas are quadripartite and consist of a sapropel at the base, followed by a homogeneous marl, a diatomite and a upper homogeneous layer at the top of the cycle (Fig. 2). The sapropels in Sorbas are very thick (aver-

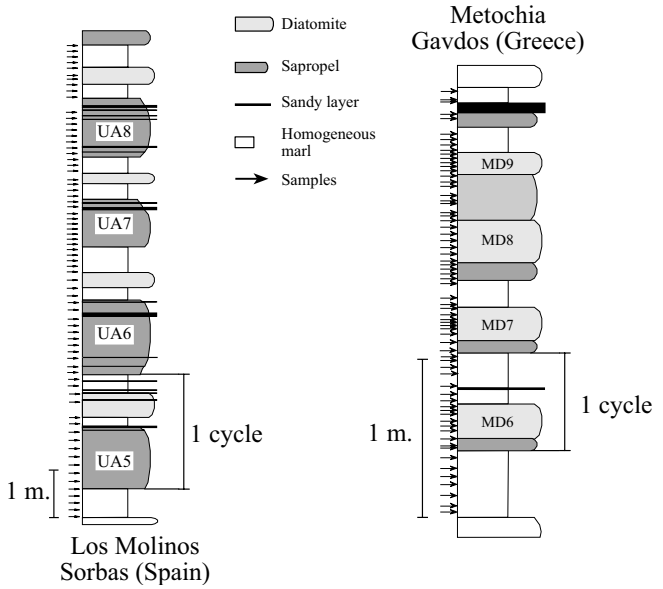


Fig. 2. Stratigraphic columns of the sediments studied. Note the different scale between the Molinos section in the Sorbas basin and the Metochia section on Gavdos. Sorbas cycles are composed of a thick sapropel, a homogeneous marl, a thin diatomite, and a second homogeneous marl. Gavdos cycles are composed of a thin sapropel, a thick diatomite and a homogeneous marl.

age thickness of 123 cm) brownish laminated marls. Thin beds of black-gray clays of approximately 5–10 mm are frequent in all sapropels. Lamination is well developed, especially in the middle part of the sapropels, whereas it is weakly developed in the upper and lower parts of the sapropel. The homogeneous layers are soft, green marls ranging in thickness from 25 to 45 cm, with relatively common fossil bivalves. The diatomites are white, sometimes weakly laminated deposits of 15–27 cm in thickness. Millimeter- to centimeter-thick red oxidized sandy layers are commonly found in the upper part of the sapropels (Fig. 2).

On Gavdos the sedimentary cycles are typically tripartite and composed of a sapropel, a thick diatomite and a homogeneous marl (Fig. 2). Although we have used the term sapropel, the layers defining the base of the cycles on Gavdos cannot be considered true sapropels, since they are in fact thin, faintly laminated reddish layers that mark the transition from the homogeneous marls to the diatomites. Sapropels on Gavdos are much thinner than those of Sorbas. By contrast, the diatomites on Gavdos are thick and prominently laminated, particularly in the middle part, because less laminated sediments are commonly found in the uppermost part of the diatomites. The homogeneous layers, which mark the top of the cycles, are gray, sometimes slightly indurated marls. No homogeneous marls are present between the diatomites of cycles MD8 and MD9; instead reddish and weakly laminated marls appear between the diatomites and consequently the whole interval was considered as a thick sapropel in our logs (Fig. 2). Some thin millimeter- to centimeter-thick, red sandy layers occur preferentially in the Gavdos homogeneous marls, but are less frequent than in Sorbas. Two more prominent sandy layers appear in cycles MD6 and MD10. The detailed sampling interval for this study ranges from the homogeneous marls of cycle MD5 to the homogeneous marls of cycle MD10 which corresponds to cycles UA4 to UA9 in Sorbas.

3. Techniques and methods

Cycles UA5 to UA8 were sampled in section

Molinos B, located on the northern side of the Río Aguas, Almería, SE Spain (see Sierro et al., 2001 for a description of the section) and the same precession-controlled cycles were sampled in the Metochia section (island of Gavdos, Greece) (see Krijgsman et al., 1999 for a general description of the section) (Figs. 1 and 2). An average of 17 samples per cycle were taken in the Sorbas basin (average resolution of 1250 years), and 14 samples per cycle on Gavdos (average resolution of 1500 years). Sand layers were not sampled as they represent turbidite layers (Fig. 2).

For the foraminiferal studies all the samples were disgregated in a solution of H_2O_2 and calgon, after drying and weighting. Samples were sieved through 150- and 62-μm meshes, with only the >150-μm fraction used for counting. The sand fractions were split to get a subset of around 350 planktic foraminiferal specimens in Sorbas, and of around 200 specimens in the less well preserved Gavdos samples. All planktic foraminifera specimens were identified and counted. The total number of planktic and benthic foraminifera per gram was calculated by extrapolating the number of specimens in the split to the whole residue. Diversity was calculated using the Shannon–Weaver index.

For diatom analyses, samples were prepared according to the randomly distributed microfossils method described in Bárcena and Abrantes (1998). For each of the samples, the initial dry weight, the suspension volume and the volume used to mount the slides were calculated. In general more than 400 fields of view were studied per slide. Magnification was $\times 1000$, and the recommendations of Schrader and Gersonde (1978) were applied as a basis for counting the diatom valves.

Around 40 specimens of *Orbulina universa* and *Globigerina bulloides* were hand-picked and ultrasonically cleaned for oxygen and carbon isotope analysis. The organic matter was destroyed by heating up to 400°C under vacuum for 2 h. The samples were then introduced in a Sira II (VG) spectrometer with orthophosphoric acid at 75°C. The results are expressed in PDB (Pee Dee Belemnite standard).

4. Results

4.1. Cyclical changes in the planktic foraminiferal assemblages

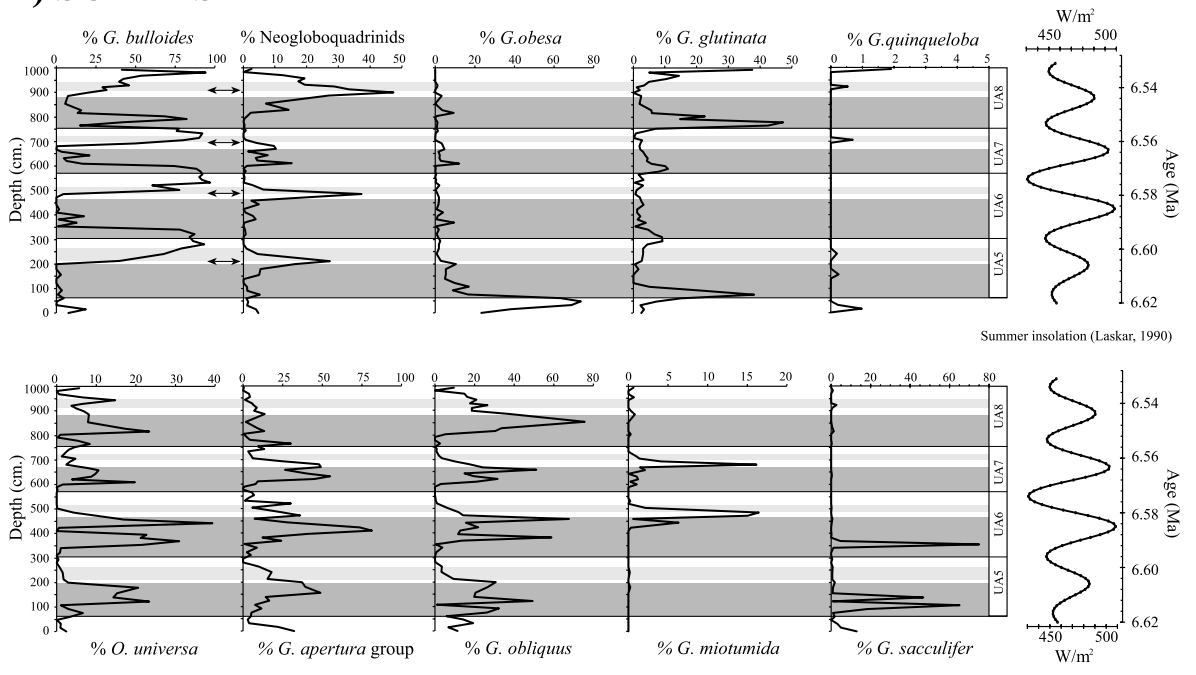
Results from the planktic foraminiferal counts of the Sorbas and Gavdos samples are shown in Fig. 3A,B. The microfaunal counting was not possible in some Gavdos samples due to the poor preservation. Different coiling directions of *Neogloboquadrina acostaensis* have been counted together. Most specimens are left-coiling because the studied cycles are older than 6.330 Ma, which is the estimated age for the major sinistral to dextral coiling-change of this species (Hilgen and Krijgsman, 1999; Sierro et al., 2001).

A series of biostratigraphic events has been identified in a number of Messinian sections based on changes in the planktic foraminiferal assemblages, including the Abad composite section (Sierro et al., 2001); two of these events are located within the interval of this study. The first abundant occurrence of *Globigerina obesa* (6.610 Ma) is located in the homogeneous marl immediately below cycle UA5 in Sorbas, and in the homogeneous marl below cycle MD6, in Metochia. In both regions this species reaches abundances close to 80% of the total assemblage (Fig. 3) and sharply decreases in abundance at around the base of the sapropels of the overlying cycle.

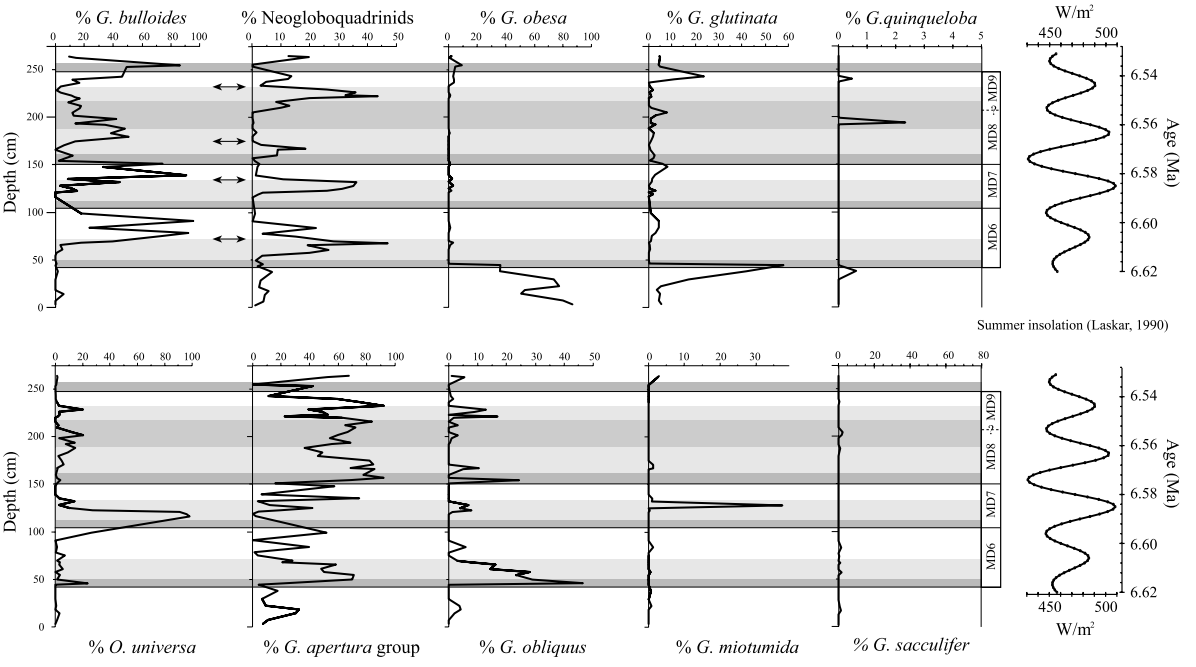
The last two prominent influxes of the *Globorotalia miotumida* group identified by Sierro et al. (2001) were located at cycles UA6 (6.585 Ma) and UA7 (6.552 Ma) in Sorbas. However, only the older one was detected on Gavdos, in the top part of the diatomite of cycle MD7 (Fig. 3B).

Despite the evident differences in the lithological succession of sedimentary cycles, the faunal successions are by contrast very similar in the Sorbas basin and on Gavdos (Figs. 3). *Orbulina universa*, *Globigerinoides sacculifer*, *Globigerinoides obliquus* and *Globigerina apertura* are abundant in the upper part of the sapropels in the Sorbas basin (Fig. 3A), and in the sapropels and the lower part of the diatomites on Gavdos (Fig. 3B). Extant *O. universa* and *G. sacculifer* live in warm-subtropical settings, and the same applies to *Globigerinoides ruber* and *Globigerina rubes-*

A) SORBAS



B) GAVDOS



cens, which are close relatives of the now extinct *G. obliquus* and *G. apertura*. These extant species usually grow in the surface nutrient-depleted waters of the mixed layer in oceanographic settings with a strong stratification in the water column (Bé, 1977; Bé and Tolderlund, 1971; Hemleben et al., 1989).

G. obliquus is relatively more abundant in Sorbas (0–60%) than on Gavdos (0–30%) whereas *G. apertura* reaches higher percentages on Gavdos. *Orbulina universa* appears in similar quantities in both sections with the exception of cycle MD7 on Gavdos, where it comprises almost 100% of the foraminiferal assemblage. *G. sacculifer* is very rare in most of the samples, with the exception of two prominent peaks in the sapropels of cycles UA5 and UA6 in Sorbas, where it consists almost 80% of the planktic foraminiferal assemblage.

The Neogloboquadrinids, particularly *Neogloboquadrina pachyderma* and *Neogloboquadrina dutertrei*, are species that proliferate in modern oceanographic regions characterized by surface water stratification and when the pycnocline and nutricline are located above the base of the euphotic layer (Fairbanks et al., 1982; Rohling, 1994). In the current Mediterranean Sea, cold-eutrophic foraminifera species (e.g. Neogloboquadrinids) are only abundant when winter temperatures are colder than 13.5°C (database of Kallel et al., 1997; see Sierro et al., 2003). Moreover, *N. pachyderma* (dextral coiling) reaches higher abundances where a shallow nutricline exists (Pujol and Vergnaud-Grazzini, 1995). During the Messinian Neogloboquadrinids were dominated by *Neogloboquadrina acostaensis*, which is very close in morphology and geographic distribution to *N. pachyderma* (dextral coiling). In the Sorbas basin, this group is very abundant in the homogeneous marls between the sapropels and the diatomites. However, on Gavdos the Neogloboquadrinids reach the highest percentages within the diatomites (Fig. 3A,B). The Neogloboquadrinids are replaced by *Globigerina bulloides* near the base of the diatomites in Sorbas and near the top of the diatomites on Gavdos; these events are marked by opposite arrows in Fig. 3A,B.

Globigerina bulloides is extremely abundant in both regions and shows a very characteristic cyclical pattern. It reaches its highest abundance (sometimes near 100% of the planktic assemblage) in the diatomites, the homogeneous marls and the base of the sapropels in Sorbas, whereas it is usually restricted to the homogeneous marls on Gavdos, except in the sapropel of cycle MD10. *G. bulloides*, as well as *Turborotalita quinqueloba*, typically thrive in shallow to the first 100 m of the water column, in oceanographic settings characterized by intensive vertical mixing or upwelling (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995; Reynolds and Thunell, 1985).

Globigerinita glutinata is a small-sized planktic foraminifera, which reaches its maximum abundance in the homogeneous marl–sapropel transitions in both locations. This species is very abundant (40% in Sorbas and 60% on Gavdos) at the base of cycle UA5 and the corresponding cycle MD6 on Gavdos. *Turborotalita quinqueloba* is very rare in the cycles analyzed in this study, but is very abundant in the diatomites and the overlying homogeneous marls of other cycles from the upper Abad (Sierro et al., 2003). In the cycles studied, small peaks of abundance of this species are invariably linked to the diatomites or the overlying homogeneous marls in Sorbas and to the homogeneous marls on Gavdos (Fig. 3A,B) but these peaks never reach 5% of the total assemblage.

As already outlined, *Globigerina obesa* is present in large numbers at the base of the studied interval, from both sections, but the rest of the samples are almost devoid of this species. These

Fig. 3. Relative abundance of the planktic foraminiferal species versus depth: (A) Sorbas, (B) Gavdos. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl. Arrows indicate change between the Neogloboquadrinids and *Globigerina bulloides*. UA: upper Abad. MD: Metochia diatomite. Based on the conclusions of this paper the top of the sapropels in Sorbas was tuned to summer insolation maxima. However, insolation maxima on Gavdos were tuned with the middle and upper part of the diatomites.

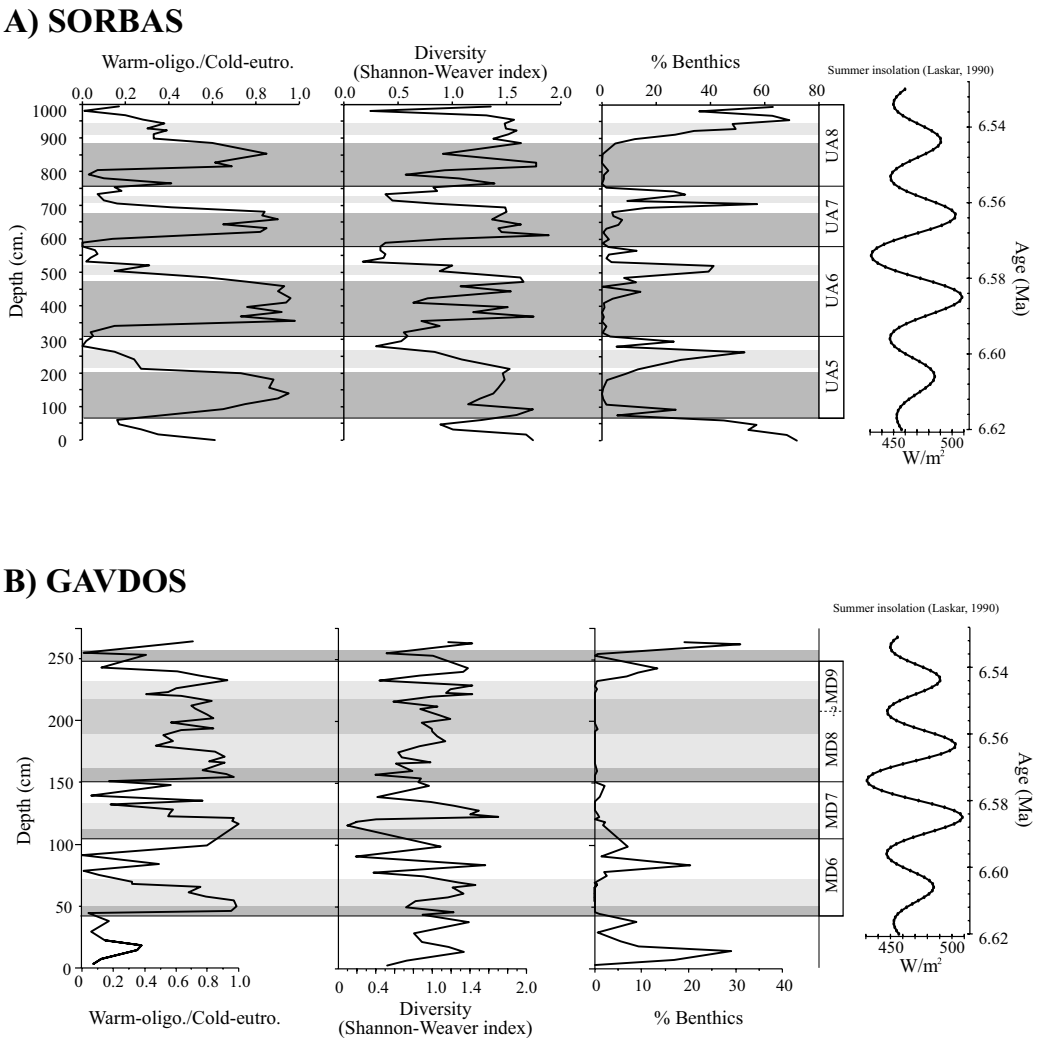


Fig. 4. Ratio between warm-oligotrophic and cold-eutrophic planktic foraminifera taxa, diversity index (Shannon–Weaver), and benthic foraminifera percentage versus depth, in (A) Sorbas and (B) Gavdos. UA: upper Abad. MD: Metochia diatomite. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl.

specimens may be considered as intermediate morphotypes between *Globigerinella siphonifera* and *Globigerina bulloides*, although these two species have very different ecological requirements.

4.2. Diversity and abundance of planktic foraminifera and planktic/benthic ratios

The diversity of the planktic foraminiferal assemblage, calculated using the Shannon–Weaver index, varies between 0 and 2 in both basins (Fig. 4A,B). The record of diversity shows very characteristic cyclical patterns in Sorbas, whereas this cyclicity is less obvious on Gavdos. In Sorbas, lowest diversities are usually found in the upper homogeneous marl or at the top of the diatomites (Fig. 4A) while the highest diversities occur in the upper part of the sapropels or in the lower homogeneous marls. On Gavdos, maximum diversities are usually reached in the upper part of the diatomites, corresponding to the peaks in abundance of the Neogloboquadrinids (Fig. 4).

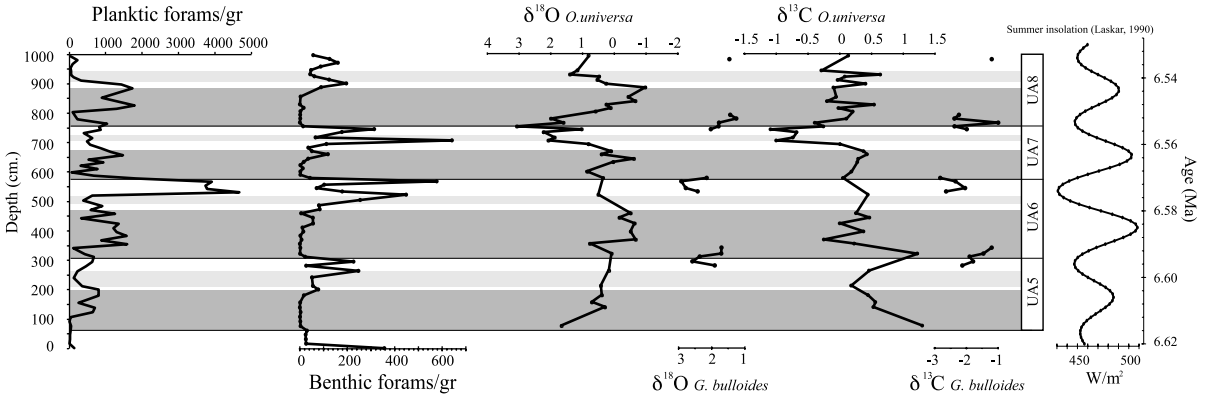


Fig. 5. Abundances of planktic and benthic foraminifera in the Sorbas basin, expressed in planktic and benthic foraminifera per gram, and stable isotope results versus depth. UA: upper Abad. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl.

The diversity record is in part similar to that of the planktic foraminifera concentration, expressed as the number of planktic foraminifera per gram of dry sediment. This index was only calculated for the Sorbas cycles. With the exception of the extremely high number of planktic foraminifera (4700 f/g) found in the homogeneous marls of cycle UA6, which corresponds to an almost monospecific assemblage of *Globigerina bulloides* (97%), planktic foraminifera are usually rare near the base of the sapropels, but increase towards the upper part of these layers (Fig. 5). Sapropels are formed under suboxic or anoxic bottom water conditions and hence the abundance of benthic foraminifera in these levels should be very low. Indeed, samples from the lower and middle part of the sapropels are completely devoid of benthic foraminifera, interpreted as anoxic conditions. However, the number of specimens of benthic foraminifera per gram increases gradually in the upper part of the sapropels, reaching the highest values within the diatomites and the overlying homogeneous marls (Fig. 4A). As a consequence, the planktic/benthic ratio in the Sorbas cycles is controlled by the increases in abundance of the benthic foraminifera in the diatomites and the homogeneous marls (which usually correspond to relatively low abundances of planktic foraminifera) and the almost complete lack of benthic forms in the lower and middle part of the sapropels. On Gavdos, the planktic/benthic ratio follows a totally different trend in relation to the lithology. Unlike the Sorbas diatomites, in which benthic foraminifera are abundant (Figs. 4A and 5), the percentage of benthic foraminifera is extremely low in the Metochia diatomites, indicating the persistence of anoxic or suboxic bottom waters at times of diatomite formation (Fig. 4B). However, the disappearance of benthic foraminifera, which marks the onset of anoxic bottom water conditions, occurs at the base of the sapropels in Sorbas and on Gavdos. The re-establishment of bottom water ventilation is inferred to occur near the top of the sapropels in Sorbas, while the same event is situated near the top of the diatomites on Gavdos (Figs. 4A and 5). An exception to this pattern is found above the diatomite of cycle MD8 where benthic foraminifera remain present with very low percentages. This observation is in agreement with the absence of a homogeneous marl in this cycle. The same exception is seen in the record of the warm-oligotrophic foraminifera, which usually decrease in the homogeneous marl, but remain with high values in cycle MD8.

4.3. Oxygen and carbon isotopes

Stable isotope analysis was carried out only in the Sorbas basin, because the preservation of the planktic foraminifera was poor on Gavdos. $\delta^{18}O$ values in *Orbulina universa* are usually high

(around 1‰, maximum 3‰) at the homogeneous marl–sapropel transitions, decreasing to reach the lowest values towards the upper part of the sapropels (between 0 and −1‰, Fig. 5). These intervals with low $\delta^{18}O$ are usually dominated by the warm-oligotrophic planktic foraminifera. The $\delta^{18}O$ in *O. universa* begins to increase in the homogeneous marls above the sapropel to reach the heaviest values within the diatomites or the upper homogeneous marls. This trend is evident in the diatomites and homogeneous marl layers of cycles UA6, UA7 and UA8, but it cannot be seen in cycle UA5, perhaps due to the low resolution of the isotope analyses in this part of the cycle. The variability of the $\delta^{13}C$ in *O. universa* is not consistent with the sedimentary cyclicity: in the sapropels of cycles UA5 and UA6 a peak of heavy $\delta^{13}C$ values near the base of the sapropels is followed by a decreasing trend towards the top; in the upper sapropels this trend does not appear. A prominent decrease in $\delta^{13}C$ occurs in the diatomite and upper homogeneous marl of cycle UA7, matching with maximum $\delta^{18}O$ values. With the exception of cycle UA5, the oxygen and carbon isotope records follow opposite trends.

Globigerina bulloides is very rare in the sapropels and therefore isotope analyses on this species were only performed in the diatomites and homogeneous marls. Although based just on a very few number of samples, it seems that $\delta^{18}O$ values in *G. bulloides* are high in the upper homogeneous marls and decrease at the base of the sapropels. $\delta^{18}O$ values in *G. bulloides* are up to 2.5‰ heavier than those seen in *Orbulina universa*, although this gradient is reversed at the transition between cycles UA7 and UA8 where high $\delta^{18}O$ values in *O. universa* correspond to light values in *G. bulloides*.

4.4. Cyclical changes in diatom assemblages

Diatoms are obviously abundant in the diatomites in both sections, while the other lithologies are completely devoid of diatoms (Fig. 6). In both sections, assemblages are dominated by *Chaetoceros* resting spores (RS) and *Thalassionema* spp. but *Rhizosolenia* spp., which is a group typically adapted to live within the nutricline (Kemp et al., 2000), is more abundant on Gavdos. *Rhizosolenia* spp. attains its highest abundances in the middle and upper part of the diatomites (together with the Neogloboquadrinids), but is replaced by *Chaetoceros* RS in the uppermost part of the diatomite. By contrast, *Thalassionema* spp. reaches its highest percentages in the lower and middle part of the Gavdos diatomites.

Chaetoceros RS attain high concentrations in nutrient-rich surface waters affected by upwelling particularly in the last stages of the biological succession once nutrients are depleted (Abrantes, 1988; Bárcena and Abrantes, 1998). The high abundance of spores of *Chaetoceros* towards the topmost part of the diatomites both in the Sorbas basin and on Gavdos could be related with silica and phosphorus depletion in surface waters at the transition from the diatomites to the homogeneous marls (Filippelli et al., 2003).

5. Discussion: western versus eastern Mediterranean pelagic response to astronomically driven climate change

Based on the faunal response to the astronomically forced climatic variability, Sierro et al. (this issue) divide the Messinian precession-driven biological cycles of the Sorbas basin in four stages, each one characterized by a different group of planktic foraminiferal species, that we can identify both in the Sorbas and Gavdos sections (Figs. 7 and 8). As climatic conditions change along every precession cycle, the changes of the hydrographic structure of the water column and of nutrient availability in surface waters induced changes in the plankton communities. Despite the fact that the lithological succession defining the precession cycle is different in the eastern and western Mediterranean, the cyclical response of the planktic communities is surprisingly similar, indicating some oceanographic link for biological processes across the Mediterranean. The succession is defined by the dominance of four different groups of planktic foraminiferal species (see summary diagram in Fig. 8); the warm-oligotrophic foraminifera dominant during stage 1 are replaced by the Neogloboquadrinids and Globorotaliids in

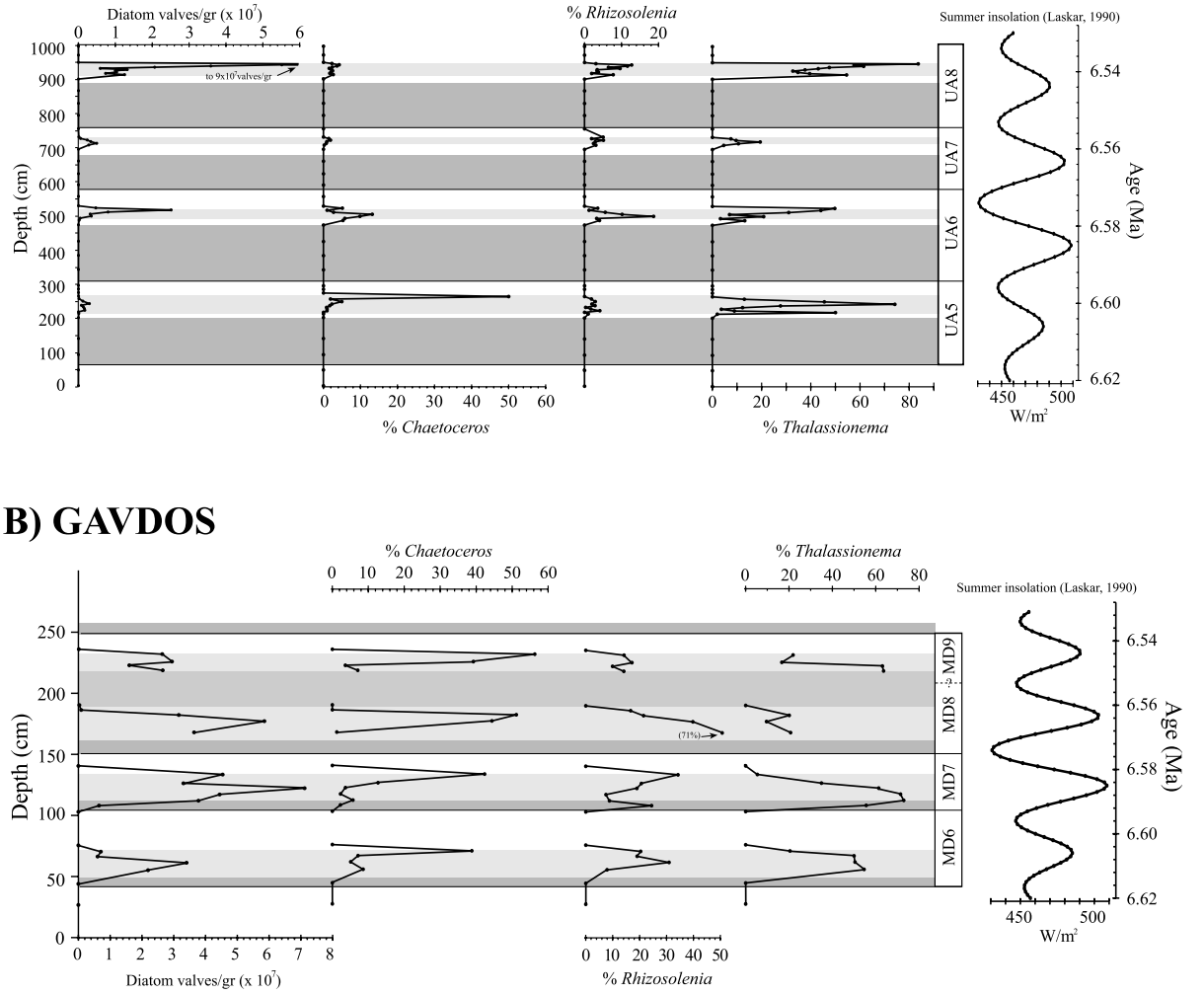


Fig. 6. Diatom valves per gram of sediment, and percentage of *Chaetoceros* RS, *Rhizosolenia* spp. and *Thalassionema* spp. versus depth: (A) Sorbas, (B) Gavdos. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl. UA: upper Abad. MD: Metochia diatomite.

stage 2, which in turn are replaced by *Globigerina bulloides* (stage 3) and *Globigerinita glutinata* (stage 4) (Sierro et al., 2003).

5.1. Stage 1 – paleoceanographic conditions during sapropel deposition

Stage 1 contains *Orbulina universa*, *G. obliquus*, *G. sacculifer* and *G. apertura* which are typical of warm-oligotrophic waters, prevailing at times of high summer insolation in the Northern Hemisphere. At those times, the low $\delta^{18}O$ values in *O. universa* are interpreted as a high freshwater input into the basin and warm surface temperatures, which would lead to strong vertical stratification in the water column. This fauna is dominant during the deposition of the middle–upper part of the sapropels in Sorbas and within the sapropels and lower–middle part of the diatomites on Gavdos (Figs. 7 and 8). The abundance of

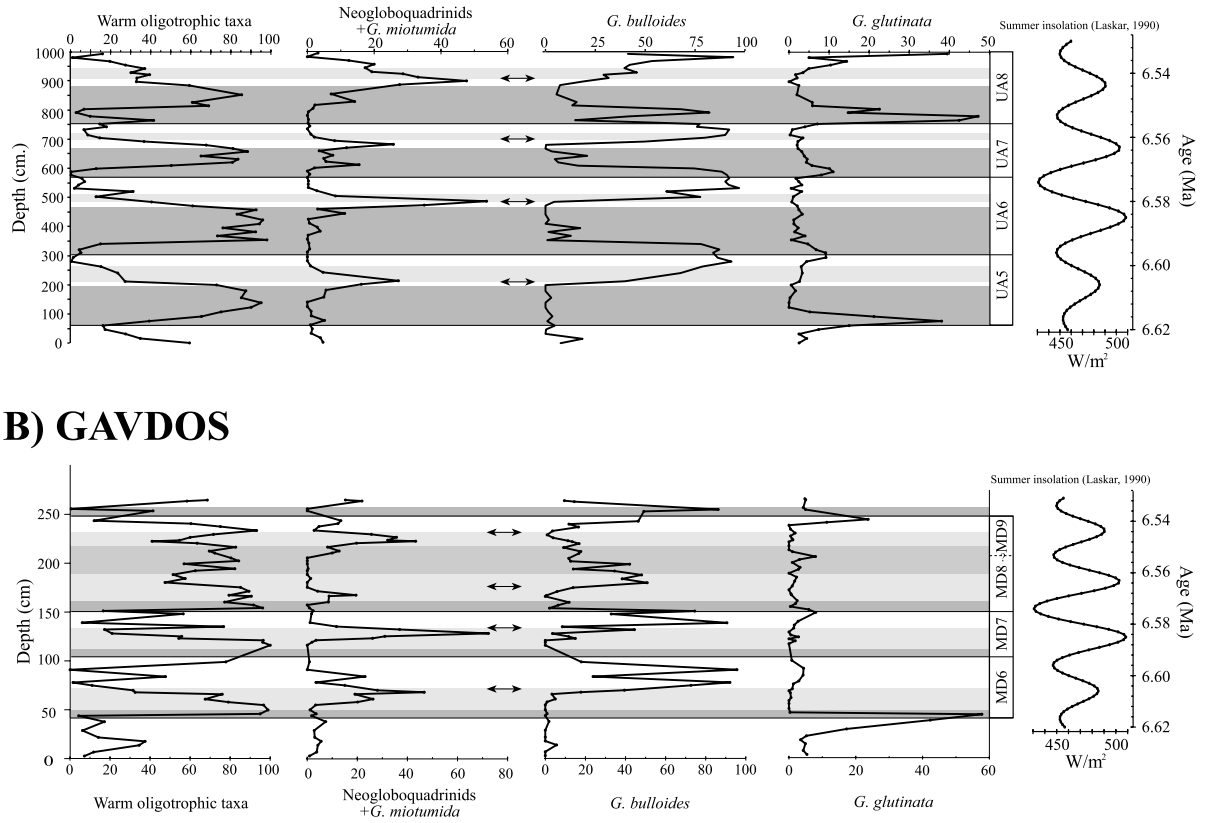


Fig. 7. The precession-driven biological cycle was divided into four stages based on the cyclical changes in abundance of four different groups of planktic foraminifera. (A) Sorbas, (B) Gavdos. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl. UA: upper Abad. MD: Metochia diatomite. Arrows indicate change between the Neogloboquadrinids and *Globigerina bulloides* (stage 2–stage 3).

these faunas together with the absence of Neogloboquadrinids is characteristic of nutrient-depleted, well stratified surface waters, in oceanographic settings (both in the Mediterranean Sea and in open ocean) where the pycnocline is located below the base of the euphotic layer. The Holocene sapropel S1, in the Ionian Sea, is dominated by warm-oligotrophic foraminifera and Neogloboquadrinids are absent (Rohling and Gieskes, 1989) (characteristic of stage 1 in our study), whereas the Pleistocene sapropels S3, S4, and S5 contain abundant Neogloboquadrinids accompanying the warm-oligotrophic foraminifera (situation characteristic of stage 2). In the eastern Mediterranean Messinian cycles, Neogloboquadrinids were abundant in sapropels deposited before the lithologic change at 6.8–6.7 Ma described above (Metochia section, Schenau et al., 1999) and, after these ages, Neogloboquadrinids became abundant in the diatomites (Tripoli Formation, Southern Sicily; Suc et al., 1995; Sprovieri et al., 1996, this study). In the modern Mediterranean Sea, Neogloboquadrinids (mainly *N. pachyderma*, dextral coiling) only become abundant when winter temperatures are colder than 14 °C (database of Kallel et al., 1997). During the Messinian, milder winter temperatures would have been responsible for the absence of Neogloboquadrinids during stage 1.

The increase of warm-oligotrophic foraminifera

in Sorbas took place well above the base of the sapropels, suggesting that deep water stagnation occurs prior to the appearance of stratification in surface waters, that favored the growth of the warm-oligotrophic foraminifera. Although the sapropels on Gavdos are very thin and consequently the number of samples analyzed in this unit is very low, it seems that the increase of warm-oligotrophic foraminifera also occurs inside the sapropels at least in cycles MD6 and MD8 (Fig. 4). Oceanographic conditions during this stage are interpreted as similar to those existing today in the Levantine and Southern Aegean Sea where surface stratification is prevalent even during winter and the warm-oligotrophic foraminifera constitute 100% of the assemblage (Cifelli, 1974; Thunell, 1978; Pujol and Vergnaud-Grazzini, 1989; Rohling et al., 2002). Winter temperatures would have been consequently high enough to prevent Neogloboquadrinids development, and primary productivity, which is usually linked to the upward mixing of nutrients during that season, would have remained low, as in the actual eastern Mediterranean.

5.2. Stage 2 – diatomite formation at Gavdos

The second stage in the pelagic biological succession is defined by the increase in abundance of the Neogloboquadrinids, which partially replace the warm-oligotrophic foraminifera. This replacement takes place in Sorbas at the top of the sapropels, and therefore the Neogloboquadrinids are abundant during the deposition of the lower homogeneous marls. On Gavdos the replacement is observed in the diatomites and the Neogloboquadrinids are dominant during the middle–upper part of this unit (Figs. 7 and 8). The transition from stage 1 to stage 2, defined by the partial replacement of the warm-oligotrophic foraminifera by the Neogloboquadrinids and Globorotaliids, would be related to an increase in the winter temperatures above $\sim$14°C (database of Kallel et al., 1997, Sierro et al., 2003). The abundance of *Rhizosolenia* spp. and Neogloboquadrinids during this time (Figs. 6 and 8) could be related to the formation of a shallow nutricline. This species is one of the taxa adapted to flourish under the low illuminated waters of the thermocline and nutricline; the 'shade flora' of Kemp et al. (2000). The particular hydrographic structure prevailing during stage 2 (i.e. vertical stratification combined with a shallow nutricline and cooler winter temperatures) favored the development of two planktic communities, those dominated by warm-oligotrophic planktic foraminifera thriving within the nutrient-depleted waters of the mixed layer, and those proliferating in the relatively nutrient-rich, subsurface waters of the nutricline, e.g. Neogloboquadrinids. These oceanographic changes are reflected in the deposition of the lower homogeneous marls in Sorbas, and in the deposition of the diatomites on Gavdos.

Since the foraminifera typical of stage 1 are related to the lowest $\delta^{18}O$ in *Orbulina universa*, and the Neogloboquadrinids in Sorbas increase in parallel to the $\delta^{18}O$ record, it is inferred that faunas typical of stage 2 occur in Sorbas at a period of decreasing freshwater input into the basin and decreasing surface temperatures, which can be related to decreasing summer insolation and increasingly dryer climates. The sapropels and lower homogeneous marls in Sorbas and the sapropels and diatomites of the Tripoli Formation in the eastern Mediterranean are interpreted as having been formed under equivalent oceanographic conditions characterized by surface water stratification. The high subsurface primary productivity and thereby the high export production may have contributed to oxygen consumption in deep waters and the subsequent disappearance of benthic foraminifera, and to the formation of the laminated diatomite sediments.

The diatomites in our Gavdos cycles occur during part of stage 1, the transition stage 1 to stage 2, and during stage 2 (Fig. 8). In this interval, the water column remains stratified, and there is no benthic foraminifera, indicating that bottom waters were anoxic. A slightly more vigorous vertical mixing of the eastern Mediterranean waters would have brought more silica into the euphotic zone at Gavdos. This may be due to the fact that the Gavdos section was in a more 'open' environment, whereas the Sorbas cycles were deposited in an enclosed basin (paleodepth <200 m; Krijgsman et al., 1999), where vertical mixing during

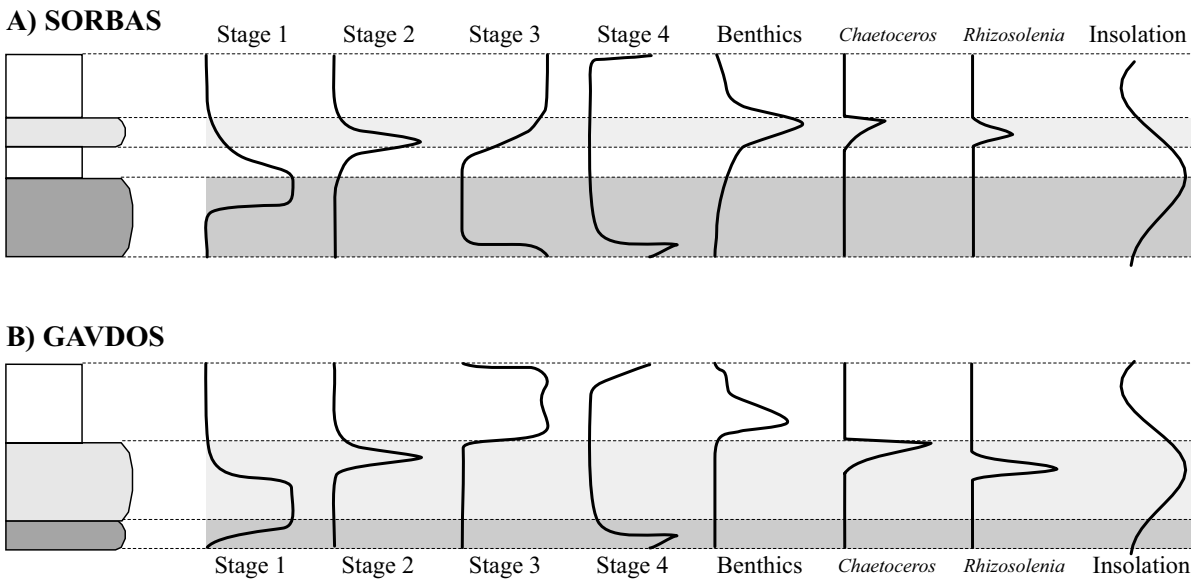


Fig. 8. Summary diagram showing similarities and differences between western (A) (Sorbas) and eastern (B) (Gavdos) Mediterranean Sea lithological and organic results during the Messinian. Dark gray: sapropel. Light gray: diatomite. White: homogeneous marl. Stage 1 represents warm-oligotrophic planktic foraminifera species; stage 2 represents Neogloboquadrinids and *Globorotalia miotumida*; stage 3 represents *Globigerina bulloides* abundance, and stage 4 represents *Globigerinita glutinata* abundance. The abundance of benthic foraminifera, two diatom species, and a reference insolation cycle are also represented. All values increase to the right.

sapropel formation would probably have been slower.

5.3. Stage 3 – vertical mixing and the prevalence of *Globigerina bulloides*

Surface water stratification was broken at the transition between stage 2 and stage 3 and the Neogloboquadrinids were replaced by *Globigerina bulloides*. This species is dominant in the nutrient-rich waters prevailing today in open ocean settings characterized by vigorous vertical mixing or upwelling (Hemleben et al., 1989; Reynolds and Thunell, 1985). *G. bulloides* lacks algal symbionts and therefore it is not restricted to the euphotic zone. The replacement of the Neogloboquadrinids by *G. bulloides* occurred at the base of the diatomites in Sorbas, whereas the same event on Gavdos occurred near the transition from the diatomites to the homogeneous marls (Figs. 7 and 8). An exception occurs at cycle MD8 where it is found in the upper part of the diatomite at the level of change between prominent and weakly laminated sediments (Fig. 7B). The high percentages of *Chaetoceros* RS that replace *Rhizosolenia* spp. near the top of the diatomites on Gavdos may be the first indication of the onset of vertical mixing and upwelling (Figs. 6 and 8). Although the decrease in silica and phosphorus at the diatomite–upper homogeneous marl transition in the Sorbas basin (Filippelli et al., 2003) seems to indicate a reduction in primary productivity, the dominance of *G. bulloides* and the large numbers of benthic foraminifera in the upper homogeneous marls are interpreted as indicative of eutrophic conditions. In addition, *G. bulloides* has been linked to high turbidity upwelling waters, in relatively nearshore settings (Ortiz et al., 1995). A high dust load in the water column (probably related to the arid precession minimum) would also have contributed for the high *G. bulloides* abundance in our Messinian sections.

The cool and arid climates prevailing at times of low summer insolation around the Mediterranean (Sierro et al., 1999) would lower surface temperatures and reduce the freshwater input,

and consequently increase surface salinities, which would account for the heavier $\delta^{18}O$ values in *Orbulina universa*.

The prevalence during this stage of active vertical mixing would have resulted in lower winter and summer temperatures and higher primary productivities. Nevertheless, oxygen in bottom waters was obviously not consumed as recorded by the abundance of benthic foraminifera in both basins (Fig. 4). The concentration of benthic foraminifera increases with enhanced rates of organic carbon fluxes to the bottom (Jorissen et al., 1995; Van der Zwaan et al., 1999; Schmiedl et al., 2000), but decreases when oxygen becomes a limiting growth factor. The double peaks in abundance of benthic foraminifera during deposition of the homogeneous marls and the diatomites in the Sorbas basin (Fig. 5) would occur during the high rates of organic carbon reaching the sea floor. The oxidation of this organic matter would lead to oxygen reduction and hence severely limit the benthic life. Less-oxic conditions were mainly attained at some levels during diatomite formation although minima in benthic foraminifera concentration were also found in the middle part of the upper homogeneous marls. Sorbas diatomites were deposited in relatively well oxygenated bottom waters evident in the abundance of benthic foraminifera, and the diatomites on Gavdos were deposited in anoxic or suboxic environments, where benthic foraminifera could not survive (Fig. 8). The change towards less laminated sediments observed in the uppermost part of Gavdos diatomites indicates a gradual recovery of benthic activity probably due to a slight increase of bottom water oxygenation. We therefore consider that diatomites and the upper homogeneous layers in Sorbas were deposited under similar oceanographic conditions to the homogeneous layers on Gavdos, although this does not necessarily mean that they were coeval.

Stages 1 and 2 are interpreted as times of well stratified surface waters and generally low bottom water ventilation, and stage 3 corresponds to times of vigorous vertical mixing and good bottom ventilation. The high surface salinities and lower temperatures would favor deep water convection, bringing nutrients stored in deep waters to the surface (see also Filippelli et al., 2003), and increasing the bottom water oxygen concentration. Silica and other nutrients, such as phosphorus, likely stored in deep waters during stages 1 and 2, would be brought to the surface in high concentrations and result in diatom blooms deposited as the diatomites in Sorbas (Filippelli et al., 2003). However, on Gavdos, silica utilization by diatoms during stage 2 led to diatomite deposition and therefore subsurface waters were already depleted in silica during stage 3, and consequently the homogeneous layers were deposited.

5.4. Stage 4 – onset of sapropel deposition

The fourth stage in the biological succession occurs at the transition from the homogeneous marls to the sapropels at both sites. This lithologic transition is marked in both locations by peaks in abundance of small-sized foraminifera, particularly *Globigerinita glutinata*, although *Globigerina bulloides* is still the dominant species. *G. glutinata* is only abundant at the base of the sapropels (Figs. 7 and 8) within an interval where the concentrations of planktic and benthic foraminifera (expressed in planktic or benthic foraminifera per gram) are very low in Sorbas (Fig. 5). Unfortunately the concentration of foraminifera per gram was not measured on Gavdos although, based on visual inspection, foraminifera are also rare in these intervals. In the modern ocean, *G. glutinata* reaches a relatively high percentage of foraminiferal assemblages only when there is a low concentration of other planktic foraminifera (Tolderlund and Bé, 1971). The low abundance of planktic foraminifera in general and subsequent increase in relative abundance of *G. glutinata* in our Messinian sections would be related to the existence of physico-chemical conditions (i.e. high salinity, or highly eutrophied surface waters) that are unfavorable for the foraminiferal growth (Sierro et al., 1999, 2003).

Since the peaks in abundance of *Globigerinita glutinata* are always linked to the onset of sapropel deposition, both in Sorbas and Gavdos, they are considered as relatively isochronous events. Although surface productivity and export produc-

tion were very high throughout stage 3, the continuous presence of benthic foraminifera is interpreted as active bottom water ventilation. This suggests that the occurrence of anoxic conditions and sapropel formation was not triggered by surface water productivity, and that decreased deep ventilation triggered the onset of sapropelitic deposition. The decrease in ventilation probably occurred at a time immediately after the summer insolation minimum, when salinity would have decreased at the surface due to the enhanced freshwater input into the basins. Consequently, high saline waters remained near the bottom resulting in stratification and deep water stagnation. Deep water stratification leading to anoxic conditions in bottom waters must have taken place well before the occurrence of surface water stratification, evident in the progressive lowering of the $\delta^{18}O$ in the initial part of the sapropel deposition, and the replacement of *Globigerina bulloides* and *G. glutinata* by the warm-oligotrophic foraminifera.

Although a bed to bed correlation between the quadripartite cycles of Spain and the tripartite cycles on Gavdos is hard to establish, it appears that the sapropels and the lower homogeneous marls in Sorbas are coeval with the sapropels and the diatomites on Gavdos (Fig. 8). The diatomites in Sorbas, which mark the change from surface water stratification to vertical mixing, may be partly equivalent in time with the topmost part of the diatomites on Gavdos, and therefore the peaks in abundance of *Chaetoceros* may be in part isochronous in both basins (Figs. 6 and 8). Part of the diatomites and the upper homogeneous marls in Sorbas may be isochronous with the homogeneous marls on Gavdos. The short influxes of *Globorotalia miotumida* and *G. scitula* recognized in some Mediterranean sections (Sierro et al., 2001) are also considered as isochronous events. One of these events (at 6.585 Ma, cited above) occurs in the lower homogeneous marls of cycle UA6 in Sorbas, and within the uppermost part of the diatomite MD7 on Gavdos. A short influx of *G. scitula* was recognized in the lower homogeneous marl of cycle UA29 in Sorbas, and in the uppermost part of diatomite MD29 on Gavdos (Sierro et al., 2001). These data strongly support the correlation of the sapropel and lower homogeneous marl in Sorbas with the sapropel and diatomite on Gavdos.

6. Conclusions

Sedimentary quadripartite Messinian cycles, recorded in the western Mediterranean, are formed by the succession of a sapropel at the base followed by a homogeneous marl bed, a diatomite and a second homogeneous marl which define the top of the cycle. The same cycles are tripartite in the eastern Mediterranean and are defined by a sapropel and a diatomite, followed by a homogeneous marl layer. Climatic oscillations due to precession-driven insolation changes are the inferred origin of these cycles.

Despite the lithological differences, the pelagic biological cyclicity is surprisingly similar; in both basins a succession of four different groups of planktic foraminifera was found in each precession-driven sedimentary cycle, defining four stages in the biological succession (Figs. 7 and 8). Stages 1 and 2, defined by the abundance of warm-oligotrophic foraminifera (stage 1) and the Neogloboquadrinids and Globorotaliids (stage 2) are linked to times of relatively high summer insolation in the Northern Hemisphere. The lower temperatures and high input of freshwater into the basins and the subsequent low salinities at surface waters evident in low planktic foram $\delta^{18}O$ resulted in a period of prevalent surface water stratification in the water column. The dominance of foraminifera characteristic either of stage 1 or 2 is dependent on the position of the nutricline and on winter and summer temperatures.

Stage 3, dominated by *Globigerina bulloides*, has been related to times of low summer insolation when the high salinities and low temperatures in winter surface waters contributed to destabilize the water column, inducing deep water convection, and upwelling of nutrient-rich waters to the surface. The ending of the vertical stratification, marked by the change from stage 2 to stage 3 (i.e. replacement of the Neogloboquadrinids by *G. bulloides*), in the foraminiferal succession is a marked event in both basins, occurring at the

base of the diatomite in Sorbas and near the top of the diatomites on Gavdos.

The onset of sapropel deposition is evident in both sites by peaks in relative abundance of *Globigerinita glutinata*, occurring at times of otherwise very low planktic foraminiferal concentration (stage 4). Despite high primary productivity and export production inferred for stage 3, the high oxygen utilization during oxidation of the organic matter did not lead to anoxic bottom water conditions. By contrast, benthic foraminifera were abundant during this interval across the Mediterranean, indicating that the rate of oxygen supply from surface waters overcame oxygen consumption at depth. After the summer insolation minimum, the presence of highly saline waters at depth in combination with decreasing surface salinities, as climate changed from arid to humid conditions, led to deep water stagnation and sapropel formation.

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